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Nils Enlund, Helsinki, Finland
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Preface

Nils Enlund

Co-editor, Chairman of the iarigai Program and Publishing Committee
E-mail: nilse@kth.se

Innovation in and through print and media technology

In an article in *The Guardian* on June 3, 2012, Emma Munro Smith, editor of *Moshi Magazine*, is quoted saying: "Computers and video games haven't killed physical toys and games, so there's no reason why the digital world should kill print. Lack of innovation or providing a poor product is far more likely to do that. The amazing range of technological opportunities that can be used to support and interact with print are definitely a bonus, not a threat."

This is exactly what this publication is about: Topical reports on scientific studies that that will help us improve print and media products, on technologically based innovations, and on new ways to support media communication and interact with media services. A veritable gold mine of information for the development of the print and media industry and for researchers in the field!

This book contains the scientific and technical papers presented at the 40th International Research Conference of iarigai, the International Association of Research Organizations for the Information, Media and Graphic Arts Industries, held in Chemnitz, Germany, on September 8 -11, 2013. The papers presented were selected by a committee of international experts through a double-blind review process.

All the papers are, in various ways, concerned with technology based innovation in the print and media field. This book is divided into four sections, reflecting the different research foci and the diverse approaches to innovation for and in the industry. The section on *printed functionality* investigates innovative ways of using printing technology for totally new purposes. The section on *printing processes and products* is concerned with the improvement of industrial processes and product development for traditional paper based information products. The section on *quality in print* looks carefully at new methods for improving and maintaining the technical and perceived quality of printed products. And, finally, in the section on *media development and the consumer*, scientists explore the problems and opportunities of satisfying consumer demands in a multimedia world.

I believe that much inspiration as well as concrete foundations for business development and further research can be found within these pages. Some of the papers presented here will later be further expanded into full-fledged scientific reports that may, after full paper peer-review be published in the scientific quarterly *Journal of Print and Media Technology Research*. Through its yearly research conferences, through the printed journal, and through digital channels, iarigai is committed to provide the print and media industry as well as the research community with topical research information. The principal aim is to actively support further innovation and development within our field.

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Functional printing

Design rules checking for printing electronic devices: concept, generation and usage

Jordi Carrabina[1], *Eloi Ramon*[1], *Francesc Vila*[2], *Carme Martinez-Domingo*[1], *Jofre Pallarés*[2], *Lluís Teres*[2]

[1] Universitat Autònoma of Barcelona
CAIAC. Escola d'Enginyeria. Edifici Q. Campus de la UAB. E-08193 Bellaterra
E-mails: {firstname.familyname@uab.cat}

[2] IMB-CNM(CSIC)
Campus de la UAB. E-08193 Bellaterra
E-mails: {firstname.familyname@imb-cnm.csic.es}

Abstract

Printing electronic devices is quite different of than printing colours since the behaviour of devices strongly rely on the geometrical properties of the layers being fabricated. This dependency is related to both superficial dimensions and thickness although designers cannot manage thicknesses.

Design rules are a set of restrictions that designers must respect in order to get working printed circuits and refer to every single layer (min width, min spacing, notch) or combinations of two (overlap, extension, margin) or more layers (i.e. electrical contacts or conductor crossing restrictions).

Those rules are mostly process independent but their values depend on the resolution of the printed machinery and on the fabrication process. Design rules have a strong effect on the performance and yield of the devices and systems due to the fact that designers tend to be aggressive in order to have a maximum device density so to occupy the minimum space to implement a given functionality or equivalently provide the maximum functionnality for a given area.

Design rules are checked using Design Rules Checker tools (DRCs) that alert from the violation of such rules. Violations should be corrected by the designer, and the foundry will not accept the fabrication of designs violating design rules. The process of obtaining design rules is critical. If these rules are aggressive they will allow high device density but at a risk of low yield whereas if they are too conservative, yield will increase but performance will probably decrease and then that process will have fewer opportunities to build complex systems, so less competitive.

This paper will show the procedures of conceiving, building and using design rules for an inkjet printing process of 5 functional layers for the fabrication of electronic circuits including pMOS OTFTs as most complex devices.

Keywords: design, integrated circuits, printed components

1. Introduction

Electronic industry in taking a significant part of the business that was formerly own by printing industry since most moving from paper format to electronic format. In this case, the electronic format is even somehow wrong. Electronics is based mainly on integrated circuits (chips) but also on active and passive devices, connectors, wires and substrates (usually ***printed*** circuit boards). Software can be considered part of electronics but it is usually not. Software people are considered themselves as Information Technology people, far away from electronics. They tend to deal with algorithms, data structures, web, semantics, etc. but also on computers architecture and related efficiency parameters such as processing speed, area or volume, cost and energy efficiency (to save battery power). Software can be applied to any different electronics platform for different purposes and for most of the applications in our developed world.

Now we are in a situation in which printing people can take a piece of the pie of the electronics business. This would happen thanks to the new printed electronics domain that opens new possibilities for the printing industry in competition with the silicon industry. This is still quite far from the information technology domain since the electronic circuits that can be printed does not show enough computational performance (mostly due to device integration density and low yield) to economically compete with the electronic industry as it has been shown in the RFID tag arena.

Electronics circuits are also divided in analog and digital electronics, but those concepts are quite different from the printing domain. Analog electronics refer to the circuits that "compute" using the "analog value" of the signal what is the electric voltage (sometimes the current) of the electrical nodes of the circuits. Digital electronics, on the other side use typically 2 values, "logic-1" and "logic-0" that can be identified as the highest and the lowest voltage in the circuit. Nowadays, digital electronics represents more than the 99 % of the chips in the world. Apart, there are other circuits such as those related to the power supply regulation or the clock management that are out of the scope of the printed electronics capabilities.

The place where printed electronics can compete with traditional electronics relies on the "sensors and actuators" and on the "energy" domain. Sensors and actuators are the devices that interact with the physical world so bridging from physical magnitudes to electric signals. Sensors and actuators connect with software processors through peripherals. Peripherals, in the electronics language, refer to the circuits that are around the central processor (although in the current chip technologies there are many processors in one chips) that connect it to the devices out of the chip. Examples of sensors are all devices that transduce physical magnitudes such as light, pressure, chemical or biological magnitudes. Examples of actuators are mainly displays such as OLEDs but also can be considered as such the radiofrequency interfaces provided by antennas. The energy domain refers to the voltage and current sources that are needed to run the electronic circuits such as batteries of photovoltaic cells.

Furthermore, printed electronics are more powerful than printed circuit boards (fabricated typically using photolithographic processes) since these contain basically the wiring support to connect chips with the rest of the components of an electronic system whereas printed electronics are capable to fabricate devices apart of wiring.

Printing electronic devices is quite different than printing colors since the behavior of devices strongly rely on the geometrical properties and interactions of the layers being fabricated. This dependency is related to both superficial dimensions and thickness.

Electronics, as well as printing, is also separated between design and technology processes that have different duties in building final products. Designers are in charge of mapping the customer's requests into descriptions that can be fabricated using well established and standardized technological processes. Process technology people controls the whole fabrication process for any given technology, being printing or electronics whereas designed does not need that much detail. This means that technology and design people agree in some standard formats and rules so that they can work as much independently one to the other.

In electronics, design rules are a set of restrictions that designers have to respect in order to get working printed circuits. This restrictions refer to single layer[1] (minimum width of a line or rectangle, min spacing between lines or geometric figures, minimum notch, etc), to two layers (overlap, extension, margin) or even to multi layer combinations (to be considered when various layers are needed to build a device as for instance the electrical contact of two different metallic layers or the transistors structures). In other words, design rules are limitations to the drawing freedom of designers related to building collections of devices and their wiring that are selected in order to build circuits with given electronic properties.

The form of those rules is mostly process independent in the sense that it can be applied to most of the processes. Opposite to that, the values of those rules depend on each specific fabrication process according to the precision and resolution of the printed machinery, the alignment between layers and the yield of the fabrication process. Design rules have a strong effect both on the performance and yield of the devices and systems due to the fact that maximum performance is usually obtained using minimum dimensions from some of the designed layers. An example of this is even the naming of silicon fabrication processes (i.e. 0,35 microns or 14 nm) that refer to the minimum gate transistor length (related to the minimum width of the polysilicon layer).

Once design rules are fixed for a given process, designers tend to be aggressive in order to have a maximum device and wiring density so to occupy the minimum space to implement a given functionality or, what is the same, to provide the maximum functionality for a given area. This is again related to yield in the sense that

[1] Layer refers to each of the levels that are drown with the same design color that correspond to features that are fabricated in the same process step.

maximum density will increase the failure risks. But since rules are coming from fabrication process, it is the job of the process people to provide the set of rules that result is a satisfactory yield, since designers are not going to pay for fabricated circuits that does not work.

Reducing circuit surface is important for two reasons. The first one is related with system level constrains, since both foils and integrated circuits have to fulfill geometrical shape restrictions in order to be integrated into a complete system or ever for usability restrictions. The second one refers to the cost. For a given process, the cost of every foil or chip depends on its surface (usually in a linear way) for a given number of fabricated units. This tends to be an important reason to squeeze the circuit to the maximum device density possible. Again, silicon processes can be qualified according to the device density that is possible to achieve (in terms of transistors per square millimeter).

2. DRC Concept

Design rules are checked using Design Rules Checker tools (DRCs). DRC tools are usually embedded of an Electronic Design Automation (EDA) framework. EDA frameworks contain the complete set of tools, plus a complex data base structure, that designers use to build their circuits such as layout editors, device and circuit simulators, synthesis tools (both for automatic layout generation and high-level hardware description languages), test analysis and generation, electromagnetic and thermal behavior, etc.

DRCs are applied on drawing layouts and alert from violations of design rules. Violations should be corrected by the designer before sending the circuit for fabrication. The foundry, in charge of fabricating the foils, will not accept the fabrication of designs violating design rules since it cannot ensure minimum fabrication yield. On the other side, if designs pass DRC it is expected that fabricated devices and circuits will work well and also with high yield, so that majority of produced design are functionally correct.

The process of obtaining design rules is critical. If these rules are aggressive they will allow high device density but at a risk of low yield whereas if they are too conservative, yield will increase but performance will probably decrease and then that process will have fewer opportunities to build complex systems, so less competitive.

Building design rules requires, on one side, the knowledge on the machinery and alignment processes, and on the other side, fabricating DRC-oriented sets of structures for the different layers and combination of layers, from which we can decide rule values after optical and electrical analysis. Some of those structures will also be used to monitor the fabrication runs when fabricated together with the circuits in the normal fabrication runs as a side monitoring structures.

In this environment related to building devices and circuits out of printing processes, this paper will show the procedures of conceiving, building and using design rules for an inkjet printing process composed of 5 functional layers for the fabrication of electronic circuits based on pMOS OTFTs as most complex devices.

3. Fabrication process description

Classical printing people (graphic designers, prepress managers and printing technologists) focus their work in achieving the best possible quality based on aesthetic requirements (color, texture, brightness, …).

Traditional printing uses techniques such as optimized superimposition of halftone screens that leads to realistic "continuous tone" images to transfer user/designer materials such as photos into any printable substrate. This tries to obtain optimal printing results with the compromise between cost, quality, resolution, gamut, etc. given by the fabrication process characteristics.

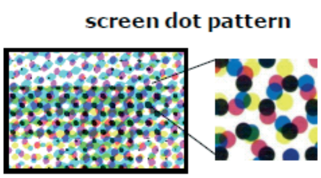

Figure 1: Example of image formation by the superposition of colour dots

This is a completely different concept compared to the one that follow printed electronics designers. These have to focus on achieving a given electronic functionality, usually defined at application level, implemented as a combination of devices connected though conductive tracks according to the electronic circuit requirements, such as for instance a flexible logic interface between a flexible printed touch sensor and a flexible printed display.

Printing devices with electrical properties require two main geometrical characteristics related to the process of printing materials:

(1) Single-layer continuity in order to reach both electrical conductivity (conductors, semiconductors) but also electric isolation (dielectrics) when separating conductive layers. This is translated in drawing geometric structures (typically - but not only- rectangles) that are connected among them (what is to say that geometric figures have contacting sides or overlapping areas).

(2) Cross-layer restrictions, according to the topologies required to build working multi-layer devices (such as OTFTs, diodes, capacitors, etc.) or to avoid short circuits (i.e. contacts and vias). The device at this stage has to be viewed as predefined combination of layers with certain rules and design parameters, such as for instance, for the OTFT, the *width* of drain and source metallic electrodes (proportional to the electric current) or the *length* of the transistor channel as the distance between drain and source (inversely proportional to the electric current).

Again, layers have a similar meaning that in traditional electronics: they refer to any material being processed at a single processing step (like processing the different color inks). Semiconductor or resistor layers can be easily identified as different layers (since they correspond to different masks in a photolithographic process or a single material inkjet printing step). But instead of color layers, in printed electronics we can have different layers that use the same material, such as several metals or even dielectrics that are printed at different stages of the fabrication process. In the case of metals, these layers correspond to different conductive levels (metal1, metal2, metal3,…) that can be connected through vias (holes on a uniform foil-wide layer) or disconnected with isolators (locally printing or dielectric areas). In the case of dielectrics, there are two different options: (i) thin dielectric, required to build the transistor gate (current is inversely proportional to the thickness of the dielectric), and (ii) think dielectric, easier to fabricate, used for isolation between metal layers.

Therefore, dot pattern printing techniques for printed electronics, are oriented to produce printed structures that have to look like the figures drawn during its design process. Drawn dimensions are related with electronic circuit function and performance, and usually come out of circuit simulation processes oriented to achieve a certain performance (usually measured in terms of area required, processing speed and energy consumption). From a technology point of view, maximum likelihood can be achieved from tuning the different parameters of the materials formulation and printing processes.

As a result, the electrical parameters of devices, such as resistance, vary according to the final printing results from an ideal behavior to a not working device through a parameter change. This phenomenon can be observed looking at the different lines printed in 0 where different widths are shown together with a discontinuous line that correspond to an early stage of the process development.

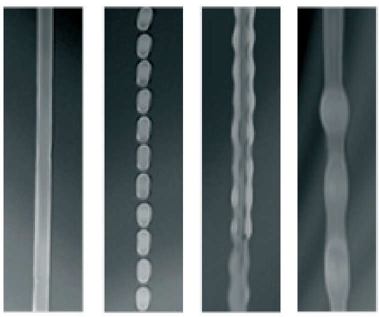

Figure 2: Example of printed patterns for the same line with different process parameters (i. e. drop spacing, drop volume)

Once the process is tuned and fixed (sometimes we call it frozen) and good quality structures (conductive tracks and devices) are produced, it should deliver a set of rules defining the minimal dimensions that designners have to fulfill in order to get working foils. These rules are basic design parameters and hidden (or abstract as we like to say) the process technology information.

Rules are defined according to set of layers defined for the fabrication process oriented to build bottom gate, bottom contact pMOS OTFTs. 0 shows a typical layer stack showing the printing order of the differrent layers fabricated in several process steps (at least one for printing layers plus others like cleaning, surface treatments, alignment, etc.). Layers at the bottom are fabricated first that layers at the top. A different process can have another set of layers although, in most cases, the layers used to draw geometries are the same (same name) even for building different circuit topologies. This is due to the fact that designers draw two dimensional shapes and the third dimension is fixed by the fabrication process (there is not any design freedom on it) so that in can be abstracted in the design process. Vertical dimensions can be viewed on what we call *vertical cuts* (similar that Figure 3 but more oriented to devices) although there are not commonly used during, except for educational purposes.

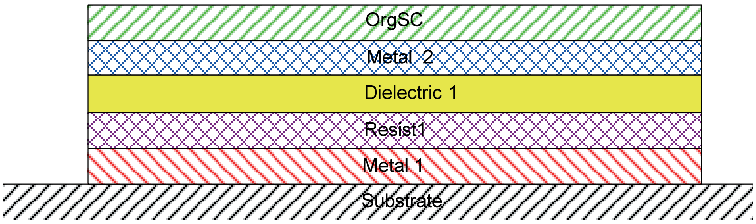

Figure 3: Layer description according to the printing order (bottom layers are printed first)

4. Design rules formulation

Design rules can be formulated as numbers on single layer figures, or on relations between geometrical figures made out of different layers (such as those needed to build devices). Later on, these rules can be checked using Design Rules Checkers (DRCs) that can be activated directly on the designed geometric (layout) drawn using design tools. Design rule checkers applied on the designed layouts highlight rule violations on top of the same layout providing information of the rule that has been violated so that they can be easily corrected, and later rechecked to verify that that error is corrected.

Figure 6 shows the kind of information that foundries provide to the designers (usually under confidentiality agreements). In this case the rules and its meaning are provided. For every process and every drawing layer there will be a specific set of values for these geometric magnitudes (width, spacing, notch) for the single layer parameters (figures in the upper row), except for devices such as contacts and vias or in some cases OTFTs that have fixed dimensions.

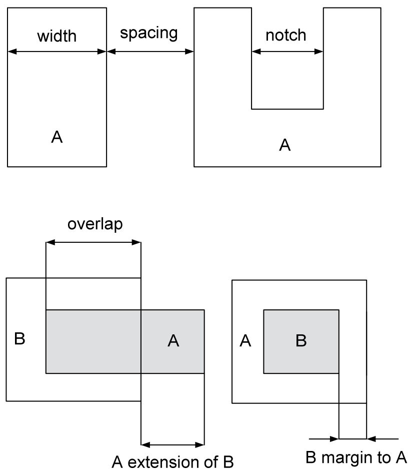

Figure 4:
Elementary rules that require the definition of minimum values for the correct fabrication of single layer geometries (top) and 2-layer structures such as an electrical contact (bottom)

Drawings in the bottom row of Figure 4 refer to two of the fundamental rules (overlap, extension, and margin) related to two layer relations required to build electrical connections and devices and rely on both the printing accuracy of every layer and also the interlayer alignment quality. 0 shows the personalization of some of DRC structures using mnemonics for the layers defined in 0. M1D1.M.1 means *Dielectric 1 margin to Metal1*. M2D1.E.1 means *Metal2 extension of Dielectric 1*. Complex rules, involving more than 2 layers are also possible. In that case, tools tend to use derived layers in order to geometrically identify those structures.M2CROS.S.1 refers to the rule concerning the separation between Metal 2 layer geometries when these are on top of metal one but not contacting them (so with dielectric between them). CROS then refers to the area in which there is simultaneously metal1 metal2 and dielectric.

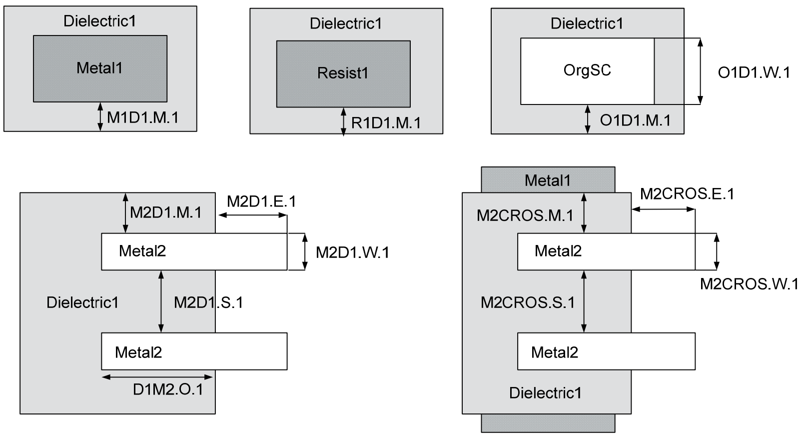

Figure 5: Example of formalization of design rules with mnemonics related to the involved layers and the involved rule for different types of structures that we will find in devices

Most of rules are common for the majority of the fabrication processes but not necessarily all of them. This will depend on specific process parameters such as thicknesses or planarization steps that can avoid restrict-tions due to printing on non flat surfaces.

5. Design rules generation

In order to set the values of the design rule parameters, once a printing process is frozen, several sets of characterization structures should be printed and analyzed mainly optically and sometimes electrically. Typically, these structures correspond to the figures where the parameters under analysis are changing between a range established according to fabrication machinery resolution and printing procedures. The final goal of design rules is to allow obtaining the maximum device density (p. e. in transistors per mm^2). 0 shows an example of test structures to obtain by optical inspection the minimum specific rule for every single layer. This rule is usually set up for the minimum line width.

Figure 6: Example of structures used to optically obtain single layer line separation design rule

For conductive layers, electrical characterization can be an alternative, especially when the spread of printed materials affect also the layer conductivity.

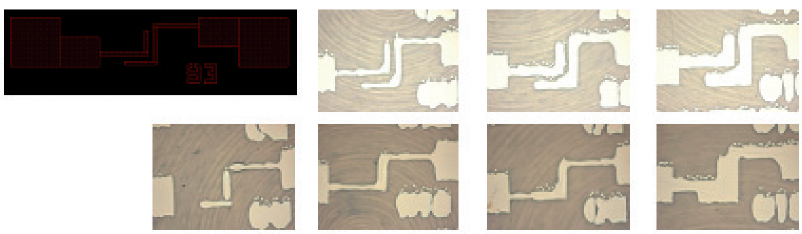

Figure 7: Example of structures used to electrically obtain metal layer line separation design rule with the design drawing (top-left) and some right (top) and wrong (bottom) of the fabricated samples

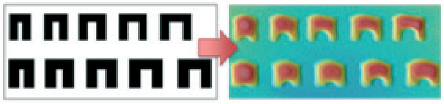

Figure 8: Example of drawing layout variations (left) and their printed structures (right) from which the corresponding design rule can be extracted (i.e. second in the top row and fourth in the bottom row)

6. Design rules usage on a Design Example

In order to show the usage of the DRC, in this paper, we will use a ring oscillator as a central example. Ring oscillators are key circuits used for monitoring and characterizing the dynamic behavior of microelectronics processes since they produce a characteristic periodic (clock-like) frequency that depend on the individual design and technology parameters of the logic gates (usually the same unique gate for every ring) that compose it, typically an inverter. This is related with the maximum speed of the system.

There are several EDA frameworks for silicon microelectronics. Most of them are commercial and range from complex design frameworks to free and/or open source tools that cover most of the design flow. Since the foundations of circuit design in between microelectronics and printed electronics are quite similar, most of them can be used for printed electronics although there are still few of them that are being personalized for printed electronics a part from the circuit simulation. Furthermore, there are very few public Technology or Process Design Kits (TDk or PDK) [OPDK] that personalize the tools for a given fabrication process. This requires a complete porting of the process parameters, including design rules and device models for simulation, packed on a design kit that can be automatically integrated in a design tool. Currently, we have available a beta version of the design kit for our inkjet processes for two different PC-based EDA tools: Clewin and Grade. The design procedure starts from a scheme (0) of the circuit using the EDA tool symbols.

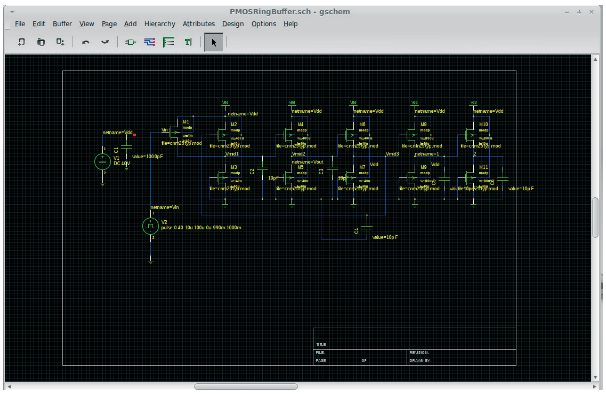

Figure 9: Schematic capture of a ring oscillator on gScheme

On that scheme, simulation is used to help the assignment of device sizes (horizontal dimensions such as width and length of transistors). This process finishes when a given performance (i. e. clock frequency is finished) is obtained from the simulation waveforms (0) on selected nodes.

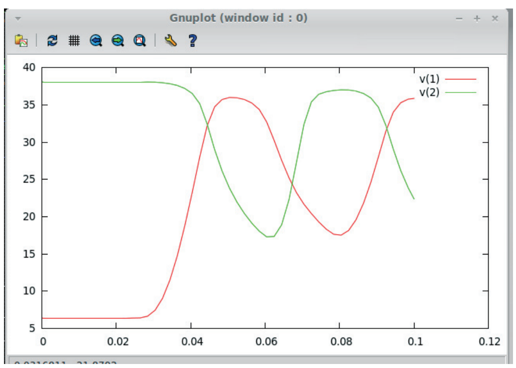

Figure 10: Ring oscillator simulation on gSpice

With those fixed dimensions and device connectivity, one can start drawing the layout of the circuit on a layout editor (0).

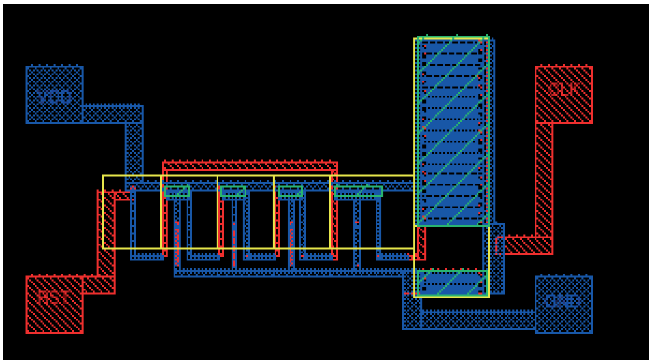

Figure 11: Ring oscillator layout on Glade

At this level, design rules are applied to find layout errors. It is easy to see, in this layout that different layers have different minimum widths as for instance (red and blue) metal layers can be narrow than (yellow) dielectric, due to the printing process.

This layout design is converted into a set of intermediate files using either printed specific f standardized formats sometimes common with silicon microelectronics (such as GDS-II). This specific design has been fabricated several times (examples are shown in 0) in the process of verifying the correctness of the de-sign rules for a given design so that we are able to observe failures optically that let to an update of the corresponding rules.

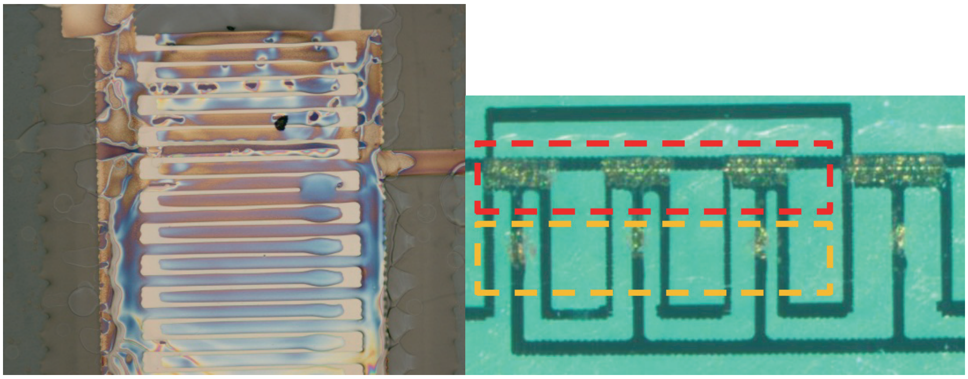

Figure 12: Final ring oscillator fabricated at TUC

7. Conclusions

Design rules suppose critical information concerning the restrictions on the geometries that electronic designers can draw in order to build circuits. These rules suppose the formalization of the completely different design methodologies from printed electronics to classical printing. These refer the geometric limits of the printed features for every layer and combination of layers and are key for the qualification of the process due to its relation with the device density that limits the number of components to be used in a given system design on a limited surface. The effect of violating design rules produces device failures that result in poor fabrication yield. So, design rules are a compromise between performance and yield or also between design and fabrication.

Electronic Design Automation tools integrate Design Rules Checkers that inform designers of violations on the design rules on a design layout. These defined on a technology file related to a given fabrication process. The generation of these design rules is a complex process that needs to be set-up after fixing the process steps. This paper illustrates the concept and formalization of design rules for a fully inkjet printed electronics process, the generation of structures to obtain design rules optically and electronically and the usage of those design rules on a design example.

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Glade http://www.peardrop.co.uk/glade/

Printing technologies for pyrotechnic devices - a design study

Uwe Weiß, Michael Espig, Monique Helmert, Dana Weise, Reinhard R. Baumann

Chemnitz University of Technology
Institute for Print and Media Technology
Department of Digital Printing and Imaging Technology
Reichenheinerstrasse 70
D-09126 Chemnitz, Germany

E-mails: u.weisz@t-online.de; michael.espig@mb.tu-chemnitz.de; monique.helmert@mb.tu-chemnitz.de; dana.weise@mb.tu-chemnitz.de; reinhard.baumann@mb.tu-chemnitz.de

Abstract

Complex electrical systems like displays, sensors and batteries are manufactured by functional screen and inkjet printing processes. With a consolidated knowledge in the different methods of printing technology it is possible to design and realize new complex systems. According to a modular concept, different single components - a battery, an ignition structure and a pyrotechnic line - should be combined to an electric pyrotechnic delay system.

With a parallel battery layout it was possible to provide a reliable amount of energy for the firing impulse. The combination of screen-printed conductive lines and the inkjet printed igniter structure allows a good adjustment of the functional elements of the system and enables an effective manufacturing process.

Keywords: pyrotechnic system, inkjet, screen printing, battery, energetic ink

1. Introduction

Functional printing reveals increasingly new fields of applications concerning active and passive electronic functional components as well as micromechanical elements. Also complex electrical systems like displays, sensors and batteries were manufactured by functional screen and inkjet printing processes. If following the progression of this technology it can be observed that especially the combination of different printing methods overcome the technical restrictions of the single methods. With a consolidated knowledge in the different methods of printing technology it is possible to design and realize new complex systems within a short development time. This should be shown with this study. Single components like batteries and pyrotechnic delaylines are known from literature but not a combined fully printed system [1, 2].

According to a modular concept, different single components - a battery, an ignition structure and a pyrotechnic line - should be combined to an electric pyrotechnic delay system. Therefore we used a combination of screen-printing and inkjet printing methods.

This system is planned to be realized on a flexible polymer substrate (PET and Kapton®) and on an electrical insulated flexible Al-substrate.

2. Experimental

2.1 Ignition structure

Actual inkjet printed silver conductive lines are intended for use as passive structures in signal processing applications. So the typical thickness of these lines amounts between 50 and 100 nm. For an application as ignition structure we need a higher line thickness more than 0.5 µm, because a high input of thermal energy into the pyrotechnic layer is necessary.

Also the lateral design has to be adapted to achieve the desired functionality. As shown in figure 1 in analogy to fluid mechanics, the current density will increase very strong if the lateral dimensions narrows extremely from a broad contact area to small functional area. Most notably for small radii of edges, a local exaggeration of the current density is to expect like for similar thin film structures. This results in an inhomogeneous joule heating behavior and a bad ignition characteristic [3].

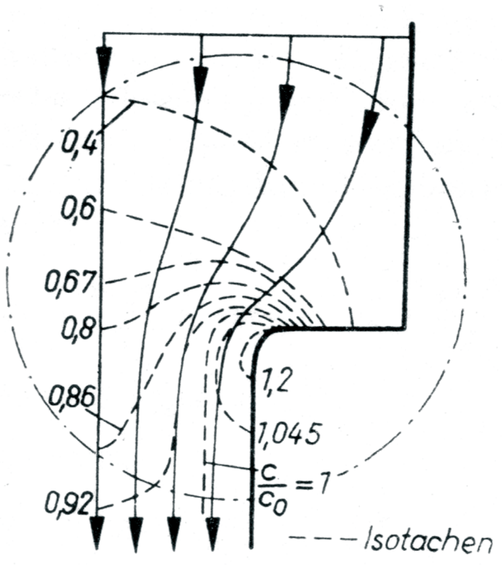


Figure 1: Flow lines and distribution of velocity (isotachen) at a strong decrease of a cross-section profile [4]; the distribution of flow velocity c has an analog behavior to the electrical current density

(I) Restrictions for electrical design

Ignition structures for typical pyrotechnic applications have to fulfill so called all fire and no fire conditions. The no fire condition is necessary to provide a safety level against electric malfunction of periphery components and the ability to apply a low-level test current [3].

The all fire condition is the current value on which the structure has to ignite the pyrotechnic layer. Typical values for the structure resistance are in the range from 0,5 to 3Ω. For our structures we planned following values:

no fire current: 0.5 A
all fire current: 1.5 A . 2A
structure resistance: 0.5 Ω . 3 Ω

(II) Lateral geometric design

According to the requirements described above we designed a butterfly test pattern consisting of two wings connected by a bar. To minimize possible exaggerations of the current density between the contact area and the bar the adjacent edges of the contact area were sloped by an angle β (see figure 2). To adjust variations of the structure resistance two types of bars (square and rectangular/constant width and single or double length) were applied. The wings are used as contact pads for the electrical measurement and as contacts to the battery system (geometric values see table 1).

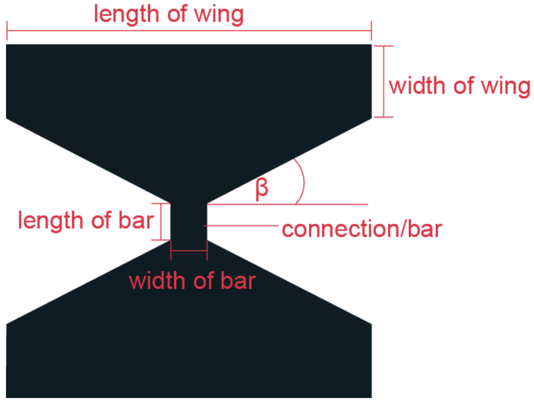


Figure 2: Layout of the used test pattern (butterfly structure)

Table 1: Values of the dimensions of the used test patterns for the igniter structures

Parameter	Values (square bar)	Values (rectangle bar)
Length of wing	2.50 mm	2.50 mm
Width of wing	0.50 mm	0.50 mm
Width of bar	0.25 mm	0.25 mm
Length of bar	0.25 mm	0.50 mm
β	30 °	30 °

(III) Printing

For printing the ignition structure, the Dimatix Materials Printer 2831 (DMP) was used with the Dimatix Materials Cartridges 11610 (DMC) which eject a nominal drop volume of 10 pL.

We used the two different nanoparticle inks SunTronic Jet Silver U5603 (Sun Chemical) and Bayink TP S LT (Beyer) for printing the samples. The SunTronic Jet Silver ink U5603 from Sun Chemical is a silver nanoparticle ink with a particle size smaller than 150 nm. The nanoparticles are dispersed in the organic solvents ethanol, ethanediol and glycerol. The second ink Bayink TPS LT is a two component ink with a low curing temperature below 130 °C.

Glass microscope slides were used as substrates for basic investigations. Then selected experiments were replicated on polyimide substrates. Before printing, the substrates were cleaned with ethanol and compressed air. After printing, the silver structure has to be sintered in an oven (Nabertherm 3000) at ambient air.

To achieve a variation in layer thickness we stacked 1, 2 and 3 layers either with the (I) wet-on-wet method or (II) wet-on-sintered method.

(I) In the wet-on-wet method first all layers were printed with the silver ink and then sintered.

(II) In the wet-on-sintered method each layer is printed and sintered at 150°C / 30 minutes before the next is printed on top.

(IV) Thermal sintering

Depending on the selected sintering parameters (sintering time, sintering temperature), a characteristic microstructure will be developed. This results in a specific resistance of the igniter structure.

To understand the influence of sintering conditions on the microstructure and the resistance, we focused on two sintering routes:

(1) A temperature route to investigate the influence of varying sintering temperatures (150 °C up to 300 °C) at a constant sintering time (30 min).

(2) A time route to investigate the influence of varying sintering times (10 min to 50 min) at a constant sintering temperature (200 °C).

(V) Electrical sintering

Due to the thermal properties of the used substrates, especially for the thermal sensitive PET, we also investtigated the influence of higher current densities to sinter our printed igniter structures. We looked for the opportunity to realize igniter structures also on thermally less stable polymeric substrates [5]. Beside of the sintering effect we wanted to know more about the structure behavior in case of an applied no fire current of 0.5 A.

For these investigations we used the fast drying Bayink printed structures. The range of the applied constant test currents lies between 0.5 A and 1.4 A. For this current treatment we observed the resulting resistance value.

(VI) Analyses / equipment

The sintered patterns were evaluated regarding the optical quality, the surface profile, the microstructure, and the electrical resistance. Optical images were taken with the light microscope Leica DM 4000 M (Leica Microsystems). The layer thicknesses and surface profiles were measured with the profilometer Dektak 150 (Veeco). The microstructure of the patterns was examined with the scanning electron microscope Aurega 60

(Carl Zeiss) and by the use of X-ray diffraction applied with the Universaldiffraktometer XRD-7 (Shimadzu). For SEM images of the cross sections, the patterns were cut with a focused ion beam. The resistance of the patterns was measured with the 4-point method (Yokogawa GS610).

The electrical sintering and the ignition behavior were characterised by means of a source measure unit (yokogawa GS610) and digital oscilloscope (yokogawa DL9040) with a current probe (pbc100) and a differential probe (pbdh1000).

2.2 Battery system

As the starting configuration we used a Zn/MnO_2-battery system, manufactured with the screen printing process. Therefore a semiautomatic screen printer (EKRA E1 XL) and a continuous-flow dryer (3D microDRY) were used. The sheet to sheet manufacturing process is shown in figure 3.

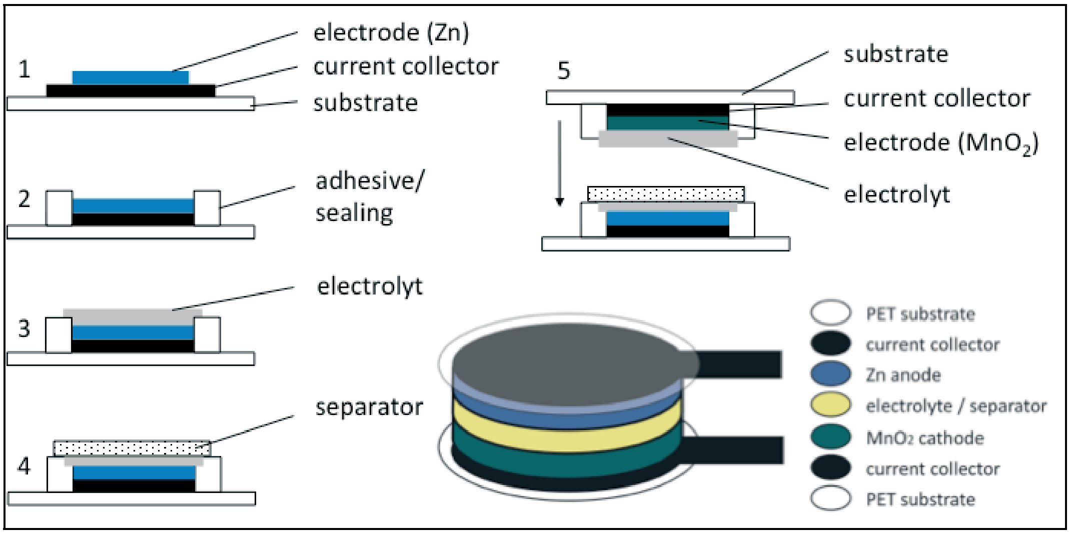


Figure 3: manufacturing process of a single Zn/MnO_2 - cell [6]

The different battery components were applied layer by layer. After each coating step the samples were dried with a continuous-flow dryer. At the first step the carbon current collectors were printed onto flexible substrate, followed by the printing of the positive and negative electrode materials (MnO_2 and Zn). Then a high performance adhesive tape is applied as a spacer to separate the electrode area. Afterwards the electrolyte, which is based on zinc-chloride, is filled into the electrode area covered with a separator [6].

After characterizing the single battery cell concerning its maximum short cut current (30 mA), we had to improve the design to obtain a higher short cut current. For a better performance we had to lower the internal resistance. This was achieved by placing a silver conductive layer under the carbon current collector. The resulting effect on the short cut current was tested in comparison to that of the original cell.

With this changed design a parallel battery system layout of 5 cells was generated and realized on PET, polyimide and silicone covered aluminum sheets.

For the estimation of the internal resistance from the short circuit current and battery voltage a source measure unit (yokogawa GS610) and a digital oscilloscope (yokogawa DL9040) with a current probe (pbc100) and a differential probe (pbdh1000) were used.

2.3 Pyrotechnic delayline

For the pyrotechnic delayline the screen-printing method was used. This technology enables coating applications of highest layer thickness [7]. This is a necessary condition to provide a high mass related with a high caloric content in the reaction zone of the burning line. Also in case of large heat loss, due to basic substrates with high thermal conductivity, this is the way to ensure the required temperature level to keep the reaction self sustained (figure 4). Screen-printing also enables the printing of almost every material with a wide variation of particle sizes.

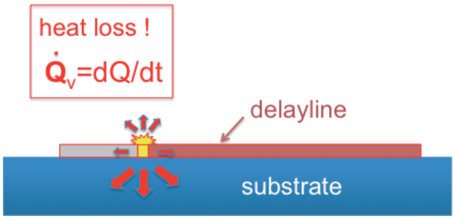


Figure 4:
Heat loss from the reaction zone of the pyrotechnic delayline

Two different energetic inks were tested in this work. For ink I Al/Fe_2O_3 and for ink II Si/Bi_2O_3 was used as the main ingredients for the fuel and the oxidizing components. The pyrotechnic powders were mixed in wet state by an ultrasonic system (Hielscher) to obtain good dispersion of the pigments. For ink I and II VITON (A) from DuPont was used as the binding agent. For both inks, a thermal analysis was carried out by TGA (TG 209 F1 Iris, Netzsch) with a calculated DSC to receive information concerning drying behavior and reaction temperature of the mixture.

The lines were printed with a semiautomatic screen printer (Alraun AT-301). The screens were polyester and metal meshes with a mesh width between 0.9 mm and 1.25 mm to realize a line thickness from 200 µm to 800 µm. In the test field we used meander, comb and snake structures with a varying line wide between 0.5 mm to 2 mm.

3. Results and discussion

3.1 Ignition structure

(I) Printing behavior - surface profile

For all printed and sintered patterns, more or less significant deviations to the digital images were noticed especially on glass substrates. They can mainly be justified by the spreading of the ink on the substrate. On the one hand the bar spreads which leads to a higher width and on the other hand the wings spread, too, which causes a decrease in the length of the bar. Due to the higher surface tension of the polyimide (Kapton®) film the spreading effect was very weak compared to glass. The quality (sharpness) of the printed structures on Kapton® (see figure 5) was better than that on glass which results in the profile diagrams in Figure 6 and 7.

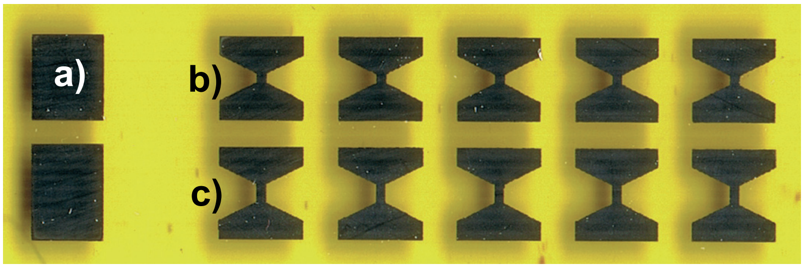


Figure 5:
Ag test structures printed on Kapton®,
a) rectangles for XRD analyses,
b) square bar structures,
c) rectangular bar structures

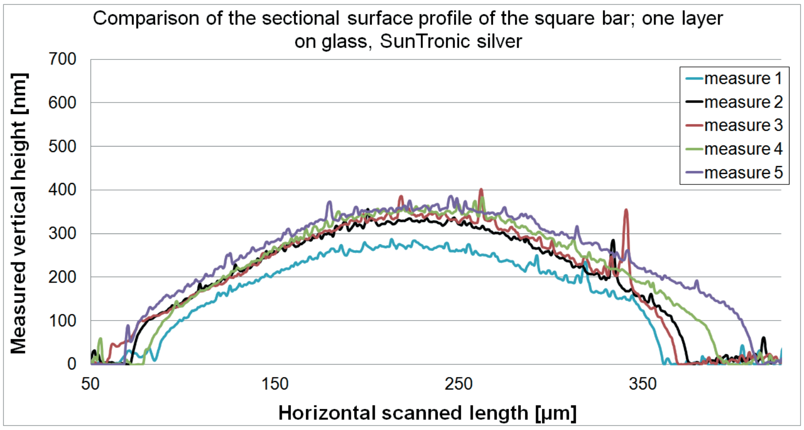


Figure 6: Surface profile across the bar between the two wings at five different sections; square bar; one layer; glass; SunTronic silver ink

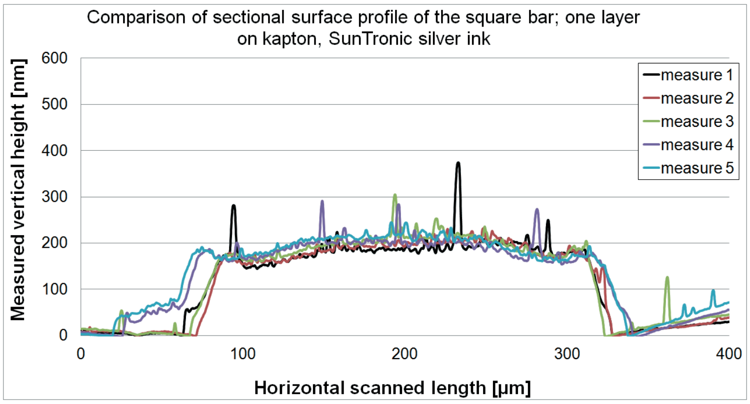


Figure 7: Surface profile across the bar between the two wings at five different sections; square bar; one layer; kapton; SunTronic silver ink

(II) Resistance

The main impact on the resistance of the printed structures has the sintering temperature. With increasing temperature, the resistance of the structures decreases for both inks (figure 8 and 9). A high fall in resistivity arises for both inks from 150 °C to 200 °C. After this the decrease is less. The reason therefore is a higher densification of the layers (see later SEM-investigations of the microstructure). For the sintering time it could be stated, that with increasing sintering time at the same sintering temperature the resistance decreases for both inks, too. But the effect on the resistance of the sintering time was less strong then the effect of the sintering temperature. The explanation is the same like for increasing the sintering temperature. The longer the samples are sintered the higher is the densification and therefore the current flow becomes improved by fewer holes. By collecting the resistance data of all printed structures depending on layer thickness and sintering conditions (temperature and time), we had now the basic knowledge to choose suitable structures with a desired resistance and applicable process conditions for our pyrotechnic system.

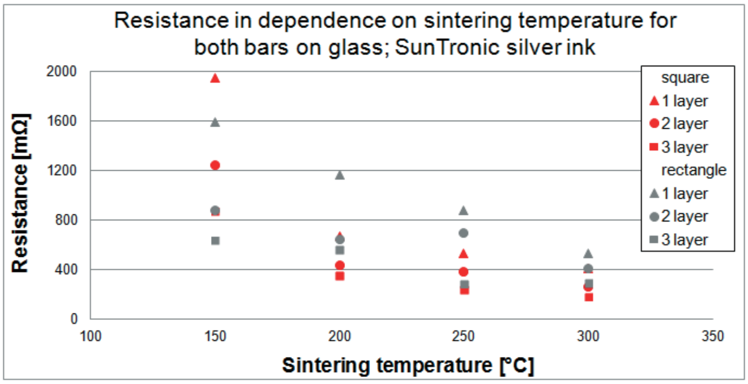


Figure 8: Resistance in mΩ dependent on sintering temperature from 150 °C up to 300 °C for both bars printed on glass; 1 to 3 layers; SunTronic silver ink

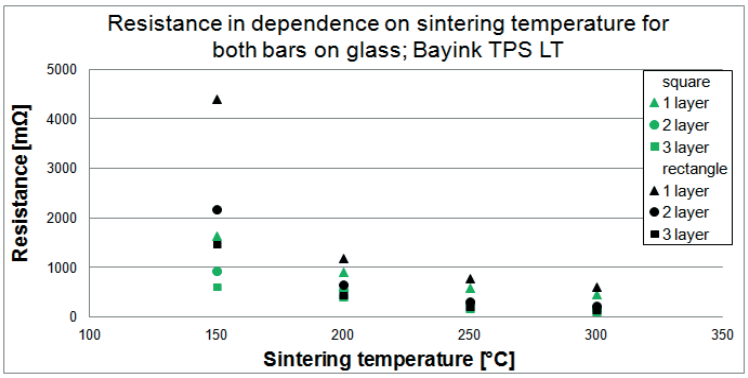


Figure 9: Resistance in mΩ dependent on sintering temperature from 150 °C up to 300 °C for both bars printed on glass; 1 to 3 layers ; Bayink TPS LT

(III) X-ray diffraction

Layer thickness / number of layers

Compared to printing one layer, the intensity of the peaks for three layers wet on wet is much higher due to the thicker layer and therefore the higher reflection and crystallization. This behavior was expected and is qualitatively the same for SunTronic ink and Bayink.

Sintering temperature / sintering time

In this and in the next sections for a better detection only the two peaks (111) and (200) are demonstrated. The following investigation shows the influence on varying sintering temperature and sintering time on the crystalline structure on the example of three layers printed wet on wet. Figure 10 shows an increase of the intensities of peak (111) and (200) with an increasing sintering temperature for the Suntronic ink.

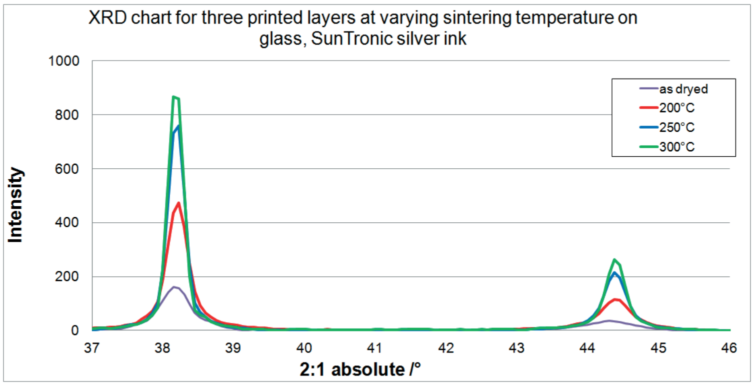


Figure 10: X-ray curves depending on sintering temperature, detail of the angle 37° to 46°; three layers, SunTronic silver ink on glass

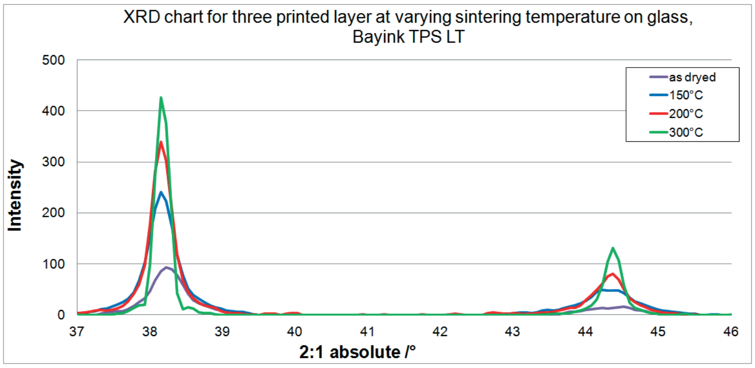


Figure 11: X-ray curves depending on sintering temperature, detail of the angle 37° to 46°; three layers, Bayink TPS LT on glass

Besides the less intensity of the peaks, the basic characteristic of Bayink (figure 11) is comparable to the Sun Tronic silver ink, the intensity of the peaks is increasing with increasing sintering temperature. Hence it can be stated that with increasing sintering temperature the intensity of the peaks and subsequently the crystallization of the inside structure rises. The intensity for the as dried layers for both, SunTronic and Bayink is in a low range. The as dried peaks for both inks have nearly the same intensities, seen in Figures 10, 11. Greater differences occur with the applying of heat especially for three layers.

Compared to the sintering temperature route the sintering time route (not graphical presented) results in very little increases in the peaks with increasing sintering time. This demonstrates the major impact of sintering temperature compared to sintering time.

Summary

With the investigation by X-ray diffraction, the relationship between inner structure and the resistance could be demonstrated. It was found out that the intensity and therefore the crystallization increases with thicker layers as well as with increasing sintering temperature and sintering time. For the same samples, a decrease in the resistance could be noted. Consequently a direct relationship between microstructure and resistance was detected. This contains a less resistance with higher crystallization caused by higher densification through higher sintering temperature and sintering time.

The same basic behavior was achieved independently on the used particle based silver ink dispersed in different solvents. Consequential it can be stated, that the inner structure does not dependent on the used solvent. The solvent itself only affects the spreading and drying characteristics. Despite different surface profiles and varying optical looks, the basic characteristic, dependent on fixed parameters like sintering time and sintering temperature, occurs.

(IV) Scanning electron microscope cross-section analysis

With this investigation we received a view on the inside structure by a cut into the pattern via focused ion beam and the execution by scanning electron microscopic images at this cut. For the two inks, three layers once wet-on-wet and once wet on sintered are analyzed.

The cut was carried out with a gallium beam at 120 pA and after this the sample was polished again with the gallium beam at 5 pA. Then the image was viewed with the scanning electron microscope (SEM).

In the next figures the cross sections of three layers printed with the printing method wet-on-sintered (Figure 12) as well as with the method wet-on-wet (figure 13) are illustrated for SunTronic silver ink and Bayink.

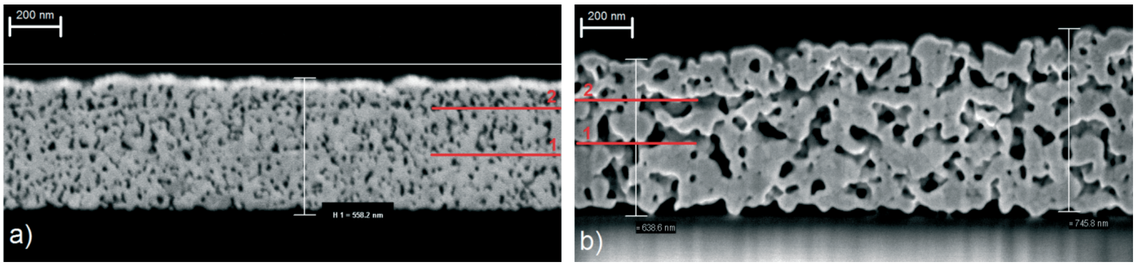
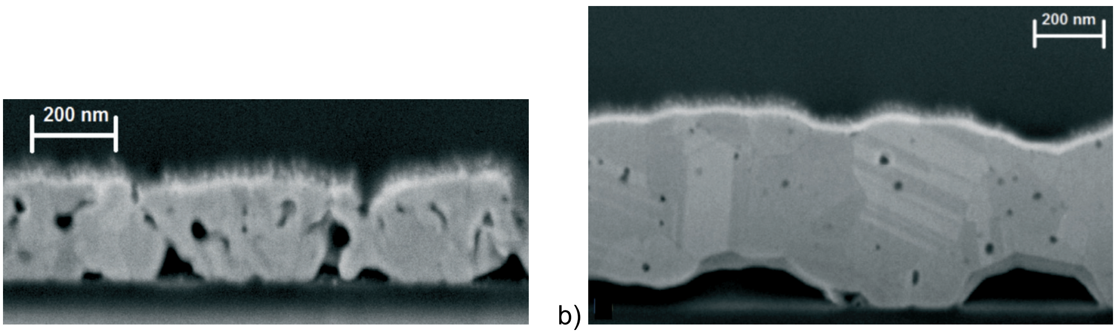


Figure 12: SEM images of silver layer consisting of three layers printed wet on sintered 200°C, 30 min each layer, magnification 50k x, a) SunTronic silver, b) Bayink TPS LT

a)


b)

Figure 13: a) SEM of SunTronic silver ink sintered at 300 °C for 30 min, magnification 50k x; b) SEM image of Bayink TPS LT sintered at 300 °C for 30 min, magnification 50k x

For the method wet-on-sintered the single layers are (not easy) to identify for both inks. A qualitative difference between the first layer, which is sintered three times, and the last layer cannot be detected. In general the structure is porous and less dense caused by the low sintering temperature of 150 °C and the individual sintering of each layer which avoids intermixing in wet condition. Outstanding for both inks is the decreasing thickness of the following layers. Basement is the change in surface energy and property between glass and the solid silver layer.

The images of the wet-on-wet method show in general an increasing densification and less porosity. For Sun Tronic silver ink (figure 13 a), the crystalline structure is not continuous and is characterized by subdivided parts. During the SEM-investigation charging effects occurred for this sample because of an incomplete evaporation of the organic ingredients of the ink. So the picture is not so sharp as the sample of Bayink (figure 13 b).

For Bayink the varying directions of the crystalline parts are clear visible. No subdivided parts as for Sun Tronic silver ink can be noticed. This shows a comparable qualitative high difference in the inside structure of the two inks at same sintering conditions. Striking for Bayink is the disconnection (dewetting) of the silver layer from the substrate. The layer is still comparable thick caused by the characteristic of the wet-on-dry printing and no intermixing of the single layers.

(V) Ignition tests of the single structure

To use one type of inkjet printed ignition structure for the system on all substrates the limiting technological parameter was the sintering temperature. In this case the maximum sintering temperature was restricted by the most sensitive PET - substrate with 120°C. So we realized the igniter structure by printing a structure with a rectangular bar with Bayink - possible to sinter at a temperature of 120°C. The measured resistance value of this structure was about 2 Ω. With this structure the ignition tests with a booster charge on the ignition structure (small pyrotechnic composition of Al and Bi_2O_3 nanoparticles) were applied.

For the ignition tests of the single structure the battery system was simulated by the current source GS 610. The output voltage was adjusted to 1.5 V (cell voltage) and the maximum current was limited to 2A.

After applying the electric pulse, the current rises to 1.38 A. Until to the point of ignition the value of current rises paired with a decreasing resistance. Reason for this behavior of the igniter structure is the electrical sintering process [5] due to the driven current.

Figure 14 shows a typical ignition curve. After period of about 300 ms the light pulse from the booster charge could be detected.

Figure 14 : Ignition current and light pulse of an ignition test of a 2 Ω structure

(VI) Electrical sintering

As seen in figure 14 the first sintering activities into the igniter structure occurred at a current of nearly 0.5 A. This was not acceptable for a reliable structure behavior at the no fire level. So we printed new thicker structures (average height between: 1300 nm to 1500 nm) wet on dry with Bayink on Kapton, sintered at 120°C (applicable sintering condition also for PET). With these structures we tested their behavior with a current treatment at the aspired no fire level of 0.5 A and for higher currents up to the point of breakdown. Table 2 shows the results of typical samples for the achieved change in the values of the structure resistance according to the applied current.

Table 2: Results for the change of the structure resistance according to the applied current

Nr.	applied current [A]	R before sintering [mΩ]	R after sintering [mΩ]	decrease of R [%]
1	0.5	253	253	0
2	0.8	274	215	22
3	0.9	268	196	27
4	1.0	262	167	36
5	1.1	264	149	44
6	1.2	272	130	52
7	1.3	258	129	50
8	1.4	252	116	54

According to these results we changed our manufacturing process for the igniter structure. After inkjet printing a sintering current of 1A was applied to adjust a reliable ignition behavior.

3.2 Battery system

(I) Single cell element

In the first step, we characterized the standard battery cells only with carbon current collector concerning their short cut current to estimate the internal resistance. For these cells we measured a maximum short cut current of about 30 mA. With a nominal cell voltage of 1.5 V, a typical internal resistance of about 50 Ω was calculated.

To achieve a higher output current, we decreased the internal resistance oft the single battery cell by applying a silver layer under the carbon current collector. The electrical characterization of this new constructed cell resulted in a typical short cut current of 400 mA to 600 mA. So the internal resistance of the single cell could be lowered from 50 Ω to 3 Ω. The rise time for the short cut current was measured by 0.5 A/µs.

(II) Battery system

To provide a reliable amount of energy for the firing impulse a battery system of five parallel mounted single cells was realized. With an internal resistance of about 0.7 Ω and a cell voltage of 1.5 V the battery system could deliver a short cut current of 2.1 A to ignite the inkjet printed ignition structure. By extending the silver layer it also serves as conductive track to the manual switch and the inkjet printed ignition structure.

3.3 Pyrotechnic delayline

(I) Analysis of basic substances

In the first step the main basic substances were analyzed by SEM to evaluate the information from the manufacturer (see table 3) about their morphology and real size of the particles and by EDX to look for possible foreign substances. Figure 15 shows as an example the SEM-picture and EDX-diagram for Al.

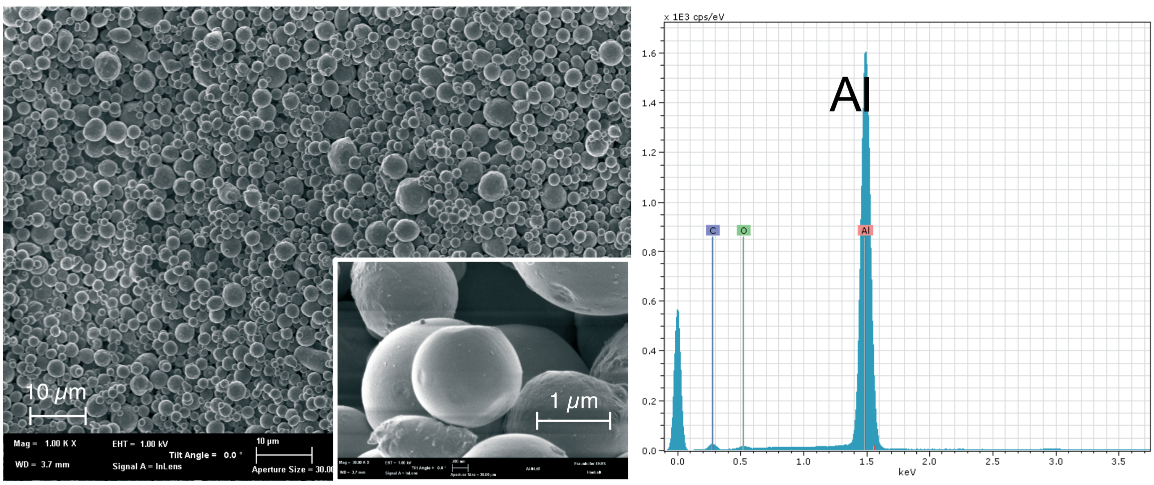


Figure 15: SEM and EDX-analysis of spherical Al - Particles from Eckart GmbH
For all basic substances, the values concerning the particle sizes could be proved by SEM analyses and with EDX no impurities were detected

Table 3: Main ingredients of Ink I and Ink II, particle size and manufacturer

Substance	Particle	Manufacturer
Ink I		
Fe_2O_3	0.7 µm .. 0,09 µm	Lanxess (Bayferrox)
Al	2.3 µm .. 6 µm	Eckart GmbH
Ink II		
Bi_2O_3	90 µm .. 210 nm	SigmaAldrich
nSi	approx. 100 nm	JSSI GmbH

(II) Ink preparation

Two inks were used for the delaylines. Ink I consists mainly of Al and Fe_2O_3 with a ratio of 50:50. Ink II was a composite of Si and Bi_2O_3 with a ratio of 66:33. For the inks we adjusted a solids content of about 70 % and 65 % to achieve a high possible layer thickness after drying. After mixing the powders in wet state with an ultrasonic system, we could observe a good dispersion and later a good distribution of the particles in the printed layer (see Figure 16).

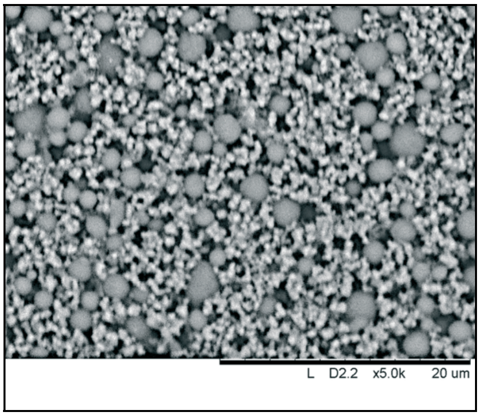


Figure 16:
SEM - cross section of a printed layer of ink I; magnifikation 5000 x

(III) Drying behavior / thermal analysis / burn-rates

Both inks I and II were analyzed by TGA (combined with a calculated DSC). The TGA analysis showed at 110 °C a loss of mass of about 30 % due to the evaporation of the solvent of ink I and a mass loss of about 35 % for ink II. For the reaction temperature of ink I a value of about 850 °C and for ink II a value of 550 °C was observed from the analyses.

As burn-rates for ink I and for ink II 25 mm/s and more than 100 mm/s were estimated.

(IV) Printing

To provide the self-sustainable reaction if a relatively slow burning delayline (ink I) is printed on metallic (aluminum) substrates with a high conductivity of heat, we had to compensate the loss of heat by a higher mass of the line structure. Therefore the aim was to print a mechanically stable line with a moderate width and a high line thickness.

Dependent on the used mesh, it was possible to print lines with a width of 2 mm and nearly up to 800 µm line thickness. For these lines, the thickness was measured at in the range of 0.74 mm to 0.81 mm. The best surface quality in these printing experiments was achieved with polyester meshes. To print structures with a lower line width of about 1 mm it was necessary to limit the line thickness to 300 µm. Figure 17 shows a combination of line structures with a width of 1 mm and 2 mm.

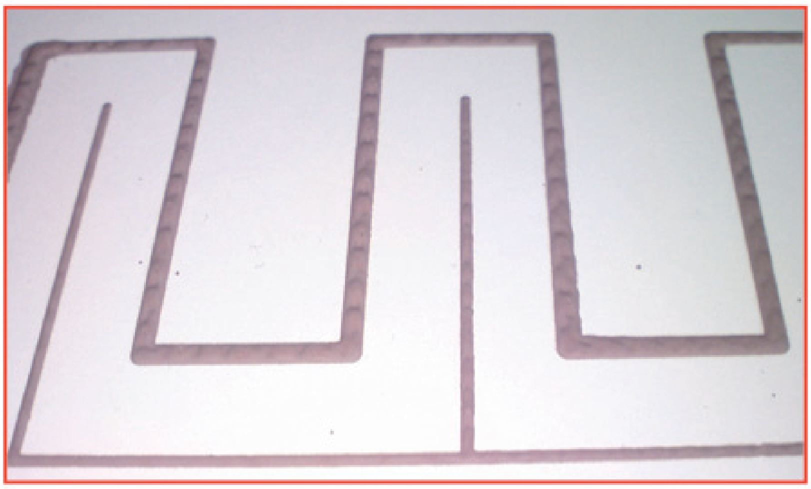


Figure 17:
Printed combined meander and comb structures with lines of 1 mm and 2 mm wide; line thickness 0.3 mm

For ink II we achieved a typical line thickness of about 250 µm. The adhesion of the printed lines with ink II was very poor. Therefore we focused on ink I for printing the whole system.

3.4 System integration

Battery system

To provide a reliable amount of energy for the firing impulse a battery system of five parallel mounted single cells was realized.

With an internal resistance of about 0.7 Ω and a cell voltage of 1.5 V the battery system could deliver a short cut current of 2.1 A to ignite the inkjet printed ignition structure. By extending the silver layer it also serves as conductive track to the manual switch and the inkjet printed ignition structure (figures 18, 19).

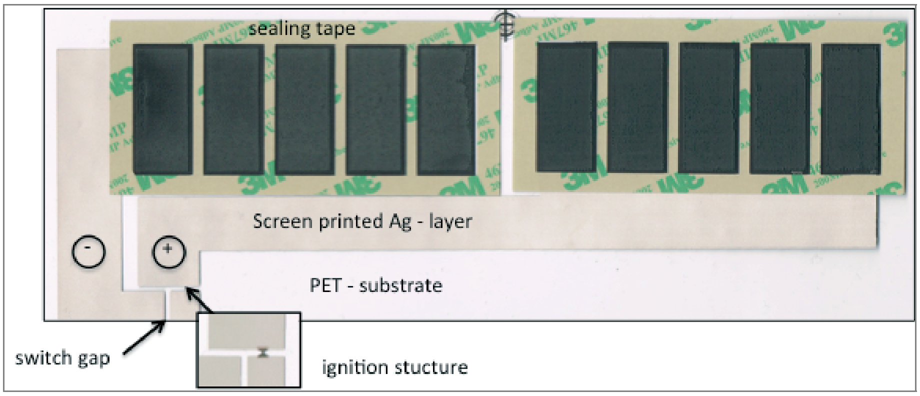
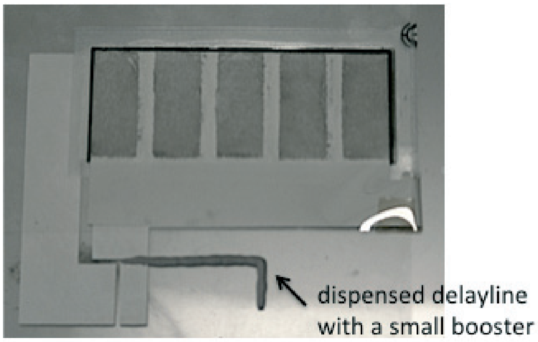


Figure 18: Parallel 5 cell-battery before the sealing step on PET-substrate; switch gap for manual switching

Figure 19: Sealed battery with dispensed pyrotechnic line (ink I) and booster charge



Ignition structure

The ignition structure was printed between the extended silver conductive tracks of the battery system for Kapton and PET substrate (see figure 18). A good interconnection between the screen-printed silver layer and the inkjet printed ignition structure was observed. In case of the silicone covered aluminum substrate it was not possible to print with inkjet directly on the silicone surface due to the high surface tension of silicone. Therefore we applied a Kapton tape at the printing area of the ignition structure before printing the battery system. So it was practicable to print the ignition structure with inkjet in this area.

Ignition tests

Because of the relative low sensitivity of ink I and II, we used a small and very sensitive booster mixture (Al and Bi_2O_3 nanoparticles) between the silver ignition structure and the delayline structure. With help of this booster mixture it should be possible to initiate the screen-printed delaylines.

But the ignition tests with this configuration were not successful. The reason therefore was the unexpected high electrical conductivity of ink I, so it works as an additional parallel resistive structure. To correct this effect, we manufactured a parallel battery with 10 cells. This battery was able to deliver a short cut current of about 4 A. With this configuration we could successful ignite the pyrotechnic line (see figure 19).

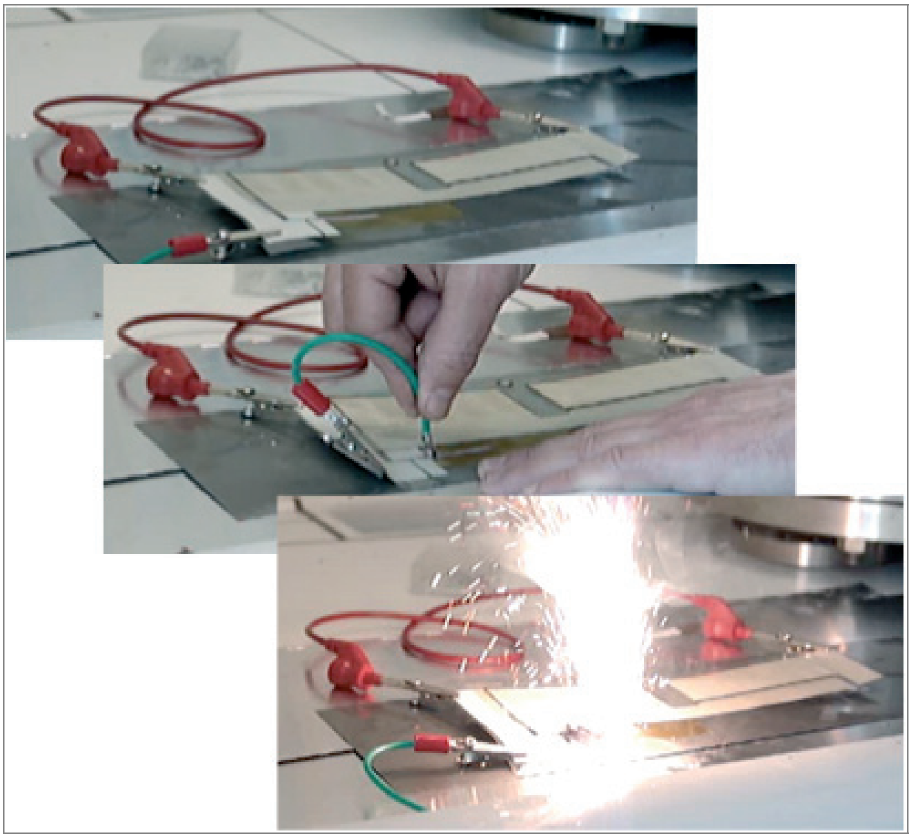


Figure 20: Ignition test of the pyrotechnic system (10 cell battery, ink I)

4. Conclusions

It could be shown that the single components work properly, separately and also the fully integrated system. It was achieved by a combination of different printing technologies to suit the needs of the single components.

With a parallel battery layout it was possible to provide a reliable amount of energy for the firing impulse. This was reached by reducing the internal resistance of the battery construction by means of an additional silver layer. In spite of the additional parallel resistance, due to the electrical conductive pyrotechnic, an extended parallel battery system enables the function of the printed system.

The combination of screen-printed conductive lines and the inkjet printed igniter structure allows a good adjustment of the functional elements of the system and enables an effective manufacturing process. Especially the printed igniter structure shows a very good interconnection with the conductive lines.

By a suitable adjustment of particle sizes for both energetic inks it was possible to achieve burning rates between 25 mm/s for Ink I and more than 100 mm/s for ink II.

The further research will focus on the development of a combined serial and parallel battery system with a higher voltage output, improved ignitor structures with a faster response time and a hermetic encapsulation for the system.

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Optical surface characterization method of silicone layers used for manufacturing of dielectric elastomer actuators

Maria Haas, *Hans Martin Sauer*, *Edgar Dörsam*

Institute of Printing Science and Technology
Technische Universität Darmstadt
Magdalenenstr. 2, D-64289 Darmstadt, Germany
E-mails: maria.haas@idd.tu-darmstadt.de; sauer@idd.tu-darmstadt.de; doersam@idd.tu-darmstadt.de

Abstract

In this paper, we present an optical surface characterization method for printed or coated layers with very high transmittance over the whole visible spectrum. We use silicone isolating layers made for dielectric elastomer actuators as example. The presented results originate from the very beginning phase of the experiments and aim to show the high potential of this method for its relative simplicity and fastness.

Keywords: functional printing, dielectric elastomer actuator, silicone, homogeneity, shadowgraphy

1. Introduction

Printing is a powerful and cost-efficient method for manufacturing thin and homogeneous layers with thicknesses in the range of few 10 nm to several µm. It is even intended to create layers of organic semiconductors for thin film transistors, organic light emitting diodes, photovoltaic cells with this method (Knob-loch, 2003), as well as dielectric layers for electromechanic sensors, or for optical anti-reflection coatings of glass. One of the biggest challenges here is not to obtain a good, highly resolved printing image, but producing precise layers of constant thicknesses, and with high homogeneity. Moreover the printing inks or liquids used here, for functional printing, often cannot fully be optimized and adapted to the requirements of the printing process for chemical reasons. Depending on the desired electronic function of the printed layer, fluctuations in layer thicknesses can severely derogate its performance or even make it useless. One case of such devices is *dielectric elastomer actuators* (DEA), which are in focus of this paper. The proper name however would be *dielectric elastomer transducers*. Nevertheless, we consuetudinary use the name "actuators" in this paper. They consist of many dielectric and conducting layers (electrodes), which in turn build a stack. The functional principle of the DEA is explained in Figure 1. The simplest DEA consists of three layers: top and bottom electrodes E and dielectric D between them. By voltage applying, electrodes get oppositely charged and attracted to each other. The dielectric layer gets squeezed between the electrodes, deflection occurs. By making structured electrodes, it is possible to "activate" only desired areas, creating buttons or input mechanisms. Stacking more layers over each other can increase the deflection up to the perception threshold. Such device can be used in different areas: e.g. sensor substitution (Braille), tactile feedback for telemanipulation tools or virtual reality, peristaltic pumps, etc. (Jungmann and Schlaak, 2002) (Lotz, Bischof, Matysek et al., 2006). Dielectric layer inhomogeneities or heterogeneous inclusions could lead to poor performance or even to short circuit.

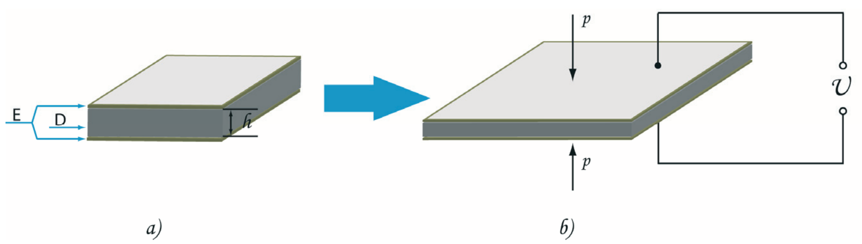

Figure 1: Functional principle of a dielectric elastomer actuator (DEA).
a) A simple DEA consists of three layers: top and bottom electrode E and dielectric layer D. b) Voltage application: dielectric layer squeezed by two electrodes (Haas and Dörsam, 2012) edited

The dielectric material is a very important factor for the DEA's performance. Silicones are often being used for their good elastic and dielectric properties. For our studies, we investigated some silicones and chose WACKER ELASTOSIL P7670 as best suitable due to its high tear strength (Elastosil, 2000) and high resistance.

It was already used for producing DEA using spin coating (Jungmann and Schlaak, 2002). Its high viscosity of 1800 mPa·s offers also application using screen printing and blade coating.

A specific feature of ELASTOSIL P7670 is a very high transmittance. Figure 2 shows an example of a screen printed silicone layer on a PET substrate. The silicone layer is bounded by the dashed line, since it is hardly recognizable without it due to almost equal refractive indices of the silicone $n_{silicone} \approx 1.50$ and of the PET substrate $n_{PET} \approx 1.53$ (Mark, 2007). This makes the usage of absorption based optical methods (Stahl, Sauer and Dörsam, 2012) nearly impossible without adding a dye. The application of microscopic profilometry for such layers is very com-plicated, since unwanted reflections appear and image stitching is needed. However as mentioned before, the layer homogeneity is of a great importance. This is the motivation to search for another possibility for the evaluation of surface properties.

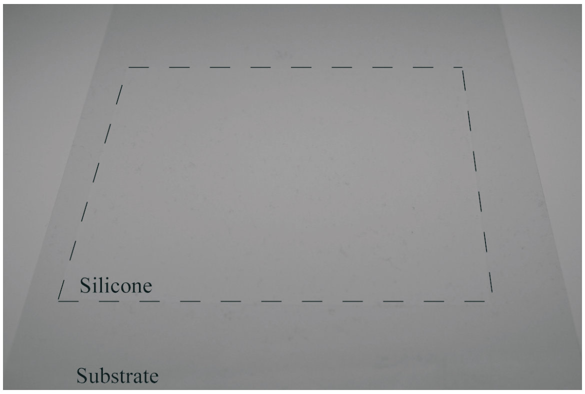

Figure 2: An example of a screen printed silicone layer (bounded by the dashed line) on a PET substrate

2. Method

The optical method presented in this paper is based on the principles of *shadowgraph techniques* and embodies *direct shadowgraphy* in particular (Settles, 2001). Imagine a planar transparent sample of a homogeneous medium with a layer thickness *D(x,y)*, where *x* and *y* are Cartesian coordinates in the substrate plane. A beam of light that passes through the sample is refracted according to its refractive index *n*, and the slope of the layer surface. In case of constant layer thickness all light rays in the beam remain parallel. An inhomogeneous sample, however, refracts and bends the rays proportional to the thickness gradients, and the refractive index. In other words, the light rays are not parallel any more, but converge or diverge. As a consequence, there appear shadows and caustics on a screen on which the refracted beam is projected on. Shadowgraph techniques take advantage of this phenomenon.

For the measurements, we used a simple optical design consisting of a point-like light source 1, a screen 4, and a camera 2 (Figure 3). The essential mathematical description of the introduced method is shown in Equation 1:

$$\vec{\nabla}(\nabla^2 D) = -\big(g(n-1)\big)^{-1} \cdot \vec{\nabla} I(x,y) \qquad [1]$$

where $\nabla^2 D$ is the Laplacian or the curvature of the layer thickness; *g* is the distance between the sample and the screen; *n* is the refractive index of the sample; *I* the measured light intensity over shadowgraph plane at a point where the ray through point *(x,y)* of the substrate hits the screen. An alteration of the curvature points on inhomogeneities in the layer.

The distances between the point-like light source and the screen h is 2 m, and between the sample and the screen g = 1 m are chosen in order to have an optimal contrast of the shadowgraph, which occurs if *g* is the half of h, which should be chosen maximal (Settles, 2001). The light source is a blue LUXEON-LED. The detecting system consists of a commercial CANON 450D camera (12.2 Megapixel) with a kit object lens. The camera is fixed on a tripod in the sample plane and is used for measurement of the intensity *I*. For camera focusing, a PET target with a laser cut pattern was placed in the sample mount. Under illumination, the pattern cast a sharp shadow onto the screen. The measurements were executed in a black matt painted room with the LED as the only light source in order to reduce the influence of light scattering.

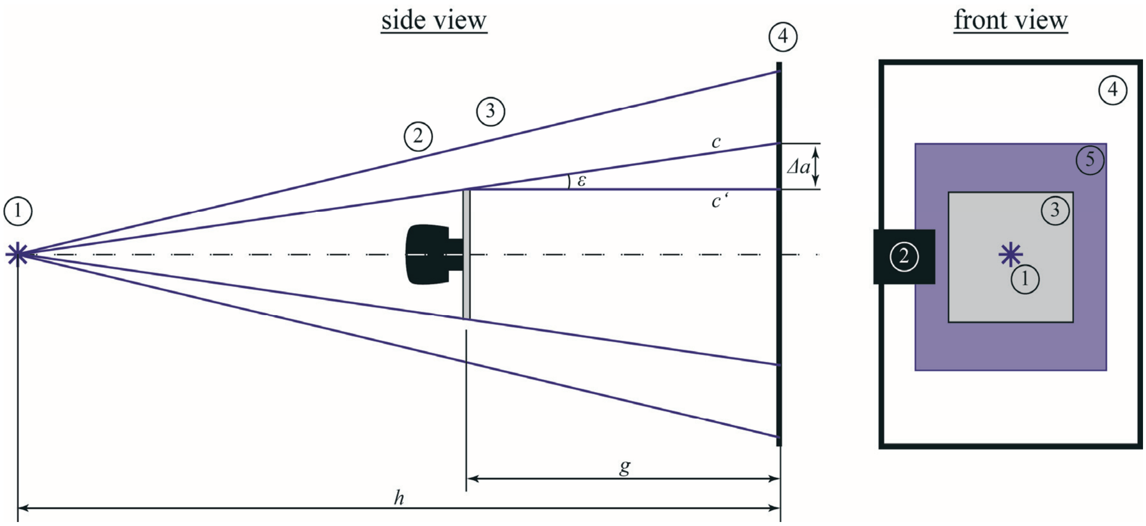

Figure 3: Experimental design consisting of the light source 1, a sample 3 and the screen 4. The camera 2 is placed in the plane of the light source. The shadowgraph 5 is projected onto the screen 4. h = 2 m is the distance between light source and screen. g = 0.5h = 1 m is the distance between sample and screen. Angle ε yields the displacement Δa between the original light ray c and the refracted ray c' (Settles, 2001) edited

3. Experiment

For the experiment, we used samples produced in four techniques:

- screen printing,
- blade coating,
- spin coating,
- casting in a thin metal form.

For samples made with screen printing and blade coating, we used PET substrates. As spin coating substrates, we used glass slides. The substrates were cleaned with isopropanol before use. The cast sample was simply peeled off from the metal form after solidification.

We took pictures of the shadowgraphs using the experimental design described above. We had three samples per application technique, except the casting, where we had only one sample.

4. Homogeneity rate and discussion

The shadowgraphs are shown in Figure 4. Shadowgraphs 1 - 3 are cast by the blade coated samples, 4 - 6 by screen printed samples, 7 - 9 by spin coated samples, 10 by silicone casting.

Since the shadows are cast by areas of inconstant curvature and thickness, they can be found by calculating the derivatives of the intensity (see Equation 1). The RGB images were converted into gray scale. For each pixel, partial derivatives along the X and Y directions were calculated as well as the full derivative. To enable further comparison, they were normed to the absolutely maximum value.

The condition for the shadow absence is the derivative $\vec{\nabla} I$ is zero, as shown in Equation 1. This means: the closer it approaches zero, the more homogeneous is the layer, or the smaller is its waviness.

The measurement uncertainty was determined by applying the method without any sample. Eight pictures were taken. Ideally, since no layer thickness related curvature alteration was to detect, the derivatives should all be equal zero. Normed average derivatives of $2.7 \cdot 10^{-4}$ were calculated and probably caused by camera noising. This value was used as a threshold in further homogeneity rate calculations.

The silicone samples have different sizes due to different manufacturing techniques. To enable comparison of diverse samples, it is reasonable to make homogeneity rate site-specific:

$$\boldsymbol{H} = \frac{\boldsymbol{N}}{\boldsymbol{A}} \qquad [2]$$

Homogeneity rate H is defined here as number N of points in the recorded digital image where the absolute value of the intensity gradient is below the noise threshold, divided by the area A of the substrate corresponding to one pixel (Equation 2).

The homogeneity rates calculated for the ten samples and averaged over the manufacturing techniques are shown in Table 1.

Table 1:
Homogeneity rates H and the direction dependent homogeneity rates H_X and H_Y averaged over samples made in same manufacturing techniques

	Blade coating	Screen Printing	Spin Coating	Silicone Cast
Homogeneity rate, *H*	0.019	0.029	0.056	0.031
Homogeneity rate in X direction, H_X	0.024	0.038	0.089	0.044
Homogeneity rate in Y direction, H_Y	0.044	0.049	0.087	0.049

The values correlate well with the visual observations. All shadowgraphs point on manufacturing not in dust-free cleanrooms. Blade coated samples are the least homogeneous. As expected, the spin coated samples are the most homogeneous.

However, these shadowgraphs show thick edges, which point on not optimal process parameters for the high viscous silicone. During the manufacturing of the screen printed samples, some cross-linkage problems occurred, which can be clearly seen in the bottom of the shadowgraph 5 and at the left side of the shadowgraph 6 (Figure 4).

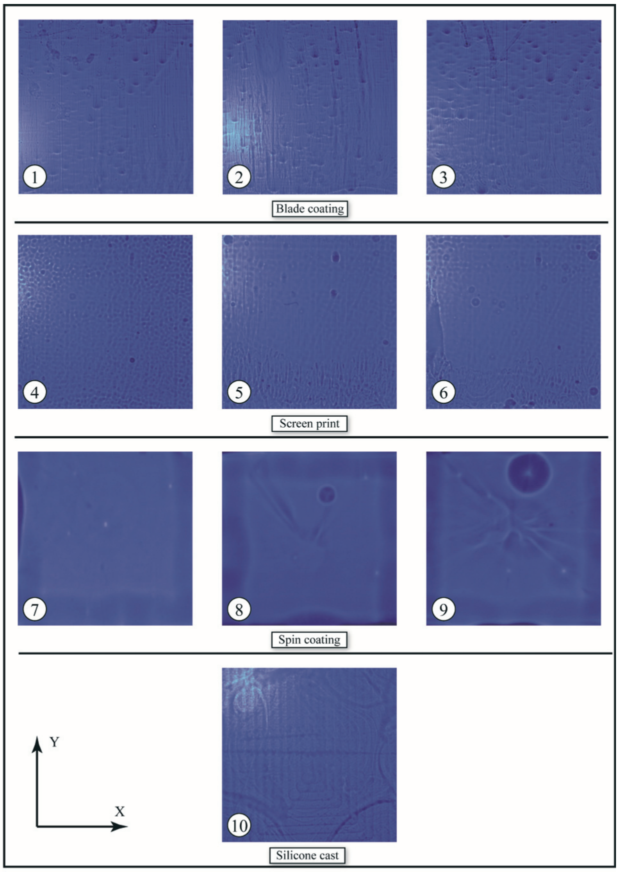

Figure 4:
Shadowgraphs: 1 - 3 blade coating, 4 - 6 screen printing, 7 - 9 spin coating, 10 silicone cast.

The coordinate system shows the X and Y directions. For samples 1 to 6, Y was the printing direction

They cause the unexpected low homogeneity rate. The shadowgraph of the cast sample shows the mill patterns of the cast form, which also lead to the relatively low homogeneity rate.

Considering screen printing and blade coating, we can clearly detect the layer dependency on the printing direction, which correlates well with the H_X and H_Y values. For the blade coated samples, this effect was predictable. In case of screen printing this was probably caused by the cross-linkage problems, since vertical patterns are only visible on shadowgraphs 5 and 6.

Direction independency of spin coated samples correlates perfectly with the H_X and H_Y values. Direction independency of the cast sample originates from the specific cast mill pattern.

5. Conclusions and outlook

In this paper, a new optical method for surface characterization of transparent layers in functional printing is introduced. It bases on the well-known method of shadowgraphy and is presented using an example of nearly not absorbing silicone layers used in manufacturing of dielectric elastomer actuators. A homogeneity rate is developed to compare the total homogeneity and the direction dependent homogeneity of the layers.

This method offers a high potential for evaluating printing or coating techniques or searching for optimal process parameters. The experimental design is relatively simple and would not cause high costs. At the same time it allows capturing the whole sample avoiding stitching procedure typical for many layer characterization methods.

Absolute measurements of the layer thicknesses are unfortunately not possible using only shadowgraphs and can be probably implemented using another approaches. However, we emphasize that it is possible to calculate the thickness gradients ∇D of the layer from the intensity gradients ∇I by numerically resolving the Laplace-Dirichlet boundary condition problem defined by Equation 1. This will be presented elsewhere.

In future research, other materials (silicones, polymers) and other printing and coating techniques should be tested. The experimental design is to be improved in the future considering parallel light, matt screen and optimal camera position.

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Tailored printed primary battery system developed for a diagnostic system

Andreas Willert[1], *Natsuru Chikushi*[1], *Monique Helmert*[2], *Michael Espig*[2], *Reinhard R. Baumann*[1,2]

[1] Fraunhofer Institute for Electronic Nanosystems ENAS
Technologie-Campus 3, D-09126 Chemnitz, Germany
E-mail: andreas.willert@enas.fraunhofer.de

[2] TU Chemnitz
Institute for Print and Media Technology
Professorship Digital Printing and Imaging Technology
Reichenhainer Str. 70, D-09126 Chemnitz, Germany

Abstract

For driving electronic applications a power source is needed. Especially for printed sensor systems a tailored printed battery solution is demanded. In this paper the investigations for printed primary battery systems are described. Besides the general idea of printed power, there are two use cases analyzed for powering the sensor system by either a Si or an organic circuitry, respectively. It turns out that one out of two built types of battery systems is adequate to power the intended application.

Keywords: printed battery, primary battery, energy system, smart system, screen printing

1. Introduction

Printing technologies enable the deposition of patterns of functional materials on various substrates. This evident benefit is widely under research for several devices and applications. To manufacture products employing mass printing technologies promises mass production with low costs. Within this scope a lot of efforts can be observed, especially in the area of Organic and Large Area Electronics (OLAE). One of the key elements to make electrons move inside any circuitry is electrical power. There are several approaches of printed batteries of different types of technologies: primary, i.e. one time discharge, (Willert, 2009) or secondary like NiMH (Wendler, 2010) or lithium based systems (Geyer, 2009).

In our efforts we concentrate on primary batteries for several reasons. Many intended applications are of limited lifetime. Therefore they have a well defined energy requirement that can be matched by a printed primary battery. The battery itself can be designed into and also integrated directly into the application. Another argument is: if we want to go for low cost and mass production, does this go along with costly recharge devices? There are also companies like Enfucell or Blue Spark that offer commercially primary drugstore-like batteries ranging from 1.5 V up to 6 V. The research presented in this paper has been undertaken in a project funded by the European Commission. This project SIMS aims to develop a smart, miniaturized sensing system through the integration of a sensor, a printed low cost display, a mobile phone interface, organic circuitry and a printed battery. The integration will take place on a single substrate employing photolithography, screen and ink jet printing and lamination process steps. The SIMS platform technology offers a broad potential, including industrial and environmental monitoring. It will be demonstrated through the sensitive detection of hydrogen peroxide. However, due to the scale of the diagnostics market and its relevance to the partners, SIMS will focus on the quantitative measurement of cholesterol.

In this paper we address solely the question of powering such kind of a system. The constraints are given by the application under investigation, such as: area limitation, required bend ability, voltage qualified to drive organic circuitry, and the one-time use of the device because the sensor material can be used only once. Therefore our primary battery with specified parameters of voltage, current flow, and an adapted capacity qualifies for the use. There is no need of recharge because the sensor system can only be used once. The main requirement for the battery is to drive a certain current at a certain voltage level for a determined period of time. Analyzing the demands of the application reveals a voltage requirement of +/- 15 V at a current of about 300 µA for about 5 to 10 mins. Before joining this project, typical voltages available in our lab have been 3 V or 4.5 V, typical discharge currents have been 200 µA. Also looking for other vendors batteries are typically offered in the range of 1.5 V or 3.0 V. Therefore the design, construction and manufacturing of such a high voltage battery are the objective of this contribution.

2. Methods

In this chapter the general approach of printed battery layout is shown including the manufacturing workflow. For the manufacturing of batteries only screen printing processes have been used. Each battery delivers a nominal voltage of 1.5 V_{nom}. This voltage may vary in case of internal resistance in dependence of the current flow. Following this basic concept, a 3 V battery has been developed to drive the intermediate application controlled by Si circuitry. For the 15 V battery investigations have been done by comparing the two approaches of battery setup. Furthermore also a material system for a solid electrolyte has been investigated.

2.1 Approach of printed batteries

The basic approach of a battery is to have two current collectors (plus and minus), anode and cathode, and in between an electrolyte enabling the ion flow between both electrodes while the electrons are flowing in the circuitry outside the battery. There are two basic approaches in arranging both electrodes: either side by side (i.e. lateral) or on top of each other (i.e. stacked), see Figure 1. The latter approach requires a separator layer between both electrodes to avoid any short circuit.

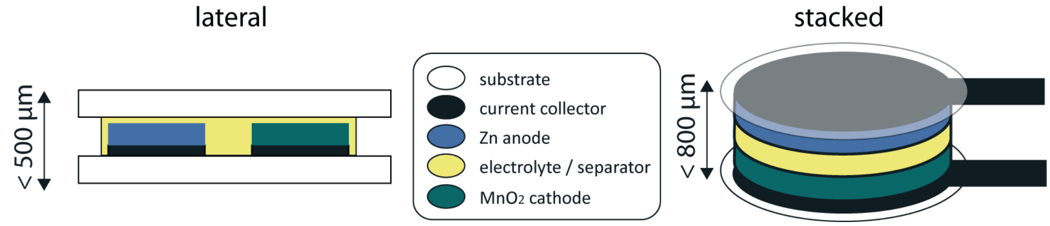

Figure 1: Basic setup of a printed battery: lateral or stacked.
In the stacked case the separator layer is needed (Willert, 2013)

For manufacturing onto the PET (polyethylene terephthalate) or the PEN (polyethylene naphthalate) substrate of 100 µm thickness, a conductive layer of carbon (Acheson Electrodag PF470C) is deposited by screen printing and dried afterwards with thermal heat. For the two electrode layers, printing inks are prepared consisting of the adequate raw metal grain and solvents. These inks are printed using a flatbed screen printer and dried after each printing step accordingly. Then the battery cells are manually assembled employing an appropriate, chemical resistant glue tape. During this assembly process a gelled electrolyte based on ZnCl is also added to the cell. In case of the stacked battery type a porous paper is used as separator.

The big advantage of employing printing technology for manufacturing is that a series connection of the batteries can be easily done as depicted in Figure 2. In this setup 4 single stacked cells, each delivering 1.5 V, summarize up to 6.0 V_{nom}. The interconnection can be done simply by using the same pattern for the carbon current collector for two batteries in each case.

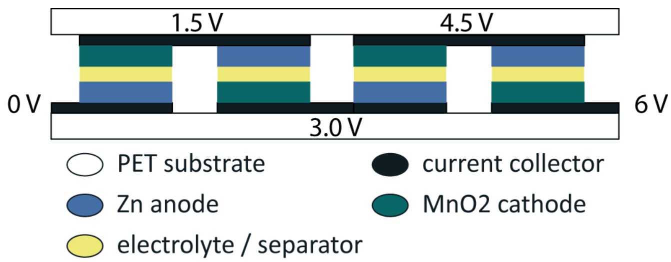

Figure 2:
Basic setup for a series connection of 4 stacked batteries delivering 6 V

2.2 Solid electrolyte

There are some concepts of using a solid electrolyte within the batteries. For this investigation basic information was found in (Hiralal, 2010). A modification was made to omit all unwanted materials acetonitrile or TiO_2. The remaining formulation procedure is depicted in Figure 3. In this case the solution was applied onto the battery by a manual squeegee process just for testing purposes.

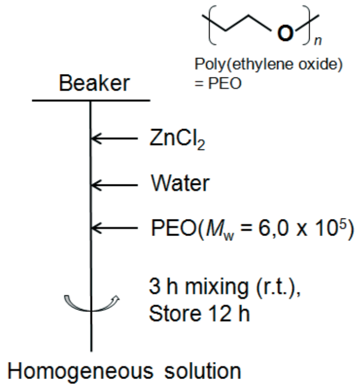

Figure 3:
Preparation scheme for a solution of solid electrolyte

2.3 Printed 3 V battery

The starting point was a printed primary battery approach delivering 3 V and about 200 µA current. This approach has been optimized and adapted to the device under investigation. It turned out that our battery approach has been able to drive the device when employing Si electronics that need a driving voltage of 3 V but at least 1 mA current. A picture from this manufactured cell is shown in Figure 4.

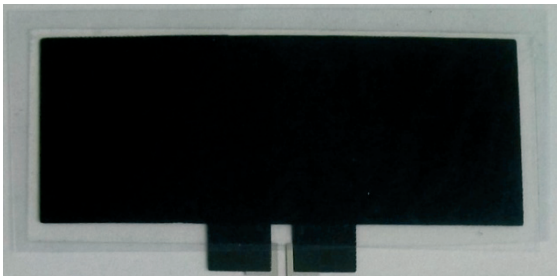

Figure 4: 3 V battery delivering 1 mA of current

2.4 Printed 15 V battery

In case of the 15 V batteries, the overall target in these investigations, the research has been extended to compare the performance of the lateral vs. the stacked battery layout. The aim was to increase the number of batteries in series connection. The objective was to deliver approx. 300 µA at a power level of 15 V. In the end the requirement of +/- 15 V the application requires a series connection of two 15 V battery systems.

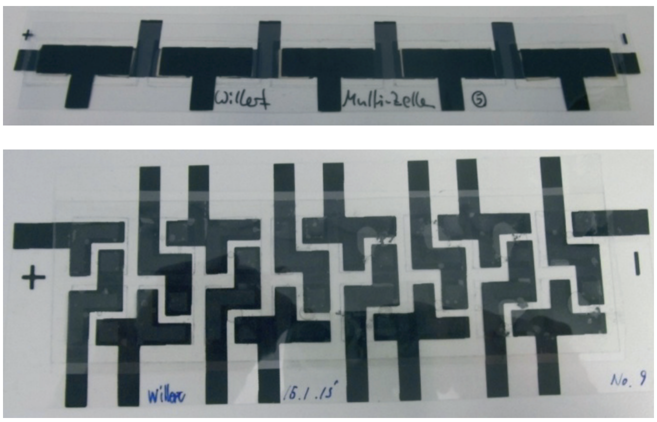

Figure 5: Series connection of 10 stacked cells (top) and 16 lateral cells (bottom)

In Figure 5 images of the two manufactured setup types are shown. In this design it is possible to access every single battery cell individually. In the top picture of Figure 5 there are 10 stacked cells available while in the bottom picture there are 16 lateral cells available. For the design of the lateral cells pre-investigations have been done for determining electrode distances and area sizes.

3. Results

For the determination of the electrical properties, all batteries have been discharged by the use of a potentiostat/galvanostat (Biologic VMP3). With this tool a constant current is drawn from the battery and the discharge behavior is being recorded.

3.1 Solid electrolyte

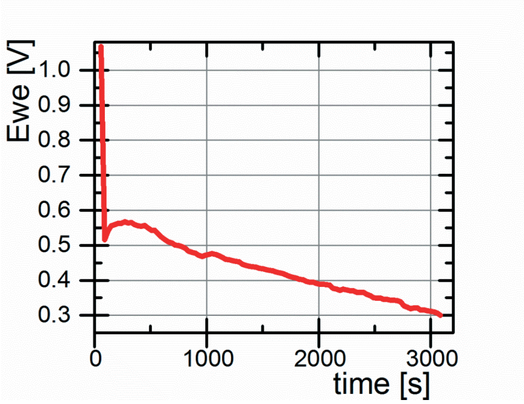

Figure 6:
Discharge curve of a battery cell with solid electrolyte @ 100 µA discharge current

The voltage of the battery cell with solid electrolyte drops to about 500 mV when being discharged by a current of 100 µA. This is about 1 V less than the intended operation voltage.

3.2 Printed 3 V battery

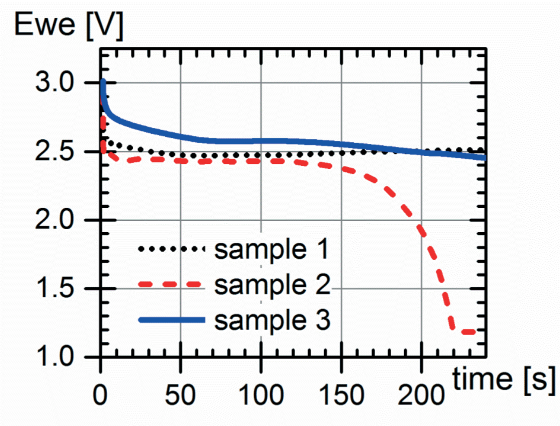

Figure 7:
Discharge curves of 3 V batteries @ 1 mA current

In Figure 7 the discharge curves of three 3 V_{nom} batteries are depicted. Due to the internal resistance of the battery and the current of 1 mA the resulting operating voltage level drops to about 2.5 V. This voltage level is constant over at least 150 mins. The intended application lifetime is 5 - 10 mins.

3.3 Printed 15 V battery

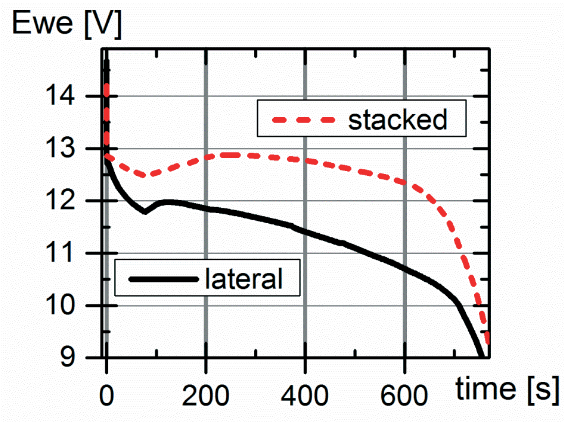

Figure 8:
Discharge curves of 15 V_{nom} batteries @ 100 µA discharge current

In Figure 8 the discharge curves of two 10 cells batteries (i.e. 15 V_{nom}) are shown. Both batteries are discharged with a current of 100 µA. At the start of the discharge both batteries show a drop in operating voltage from about 15 V to about 12.9 V because of the internal battery resistance. The voltage level of the stacked battery remains during the discharge period of 12 hrs significantly higher than that of the lateral approach which decreases all the time.

In a further research the stacked type of battery was chained with 12 single cells delivering a nominal voltage of 18 V_{nom}. The discharge curve for a current of 300 µA is depicted in Figure 9. In the beginning of the discharge a drop from about 18 V to about 17 V can be observed. There is continuously a decrease in voltage over more than 700 s.

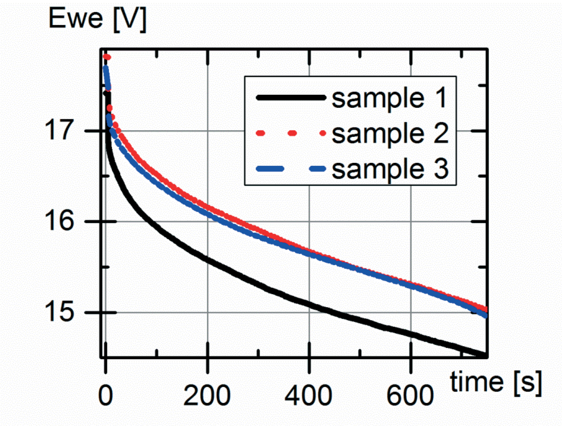

Figure 9:
Discharge curve of 12 cells stacked batteries @ 300 µA discharge current

4. Discussion

The results of the investigations of the solid electrolyte are extremely poor so that we stopped further investigations in this direction so far. All research in this research project done further on was based on a gelled electrolyte type.

For the 3 V battery the discharge curve clearly shows that it was possible to achieve a discharge increase from 200 µA to 1 000 µA - an increase by a factor of 5. In Figure 7, a dashed line (sample 2) is also presented showing a clear deviation from the other two curves. The drop of this line to a level of 1.2 V at a time of about 200 mins indicates that one of both batteries became empty during the discharge. It can be seen that the manufacturing quality seems to be an issue for these single samples of manually build batteries. Looking for mass production or automatic manufacturing processes, an increase in quality is expected.

Investigations for 15 V batteries reveal that for our intended application the stacked battery layout is more powerful than the lateral one (Figure 8). Over a longer period of time the operating voltage remains on a higher level. Therefore further improvements were concentrated on the stacked layout. With this cell layout, a newly designed battery was manufactured consisting of 12 chained single cells of each 1 cm² active area. Three of these newly built batteries have been discharged with a current flow of 300 µA (Figure 9). The voltage level decreases from about 17 V to about 15 V in a period of more than 700 s. Therefore these discharge properties fulfill the requirements of the intended application.

5. Conclusions

In this paper printed battery investigations are described that clearly show the potential of this type of energy container. Customized battery performance can be manufactured enabling driving a sensor system with Si electronics by a 3 V battery as well as organic electronics by a 15 V battery. The requirements of driving a current of 1 mA for a 3 V battery as well as driving a current of 300 µA for a 15 V battery can be fulfilled. With the 15 V batteries the usually available voltage of up to 6 V as a printed battery has been doubled.

The results of our investigations encourage evaluating this kind of battery for similar applications.

Acknowledgements

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Printed DSSC solar cell with UV cured barrier layer

Tomáš Syrový, Michal Hatala, Markéta Držková, Lucie Syrová

University of Pardubice
Faculty of Chemical Technology
Department of Graphic Arts and Photophysics
Studentská 95, CZ-532 10 Pardubice, Czech Republic

E-mails: tomas.syrovy@upce.cz; hatalamichal@gmail.com;
marketa.drzkova@upce.cz; lucie.syrova@gmail.com

Abstract

Functional DSSC devices were prepared by screen-printing technique. Variation of materials used has significant influence on conversion efficiency of prepared solar cells. The SEM micrographs had shown that some photoelectrodes have cracks, therefore, the sintering process and ink formulation need to be improved. The barrier layer for sealing the bus bars and whole cell was printed using UV curable ink instead of commonly used thermoplastic polymer. Chosen type of UV curable ink was resistant to aggressive electrolyte, especially to electrolyte based on ethylene glycol. For electrolyte based on acetonitrile it is necessary to develop the printable barrier layer with even higher barrier properties and better durability.

Keywords: DSSC, screen-printing, barrier layer, UV curable ink

1. Introduction

There is a growing interest in printed functionalities in the area of the printing industry. Existing or upgraded production facilities can produce various types of printed electronic devices, usually called "printed electronics". Structures forming functional electronic elements could be prepared using special printing materials (printing substrates, printing ink formulations) in appropriate combination. Different types of functional elements have different demands on the geometric characteristics of the layers (layer thickness, layer topology, the width of conductive paths, etc.). According required properties of functional layers and in dependence on printing materials properties, various printing techniques are used and their appropriate technological setup differs as well. Among the most used ones belong screen-printing, gravure printing, flexography and ink-jet. Nowadays, a number of electronic elements are made by means of these printing processes.

Important part of printed functionalities constitute energy harvesting devices like dye-sensitized solar cell (DSSC), which could be together with hetero-junction organic photovoltaics (OPV) included in the third generation of solar cells. In 1991, Brian O'Regan and Michael Grätzel DSSCs were published, based on TiO_2 as a photoanode and ruthenium complex as a sensibilizing dye, with conversion efficiency over 7 % in simulated solar light. These chemical compounds are basic parts of the most efficient DSSC system till present time (O'Regan, 1991). During several years of DSSC solar cells development, various materials were used for their preparation. Material and approach modification for DSSCs preparation lead to conversion efficiency of 11.0 ± 0.3 % for cells with active area around 1 cm^2 and 9.9 ± 0.4 % for cells with active area in tens of cm^2 (Green, 2012). In many cases, process conditions of published DSSCs are not suitable for mass production, especially with respect to the deposition of the materials in question, their stability and the stability of the whole cell.

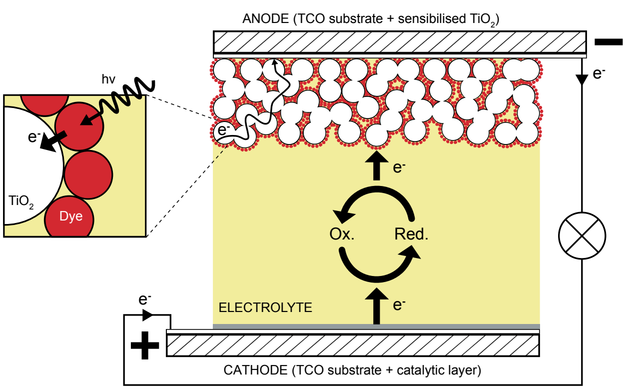

Figure 1:
Scheme of operation principle of DSSC

The basic components of DSSC solar cells are photoelectrode (anode), counter electrode (cathode) and the electrolyte (Fig. 1). Photoelectrode consists of a thin layer of semiconductor oxide, mostly of titanium dioxide (TiO_2). TiO_2 layer is deposited on a transparent substrate (glass, polymer film) coated with a TCO (Transparent Conducting Oxide) layer, which usually consists of ITO (SnO_2:In) or FTO (SnO_2:F). TiO_2 layer is sensitized by dye, in most cases based on ruthenium complex that creates monomolecular layer on the dioxide particles surface. Counter electrode is formed by the catalytic layer of platinum (Pt) or carbon (C), deposited also on a transparent substrate coated with a TCO layer. The electrolyte usually consists of an organic solvent containing a redox couple I^-/I_3^-, which provides charge transfer from counter electrode to photoelectrode, including regeneration of the dye. An alternative is the use of ionic liquids, or solid-state electrolyte, such as organic materials or inorganic P-type semiconductor (hole conductivity). (Hagfeldt, 2010; Hashmi, 2011; Luque, 2011)

An important part of the DSSC cell is the photoelectrode, which provides a sufficiently large surface area for adsorption of sensitizer and ensures transport of the electrons to the conductive TCO layer on the substrate. The electrons from sensitizer are injected into an appropriate location in semiconductor energy levels. Required surface of photoelectrode and its thickness are determined by molar absorption coefficient of the sensitizer, while limiting factor for the thickness is the electron diffusion length (Toivola, 2010; Luque, 2011). Materials used for photoelectrodes are usually metal oxides: TiO_2, ZnO, Fe_2O_3, ZrO_2, Nb_2O_5, Al_2O_3, CeO_2, SrTiO, and Zn_2SnO_4. In terms of electron configuration, the most appropriate are titanium dioxide (TiO_2), zinc oxide (ZnO) or niobium pentoxide (Nb_2O_5). Besides the selection of materials, the research in recent years has focused on the morphology of nanostructured photoelectrodes. An alternative to the random arrangement of nanoparticles is based on the form of regularly arranged structures like nanotubes and nanowires. Organized structures should provide more efficient charge transfer and better possibilities for filling of pores of materials by electrode, especially for solid-state electrolyte (Jose, 2009; Hagfeldt, 2010).

Primary task of counter electrode (in the case of using the electrolyte containing I^-/I_3^-) is to ensure the regeneration of the electrolyte. The effective reduction of oxidized triiodide I_3^- back to iodide I^- occurs only in case of high electrocatalytic activity of counter electrode material. Catalytic properties of materials can be evaluated on the basis of the charge transfer resistance R_{CT} (Ω/cm^2) parameter for the reduction of triiodide. Other important parameters are the chemical stability of the catalyst layer in the presence of an electrolyte, the mechanical stability and in reverse configuration of DSSC cell also the optical properties. The most commonly used catalytic material is platinum (Pt) layer, thanks to its strong catalytic effect and transparency, the alternative materials include carbon or conductive polymers (Hashmi, 2011; Luque, 2011).

The electrolyte in the DSSC cell is a medium for transport charge between electrodes. There can be distinguished liquid, solid-state and gel (quasi solid-state) electrolytes. Liquid electrolytes can be subdivided into two categories - electrolytes containing organic solvents and with ionic liquid. Among the desired properties of liquid electrolytes belong chemical stability, low viscosity and ability to dissolve all the necessary components of the electrolyte (Hagfeldt, 2010; Hashmi, 2011). The first group of liquid electrolytes consists of an organic solvent, oxidation-reduction pair and additives. The most widespread redox couple is the above mentioned I^-/I_3^- created by dissolving iodide (LiI, NaI, KI), tetraalkylammonium iodide (R_4NI) or derivatives of imidazolium iodide in concentration of 0.1-0.5 M together with iodine (I_2) (0.05-0.1 M) in an aprotic organic solvent. However, corrosive effects of triiodide have the negative impact on the long-term stability of the cells.

Another disadvantage is that the solution containing triiodide has absorption in the VIS range of spectra, especially at higher concentrations. For these reasons, alternative oxidation-reduction pairs (Br^-/Br_2^-, SCN^-/SCN_2^-, complexes with $SeCN^-/SeCN_2^-$) are used in some articles. The mainly used organic solvents include nitriles with relatively low viscosity such as acetonitrile (ACN), propionitrile (PN), methoxyacetonitrile (MEAN), 3-methoxypropionitrile (MePN) and others solvents as N-methyl-2-pyrrolidone (NMP) and ethylene glycol (EG) (Nogueira, 2004; Wu, 2008; Hagfeldt, 2010; Taura, 2010; Toivola, 2010; Hashmi, 2011; Luque, 2011).

An alternative to liquid electrolyte containing volatile organic solvents are electrolytes based on ionic liquids (Wu, 2008; Hagfeldt, 2010; Hashmi, 2011; Luque, 2011). Their main advantages are the negligible partial vapour pressure, flame resistance, electrochemical and thermal stability and relatively high ionic conductivity. The most commonly used ionic liquids are based on imidazoles such as 1-hexyl-3-methylimidazolium iodide (HMImI) or compounds with other counterions. The problem with pure ionic liquids is their relatively high viscosity, negatively affecting the rate of ion transport and also recovery rate of the oxidized dye. The viscosity of ionic liquids is limiting factor also in terms of electrolyte impregnation. One option is to reduce the viscosity by heating the electrolyte.

Problems with long-term stability of the liquid electrolyte caused by evaporation or evasion of the solvent is the primary reason of development of solid-state and gel electrolytes (Wu, 2008; Hashmi, 2011; Luque, 2011). Gel electrolytes can be described as a system consisting of a polymeric network swelling liquid electrolyte. Due to its hybrid structure, gel electrolyte combines good cohesive properties of solids with the ability to diffuse transport of liquids. This implies better long-term stability than those of liquid electrolytes, and high ionic conductivity with good interphase contact in comparison with solid-state electrolytes. Gel electrolytes are usually prepared by mixing liquid electrolyte into monomeric or polymeric matrix. Polymer networks given by physical forces form a thermoplastic gel electrolyte. When the polymer network formation takes place by chemical mechanism, it is a thermosetting electrolyte. In terms of stability, thermosetting based electrolytes are better than thermoplastic based systems. As a gelling agent, e.g. polyethylene glycol (PEG), 1,3:2,4-di-O-dimethylbenzylidene-D-sorbitol (DBS), poly(acrylic acid)-poly(ethylene glycol) (PEG-PAA), polyvinylpyridine (PVP), polyacrylonitrile (PAN) are used.

Sensibilisation of the photoelectrode is performed by sensibilizing dye. The most effective sensitizers are dyes belonging to the ruthenium complexes as di-tetrabutylammonium cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II) (N719). To a lesser extent, complexes of other metals (Fe, Pt, Os, Re) were tested as sensitizers. An alternative to rutenium complexes are various organic dyes with appropriate properties (Halme, 2002; Hagfeldt, 2010; Nazeeruddin, 2011). Sensitized photoelectrode layer is formed by electrode immersion in the solution of dye for more than 12 hours. Molar concentration of sensitizing dyes is usually of the order of 10^{-4} M. There are used several types of solvents, commonly ethanol, methanol or a mixture of tertiary butanol and acetonitrile in a weight ratio of 1 : 1 (Toivola, 2010; Luque, 2011). Solar cell performance is largely influenced by photophysical and electrochemical properties of the sensitizer adsorbed on the surface of semiconductor particles. Oxidation potential determines the maximum attainable value of the V_{OC} (open-circuit voltage) and molar absorption coefficient the value of I_{SC} (short current).

With a focus on the progress toward the mass production, the aim of this work was to prepare the majority of elements of DSSC by printing. The materials used for screen printing of photoelectrode, counter electrode, silver based bus bars and sealing barrier layer were chosen based on literature research.

2. Materials and methods

The layout and order of layers of prepared DSSC solar cell is presented in Figure 2. The active area of the cell was 7.8 cm^2 and consists from three parallel connected cells. Cells were fabricated on ITO coated glass from Solaronix with thickness of 2.2 mm and surface resistivity of 7 Ω/sq.

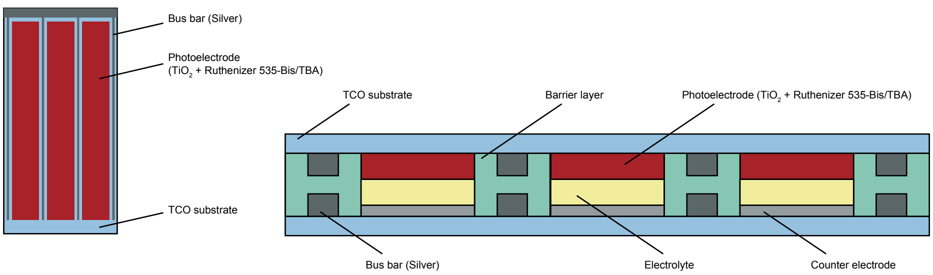

Figure 2: Schematic and cross-section of DSSC with parallel connected cells

Before fabrication of cells, ITO glass was cleaned in a series of solvents (methanol, acetone, 2-propanol). During the production of cells, the elements of upper and lower part were printed at first and then the DSSC system was finished by printing the barrier layer, adding the electrolyte and sealing the whole cell. Photoelectrode was screen-printed by custom-formulated printing paste based on Sigma-Aldrich anatase TiO_2 (21 nm) and Precheza TiO_2 (180 nm) for light scattering. Printed photoelectrode was dried and then sintered at 450 °C for 30 minutes. Sintered photoelectrode was immersed in 0.3 mM Ruthenizer 535-Bis/TBA solution in acetonitrile/2-butanol for 72 hours and then was washed by ethanol. Subsequently, silver-based bus bar as a current collector was fabricated by screen-printing using ECM CI-1001 printing paste. On another piece of substrate, the carbon or platinum counter electrodes were screen-printed by Gwent C10903P14 carbon paste and Solaronix Platisol T/SP printing paste, respectively. After the printing, the layers of Gwent C10903P14 carbon paste were dried at 120 °C for 20 minutes and the layers of Solaronix Platisol T/SP printing paste were sintered at 450 °C for 10 minutes. Further, the silver-based bus bar was screen-printed the same way as described above.

The novelty of the approach was the usage of printed UV curable system for encapsulation of the silver-based bus bars, separation of the electrolyte and assembly of the whole DSSC solar cell. The electrolyte used for filling of DSSC solar cells consisted of acetonitrile or ethylene glycol as a solvent and LiI (0.1 M) and I_2 (0.05 M) as a redox system. Various screen-printable UV curable systems were used and tested for their resistance to electrolyte. The most durable one was found to be a dielectric screen printing paste DI-7502 (Entech Electronics). In the first step, the printed and sintered photoelectrode and counter electrode of each DSSC solar cell were merged by printed UV curable dielectric ink. After the curing, the electrolyte was filled into the cell through the channels left in the barrier layer. In the last step, the whole cell was completely sealed by the same UV curable ink. Finally, the wires were connected to bus bars by colloidal silver and for higher mechanical endurance were fixed by epoxy glue (Fig. 3).

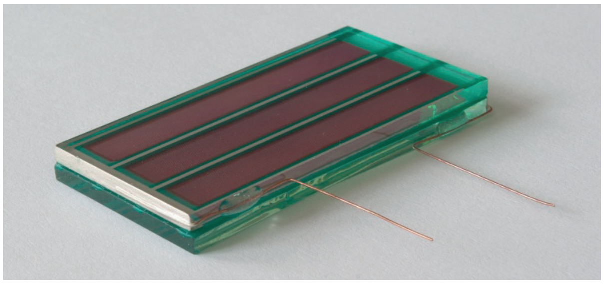

Figure 3: Photograph of fabricated DSSC with active area of 7.8 cm^2

Various modifications of DSSC solar cells were prepared under described conditions, represented by variety of used materials and structural properties of photoelectrode, counter electrode and electrolyte. The comparison of fabricated DSSCs were based on current-voltage (I-V) characteristics, which were measured using multimeter UNI-T UT39A and resistor cascade under Xenon lamp of Q-SUN Xe-1-B device and alternatively under Philips MASTER TL-D 90 De Luxe light source. The thickness of selected layers was measured by mechanical profilometer DektakXT (Bruker AXS). Structure and topology of printed layers was observed by SEM (JEOL JSM-5500LV) and optical microscope Bresser Erudit. Spectral characteristics of dyes used for sensitizing were measured by Specord 210 (Analytik Jena).

3. Results and discussion

The samples of DSSC solar cells varied in materials used for preparation. In experimental design, parameters of photoelectrode, material of counter electrode and solvent of electrolyte were varied. The aim was to study the influence of these variables to the resulting characteristics of solar cells. Five selected combinations are listed in Table 1.

Table 1: Variations of printed DSSC

Sample	Photoelectrode	Counter electrode	Electrolyte solvent	Sensibilisation dye
A	2 layers of 21 nm TiO_2, 2 layers of 180 nm TiO_2	Pt	Acetonitrile	Ruthenizer 535-Bis/TBA
B	3 layers of 21 nm TiO_2, 1 layer of 180 nm TiO_2	Pt	Acetonitrile	Ruthenizer 535-Bis/TBA
C	4 layers of 21 nm TiO_2	Carbon	Acetonitrile	Ruthenizer 535-Bis/TBA
D	4 layers of 21 nm TiO_2	Pt	Ethylene glycol	Ruthenizer 535-Bis/TBA
E	4 layers of 21 nm TiO_2	Carbon	Ethylene glycol	Ruthenizer 535-Bis/TBA

For typical layers of photoelectrode, counter electrode, bus bar and barrier layer, the thickness was measured by means of profilometer. The thickness of photoelectrodes was 8-9 µm in dependence on the number of layers with larger TiO_2 particles, the mean thickness of carbon counter electrodes was 15 µm. The mean thickness of silver bus bars was 3 µm and the barrier layer was 80 µm thick, which also determined the gap between photoelectrode and counter electrode. Each layer was investigated by SEM (Fig. 4) and optical microscopy. From SEM images it is obvious that the size of primary particles of TiO_2 is in the range of tens of nanometres. In some photoelectrode layers were present small cracks, which should have impact on the conversion efficiency of cells. The photoelectrodes containing layers with large TiO_2 particles were less prone to the creation of the cracks. The particles in carbon electrode are flakes with maximal dimensions in tens of micrometres. The dimensions of platinum particles reduced from its precursor (H_2PtCl_6) are in nanometre scale. The catalytic activity of carbon and platinum layers was checked using hydrogen peroxide.

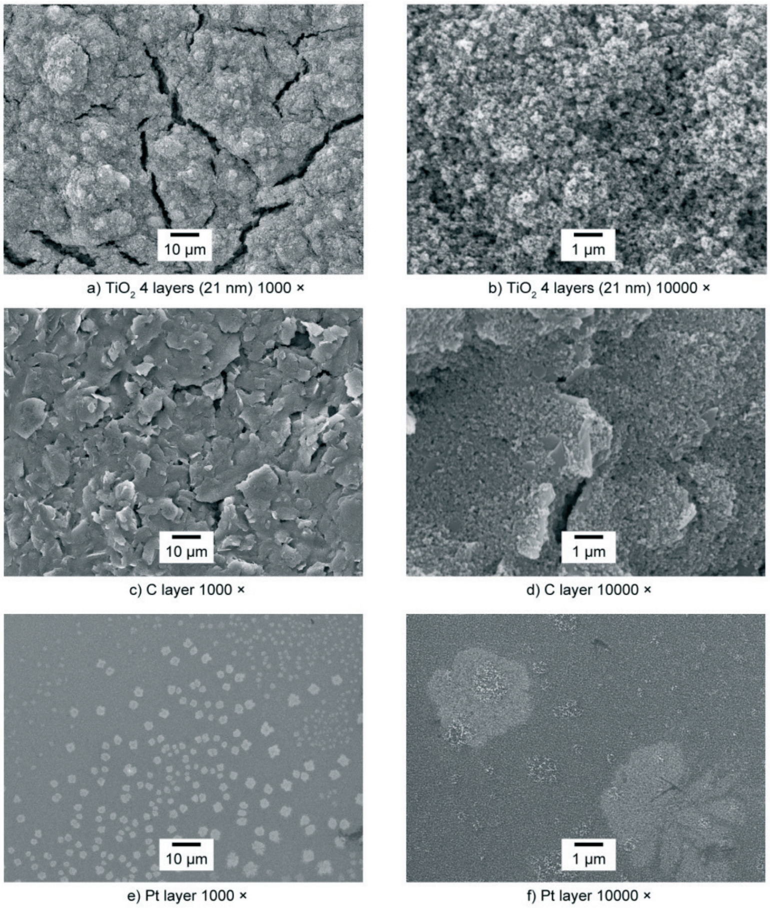

Figure 4: SEM microphotographs of selected sintered TiO_2 layers (a, b) and C (c, d) and Pt (e, f) counter electrodes

Figure 5 shows I-V characteristics for various samples of DSSC solar cells under Philips MASTER TL-D90 De Luxe light source and in case of sample D also under Xenon lamp of Q-SUN Xe-1-B instrument. Because the output characteristics of Philips MASTER TL-D 90 De Luxe light source are hugely different in comparison with the standard terrestrial spectra of AM1.5G, which are usually used for estimating of conversion efficiency, the results estimated under Philips light source were used only for relative comparison of fabricated samples of DSSC cells.

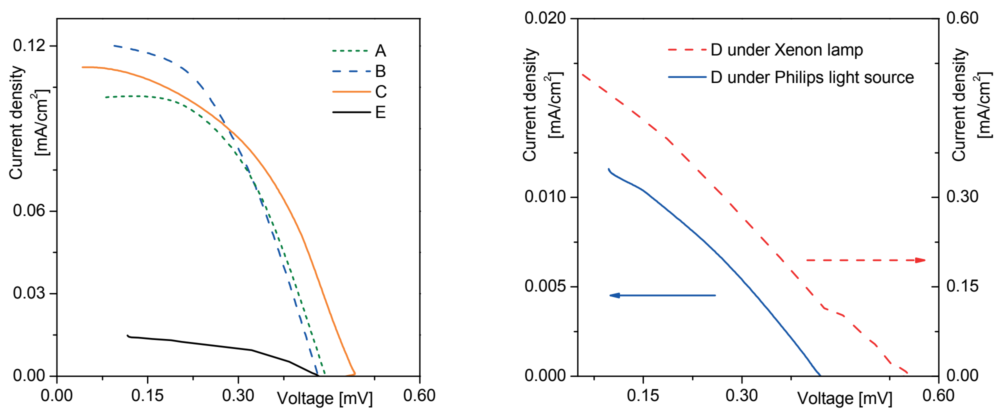

Figure 5: Photocurrent-voltage curves for samples A, B, C, E under Philips light source (left) and for sample D under both light sources (right)

From I-V curves for samples A and B it is obvious that the difference is relatively small and the influence of thicker light scattering layer containing large TiO_2 particles is not beneficial. The cell of sample C does not contain the light scattering layer and its counter electrode is based on carbon par-ticles. From I-V curve it is clear that the open-circuit voltage is higher, arguably due to larger interface area of TiO_2/dye, because the photoelectrode is formed by four printed (wet-on-dry) layers with small primary particles TiO_2.

Samples of DSSC cells containing electrolyte based on acetonitrile did not provide stable long-term functionality of the cell due to corrosion of barrier layers and bus bars, which was caused by solubilizing properties of solvent boosted by iodide/iodine redox couple. For this reason, the samples D and E were filled with electrolyte based on ethylene glycol, because lower aggressiveness and volatility of this solvent resulted in better stability of electrolyte as well as its less damaging effect on barrier layer and thus in longer lifetime of whole fabricated cell. These benefits were paid by higher viscosity of electrolyte, its lower conductivity and low ionic mobility, which overall resulted in significantly worse output characteristics of cells (Fig. 5). Decline of the output characteristics is evident from comparison of I-V curve of sample E with curve of sample C, which differs in electrolyte solvent only. These characteristics measured under the same light source show that current density for sample E is approximately 8 times lower than for sample C. The DSSC solar cells of samples D and E were also measured under Xenon lamp of Q-SUN Xe-1-B instrument, which intensity corresponds to one sun. Output I-V characteristics of sample D under both light sources are compared in the right part of Figure 5. It can be concluded that output characteristics, especially current density, are approximately 40 times higher for Xenon lamp light source due to its power. Based on the known output power and spectral emissivity of the light source it was possible to calculate conversion efficiency of these samples; all characteristics of DSSC solar cells D and E are listed in Table 2. The characteristics are slightly better for cells with platinum counter electrode. It is probably caused by higher catalytic activity and higher conductivity of Pt layer.

Table 2: Calculated characteristics for samples D and E under Xenon lamp light source*

Sample	V_{OC} [V]	I_{SC} [mA]	J_{SC} [mA/cm^2]	I_{MAX} [mA]	V_{MAX} [V]	P_{MAX} [mW]	FF [%]	η [%]
D	0.55	4.21	0.54	2.40	0.27	0.64	28	0.13
E	0.49	3.90	0.50	2.40	0.19	0.46	24	0.09

* Open-circuit voltage (V_{OC}), short current (I_{SC}), current density (J_{SC}), maximum power current (I_{MAX}), maximum power voltage (V_{MAX}), maximum power (P_{MAX}), fill factor (FF) and conversion efficiency (η)

4. Conclusion

By means of screen printing technique, DSSC cells with active area of 7.8 cm^2 and three parallel connected cells were fabricated. The majority of parts of the functional DSSC devices including barrier layer were prepared by printing. The proposed barrier layer for sealing the bus bars and the whole cell was printed using UV curable ink instead of commonly used thermoplastic polymer Surlyn, which leads to the easier process of cell fabrication. Chosen type of UV curable ink was resistant to aggressive electrolyte, especially to the one based on ethylene glycol solvent. The DSSC cells with ethylene glycol based electrolyte provided good functionnality after 40 days. For cells based on electrolyte containing acetonitrile it is necessary to develop the printable sealing layer with higher endurance to corrosive properties of electrolyte, i.e. with better barrier properties to achieve the long-term durability of the whole DSSC cell. For the varied materials, influences on conversion efficiency of prepared solar cells were estimated based on relative comparison. The best results were achieved for cells with photoelectrode containing small primary particles of TiO_2, with counter electrode based on Pt and electrolyte based on acetonitrile. On the other hand, this type of cell was stable only in range of hours due to corrosive effect of electrolyte on the sealing layer. Micrographs of the photoelectrode captured by the optical and scanning electron microscopy have shown cracks of the layer, therefore, the sintering process and ink formulation need to be improved.

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Development of a fully printed flexible battery on a roll-to-roll printing press - Part 1: Development of a printable electrolyte

Alireza Saidi[1], *Jean-David Lebreux*[1], *Catherine Lanthier*[1], *Christiane Lecomte*[2], *Gilles Picard*[2]

[1] Quebec Institute of Graphic Communications (QIGC)
999, Avenue Emile-Journault East
Montreal (Quebec) Canada H2M 2E2
E-mails: asaidi@icgq.qc.ca; jdlebreux@icgq.qc.ca; clanthier@icgq.qc.ca

[2] Ahuntsic College
9155 Rue Saint-Hubert
Montreal, QC H2M 1Y8
E-mails: Christiane.Lecomte@collegeahuntsic.qc.ca; gilles.picard@collegeahuntsic.qc.ca

Abstract

Thin-film batteries are positioned to become the next generation of power sources for portable electronic applications. Printing batteries on a R2R process has thus become an inevitable solution to manufacture, at low-cost, high volumes of power sources on flexible substrates. Despite an increasing interest in developing printed flexible batteries and the release of few commercial products, these are still not 100% printed. Indeed, formulating a printable electrolyte still constitutes a major obstacle to overcome: the printed layer needs to remain wet and stable for the entire batteries' lifetime! As no printable solution has been found yet, the actual alternative prevents to produce batteries on an industrial printing platform. This project consists in developing a printable electrolyte to be finally integrated into a fully screen-printed flexible battery on a PET substrate. A side-by-side architecture using a silver-zinc screen-printed cell has been investigated. Along the project, several polymeric electrolytes and cellulosic gels have been considered to keep wet and stable over time the electrolyte required for the selected electrochemistry. The goal consists in obtaining a gel allowing a good ink transfer through the printing mesh while not affecting the layers' quality. Once the optimized compromise between rheological behavior and gels' conductivity is determined, full printed batteries have been produced. This study is of prime importance because it demonstrates that a battery can be fully printed on a roll-to-roll standard press on a flexible PET substrate, with appropriate materials and suitable printing parameters. This constitutes definitely a major step to scale up the manufacturing of flexible batteries from prototyping to a real high-speed industrial production.

Keywords: battery, screen printing, electrolyte, polymer gel

1. Introduction

A growing willingness of portability, combined with the desire to be connected to the internet at all times (i.e.: evernet), as well as an increasing need for product traceability and solutions to address major food safety concerns drive the development of printed electronic applications. The growing adoption rate of micro-devices impacts significantly personal power consumption and will make it evolve significantly in the coming years. As mobility and connectivity are becoming the norm, individuals will be freed from large power grids to rely on mobile power systems. That is the reason why thin flexible batteries have a key role to play in the "printed electronics" revolution. Up-to-date market studies forecast that thin-film batteries are positioned to become the next generation of power sources for some portable electronic applications. The production of dynamic printed electronics media requires an appropriate power source. Other applications such as assisted passive and active RFID tags, smart packaging, powered smartcards, sensors, medical and cosmetic patches, smart bandages, and even certain types of displays could also benefit from the development of printed batteries. In comparison with other types of batteries, printed batteries are distinctive in combining both the advantages of thin batteries, namely lightness and flexibility sought by the progress of the current electronic trends, and advantages of printing such as low cost and massive production, available machinery and known fabrication technologies. Printing batteries on a roll-to-roll (R2R) process does not only bring low-cost solutions for high volume manufacturing, but it is also a unique way to manufacture power sources on flexible substrates. Also, printed batteries can be designed in any size or shape with a wide range of energy densities.

Despite an increasing interest in developing printed flexible batteries and the release of few commercial products, these batteries are still not fully printed. More specifically, a battery is called "printed" when one or more of its components are produced by a printing technique. Printed batteries are mainly based on silver-zinc or zinc-manganese dioxide electrochemistry where there is a need for the electrolyte to remain wet and stable for the entire lifetime of the battery to ensure high performance. Up to this point, only the electrodes and current collectors are printed whereas the liquid electrolyte is applied mechanically. Due to particle size, amount of electro-active materials, and the required thickness of each layer, screen-printing still remains the most widely used printing method for battery electrodes. On the other hand, formulating a printable electrolyte still constitutes a major obstacle to overcome in order to realize a fully printable battery. As no printable solution has been found yet, the actual alternative consists in imbibing a separator layer with an electrolyte and depositing it over/or between electrodes to form the separator-electrolyte layer. This prevents the massive production of flexible batteries at low costs.

This study therefore focuses on the development of a printable electrolyte to be integrated into a fully R2R printed flexible battery on PET substrate. During the project, several polymeric and cellulosic gels were tested as means to maintain the wetness and stability of the pure KOH electrolyte that is required for the silver-zinc electrochemistry. A challenging aspect of this work is to find a compromise between the rheological properties - required to obtain a screen-printable gel -and an acceptable ionic conductivity.

2. Methods and experiments

A printed battery on a flexible substrate is typically composed of two current collectors, two electrodes and an electrolyte in between. In the present study, two current collectors are printed using a carbon conductive ink. Electrodes are composed of dried metallic printable materials deposited onto the current collectors. A silver-zinc cell was investigated using a silver cathode and an anode made of a mixture of zinc oxide and pure zinc powders. The silver-zinc couple is the preferred choice when high specific energy/energy density, coupled with high specific power/power density are required for high-rate, weight or size/configuration sensitive applications. Once the electrolyte is laid down, the battery is laminated with a barrier film to prevent any degradation to the battery's performance caused by oxidation, exposure to moisture and physical leakage of the electrolyte. Regardless of the cell chemistry, the cell configuration results from a compromise between numerous and often conflicting constraints, such as: size, weight, capacity, discharge rate, withstand lifetime, cycle life, environmental impact, and safety. With high specific power and energy output being of paramount importance, battery engineering has yielded a large variety of architectural designs.

The sandwich model (or stack layout) is generally the preferred architecture in thin battery design because it offers the advantage of a very short, parallel ion path leading to much higher charge and discharge currents. This architecture has also been very attractive in a laboratory environment, where small-scale production is manually performed. However, this configuration requires multiple printing passes, where it is comprised of a superposition of layers including electrodes and the electrolyte. The electrolyte in the middle of the stack must remain wet during the manufacturing of the battery. This poses as a challenge because it is common practice to dry individual printed layers before the subsequent pass. Common to this cell architecture, each half cell is printed on a separate substrate or on different areas of the same substrate, with only one half cell coated with the electrolyte. Finally, the substrates are stacked or folded such as the two half cells form a complete stacked battery structure. As the battery has to be thin, flexible and preferably printed inline, a fabrication method that requires mechanical substrate manipulation is not economically viable.

Since batteries are designed to be part of flexible printed electronics, the *"printability"* was definitely the main parameter to consider in our project. A side-by-side architecture (planar) was selected to avoid the usage of a separator layer. In fact, the risk of an internal short-circuit is almost zero due to the absence of any physical contact between electrodes. In the case of a planar configuration, both electrodes are printed adjacently on top of the current collectors, then both are coated with the electrolyte. In this case, the number of overlaid elements is reduced. In addition, this design offers greater flexibility. Consequently, the planar thin flexible battery is much simpler and can be screen-printed. The overall efficiency of the planar battery is expected to be lower than the efficiency of a battery with a sandwich structure; however, complete printability remains its biggest advantage. This compromise is acceptable given the practical objectives of flexible electronics. Later studies on different planar design may overcome this disadvantage.

In this work battery prototypes were printed with a screen printer (Ekra, X1-SL). The main steps of the process are illustrated in Figure 1. Through the first pass, carbon conductive current collectors (DuPont 7105) are deposited on a poly(ethylene terephthalate) (PET) substrate (DuPont Teijin Films, MYLAR-48EL). The substrate material has to withstand thermal treatments at around 130 °C required to dry the printing pastes.

Each electrode is printed separately. First a zinc conductor (DuPont BQ311) is printed on one current collector, followed by a silver conductor (DuPont 5025) printed on the second current collector. Next, a sealing material is printed during the fourth pass to hold the electrolyte which is laid down in the following pass. Finally, the whole battery structure is laminated with an appropriate barrier film.

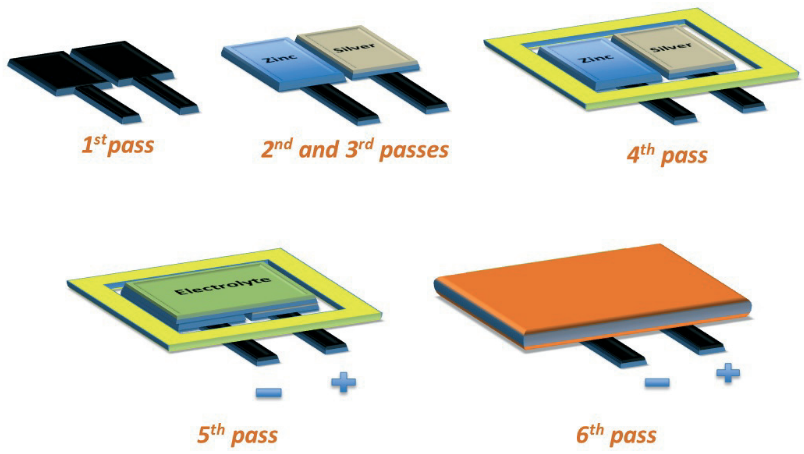

Figure 1: Printing sequence of a fully printed silver-zinc battery

Prior to printing the battery prototype, an appropriate printable electrolyte gel had to be produced. Typical silver-zinc battery cells use KOH electrolytes with molarities ranging from 4 to 10M depending on the cell construction and desired performance. In general, solution conductivity increases with increased KOH molarity. Consequently the main challenge was to find a compromise between the rheological properties - required to obtain a screen-printable gel - and a good ionic conductivity. The high ionic conductive electrolyte must allow for a good ink transfer through the printing mesh, while not affecting the sheet release, ink spreading and ink adhesion to the previously printed layers. During the project, several polymeric and cellulosic gels were considered as materials to hold the KOH electrolyte while maintaining its stability and wet nature. Polyethylene oxide (PEO) (Sigma-Aldrich, Mw = 100,000; 200,000; 1,000,000), polyacrylic acid (PAA) (Sigma-Aldrich, Mw = 1,000,000), polyvinyl pyrrolidone (PVP K30) (ISP, Mw = 40,000 to 80,000), PVP K90 (ISP, Mw = 900,000 to 1,500,000), sodium carboxymethyl cellulose (Na-CMC) (Walocel, Mw = 60,000) and nanocrystalline cellulose (NCC) (Celluforce) were investigated in the formulation of electrolyte gels.

The electrolyte gels were produced according to the following steps: first, an aqueous solution of the core matrix was prepared to evaluate the impact of both material concentration and polymeric molecular weight on gel consistency at room temperature. Then a sufficient amount of KOH was added to the gels. Once the most homogenous and consistent electrolyte gels were obtained, their respective ionic conductivity was evaluated with an ionic conductometer (Mettler Toledo, S230). The most conductive electrolyte gels were considered for rheological analysis. The shear flow behaviour of the electrolyte gels was evaluated through shear rate sweep tests (10^{-2} - $10^{2}s^{-1}$) with a rheometer (Rheologica Instruments, Stresstech HR). The hysteresis loops in strain measurements were also obtained by sweeping the shear rate to assess the rheological hysteresis. By carrying out this analysis, the electrolyte gel behaviour under the screen printing squeegee pressure can be simulated.

3. Results and discussions

Nanocrystalline cellulose (NCC) is a pseudo-plastic and thixotropic material, which is obtained from natural fibres by an acid hydrolysis, engendering highly crystalline and rigid nanoparticles (100 to 1000 nanometres). It exhibits the gel-like properties under normal conditions while flowing under stress as a shear-thinning material. The high viscosity of NCC at low concentrations makes it suitable as a stabilizer, gel or thickener in different applications used in the food industry and coating formulation. Different NCC concentrations in an aqueous solution were investigated for the current study. While solutions with concentrations over 10 % become insoluble in water, concentrations lower than 5 % are far from a gelatinous texture. As the concentrated NCC becomes gelatinous in the presence of small amounts of KOH, it tends to become highly viscous and difficult to manipulate when printing, hence, less concentrated NCC gels were considered. Moreover, the less concentrated NCC gels were likely to liquefy when the KOH molarities were increased. However, NCC stable gels degraded in the presence of a high amount of KOH, thus impacting its texture and conductivity level. While pure cellulose can be treated with alkali solutions under certain conditions, this kind of treatment causes changes in their crystalline structures. The NCC degradation could be due to its high aspect ratio which makes cellulose nanofibrils more vulnerable to alkaline environments. In this work, the incorporation of KOH with molarities around 2M resulted in the most successful formulations with an ionic conductivity of almost 210 mS/cm. The deterioration of the cellulosic gel affects significantly its rheological properties required for printing. As they show good stability over time, cellulosic gels can still be considered as suitable electrolytic gels when combined with smaller KOH concentrations as long as lower conductivities are acceptable.

In this study, particular polymer gel electrolytes (PGE) were also studied. Some of them have previously been used in batteries and capacitors due to their mechanical stability, tuneable ionic conductivity and ease of processing. For instance, PVP is used as a dispersant in conductive inks used in printed circuits and a hydrophilic separator in batteries. Its relatively stable viscosity over a large pH range makes the formulation easier over different KOH concentrations. PVP suspensions are stable over time when protected from air, they are also non-thixotropic and are compatible with different resins.

PAA is a well-known hydroponic polymer gel. It has a high water holding capacity (20 to 100 times its weight), high gel strength, and relatively low cost. Once added to an aqueous solution, the gel tends to expand, swells, and becomes elastic. Consequently, the required electrolyte quantity to occupy a specific cell volume is reduced. PAA can be a suitable candidate for alkaline batteries and is used as Zn-MnO_2 electrolyte demonstrating suitable cell capacities. Electrolytes based on PAA can also be attractive for silver-zinc systems. Indeed, PAA-based polymeric electrolytes show a higher ionic conductivity than pure KOH solutions at low KOH concentrations and are chemically very stable.

PEO as a synthetic polyether is readily available in a wide range of molecular weights. This amphilic polymer is soluble in water as well as in many organic solvents. Low molecular weight PEOs could be viscous enough, while higher molecular weight ones are waxy. It has been previously studied as a polymer gel electrolyte. The main proposal of previous researches was to provide mechanical stability, eliminate the problem of solvent evaporation and interfacial incompatibility with electrolytes in thin batteries. However, PEO has mediocre ionic conductivity and only achieves better performance in the amorphous state. PEO electrolytes at room temperature are composed of crystalline phases and their amorphous phases generally occur around 60-80 °C. Nevertheless, ceramic nanoparticles can be used to improve their mechanical stability and also ionic conductivity. Accordingly the ceramic filled PEO gels have previously been used for lithium ion and zinc ion systems.

Finally, we have also considered sodium carboxymethyl cellulose, which is largely used as a thickener or emulsion stabilizer in diverse applications such as prints and food packaging. With its carboxymethyl groups bound to some of the hydroxyl groups of the glucopyranose monomers making up the cellulose backbone, CMC proves to be compatible with a sliver-zinc system. The use of Na-CMC as a polymer gel electrolyte can decrease the battery internal resistance if high methyl content is applied.

We explored the possibility of preparing printable polymer gel electrolytes at different molecular weights. Lower molecular weight polymers seem to decrease the anode corrosion providing longer lifespan, while higher molecular weight polymers tend to decrease the internal resistance of the battery. Although polymer concentrations change from one PGE to another, during our experiments we have observed that at lower molecular weights, the increase of KOH molarities tends to induce gel leakage as well as a loss of their gelatinous texture and homogeneity. At higher molecular weights, more pure electrolyte concentrations can be absorbed. It can be explained by the growth of pore size with greater molecular weights, which can increase the volume of water absorbed. There is however an exception with high molecular weight PEO where the addition of KOH results in ionic crosslinking and makes the gel very elastic. While both liquid and solid state electrolytes can show high ionic conductivity and be useful in some cell configurations, they cannot be considered because they prevent deposition of the electrolyte layer by a screen printer. It is noteworthy that in some cases, alcohol components or wetting agent have been used to prevent the gelatinous texture leakage. These components prove to be relevant to improve the gel transfer through the screen meshes and enhance the adhesion of electrolyte at electrode surfaces. While wetting agents do not seem to influence the ionic conductivity, excessive use of alcohol-based components can degrade the conductivity.

Carried out rheology analysis showed that prepared polymer gel electrolytes are highly viscous under no external stress, but they exhibit shear-thinning behaviour and their viscosity decreases with shear rate. While the shear thinning behaviour of the PGE can be used advantageously to allow printing with a lower pressure head, its high viscosity facilitates lamination of the barrier film and prevents its leakage if the cell ruptures.

Preliminary results show that the selection of a PGE with appropriate rheological properties and ionic conductivities (i.e.: ranging from 430-570 mS/cm,) results in printed battery prototypes reaching nominal voltages of 1.3 to 1.4 Volts. Utilizing the flexibility of printing processes to design various architectures and layouts, different designs can be examined to explore the possibility of improved battery performance. On the other hand, the influence of selected gels and printing process parameters on the layer surface quality also needs to be evaluated. Squeegee parameters (pressure, angle, speed, material) the edge geometry and the mesh type, the press parameters still need to be fine-tuned and recorded to obtain the most homogenous surface. Our current investigations on the improvement of battery performance and adjustment of press parameters will be covered in forthcoming publications.

4. Conclusion

In summary, the impact of different polymer concentrations at various molecular weights on printability and conductivity were studied. By finding a compromise between the rheological properties and the required conductivity of electrolyte gels, results of this study demonstrate the feasibility of developing a fully printable battery. However these outcomes must be transferred on a flexible PET substrate printed on a roll-to-roll standard press. This constitutes a major step to scale up the manufacturing of flexible batteries from prototyping to real high-speed industrial production. The first prepared samples are rudimentary prototypes, but additional tests are currently being performed to increase their performances to meet the requirements of batteries assisting passive RFID tags.

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Design and inkjet printing of RF devices in the GHz range

Daniele Sette[1], *Anne Blayo*[2], *Christophe Poulain*[1], *Denis Mercier*[1]

[1] CEA, LETI, MINATEC Campus
17 Rue des Martyrs
F-38 054 Grenoble Cedex 9, France
E-mails: daniele.sette@cea.fr; christophe.poulain@cea.fr;
denis.mercier@cea.fr

[2] Grenoble INP - Pagora
461, Rue de la Papeterie - BP 65
F-38 402 Saint Martin d'Hères, France
E-mail: anne.blayo@pagora.grenoble-inp.fr

Abstract

This paper presents a radio frequency filter fabricated on a low cost substrate by inkjet printing of a silver nanoparticles ink. This work focuses on the inkjet fabrication process and the setting of optimal printing conditions to achieve a band-pass filter working at 17 GHz.

This RF filter is, to our knowledge, by far the highest center frequency inkjet printed filter reported up to now. It demonstrates the potential of inkjet printing technology for high frequency filtering applications.

Keywords: inkjet printing, printing conditions, flexible substrate, band-pass filter, silver nanoparticles

1. Introduction

Printed electronics is a promising technology that can provide low cost devices [1]-[2]. If printing processes cannot reach the resolution of photolithography, they allow patterning large areas with resolution as high as 5 µm [3] and saving material as direct writing methods.

Also, they are compatible with a large variety of substrates: rigid, flexible and even 3D shaped. These properties offer to printing technologies major assets in radio frequency (RF) devices manufacturing. Thanks to the development of telecommunication applications, the demand for RF devices is fast-growing. The most advanced potential RF application of printing technology is the RFID tag in the Ultra High Frequency (UHF) range. Although other printed devices at higher frequencies have been developed, specific substrates reducing transmission losses are used [4]-[5].

This paper focuses on inkjet printing technology of conductive materials. The purpose is to describe the optimization of the printing process in order to achieve a 17 GHz filter on a polyimide substrate offering similar performance as devices fabricated by other techniques such as silicon micromachining [6], which are much more expensive.

2. Filter design

The filter layout is presented in Figure 1 and the optimized dimensions of the filter are given in Table 1. For further details, refer to the previous work in [7].

The device is a two pole filter centered at 17 GHz, it has a 4 % bandwidth with transmission zeros to improve the rejection.

The filter is based on suspended microstrip lines enclosed between two brass cavities as shown in Figure 2, with coplanar feed lines to facilitate measurements. The filter has been designed following the procedure detailed in [6] and [8]. The filter response has been computed and optimized with the software Agilent Momentum based on the method of moments.

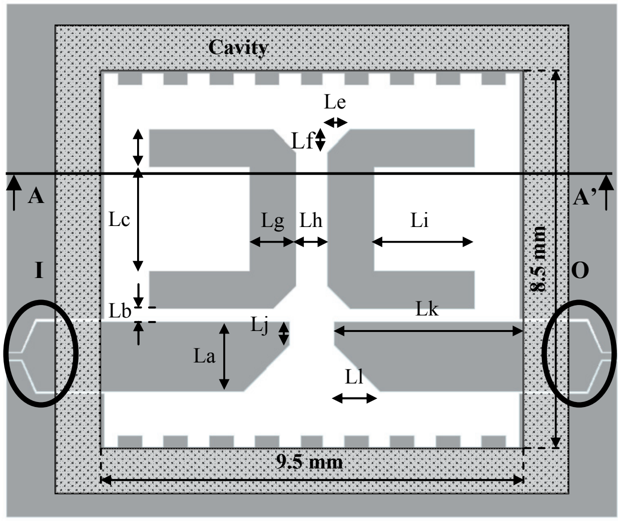

Figure 1: Top view of the filter. Dimensions are detailed in Table 1

Table 1: Dimensions of the Filter

	Length (µm)		Length (µm)
La	1500	Lg	1000
Lb	300	Lh	700
Lc	2300	Li	2200
Ld	800	Lj	500
Le	500	Lk	4250
Lf	500	Ll	1000

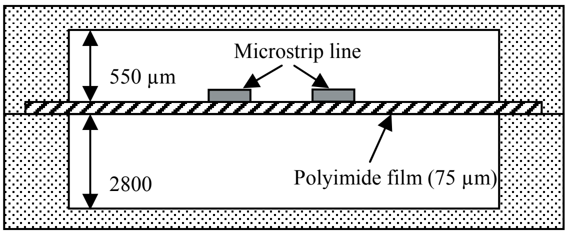

Figure 2: Cross-section of the filter along AA'

3. Filter fabrication

Printing a pattern with high conformity with the design relies on the equilibrium of the printing process, the ink rheological properties and the substrate properties such as surface energy, porosity and roughness.

3.1 Printing equipment

Printing is realized on a Dimatix DMP2800 printer with 21 µm side square nozzles. Nozzles have piezo-electric actuation that allows setting both individual actuation voltage and global temperature. The meniscus can also be set. The substrate is held on a chuck that can be heated up to 60 °C. The input pattern format is binary bitmap. Droplet ejection can be observed with an embedded stroboscopic camera.

3.2 Ink and substrate properties

A commercial ink (SunChemical) charged with silver nanoparticles at 40 % in weight is used to print the filter pattern on a 75 µm thick polyimide substrate (Kapton HN, Dupont).

The substrate surface energy measurement has been carried out with the contact angle method using an OCA Dataphysics goniometer. The Owens-Wendt model is used to calculate the surface energy using five different probe liquids that are reported in Table 2.

Table 2: Probe liquids for surface energy measurement and contact angle measured on Kapton HN

Surface tension at 25°C (mJ.m^{-2})	Total γ_l^T	Dispersive component γ_l^D	Polar component γ_l^P	Contact angle (°)
Water	72.8	21.8	51	73.9
Glycerol	63.4	37	26.4	70.4
Diiodomethane	50.8	50.8	0	38.7
Hexadecane	27.4	27.4	0	18.5
Bromonaphtalene	44.6	44.6	0	32.0

Five measurements of the contact angle for each probe liquid have been realized. The extracted value of the Kapton HN surface energy is 39 mJ.m^{-2} and the R² of the linear fit value is 0.86. The ink surface tension has been measured on the same equipment with the pendant drop method. This results in a value of 24 mJ.m^{-2} with a standard deviation of 8 mJ.m^{-2} on five measurements. The ink has a viscosity of 13.5 mPa.s measured on an Anton Paar Physica MCR 301 rheometer at 25°C and 1000 m.s^{-1}. The measurements are in agreement with the manufacturers data reported in Table 3.

Table 3: Ink and substrate properties

Ink EMD5714 - SunChemical		
Viscosity at 25°C	10-13 [9]	mPa.s
Surface tension at 25°C	27-31 [9]	mJ.m^{-2}
Density at 25°C	1.56 [9]	
Substrate Kapton HN 75 µm - DuPont		
Surface energy	46 [10]	mJ.m^{-2}
Dielectric constant	3.5 [11]	
Thermal Coefficient of Expansion	20 [11]	ppm/°C

The filter performance improves with the electrical conductivity of the printed layer. Silver nanoparticles ink is chosen since it allows reaching conductivities higher than 10^7 S.m^{-1}. The polyimide substrate is selected for its low dielectric constant and tolerance to temperature up to 400 °C. Moreover, it has smooth surface and poor porosity, which prevents nanoparticles infiltration into the substrate.

3.3 Printing process

The ink solvent is ethanol, thus nozzles temperature is set to ambient to prevent solvent evaporation which may cause clogging at temperatures higher than 35 °C. The actuation voltage is set around 23 V at a 5 kHz firing frequency resulting in a 14 µm diameter droplet, which corresponds to 11 pL volume. During droplet formation there are no visible satellite droplets and the filament completely disappears at 300 µm from the nozzle. The jetting waveform recommended by the ink supplier is illustrated in Figure 3. The meniscus is set to 5 in. of H_2O.

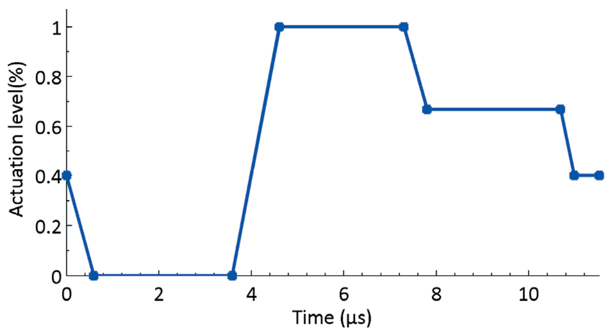

Figure 3: Jetting waveform

For pattern resolution higher than 555 pixels/cm, corresponding to 18 µm pitch between droplets, borders are well defined during printing, although few minutes afterwards the ink spreads under the influence of gravity and the pattern loses its shape. Decreasing the resolution leads to a dewetting phenomenon during drying at ambient temperature as shown on Figure 4. In conclusion, high resolution brings too much matter and gravity effect causes ink spreading while the affinity between the ink and the substrate is not adequate for lower resolution which hinders ink spreading. Those unwanted phenomena have been eliminated by accelerating the drying step by heating the substrate chuck at 60 °C. The best printing definition on the polyimide film is obtained at 476 pixels/cm (21 µm pitch) while heating the printer chuck at 60 °C.

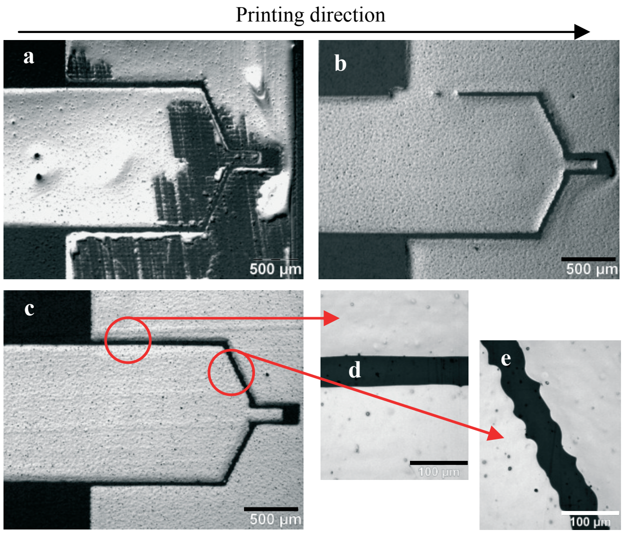

Figure 4: a) Ink dewetting; b) Ink spreading; c) High quality printing; d) Pattern edges parallel to printing direction; e) Pattern edges not parallel to printing direction

3.4 Pattern design

The most critical parts to print are located at the input/output (I/O on Figure 1) lines of the filter. The gap between the feeding strip and the ground plane is 50 µm and even a single pixel connecting those two elements causes a critical short-circuit. Figure 4 illustrates that edges parallel to the printing direction are well defined while droplet shape (pixel) is visible when the printing direction has an angle with the border orientation. Pixels of the border have been manually set in a regular arrangement, e.g. Figure 5, and different configurations of spacing have been printed in order to obtain a reliable printing and a conform printed pattern.

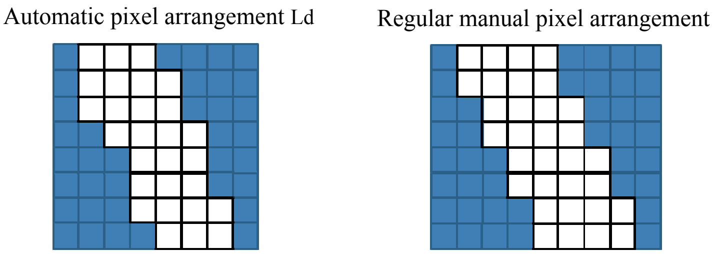

Figure 5: Examples of pixel arrangement

3.5 Annealing

Once the pattern is printed and dried, annealing is necessary to evaporate the remaining solvent, to burn organic compounds such as surfactants and nanoparticles steric coating and finally to activate nanoparticles coalescence. The annealing has been realized in an oven, the conditions are specified in the paragraph IV.

Nanoparticles exhibit a melting temperature which depends on their size [12]. This property allows modifying the microstructure of the printed silver layer at temperatures much lower than the bulk silver melting temperature (961 °C [13]) making the annealing step compatible with organic substrates. The Atomic Force Microscopy (AFM) scans in Figure 6 illustrate the surface modification of the printed layer with the increase of the annealing temperature.

The grain size increases while their number drops. The evolution of the granular microstructure of the printed layer has a strong effect on both its mechanical and electrical properties. The dependency of the electrical properties of the printed silver layer with the annealing temperature is studied in depth in the next paragraph.

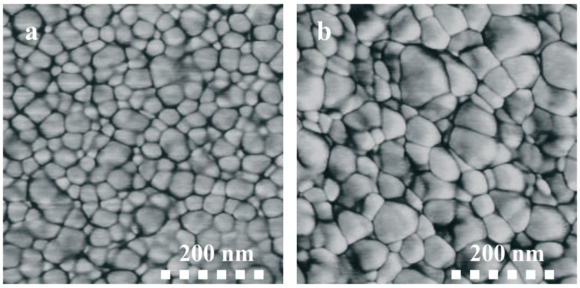

Figure 6: Phase data of AFM scans on the surface of printed silver ink. a) 150°C - 1h. b) 250°C - 1h

4. Experimental results

4.1 Electrical conductivity of the printed silver layer

The silver printed layer electrical conductivity highly depends on the annealing temperature. To study such dependency, conductivity measurements are realized with a four-point method on 1 mm² Van der Pauw printed patterns [14] on a SiO_2/Si substrate (Figure 7). The silicon substrate has been selected for its stability up to 1 000 °C. A silicon thermal oxide of 1 µm thickness is grown to ensure electrical isolation between the printed silver layer and the silicon. Also, SiO_2 has similar surface energy as Kapton HN, thus the same printing parameters can be applied.

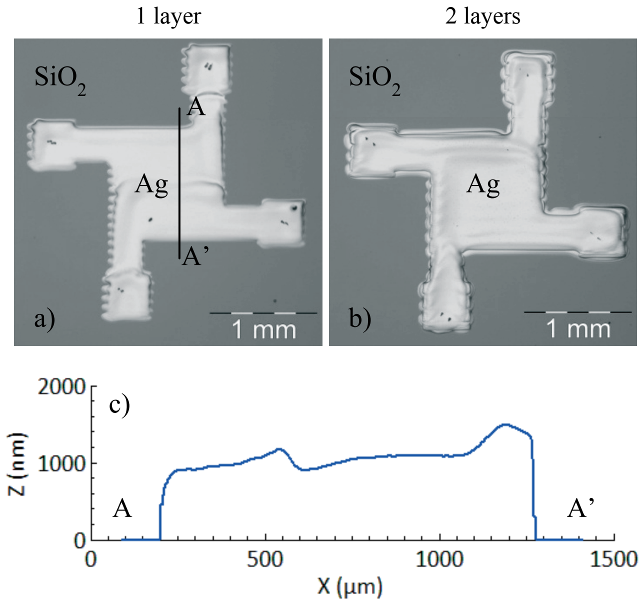

Figure 7: Van der Pauw patterns printed on SiO_2/Si substrate. a) One layer. b) Two layers. c) Profile AA'.

Spring probes are used in order to prevent from damaging the patterns and the electrical measurements are made by a Keithley 2182A nanovoltmeter. The electrical conductivity of the printed layer σ is extracted using equation (1).

$$\sigma = \frac{1}{R}\frac{\ln(2)}{\pi t} \tag{1}$$

Where R is the Van der Pauw patterns resistance and t their thickness. The measured thickness and the extracted conductivity are plotted versus the annealing temperature in Figure 8.

The electrical setup allows measuring the resistance of the Van der Pauw patterns with high precision. However, an error on the conductivity extraction is brought by the thickness measurement on the printed layer. Indeed, both on the top view microphotographs and in the profile in Figure 7, the thickness of the printed layer appears irregular. For the conductivity extraction, a mean value of the measured thickness by optical interferometry has been opted for.

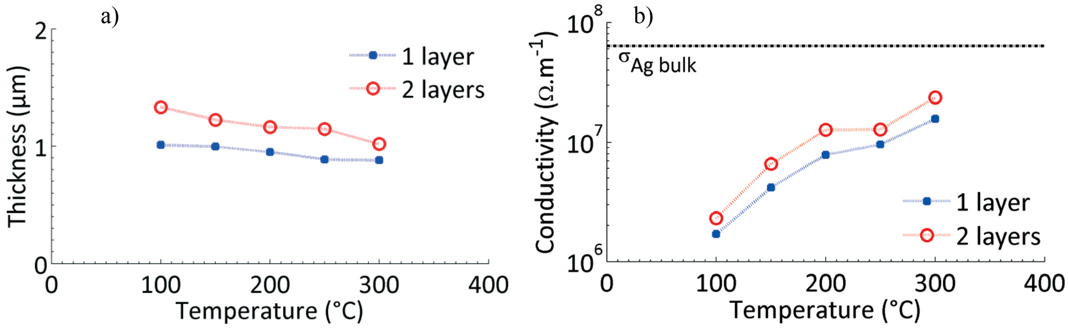

Figure 8: a) Measured thickness of the printed Van der Pauw patterns. b) Extracted conductivity

The thickness of the printed layer decreases with the annealing temperature, proving a densification of the microstructure. At the same time, the electrical conductivity increases, reaching near bulk values. The Van der Pauw patterns with two printed layers exhibit both a higher thickness and conductivity.

For annealing temperature above 300 °C, the microstructure of the printed layer continues to evolve and grain size reaches several micrometers. The thickness of the layer becomes highly irregular and the electrical contact with the spring probes is submitted to random contact resistances. As a consequence, even if the electrical measurement is possible, the extraction of the intrinsic printed layer conductivity cannot be relevant.

4.2 Filter electrical properties

The characterization of the electrical conductivity with the annealing temperature results in the following annealing conditions: 220°C during one hour. The values of thickness and conductivity extracted from Van der Pauw patterns printed on Kapton near the filter are given in Table IV.

Table 4: Conductivity of the printed layers

Number of passes	Thickness (µm)	Conductivity ($S.m^{-1}$)
1	0.85	1.4×10^7
2	1.30	1.5×10^7

Even if the increase in conductivity is lower than 10 %, the layer printed with two passes better covers substrate defects and the surface state is more homogeneous, which highly decreases transmission losses.

4.3 Filter assembly

The final step in fabricating the filter is the assembly of the printed layer with top and bottom cavities. Top cavity is glued with silver paste on the ground plane while the substrate is glued with Araldite® on the bottom cavity. Both cavities are electrically connected with silver paste. Figure 9 shows the final device with top cavity open.

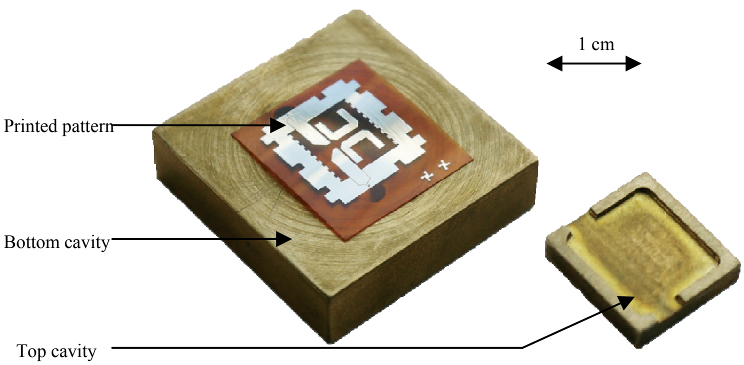

Figure 9: Printed band-pass filter

4.4 Frequency response of the filter

The filter has been measured with an Agilent N5230A vectorial network analyzer and a SOLT calibration. The measurement of the two printed layers presented in Figure 10 show that the filter is centered at 17 GHz and has a 4% bandwidth. It has 3.6 dB of insertion loss (S21) and a return loss (S11) better than -10 dB on the whole bandwidth. The insertion loss of the one printed layer filter is 5.6 dB.

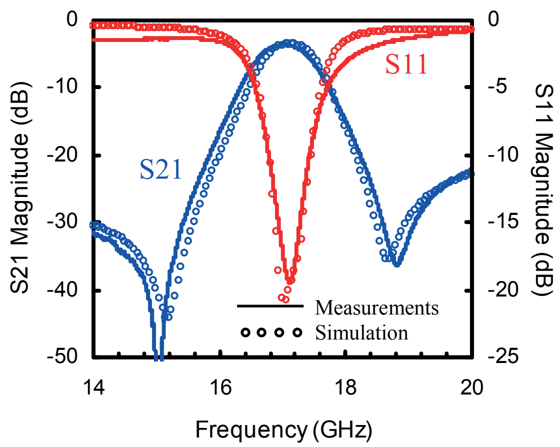

Figure 10: Measured and simulated response of the filter including metallic and dielectric losses

5. Conclusion

In this paper, the inkjet printed filter which has to our knowledge the highest center frequency reported up to now is presented. Printing parameters on the Dimatix DMP2800 have been optimized in order to reach a printed pattern with high conformity with respect to the design.

When dealing with inks charged with conductive nanoparticles, the annealing step is necessary to activate and improve the electrical properties of the printed pattern. The evolution of those properties have been studied in depth up to 300 °C, showing that extracting the intrinsic conductivity is a major issue because of the irregular thickness of the printed Van der Pauw patterns.

This work demonstrates the possibility of using inkjet printing technology for RF devices fabrication working at frequencies higher than 10 GHz. Inkjet printing is a versatile technology which let consider an easy development of inkjet printed millimeter-wave devices on ultralow cost substrates.

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Development of a printed pressure sensor for plantar foot pressure measurement

Marko Illing, Dominik Krumm, Arved C. Hübler

Chemnitz University of Technology
Institute for Print and Media Technology
Reichenhainer Straße 70
D-09126 Chemnitz,
Germany

E-mails: marko.illing@mb.tu-chemnitz.de;
dominik.krumm@mb.tu-chemnitz.de; arved.huebler@mb.tu-chemnitz.de

Abstract

The diabetic foot syndrome is a spreading disease among diabetics. High pressures at the foot cause ulcerations which can lead to amputation. Existing systems for monitoring foot pressure are not suitable for daily use, expensive and not be applicable to the specific case. Advanced printing technologies enable low-cost production of pressure sensors for various applications and can thus deliver an approach to solve this problem. In this work, fully printed piezoresistive pressure sensors were fabricated and successfully tested for their functionality in compression tests. Furthermore the possibility to integrate the printed sensors was investigated.

Keywords: pressure sensor, printed devices, piezoresistivity, tactile sensing

1. Introduction

Due to demographic changes within the population, for several years a growing interest in systems to maintain and improve the health-related quality of life can be observed. In terms of this, devices for pressure measurement can be found in several health-related applications. Diabetic patients require regular monitoring of foot pressure in order to avoid any severe injuries. Medical equipment for measurements of plantar foot pressure is currently very expensive, mostly rigid and not portable. Here we report a low-cost mass-produced flexible pressure sensor for the daily usage. It would help to monitor pressure and hence to prevent foot diseases like ulceration - a typical injury for diabetic patients (Bou, 2010).

There are several pressure sensing technologies like capacitive (Pal, 2006), piezoelectric (Dan, 2010) and piezo-resistive sensors (Pap, 2002) available. The review in (You, 2011) delivers a comprehensive overview for tactile sensing and states that piezoresistive devices are dominant in this area.

The approach of this work is to utilise high throughput printing technologies for a mass production of pressure sensing devices for a daily usage. With appropriate layouts and functional inks pressure-sensitive devices are printed on different flexible substrates. To change relevant parameters like sensitivity or pressure range and therefore the sensor properties, various options are available.

Printed pressure-sensitive devices are flat and flexible which makes it possible to integrate them into different host structures like carbon fibre reinforced polymer (CFRP). The usability of printed and integrated pressure sensors as well as the influence of the integration on the sensor characteristic and the host structures are topics of current studies (Kru, 2013).

2. Printable piezoresistive devices

There are different settings for printed pressure sensing devices. One common build-up (Leb, 2008) is printing interdigital electrodes on a substrate like polyethylene terephthalate (PET) foil and printing a semiconductive layer on a second PET substrate (Fig. 1). In this case semiconductive means that the layer becomes conducting under a compressive force. In an unstressed condition it is non-conducting. With an adhesive layer both substrates are assembled to the final device.

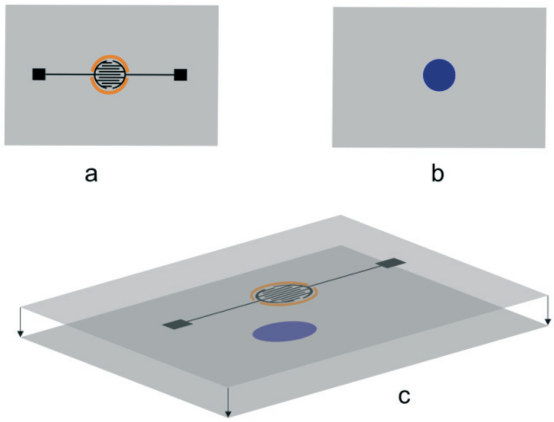

Figure 1: Sensor design. a: interdigital electrodes (black) and adhesive layer (orange); b: semiconductive layer; c: assembly

When a compressive force is applied to a piezoresistive device the resulting deformation of the layers leads to a decrease of its total resistance. This decrease depends on the materials used. Printable inks for this application consist of an insulating, elastic polymeric matrix and a conductive filler material. Typical conductive particles used in this set-up are carbon black, graphite and carbon nanotubes.

The mechanism of these piezoresistive devices is still not fully understood. Several overlapping effects determine the pressure sensitive behaviour. Not only the volume resistivity of the semiconductive layer determines the sensor behaviour, but also interface effects between electrodes and the semiconductive layer are very important for this type of sensor. Semiconductive in this case means that the layer becomes conductive under a compressive force. Because of a given roughness of these two printed layers their area of contact increases with higher compressive forces, as the semiconductive layer is elastic and deformable (Fig. 2). This results in a decreasing contact resistance.

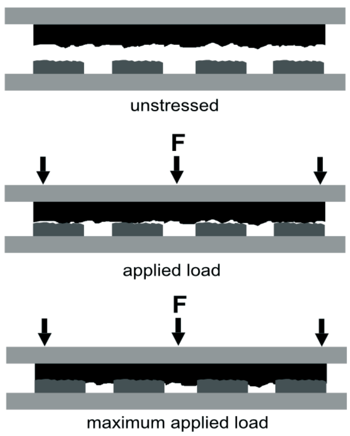

Figure 2: Sideview of the printed layers in different load cases

The advantage of printed piezoresistive pressure sensors is the possibility to print large areas with fabrication techniques at very low cost, the flexibility of the devices, lower thickness, less weight as well as simple read-out electronics compared to other sensing technologies. Main disadvantages are the hysteresis of the composite material, drift and a non-linear force-resistance characteristic.

3. Methods and materials

The fabrication of printed pressure-sensitive devices was done on the semi-automatic screen printer EKRA X1-Sl. The layouts from above are used on a 61/64 (mesh count per cm/thread diameter in µm) PET screen in combination with a squeegee with 75 Shore A hardness. Melinex 401 CW PET foil with a thickness of 50 µm has been used as substrate. Two functional inks were printed in the following experiments. For the interdigital electrodes silver paste 5028 was obtained from DuPont and used as received. The semiconductive layer was made out of an experimental ink received from E-Pinc GmbH. The ink was especially developed for this pressure-sensing application which is very useful when it comes to necessary adjustments for changing the properties of the layer. It contains graphite as conductive filler material and an elastomer as insulating matrix material. For printing the spacer the UV-curable adhesive SP-7514 from 3M was used as received in combination with a ALRAUN UV-curing unit.

4. Experiments and results

In the following steps the samples for a pressure-sensing device were fabricated. Screen printing was carried out under room conditions. On the first substrate the interdigital electrodes were printed. A circular layer of se-miconductive material was printed on the second PET substrate. The interdigital electrodes of a second series of samples were printed under the same conditions but with a different screen (PET 120/34). This aimed to achieve a different roughness of the structures and thereby a modified pressure sensor behaviour.

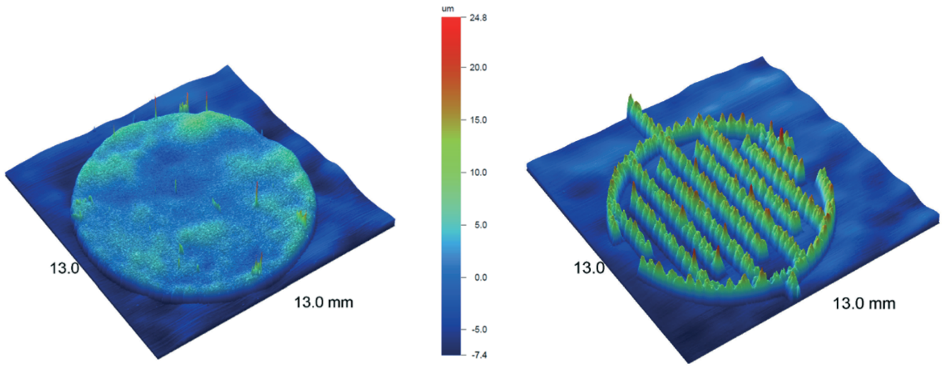

Figure 3: Surface profiles of printed structures (61/64 screen), left: semiconductive layer, right intergitial electrodes

The thickness and roughness of the layers has been measured with a Veeco Dektak 8M profilometer. Thicknesses of 7.7 µm ± 0.45 µm for the semiconductive layer and 12.3 µm ± 1.2 µm (61/64 screen) and 5.5 µm ± 0.55 µm (120/34 screen) for the electrodes were obtained. In Figure 3 the surface profile of the printed layers can be seen. The mesh of the 61/64-Screen can be clearly seen in the printed electrodes (Fig. 3 right) causing a rough surface. Table 1 gives an overview of the measured roughness. The electrodes roughness was measured directly on the electrode fingers.

Table 1: Roughness values of printed structures

Screen	Layer	R_a [µm]	R_z [µm]
PET 61/64	semiconductive	0.41	2.57
PET 61/64	electrodes	2.47	10.52
PET 120/64	electrodes	0.88	4.44

The assembly of both series was done with the help of a UV-curable adhesive. It was printed around the interdigital electrodes providing two features. The sandwich is permanently clued and the adhesive layer acts as a spacer. This helps to add a certain threshold to the sensor. In the unstressed condition the resistance is infinitely high. This means the layers are not in contact at any point in between the overlapping area. When the load is removed it supports the relaxing of the sensor. After printing, the adhesive was cured in two steps. In the first step only the initial printed substrate ran through the curing unit to be pre-dried. Afterwards the second substrate was adjusted over the electrodes and was put on top of it. A load of a calibrated 20 g weight was applied to the sandwiched PET foils. This was necessary to achieve a reproducible thickness of the spacer layer. In the second drying step the assembled sensor ran through the curing unit reaching the final drying state.

The produced sensors (Fig. 4) were investigated in compression tests. A stamp in the size of the sensor area (74.54 mm²) was applying a stepwise pressure up to 40 kPa. During the application and the removal of load the resistance of the sensor was measured using a two-wire measurement method and the universal measuring module NI cDAQ 9219.

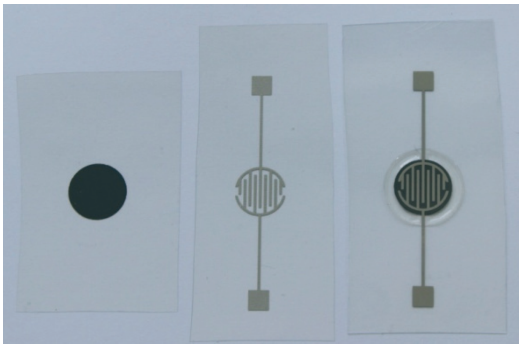

Figure 4: Printed sensor, left: semiconductive layer; middle: interdigital electrode; right: clued layers, final device

The graph in Figure 5 shows the non-linear pressure dependent resistance of the printed samples. With an increasing pressure the electrical resistance of the sensors of both series decreases. Therefore the functionality of the printed sensors could be shown.

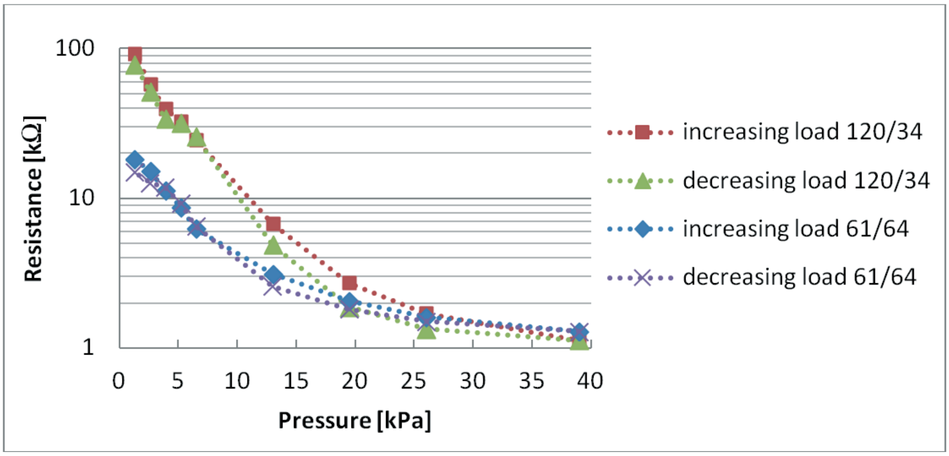

Figure 5: Pressure dependent characteristic of the resistance.

The samples of the 120/34-screen have a higher starting resistance, which can be explained with the lower layer thickness of the electrodes. At the starting pressure of ~1 kPa there is less contact area compared to the samples of the 61/64-screen resulting in a higher resistance. At the maximum pressure the resistance of both samples is nearly the same. The reason for this is assumed to be leveling of the printed layers at a certain pressure. As mentioned before the working principle concentrates on the interface effects of the two printed layers. But with adjustments on the semiconductive layer several improvements are possible.

For example pressure range could be modified as well as the sensitivity. It is also visible that a certain hysteresis occurs, explainable with the viscoelastic behaviour of the semiconductive layer. Changes are also possible in the layout of the sensor or thickness of the spacer. All these parameters influence the sensors characteristic making it highly adaptable to the specific application. It has to be stated that all the tests were carried out on rigid ground. The influence of bending while built-in into flexible host structures cannot be disregarded and needs to be investigated in further experiments.

In an additional experiment printed sensors produced in the described way were integrated into a commercial insole of a sport shoe. CFRP has been used to laminate the sensors onto the bottom side of the insole. First tests have shown that the sensors are still responding.

5. Conclusion and outlook

Fully printed single sensors for pressure measurements have been presented. It is possible to adjust these sensors to different applications e.g. measuring of plantar foot pressure. For measuring a pressure distribution the development of a sensor array is planned. The integration of the printed sensors in different host structures is a promising approach for the production of cheap and replaceable systems for monitoring plantar foot pressure.

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Printing of GHz antenna pattern on flexible substrates for the manufacturing of intelligent light-weight structures

Peter Ueberfuhr[1], *Frank Siegel*[1], *T. D. Großmann*[2], *M. Gaitzsch*[2], *S. Kurth*[2], *Reinhard R. Baumann*[1,3]

[1] Chemnitz University of Technology, Digital Printing and Imaging Technology
Reichenhainer Str. 70, D-09126 Chemnitz, Germany
E-mails: peter.ueberfuhr@mb.tu-chemnitz.de; frank.siegel@mb.tu-chemnitz.de; reinhard.baumann@mb.tu-chemnitz.de

[2] Fraunhofer ENAS, Multi Device Integration
Technologie-Campus 3, D-09126 Chemnitz, Germany
E-mails: markus.gaitsch@s2007.tu-chemnitz.de; toni.grossmann@enas.fraunhofer.com; steffen.kurth@enas.fraunhofer.de

[3] Fraunhofer ENAS, Printed Functionalities
Technologie-Campus 3, D-09126 Chemnitz, Germany
E-mail: reinhard.baumann@enas.fraunhofer.de

Abstract

For antenna pattern suitable in the GHz frequency band up to 24 GHz ciritical dimensions in the lower micrometer range (<100 µm) are required. For their manufacturing inkjet printing as a rapid prototyping technology of various antenna designs and gravure printing as a mass production technology are investigated. The main objectives are the definition of a tool set for the digital layout development and simulation of antenna pattern and the comparison of the two manufacturing technologies in terms of critical structure sizes. First of all, a simulated patch antenna design for a frequency of 11GHz was successfully manufactured by inkjet printing. Using a network analyzer measurement device, absorption maximum of the printed antenna pattern in the 12-13GHz range was demonstrated. Furthermore, it can be shown, that smallest conductive lines with 70-80 µm width are printable with both technologies. However, inkjet printing shows advantages in terms of edge sharpness and minimal layer thickness. The further approach is the manufacturing of a comparable antenna using gravure printing technology and the development of an optimized antenna layout working in the 24 GHz band, considering the possible critical structure sizes.

Keywords: antenna, printing, inkjet, gravure

1. Motivation

Resource efficient manufacturing and product design are key tasks in all production fields to save raw materials, reduce CO_2 emmission and protect the environment [1]. For example, the automotive industry commonly uses steel in car chassis, which can be replaced by light-weight structures. Thus, the weight of cars will be dramatically reduced, what results in a decreased CO_2 emission [2]. For the development and the optimization of such light-weight structures it is important to know about their behavior under mechanical stresses such as bending, tensile or shear stresses. Beside computer aided FEM simulation tools, inline analysis on real materials can be done by the integration of microelectronic sensors and actors. Additionally, for the operation of these components a power supply as well as a communication channel for an external evaluation unit are required which are commonly adapted via wire connection. However, the wired connection can cause negative effects such as complex cable management and a certain (additional) stress impact at the conducting points. Therefore, a novel method is the integration of foil based sensors combined with printed GHz antenna structures for the wireless communication and power transfer.

2. Objectives

There are different additive material deposition methods based on printing technologies available. Digital printing technologies such as piezo driven inkjet is a very clean and a high resolution method, if the system is running slowly in a drop space of 5 µm for example. For this reason inkjet is applied as a tool for prototyping electrical devices and for manufacturing in short run lengths in the frame work of digital fabrication for individualized units (mass customization). If there is no need for individualization of single geometries and the lot size is very large, conventional printing technologies are suitable for the manufacturing [3-5].

In this paper a comparison of inkjet and gravure printing is presented for simple geometries which are later on applied for the prototyping and production of GHz antennas. The focus will be on single lines and closed layers manufactured with silver nano particle ink from SunChemical® (inkjet printing) and PChem Association Inc. (gravure printing). The geometric design of antennas depends on the targeted frequency. An antenna working in the 5.8 GHz operating frequency band has dimensions in the range of centimeters [6]. However, higher frequencies require smaller antenna dimensions with adapted designs to realize power and signal transfer in a simultaneous way [7]. The aim is to develop a tool set for antenna simulation of a frequency range up to 24 GHz to prototype and manufacture them.

Figure 1 shows a scheme of a simulated patch antenna layout. The important dimension range as well as surface and edge properties are marked. To guide the absorbed signal to the receiver a ground-signal-ground (GSG) contact component is necessary, where the signal conductor has to be smaller than 300 µm. Furthermore, the absorbing patch has to have good surface characteristics in terms of a closed homogenous layer and sharp edges. These critical structure sizes are important for manufacturing as well as the development of the antenna pattern and will be considered in further antenna designs.

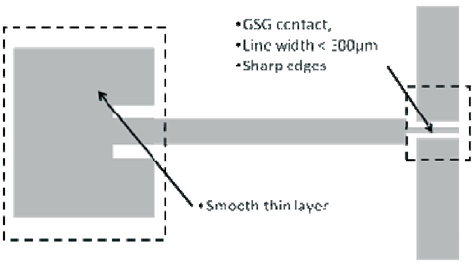


Figure 1:
Scheme of a simulated antenna pattern with marks on critical structure sizes and surface properties

2. Experimental setup

2.1. Machinery

The gravure printing experiments will be done with a laboratory rotogravure printing machine LABORMAN from formerly manroland (Figure 2, a) with a maximum web width of 140 mm. This printing machine is equipped with a gravure printing unit using the sleeve technology and a combined inking and doctor blade chamber.

The inkjet printing experiments will be realized using the Fujifilm Dimatix materials printer DMP2831 (Figure 2, b). The printer is equipped with a cartridge printhead generating drops with 10 pL drop volume.

Figure 2: a) Roll-to-roll rotogravure printing machine LABORMAN from manroland.
b) Inkjet printer Fujifilm Dimatix materials printer DMP2831 (www.fujifilmusa.com)

2.2 Materials

All the experiments were done on PET substrate. But the inkjet printing tests are applied on PET Melinex 506, 175 µm from *DuPont Teijin Films* with an acrylic coating. The gravure printing tests were done on PET

Melinex 401 CW without an acrylic coating. Furthermore to achieve sufficient electrical conductivity metal inks are required. Most of those inks are solvent- or water based dispersions or suspensions with small metal particles in dimensions of micro-down to the nanometer range. These particles can have different shapes like spheres, flakes or wires. Due to the critical structure size of the GHz antenna patterns, only inks with sphere-cal particles in the nanometer range are suitable. Furthermore, literature shows that especially silver nano-par-ticle inks have a good printability as well as an excellent conductivity after a certain sintering process [8-9]. However, depending on the printing technology, the ink must have specific rheological properties. Especi-ally, in the case of inkjet printing: Using the *DMP2831* the recommended ink viscosity should be in the range of 10 to 30 mPas. Therefore, the *Suntronic Jet Silver U5603* ink from *SunChemical*® will be applied and prin-ted with 10 kHz drop ejection frequency. As post-treatment a heating of 100 °C over 60 min is used to get the applied layers conductive. The gravure printing technology allows a comparable wide range of ink viscosities from 10 up to 200 mPas [10] and beyond. All realized gravure printing experiments are done with the silver ink PFI-722 from *PChem Associates, Inc.*, a velocity of 1 ms^{-1} and an infrared post-treatment step to get the layer conductive.

3. Experimental results

As mentioned in the motivation it is the aim to manufacture line geometries as well as closed layers for the manufacturing of antennas. That is why the lines are subjected to certain quality criteria like width and cross section of the line, material deposition quality (cleanness) and functional properties (electrical conductivity).

3.1. Printed line characterization and manufacturing technology comparison

Diagram 1 shows a width comparison between gravure printed lines using different engraved line geometries in the gravure cylinder (left) and inkjet printed lines with different drop spacing (right). In gravure printing, engraved lines are formed by an arrangement of small cavities very closely in one direction. The distance of the neighbored cavity centers is defined as lines per centimeter [Lcm^{-1}]. The dimensions of the cavities define the gutter between them. Applying electro-mechanical engravement methods the depth and cross section di-mensions of the cavities are modulated at the same time, representing different printed line geometries. On this account a direct laser engravement was utilized to manufacture lines with different widths but same depth [11]. Gravure printed lines are always wider than the engraved ones and the closer the cavity center distance, the smaller the printed line width occurs.

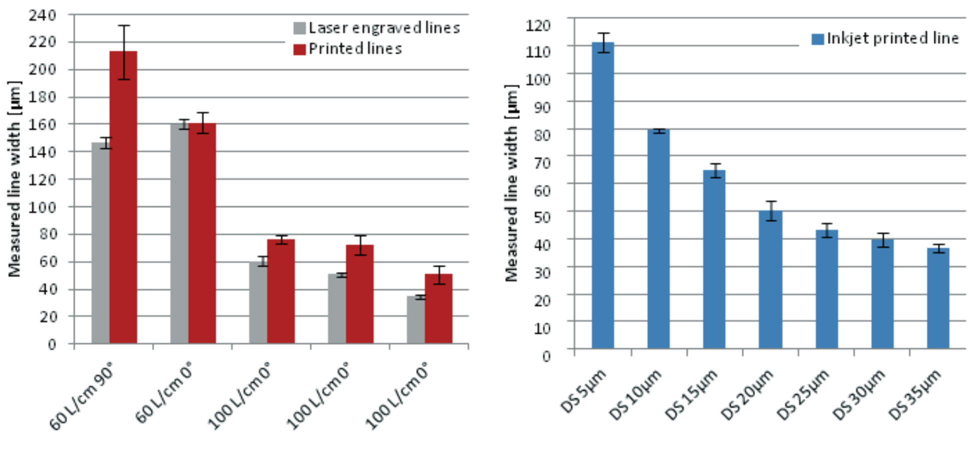


Diagram 1: Comparison between laser engraved and printed lines in gravure printing 60 Lcm^{-1} and 100 Lcm^{-1} (left) and printed lines with different drop spacing (right)

In opposite to gravure printing, the inkjet printing technology does not require a solid printing form, but a di-gital one. The used material printer needs monochromic bitmap-based pixel-raster images with 1 bit color depth. The digital resolution of the images defines the drop spacing of the printed material on the substrate and has a huge influence on the resulting printed line dimensions and geometries [12] and is given in Diagram 1 (left) for the used silver nano-particle ink. The printing image of each printed line consists of only one pixel row with different digital resolutions. This results in a maximum achievable average line thickness of 110 µm and 37 µm in the minimum. Drop spacing above 35 µm results in interrupted lines with single sessile drops in between (Figure 3).

The direct comparison of achievable line widths between inkjet printing and gravure printing shows an advantage of inkjet printing in terms of minimum line width. Furthermore, comparing the standard deviation of the measurements, what is an indicator of the edge sharpness, the inkjet technology provides smoother line edges. This behavior will be substantiated by the following microscopic view on the respective manufactured lines in Figure 3 and Figure 4.

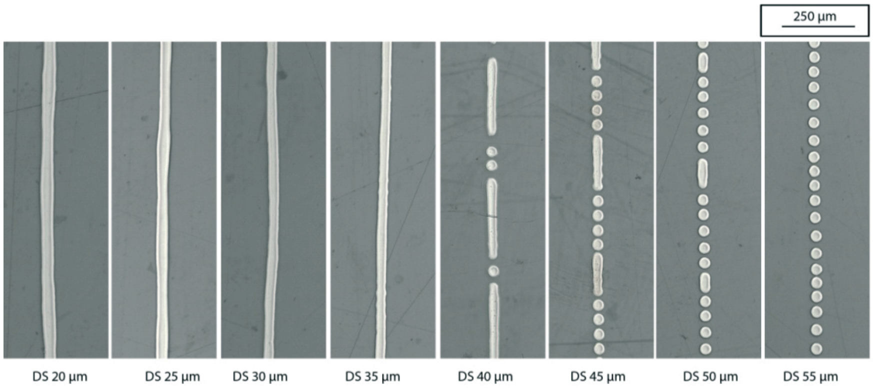


Figure 3: Inkjet printed silver lines using drop spaces from 20 µm up to 55 µm

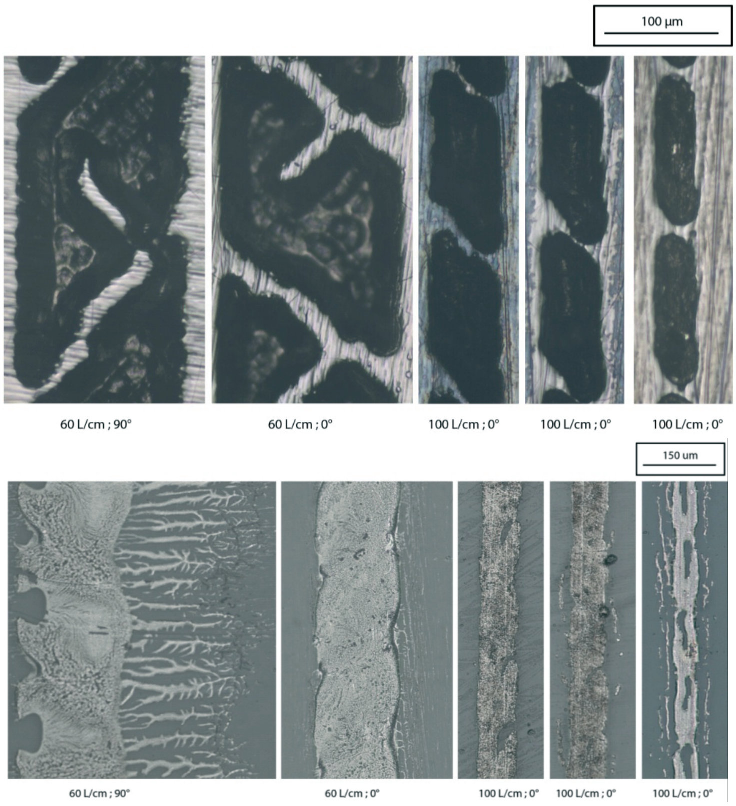


Figure 4: Comparison laser engraved lines (60 Lcm^{-1}and100 Lcm^{-1})
and the printed lines with different width, respectively

Furthermore, the upper microscopic images of Figure 4 show the engraved lines with different line cavity sizes and the respective printed line below. It was observed, that lines printed with 100 Lcm^{-1} screen ruling have elliptic defects in the middle, which could also be described as pinholes. Reasons for that, especially for very thin engraved lines, could be:

- bad volume to area ratio (cavity volume and gutter width)
- too low ink transfer
- bad filling of the cavities (bubbles are emerging)
- particle agglomeration in the cavities and clogging of the cavities

Additionally, it was figured out, that the angle of the engraved line referred to print direction (0°) has an influence on the printing quality of the line. Lines in print direction compared to lines in perpendicular direction have better edge sharpness as well as fewer defects. All lines are showing a shadowing in printing direction caused by the doctoring of the cylinder and the printing velocity dependent fingering effects. Admittedly, a low viscous ink is applied, in combination with a printing velocity of 1 m/s.

During the doctoring process the blade takes the ink of the surface of the cylinder. The remaining ink in the cavities is affected by this process depending on the intrinsic forces in the ink (viscosity). That is why the blade moves partly ink out of the cavity. At the opposite edge wall of the cavity, the doctor blade flexes over it, loses the contact to the printing cylinder for a very short time and ink remains at non printed areas behind the cavities.

Because of figuring out critical structure sizes for the design of antennas suitable in the GHz range, further considerations in this chapter focus on low line width manufactured by the two different printing technologies.

For a precise development and simulation of realistic mating antenna designs a characterization of line thickness and cross section profile is required.

Following, the Diagram 2 measured cross section profiles of inkjet printed lines with different drop spacing.

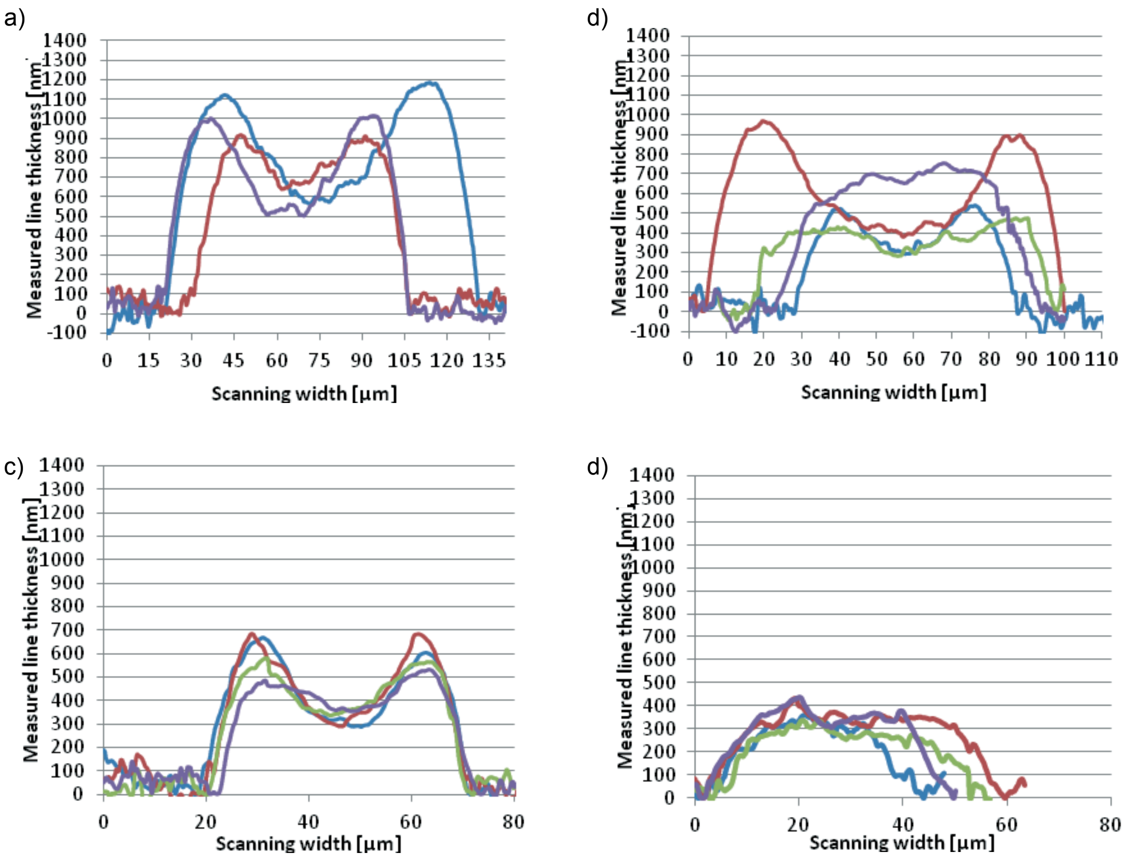


Diagram 2: Measured line thickness of inkjet printed lines with varied drop space from a) 10 µm, b) 15 µm, c) 20 µm, and d)25 µm

For each drop space 4 profile measurements are shown to give a representation of the thickness homogeneity. A drop spacing of 10 µm, 15 µm and 20 µm results in a typical inkjet printed line cross section, known as coffee strain effect [13], see the graph a), b) and c). At a drop space of 25 µm this effect cannot be observed anymore (graph d). Therefore, in Table 1 the values of the average measured thickness and the observed maximum peak are listed. Due to the fact that less material per area is deposited with increased drop space the printed lines become thinner. However, for lines printed with a drop space above 25 µm a height profile measurement results in non convincing result, because the surface roughness of the acrylic coated substrate with a value of Rz = 153 ± 17 nm are too rough to really differ between printed line and substrate surface.

Table 1: Measured average line thickness, the maximum peak and the substrate roughness of inkjet printed lines with varied drop space

Measured sample	Average height [nm]	Peak [nm]	Rz [nm]
Line DS 10 µm	758 ± 97	1318	
Line DS 15 µm	555 ± 129	1017	
Line DS 20 µm	407 ± 24	687	
Line DS 25 µm	257 ± 33	440	
Substrate			153± 17

Hence, considering the real thickness of the printed lines, they could be approximately 150 µm lower or even higher than measured ones.

To compare to the inkjet printed lines, in Diagram 3 cross section profiles of gravure printed lines are given.

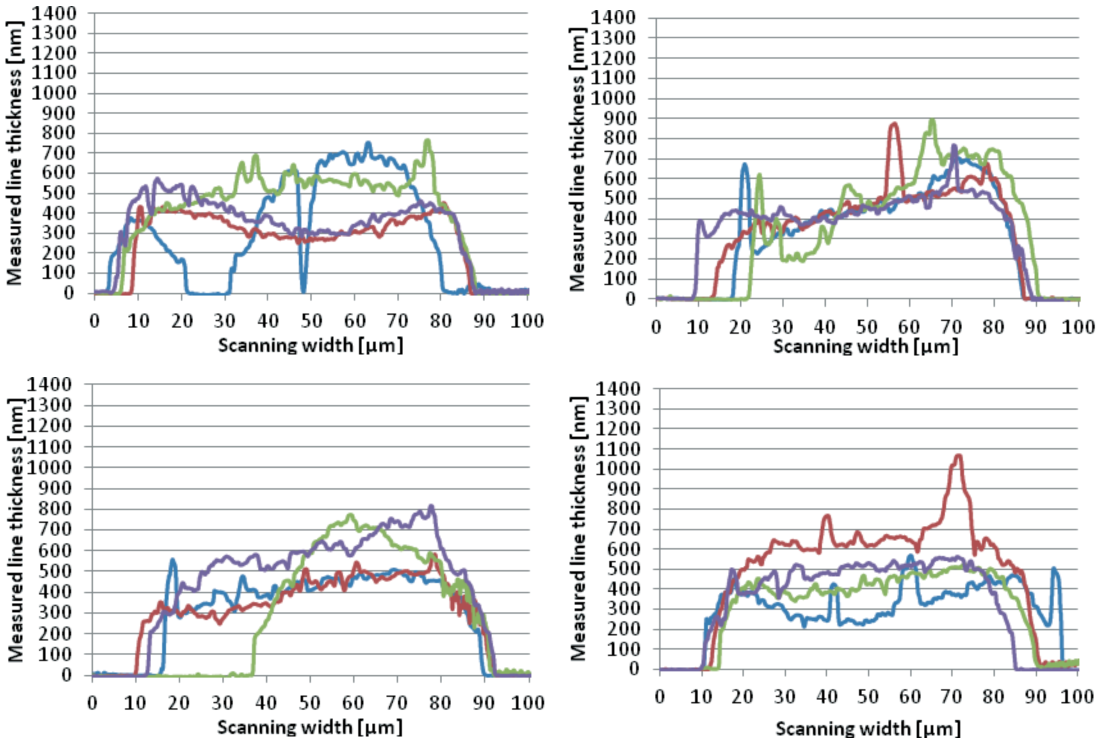


Diagram 3: Randomly measured line thickness of gravure printed lines with a 76 µm average width and an angle of 0°, 10°, 20° and 30° referred to the print direction

The cross section profile measurement was done for lines printed with a 51 µm wide engraved line with a 100 Lcm^{-1} screen ruling only. Therefore, the influence of line angles of 0°, 10°, 20° and 30° referred to the print direction are investigated. Similar to Diagram 2 for each angle 4 profile measurements are shown. Compared to the cross section of inkjet printed lines, a specific cross section profile of the gravure printed lines is not observed. Rather the profiles are very different and, regarding to the varied angles, it is not really possible to distinguish. To emphasize this objective fact Table 2 gives the average thickness and the maximum detected peak for each angle, respectively.

Table 2: Measured average line thickness and maximum peak of gravure printed lines with varied angle referred to the print direction

Line angle	Average height [nm]	Peak [nm]
0°	398 ± 79	766
10°	453 ± 29	898
20°	459 ± 82	819
30°	443 ± 111	1068

Except the line in 10°, the standard deviation of lines in 0°, 20° and 30° angled position indicates a rougher surface compared to inkjet printed lines but is also too high to define thickness variation based on the angle. Possibly, using an angle of 10° smoother lines can be applied, but therefore further experiments have to be done.

In summary, on a geometric point of view, inkjet printing enables smaller line widths than in standard gravure printing. For this reason a more suitable manufacturing of small antenna patterns is given by inkjet. Following SEM images in Figure 5 show two line samples. Form qualitative point of view, on the left image the gravure printed line shows a much worse edge sharpness than the inkjet printed line.

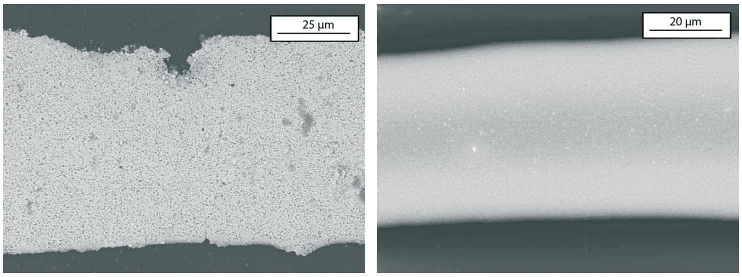


Figure 5: Scanning-electron-microscopic images of a gravure printed line (left) and a inkjet printed line (right)

Furthermore, the gravure printed line on the SEM image, seems to have black dots. On higher magnifications a porous-like structure was observed, but not in the inkjet printed lines.

The basic geometric properties are investigated and compared, in the following electrical properties are discussed.

For all thin lines, a resistance measurement is done with a fixed distance of 11 mm. In Diagram 4 the average resistances of gravure printed lines with different thickness and angled positions to the printing direction is shown. On purpose, there is no standard deviation given, because in some cases resistance values above 10 MΩ were measured. This indicates non conducting segments or cracks in these respective lines. However, the value above the respective measurement bar in the chart stands for the percentage of conductive lines from all measured ones.

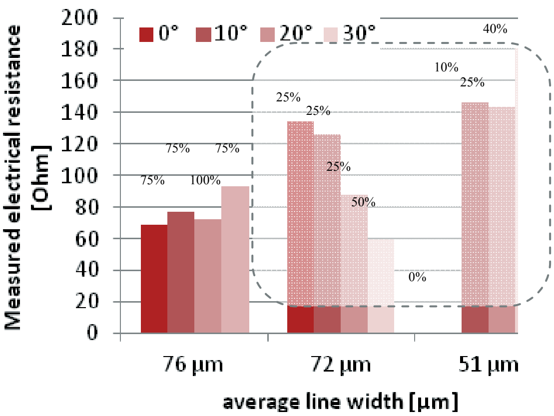


Diagram 4: Measured electrical resistances of gravure printed lines with a distance of 11mm

It can be assumed, that gravure printed lines with an average width of 76 µm and a length of 11 mm have an electrical resistance in the range of 70-90 Ω with a manufacturing yield of 75 %.

The influence of the angle position of the line cannot figure out, yet. Also, the resistance measurement of lines with smaller widths than 76 µm exposes in low yields of nearly 25 %, as highlighted in the left chart Diagram 4. For these small lines a convincing conclusion is not derivable. In these cases better gravure cylinders should be developed with optimized screens regarding thin lines. But, it can be expected that a decreasing line width result in an increasing electrical resistance.

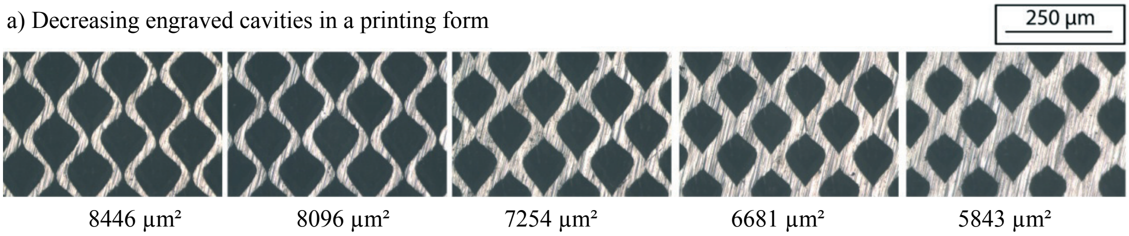
Unfortunately, the measurements of inkjet printed lines show, that only 79 µm and 65 µm width lines are conductive, with 69 ± 15 Ω and 855 ± 399 Ω, respectively. Below 65 µm what corresponds to a 15 µm drop spacing no conductivity could be measured. Possible reasons are the capillarity flow of the nano dots during the drying/sintering cause non conducting sections within the line. This will be investigated in further experiments.

Summarized, regarding the critical structure sizes of antennas for the GHz frequency range inkjet printed as well as gravure printed lines with a width down to ≈80 µm are suitable for designing antenna layouts.

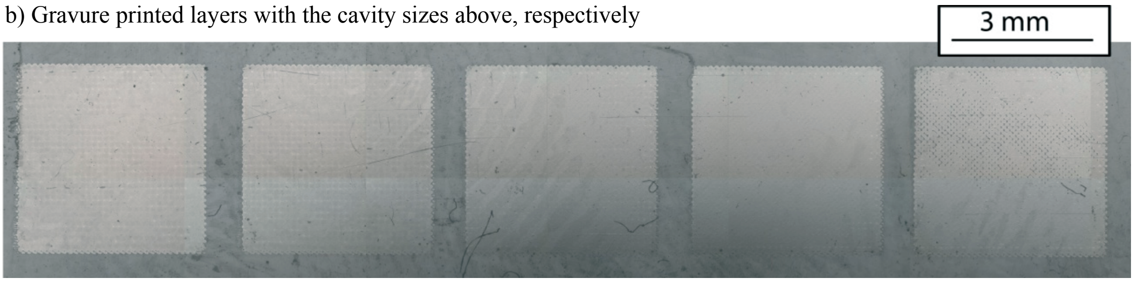
3.2. Printed layer characterization and manufacturing technology comparison

For the antenna manufacturing beside lines, manufactured as wires, there is a need of larger geometrical elements containing of closed conductive layers to absorb the high frequent electromagnetic waves. Therefore, 5 x 5 mm² samples are gravure- and inkjet printed for direct comparison. For the gravure printed samples, open area of the engraved cavities in the printing cylinder changes from 8207 µm² down to 5843 µm² with a line screen ruling of 90 Lcm^{-1} (Figure 6, a).

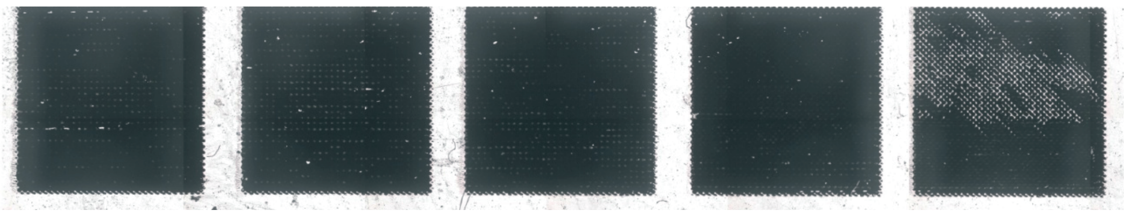
a) Decreasing engraved cavities in a printing form



b) Gravure printed layers with the cavity sizes above, respectively



c) Transmitted light microscopic images of gravure printed layers of the samples above



d) Inkjet printed layers with the different drop spacing.

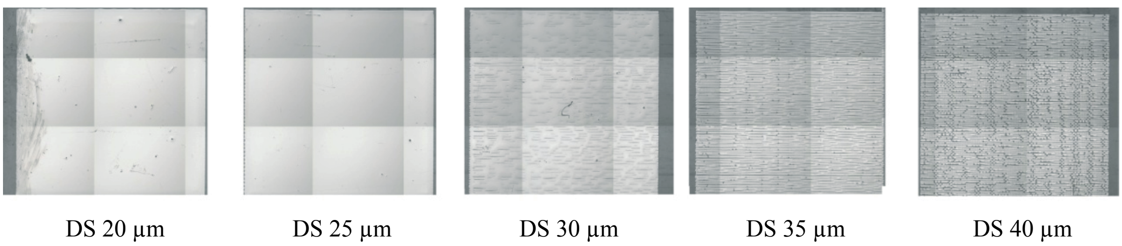


Figure 6: Printed 25 mm² squares:
a) Engraved cavities in the printing form, with decreasing area size of 8207 µm², 8096 µm², 7254 µm²,6681 µm² and 5843 µm² (from left to right); b) Gravure printed with 90 L/cm with decreasing cavity size from left to right in the printing form; c) transmitted light microscope image of the previous structures; d) Inkjet printed with increasing drop spacing (20 µm, 25 µm, 30 µm, 35 µm and 40 µm from left to right)

Figure 6 (b) and (c) microscopic images of the squares printed with the respective cavity sizes are shown. According to the gravure printed samples in Figure 6 (d) inkjet printed squares are shown. They are printed with different drop spacing between 20 µm to 40 µm. The microscopic images are showing that layers printed with drop spaces below 25 µm are not closed, anymore. These drop spaces lead to the formation of missing lines. Generally, based on the microscopic observation of the layers a comparison between inkjet and gravure printed layers results in an advantage of inkjet printed layers in terms of smooth layer surfaces and higher edge sharpness.

Similar to the previous line characterization, the printed layers have to be investigated regarding their conductive properties. Therefore the surface resistivity was measured for the inkjet and gravure printed layers considering the drop space and cavity size respectively. The results are shown in the following Diagram 5.

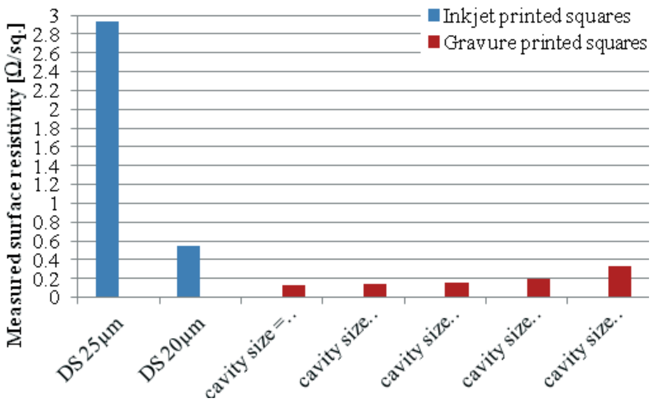


Diagram 5: Comparison of measured inkjet- and gravure printed surface resistivity and the varied drop spaces. 5 x 5 mm² squares are measured with 100 mA current and a voltage limited to 1 V

It can be recognized, that the gravure printed layers have a lower surface resistivity of about 0.1 - 0.3 Ω/sq. than the inkjet printed ones. But, the surface resistivity depends on the layer thickness, too. It is assumed that the gravure printed layers are thicker compared to inkjet. This is indicated by the comparison of the different drop spaces where lower drop spaces cause higher layer thicknesses and an even lower surface resistivity. Similar to that, a decreasing cavity size causes a higher surface resistivity at gravure printed layers. However, defects in the layers can cause an increased surface resistivity, as well.

In sum, it is determined that gravure printed layers have a lower surface resistance than inkjet printed layers, but without considering the layer thickness. The influence of the thickness has to be investigated in further experiments.

4. Conclusion and outlook

Generally, based on the experiments it can be said, that gravure printing- as well as inkjet printing technology enables the manufacturing of antenna pattern. This will be sustained by an inkjet printed antenna prototype for the frequency range of 11 GHz, shown in Figure 7 (left).

The antenna was printed with a 25 µm drop spacing to apply an absorber with a closed layer and a good edge quality. In the first state of the antenna design the signal conductor has a width of 300 µm. The graph in Figure 7 (right) gives the return loss value of the simulated compared to 4 measured antenna pattern, using a network analyzer. The result is an absorption peak in the range of approximately 12 - 13 GHz what generally demonstrates the functionality of the printed patch antenna.

For further developments a set of design rules is investigated. Firstly, considering lines, with both technologies conductive lines with an average width of 80 µm and an electrical resistance of 70-90 Ω can be manufactured. However, inkjet printed lines have advantages in a better edge sharpness, smoother surface roughness as well as thinner lines down to 257 µm. Unfortunately, at lines below 65 µm width an electrical resistance could not be measured.

Secondly, the comparison of manufactured squares result in similar advantages of inkjet printed layers. But, gravure printed layers have a lower surface resistance of 0.1 - 0.3 Ω/sq., without considering the layer thickness.

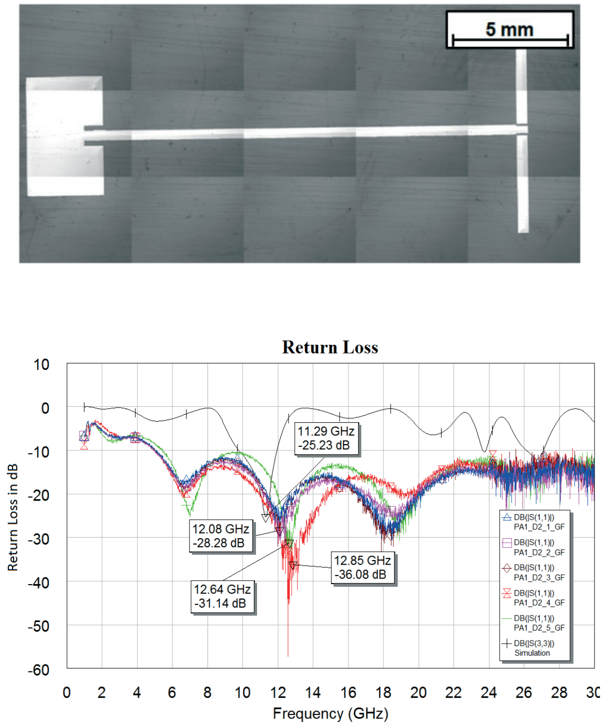


Figure 7: Inkjet printed patch antenna pattern (above) and the measurement of the return loss (bellow) compared to the simulated curve

The further approach is the development of a gravure cylinder with several new designed antenna pattern for the 24 GHz frequency range. Also, the influence of the substrate will be investigated considering surface- and layer roughness. Moreover, new developed antenna pattern should go into the critical dimension range to evaluate suitability of lines with the smallest width investigated in this paper.

Acknowledgements

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Simulation of a print head for electrically conductive inks

Micha Güdel and Karl-Heinz Selbmann

Institute for Print Technology
Bern University of Applied Sciences
Pestalozzistrasse 20, CH-3400 Burgdorf, Switzerland
E-mails: micha.guedel@bfh.ch; karl-heinz.selbmann@bfh.ch

Abstract

Printing functional structures often requires electrically conductive inks. Common piezo-based print heads have major drawbacks when used with such fluids. For this reason, the Institute for Print Technology is developing a print head based on the Lorentz force principle.

The objective of the investigations presented in that paper was to prove the feasibility of such a print head with a prototype as well as to examine the physical effects with multiphysics simulations.

A simple prototype was built and operated with permanent magnets and voltage pulses of 35 Volts (5 ms). With phosphoric acid as fluid, it was possible to detach distinct droplets with an average volume of 0.63 µl. Additionally, steady-state as well as transient two phase flow simulations of the prototype were implemented with the simulation software COMSOL Multiphysics. Neglecting the occurring electrochemical processes such as electrolysis and polarisation, the models could be validated with measurements.

It has been shown that a print head based on the Lorentz force principle is feasible. Possible fields of application are numerous and diverse due to its simple build-up without moving parts and the possibility to build highly temperature resistant print heads.

Keywords: functional printing, electrically conductive ink, multiphysics simulation, print head

1. Introduction

The keyword "Functional Printing" summarises forward-looking, non-graphical applications for printing technologies. At the date of this paper's writing, complex items like electrical circuits or 3 dimensional objects can be printed with such methods. However, producing structures like these often requires electrically conductive inks.

Commonly used piezo-based print heads are only suitable to a limited extent for such inks due to their sensitivity to high temperatures and the electrical insulation that is required. Furthermore, the volume of suspended solids in the ink and the particle size of these solids are limited to a narrow range.

The Institute for Print Technology is developing a new print head based on the Lorentz force principle, suitable for electrically conductive inks, to address these limitations. Within the framework (and boundary conditions) of the investigation carried out in this paper, this Lorentz force based alternative approach has been simulated and tested. The goal was to prove the feasibility of such a print head as well as to examine the physical phenomena involved therein with multiphysics simulations.

The Lorentz force is the force experienced by a point charge travelling in a magnetic field. By means of an electric current (I) conducted through the ink, electrons in the ink are set in motion. The application of a magnetic field, characterised by the magnetic flux density (B) in the ink, causes a propulsive Lorentz force perpendicular to both I and B.

In the special case that the electric current direction and the magnetic field are perpendicular, and with an l unit length (meters in the SI system) between the electrodes, the absolute value of the resulting force F_L is given as:

$$F_L = I \cdot B \cdot l \qquad [1]$$

The direction of F_L is given by the right-hand rule as depicted in Figure 1.

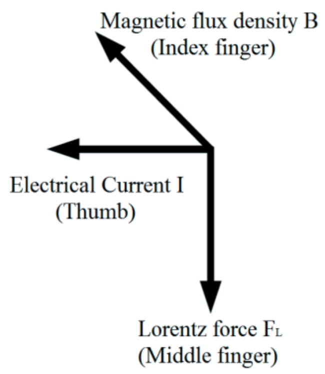

Figure 1: Right-hand rule

The fundamental layout of the print head is shown in Figure 2. An electrical potential is applied to the electrodes, which causes an electric current to conduct through the ink. As the whole system is situated in a magnetic field orthogonal to the current direction, the Lorentz force acts in the direction of the nozzle and forces the ink to flow out.

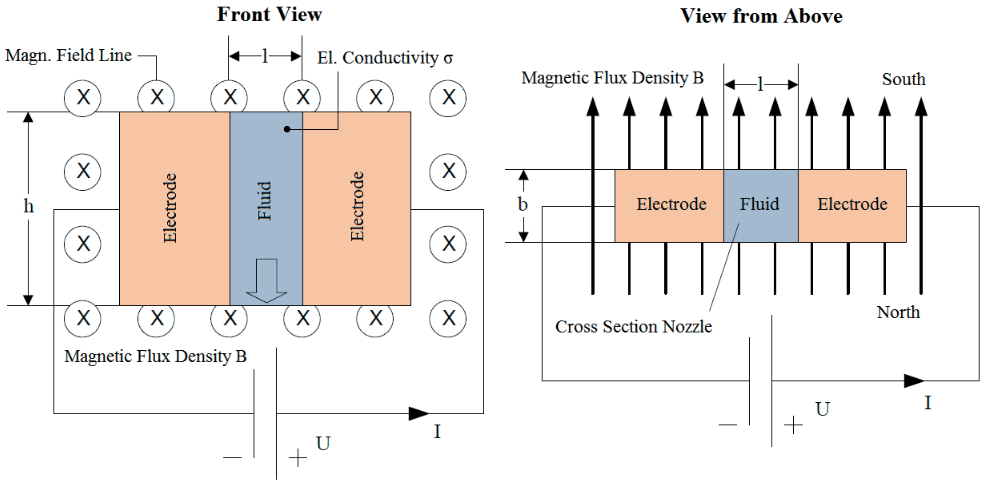

Figure 2: Principle and definitions

2. Method

Initially, a prototype of the print head, using the principles described above, was designed, with a focus on a simple yet appropriate design, allowing examination of relevant physical effects. Simplified calculations with Bernoulli's incompressible flow equation were made to approximate the device's dimensions. Later, tests and experiments were conducted with the prototype, proving its functionality and validating the results of multiphysics simulations.

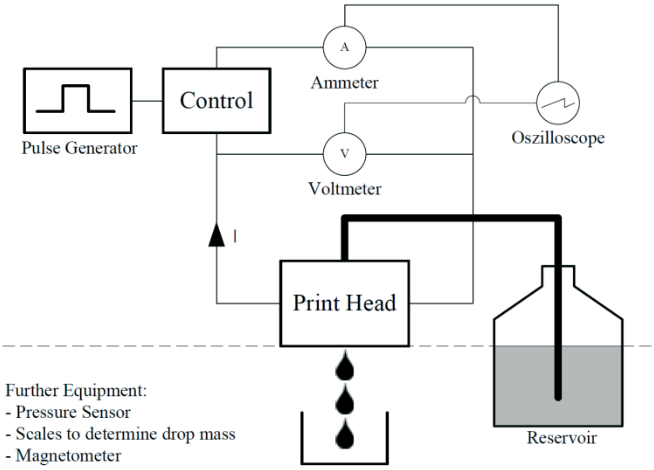

Figure 3: Experimental setup

The principal experimental setup for taking measurements is shown in Figure 3. The print head was driven by an open-loop control box, triggered by a pulse generator. The fluid level in the reservoir was aligned with the outlet of the print head to eliminate static pressure differences. An oscilloscope was used to log the measured data. During testing, the average drop mass was calculated by weighing a series of drops. In order to determine the pump pressure, the nozzle of the print head was sealed with a miniature pressure sensor.

The simulations were carried out with COMSOL Multiphysics, a finite element simulation software. The aim was to describe the magnetic, electric and fluidic properties of the prototype with coupled models.

Initially, parameterised steady-state models were implemented to determine fundamental parameters such as outflow velocity and pressure distribution. The simulations were based on the following physical principles:

- Charge conservation, stating that electric charge is conserved

  $$\nabla \cdot \vec{J} = 0 \qquad [2]$$

- Ampère's circuital law, stating that an electric current produces a magnetic field.

  $$\nabla \times \vec{H} = \vec{J} \qquad [3]$$

- Ohm's law, describing the relationship between the current density $\vec{J}$ and the electric field $\vec{E}$, given by the conductivity σ.

  $$\vec{J} = \sigma \vec{E} \qquad [4]$$

- Introduction of the electric field $\vec{E}$.

  $$\vec{E} = -\nabla V \qquad [5]$$

- Introduction of the magnetic flux density $\vec{B}$ by the magnetic vector potential $\vec{A}$.

  $$\vec{B} = \nabla \times \vec{A} \qquad [6]$$

- Navier-Stokes equations for incompressible fluids. $\overrightarrow{Fvol}$ represents the Lorentz volume force on the fluid.

  $$\rho(\vec{u} \cdot \nabla)\vec{u} = \overrightarrow{Fvol} - \nabla p + \mu \cdot \Delta \vec{u} \qquad [7]$$

  $$\nabla \cdot \vec{u} = 0 \qquad [8]$$

Using the results from the steady-state simulations, transient two-phase flow simulations were then generated to study the process of droplet formation and detachment. To verify the simulations, simplified calculations were made using conventional methods.

Based on the outcomes of simulations and measurements, possible improvements to the prototype and experimental methods were considered and suggested for further research.

3. Results and discussion

Using Bernoulli's incompressible flow equation, the optimal dimensions of the prototype were approximated for different fluids with respect to their fluidic properties. As a high outflow velocity is desirable, due to the better detachment of drops, this parameter was considered the main criterion to optimise. Assuming a square nozzle cross section and setting the height to h = 10 mm, the calculated outflow velocities for several fluids are shown in Figure 4. Other parameters, such as the magnetic flux density B and a feasible current I, were estimated based on experience.

The CAD model of the prototype is shown in Figure 5. The cross section of the nozzle was 0.6 x 0.6 mm (l x b) and the height was set at h = 10 mm. Permanent magnets were used to apply the magnetic field and phosphoric acid H_3PO_4 (50%, σ = 15.3 S/m, η = 5.14 mPa·s) was chosen as an electrically conductive fluid to test the print head. Unlike other fluids, phosphoric acid is relatively chemically inert, and poses a low hazard to experimenter and equipment.

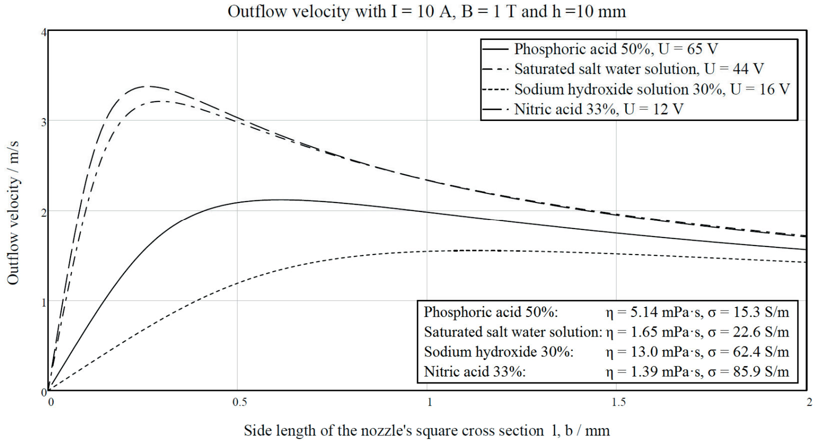

Figure 4: Approximated outflow velocities

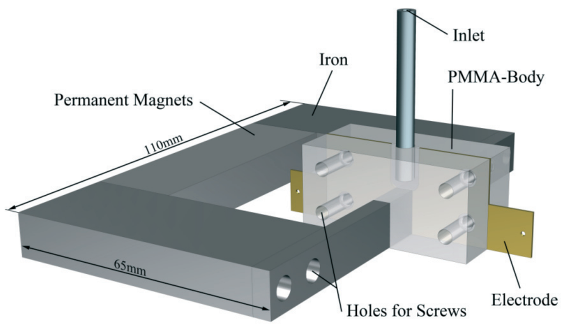

Figure 5: CAD model of the prototype

The system was operated with voltage pulses of U = 35 Volts (DC) and 5 milliseconds of duration. With that setup, it was possible to dose a series of distinct droplets with an average droplet volume of 0.63 µl. During a pulse, the parameters voltage (U) and electrical current (I) were measured. Further, the drop formation was recorded with a high speed camera. This data, for a typical pulse, is shown in Figure 6. The maximum current value reached was 10.8 A. The decline in current visible in the diagram is caused by electrochemical processses, namely electrolysis and polarisation, which diminish the electrical conductivity of the ink over the duration of the pulse. The decrease in current causes the volume flow rate of the fluid to drop at the end of the pulse, as can be observed in Figure 6.

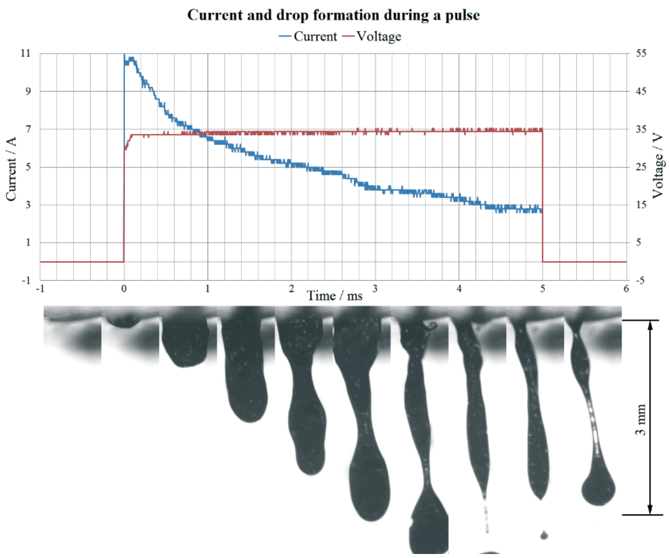

Figure 6: Current and drop formation during a pulse

In an effort to determine the pressure caused by the Lorentz force, the nozzle of the prototype was closed by means of a miniature pressure sensor. The results of those measurements are shown in Figure 7. As the pressure generated is directly proportional to applied current, its decline over time is to be expected given the drop in current explained above. The evident oscillation of the pressure is most likely caused by gas bubbles formed by electrolysis. The maximum pressure at the beginning of the pulse was measured as 0.14 bar.

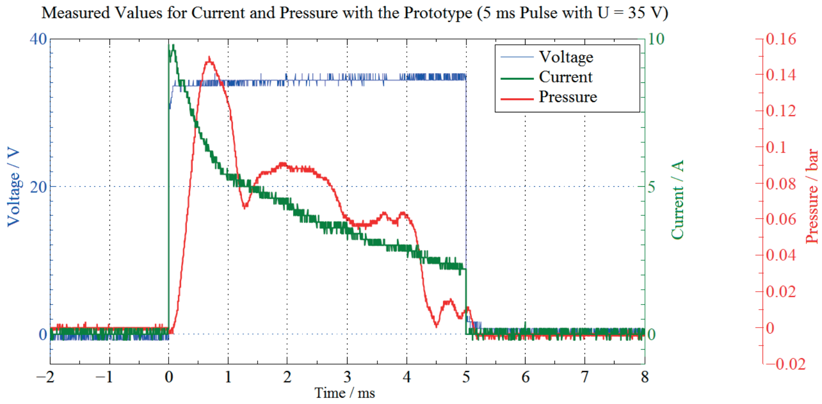

Figure 7: Measured values for current and pressure (Nozzle closed)

Coupled simulation models were implemented with COMSOL Multiphysics. Firstly, steady-state simulations respecting the magnetic, electric and fluidic properties were used to gain information about magnetic flux densities, pressure distributions and outflow velocities for different configurations. The meshed finite element model is shown in Figure 8.

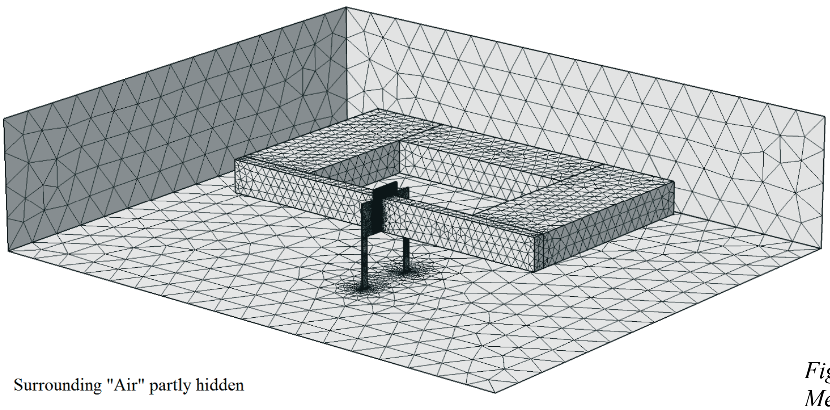

Figure 8: Meshing in COMSOL

The computed volume force F_{vol}, caused by the Lorentz force F_L, is depicted in Figure 9. The force is evenly distributed throughout the nozzle.

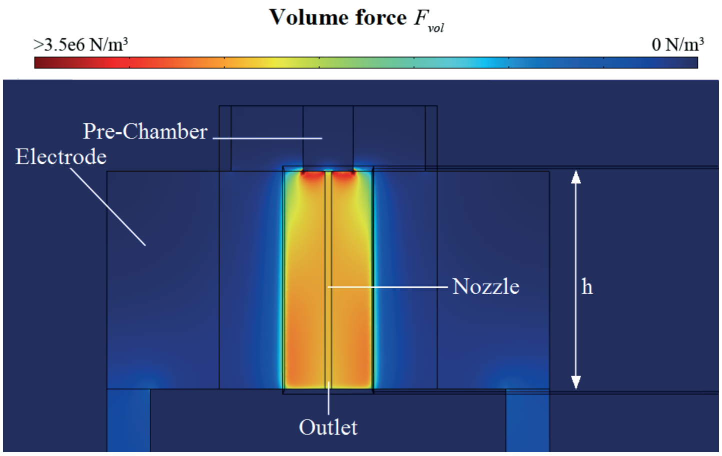

Figure 9: Lorentz volume force distribution

The simulated velocity and pressure distributions resulting from this volume force are visualised in Figure 10.

As new fluid is drawn in, the pressure in the nozzle is reduced. The flow pattern is laminar due to the small Reynolds number (viscous effects outweigh inertia forces).

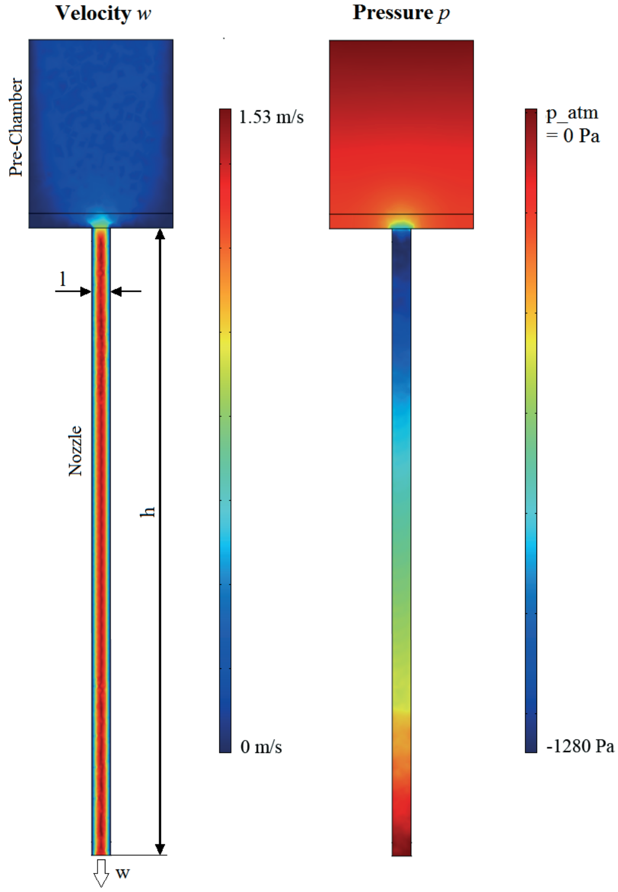

Figure 10:
Simulated velocity and pressure

A comparison between the measured and simulated data from the prototype is shown in Table 1.

Table 1: Comparison between measurements and simulation

	Measurements	Simulation
Magnetic Flux Density B (modified distance l)	0.51 T	0.72 T
Electrical Current I	10.8 - 2.2 A	7.6 A
Pressure p	0.144 bar (max.)	0.166 bar
Volume Flow Rate Q	0.127 ml/s (max.)	0.560 ml/s

The considerable difference between the measured and simulated volume flow rate Q which is evident, is the result of electrochemical effects which could be observed during measurement (compare Figures 6 and 7).

These phenomena had not yet been taken into account in the simulations. However, it was possible to validate the steady-state simulation model with calculations and the measured data from the prototype with sufficient accuracy.

Furthermore, transient two phase flow simulations were used to examine the process of how drops form and detach. It could be shown that a modified pulse pattern had a positive effect on drop detachment. That pulse pattern was characterised by the addition of a short pulse with opposite polarisation at the end of the main pulse. Changing the direction of the electrical current in the ink causes the Lorentz force to change direction (acting as a pump) and draw back the fluid. This results in a faster and clearer detachment of the drops.

The results of these examinations are shown in Figure 11. It was not possible to validate these simulations due to the geometrically undefined prototype nozzle.

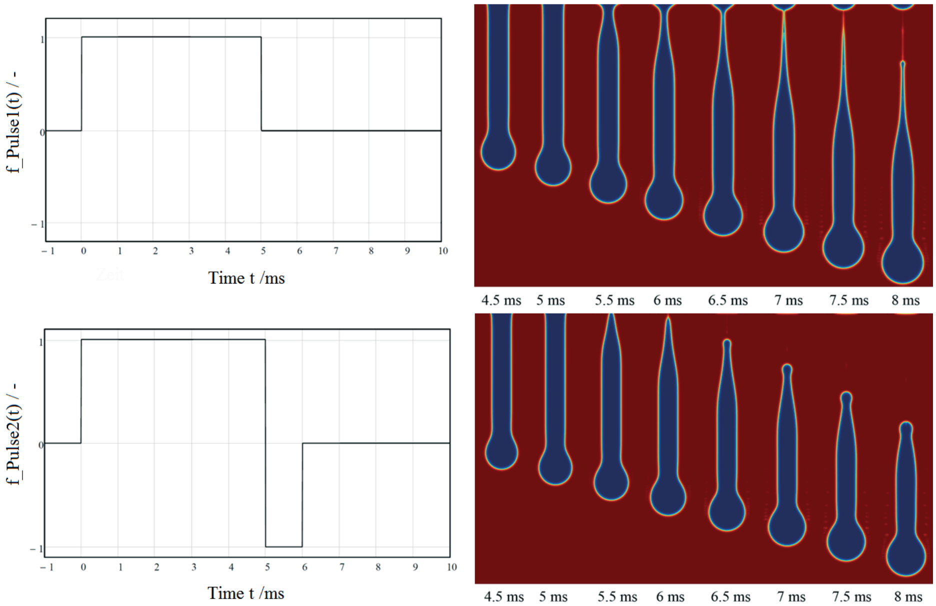

Figure 11: Simulated drop detachment for two different pulse patterns

4. Conclusion

It has been shown that a print head based on the Lorentz force is, in principle, feasible. The possible fields of application of a Lorentz force based print head are numerous and diverse. Due to its simple construction, which does not include moving parts, such print heads would be cost-effective and could be designed as disposable, single use devices for medical, chemical or biotechnological applications. Even the use of molten metals as working fluids would be possible as such print heads can be built from heat resistant materials. This characteristic would make this style print head particularly suitable for 3-dimensional prototyping or applications in the area of printed electronics. The use of molten metals would have the additional benefit of preventing unwanted electrochemical effects which negatively impact print head reliability.

However promising the results, further research in this field is needed. Improvements to prototype and methods were suggested in the thesis; tests and experiments with different fluids, prototypes and triggering patterns are pending. These experiments will focus on the diminution of the interfering electrochemical processes and the intensification of the Lorentz force acting on the ink.

Acknowledgement

Sincere thanks are given to Manfred Schär, Philip Marmet, Philipp Haslebacher and Brian von Gunten for their support.

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Flexography as a structured application method for etching resist

Constanze Ranfeld, *Edgar Dörsam*, *Hans Martin Sauer*

Institute of Printing Science and Technology,
Technische Universität Darmstadt
Magdalenenstr. 2, 64289 Darmstadt, Germany

E-mails: ranfeld@idd.tu-darmstadt.de;
doersam@idd.tu-darmstadt.de; sauer@idd.tu-darmstadt.de

Abstract

Wet etching within a photolithographic process for microelectronics production is very well known. Commonly, the etching resist is either applied as a solid area with subsequent structuring or, for larger structure sizes, screen printing. In this paper, we present the idea of utilizing flexographic printing for the structured printing of etching resist. The process as we propose it can be incorporated into generic roll-to-roll (R2R) coating processes.

Keywords: functional printing, flexography, silver, wet etching, printed resist

1. Introduction

For quite some time now, printing techniques returned to the focus of research, not for visual purposes but rather as production methods for low-cost electronics. However, it is not feasible to just substitute colored inks by fluids with certain functions, i.e. semiconductors. In fact, the printing techniques themselves and certain process features need adaption.

Some adjustments concern printing press related issues, e.g. novel printing plate materials, higher accuracies or explosion protection due to hazardous solvents used. Other improvements involve the processes themselves. And some refer to the accommodation of processes from other fields of research such as classical microelectronics production.

In this paper, we present the idea of utilizing flexography for the structured printing of etching resist. In lithography as known from micromechanical and microelectronics production, etching resist is commonly applied by either spin-coating with subsequent structuring by light either directly (e.g. laser) or indirectly through a mask. Or it is applied in a pre-structured way using screen printing.

The former usually results in substantially smaller feature sizes whereas the latter is the faster method. Both are beneficial for their respective applications but are not easy to incorporate into processes for printed electronics.

2. Method

Commonly, a lithographic process begins with the coating of the resist onto the layer that is to be structured. We use poly(methyl methacrylate) (PMMA) as resist layer which we print using flexography onto a solid area silver layer, also produced by flexography (cf. figure 1). PMMA is a transparent thermoplastic, also known under the brand name "Plexiglas". In microelectronics production, it is mainly used as resist for ion beam lithography. The method for the application of the silver layer is not relevant for the process itself, but it might affect the etching rate as described later on.

Thereafter, the layer stack is etched in nitric acid which transfers the structures of the PMMA layer onto the silver layer by protecting the silver underneath the PMMA. Subsequently, the resist is stripped off the silver layer by acetone.

The remaining silver layer is now structured with the pattern of the PMMA layer. A digest of the process is depicted in figure 1: The lower left branch shows the above mention flexographic printing of the resist layer as we propose it, compared to the right branch which depicts the simplified process steps as common in microelectronics production (Benor, 2011), (Lee, 2009), (Ranfeld, 2012).

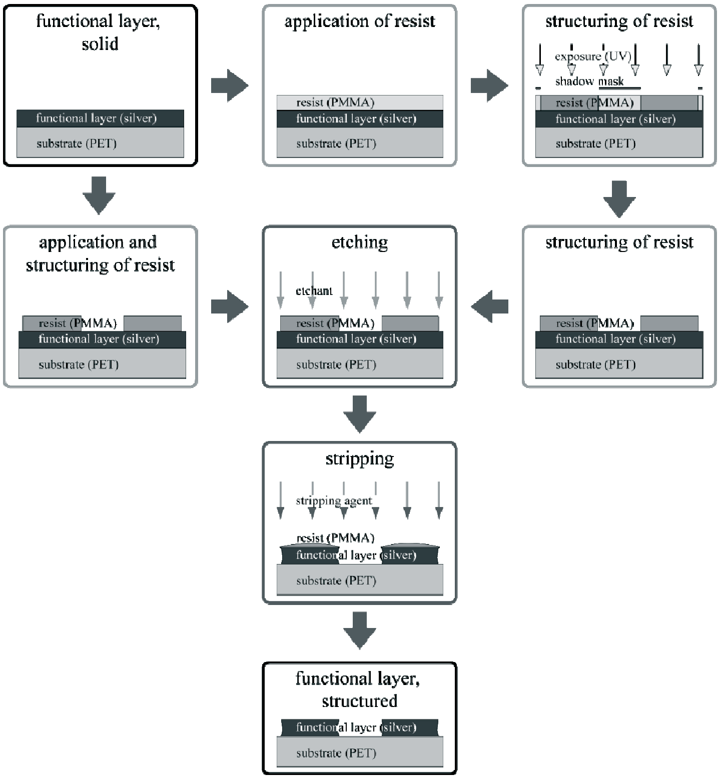

Figure 1: Lithographic process with conventionally applied resist (right branch) and flexographically printed resist (left branch)

The process steps as we present them are easy to integrate into a roll-to-roll (R2R) process for the production of printed electronics without alterations for the application unit of the functional layer. It is also possible to use substrates with solid area pre-coated functional layers. For structured coating of the resist, a flexographic printing unit is needed and two additional dip units for etching and stripping, respectively. Additional drying units (e.g. hot air) are not needed for the resist layer, but possibly after the stripping unit.

The main factor influencing the process speed is the etching rate r. It defines the ablated thickness of a layer (h_{etch}) in a certain amount of time (t_{etch}), as stated in the following equation 1:

$$r = \frac{h_{etch}}{t_{etch}} \qquad [1]$$

For isotropic etching, as in the present case, the length of undercutting (l_U) equals the ablated height (h_{etch}) as stated in equation 2. If the ablated height and the layer thickness both are significantly lower than the lateral di-mensions of the layout, the undercutting can be disregarded.

$$l_U = h_{etch} \qquad [2]$$

As the etchant also affects the resist, though considerably less than the functional layer, the undercutting might have to be taken into account when the selectivity is low. As equation 3 states, the selectivity S of an etchant is the ratio of the etching rate of the functional layer (r) and the resist (r_{res}).

$$S = \frac{r}{r_{res}} \qquad [3]$$

The etching rates of specific etchants for silver known from literature (e.g. (Köhler, 1998)) cannot be applied to printed silver layers. This is due to the completely different structure of printed layers compared to ones obtained by vacuum processes such as evaporation or sputtering.

Printed silver layers will show significantly higher etching rates due to their porosity resulting from the ink and the method of applying the same: Commonly, silver nanoparticles for ink formulations are coated with polymers to prevent aggregation and are then dispersed in a solvent (Schroeder, 2006).

After transfer of the ink onto the substrate it will be dried by evaporation of the solvent. Note that the coating of the silver nanoparticles is most likely still in place. Thus, the silver particles form a more or less porous layer. To reduce the porosity, allow the silver particle to contact and thus enhance the conductivity, the printed layer is some-times subsequently sintered using a heat or other energy source.

In this study, we used a pulsed xenon flash (NovaCentrix PulseForge 1200). The silver layer will absorb the broad-spectral light pulse and transform the energy from the light into heat. Thus, the silver will increase temperature very quickly and induce the sintering process. As the surface to volume ration in nanoparticles is higher, the particles will melt at significantly lower temperatures than the melting point of bulk silver (Schroeder, 2006).

Note that as the absorption spectrum of the PET-foil is not similar to the spectrum of the xenon lamp, the substrate will not absorb as much energy and thus not heat as a direct effect of the light flash. It will warm indirectly by thermal conduction of the silver layer though.

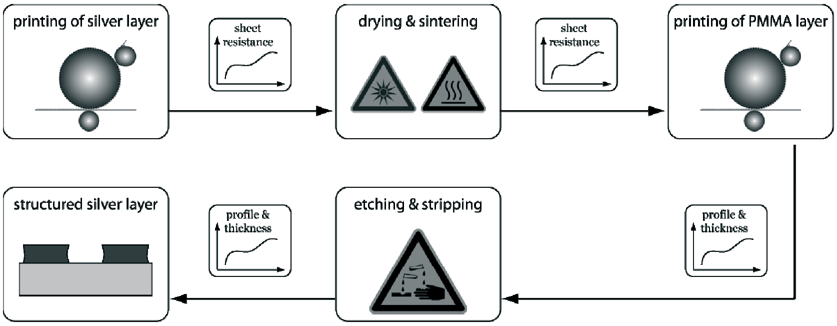

Figure 2: Sequence of process steps conducted in this study: First, we printed a (solid) silver layer. Before and after drying and sintering of this layer, we measured the sheet resistance and subsequently printed the resist (PMMA) layer. Before and after the etching and stripping steps, we determined the layer thicknesses and profiles in order to be able to calculate the etching rate

Before and after sintering, we measured the sheet resistance of the silver layers using the Van-der-Pauw method. We use the change in the sheet resistance as an indicator for the layer porosity. Subsequently, we printed a resist layer onto the silver.

Before and after etching, we measured the layer thickness of the silver in order to calculate the etching rate using equation 1. The process steps are illustrated in figure 2. The measurements we performed are indicated between the respective process steps.

3. Experiment

We conducted all printing test in this paper on a printing proofer IGT F1. Although the printing tester's capabilities are limited, its low consumption of fluid makes it suitable equipment for functional printing where fluid amount is always a critical parameter. A picture of the printing proofer and a schematic of its printing unit is shown in figure 3.

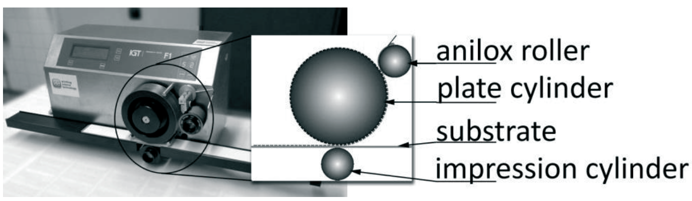

Figure 3: IGT F1 printing proofer and schematic of its printing unit

For printing of the conductive layer, we used a commercially available silver nanoparticle ink from InkTec (PR030), which we consecutively dried in a ventilated drying chamber at 120 °C for 10 min in order to remove the solvent. As resist fluid we used a 18 wt% soluition of PMMA (120,000 g/mol, SigmaAldrich) in anisole ($CH_3OC_6H_5$) (Stahl, 2012) with small amounts of a red dye (Lumogen F Red 305, BASF) for better visualization. As anisole evaporates relatively fast, this layer will dry under ambient conditions within few seconds. Thus, no post-treatment is needed for this layer.

Despite results shown by Theopold in (Theopold, 2012) that common printing plates used in the graphical industries are not suitable for most of the solvents used printed electronics, we used a photopolymeric printing plate for preliminary test. As expected, the tests confirmed Theopold's results: The printing plates were strongly affected by the solvent used in the PMMA fluid, Anisole, and showed signs of disintegration within a few printing runs. Toluene, the solvent used by Theopold, and Anisole are quite similar in this respect. Hence, we switched to more solvent resistant printing plates made of a custom fluorinated rubber (Felix Böttcher GmbH & Co. KG) for the actual printing trials. We used a sleeve plate on a custom made sleeve cylinder suitable for the printing proofer IGT F1.

Literature states that pure nitric acid is usually not suitable for etching of small silver structures due to its high etching rate and suggests different etchants as e.g. ammonium-methanole-hydrogen peroxide solution or other toxic etchants to obtain lower etching rates (Köhler, 1998). Nevertheless, we favored nitric acid because it is easy to dilute and thus the etching rate can be adjusted to the respective needs. To achieve an acceptable etching rate, we diluted the nitric acid down to 40 vol% in aqua purificata. Higher dilution resulted in to low etching rates where-as lower dilutions removed the silver too fast.

After the etching step, we rinsed the samples with aqua purificata to stop the etching reaction. For stripping of the resist, we use acetone as it quickly dissolves PMMA and does not affect the silver layer.

The samples included in this study were

dried, i.e. after solvent evaporation with a high sheet resistance;

dried and sintered as described above with significant lower sheet resistance;

vacuum evaporated as reference samples.

4. Results

An example for the profile and layer thickness measurements is depicted in figure 4. It shows the edge of a printed silver shape before the etching step (above). A the lower image is the profile section indicated by the black line in the image above. In this example, there is a wide raised boarder around the shape.

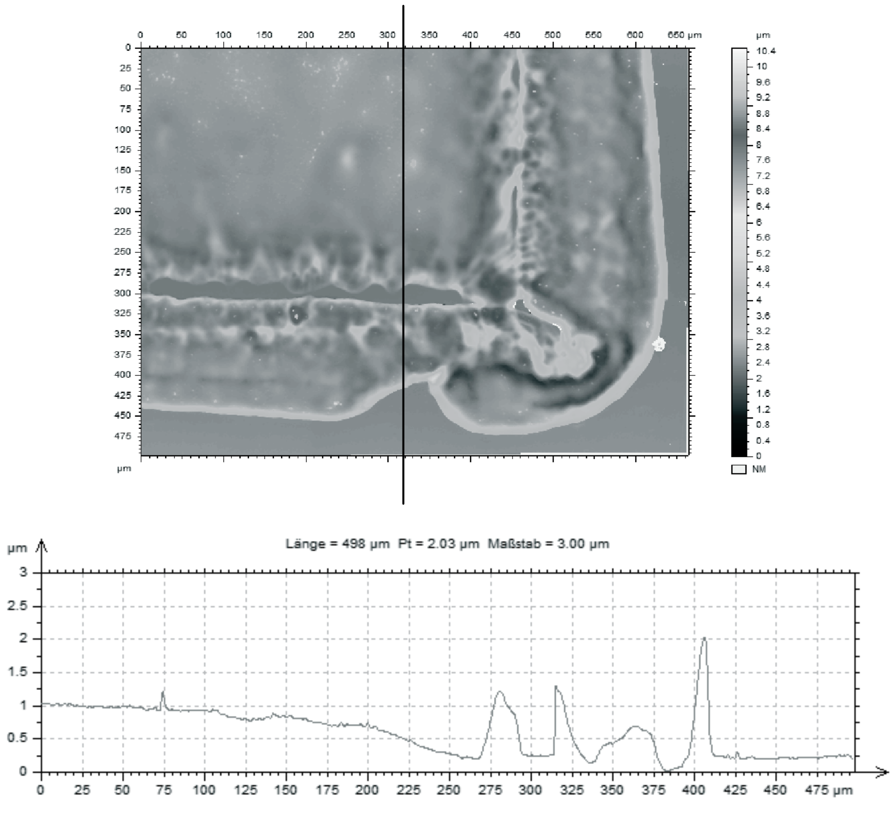

Figure 4: Confocal microscopic image of a printed silver layer before etching (previous page) and profile section as indicated by line (above)

This effect is typical for flexographic printing and is commonly call halo effect. This rim is usually higher than the rest of the printed element (Ranfeld, 2011). With this sample, we obtained a layer thickness of about 1 µm. After etching, we were able to measure a layer thickness of about 700 nm as illustrated in figure 5. With an etching time of 2 s this equals an etching rate of roughly 150 nm/s. As stated above, the etching rate can be adapted by adjusting the dilution of the nitric acid.

However, we were not able to observe a significant difference in the etching rates of sintered, non-sintered and vacuum deposited silver layers. We attribute this high errors regarding the exact time the sample is in contact with the etchant due to manual processing.

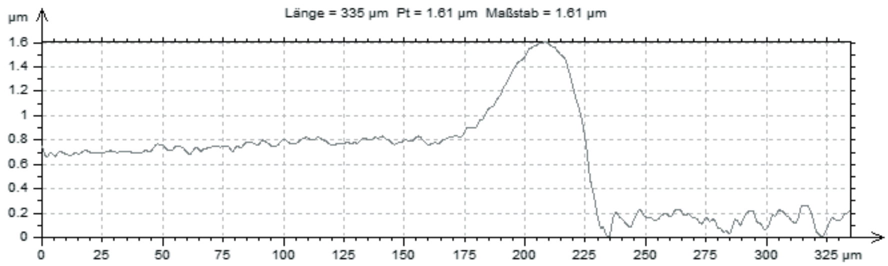

Figure 5: Profile section of etched silver layer. The peak indicates the raised boarder (i.e. halo effect) around the printed shape

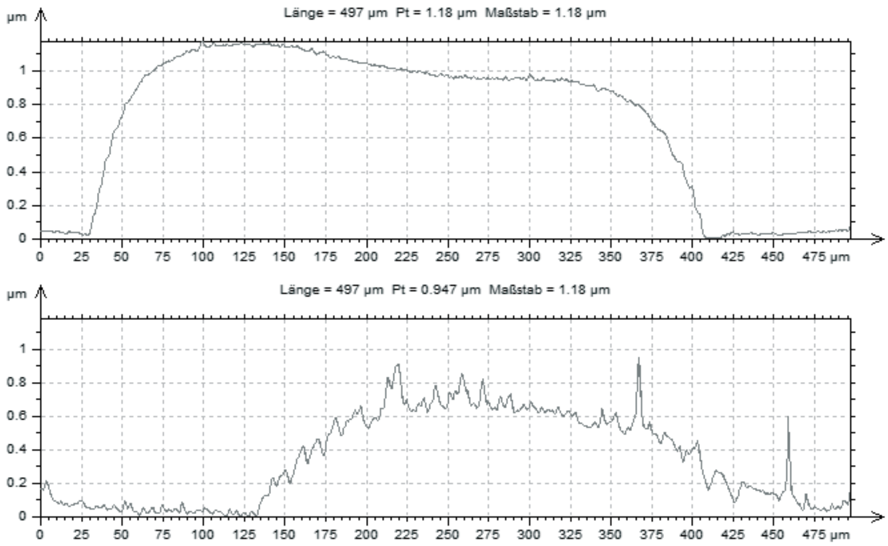

Figure 6: Profile section of flexographic printed PMMA line. Top: before etching step, bottom: after etching step

As figure 3 clearly shows, the resist layer is also affected by the etching step. Not only will the layer thickness decrease but also the line width. Thus, by carefully adjusting the parameters such as etchant and therefore the selectivity as explained above, significantly smaller structure sizes can be obtained compared to directly structured printing of the functional layer.

5. Discussion, conclusion and outlook

We presented a promising method of post-structuring of conductive layers, e.g. after printing. The velocity of the individual process steps (printing of resist, drying of resist, etching, stripping) indicate a straightforward integration into printing or other roll-to-roll processes and machines. The etching rate can be adapted by adjusting the dilution of the etchant. With the samples included in our study and a 40 vol% diluted nitric acid, we obtained etching rates of roughly 150 nm/s.

We also showed that by etching, we are able to reduce the feature sizes than the ones directly printed. With carefully adjusted printing and etching parameters, it should be possible to obtain feature sizes smaller than the ones currently possible by flexography when using the proposed method. However, the reproducibility of the resist structures is unsatisfactory as yet and needs further improvement. This may be either by adjustments to the process of flexographic printing as the authors are currently investigating or by using other printing techniques such as gravure printing.

Nevertheless, with the appropriate parameters, such as etching rate and etchant, known, the generic process presented can be transferred onto other functional materials and layers.

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2

Printing processes and products

Modeling the process of transformation of text and graphic information in prepress

Natalia Gurieva [1], *Iuliia Gubnytska* [2], *Victor Hugo Robles Francia* [1]

[1] Department of Digital Arts and Management
Division of Engineering, University of Guanajuato
Carretera Salamanca - Valle de Santiago
Salamanca, Gto. Guanajuato, Mexico
E-mail: natali.guryeva@gmail.com

[2] Department of the Engineering and Computer Graphics
Kharkov National University of Radio Electronics
Lenin av., 14 UA-61166, Kharkov, Ukraine
E-mail: julgub@ukr.net

Abstract

It was investigated the reproduction process of text and graphic information into the publishing system. To manage the data flow between various prepress steps it was proposed information model of prepress digital workflow, transformations of text and graphic information which describes all stages of the prepress process: input the text and graphic information into the publishing system; editing of text fragments, creating and processing of graphic fragments of articles; automate imposition, combination of many pages into a single layout; separation and applying individual printing media properties; organization of color management process at all technological stages of prepress. It was developed two methods of imposition of the publication: the method of assembling the fragments of text and graphics in the article, including automatic method without possibility of segmentation of text fragments and automatic method with possibility of segmentation algorithms of text fragments; the method of arrangement articles on print area of a page of the publication including automatic placement algorithm for unrelated articles and automatic algorithm for placement related articles taking into account the forbidden area. Also it was developed the application for iterative imposition process as a part of general platform for automated publishing. The proposed methods are required for optimal transformation of text and graphic information in prepress depending on the aim of the publishing process and types of the printed production.

Keywords: layout, automate imposition, information model, prepress

1. Introduction

Commercial publishing process adapting to the realities of the digital era provides now quick and efficient satisfaction of the customer needs. The requirements for quality commercial printing products are increasing meanwhile the quality of the final product mostly depends on the proper prepress processing this publication [1]. The set of procedures used in any particular prepress environment is known as a workflow. Workflows vary, depending on the printing process, the final product and the implementation of specific prepress technologies [2, 3].

An essential step of manufacturing such products, including books, newspapers, magazines is prepress process which will largely determine not only the quality but also the cost of the product. The first and dominant part of the prepress process is a stage of publishing, characterized by heterogeneity of publishing concepts, information technologies, hardware and software. And there is no methodologically unified view of the editing stage and recommendations that need for improving the efficiency of workflow at this stage [4, 5].

In this paper it is proposed to improve the information model of the editorial prepress process presented in [4]. Conceptually this model differs from existing analogs by comprehensively analyzing the different variants of composing layout; this model is used for the production of a new information technology task of forming a layout of publication.

A lot of automatic methods of placement of articles on a page of edition are developed, in which the participation of the expert is limited to the task of the initial information [8]. However layouts, received as a result of application of these methods, practically always are not final and usually need to be corrected by different means.

Thus, research of the editing process and creation of information models and methods for layout composing are the actual scientific problems. Development of the article fragment placement methods is the actual practical problem.

2. Dataflow diagram for a prepress process

The information model of prepress digital workflow (fig. 1) describes transformations of text and graphic information at all stages of the prepress process:

1) Input the text and graphic information into desktop publishing (DTP).
2) Editing of text fragments, creating and processing of graphic fragments of articles.
3) Imposition, combination of many pages into a single signature form.
4) Separation, or specifying images or text to be put on plates applying individual printing media properties.
5) Organization of color management process at all technological stages of prepress.

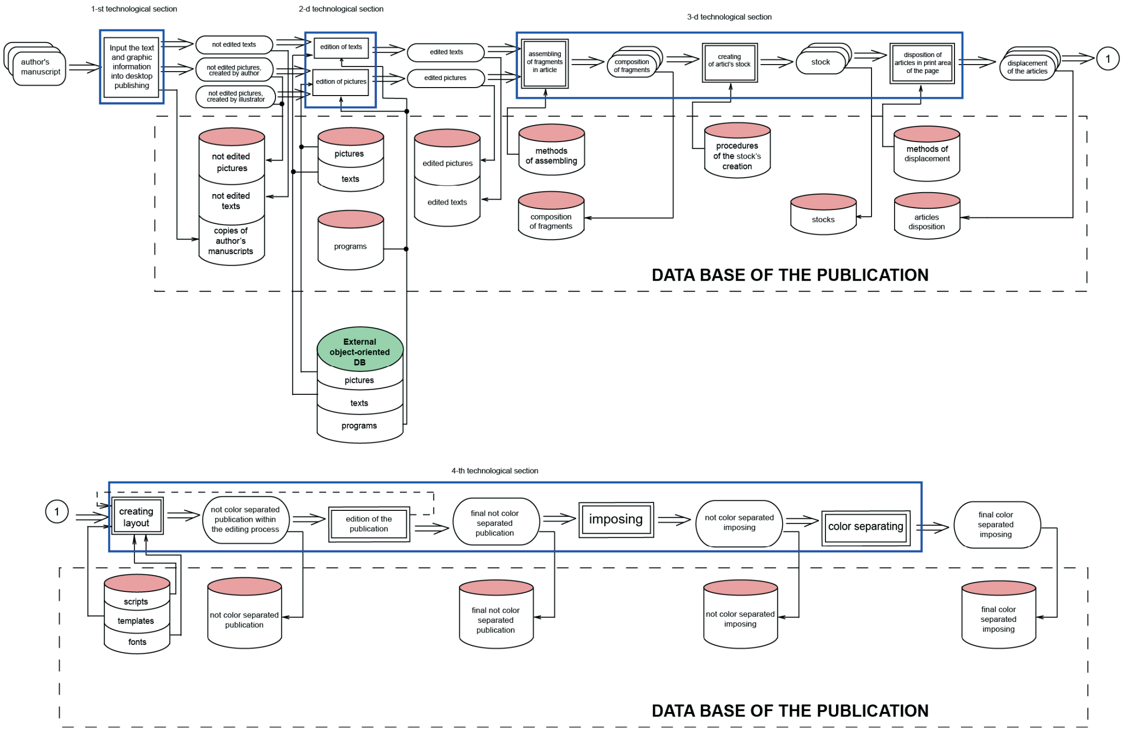


Figure 1: Dataflow in prepress process

This model is capable of describing the hierarchical structure of the information prepress processes. The information model describes publication in several states: as a digital text and graphic originals, as an imposition, as prepress proofs or samples, and as color separated layout (ready-to-print composite PDF with CMYK or CMYK and spot colors). During prepress process the initial layout of the edition passes a sequence of transformations and reaches a final version as a result of the editorial stage of the prepress process (ESPP). Information, first like manuscript, starts to move from one stage to another and after a few iterations reaches a final version of layout that it is ready for printing. On the scheme is also shown database where all texts, images and layouts are saved. And on each part of the ESPP the information from database of a publication or external database is available for using.

3. Process of transformation of text and graphic information

The technological task of the composing of the layout according to the editorial stage of the prepress process is determined by three sets (Y, Y_0, Y_R,), in which $Y = (\Pi, \Omega, \Theta)$, where Y - subject domain of a task; Y_0 - initial condition of a subject domain; Y_R - required condition of a subject domain; $\Pi = \{\pi\}$ - set of subjects; $\Omega = \{\omega\}$ - set of operations given on Π, $\Theta = \{\theta\}$ - set of attitudes given on Π and Θ. The descriptions of the main variables are given in Table 1.

$$\Pi = I \cup A \cup \Phi \cup H \cup Z \cup K \cup B \cup M \quad [1]$$

Table 1: The basic variables

Designations		Name
Element	Set	
	I	edition
β	**B**	print area of a page
α	**A**	article
φ	**Φ**	fragment of the article
η	**H**	set of the orders
K	**K**	assembling [result of metric displacement]: 1) fragments in article; 2) articles in the print area of the page]
	M	layout

For a subject (π) of each type the set of properties $\Lambda^{(\pi)} = \{\lambda^{(\pi)}\}$ and set of conditions $\Gamma^{(\pi)} = \{\gamma^{(\pi)}\}$ is determined.

An edition (**I**) like the final product of the publishing process consists of one or several articles. The edition consisting of one article is named as the edition of a book ($\bar{\mathbf{I}}$). The edition consisting of two or more articles, is named as a newspaper-journal edition ($\tilde{\mathbf{I}}$).

It is accepted, that the edition can be in four states: $\mathbf{I}^{(\gamma 1)}$ - as a digital color separated layout; $\mathbf{I}^{(\gamma 2)}$ - as color separated layout on the printing plate, film, tracing-paper etc.; $\mathbf{I}^{(\gamma 3)}$ - as a print; $\mathbf{I}^{(\gamma 4)}$ - as a ready product. During ESPP the edition can be only in a one state - $\mathbf{I}^{(\gamma 1)}$.

Methodologically, the most important subject is an article. Articles of the edition make a set: A = {αi}. I = $\overline{1.n}$, n ∈ N. On first technological stage of ESPP some articles α form a set **Φ** consisting of one or several elements. They are named as fragments of article (ϕ):αI)=> $\mathbf{\Phi}_i$={$\mathbf{\Phi}_{\mathrm{I,j}}$}, where j = $\overline{1.k}$; k ∈ N; the symbol)=> designates forming.

In publishing industry it could be several kinds of text or graphical fragments. Three kinds of fragments of the article: a textual (t), fragment "text - insert" (t *), graphic element (g) and the corresponded fragments:

φ(t), φ(t *), φ(g).

$\mathbf{\Phi}_i^{(t)} = \varnothing$ or $\{\varphi_1^{(t)}\}$, i = $\overline{1,n}$; n ∈ N - set of textual fragments of article αi;

$\mathbf{\Phi}_i^{(t^*)} = \varnothing$ or $\{\varphi_{i,j}^{(t^*)}\}$, j = $\overline{1,k}$; k ∈ N - set of fragments "text - insert";

$\mathbf{\Phi}_i^{(g)} = \varnothing$ or $\{\varphi_{i,j}^{(g)}\}$, j = $\overline{1,l}$; l ∈ N - set of graphical fragments.

Thus, $\Phi_i = \Phi_i^{(t)} \cup \Phi_i^{(t^*)} \cup \Phi_i^{(g)}$.

The elements of the set **A** have property $\Lambda^{(\alpha)}$. This property is considered as set of individual properties (internal parameters). They are divided in three categories: identification, geometrical and publishing.

Five different types of articles depending on the number and types of fragments which are included in article are represented below:

1) $\alpha_i^{(t)}$)=> $\mathbf{\Phi}_i^{(t)} = \{\varphi_{i,1}^{(t)}\}$

2) $\alpha_i^{(g)}$)=> $\mathbf{\Phi}_i^{(g)} = \{\varphi_{i,1}^{(g)}\}$

3) $\alpha_i^{(tt^*)}$)=> $\mathbf{\Phi}_i^{(t)} \cup \mathbf{\Phi}_i^{(t^*)} = \{\varphi_{i,1}^{(t)}\} \cup \{\varphi_{i,j}^{(t^*)}\}$, where j = $\overline{1, m}$, m ∈ N.

4) $\alpha_i^{(tg)}$)=> $\mathbf{\Phi}_i^{(t)} \cup \mathbf{\Phi}_i^{(g)} = \{\varphi_{i,1}^{(t)}\} \cup \{\varphi_{i,j}^{(g)}\}$

5) $\alpha_i^{(tt^*g)}$)=> $\mathbf{\Phi}_i^{(t)} \cup \mathbf{\Phi}_i^{(t^*)} \cup \mathbf{\Phi}_i^{(g)} = \{\varphi_{i,1}^{(t)}\} \cup \{\varphi_{i,j}^{(t^*)}\} \cup \{\varphi_{i,l}^{(g)}\}$,

where: j = $\overline{1, k}$; l = $\overline{1, m}$; k, m ∈ N.

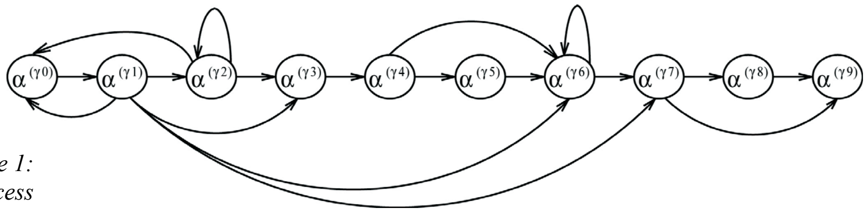


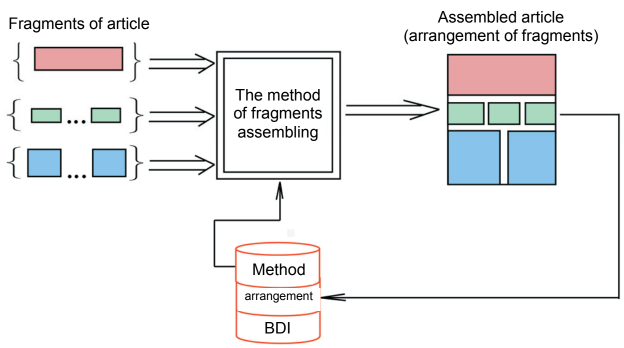
Figure 1:
Dataflow in prepress process

Also, the model includes the articles transformations from one state into another according to appropriate technological operations:

$$\gamma_0^{(\alpha)} \xrightarrow{\Omega_{0-1}^{(\alpha)}} \gamma_1^{(\alpha)} \xrightarrow{\Omega_{1-2}^{(\alpha)}} \gamma_2^{(\alpha)} \xrightarrow{\Omega_{2-3}^{(\alpha)}} \gamma_3^{(\alpha)} \xrightarrow{\Omega_{3-4}^{(\alpha)}} \gamma_4^{(\alpha)} \xrightarrow{\Omega_{4-5}^{(\alpha)}} \gamma_5^{(\alpha)}$$
$$\gamma_5^{(\alpha)} \xrightarrow{\Omega_{5-6}^{(\alpha)}} \gamma_6^{(\alpha)} \xrightarrow{\Omega_{6-7}^{(\alpha)}} \gamma_7^{(\alpha)} \xrightarrow{\Omega_{7-8}^{(\alpha)}} \gamma_8^{(\alpha)} \xrightarrow{\Omega_{8-9}^{(\alpha)}} \gamma_9^{(\alpha)},$$

where $\Omega^{(\alpha)} = \Omega_{0-1}^{(\alpha)} \cup \Omega_{1-2}^{(\alpha)} \cup \Omega_{2-3}^{(\alpha)} \cup \Omega_{3-4}^{(\alpha)} \cup \Omega_{4-5}^{(\alpha)} \cup \Omega_{5-6}^{(\alpha)} \cup \Omega_{6-7}^{(\alpha)} \cup \Omega_{7-8}^{(\alpha)} \cup \Omega_{8-9}^{(\alpha)}$ is a set of operations performed on text and graphic information of the articles.

$\gamma_0^{(\alpha)}$ is the initial state of article as the author's manuscript;
$\gamma_1^{(\alpha)}$ is not edited electronic version of the article as a set of textual and graphic fragments;
$\gamma_2^{(\alpha)}$ - edited article as set of the edited textual and graphic fragments with color correction;
$\gamma_3^{(\alpha)}$ - article, assembled from fragments (composition of fragments);
$\gamma_4^{(\alpha)}$ - article as an part of the set of the orders;
$\gamma_5^{(\alpha)}$ - article as an element of print area of a page of the publication;
$\gamma_6^{(\alpha)}$ - article as a part of not separated color publication within the editing process;
$\gamma_7^{(\alpha)}$ - article as a part of final not separated color publication;
$\gamma_8^{(\alpha)}$ - article as a part of not separated color imposing;
$\gamma_9^{(\alpha)}$ - article as a part of final color separated imposing.



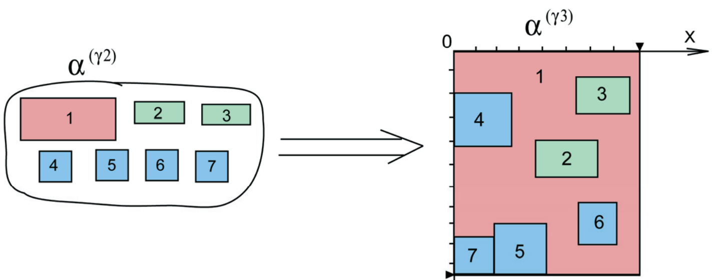


Figure 2:
Example of the composing process

This formalization allows to develop two methods of imposition of the publication.

4. Methods of the composing of the layout of the publication

Two methods of composing are developed based on a data flow diagram of the prepress process:

1) the method of assembling the fragments of text and graphics in the article (AF), including automatic method AF-A1 without possibility of segmentation of text fragments and automatic method AF-A2 with possibility of segmentation algorithms of text fragments and algorithm AF-D (in a mode of dialogue, with an opportunity of segmentation of a textual fragment);

2) the method (PA) of arrangement articles on print area of a page of the publication including automatic placement algorithm PA-A1 for unrelated articles and automatic algorithm PA-A2 for placement related articles taking into account the forbidden area and algorithm and PA-D (in a mode of the dialogue).

Automatic algorithm based on the optimizing of the function that includes the following set of the criteria for assessing the quality of arrangements of the articles:

1) economic and aesthetic criteria for arrangements of the *articles*: total number of the text information - amount of articles placed on page; covering - total area occupied by articles on page; occupancy – percentage of filling of the page work area; importance - total information importance; rating - total rating of the placed articles; profitability - total profit of placed articles; advertising - percentage of filling area of a page with advertising articles; textografity - ratio of textual and graphic fragments on a page; centrality - ratio of articles placed in center zone of a page and peripheral zone; Balance - sign of articles uniform distribution in four quarters on the page; linear proportions- number of the nonlinear proportions; proportions of the squares; chromaticity - ratio of total squares of color and monochrome articles; symmetry - ratio of total squares of articles placed on the left and on the right half of page work areas.

2) economic and aesthetic criteria for arrangements of the *fragments*: occupancy - percentage of filling of area of the fragments placement; linear proportionality - number of the nonlinear proportions among placed fragments; proportions of the segments - disproportionate areas of placed fragments; segmentation of the text fragment - percentage of textual fragment division.

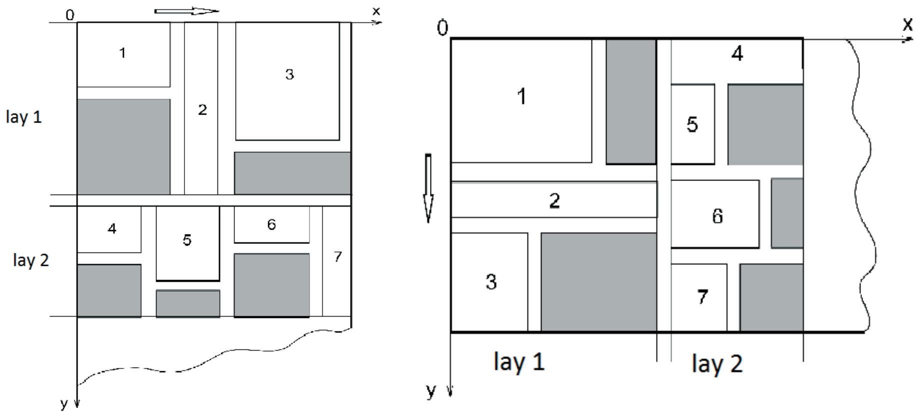
Let's consider algorithm PA-A1 more in detail.

Essence of algorithm is level-by-level consecutive -single placement of articles in a direction given by the user. Generally, articles are placed in working area of a page in two stages: the basic placement and placement in bonded areas (additional). As the result of these accommodations we have synthesized variant of configuration. On the basis of set of generated rearrangements of articles in a set of variants of configurations is formed, from which best is selected by criterion given by the user.

The algorithm assumes performance next 10 steps: 1) input, the logic control and, if is necessary, updating of the initial data; 2) the initial ordering, if is demanded, articles in a set by the given criterion; 3) basic placement of articles in working area; 4) additional placement of articles in bonded areas; 5) calculation of parameters of quality of the generated variant of configuration; 6) if the updating of record configuration is required; 7) if the conditions of breakage of computing process are executed, transition to a step 9, differently - to a step 8; 8) rearrangement of articles in a set and transition to a step 3; 9) formation of the table of final record configuration; 10) formation of the table of economic and aesthetic parameters of final configuration.

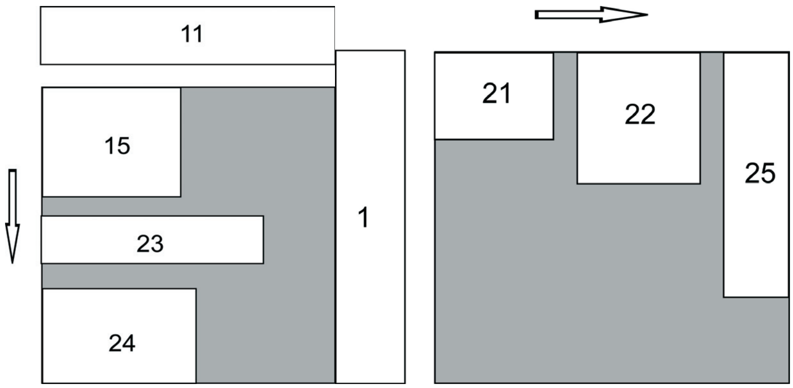
Let's note, that the basic placement of articles is made on layers in a horizontal or vertical direction according to the task of the user. At a horizontal direction of placement height of each horizontal layer coincides with maximal height from heights of all articles placed in the appropriate layer (a fig. 2a). At a vertical direction of accommodation width of each vertical layer coincides with maximal width from width of all articles placed in the appropriate layer (a fig. 1b). At the basic placement (both in horizontal, and in a vertical direction) the given restrictions on the minimal distances between articles are maintained.

After end of the basic placement of articles in working area there appear zones named as bonded areas (grey rectangular on a fig. 2). Placement of articles in bonded areas, if it is demanded, is made in each layer in a horizontal or vertical direction according to the task of the user. In a fig. 3a the example of filling of a bonded area in a horizontal direction, and in a fig. 3b - in a vertical direction is given.



a) b)

Figure 2: Level-by-level placement of articles in working area



a) b)

Figure 3: Placement of the article segments into bonded areas

In a figure 4 the sketches of configurations of articles received as a result of application of algorithm PA-A1 are given.

In configuration given fig. 4a, direction of the basic placement of articles - horizontal, and direction of placement of articles in bonded areas - vertical; in configuration given in a fig. 4b, accordingly, - vertical and horizontal.

Dialogue method of the articles composing into the working area of a page gives to the expert an opportunity to create initial layout on the basis of the certain editorial idea.

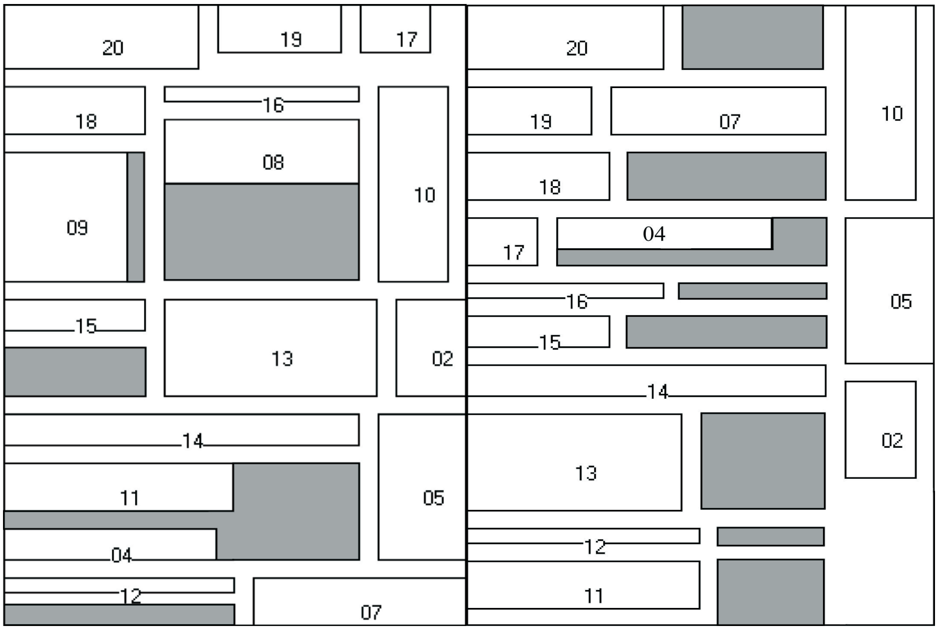
The method enables the expert in a mode of dialogue to set all the requirements determining a placement of the articles. The basic commands are: "place", "move", "pair exchange", "check crossing".

Additional commands are: "table" (display of coordinates of base points and other parameters of placed articles), "sketch" (graphic display of layout), "evaluation" (quality of layout).

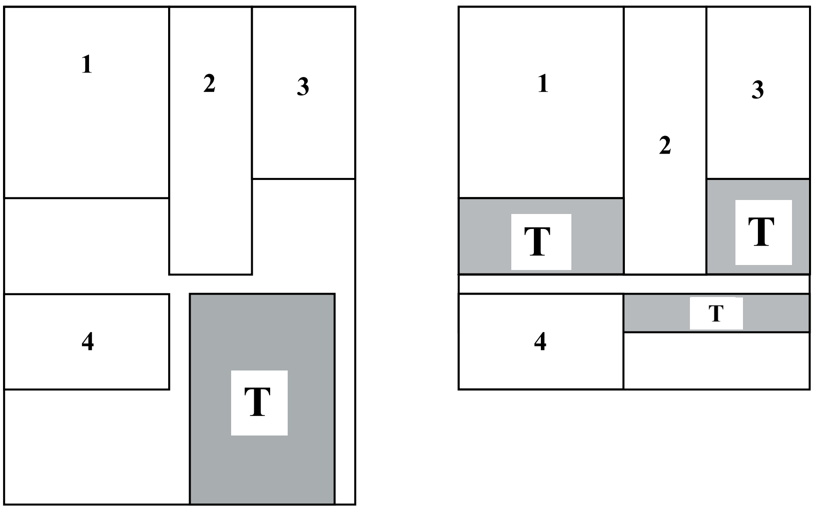
The basic opportunities of the user using algorithm AF-D, illustrates Figure 5.

The proposed methods are required for optimal transformation of text and graphic information in prepress depending on the aim of the color reproduction process and kinds of printed production.

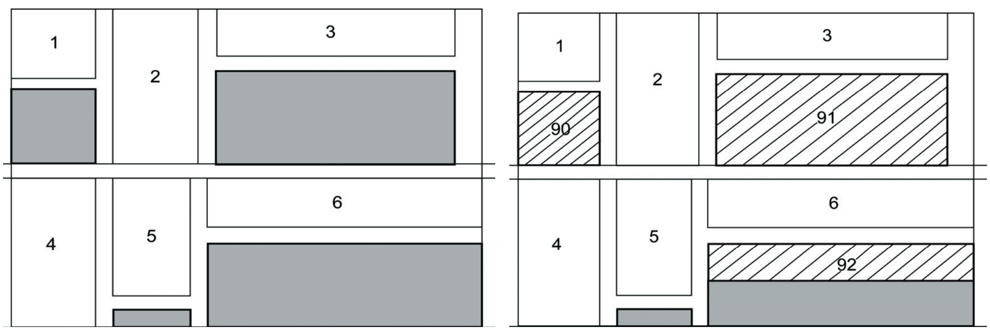
In practice, designer for each page of the newspaper or magazine could compare three or maximum four different versions of the layout. Using proposed methods, in a one second we can choose the best imposing of 10 000 options, evaluate it, and if it is necessary to change or correct the final layout using a dialog window. In the existing software imposing is realizing with a simple method of "drag and drop" (by dragging objects with a mouse), but it does not allow a possibility of a multivariate layouts. Also, the existing systems do not take into account the hierarchy of the fragments and articles.



a) b)



Difference between two methods of composing



Segmentation of the text fragment

Figure 4: Sketches of the articles placement

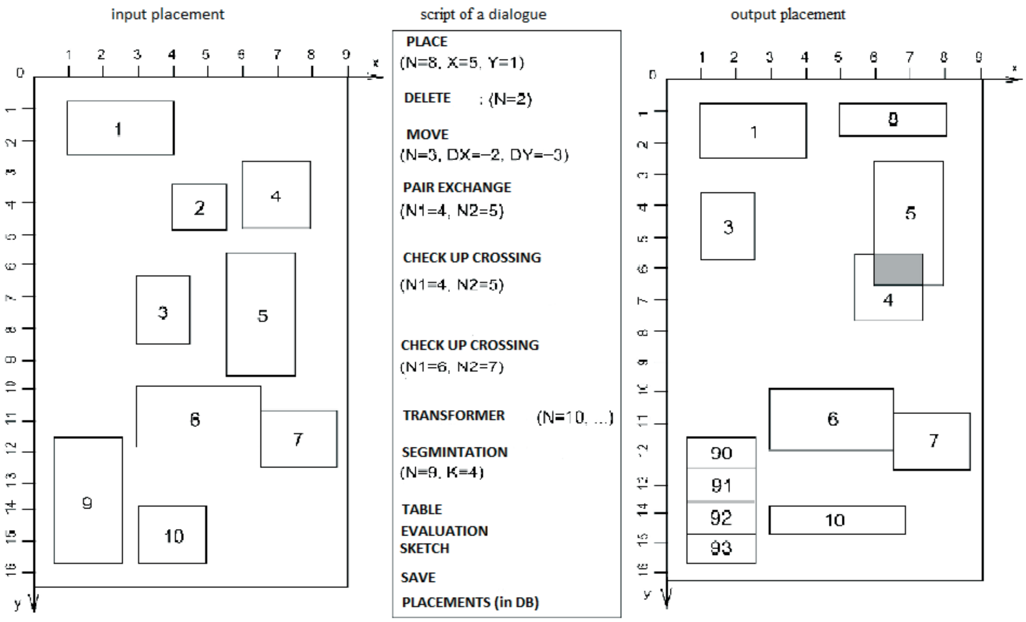


Figure 5: Illustration of the layout optimization dialog window

5. Conclusions

In this paper the process of reproduction of text and graphic information is considered and proposed information model of the prepress process, which allows develop information technology of priority composing of the text and graphic segments in one optimized layout and improve the quality of the prepress system. It is also created the methodological foundations for assessing the quality of the final layout and imposition.

The proposed formalization makes possible to improve the quality of the layout and the publication and to reduce the time of its production.

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An innovative project management method for a newspaper printing press installation during full production

Johan Stenberg

Bold Printing Group
Box 36 SE-16493, Kista, Sweden

and

KTH Royal Institute of Technology, School of Computer Science and Communication,
Department of Media Technology and Interaction Design,
SE-10044 Stockholm, Sweden

E-mails: johan.stenberg@boldprinting.se and jostenb@kth.se

Abstract

The market for printed newspapers is under hard pressure in many countries. Installation of newspaper printing presses does often imply very high investment costs. A rough figure just for a printing press and its auxiliaries can be 20-25 million Euro for a 96 page 90 000 copies per hour tabloid printing press and including auxiliaries. Such an investment implies 10-15 years use and capital costs.

A project has be accomplished where new, highly automated newspaper printing presses have been installed in the same building and on the same press tables as the old presses.

The objectives have been to run a lean project, reduce costs and improve the productivity and competitiveness in two major Swedish newspaper printing plants printing around 2 million copies per day.

This paper is a case study of the two press installations including analyses of the somewhat unusual project methods used and needed in order to replace the old printing presses in parallel to serving some of the largest newspapers in the country on a daily business-as-usual basis throughout the complete project. The preconditions for the project and the project methods are described and analyzed and the project results reported.

Keywords: newspaper printing presses project method

1. Introduction

Installation of newspaper printing presses does often imply very high investment costs in production equipment and new buildings. A rough figure just for the printing press and its auxiliaries can be 20-25 million Euro for a 96 page 90 000 cph tabloid press. Such an investment implies 10-15 years use and capital costs.

Bold Printing Group ("BPG") is part of the international media group Bonnier (Bonnier, 2013). BPG, based in Sweden, is one of the largest printing groups in the Nordic area producing around 2 million copies per day and with approximately 100 million Euro revenue in 2012. A majority of the copies are printed between 20:00 in the evening and 06:00 in the morning. BPG consists of three newspaper printing plants on different locations in Sweden: Bold Printing Group Stockholm in Akalla - Stockholm, Bold Printing Group Malmö in the south and Borås Tidning Tryckeri AB in the western part of the country.

The printing group serves internal Bonnier customers as well as a large number of external customers such as free papers and commercial advertising products (Bold, 2013).

During 2008 a project was started in order to secure a cost efficient future printing business. In Akalla and Malmö the printing presses used then were installed 1992-1994 and their manning and productivity could not, around fifteen years later, compete with modern and highly automated newspaper printing plants such as the BPG plant in Borås from 2002. In order to stay competitive in the long run, a modernization of the plants was considered as an alternative to closing the two old plants down and outsource the production.

During periods of strong newspaper economy in Sweden, for instance 1980's - 1990's, many newspaper moved their city located print facilities to new green field sites outside the city centre. This caused heavy investments in buildings, equipment and businesses at two sites during the project period. This was the case when the new plants of Göteborgs-Posten 1985, Aftonbladet/Svenska Dagbladet 1989 and Dagens Nyheter/Expressen 1993 were built.

The total cost for new buildings and new equipment makes the transition from the old to the new plant very capital intense, less risky in terms of production risks and gives a strong platform in order to establishing a new company culture. With a new building, the daily publishing and its printing can continue on a business-as-usual basis in the old plant in parallel to the green field project. When the new plant is prepared and ready for production, the production can gradually be moved from the old to the new plant.

One key question when dealing with this kind of long term investments, is which direction the market for printed newspapers are heading when the publishing world is getting more and more digital. Therefore the project had a strong need to answer questions regarding the future circulation for daily newspapers, development regarding the number of pages, editions, inserts and new opportunities for printed products.

This paper is a case study of the two press installations including analyses of the somewhat unusual project methods used and needed in order to replace printing presses in parallel to serving some of the largest newspapers in the country on a daily business-as-usual basis throughout the complete project.

The objective is to describe and analyze the preconditions for the project and the project methods developed and used in order to manage a heavy investment and a complex project in a shrinking market.

2. Methods

Initially, a project organization was put together and a decision was taken to use the PPS-method developed by TietoEnator as the main framework for all project work. PPS has a strong focus on structures, specifications, routines and project organizations (TietoEnator, 2002), (TietoEnator, 2013). Other methods like PROPS and the later version XLPM (Klamer 2012), (Semcon, 2010) were considered, but PPS was chosen mainly because it is a well established, business independent, project method widely used in Sweden with a large base of trained people, courses and professional companies supporting with knowledge and tools.

The project went through a number of consecutive stages: pre-study, pre-project, installation, go-live, take over and project finalization. The way the work was organized was throughout the complete project period 2008-2013 based on PPS. In addition, some of the stages required different supplementary methods depending on the objectives and characteristics for the specific stage. The project aimed for a large involvement from operators as well as experts already from the early project phases and that was managed by the organizational support found in PPS with steering committees, project management team, specialist groups and references groups. Some samples of the various skills used in the project organization are international printing plant layout experts, local architects and static engineers together with teams of printers and production managers.

Especially during the pre-study and pre-project stages, a combination of literature research and semi-structured interviews with newspaper customers and suppliers of equipment and systems to the newspaper industry were carried out in order to collect data. The literature research used sources like statistics from the Swedish Media Publishers' Association (Tidningsutgivarna, 2008), (Tidningsutgivarna, 2009), (Tidningsutgivarna, 2010) and WAN-IFRA.

A strategy framework with an Inner-Out and Outer-In approach according to (Regner, 2005) were then used together with the method described as Porters five forces (Porter, 2008).

Other questions initially dealt with was the performance of the stage-of-the-art printing presses and the future development of equipment and systems for newspaper production in general and specifically printing. During the first two stages a number of visits to new print sites and industry exhibitions around Europe was included in the project work. Production statistics representing the situation in the three internal BPG-plants was compared to real production data from reference sites representing the different printing presses considered. During the study visits semi-structured interviews were carried out with operators and managers. Both questions related to the new equipment and the installation projects were asked.

During the pre-study and pre-project COmpetition Driven Supplier INvolvement, the CODSIN-method, was developed by the project team. Instead of telling the press suppliers exactly what to offer in terms of a carefully worked out specification, they were given a framework for the future business and as part of the RFP-process (Request For Proposal), the suppliers were then asked to present their solutions including future scenarios, propose suitable printing press solutions, present drawings and requirements with respect to the building and its peripherals, third party investments needed, associated production plans and need for operators and maintenance staff.

Workshops were carried out with all printing press suppliers involved and each of them were asked to present their proposal according to the structure requested in the RFP. Four different suppliers were invited to the first round and in total seven different solutions were presented. An evaluation matrix was developed covering technology, economy, company and project credibility. Each factor was given a grade from 1 to 6. The future cost structures were drawn particular attention and calculations based on NPV with a 15 year depreciation was prepared and analyzed (Brealey et al, 2006).

The pre-studies ended in December 2009 and two suppliers and two different press concepts was chosen for the final round - a pre-project in two stages with the objectives to fine tune the technical solutions, time tables, costs, risks and finally chose one supplier for the two plants. During the pre-project the CODSIN-method was further developed. Three different teams worked in parallel to develop the best concept - one paid for team from each press supplier and one internal expert team.

From January 2010 until the project was more or less finished in the end of 2012 the PPS-method was the main method used. This was in line with the plans as most open questions where then answered and the project went in to a rather strait forward installation, training and go-live phase.

3. Results

The circulation figures and advertising income related to newspapers in Western Europe and North America is under pressure. The newspapers business meet hard competition from a variety of digital substitute products and services competing about the attention of the readers and money from the advertisers described by for example (Naldi et al, 2012) and (Berman et al, 2011). The circulation (see figure 1) and printed advertising income in Western Europe and North America has dramatically declined since 2007 (WAN-IFRA, 2012).

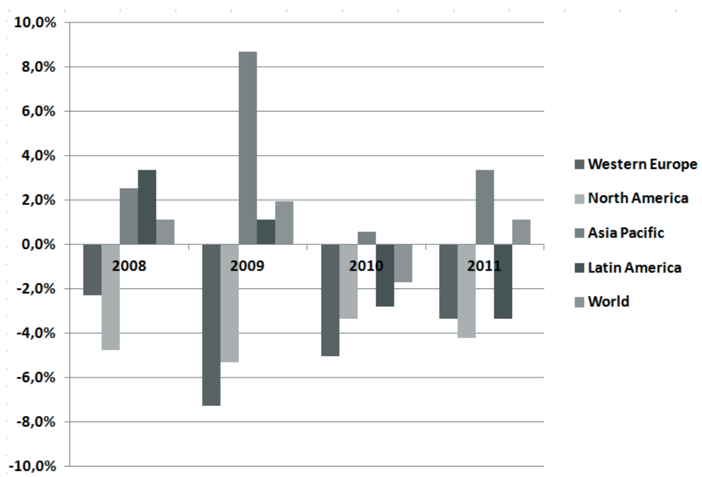

Figure 1: Year on year circulation trends by world region (WAN-IFRA, 2012)

In figure 2 the situation in Sweden is illustrated and it follows the trend in Western Europe and is according to the figures from the Swedish publishers' association even worse than in average countries in Western Europe. Interviews with Swedish newspaper executives indicate that this trend is expected to continue for the foreseeable future. A 3-5 % annual drop with respect to circulation figures per year is often mentioned for the period 2013-2015.

For the print sites, one way to manage the shrinking newspaper market is to improve the productivity and meet the decrease in revenue with cost reductions. Already during the 1980's and 1990's printing presses and mailroom equipment gradually became digitally controlled and new automation technologies improved the performance (Stenberg, 1997).

If the basic process infrastructure in terms of hardware and control system has reached end of life from a financial or technological stand point, investments in modern technology can be a way to survive.

During the first decade of 21th century highly automated and compact newspaper printing presses became mature. The shaftless technology means among others, new possibilities to do different make-ready activities in parallel. Thereby the lead time for non-productive activities can be substantially reduced.

A comparison based on actual production data shows how the technical development of newspaper presses can improve the productivity. The comparison focus on the lead time for a print job made in an almost 20 year old newspaper printing press (manroland Colorman S) and a modern press (KBA Commander CT), (KBA, 2013). The result is shown in figure 2.

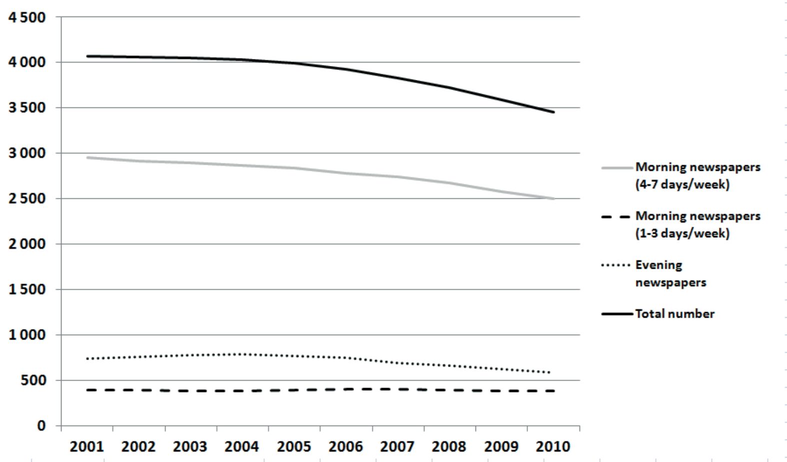

Figure 2: Circulation trend in Sweden 2001-2010 in expressed in 1 000 copies/publication day (TU, 2012)

The make-ready time for similar products have been reduced from 75 to 20 minutes and the net output has gone from 50 000 copies per hour to 75 000 copies per hour for similar production runs in one single folder.

The total effect is a lead time reduction (incl. slack) from 4,6 hours to 2,6 hours for a single 150 000 copy print run. This potential productivity enhancement paved the way to go from a pre-study to a pre-project. The project was then close to an investment decision.

A conclusion drawn is that the development of automation technologies in the printing industry, implies plants that needs less space and less manning. The BPG case showed that one new modern printing press from year 2010 could replace two old presses from 1993. Compared to the old equipment, the new presses in one of the plants (Akalla) just required 25 % of the space and 50 % of the staff in order to produce similar products and volumes.

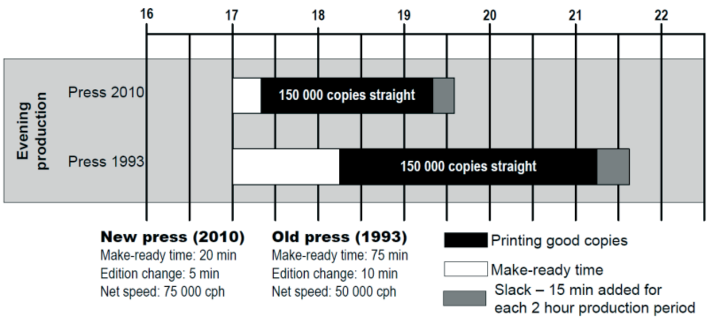

Figure 2: Lead time for a single job in a newspaper press from 2010 and 1993

In recent years not very many large and completely new print sites have been built in Western Europe or North America. But, table 1 includes figures for three modern green field newspaper print sites completed 2007-2008. The table also contains information about one of the older print site in the case study - Bold Printing Group Akalla.

Table 1: Share of building costs in four green field newspaper print site project (Newsprinters, 2013)

Site	Capacity	Building size (sqm)	Total investment	% Building costs	Year
Newsprinters Eurocentral Glasgow, Scotland	172 000 cph - maximum 144 tabloid pages	14 195	56 000 000 GBP	46	2007
Newsprinters Broxbourne, London, England	1 000 000 cph - maximum 120 tabloid pages	87 000	348 000 000 GBP	54	2008
Newsprinters Knowsley, England	430 000 cph - maximum 120 tabloid pages	38 000	120 000 000 GBP	45	2007
Bold Printing Group Akalla, Stockholm Sweden	240 000 cph - maximum 160 tabloid pages	93 000	2 400 000 000 SEK	58	1993

The Akalla plant was from the beginning designed for 320 000 copies per hour (cph) in the late 1980's, but one press line was cancelled during the project phase in the early 1990's and this, in combination with a considerably large building, is the explanation for the very large share of building costs in this case - 58%.

In the case study, a BPG decision to stay in the existing buildings was taken during the pre-project with support from budget figures from one of the suppliers in the CODSIN-process. This specific supplier prepared one solution with a lean, green field site. But, just the additional building costs including necessary auxiliaries reached 21,6 million Euro (+/- 15 %) for an 18 000 sqm plant if the expected production capacity should be hosted. Costs for land and roads were not included in the budget figure mentioned. An extension of the existing Akalla building in order to host a new press line was also studied. The expected costs for this building extension was substantially higher than the necessary modification needed in order to re-use one of the existing press halls. A decision was taken to host the new presses in the present buildings and develop methods to manage the installation process in parallel to the daily production.

Installation on an existing press table, next to a press running in full operation means large risks. Another risk to manage was the difficulty to handle the overall time table and its mile stones. New technology and need for changed processes and routines in parallel to the start-up phase, implies production problems which may influence the customers in terms of late deliveries due to production disturbances. A delayed project time table may also cause lack of money in the end of the project. And according to Kerzner a complex project must be carefully planned and risk management should be an integrated part of the project work (Kerzner, 2013). To manage the risks a decision was taken to list, review and validate project and process risks on a monthly basis.

The most creative phase of the project was the pre-project. In order to define a project that would meet the requirement of re-using the existing buildings and mailrooms and no production limitations for the customers, a rather different project approach was used.

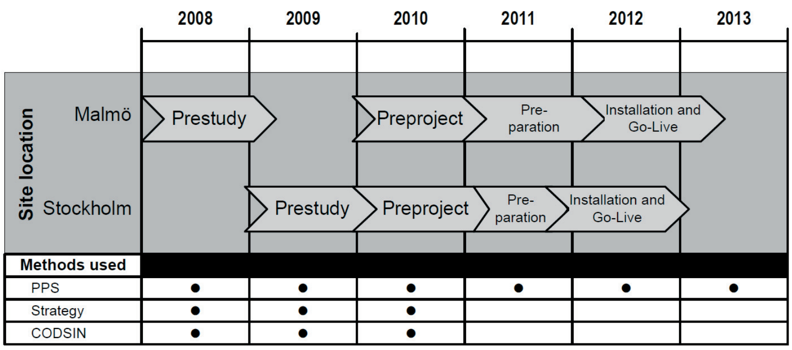

Figure 3: The project phases and methods used

Only two of the four suppliers went on from the pre-study to the pre-project phase and the two suppliers were asked to prepare an offer for a pre-project in order to develop a printing plant concept including all associated project costs, future manning and other operational costs related to the concept proposed. The suppliers in their turn hired international printing plant designers in order to develop the best possible solution.

This was a "competition" and a paid for work, but the costs should only be paid to the supplier that did not get the final order. If no supplier got the order both of them got paid for the pre-project. The costs for this "competition" was less than 1 % of the total budget for the final investment.

In addition, an internal team - extended with some freelance experts - developed a third concept. After a milestone in the pre-project during the summer 2010, the number of concepts was reduced and both supplier were once again asked to develop a more detailed solution including technology, project plans, quotes and a risk analysis. The internal team continued in parallel to the two suppliers and their contracted experts. In the end of the pre-project, all three concepts and the associated projects were evaluated and an investment proposal was prepared for the board.

In the final proposal the ideas, budgets and time tables from all three reports were analyzed and to some extent merged. The final report before the investment decision gave the project team a solid ground for the implementation project and many questions were deeply penetrated - especially costs, technical solutions, risks and time tables for the installation.

For the Stockholm plant the investment decision came in December 2010 and the contract with KBA for a 96 page, 90 000 cph Commander CT was signed in January 2011. Instead of replacing all three old press lines in the Stockholm plant, it was decided to keep one old press line for a limited number of years. This means that two old press lines was replaced by the new press. The main reason for this, was the uncertain newspaper market and the risks to invest in too much production capacity. The Malmö-decision came a few months later.

The pre-project result contained a master plan showing how to stay in the same press halls and install the new presses on the same press tables and just a few meters away from an ongoing daily production. During 2011-2012 BPG have installed two new highly automated newspaper presses - one at each site.

In addition, a completely new solution for the internal paper logistics, new CTP-lines, a new prepress workflow system and production management software for copy counting have been installed. The guide lines for each project contained the following statements:

1. Installation of six printing towers and reel stands.
2. Installation of a 2:5:5-folder and a separate quarter folder.
3. Installation of a new system for internal reel logistics.
4. Installation/modification of system interfaces related to supply processes and IT-systems such as prepress, mailroom, material handling and system for order administration.
5. Installation of new CTP equipment including punch and bend and plate sorters.
6. Installation of pickup-stations and gripper-conveyors into the mailroom.
7. Necessary construction work and modification of cooling, heating, air condition etc.
8. Development of new working procedures suitable for the new situation.
9. Training and re-organized routines and workflows.
10. Retrofit of the working environment in terms of furniture and interior.
11. Dismantling and scrapping of the old printing presses.

Each installation project started with modifications of the old manroland presses. Initially, some mechanical and control system modifications were made in order to manage the product specification despite a reduction from ten to seven printing units. The next step was dismantling of three units in the old presses. There was also a need for a process supply preparation for the new press including installation of a power supply and preparation for parallel feeding of ink, water, cooling and electricity to the old and the new press.

After dismantling and bringing out three old units there was enough space to install four new compact towers and a folder - enabling printing of 64 page tabloid product with full color in straight run. The installation and commission of this first section of each press took roughly four months and in parallel to this work the production went on as usual in the old presses next to the preparation work.

The first month after go-live the production runs were managed in parallel in the old and the new press in order have a backup-solution. When the new 64 page press preformed stable enough and some pre-defined productivity figures were met, the old presses was finally closed. It took a three weeks longer than planned to reach this stability.

The second installation phase included two more printing units and the print capacity was increased from 64 to 96 tabloid pages. Additional towers in the old press were dismantled in order to create space for the new printing units. This was followed by installation and commissioning work and this complete second stage took three months to finish. The final installation and commissioning phase was followed by a very long period with daily production in parallel to fine tuning of parameter settings in the press control system, mechanical fine tuning of the printing press and implementation of new working procedures and training activities.

The overall result was that the initial time table was managed with a few exceptions:

- A strike at one of the factories manufacturing parts to the new press delayed the project five weeks already from the start. This could not have been predicted during the planning phase.
- A second minor delay occurred after the go-live. The time needed to reach the target productivity figures for the new press could not be managed within the planned two weeks. Instead five week was needed in order to reach enough stability. The planned short start-up period was questioned by BPG during the planning phase, but the supplier insisted that this the planned time was enough. The reality showed that five weeks was needed.
- The largest delay is related to the final acceptance of the presses at both sites. Most critical milestones during the project were met, but in order to get final acceptance a number of productivity and stability related targets should be achieved. The presses have produced every day since go-live, but to reach the productivity figures has been a tough challenge for the supplier. Especially key figures related to up-time (error free production time) and press speed when printing high pagination has been given a lot of attention.

In the end, the overall time table in which the project should be ended during 2012 was managed and in general the planned productions have been managed in the new presses. A majority of all planned project activities were finished in conjunction with the key mile stones in the master plan. But, stability and productivity issues resulted in a rest-list and a rest-project followed during the first half of 2013. The total cost was within the budget plan settled already in the end of the pre-project prior to the investment decision.

4. Discussion

The CODSIN-method developed resulted in a very strong knowledge-base with professional experts that all together focused on solving a complex task given some basic input about the present business and expected future development. In this kind of large scale, big budget projects, the cost for this kind of pre-project activity is rather small compared to the total budget.

In the tough economic climate after 2008 it was rather easy to find skilled professional experts and hungry suppliers willing to put in a lot of their own time and money in order to get a big printing press contract. In a strong or even normal economy it might be harder to obtain such strong teams without much higher costs.

Compared to recent large scale green field print sites about 50 % of the investment sum could be saved. The method used minimized the need for non-productive investments, but still around 50 million Euro has been invested at the two sites. In this case is difficult to see any other alternatives and to do nothing at all was a great risk. The cost structure in the old presses could not met the market and resulted in high production costs for the internal customers due to manning, large buildings and high waste figures. Due to the investment and the reduction in space needed in Akalla, the building itself could be sold and a large share of it will be used for other purposes in the future.

A lesson learned in this project is that all kind of new technology must be either validated through real live installations and real data or considered as non-validated and given extra time in the project plan. The main technical problem areas this project dealt with were a new control system generation and a non-proven combination of folder, pagination and press speed. Even more time should have been spent on verifying the technology during the pre-project phase. Despite the carefully worked pre-study and pre-project there was a lack of awareness from BPG that part of the installation contained new solutions not tested nor proven under the circumstances they were supposed to manage in the BPG business. But, two years after the investment decisions the two plants are more or less fully operational with all the new equipment and systems in place, and this has happed without too much pain for neither the customers nor the organizations.

5. Conclusions

In this case study the competition from new media is managed through cost reduction in terms of modernization and productivity enhancement in two printing plants studied. Modern equipment have been installed at the same time as the project budgets were be kept at a minimum in order to avoid future fixed capital costs in a decreasing market. To achieve this, a key factor was to re-use the buildings and thereby reduce the size of the investment by approximately 40-50 % in comparison with a green field solution.

Instead of investing a significant amount in new buildings all focus was on highly automated process equipment, training and process development. Around 50 million Euro has been invested at the two print sites and less than 10 % of the budget was spend on building related costs and construction work. The project was started already in 2008 after a long planning phase and careful evaluation of a number of different alternatives. The decisions to go for new printing presses in the old buildings were taken late 2010 (Akalla) and early 2011 (Malmö).

The two new 96 page and 90 000 copies per hour KBA Commander CT presses have been installed during full production during 2011-2012. A key factor to the success of the project is the project methods used. The investment decision was carefully planned and almost three years was spent on pre-studies and pre-projects in order to identify suitable equipment based on the expected market conditions, evaluate different alternateves regarding where and how to install the printing presses in parallel to the daily business and last but not least identification of risks and costs for the project.

An important factor in the project has been the CODSIN-method developed in the project. The fundamentals of CODSIN has been to create a framework explaining the preconditions for the future situation and let expertise in terms of suppliers with the potential to win the printing press contract, compete in order to design the technical solutions, project plans and associated costs and risks. In parallel to the machine suppliers an expert group made a similar solution and in the end the different proposals were compared and the best ideas were put together in order to secure that nothing or very little was foreseen.

Most deadlines and project objectives have then been met according to the initial project definition with a few exceptions - mainly related to the new control systems including software and parameter settings. There is still an open items list with minor problems that needs to be fixed. This means that the final deadline for closing the project could not be met, but the presses have been used in daily production more or less according to a revised project plan worked out during the spring 2010.

In terms of budget issues the budget developed after the pre-study have been carefully observed on a monthly basis and there has been no need for additional funding after the initial board decision. The forecast is that the annual costs in the two plants will be reduced by more than 20 % from 2015 with equivalent volumes and the pay-off for 15 year investment wills be less than 5 years.

Acknowledgements

This paper is a result of the a co-operation between the Bonnier Group and KTH Royal Institute of Technology. Over the last couple of years both organizations have shown a willingness and made efforts to let the academia and the industry exchange knowledge, ideas and resources. A special thank to Leif Wiklund, now a retired former CEO of BPG, who first hired me and in addition was positive to the KTH co-operation.

The project work itself has been a hard fight that lasted almost five years - that is a long period for a project. With huge efforts from colleagues, suppliers, different specialists and with strong support from owners and boards this impossible project became real and even successful. Thank you all! Last but definitely not least, I would like thank my family for their patience and support throughout these five years.

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Potential cost reductions driven by management tools at a packaging printer

Csaba Horváth, Zoltán Vandra, Rozália Szentgyörgyvölgyi

Óbuda University
Rejtő Sándor Faculty of Light Industry and Environmental Engineering
Institute of Media Technology
and Light Industry Engineering
Doberdó u. 6, H-1034 Budapest, Hungary

E-mails: horvath.csaba@rkk.uni-obuda.hu; vandrazo@gmail.com;
szentgyorgyvolgyi.rozsa@rkk.uni-obuda.hu

Abstract

Amidst the circumstances of sharp global competition in recent years, an increasing number of companies have found interest in lean management in the hope of gaining a substantial competitive edge. It has become evident that the procurement of the most novel production equipment alone would not make a company successful. Beyond state-of-the-art production machinery, another source of advantage in competition can be a value-adding process of manufacturing that focuses on customer demands as a basis of lean management. Experience shows that the competitiveness of companies applying lean management is on the rise because of the smaller costs, more productive labour, shorter lead times and higher quality.

The objective of the research has been to support the introduction of lean management and the use of modern printing technologies by assessing the loss-making constituents of AR Carton Packaging Group's printing processes, offering solutions to mitigate or fully eliminate these impacts, as well as confirming the actual implementation of cost reduction.

In their studies, the author have focused on promoting the introduction of the already initiated lean attitude by bettering the technological processes of printing in order to make perceivable achievements. In this manner, the interrelated projects have reinforced each other, and brought about the foreseen results. The optimal corrective actions have been determined with a step-by-step review of the technological aspects of the printing process.

Keywords: lean management, packaging printing, setup reduction

1. Introduction

The ultimate goal of all business activities is value creation. Value creation is a process that yields a product or service for which a customer is willing to pay. However, in the process of value creation there are active-ties not representing any value. Although they are parts of the process, it does not mean that the customer is pleased to expend money on them.

Lean Manufacturing is a philosophy of production that has a focus on rationalizing and optimizing value-adding processes, circumventing and eliminating potential losses. It puts a production system in place that allows the making of high-quality products at moderate costs and with short lead times. The aim is to align the process of production with the expectations of the customer. Consumers tend to demand increasingly better quality, lower prices, short lead times and a broader selection of products. Developed by Toyota, the efficiency of Lean Manufacturing is inherent in the underlying principles its rules, means and philosophy operate in harmony in order to eliminate losses from the processes.

2. Objectives of the research

The fundamental hypothesis of this thesis is that Lean Principles are value-centered, and facilitate the elimination of losses. In our case, a graphic enterprise can considerably improve the efficiency of the printing process (from the customer to the prints) with the application of Lean Manufacturing, promoting an increase in the profit. Our objective is to examine the losses incurred with the printing processes of cardboard packaging materials by the company under review, and investigate how the application of the means of Lean Manufacturing can cut back or fully eliminate the revealed losses. In addition to looking at the printing process, we also want to know what impacts these changes may have on the reduction of costs.

The objective of this thesis has been to support the introduction of lean management and the use of modern printing technologies by assessing the loss-making constituents of AR Carton Packaging Group's printing processes, offering solutions to mitigate or fully eliminate these impacts, as well as confirming the actual implementation of cost reduction, continuing our research job published in last Iarigai conference.

3. Lean printing

In the printing process, the value for a customer is the creation, reproduction of the conceived design, colour, while for the printer the satisfaction of these demands in a cost-efficient manner. For the customer, the essential aspects are the colour, form and deadline of delivery, whereas for the printer the keys to profit lie in the short adjustment time and quick printing of the requested number of useful copies. In the printing process, the Lean Philosophy is embodied in the efficient and inexpensive satisfaction of customer expectations. The specific working process of Lean Manufacturing and the printing technology should work together effectively. It means that Lean proves to be insufficient if the management of the printing technology fails, while without the lean component even the best technology will be less effective. They together provide the best environment for the operation of a competitive printer.

4. Research methods

Procedure and methodological approach:

- analysis of the principles, means of Lean Manufacturing,
- study of the values, losses of the printing process,
- determination of the measures to improve efficiency, actual steps to accomplish the objective
- implementation of the enhancement of efficiency, explanation of results.

The aim of our research is to rely on certain technical processes and printing technologies in combination with the lean methods towards the improvement of the efficiency of the printing process, and thus to reduce costs at AR Carton Packaging Group. As specific aspects of these examinations, those means of lean, operating safety and printing technology have been selected that have the potential to improve the efficiency of the process to the farthest extent, eliminate or minimize losses.

5. Establishment of orderly work conditions, effective base material flow

In order to make the working environment of the printing presses more orderly and safer, 5S was applied. The objective was to establish an efficient, safe and high-standard work environment. Whatever was not needed for the performance of daily tasks in the printing press was sorted out and removed. After this process of selection, it was re-considered whether such materials and devices had been retained in the work area that were integral parts of daily work, and if their quantities had indeed been effectively cut back. For the required tools, expedient storage places were accurately defined and created, while other objects were stored in an easily recognizable arrangement. As a fundamental rule, objects, base materials that were necessary for adjustment or production were placed so that they should become accessible in the quickest and shortest way.

Figure 1:
Surroundings of the KBA Rapida 142 sheet-fed offset press

Figure 1 demonstrates the working environment of the KBA Rapida 142 sheet-fed offset printing press. Following the completion of the 5S process, only the necessary tools remained in the work area, in ergonomic, visually recognizable arrangement.

The established system was designed to sustain and develop the existing work environment. With the use of a questionnaire, the surroundings of the printing press are now reviewed on a monthly basis. The questions are scored in order to quantify the existing conditions, whether they are perceived as improvement and/or regression.

Beside the work environment of the printing press, the 5S method was also applied to the base material flow of the manufacturing process. The existing material flow was assessed and visualized as shown in *Figure 2*.

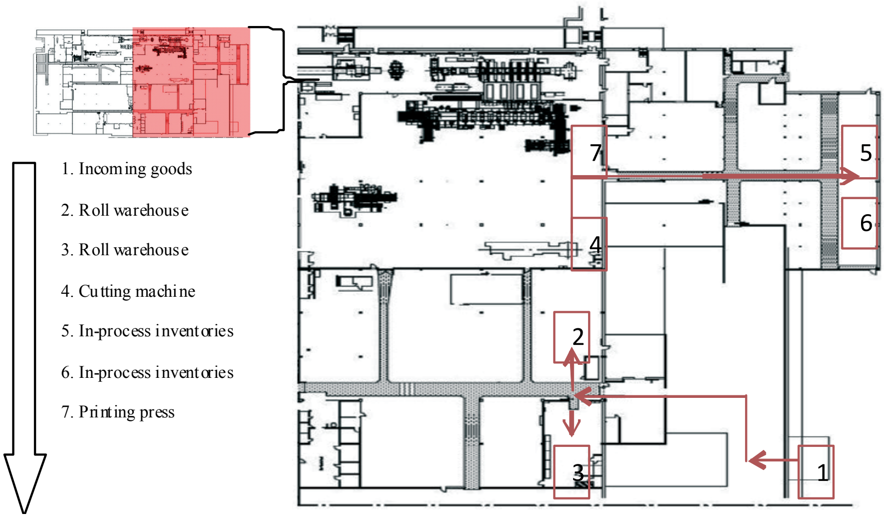

Figure 2: Unoptimized material flow

Having reviewed the given material flow for print carriers, we had to admit that neither the location of the in-process inventories, nor the place of the roll warehouse was optimal. The movement of print carriers demanded considerable time and energies due to the considerable distances. The base materials were not available where they were actually needed.

Owing to the new arrangement, the distance between the printing press and in-process inventories was reduced from 100 meters to 20 meters.

Therefore, the base material can now be carried to the printing press in a shorter while, with smaller loss from the operators' time. The achieved time saving can be utilized to perform other operations on the printing press.

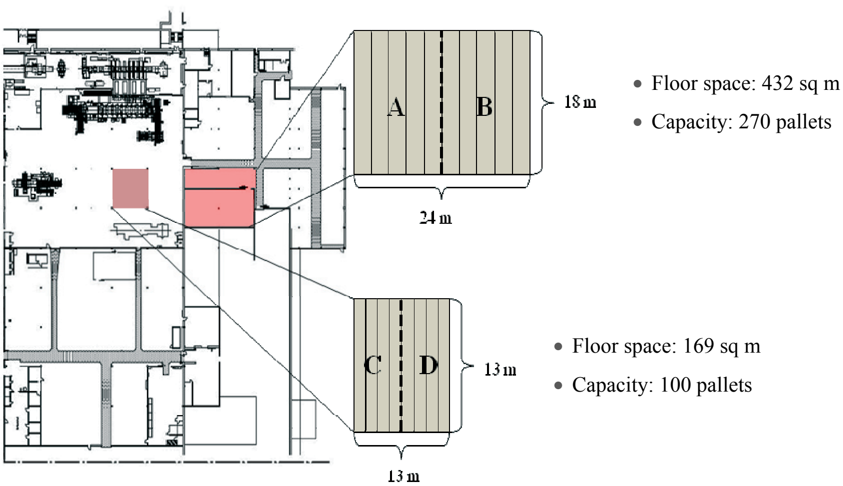

Figure 3: Optimized material flow

6. Improvement of the reliability of the printing press

As within the plant no sufficient expertise is available, the maintenance and servicing of the KBA Rapida 142 sheet-fed offset printing press were outsourced to the supplier of the printing press. In detailed consultations and negotiations, the terms and conditions of maintenance and repair servicing activities were defined and set forth in the form of a contract. The partner program implemented in the framework of the given con-tract was aimed at reducing the time losses arising from machine failures, and guaranteeing an appropriate level of operating safety. The contract consisted of three modules. The first module was designed to ensure the monthly servicing of problems with the machines to maintain the initial conditions of the equipment, and sustain the perfect operation of all the functions of the printing press. The second module allowed remote servicing all around the clock. The last module covered the assessment of the prevailing conditions of the machines on a half-yearly basis. The printing press was not set to be inspected solely for mechanical problems, but diagnostic test printing was required to be executed. The defined checks included the printing characteristics, reproduction capabilities of the press, as well.

7. Colour calibration of the printing press

The aim of the colour calibration process was to define, and then standardize the technological parameters of the devices used in the printing process (sheet-fed offset printing press, subcontracted colour proofing) on the basis of the test prints. The parameters determined in the course of test printing (CIE L*a*b*colour space, tone value increase) were examined on the basis of the target values set by Standard ISO 12647-2. After the drying of the prints, the tone value increase of the printing press was determined from the average of the measurement results of several prints. On the basis of the measured values, the tone value projected on the form was modified so that in the course of printing the tone value increased by the printing press in the print should comply with the value specified in Standard ISO 12647-2.

Calibration was also performed for the subcontracted proofing, i.e. the inkjet printer. The effectiveness of calibration was verified by making the test print again.

In addition to instrumental evaluation, prints were subjected to visual checks, because the majority of customers would judge the colour spectrums of printed products in the same way. The prints of the plates that had been scanned with the settings originating from the process calibrations were compared with the similarly calibrated, subcontracted colour proofs, and eventually it was concluded that the calibration was successful.

In the course of digital pre-processing, appropriate colour separations could be made for printing. The two work processes became harmonized, and - as a very important aspect - mutually verifiable. The roots of problems now proved to be distinguishable, and the efficiency of the process bettered. The settings of printing became unambiguous, individual, occasional adjustments in the machine room could be avoided, reproducibility hugely improved.

8. Summary of results

In our studies, we have focused on promoting the introduction of the already initiated lean attitude by improving the technological processes of printing in order to make perceivable achievements. In this manner, the interrelated projects have reinforced each other, and brought about the foreseen results. The optimal corrective actions have been determined with a step-by-step review of the technological aspects of the printing process. The performance indicators suggest whether changes have taken an appropriate direction. The tasks described in association with the objective of the research have been executed in three groups.

The 5S practices that have already been introduced to the operations concerned have been perfected on the KBA Rapida 142 printing press. In line with the expectations, as a result of the optimization of the material flow the idle time of the printing press has been considerably reduced.

By adapting new maintenance practices, the operating safety of the printing press has been enhanced. A maintenance system applying a more efficient strategy has been set up to make the manufacturer of the printing press responsible for sustaining the required technical conditions of the machine. With the use of this developed system, maintenance planning has become feasible, while frequent machine failures can be avoided.

By reconciling printing press and prepress processes, a major step has been taken towards the acceleration of machine changeover. By completing the calibration process, the number of cancelled prints to be adjusted has been decreased by 39 %, while the desired design colours can be implemented more quickly.

With the application of the SMED device, the time demand of machine changeovers could be cut. In practice, the solution was implemented on the KBA Rapida 142 printing press. The time demand of changeovers dropped by 45 % when the standard operating procedures were introduced.

The results of the actual implementation of the measures taken for the improvement of productivity as described in the discussion part of the research are demonstrated in *Table 1*. The table shows the performance indicators of the KBA Rapida 142 printing press before and after the adaptation of the corrective measures.

Table 1: Performance indicators of KBA 142 sheet-fed offset printing press in 2009 and 2012

Performance indicators	**Production figures in 2009**	**Production figures in 2012**
Operating time (hours p.a.)	3913	5057
Setup time (hours p.a.)	717	1126
Idle time (hours p.a.)	1764	1187
Production time (hours p.a.)	1432	2762
Idle time (%)	43.8	23.4
Average setup time (h)	1.39	0.64
Number of setups	515	1754
Average number of make ready (sheets/job)	277	169
Number of make ready (sheets p.a.)	142,597	296,426
Number of waste sheets during the printing (p.a.)	477,182	198,015
Total number of waste sheets (sheets p.a.)	619,779	494,596
Total number of waste sheets (%)	4.5	1.8
Average printing speed (sheets/h)	9100	9920
Average number of print runs	25,308	15,614
Number of prints (sheets p.a.)	*13,654,621*	*27,890,000*

It can be claimed that the primarily examined key performance indicators have been substantially improved by the corrective measures. On the other hand, it can be also confirmed that the enhancement of production efficiency is accompanied by cost reduction. The average duration of idle times has fallen from 43.8 % to 23.4 %. This newly recovered, additional time offers free capacity for the manufacturing of further products, real and profitability operations.

8. Conclusions

The handling of the means of lean management and the development of the processes of printing technology with a common approach has clearly visible and measurable outcomes. In consequence, it can be claimed that the application of lean methods with proper view of industrial characteristics, i.e. "lean printing" is a truly useful tool. Without a thorough knowledge of the technology, the means of lean management may be successfully applicable, though cannot be vehicles of a breakthrough.

The ways of practical use described in my thesis unequivocally underline this statement. Both cost reduction and the enhancement of production efficiency can be continued. It is a never-ending process. There will always be new losses occurring, and they can eliminated from the process to drive further improvement.

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Investigation of vibrations of printing unit of sheetfed offset printing press and their influence on streaking phenomenon

Juliusz Krzyżkowski and Yuriy Pyryev

Warsaw University of Technology
Institute of Mechanics and Printing
Division of Graphic Arts Technology
Konwiktorska 2, PL-00217 Warszawa, Poland

E-mail: y.pyryev@wip.pw.edu.pl

Abstract

The scope of experiment presented in this paper was to analyse correlation between vibrations of printing unit's elements and tone value fluctuations, which are revealed on the print in a form of streaking phenomenon. There was assumed that it is possible to find sources of certain stripes on the prints. In researches plate, blanket and impression cylinder as well as plate inking rollers were taken into account.

In the experiment standard machinery diagnostics methodology, based on accelerometers as vibration detectors, was used. Simple analysis of the signals in time domain was carried out and results were compared to printed test images. The carried out analyses showed, that there is visible correlation between vibrations of investigated printing unit's elements and undesirable changes on the print.

Preliminary results of experiment presented in this paper show, that it is possible to implement used methodology to realize scopes of the work.

Keywords: vibrations, streaking, offset printing press

1. Introduction

Streaking is a very common problem in offset printing technique. It appears on the prints in a form of stripes parallel to the cylinders' axes. Streaking is especially noticeable on areas, which are evenly covered with the ink, i.e. tints and full tones.

There are many reasons of this phenomenon. Some users of offset printing presses claim, that streaking may be caused by such ordinary issues as dirt in inking unit (glaze on inking rollers), improper parameters of ink or dampening solution as well as by using supplies, which are not in accordance with guidelines of printing press's manufacturer (e.g. to high hardness of inking rollers). Improper settings of contact pressure between plate and blanket cylinders as well as between plate cylinder and plate inking rollers may also be the source of streaking. All reasons mentioned above, when detected, are relatively easy to solve. However, streaking may be also associated with construction of printing unit and its technical condition (Kulikov, 2008). In the first case, some publications blame so called, cylinder gap shock (CGS), for causing streaks on the prints.

CGS is a sudden impact, which occurs between plate and blanket cylinder (Kipphan, 2001; Gao, 2001). It is generated when edges of canals, situated on both cylinders, hit each other and excite vibrations. CGS may cause disturbance of ink transfer between cylinders (Pyryev, 2012) and between plate cylinder and inking rollers as well. These disturbances may be visible on prints as parallel stripes.

In the second case, for the main origin of streaks is considered wear of bearings and gears (hence streaking is often called "gear streaking" (Destree, 2007)), what also may be the reason of excessive vibrations in printing unit.

However, printing presses are very complicated systems, where intensive vibrations are natural phenomena, not always related to poor technical condition of the machine. Hence the cylinder gap shock should not be considered as the only source of vibrations associated with construction of printing unit, which cause streaks on prints.

It seems to be important to verify, what are main sources of vibrations in printing unit and what role they play in creation of streaks on the prints.

The aim of the researches presented in this paper was to analyse relation between vibrations, which occur in offset printing unit of sheetfed offset press and their influence on intensity and pattern of streaking phenomenon.

2. Method

Measurements of vibrations were carried out on Romayor 314 printing press. Printing unit of that machine has relatively simple construction and, what is very seldom nowadays, its plate and blanket cylinders do not have cylinder bearers (also known as bearer rings), what additionally increase vibrations. In measurements plate, blanket and impression cylinders as well as plate inking rollers were taken under consideration. Their parameters are presented in Table 1.

Table 1: Parameters of Romayor 314 printing press

Parameter name		**Description / Value**
Cylinders	plate	Diameter: 176 [mm]
	blanket	
	impression	
Plate inking rollers	Roller I	Diameter: 62 [mm]
	Roller II	Diameter:54 [mm]
	Roller III	Diameter:50 [mm]
Blanket		compressible, for sheetfed printing

Vibration measurements were performed in two machine conditions. The first one was standard machine work with all units enabled, the second one was carried out with disabled feeder and delivery unit (drive transmission chains and grippers were removed). In the latter case making the print was impossible, but printing conditions were simulated, i.e. to hold printing pressure paper sheet was glued to impression cylinder, inking and dampening units were set as if printing was performed.

Measurements were carried out with accelerometers in vertical or radial direction (Fig. 1.), respectively for cylinders and plate inking rollers. Transducers were mounted on bearing boxes of machine operator side.

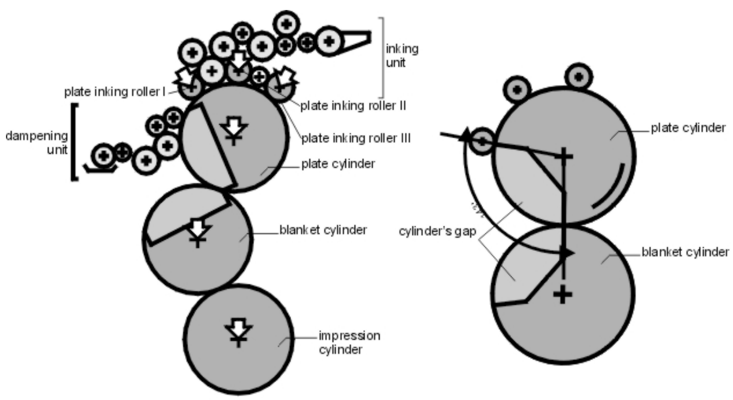

Figure 1: Printing unit of Romayor 314 printing press and transducers placement (white arrows), at the right plate and blanket cylinders with the gaps marked

This attitude to vibrations measurements is commonly used in diagnostics of rotating machinery. Although results obtained in that way do not give direct and precise information about displacements of cylinders and rollers, they indicate disturbances, that occur in bearings, what in result may also affect on work of aforementioned elements.

Simultaneously to vibrations measurements, the test image was being printed. Test image were prepared according to BVDM methodology (BVDM, 1996), but enriched with full tone patches. Parameters of test image are presented in Table 2.

Printing was performed with three different speeds: minimal possible, 50 % of maximal printing speed and 80 % of maximal printing speed.

Table 2: Parameters of test image

Parameter name	Description/ Value
Tone value	70 %
Screen dot	Round
Screen angle	0°
Screen frequency	150lpi
Ink	

Prints were made on coated paper, which parameters were assumed to be possibly similar to those of group 1 of standard ISO 12647-2. In research cyan ink was used. Inking was set, so the colour coordinates of full tone patches were as close as it possible to satisfy ISO 12647-2 standard.

Printed test images were scanned. Paper sheet was situated in the scanner in a way so streaks were perpendicular to scanning beam. In that manner scanning errors caused by possible beam's driving system irregularity can be avoided.

According to Kotelnikov-Shannon theorem, resolution of scanning was twice as big as screen frequency, i.e. 300 dpi. In that way digitalized prints in a form of matrix of pixels were obtained. Such matrix could have been very precisely analysed. From the whole printed area, narrow stripe (submatrix of pixels) was chosen. The width of this stripe was at least 150 screen rulings and the length was equal to the length of the test image. This ensured, that ink layer across analysed area is equally distributed and fluctations of ink layer along this area are emphasised and not disturbed by any other printing errors.

In the next step, tone values of pixels in accordance with ISO 12647-1 were calculated. Afterwards tone values were averaged across the chosen submatrix. The product of described procedures was vector of tone values along paper sheet. To eliminate small, unreasonable disturbances in tone values, the second averaging along the vector was carried out. Tone values of every four subsequent pixels of the vector were averaged and in result it was divided into pieces of the width of about 0,3mm each. Scheme of digitalization of the prints is depicted in figure 2.

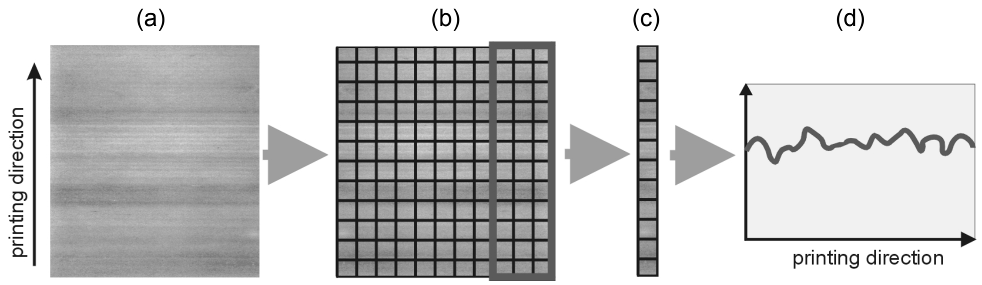

Figure 2: Procedure of digitalization of prints: (a) analogue print, (b) scanned print (matrix of pixels), (c) averaged tone values vector, (d) curve of tone values variations obtained from digital data

3. Results

In all figures presented below tone value fluctuations are shown as a function of angle of plate cylinder's revolution. It denotes the moment of printing cycle. Angle equals to 0° represents the beginning of ink transfer process between cylinders, i.e. plate and blanket or blanket and impression cylinder as well as plate inking rollers and plate cylinder. In all figures there is considered angles' spread between 0°-170°, because only such area of cylinders was covered by paper sheet. Rest of printing area could not be analysed because of scanner's size limitations.

In Figure 3 can be noticed, that most of characteristic disturbances of tone value curves occur for each of analysed printing speeds. It lets assume that there is possibility to find relation between vibrations of certain elements of printing unit and streaking phenomenon.

In figure 4 vibrations of plate cylinder have been compared to tone value curve.

Vibration signal in this and all following figures is presented as *RMS* (root mean square) curves, i.e. original signal obtained from accelerometers was converted into *RMS* by the function:

$$RMS = \frac{1}{n}\sqrt{\sum_n x_n{}^2} \qquad [1]$$

where: n - number of averaged samples,
x - amplitude of the signal.

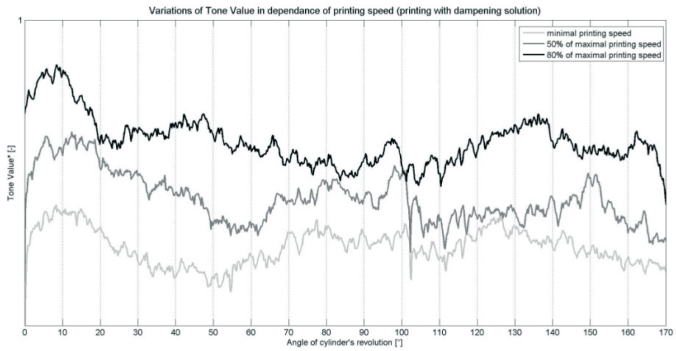

Figure 3: Variations of tone value on the prints in dependence of printing speed

As one can see in fig. 4a, there is high vibration peak caused by cylinder gap shock at the 0° angle point. There are also visible intensive vibrations up to angle of 20°, which correspond with the "hill" on the tone value curve. Such correlation is also indicated about angles 60°, 80° and 100°.

Vibrations signal obtained with disabled feeder and delivery unit (Fig. 4b) shows, that in general vibrations of the plate cylinder decreased.

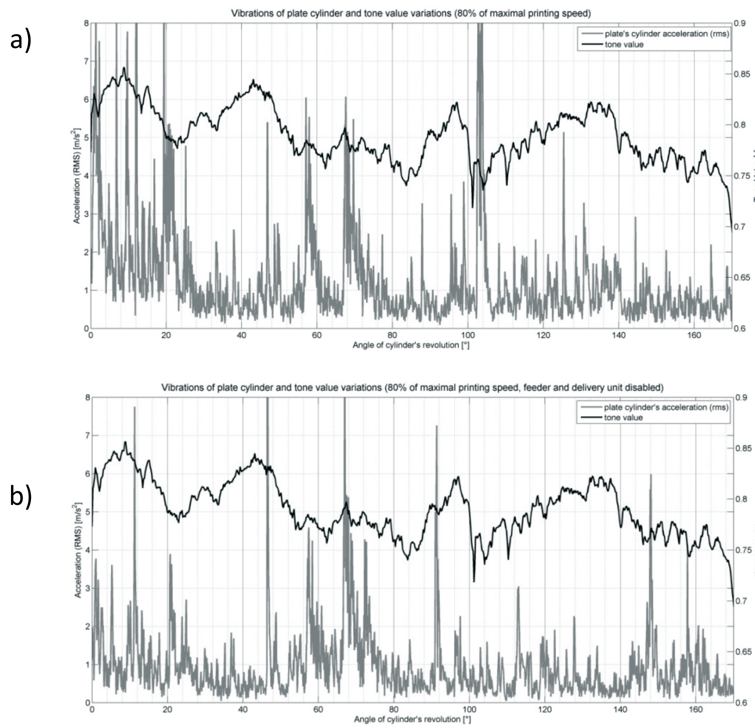

Figure 4: Vibrations of plate cylinder and tone value fluctuations on the print:
machine fully working (a) and with disabled feeder and delivery unit (b)

However, all peaks mentioned above are still intensive, what let assume that they are directly related to plate cylinder's vibrations.

Comparison of vibration curves in fig. 4a and 4b shows, that high peak at angle of 105° disappeared, what means its source was one of disabled units. Comparison of the signals obtained from transducers mounted on plate and blanket cylinders showed, that both cylinders strictly influence each other and vibrate in similar manner.

Hence all relations between vibrations of plate cylinder and tone value fluctuations (depicted in Figure 4) find their reflection in case of blanket cylinder (Figure 5).

a)

b)

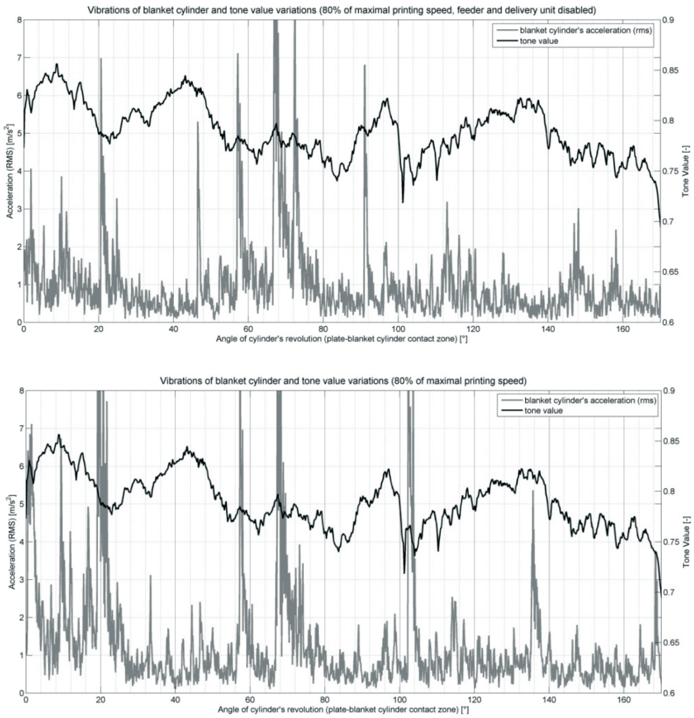

Figure 5: Vibrations of blanket cylinder and tone value fluctuations on the print: machine fully working (a) and with disabled feeder and delivery unit (b) (plate-blanket cylinder contact zone)

Vibrations of blanket cylinder at a moment of ink transfer to printing substrate (contact zone between plate and impression cylinder) are presented in Fig. 6. As one can see, there is visible correlation between blanket's cylinder oscillations and tone value fluctuations, e.g. in sections 50°-60°, 90°-100°, 130°-140°.

a)

b)

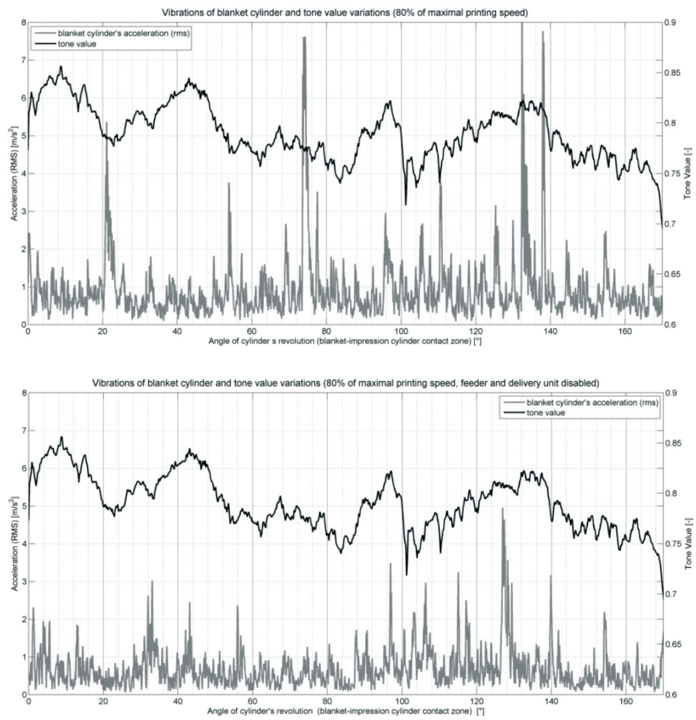

Figure 6: Vibrations of blanket cylinder and tone value fluctuations on the print: machine fully working (a) and with disabled feeder and delivery unit (b) (plate-impression cylinder contact zone)

For interests deserves peak, which occurs at point 20 ° in Fig. 6a and corresponds to peak at 140 ° point in Figure 5a. In a plate-blanket contact zone (Figure 5a) presence of this peak was correlated with a peak on the tone value curve. However, in Figure 6a it corresponds to "bottom" of that curve. It is reasonable, because increased pressure in plate-blanket contact zone causes its decrease between blanket and impression cylinder, what would explain observed tone value disturbances at aforementioned points.

Switching off feeder and delivery unit caused similar effect in case of blanket cylinder as it was noticed in plate cylinder, i.e. general decrease of vibrations and disappearance of peak at angle of 20 °.

Figure 7 presents vibrations of impression cylinder. Comparison of vibration curves depicted in figures 6a and 7a shows, that vibrations both blanket cylinder and impression cylinder are very similar, i.e. most intensive peaks recorded by transducers correspond to each other. However in the latter cylinder they have higher amplitudes, e.g. peaks nearby angles 55 °, 75 °, 135 ° and 138 °. Similarly to cylinders discussed above, here is also noticeable correlation between cylinder's vibration peaks and fluctuations of tone value curve.Turning off delivery unit and feeder resulted in decreasing of total vibrations and disappearing of some peaks, for instance, in close near of angles 55 ° and 75 °.

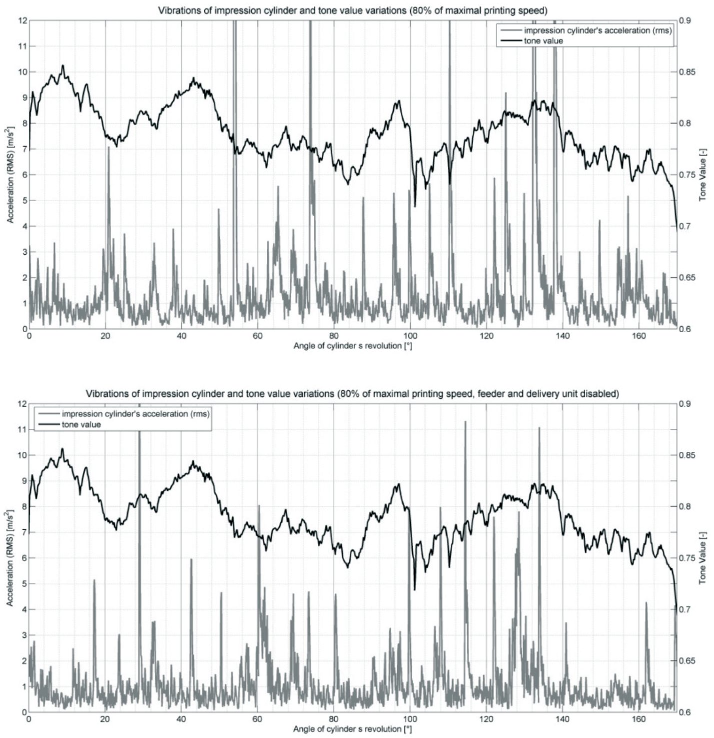

Figure 7: Vibrations of impression cylinder and tone value fluctuations on the print: machine fully working (a) and with disabled feeder and delivery unit (b)

In figures 8-10 are depicted vibrations of plate inking rollers. In these figures point 0 ° represents moment, when the edge of the plate cylinder's gap hits each inking roller. Starting from this point, roller is in contact with plate cylinder and it stays in it till the next meeting with the cylinder's gap. Figure 8 presents vibrations of plate inking roller I. Analysing trends of vibration curve, one can see that in some areas, excessive vibrations of the roller correlate with variations of tone value on the print, e.g. area of the first 25 °, area between 40 °-50 ° corresponds to "hills" of tone value, however, observed correlation is rather weak. Different situation is close to 0 °, where very intensive vibrations caused, most probably, by impact of cylinder's gap clearly correspond to peak of tone value curve. In case of inking roller II (fig. 9) correlation between vibrations and tone value curve is more significant. Next to characteristic peak at 0 °, which is related to hit of cylinder's gap, there are also noticeable trends in vibration curve, which correspond to run of tone value curve, e.g. between 40 ° and 60 °. In general vibrations of roller II are more intensive than the inking roller I. Figure 10 presents vibrations of plate inking roller III. It is distinctly noticeable that oscillations of this roller are most intensive. However, there is not visible peak related to impact of cylinder's edge. Correlation between vibrations and ink layer on the print is noticeable, for instance near angle 20 °, between angles 80 °-90 ° and 100 °-110 °. For inking roller II and III very important is an angle, respectively, 160 ° and 115 °, because at this moment cylinders gap shock takes place and excite vibrations in plate and blanket cylinder. As one can see, these vibrations affect on rollers II and III, because high peaks are noticeable then. For inking roller II in Figure 9a and for inking roller III in Figure. 10b.

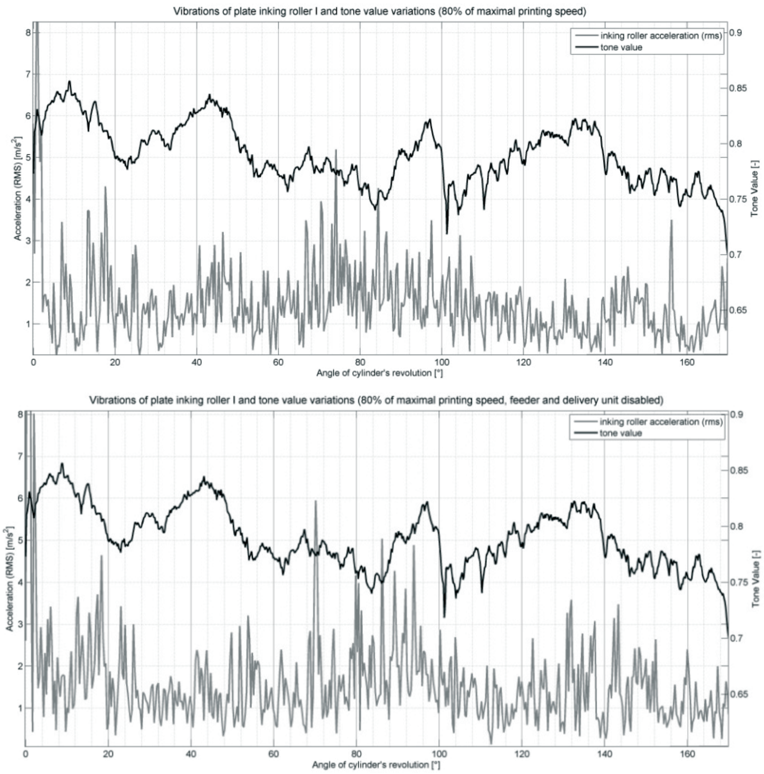

Figure 8: Vibrations of plate inking roller I: machine fully working (a) and machine with disabled feeder and delivery unit (b)

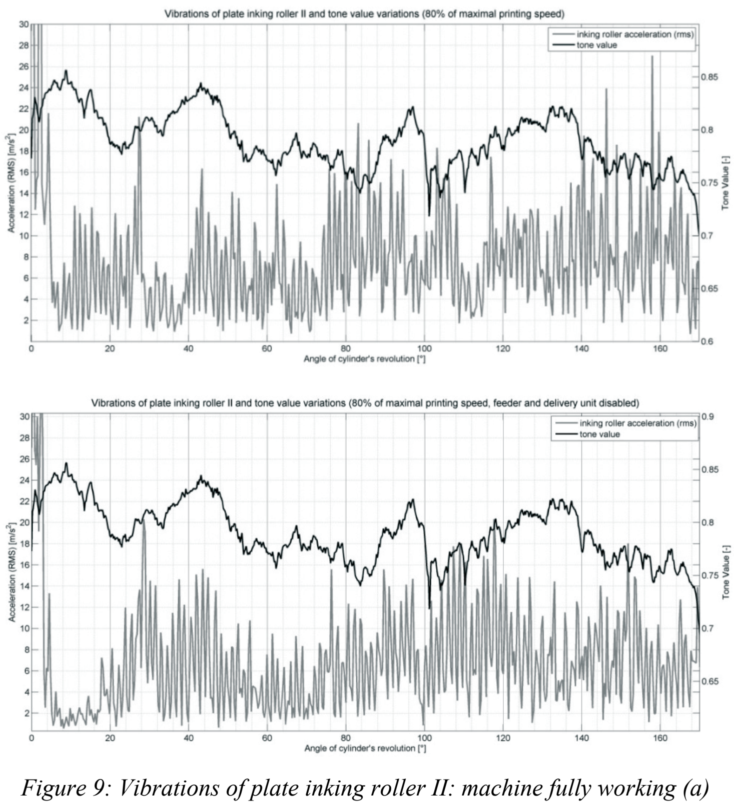

Figure 9: Vibrations of plate inking roller II: machine fully working (a) and machine with disabled feeder and delivery unit (b)

Comparison of vibrations of all rollers (Figures 8a, 9a, 10a) shows that intensity of rollers oscillations are the more intensive the closer of ink fountain they are.

Influence of feeder and delivery unit is not so significant in case of inking rollers at it was observed in case of cylinders.

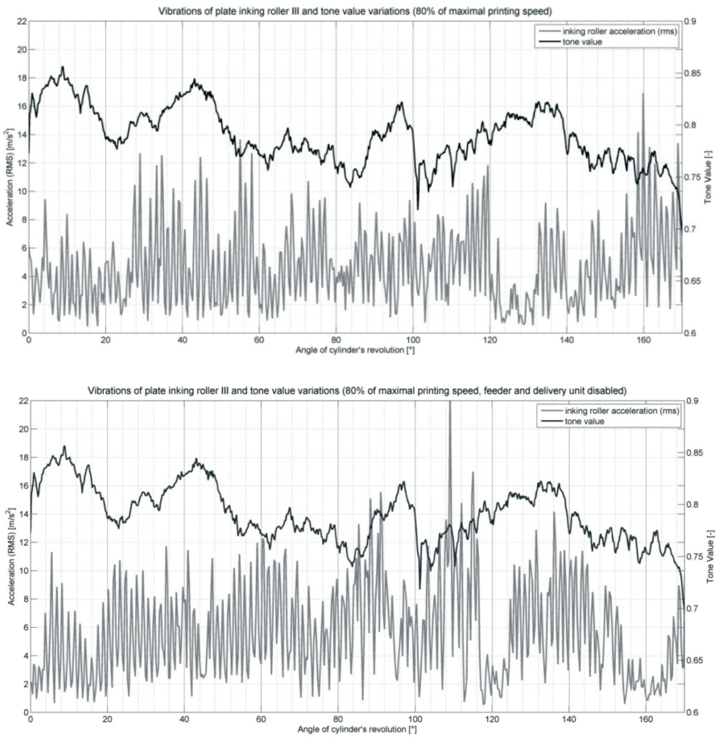

Figure 10: Vibrations of plate inking roller III: machine fully working (a) and machine with disabled feeder and delivery unit (b)

4. Discussion

Experiment showed that it is possible to implement methodology used for machines diagnostic to find relations between vibrations and undesirable changes on the prints. However, it has some inconvenients, i.e. this methodology of vibration analyses sometimes may be misleading, because high accelerations may not mean high displacements, especially in case of heavy bodies, such as cylinders. *RMS* indicator used to signal analyses gives information about energy of the signal, what is more convenient and legible way to present disturbances occurring in the system than the "raw" signal obtained directly from transducers, but it causes loose of information about direction of acceleration, what would be helpful in carried out analyses (by an assumption, that acceleration and displacement have the same direction).

Carried out analysis showed, that vibrations of plate inking rollers influence more on general shape of tone value curve, i.e. their affect is visible on wide spread of angles. In most cases it is difficult to find peaks on rollers' vibration curves, which exactly correspond to peaks on tone value curve.

It presents completely different in case of cylinders, where general trends of vibration curve are not correlated with fluctuations of tone value, but on the other hand there are noticeable certain peaks, which correlate with sudden, occurring at narrow angles, intensive changes of tone value. However, there should be made an analysis of marks created by inking unit on the printing plate, so possible stripes related to construction of inking unit (not its vibrations) would be ignored in later analyses.

Vibrations of cylinders decreased and some of the peaks disappeared from their signal, when feeder and delivery unit was disabled. It means that vibrations of these two units of the machine may also have influence on quality of the print. It was not noticed, that feeder and delivery unit have serious influence on plate inking rollers vibrations.

5. Conclusions

Preliminary results of performed experiment showed that there is correlation between vibrations of printing unit's elements and amounts of ink transferred to the substrate. Vibrations of inking roller suggest that they are responsible for general character of tone value curve, but oscillations of cylinders correspond to narrow-angled, sudden disturbances of tone value. In the future precise analysis of cycles of machine's mechanisms should be carried out to verify which printing unit's elements can be responsible for which vibration and tone value peaks. However, this task may be very difficult to realise, because as present results shows, elements of printing unit significantly influence each other (plate and blanket cylinder, for instance) and distinction of the peaks' sources may be in some circumstance imprecise.

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Optimization of the quantity of two-component primary lacquer to be applied to the gravure printing technology

Rozalia Szentgyörgyvölgyi[1], *Erzsebet Novotny*[2], *Csaba Horváth*[1]

[1] Óbuda University, Rejtő Sándor Faculty of Light Industry and Environmental Engineering
Insitute of Media Technology
Doberdó u. 6, H-1034 Budapest, Hungary
E-mails: szentgyorgyvolgyi.rozsa@rkk.uni-obuda.hu; horvath.csaba@rkk.uni-obuda.hu

[2] ANY Security Printing Company
Halom u. 5, H-1102 Budapest, Hungary
E-mail: novotny@any.hu

Abstract

In addition to the realization of high-quality prints, gravure printing technology offers broad-ranging options for the development of such engraving parameters for the printing block that are suitable for reducing the prime costs of the finished product. One group of the base materials in food packaging is constituted by metallized laminated films whose surface printing is recommended to be performed with the use of appropriate primary lacquers. The quantity of primary lacquer applied in the course of gravure printing is primarily determined by the characteristics of the screen structure of the gravure cylinder, and the volume of the applied lacquer is also influenced by the properties of the lacquer and the speed of the gravure printing machine.

For our studies, we examined and compared eight different screen structures with the screen structure that was specified and used in practice. When determining the parameters of the printing cylinder, the primary goal was to develop a screen structure that could be used to reduce the quantity of the applied primary lacquer in comparison with the original standard design. In the samples made with test printing, the authors studied the quantity of the applied lacquer and abrasion resistance of the applied lacquer and cover white ink with reliance on microscopic images.

Keywords: primary lacquer, metallized film, gravure printing

1. Introduction

Gravure printing is a high-speed printing process based on rotary (roll-to-roll) technology. It is used in three essential market areas: publication, packaging and specialty printing. Gravure printing is a simple printing technology featuring outstanding quality and high consistency even in large print runs. While for many years publication printing struggles with the changes of the market structure caused by the internet, the production of packaging materials produced with gravure printing flourishes. This growth is all the more surprising as only a few years ago gravure printed packaging manufacturing was stagnant and flexography seemed to be more flexible and cost-effective. Taking a look at the proportion of different printing technologies used for producing flexible packaging materials it is obvious that gravure printing is in an excellent position. Gravure and flexo printing have identical market share in this important segment in Europe and gravure printing is clearly a leading process in the dynamically growing packaging market of the emerging countries in Asia *(Heintze, 2003) (Silver, 2011)*.

The attractiveness of the external packaging of the products has become a fundamental expectation for the majority of consumers. The basic demand of customers in relation to packaging is similarly the proper consideration of the needs of the target consumers, high-standard and aesthetic appearance that is suitable for generating profit. One way to achieve this effect when manufacturing flexible packaging materials is printing on metallized film which immediately arouses the interest of customers with its "bright" appearance (Figure 1). Printing business operating gravure printing technologies can serve the broadest possible circle of customers with this solution. The basis of metallized films is a polymer film coated with a thin layer of metal, usually aluminium. The reflective silver surface of metallized films is similar to the surface of aluminium foils. The coating also reduces the light, water and oxygen permeability of the foil. The properties of metallized films, including higher toughness, weldability and lower density, are combined with lower costs compared to the cost of aluminium foils *(Application Insight, online) (Plastic Packaging, 2010)*.

Figure 1: Metallized film

Suitable inks should be selected for printing metallized films and it is recommended to subject the machine to renewing corona treatment in order to increase the surface tension of the metallized layer and to achieve consistent ink adhesion. Besides corona treatment appropriate ink adhesion can be facilitated by pre-printing with primary lacquer. When using metallized films pre-printed with primary lacquer it is recommended to print opaque white ink on the surface as an undercoating before printing process colours and spot colours *(Breiholdt, online).*

Due to the crisis and the accelerated world of business every company in mass production makes efforts to prepare and sell its products at the smallest possible material consumption, as cost-efficiently as possible and in the best possible quality in order that market position and sales volume is not lost. In addition to the realization of high-quality prints, gravure printing technology offers broad-ranging options for the development of such engraving parameters for the printing cylinder that are suitable for reducing the prime costs of the finished product *(Kapur, 2003; Chiawei, 2010)*.

The volume of primary lacquer applied by gravure printing is principally determined by the screen structure characteristics of the cylinder (Figure 2).

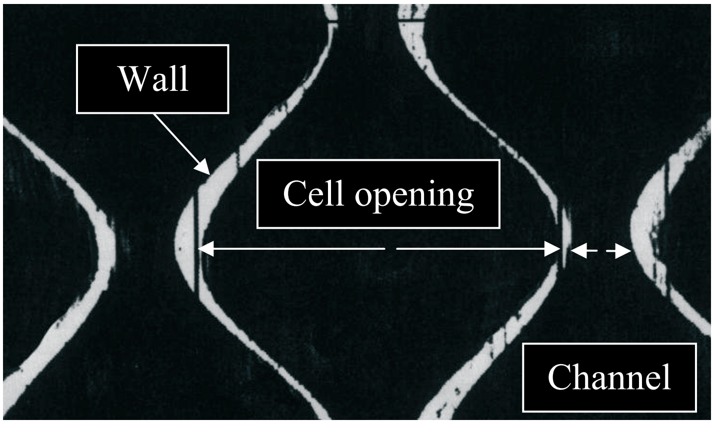

Figure 2: Characteristics of the cell

The volume of the lacquer applied is also influenced by the properties of the lacquer and the speed of the gravure printing press.

Electromechanical engraving is a standard method for producing gravure cylinders. Simplicity, stability and good reproducibility are among its advantages as well as the semi-autotipical (variables of depth and area) manufacturing method. Diamond stylus is used to cut cells in the copper layer to produce the desired image. The image of the printing elements of the gravure cylinder is influenced by the ink, the print media and obviously by the printing press itself. The geometry of the diamond stylus, screen ruling and screen angle also have an effect on the quality of the print. These parameters influence the transfer behaviour of the cylinder. The following parameters determine the volume of the cell: stylus angle, angle of the screen compression, cell wall, channel and screen ruling *(Wessendorf, 2003) (GST, 2010)*.

The stylus does not control cell opening, however, it does effect depth and, therefore, volume. A change to the screen ruling, angle, wall, or channel will change the cell opening. Main parameters influencing ink transfer: the ink, the print media as well as the relationship between cell size and dot size. The choice of cell and screen ruling depends on the ink applied and the print media influences the choice of cell characteristics. Metals or plastic films lift the ink from the cell differently than calendared paper orheavy cardboard. The Moiré pattern can be avoided by the proper selection of line screen and stylus *(Brethour, 2001)* (*Clist at al, 2005)*.

2. Methods

The aim of this research was the examination of the screen parameters of the printing cylinder and the optimization of the quantity of primary lacquer applied during the gravure printing process. A cylinder surface structure necessary for test printing optimization was designed. To perform the test printing, a gravure cylinder surface structure required for the optimization of test printing was developed. On the surface of the cylinder, nine bands of identical width were engraved with varied screen properties. In between the engraved 125 mm bands, 5 mm wide unprinted areas can be seen to easily distinguish the bands from each other. The examination and evaluation of the different structures took place by changing the speed of the printing press and the viscosity of the primary lacquer. The properties of the screen structures on the cylinder were determined by the contact angle between the diamond stylus and the gravure cylinder, the screen ruling and the screen shape *(Bohan at al., 2001) (GST, 2010) (Beißwenger, online)*. On the surface of the test cylinder, grid types featuring the following parameters were established (from left to right on *Figure 3*): Band 1: 120^0/70/0; Band 2: 130^0/70/0; Band 3: 130^0/70/4; Band 4: 120^0/80/0; Band 5: 130^0/80/0; Band 6: 130^0/80/4; Band 7: 120^0/90/0; Band 8: 130^0/90/0; Band 9: 130^0/90/4.

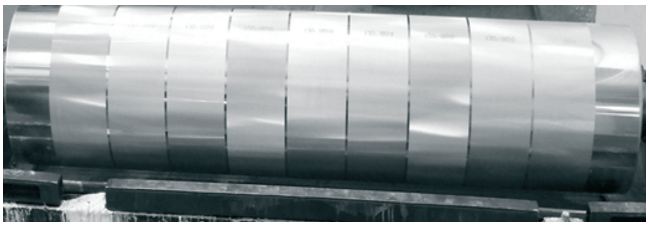

Figure 3: Lacquer gravure cylinder with nine bands

Band 1 and the surface structure of 120^0/70/0 was the standard (etalon) (*Figure 4)*.

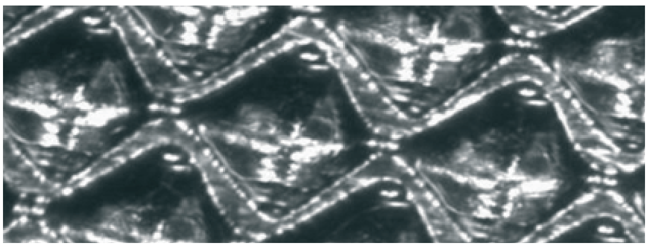

Figure 4: Surface structure 120^0/70/0

The gravure printing form was produced by cylinder engraving equipment type Hell Gravure System Gmbh K405. The diamond engraving stylus engraved the printing elements of the cylinder with a frequency of 8000 Hz. The total time taken for completely engraving the printing form cylinder was 10 hours.

Test printing was performed on OPP metallised film (manufacturer: Tagleef), thickness: 25 µm. Its structure is illustrated on *Figure 5*.

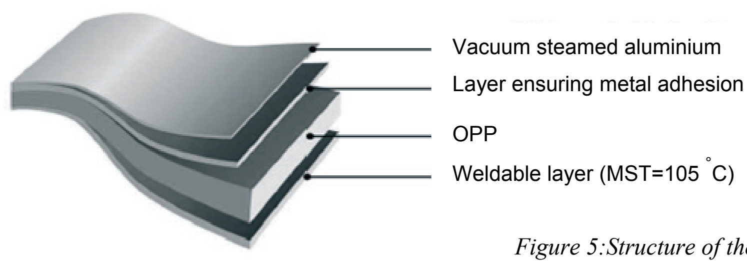

Figure 5:Structure of the metallised film print media examined

Printing was carried out by Cerutti 940 type 10-colour gravure printing press. After unrolling the surface of the print media was renewed in the corona equipment. The gravure press had warm air drying system. In the printing unit the circumference of the cylinders was 380-920 mm which at the same time indicates the minimum and maximum dimension of printed packaging materials. The maximum printable width of the print media is 1320 mm equal to the width of the impression cylinder. To facilitate the proper printability of smalller screen dots of the printing form an Eltex unit was mounted into the printing units. This system ensures that the smallest (2-3 %) screen cells are completely emptied which is triggered by the electric field through the impression (pressure) cylinder.

Printing was performed under normal operating conditions. During the tests the production speed of the printing press and the viscosity (outflow rate) of the primary lacquer were changed as follows:

- 160 m/min printing press speed and 15 s lacquer viscosity,
- 210 m/min and 12 s lacquer viscosity.

The characteristics of the materials used in the tests:

Primary lacquer: Siegwerk 10-600151-4 GA 2K 10

Harter: Siegwer 10-6000015-1 H

Dry matter content of the two-component primary lacquer system: 21%

Opaque white ink: Siegwerk NC-48.1 type nitrocellulose acrylic-based ink

Solvent: ethyl acetate

The wet quantities of the applied primary lacquer were measured and compared for the different screen types of the cylinder. Furthermore, we examined the abrasion resistance of the prints produced with the combined use of primary lacquer and nitrocellulose acrylic-based opaque white ink.

3. Results and discussion

During test printing the primary lacquer layer was first applied to the surface of the metallized foil with the cylinder with bands. Following the application of the primary lacquer sample sheets were taken off from the printing press to carry out further measurements and tests. After printing the primary lacquer layer the opaque white tone surface was directly printed. The engraving structure of opaque white was used in accordance with the practice used previously. The cylinder surface was not modified. The viscosity of the opaque white ink was 12 s. The viscosity of the primary lacquer and the opaque white ink was checked with a standardised measuring cup Ford at regular intervals during the period of test printing.

3.1 Applied quantity of wet primary lacquer

Knowing the parameters (dry matter content) of the primary lacquer the quantity of the wet lacquer applied was determined by weighing the sample sheets on a FZ-300I type digital balance. The evaluation considered the quantity of wet primary lacquer application recommended in the specification of the lacquer manufacturer (2–2.3 g/sq m). In case of 160 m/min printing press speed and 15 s lacquer viscosity, structures 120^0/80/0, 130^0/90/0 and 130^0/70/4 resulted the application determined in the specification (*Table 1*).

Table 1: Applied quantity of wet primary lacquer at 160 m/min machine speed and 15 s viscosity in case of different structures

Screen structure	Applied quantity of wet primary lacquer, g/sq m
120^0/70/0	5.23
120^0/80/0	**2.23**
120^0/90/0	4.14
130^0/70/0	2.85
130^0/80/0	2.85
130^0/90/0	**2.23**
130^0/70/4	**2.04**
130^0/80/4	0.95
130^0/90/4	1.57

In the case of 210 m/min printing speed and 12 s viscosity, the most favourable application was found for the 130^0/70/0 and 130^0/80/0 (*Table 2*).

Table 2: Applied quantity of wet primary lacquer at 210 m/min machine speed and 12 s viscosity in case of different structures

Screen structure	Applied quantity of wet primary lacquer, g/sq m
120^0/70/0	3.80
120^0/80/0	0.47
120^0/90/0	1.28
130^0/70/0	**2.04**
130^0/80/0	**1.90**
130^0/90/0	2.85
130^0/70/4	1.76
130^0/80/4	1.09
130^0/90/4	1.28

Out of the 18 lacquer samples 5 samples were satisfactory when evaluating the wet application quantity. These were examined under microscope to view the structures. With the help of the images taken with the microscope we examined and compared the spread and coverage of the structures. The tests were carried out using Carl Zeiss-Jenatech type microscope and the images taken of the samples were recorded using a special program: Scope Photo. It can be stated that on the image taken with the microscope of screen type $120^{0/}$80/0 the metallized effect of the raw material prevails and the contours of the engraved cells become distinct. The sample is more covered in case of screen 130^0/90/0 and the contours of the cells are paler. The metallized effect of the raw material was also insignificant unlike in case of screen type 120^0/80/0. It was characteristic of screen 130^0/70/4 that the contours of the cells were distinct and the metallized effect of the raw material was more considerable than in case of the previously examined two screen types. In case of screen type 130^0/70/0 the contours were pale and the metallized effect was not significant either. It can be stated that in case of screen type 130^0/80/0 the contours of the cells were pale and the raw material has no significant metallized effect. These microscopic studies confirmed our earlier examination results (*Table 3*).

Table 3: Summary of the applied quantity of the wet primary lacquer and the visual results of the microscopic examination

Screen structure	Printing speed m/min	Primary lacquer outflow rate, s	Applied primary lacquer, g/sq m	Microscopic results
120^0/80/0	160	15	2.23	Very good
130^0/90/0	160	15	2.23	Appropriate
130^0/70/4	160	15	2.04	Very good
130^0/70/0	210	12	2.04	Appropriate
130^0/80/0	210	12	1.90	Appropriate

As a summary it can be stated that out of 5 samples, all samples examined were satisfactory at the visual microscopic examination. We could ensure with 2 screen structures that by applying the appropriate quantity of primary lacquer the coverage and spread values were appropriate.

3.2 Abrasion resistant

From the mechanical tests of packaging materials one of the most important tests is the abrasion resistance test. Inappropriate abrasion resistance of printed plastic foils may lead to numerous problems. The purpose of the abrasion resistance test is primarily the examination of smearing of prints and the abrasion resistance examination of the opaque white ink layer applied on the primary lacquer surface in various layer thicknesses. It is an important aspect that the coverage properties of the opaque white ink layer, printed on the primary lacquer layer with irregular bands, are appropriate. The tests were carried out on Prüfbau Quartant equipment. During the test the stamp pressed the sample piece against the 250 g/sq m 50 x 110 mm cardboard fastened to the surface of the support with 620 g weight. 50 cycles were specified as the cycle of abrasion resistance reproducing the typical stress of metallized films. One cycle meant one back and forth movement during which the pressure stamp rotated with 22.5°, according to the toothing of the tool. After rubbing the sample sheets printed with primary lacquer and opaque white layer the scratches and alterations generated on the surface of the rubbed sheets were evaluated with a Carl Zeiss Jenatech microscope at 20x magnification. *Table 4* illustrates the results of the abrasion resistance tests and visual microscopic examinations of the sample pieces.

Table 4: Summary of the abrasion resistance results of the tested screen types

Screen structure	Printing speed, m/min	Primary lacquer outflow rate, s	Applied primary lacquer, g/sq m	Abrasion resistance
120^0/80/0	**160**	**15**	**2.23**	Appropriate
130^0/90/0	160	15	2.23	Non appropriate
130^0/70/4	160	15	2.04	Non appropriate
130^0/70/0	**210**	**12**	**2.04**	Appropriate
130^0/80/0	210	12	1.90	Non appropriate

Samples having screen structures 120^0/80/0 (15 s; 120 m/min) and 130^0/70/0 (12 s; 210 m/min) were satisfactory on the abrasion resistance tests. Based on the technological parameters of printing (viscosity 12 min, speed 210 m/min) from the tested structures cylinder structure 130^0/70/0 was optimal.

4. Conclusions

We studied 8 different screen structures during the test and compared them with a screen structure already used and specified in practice thus we considered structure 120^0/70/0 as the etalon. The primary goal when determining the parameters of the engraved cells was to develop a screen structure that would help reduce the quantity of the primary lacquer applied compared to the original standard structure. We have changed the contact angle between the diamond stylus and the cells, the screen ruling and the screen compression. Different structures were examined by increasing the speed of the printing press and reducing the viscosity value of the primary lacquer.

Based on the qualitative examination of the wet primary lacquer applied five out of nine screen structures arranged on the surface of the printing form cylinder complied with the primary lacquer application quantity recommended by the specification. Based on the technological parameters of printing (viscosity 12 min, speed 210 m/min) and on microscopic examinations and abrasion tests from the tested structures cylinder structure the optimal cylinder structure (130^0/70/0) is characterised by a smaller angle diamond stylus and identical screen ruling and compression, compared to the etalon. Printing was performed at a higher speed and lower viscosity. The optimal cylinder structure results in considerable savings in the primary lacquer quantity and is a cost-effective solution.

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UV LED curing of clear varnish

Manfred Schär[1], *Marion Noël*[2], *Ingo Mayer*[2], *Urs von Arx*[2], *Ramon Felder*[1], *Karl-Heinz Selbmann*[1]

[1] Institute of Print Technology
Bern University of Applied Sciences
Pestalozzistrasse 20, CH-3400 Burgdorf, Switzerland

[2] Bern University of Applied Sciences
Architecture, Wood and Civil Engineering
Solothurnstrasse 102, CH-2504 Biel, Switzerland
E-mail: manfred.schaer@bfh.ch

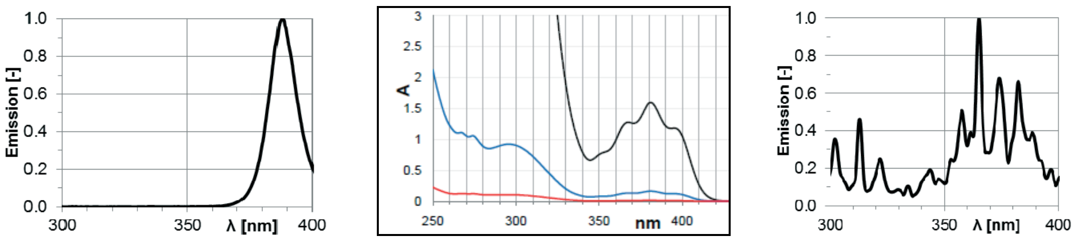
Abstract

The objective of the research was to show that clear varnish can be UV-cured with UV-LEDs.Therefore a range of UV curable varnishes had to be formulated which should be tested on substrates such as wooden materials. The formulation of at least one verified radical curing version and one verified cationic curing version of the clear varnish was requested. Concurrently, a dedicated UV-LED lamp as the curing source should be developed.At the beginning of the research was an evaluation step to find the most promising LEDs, initiators and sensitizers. The measuring of the emission spectra and radiometric powers of the LEDs as well as the absorption spectra and the extinction coefficients of the initiators and sensitizers resulted in a database. The characterisation of the LEDs was done with an integrating sphere with and a Mini-Array spectrometer. Big chip LEDs were preferred over emitters with large arrays of small LED chips. To achieve an optimal polymerisation reaction the selected initiators and sensitizers must have their absorption maxima at the emission peak wavelength of the LEDs. With 5 acrylates, 2 epoxies and one oxetan as raw materials a total of 12 different clear varnishes were formulated, thereof 8 radical curable systems and 4 cationic curable systems. The curing tests were done on a linear transport system. The thickness of the coating was 40 µm per run. Two acrylate varnishes and all 4 cationic varnishes were fully cured at the highest speed of 24 m/min. One of the cured varnishes showed a yellowish colour change which is the result of the used initiator that has a blue part in the absorption spectrum. The UV curing of clear varnish with UV-LEDs was laboratory-confirmed. Comparatively thick coatings of 40 µm on wooden substrates could be full cured in one pass at a maximum feed speed of 24 m/min.

Keywords: varnish, UV-LED, polymerisation

1. Introduction

The objective of this research was demonstrating the feasibility of curing clear varnish coatings with UV-LEDs (ultraviolet light emitting diodes). Therefore, suitable UV curable varnishes had to be formulated and then tested on desired substrates, such as wooden materials. Further, a special UV-LED lamp with an electrical controller, a cooling system and a feeder was then developed for the purposes of curing the varnish. Since LEDs emit nearly monochromatic radiation, the desired clear coatings must be formulated such that the energy of the LED-lamp transfers highly efficiently into the varnish, triggering the polymerisation reaction during the curing process. Optimal polymerization can be achieved by using initiators and sensitizers which have their absorption maxima at the emission peak wavelength of the LED and can, consequently, optimally utilize the relatively low total radiation power transmitted by the LED.



a) b) c)

Figure 1: Comparison of spectra, (a) monochromatic emission spectrum of a high power UV-LED lamp, b) absorption spectrum of an initiator, c) broadband emission spectrum of a conventional UV curing lamp

Two basic polymerisation mechanisms are relevant for UV-curing, namely, radical- and cationic polymerisation. It was decided that for this research project several formulations of both mechanisms would be developed.

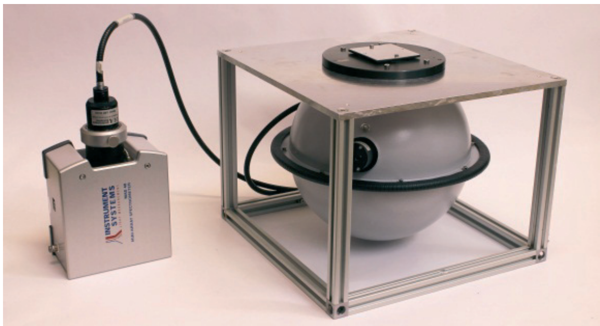
The main research goal was the development of clear varnishes, and the verification at least one radical and one cationic curing version. Acrylates are used for the radical version, while epoxies and oxetanes are used for the cationic version (Glöckner et al., 2008). The research should reveal which of the versions show better curing results with the UV-LED lamp in terms of completeness of cure and short requisite exposure time. Additionally, since the cationic curing reaction continues a short time after exposure to curing lamps, it may present an advantage over the radical curing reaction, given the lower energy available from the LEDs (Nakajima et al., 2008).

LED technology has several clear advantages when compared to conventional UV-lamps. Firstly, LED technology is more energy efficient. Secondly, UV-LEDs do not contain potentially hazardous amounts of toxic materials such as mercury, which is used in conventional UV-lamps. Finally, UV-LEDs do not emit unwanted infrared irradiation, have a longer lifetime and can be instantly switched on and off.

2. Methods

Recent rapid progress in the development of UV LEDs and curing initiators necessitated an evaluation and characterisation step at the beginning of the research project to identify the most promising LEDs, initiators and sensitizers available. The characterisation step included measurement of the emission spectra and radiant flux of the LEDs as well as the absorption spectra and the extinction coefficients of the initiators and sensitizers.

The characterisation of the LEDs was undertaken with an optical measuring system consisting of an integrating sphere with a diameter of 250 mm and a mini-array spectrometer. The measurement results for a LED include the emission spectrum and the radiometric power.



a) b)

Figure 2: Optical measuring system with a) the mini-array spectrometer MAS40-111 and b) the integrating sphere ISP250-211 to measure the emission spectrum and radiometric power of the UV-LED

The LED whose emission spectrum and radiant power best matched the absorption spectrums of the initiator and sensitizer was chosen for integration into the UV-LED lamp. Simulation and development tools were used during the research project to identify and develop an optimal lamp assembly. The program Trace Pro was used to simulate the optical path and radiation distribution of the finished lamp.

Special care had to be taken when considering thermal management of the LED to insure a long lamp lifetime. Exceeding the allowable working temperature specified in the LED technical literature leads immediately and irreversibly to shorter lifespan or destruction of the LED unit.

The characterisation of performance of the developed LED-lamp was once again undertaken using the integrating sphere and the mini-array spectrometer. The measurement results thus acquired are, again, the emission spectrum and the total radiometric power.

In order to perform the curing tests efficiently, a special test stand was developed. The test stand included a UV-LED lamp system consisting of the LEDs, a cooling system, an electrical controller and a simple human interface. A feeder system utilizing a servo motor was required to move coated samples under the LED-lamp to a high degree of repeatable accuracy.

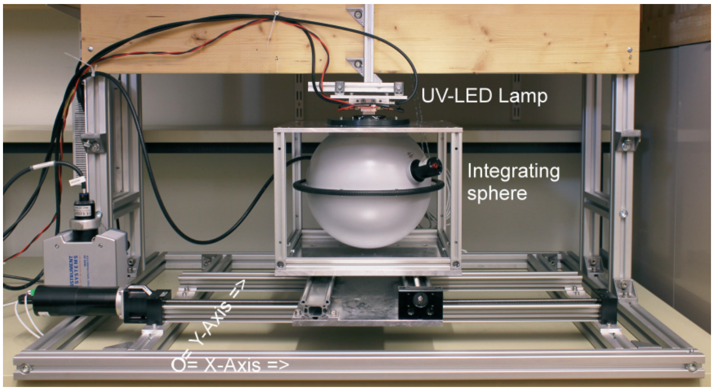


Figure 3: Laboratory test stand for measuring the radiometric properties of the assembled UV-LED lamp, mainly the emission distribution in variable distances from the emission window

The usual tests and chemical analysis using ATR-FTIR spectroscopy were performed in order to characterize the cured coatings.

3. Results

The primary requirement for curing varnishes with UV-LEDs is a good overlap of the absorption of the initiators and the monochromatic emission of the LED. With the radiometric measurement of the emission spectra of high power LEDs, compared with the measurement of the absorption spectra of pure initiators, several combinations with matching optical properties were identified. In total 4 radical and one cationic initiator were evaluated.

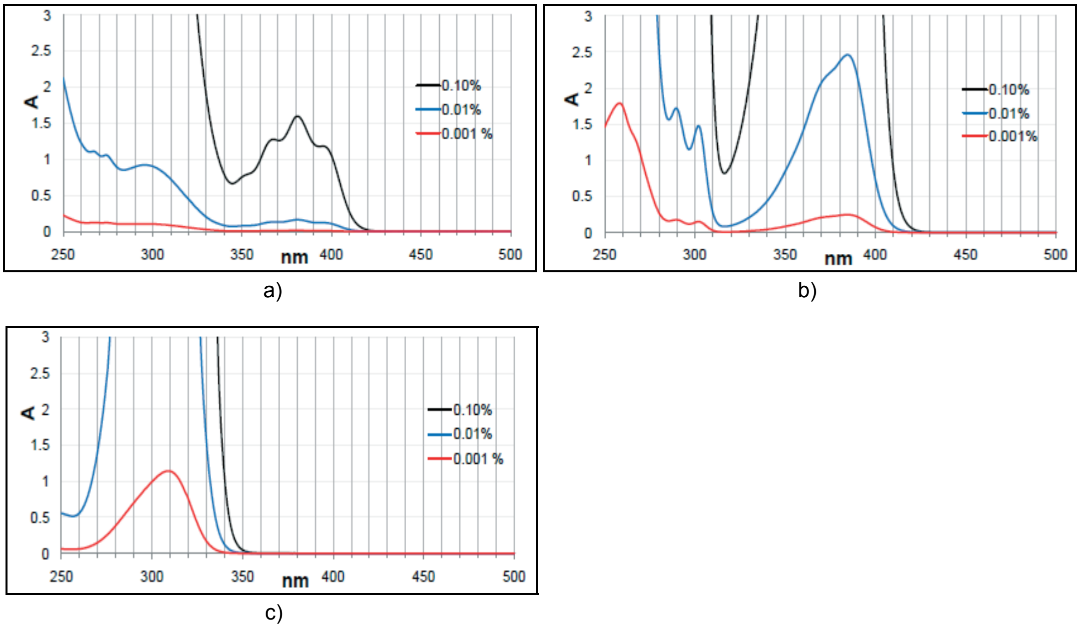


Figure 4: Examples of absorption spectra of photo initiators with a) weak absorption in the range of 350 ... 400 nm, b) strong absorption in the range of 350 ... 400 nm, c) no absorption in the range of 350 ... 400 nm

For the evaluation of the potential LEDs only high power devices with emission wavelengths lower than 405 nm were considered. A Big Chip LED with an emission wavelength of 390 nm and 8 W radiometric powers at a forward current of 18 A was considered especially promising. Other LED-arrays which utilized many small chips did not perform well in comparison. Specialized manufacturers are able to assemble LED arrays using small chips but generally do so only for their own purposes (EP1756876, 2007).

A LED-lamp was then constructed using two Big Chip LEDs and an emission window with the dimensions 24×10 mm. An optical scrambler made out of UV-reflective material was added to ensure an even distribution of emitted light. The total radiometric power of the LED-lamp measured 15.5 W at a forward current of 18 Amps, resulting in a radiation intensity of 6.4 W/cm^2 at the emission window. To maintain the allowed working temperature of the LED, a water-cooling system was developed.

The housing of the LED-lamp is made from aluminium, which contains a coolant duct. The LEDs are mounted on a special electrical insulation plate made out of a Ceramtec heat conductive ceramic. The electrical insulation thus provided is necessary to prevent short circuits between the copper body of the LED and the grounded housing.

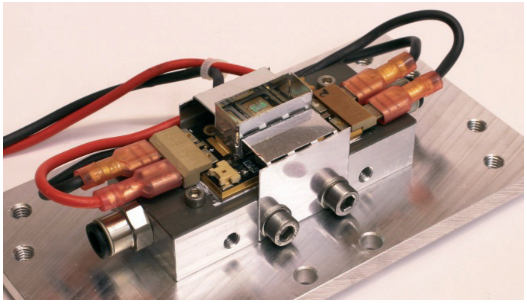


Figure 5: Realized prototype of the UV-LED lamp with a nominal emission peak wavelength at 390 nm

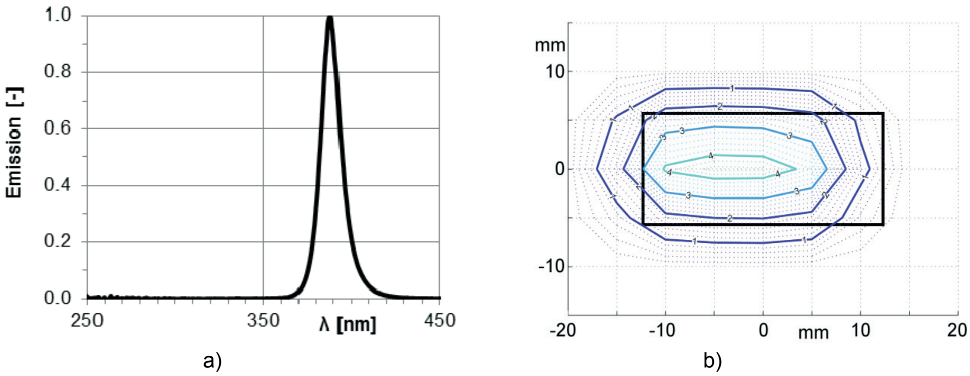


Figure 6: Measured spectrum of the UV-LED lamp with the peak emission wavelength at 388 nm, b) emission distribution at a measuring distance of 2 mm from the emission window. Due to optical losses the measured peak power is 4 W/cm^2. The emission distribution is asymmetrical due to optical misalignment of the reflector planes

The test stand for the curing experiments is basically a linear axis with a carrier for the coated substrate. The LED lamp is placed over the carrier which is driven back and forth beneath it by the linear axis.

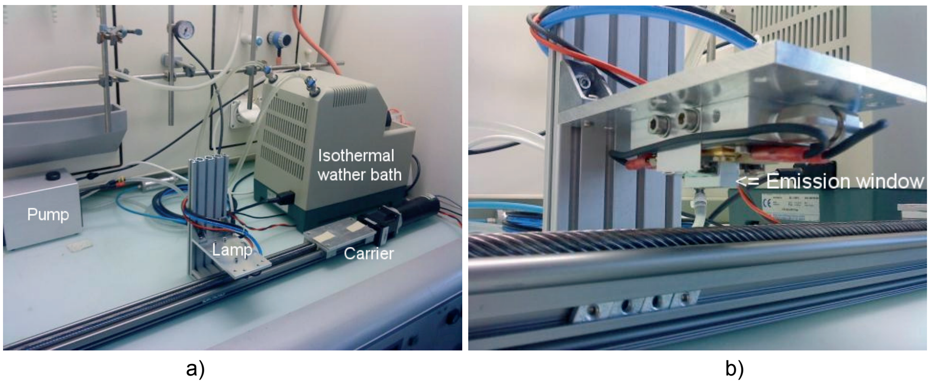


Figure 7: a) Overview of the laboratory test stand for the curing tests, b) alignment of the UV-LED lamp

The desired curing speed can be adjusted in the range of 0.3…24 m/min. The achievable exposure time of the coating to the UV irradiation lies within the range of 25…2000 ms. The LED current is provided by a laboratory power supply and is switched on and off with a semiconductor relay. A flow meter in the cooling circuit monitors coolant flow and interrupts the LED current in case of constricted flow, mitigating the danger of accidental overheating.

With 4 acrylates, 2 epoxides and one oxetan a total of 12 different clear varnishes could be formulated, of which 8 were radical and 4 were cationic curable. Curing tests were done using the linear transport system to effect 5 distinct linear speeds (0.3; 2; 4; 8; 24 m/min).

The thickness of the applied coating was 40 µm per run. Two of the acrylate varnishes and all 4 cationic varnishes were fully cured at the highest speed tested. One of the varnishes tested showed a yellowish colour change upon curing. The yellowish colour change observed was the result of the initiator which was utilized. This initiator causes absorption at blue wavelengths.

Table 1: Starting point of the mixing process with the selection of different raw materials

2 radical resins	**2 radical reactive monomers**	**2 cationic resins**	**1 cationic diluent**
aromatic urethane acrylate	polyether acrylate, amine modified	high purity cycloaliphatic diepoxide	oxetan
modified epoxy acrylate	ester acrylic acid	non modified epoxy resin based on bisphenol A	

Table 2: Mixture properties

Mixtures	**4 radical mixtures (urethane acrylate)**	**4 radical mixtures (epoxy acrylate)**	**4 cationic mixtures**
System	R5, R6, R7, R8	R30, R31, R39, R41	C1, C2, C3, C4
Fixed components	72 % resin	64 % resin	97 % oligomers + 3 % photoinitiator
	24 % reactive monomers	32 % reactive monomers	92 % oligomers + 5 % reactive diluent + 3 % photoinitiator
	0.6 % stabilizer	0.5 % stabilizer	
Variable components	3 % photoinitiator (or 2 % photoinitiator + 2 % H-donor)	3 % photoinitiator (or 2 % photoinitiator + 2 % H-donor)	

The coating was applied in two layers onto sanded wood samples (spruce veneer 20 × 150 × 0.7 mm). All coatings were applied using a 40 µm roller applicator.

The first layer was applied, fully cured and again sanded. The first layer prevented the penetration of the second varnish layer into the wood sample. The second layers were applied and cured at variable transit speeds.

Table 3: Application steps and process parameters utilized for the coating

Steps	**Remarks**	**Transit speed calculated exposure time**				
		0.3 $^{m}/_{min}$ 2 s	2 $^{m}/_{min}$ 300 ms	4 $^{m}/_{min}$ 150 ms	8 $^{m}/_{min}$ 75 ms	24 $^{m}/_{min}$ 25 ms
1) Sanding	200 grit designation					
2) First layer	40 µm roller applicator					
3) Curing	390 nm UV-LED	×				
4) Sanding	200 grit designation					
5) Second layer	40 µm roller applicator					
6) Curing	390 nm UV-LED	×	×	×	×	×

Figure 8: Application of the clear varnish on spruce veneer by manual roller coating

Immediately after the curing of the second layer, the curing level was examined with a rubbing thumb test to estimate the curing level. If the coating was not sticky and felt firm the coat was regarded as cured. If the coating was sticky and felt soft the coat was regarded as incompletely cured.

To quantify the degree of polymerisation the cured coatings were examined with ATR-FTIR spectroscopy. Characteristic peaks in the spectrum will disappear with better curing and consequently more complete polymerisation. For example, with the radical curing mixtures three peaks in the range 780…820 cm^{-1}, 1390…1430 cm^{-1} and 1630…1650 cm^{-1} were identified which allowed the quantification of polymerisation degree.

a) t = 0 h
green = cured
red = not cured
black = not tested

b) t = 4 h

Figure 9: Physical characterization of the coating by the rubbing thumb test, a) immediately after curing, b) 4 hours after curing

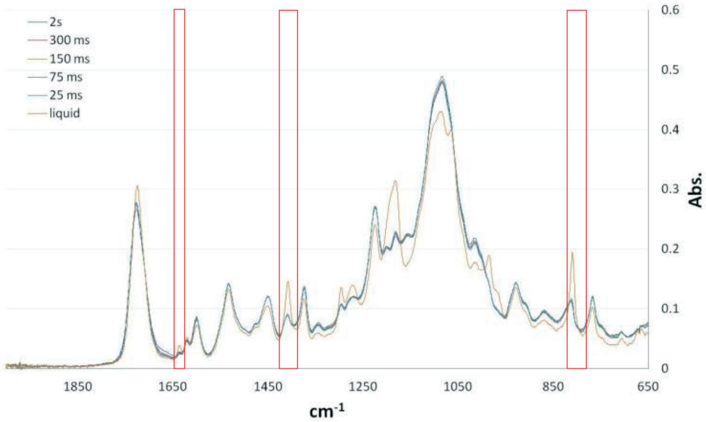


Figure 10: Chemical characterization of the R5 system with ATR-FTIR spectroscopy

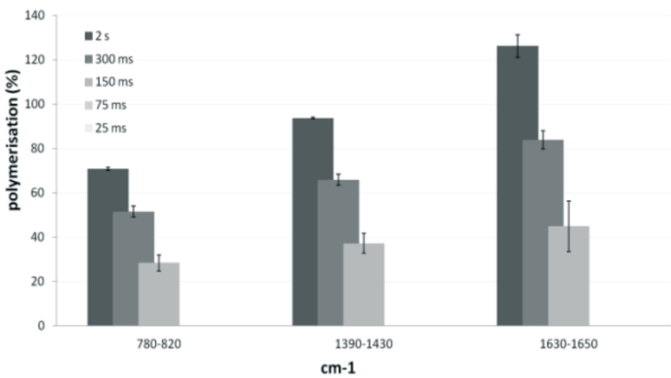


Figure 11: Chemical characterization of the R7 system with ATR-FTIR spectroscopy

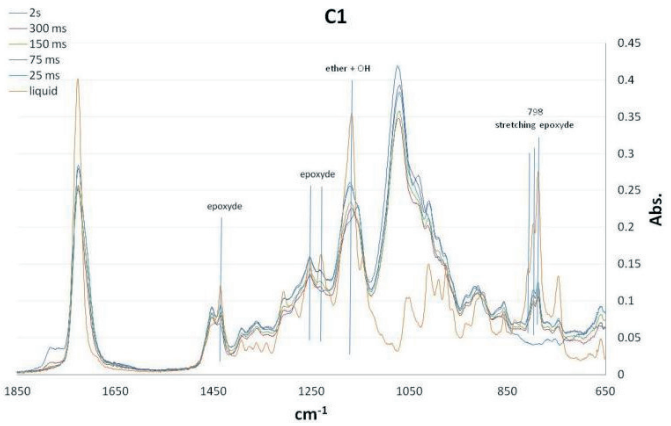


Figure 12: Chemical characterization of the C1 system with ATR-FTIR spectroscopy. Cationic mixtures show a much more difficult chemistry. Hence no significant measurement could be obtained to quantify the polymerisation

An important parameter of clear varnishes is the colour change of the coated sample in comparison with an uncoated sample. Since the UV-LED lamp emits radiation near the visible spectrum and the initiators absorb light near the visible spectrum a significant colour difference is measured.

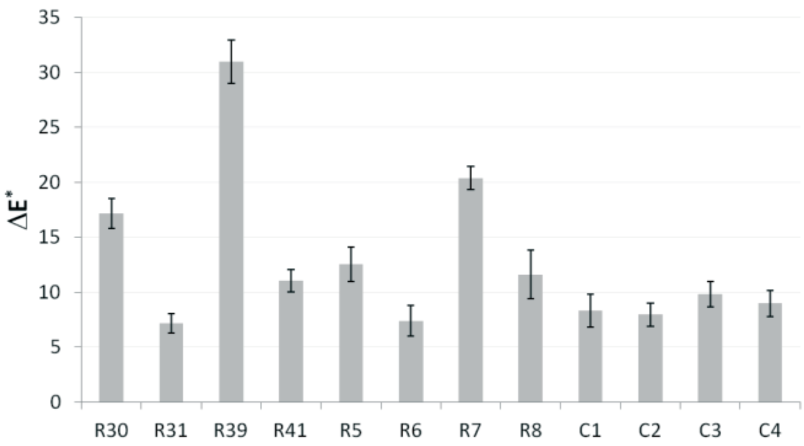


Figure 13: Colour difference ΔE^* of the coatings before and after application

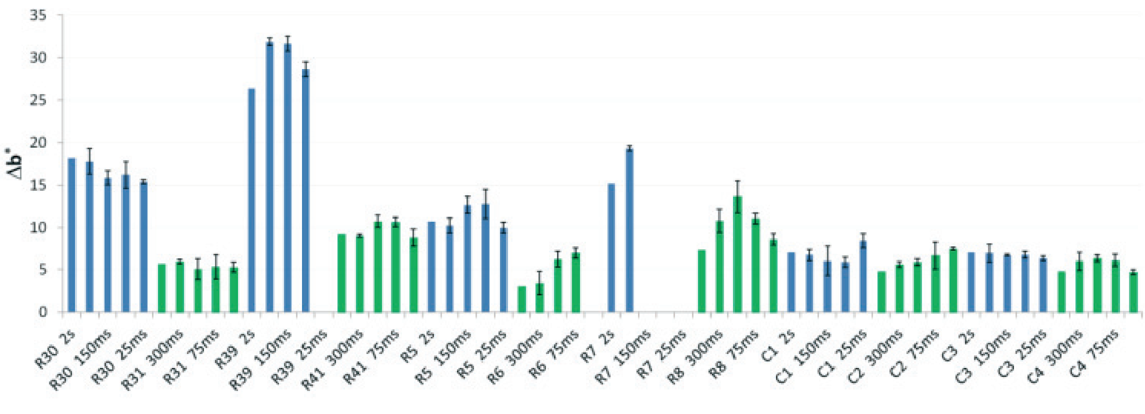


Figure 14: Colour measurement of Δb^* (yellowing)

A very interesting find which emerged out of the research is that even relatively thick coatings of up to 40 µm can be cured using the LED at typical printing speeds and in a single pass. Our experience up to this point has been with radical curable inks used in the flexo printing process, which produce 2 µm thick coatings.

4. Conclusion

The feasibility of UV curing clear coatings with LEDs has been confirmed in the laboratory. A suitable water-cooled UV-LED lamp with an electrical controller was designed for this purpose. The Big Chip LEDs demonstrated reliability for UV-curing applications. Relatively thick layers (40 µm) of clear coatings could be fully cured at the highest pass speed tested, 24 $^{m}/_{min}$. The basic physical characteristics of the cured layers have yet to be assessed. The formulations will require optimization to minimize the colour difference which was measured (yellowing).

Acknowledgements

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Integration of printing technologies in the injection molding process

Alexander Böddicker[1], Nora Wetzold[1], Uta Fügmann[1], Agnieszka Kalinowska[2], Thomas Härtig[2], Eike-Christian Spitzner[3], Michael Gehde[3], Robert Magerle[3], Arved C. Hübler[1]

Chemnitz University of Technology
Reichenhainer Straße 70
D-09126 Chemnitz, Germany

[1] Institute for Print and Media Technology
E-mails: Alexander.Boeddicker@mb.tu-chemnitz.de, Nora.Wetzold@mb.tu-chemnitz.de, Agnieszka.Kalinowska@mb.tu-chemnitz.de, Arved.Huebler@mb.tu-chemnitz.de

[2] Institute of Materials Handling, Conveying and Plastics Engineering
E-mails: Agnieszka.Kalinowska@mb.tu-chemnitz.de, Thomas.Haertig@mb.tu-chemnitz.de

[3] Faculty of Natural Sciences
E-mails: name.surname@mb.tu-chemnitz.de, Eike-Christian.Spitzner@physik.tu-chemnitz.de

Abstract

First, the developed process principle In-Mold Printing is introduced. In-Mold printed test samples on polycarbonate and polypropylene are presented. First basic research regarding the ink transfer and the ink adhesion on the polymer is carried out. Furthermore, special measuring methods for the analysis of the ink transfer have been developed and are presented.

Keywords: IMD, IML, ink adhesion, decorative effects

1. Introduction

Plastic components can be decorated with a variety of different technologies, e.g. painting processes, direct printing, transfer decoration and In-Mold Decoration [Cha06]. In order to improve the printability, surface treatments like corona or flame treatment (especially for polyolefins) are frequently used [Awa09]. In terms of the decorating costs, in-mold technologies are aiming to apply the decorative effect directly in the mold and obviate the need for subsequent decorating operations [Ehr12]. The technologies In-Mold Labeling (IML) and In-Mold Decoration (IMD) make use of carrier foils to transfer the image to the plastic parts during the injection molding process [Kam09].

The approach of this work is to proceed without additional production materials or surface treatments so that the lower handling and material effort results in lower production costs. Within the new process principle In-Mold Printing (IMP), the image is directly applied to the surface of the injection molding tool and will be transferred to the developing polymer part during the injection molding process [Har13]. Figure 1 shows a schematic of the In-Mold printing process.

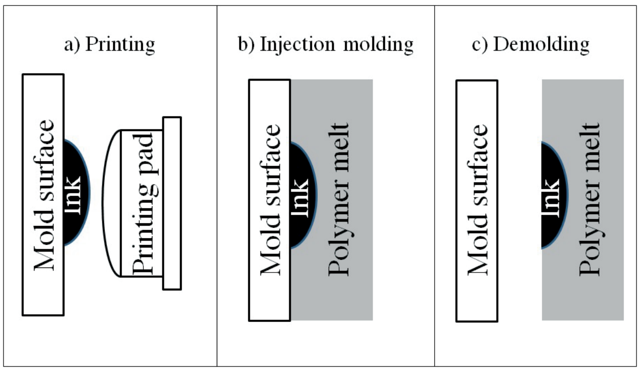

Figure 1:
Technical procedure of In-Mold Printing (schematic figure, after [Har13])

In order to accomplish a complete ink transfer during the demolding process, it is required that the forces of adhesion between the ink and polymer are higher compared to those between the ink and the mold. Unfortunately, the ink must adhere well to the injection molding tool, otherwise the printed image could misalign or blur during the In-Mold Printing process. The complex adhesive mechanisms provide major challenges regarding the chemical formulation of the ink system and the parameter selection relating to the injection molding process. First research results regarding the ink transfer and the ink adhesion on the substrate is presented in this paper.

2. Methods

Within the scope of preliminary investigations, commercial polymers and pad printing inks were tested for their capability for the In-Mold Printing process. In terms of this, a manual ink transfer on the tool of the injection molding machine (KraussMaffei 90-340 B) was realized. Subsequently the ink was back-molded with the polymer melt and the demolded specimens were subjected to qualitative analysis in regard to the amount of ink transferred. The promising material combinations provided a basis for further research and are listed in table 1.

Table 1: Basic components for the In-Mold Printing process

Polymer	Ink
Polycarbonate: Makrolon 2805 Bayer AG	Maramold 980 Marabu GmbH
Polypropylene: PP Moplen 501 LyondellBasell Industries Polyolefine GmbH	NoriProp N948 Pröll KG

Based on the results of the preliminary investigations, the determined basic components were adapted within the In-Mold Printing process. Therefore, the direct imaging of the injection molding tool was realized by pad printing technology. During the opening phase of the mold, the ink transfer was realized by the laterally placed pad printing machine (Tamponcolor TC 60-80T-KH). The flexibility of the elastic silicone-rubber printing pad enabled indirect ink transfer from the printing plate (cliché: Tamponcolor NP300) to the cavity wall irrespective of the shape of the mold. With regard to a simplified analysis of the mold surface after the In-Mold Printing process, removable specimen in shape of metal plates were used as intercarrier for the printing image (Fig. 2a). After the printing process, the ink film was back-molded with hot polymer melt. The plastic part was removed once the melt had solidified. On the basis of the experimental samples, extensive analysis of the ink transfer and the ink adhesion on the substrate was carried out. A peel test according to [ISO 2409] was conducted in order to measure the adhesion behavior of the ink on the polymer. For this purpose an adhesive tape was applied to the ink film and removed under consistent conditions; the percentage of the remaining ink was taken as a reliable value to be used for comparison of the adhesion forces between the ink and polymer. The ink transfer was investigated by several imaging methods, including optical microscopy and atomic force microscopy (AFM).

3. Results

On polycarbonate a complete ink transfer during the In-Mold Printing process was successfully achieved (melt temperature: 300 °C, mold temperature: 80 °C). Even the fine structures of the test motif (100 µm) were transferred completely without any detectable blurring or misalignment. In concern to the adhesion of ink on the polycarbonate, the In-Mold Printing test samples were comparable to subsequent printed examples. Results for the tests carried out with the adhesive tape showed that the entire ink remained on the substrate, assuring proper adhesion. Figure 2 shows an exemplar of the specimen.

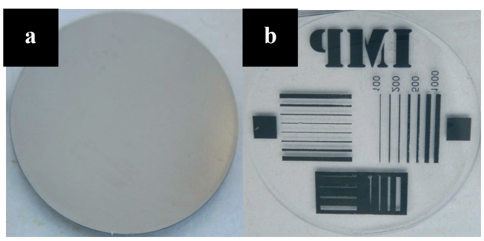

*Figure 2:
Test sample; a) Mold surface after demolding;
b) Decorated polycarbonate surface after
In-Mold Printing (from [Har13])*

The In-Mold printing process was utilized to print on a polypropylene to analyze the printability. The results, however, indicated an increased difficulty in the process. The injection molding at standard parameters (melt temperature: 230 °C, mold temperature: 30 °C) did not exhibit ink transfer onto the polymer. Also a gradual increase of the melt temperature until a maximum temperature of 280 °C could not positively influence the ink transfer. However, in contrast to the melt temperature, the increase of the mold temperature showed a significant influence on the ink transfer. Above a temperature limit of 80 °C, almost a complete ink transfer on the polypropylene substrate was realized. In order to analyze this phenomenon, the rheological properties of the ink depending on the temperature were measured. Therefore the shear viscosity of the used ink formulation composed of NoriProp N948 and 25 wt. % thinner Norilit U 090 was analyzed in a rotational rheometer (Anton Paar MCR 301) within a temperature range of 20 °C to 150 °C (Fig. 3).

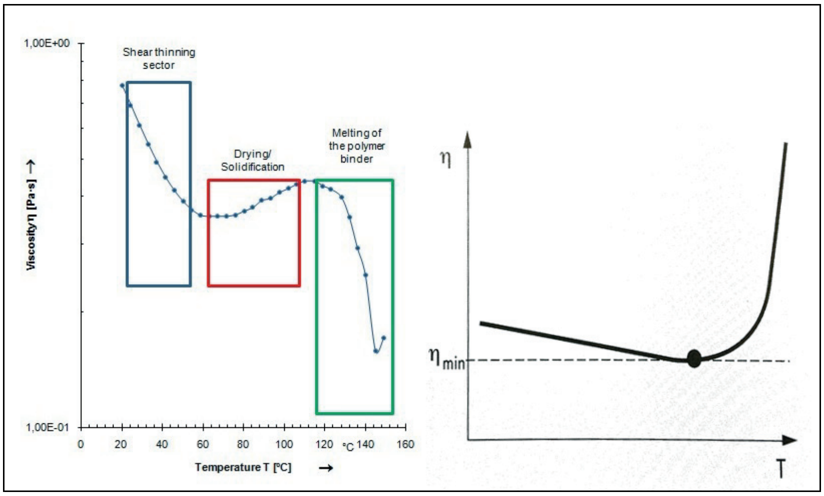

Figure 3: Left: viscosity of the ink NoriProp N 948 as function of the temperature (shear rate 100 s^{-1}, heating rate 5 °C/min); right: hardening specimen, schematically (from [Mez06])

Up to a temperature of approximately 63 °C a shear thinning behavior was observed. A different behavior in the temperature range of 63 °C to 115 °C was observed wherein the drying and hardening of ink caused a subsequent increase of viscosity. During this stage, the contained solvent mixture evaporates. A further increase in temperature, above 119 °C, leads to a decrease in the ink viscosity towards its minimum value. This can be explained as a consequence of melting of the polymeric, epoxy-based binder contained in the ink. For such material systems, a comparable temperature dependence of the viscosity is described in the literature [Mez06]. By means of rheological analysis of the ink, physical drying starting at a temperature of approximately 60 °C was proved. It can be assumed that the residual solvents evaporate out of the ink film in the direction of the cavity wall as a result of this drying. Therefore, it is conceivable that the vapor concentrates at the mold-polymer interface and aid the ink transfer.

The peel test results showed insufficient adhesion on polypropylene since the ink was transferred over onto the tape during the tests. Due to these results, an improvement of the chemical ink formulation was necessary. For this purpose, several ink formulations with different additives were prepared and processed with the In-Mold Printing technology. Based on these test samples the influence of the additives on the wetting behavior and the adhesion of the ink on polypropylene was investigated for studying ink transfer properties.

Using the base component composed of NoriProp N948 and 25 wt. % thinner Norilit U 090 ink formulations with following additives were produced and tested during the In Mold Printing procedure:

- Adhesion promoter Trapylen 187 S (Tramaco GmbH, addition of 5 wt.%)
- Adhesion promoter Trapylen 128 S (Tramaco GmbH, addition of 5 wt.%)
- Adhesion promoter Trapylen 145 X5 (Tramaco GmbH, addition of 5 wt. %)
- Hydrophobing agent Tego Phobe 1505 (Evonik Industries AG, addition of 1 wt. %)
- Surfactant Tego Wet 245 KL (Evonik Industries AG, addition of 1 wt. %)
- Surfactant Capstone FS 22 (DuPont, addition of 1 wt. %)

First, these formulations were investigated regarding the ink transfer during In-Mold Printing. In this context, the mold temperature [20 °C; 80 °C] and the melt temperature [220 °C; 280 °C] were varied in 10 degree steps. Afterwards, the percentage of ink residues on the mold was analyzed. The ink formulations which showed no ink residues on the mold are listed in table 2; in addition, the lowest possible process temperatures which allowed a complete ink transfer are scheduled.

Table 2: Ink formulations and injection molding parameters for a complete ink transfer during In-Mold Printing on polypropylene

Additive	Mold temperature [°C]	Melt temperature [°C]
5 wt. % Adhesion promoter Trapylen 187S	50	220
5 wt.% Adhesion promoter Trapylen 145X5	50	260
1 wt.% Surfactant TegoWet 245 KL	50	260

The additives listed in Table 3, caused complete ink transfer at lower mold temperatures (50 °C) in comparison to the basic ink formulation (mold temperature: 80 °C). However, these additives did not lead to key improvement towards the ink adhesion on the substrate. Only the adhesion promoter Trapylen 128 S provided a significant increase of the adhesion in a manner that no ink residues were observed on the adhesive tape in the peel test.

On the basis of these experiments an additional ink formulation was created to combine the positive effects regarding the ink transfer and the adherence. On the one hand 1 wt. % of the surfactant TegoWet 245 KL was added to the basic components to enable a complete ink transfer at lower mold temperature, and on the other hand, adhesion promoter Trapylen 128 S was added at a concentration of 5 wt. % to increase the adhesion between the ink and the polymer. As expected a complete ink transfer at a mold temperature of 50°C could be realized with this ink formulation. The observation of the better ink transfer by adding the surfactant Tego Wet 245 could be confirmed by contact angle measurements of the basic ink and the modified ink (Tab. 3). The surfactant causes a significant reduction of the contact angle from 44.3° to 40.7°. This effect indicates a better wetting behavior which is responsible for the improved ink transfer at a lower mold temperature.

Table 3: Measurements of contact angles of different inks on polypropylene

Ink formulation:	NoriProp N 948 + 25 wt. % Norilit U090			NoriProp N 948 + 25 wt.% Norilit U090 + 5 wt. % Trapylen 128S + 1 wt. % TegoWet KL 245		
Measure-ment No.	Contact angle [°]		Average [°]	Contact angle [°]		Average [°]
	Left	Right		Left	Right	
1	43.7	44.4	44.1	38.9	39.8	39.4
2	43.8	47.0	45.4	40.1	41.2	40.7
3	44.0	43.1	43.6	41.1	42.9	42.0
	Average:		**44.3**	Average:		**40.7**

In contrast to the expectation that the addition of the adhesion promoter Trapylen 128 S increases the adhesion at the interface between the ink and the polymer, no improvement of adhesion could be proved. This indicates that the addition of the surfactant limits the effect of the promoter on the adhesion. For this purpose (under the premise of an entire ink transfer during the In-Mold Printing process) new ink formulations with varied combination of additives and their respective concentrations, other than those investigated here are necessary to improve the adhesion on polypropylene.

For the detailed investigation of the ink transfer mechanism on the micro- and nanoscale, we established a custom experimental procedure based on optical microscopy and atomic force microscopy (AFM). We marked the pad printed metal plate with some scratches. These scratches are visible in optical microscopy (Fig. 4) as well as AFM images (not shown here). This enabled us to visualize the same spot on the metal plate before and after back-molding. Due to the fact that after back-molding the shape of the scratches is also visible in the surface of the polymer, we were also able to image the same spot on the plastic part after the part removal.

Figure 4 shows images of the same spot on the surface of the metal plate (mold) before (Fig. 4a) and after back-molding (Fig. 4b), as well as the surface of the plastic part after part removal (Fig. 4c). First, it is visible

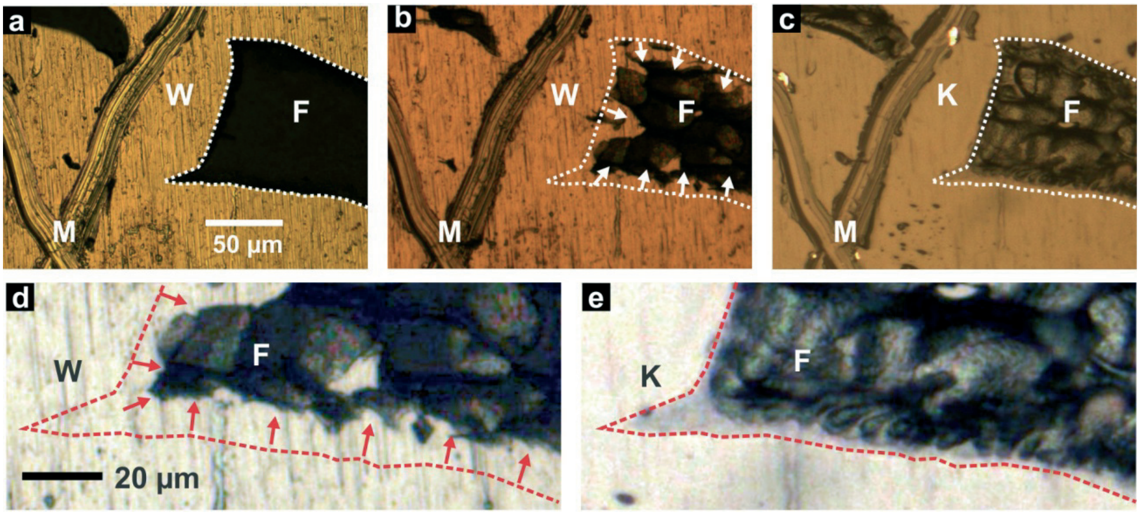

*Figure 4: Optical microscopy images of the mold and plastic part surfaces. All images show the same spot of a printed line with a width of 100 µm (**F**). The scratch **M** is used align the images of the different surfaces. The arrows indicate the direction of ink flow during the process of ink separation. (a) Pad printed metal plate (mold) **W**, (b) metal plate (mold) **W** after back-molding and part removal, (c) plastic part **K** after back-molding (image vertically mirrored), (d) detail in (a), (e) detail in (c).*

that the ink was peeled off in flakes without residual ink left by scratching the surface (Fig. 4a). The ink appears brittle and sharp breaking edges occur. It is not completely transferred during In-mold Printing, but a certain amount is left on the mold surface. This process is called ink separation. The shape of the ink on the plastic part indicates that the ink was, at least partially, fluid during the In-mold Printing procedure. In the literature, the structures visible in Figure 4c and e are referred to viscous fingering, or a Saffman-Taylor-instability [Saf58] [Lin05].

The detailed analysis of the mechanical properties of the ink was performed with AFM. The ink consists of 10 to 100 nm large stiff particles, embedded in a softer polymeric binder. Dried after pad printing onto the metal plate, the ink exhibits drying cracks. The thermal analysis shows that the ink starts to soften at temperatures of 70 to 90 °C. At and above these temperatures, the surface gets smoother, but no dewetting or flow on the micrometer scale was observed. These results indicate that the heating of the injection mold, which is done to achieve a better ink transfer, has no negative influence on the shape of the printed image.

4. Conclusion

First, the developed process principle In-Mold Printing is introduced. In order to accomplish this, pad printing technology was successfully integrated into the injection molding process so that the surface of the injection molding tool can be directly pad printed. In-Mold printed test samples on polycarbonate and polypropylene are presented. First basic research regarding the ink transfer and the ink adhesion on the polymer is carried out. On the basis of fundamental ink formulations, the influence of various additives on the ink transfer and the adhesion between the ink formulations and the polymers is investigated for different injection molding parameters. Furthermore, special measuring methods for the analysis of the ink transfer have been developed and are presented.

Acknowledgements

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Raised printing used as a connection between images and people who are blind and visually impaired

Tjaša Krivec[1], *Tadeja Muck*[1], *Rolanda Fugger Germadnik*[2], *Marica Starešinič*[1], *Raša Urbas*[1], *Gorazd Golob*[1]

[1] University of Ljubljana, Faculty of Natural Sciences and Engineering
Aškerčeva cesta 12, SI-1000 Ljubljana, Slovenia
E-mails: tjasa.krivec@gmail.com; tadeja.muck@ntf.uni-lj.si; marica.staresinic@ntf.uni-lj.si; rasa.urbas@ntf.uni-lj.si; gorazd.golob@ntf.uni-lj.si

[2] Celje Regional Museum
Trg Celjskih knezov 8, SI-3000 Celje, Slovenia
E-mail: rolanda@pokmuz-ce.si

Abstract

Introducing art to the blind and visually impaired people presents great challenge. In museums, painting exhibitions and galleries adapting objects presents a usual practice where direct touching of originals or its 3D reproductions is common but in some cases undesired act. Due to the fact that 3D reproduction cannot be applied to paintings tactile adaptations must be made.

Tactile rendering can be achieved by two techniques - micro-capsule or thermo-vacuum. For this study new layering technique using inkjet printer Roland UV LEC-330 has been selected. Raised relief surfaces were achieved by special UV curable varnish which was printed layer on layer. This new layering technique enables preparation of extremely complex textures and lines. Beside the technical part of the study ways of conveying the content of the actual art painting was studied. Portrait of Empress Elizabeth of Habsburg (painted by Georg Martin Ignaz Raab in 1873-1875) was carefully transformed to tactile adaptation with the help of museum experts, for preserving all historically important data.

Adaptations were evaluated by interviews with blind and visually impaired art enthusiasts. Through the research three different adaptations were made, each new one was an improved copy of the previous.

Keywords: tactile image, the blind and visually impaired, inclusive design, relief printing, inkjet

1. Introduction

Visually impaired and blind people experience the surrounding world by touch. There are 285 million people visually impaired worldwide: 39 million are blind and 246 million have low vision (WHO, 2011). In Europe and around the globe many efforts have been made in order to include them in the cultural life (EBU, 2011; Salzhauer Axel, Sobol Levent, 2003; BANA, 2010). Since visual signals are very hard to adjust to the sense of touch, visually impaired and blind people are often deprived of visual arts, for example paintings or graphics. In order to enable them to enjoy arts, the 2D image must be transformed into a tactile image. Tactile image is an adaptation of the original, which includes the third dimension, and is therefore called tactile painting or tactile adaptation of a painting. The concern that blind and visually impaired are not capable of imagining perspective is also redundant. Certain studies confirm that with the right approach, perspective can be learned (Kennedy, 2003). Blind people have a similar vision of the 3D world around them as people who see. If challenged, they won't draw what is on their retina; rather what their mental space model shows them. Expressionists did the same in art (Kurze, 1996). In order to be successful in practical work, experience and support are both needed (Wright, 2009). Many blind and visually impaired adults are not satisfied with their ability of reading tactile paintings, as they encounter with them too seldom.

Throughout the years, many methods evolved which enabled the production of tactile paintings for the use in books, schools and galleries. One of the simplest methods is gluing various materials on different surfaces in order to produce a tactile image. There are no limitations; different materials can be used, as long as they can be distincted by touch. However these tactile images, if poorly made, never last long (Brvar, 2010). The second widely used method derives from Braille. A raised embossed image is created with a series of small dots, which form a line or an area. Dots that form a tactile image are created with Braille or special embossing relief printer, which is used only for the purpose of creating dots in different order. The advantages of embosssing relief printers, are the use of digital originals, which enable simple corrections of errors, facilitation of saving, reusing and distributing the adjusted image (BANA, 2010). Other widely used method of creating tactile images uses special Micro-capsule or Swell paper. A tactile image is created digitally and printed with black ink on micro-capsule paper. Under IR radiation the printed surfaces absorb more thermal radiation and they therefore rise (Rener, 1992).

However, disadvantages of this procedure are limitations in dot height. With lines, made in micro-capsule technique, it´s not possible to produce more demanding or complicated forms. This method enables simple corrections of digital original and unlimited reproduction (BANA, 2010). The last well-known method is thermo-vacuum technique that is usually used to reproduce maps. The process is complicated, as a special 3D matrix is prior needed. The special plastic foil is heated and the vacuum sucks the foil to the surface of the matrix. The cooled foil is the exact reproduction of the 3D model. Matrixes are reproduced with special 3D printers or more common with etching on metal (Rener, 1992).

For this study new layering technique, using inkjet printer Roland Versa UV LEC-330, has been selected. The inkjet technology started to evolve in the late fifties (Magdassi, 2009). Due to its accuracy it is today, in addition to printing, used for many different purposes such as bio-printing and numerous electronical components (Van Wijngaarden, 2008). Raised relief surfaces were in this study achieved by special UV curable varnish, which was printed layer on layer. This new layering technique enables preparation of extremely complex textures and lines.

A tactile image is not a mere transformation of lines and planes to a relief version. The inequality between the sense of touch and the sense of sight is the cause that some differences must be made. It is important to preserve the authenticity of the original image. The latter is accomplished by the exact studying of the original. Due to many compromises that must be made in order to coordinate the technical difficulties and problems containing visual adaptation (such as perspective, colors, details etc.), adaptations that would reproduce the exact copy of an original picture, are unfortunately, an illusion.

In this experiment Portrait of Empress Elizabeth of Habsburg (image 1) (painted by Georg Martin Ignaz Raab in 1873-1875) was, through a series of tests, transformed to a tactile adaptation. Adaptations were evaluated by interviews with blind and visually impaired art enthusiasts. Through the research three different adaptations were made, each new was an improved version of the previous.

Image 1:
Original Image from Celje regional museum
79 × 63.3 cm

2. Methods

The experiment was divided into three phases. The first one was the digital elimination of unnecessary image details and preparation of the digital image. The second was printing with Roland Versa UV LEC-330, and the last one, the evaluation of interviews made with blind and visually impaired people. In order to achieve a satisfying result, the whole experiment was, with minor differences, repeated three times. For the purpose of this article, we have focused on the printing and the digital preparation of the textures and lines, which were used in the adaptation of the mentioned portrait. For the whole tactile adaptation five different textures were needed. They represented hair, clothes, background canvas, ornaments and skin. We also used three different lines, which helped to differentiate facial features, ornaments and other lines. In the process of preparing the digital adaptation, we were trying to find an automated solution for creating lines using photo-filters. The idea was discarded since the lines have to be extremely smooth, clear and even, in order to be successfully recognized by the users of tactile image. The image preparation was done with the help of two programs: Adobe Photoshop and Adobe Illustrator. With the Adobe Photoshop we made a black and white version of the image with different contrast, which can be seen on the image 2. On the left picture of the image 2, we can notice high contrast between the background and the upper part of the hair. The eyes are nicely seen as well as the floral ornaments in the hair, on the band around the neck, and on the necklace. On the right picture of image 2, different details are revealed. A line forms a nice barrier between hair and the forehead likewise all the facial features (lips, nose, eyebrows) and arm are clearly defined. The combination of the both pictures - the left and the right in image 2, served as a template for creating a vector image in Adobe Illustrator.

Image 2: The black and white images with different contrasts

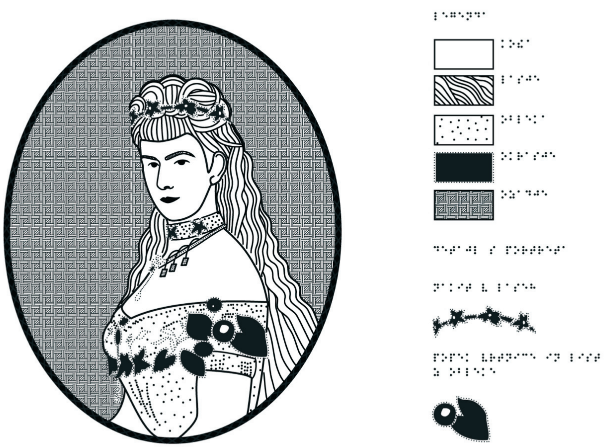

Image 3: The vector image, ready for printing

The final version of the vector image, well accepted among the blind and visually impaired people can be seen on image 3. The legend of five used textures and two isolated painting motives were included on the right side of the adaptation. The UV inkjet printing technique is appropriate for creating tactile adaptations of fine arts as it enables rendering of extremely delicate and exact lines and numerous different textures. The relief was generated with a series of layers, printed on the same substrate (for creation of the last - third adaptation 14 layers were needed). Image 4 shows some details of the printed version, that can bee seen on image 5.

In the process of creating a final adaptation, the most appropriate (decided on the basis of the interviews) of the given five textures was selected for each motive on the adaptation - canvas, dress, hair, skin and ornaments. Textures were composed of straight and curvy lines, circles, doted and full texture. According to the results individual textures for motives were selected and used for the reproduction of the selected adaptation.

The participants in the interview were aged from 10 to 65 years; each age group was represented equally. 46% had sight problems since their youth, in 36% the problems occurred between the age of 10 to 18, and the rest 18 % lost their sight when older.

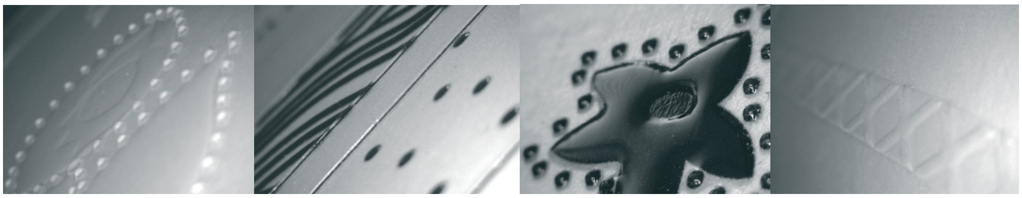

Image 4: Details from the final adaptation

Image 5: Printed version (36 × 29 cm). Translation of words on the right side starting with the one on top: legend, skin, hair, dress, ornaments, canvas, details from portrait, ornaments in the hair, flower and burst from the dress.

3. Results

The following images from 6 - 10 show results regarding selected textures. People included in the study were asked which structure they preferred for the canvas, skin, hair, ornament and dress motive. It was shown that: for the canvas texture 1 was preferred by 64% (image 6), for the skin texture 5 was preferred by 80% (image 7), for the hair texture 4 was selected by 42% (image 8), for the ornament texture 2 was selected by 50% (image 9) and for the dress texture 3 by 50% (image 10).
Not all of the chosen textures were used in a final adaptation, but the results presented a great help during the research.

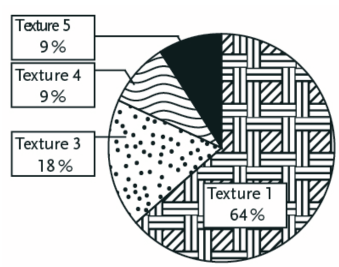

Image 6: Distribution of textures for the canvas motive

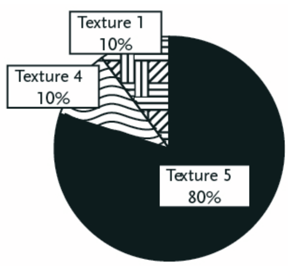

Image 7: Distribution of textures for the skin motive

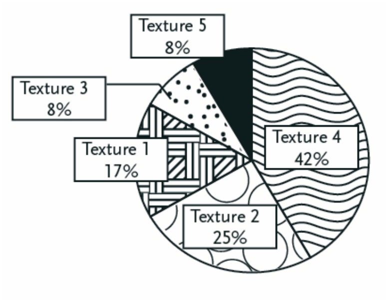

Image 8:
Distribution of textures for the hair motive

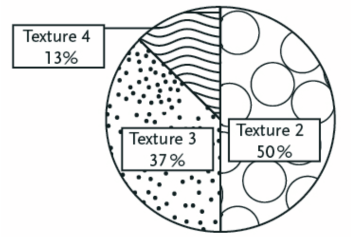

Image 9:
Distribution of textures for the ornament motive

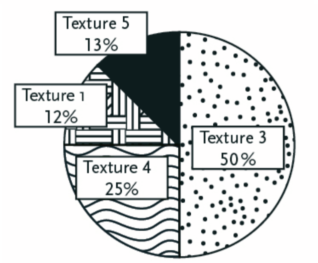

Image 10:
Distribution of textures for the dress motive

The study indicated that lines are better distinguished when they are sharper and have appropriate width. The height of the lines included in the second and in the third adaptation achieved values from 0.03 to 0.47 mm. It was established that even if the printed lines achieved adequate height (0.31 mm) they weren't recognized if they were too thin (0.41 mm). Wider lines (0.81 mm) gave better results. The line width gain, caused by the printer, was between 4 and 16 %, depending on the line or texture form. Three different types of lines were used; a primary, secondary and a dotted line. The primary lines were used for main motive border and the seconddary for secondary features e.g. face features. The dotted line was used for ornaments border. Quality of printed layers was evaluated with microscopic analyses of topography and profile of primary and secondary lines (image 11 and 12). Different profiles - created using different width of lines in separate layers - were studied.

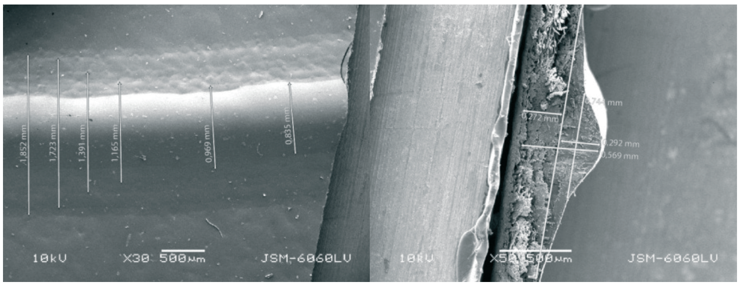

Image 11: Topography and profile of primary line, made with Scanning Electron Microscope

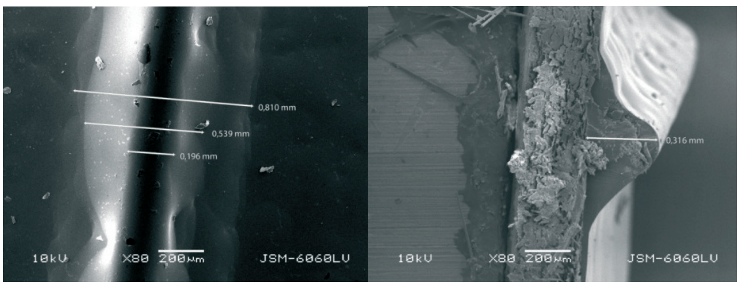

Image 12: Topography and profile of secondary line, made with Scanning Electron Microscope

4. Discussion

Textures 1 and 5 were used in the final adaptation. Some difficulties appeared with texture 2 due to too large elements, which could not be applied properly to the small details in the ornament. Therefore second best, texture 3 was used for the ornament. For the dress half of the test subjects selected texture 3. Because this texture was already used for the ornaments the new similar, but different texture was created. Study indicates that the direction of touching played an important role for the recognition of the texture 4. It was established that only when touched parallel according to the lines, the texture 4 lines could be recognized. When touched perpendicularly to texture lines, texture 4 felt alike texture 1. Texture was therefore improved in the last adaptation; the size of the lines and spaces between lines in texture 4 were increased. It was also established that the textures must contain elements of adequate size otherwise they might feel too alike.

The study also indicated that the textures were more appropriate when printed in matte mode, where the raised relief was built layer on layer. Printing in gloss mode resulted in spreading of the new layer over the previous one. Concluding from the results the adjustments should be made on a coated medium substrate as it enables best possible height, precision and appearance.

Different profiles of the lines are as important as good texture. The most effective differentiation was achieved between dotted and the other two lines. Using lines as additional information gains a lot of credit in better recognition of the adaptation.

5. Conclusion

Study confirmed that presenting art works - paintings to blind and visually impaired people even with modern techniques presents several obstacles. Without the tool of color and with limitation of usable structures, which can be printed, complete reproduction gathering of all the details is impossible.

This study showed that adequate adaptions could be made if certain simple rules are followed - height and width of lines, size of textures, sharpness of the edges and also elimination of details from the original.

The biggest success in presentation of this selected portrait was in adaptation of the frame and facial features. The final adaptation is now part of the Cultural and Art historical Collection in Slovenia, in Celje Regional Museum. Its purpose is to connect the blind and visually impaired visitors to the complex sense of vision.

Three adaptations of the original were made, after each one people with visual impairments and blindness evaluated the created tactile image. The first adaptation used low lines with too smooth profile; therefore the touch experience was not good. According to that the second and the third adaptation included higher lines, with sharper profile. They were made with textures, which extremely positively affected the touch recognition of the motive.

The selection of the textures used in an adaptation is a complicated procedure, which was completed through the series of interviews and with comparisons of different textures. The study showed that for achieving successful differentiation of textures the texture elements should not be too small. Eyes are namely capable of distinguishing many more textures than the sense of touch. It was also conducted that the line width is important - it can't be recognized if it is to thin even if it has an appropriate height.

Acknowledgements

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Characterization of a printed 2D code by image analysis

Lionel Chagas, Nadège Reverdy-Bruas, Michaël Pflimlin, Raphaël Passas

LGP2
(Laboratory of Pulp and Paper Science and Graphic Arts)
Grenoble Institute of Technology,
461 rue de la Papeterie, F-38400 Saint Martin d'Hères, France
E-mails: lionel.chagas@pagora.grenoble-inp.fr; nadege.reverdy@pagora.grenoble-inp.fr

Abstract

To fight against growing counterfeiting becomes necessary. That is why many techniques are developed to secure the printed labels or documents. 2D codes are one of the cheapest and easiest methods. But most of them can be copied, thus the security 2D codes are printed with the highest printing resolution available. Their unforgeability is based on united effects of two noises. The first one is the determinist noise, which is represented by the dot gain, the enlargement of the dots which cluster and by the percent of fidelity related to the numeric file. The second is the random noise, the intra-variability of the codes, represented by standard variations and the associated distribution of probability of the previous criterions. This study aims to characterize the noise in global printed 2D codes, depending on the printing process, printing resolution, support and theoretical ink coverage. The shape of the individual dots has also been studied, and these criterions have permitted to distinguish several counterfeited codes from the original one.

Keywords: 2D codes, security, determinist noise, random noise, image analysis

1. Introduction

The general framework of this study is the fight against counterfeiting for which different 2D codes can be used [Dyb, 2006]. Counterfeiting is a continuously increasing plague in the world: experts claim that it would affect 10 % of the world trade, that is to say 200 to 300 billion euros and 20 % of wines sold are concerned [God, 2012]. A lot of technologies have been designed to secure documents: Cryptoglyph®, microtaggants, geometrical distortion analysis, multilayer stickers, selective varnishes, special papers, special inks, micro text, holograms, RFID chips etc [Jot, 2005]. These security devices have been classified into three levels [Van, 1997, Moi, 2002]. Level 1 concerns the securities which are seen directly without specific equipment. Level 2 concerns the securities which are detected by simple equipments, for example by UV, IR irradiation or with small microscopes. By level 3 are designated the security systems involving expert or big equipments like nano text in a hologram adapted for visualization by specific, expensive microscopes. Among this variety of security systems, 2D codes are cheap and easy to implement in a production line. Moreover, the large amount of free generators available on the web promotes the global expansion of their use in various domains. This type of security system is classified in the second level. The system is simple: a 2D code is printed with a high resolution 800, 1200 or 2400 dpi. This code can be the same for a product batch (offset printing) or different for each product (numerical printing). In this last case each product can be authenticated. The system is fast to use, the authentication can be made with a smartphone if its picture resolution is sufficiently high. The authenticity of a product can be deduced from the matching of its description and of its theoretical characteristics. Detecting a counterfeited item require to define relevant characteristics, so that controls can be performed in a reasonable time - most of the time these characteristics should involve technical parameters quickly recognizable.

It is important not to confuse identification and authentication: identification helps to visually recognize the protected product (brand, logos, various indications…), whereas authentication consists in checking this identity, the correspondence between the product and the indications. Finally traceability is possible with this type of code. Traceability means collecting information - by single product or product batch - about the production stages and location data. Such indication can be consulted on demand but it is not a mean of authentication (anomalies in traceability can still trigger suspicion). On Figure 1 the use of this security is depicted.

The 2D code is composed of very small modules (down to 10 µm) corresponding to the smallest dots printable at high resolution (up to 2400 dpi). This parameter makes it really different from classical 2D codes such as QR codes; the following table 1 summarizes orders of magnitude of widely used 1D and 2D codes.

Figure 1: Principle scheme of the use a 2D code for authentication and traceability

Table 1: Characteristics of different 2D code

Name	Storage capacity	Module size	Code size
1D barcode (EAN-13)	13 digits - 46 bits	1 mm * 1.5 cm	3 cm * 2 cm
QR code	Up to 7089 digits or 4296 alphanumeric data – 24800 bits	1 mm * 1 mm	2 cm * 2 cm
Data Matrix	Up to 3119 digits or 2335 alphanumeric data – 10900 bits	1 mm * 1 mm	1 cm * 1 cm
High resolution code	Around 60000 bits	20 µm * 20 µm	5 mm * 5 mm

It clearly shows that high resolution code has a 250 higher data storage density than traditional 2D codes, according to the module sizes. The small size of the modules makes this code impossible to copy. When counterfeited, the printed code is reproduced by means of a printing process that may be different from the original one. This study aims to characterize the first print of the code, macroscopic and microscopic behaviors and relevant parameters. Indeed, it is necessary to perfectly define the original printing process and its variability to be able to discriminate a copy from an original. Few results about the counterfeited code are presented at the end of the study. Figure 2 describes the global production-counterfeiting chain. The influence of process parameters - such as the substrate and file parameters - such as the theoretical dot size and the ink coverage - were varied in order to point out their relative influence on the resulting 2D printed code. Then, a picture acquisition of the first printed code (2) was performed and an image analysis methodology was established to precisely characterize the printed code in terms of measured ink coverage and percentage of fidelity (similar pixels between the 2D code numeric file (1) and the picture of the first printed code (2) binarized by means of different methods).

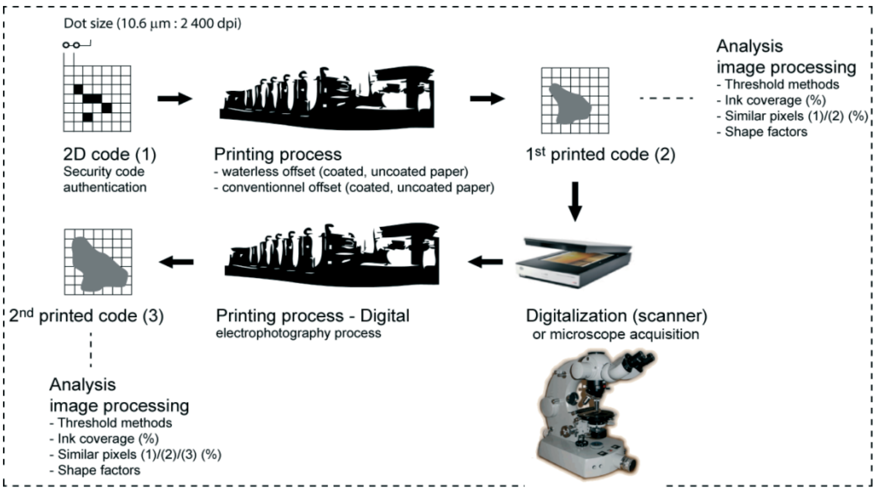


Figure 2: General context of counterfeiting- from the digital code to the 1st print and then a 2nd print after digitalization

Another important factor to point out is the noise generated by the global printing system on the authentication of the code. It can be:

- A determinist noise: dot gain value, mean percentage of measured ink coverage, mean percentage of fidelity
- A random noise: represented by the standard deviation of the mean values and the associated probability distribution
- In a first step, the determinist noise was brought out on a complete 2D code and then, on individual dots isolated within this code. In a second step, attention was paid on characterizing the random noise because it is the one that can enable to improve the authentication system.

2. Methods

A chart test was designed, on which random 2D codes (100 x 100 dots) were inserted with varying parameters:

- dot size - four theoretical dot sizes: 10.6, 21.2, 31.8 and 42.3 µm, corresponding to the printing resolution, respectively to 2400, 1200, 800 and 600 dpi.
- ink coverage - ranging from 0 to 100 % - only the 70, 40 and 20 % ink coverage were characterized (Figure 3).

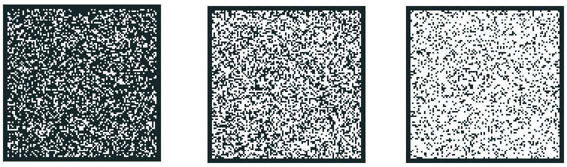


Figure 3: Pictures of the digital files of the three studied patches, 70, 40 and 20 % ink coverage (100 x 100 dots)

The chart test was printed by conventional and by waterless offset on coated and uncoated papers. For conventional offset, only the 10.6 µm dot size was available. Industrially, 2D codes are printed with the highest resolution, thus the study focused on 2400 and 1200 dpi resolutions.

Samples were pictured with an AxioCam camera installed on a Zeiss Microscope. The acquisition parameters aim to maximize pictures quality, contrast and resolution. Image was sized by 1000 x 1000 pixels, 100 pixels for one theoretical dot. Then, the RGB pictures were analyzed with an image analysis software (Visilog 7.0). The picture was transformed in grayscale levels keeping only the blue channel that brought the best contrast. Afterwards, three thresholding methods [Pet, 1998, Naz, 2013] were applied: visual, entropy and fidelity methods (Figure 4).

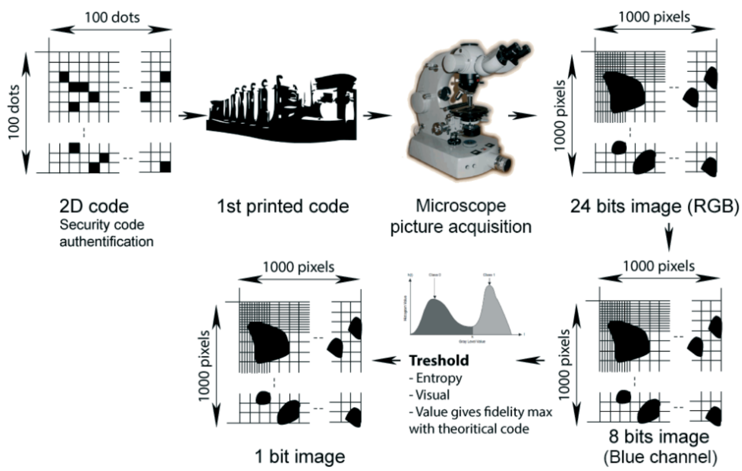


Figure 4: Image acquisition and treatment methods

2.1 Characterization of a complete code

Properties characterized on the printed material after thresholding are the percentage of measured ink coverage calculated according to the following formula:

Measured ink coverage (%) = (Nb of black pixels/Total Nb of pixels) x 100 (1)

And the percentage of fidelity calculated according the following formula:

Percentage of fidelity (%) = (Nb of similar pixels/Total Nb of pixels) x 100 (2)

The number of similar pixels corresponds to inked, as well as non-inked areas, in the numeric file and in the printed binarized code, including the borders. Finally, comparison was done with the logic gate «exclusive or», xor. Figure 5 describes the xor principle treatment and Figure 6 depicts the treatment for an example of 20 % theoretical coverage.

Figure 5: xor treatment on a simple example of 4 pixels (first square represents the printed sample, the second one, the numeric file and in the last one, the black dots symbolize the similar pixels)

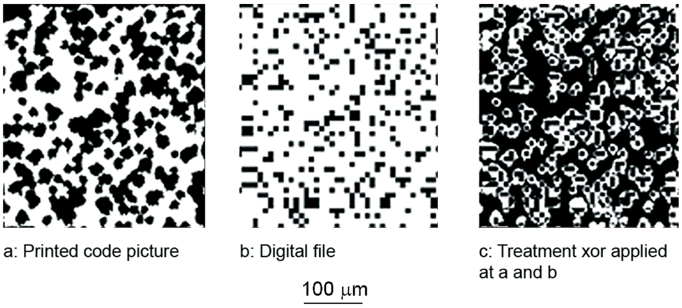


Figure 6: Example of XOR treatment on a magnified view of a visually thresholded sample - waterless offset, coated paper, 20 % theoretical coverage, 21.2 μm theoretical dot size

2.2 Characterization of each dot

Determinist and random noise had been investigated for each dot. Determinist noise is represented by means of criteria such as the dot area, the equivalent diameter and the Crofton perimeter [Oli, 2002]. Random noise is linked to statistical scattering of these values and to the associated probability distribution.

Figure 7 depicts the visual comparison between theoretical and printed dots.

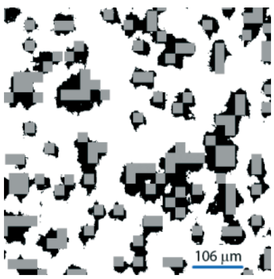
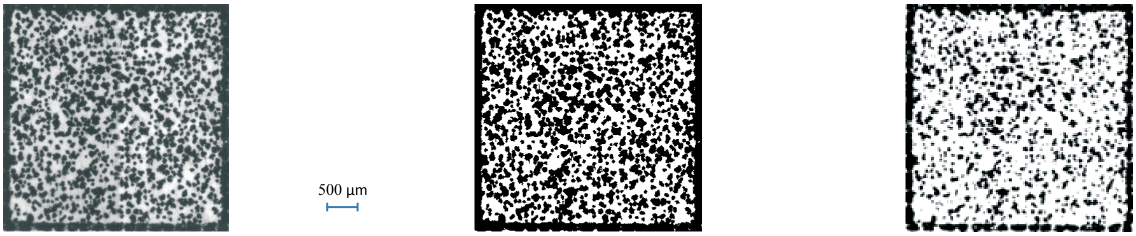


Figure 7: Comparison between theoretical dots (gray) and printed dots (black) - waterless offset, coated paper, 20 % theoretical coverage

3. Results and discussions

3.1 Characterization of a complete code

Figure 8 depicts two methods of thresholding. The visual method is considered as representative of the observed print. On the contrary, the fidelity method does not match with the printed code. In the same way, limits of the entropy method were highlighted. In some particular cases - one single peak in the image histogram - the entropy method highly deviated from the visual perception. For these reasons, in the following results the visual method was chosen.



a. Printed code picture *b. Visual method thresholding* *c. Fidelity method thresholding*

Figure 8: Example of two thresholding methods - waterless offset, 20% theoretical ink coverage, coated paper, 1200 dpi

On Figure 9, the fidelity percentage is plotted versus the percentage of theoretical coverage for uncoated paper, for each theoretical dot size. The first result to point out concerns the fidelity increases as the dot size increases. That is why the highest resolution (small dot size) should be preferred in order to maximize the determinist noise. It can also be noticed that the minimum fidelity observed at 40% for the smallest dot size (10.6 µm) tends to shift to 50% for larger dots. This information could be useful to maximize the determinist noise on the printed code.

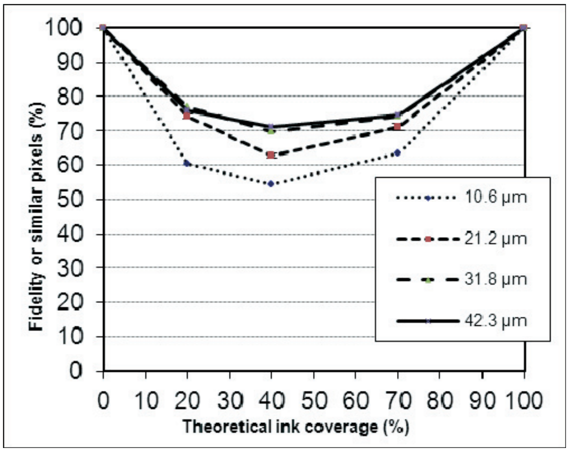


Figure 9: Similar pixels (fidelity) versus theoretical ink coverage (calculated with equation (2)) for the different dot sizes - waterless offset, uncoated paper

The evolution of dot gain (experimental ink coverage - theoretical ink coverage) versus theoretical ink coverage is shown on figure 10 for coated and uncoated paper.

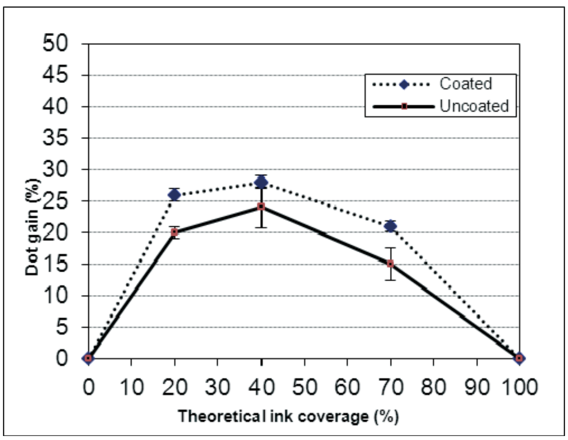


Figure 10: Evolution of dot gain versus theoretical ink coverage, for coated and uncoated paper, 21.2 µm theoretical dot size, 1200 dpi

One maximum is observed at 40% ink coverage for both kinds of papers. Reproducibility is improved with coated paper, and standard deviations substantiate that the gap between the curves is representative. The conclusions are similar for each printing definition. Random noise is the substance of unforgeability: it is expected to be, neither too big, because the code has to be camera-readable, nor too small to ensure its security so that no algorithm could retrieve the original source file. In biometrics language, these considerations look for the best compromise in minimizing FAR (False Acceptance Rate) and FRR (False Rejection Rate) [Bon, 2008]. The established method allows following the evolution of this error. On Figure 10, for a theoretical 21.2 µm dot size, maximum random error is observed with uncoated paper, at about 40 % theoretical coverage. Indeed, measured dot gain is 24 % ± 3 %.

3.2 Characterization of each dot

Figure 11 depicts an example of the statistical measurements on each individual dot. Results highlight that coated paper has higher dot enlargement but a lower perimeter, meaning that dot shape is more irregular on uncoated paper. This point out that coated and uncoated paper may have a different influence on the determinist and random noise.

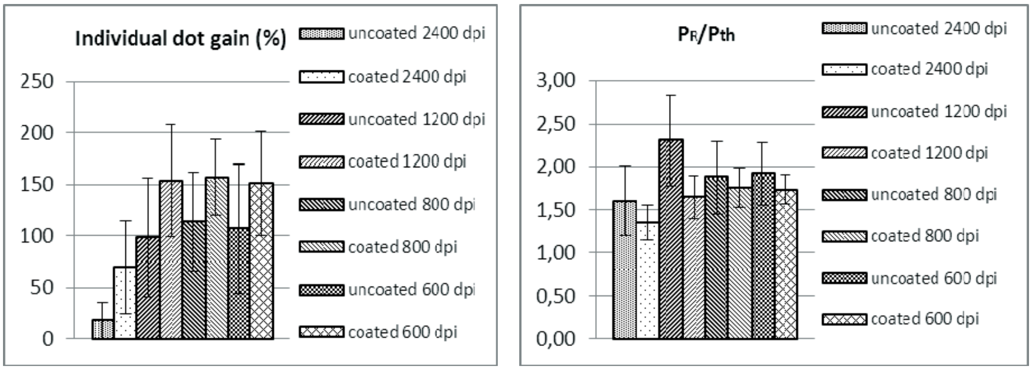


Figure 11: Statistics on elementary dots. Individual dot gain versus Crofton perimeter (P_R)/theoretical perimeter (P_{th}) ratio, for each paper and resolution

3.3 Counterfeiting assesment: highlight on criteria relevance

A sample printed by Waterless Offset, 20 % theoretical, coated paper, 1200 dpi was chosen as the original code that will be counterfeited. The first printed code acquired was reprinted by electrophotography process on another uncoated paper to get a second printed code, the counterfeited one, that is also acquired with Zeiss AxioImager Microscope.

The original code is reprinted with a resolution of 1200 dpi, from 106*106 pixels file (like the original) but also from 212*212 and 424*424 pixels (figure 12).

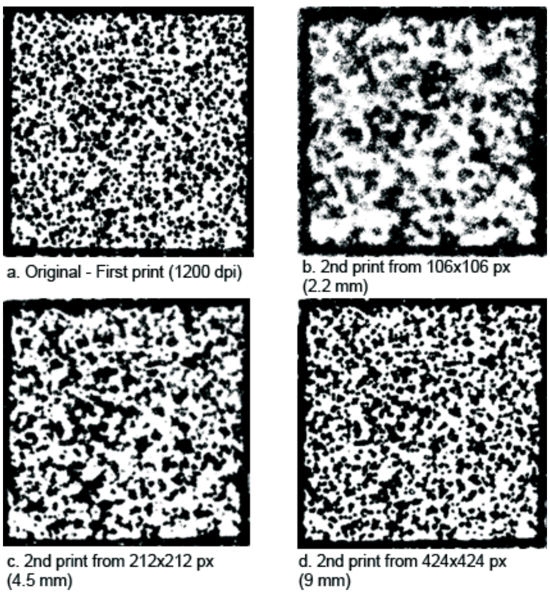


Figure 12: Thresholded pictures of original and counterfeited codes, 20% theoretical ink coverage

Table 2 summarizes the results of characterization of a complete code.

Table 2: Characterization of the counterfeited samples, 20% theoretical ink coverage

samples	counterfeited 1200 dpi, 106px²	counterfeited 1200 dpi, 212px²	counterfeited 1200 dpi, 424 px²	original 1200 dpi
fidelity to the original (%)	69.3	70.9	77.1	(100)
measured ink coverage(%)	39	41	45	47

As expected, the fidelity and the details of the dots of the counterfeited samples decrease when the printing resolution increases. All measured ink coverage percentages are lower than the original ones. No individual dot is reproduced in counterfeited 1200 dpi, from 106 pixel² binary file. Only the big clusters are reproduced. 54% of individual dots are reproduced in counterfeited 1200 dpi, from 212 pixel² binary file, the others are clustered or lost (or just become traces, unconsidered). And all the individual dots are reproduced in counterfeited 1200 dpi, from 424 pixel² binary file.

Counterfeited, statistics on individual dots are measured and compared to the measures on the original sample. Figure 13 depicts the main results.

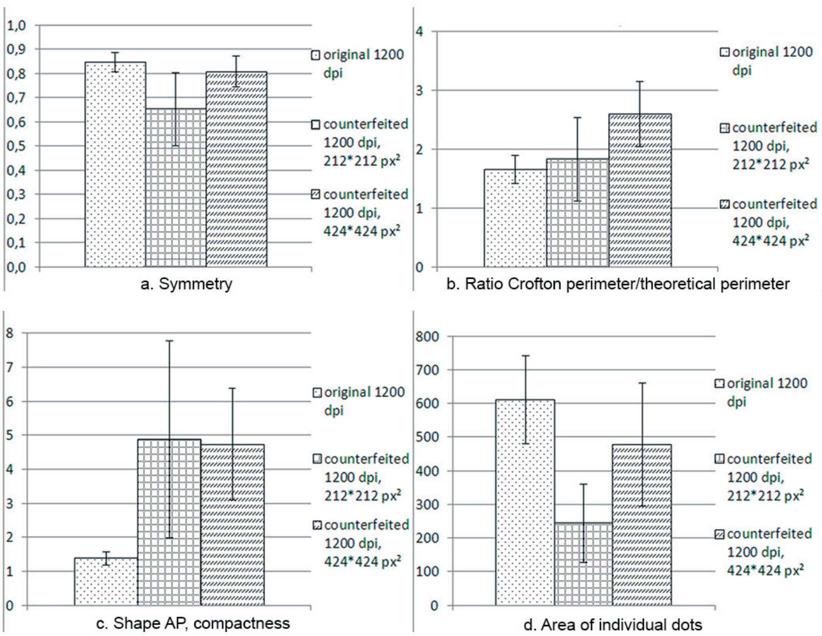


Figure 13: Shape criteria of original and counterfeited samples

Figure 13 d shows that individual dot enlargement is 22% lower on counterfeited 1200 dpi 424*424 pixel² and 58% lower on counterfeited 1200 dpi 212*212 pixel² than the original. Shape factors Figures 13 a, b and c show that the dot distortion increases: the original printing has more symmetrical individual dots, a lower perimeter and is 4 times more compact, with a lower standard deviation for all criteria.

Even if the standard deviations of the shape AP factors are taken into account, there are no overlapping values between original and counterfeited measurements. This demonstrates the performances of the proposed analysis protocol.

4. Conclusions

Noise analysis and associated models would enable to improve the performance of codes authentication systems and to conceive codes difficult to counterfeit. For a complete code the percentage of similar pixels and the dot gain have been investigated for coated and uncoated paper printed with waterless offset process. For each dot the area and criteria of dot shape have been studied.

As a compromise, a printing strategy must be found between parameters that generate maximum noise and that let the 2D code decodable [Sim, 2008]. This compromise depends on the process and on the printed substrate. This study provides quantitative knowledge for developing future models of 2D code printing taking into account digital data as well as process parameters.

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A life cycle approach to environmental aspects in the printing and packaging industry

Kirsten Radermacher, Ulrich Jung, Joachim M. Marzinkowski

University of Wuppertal
Print and Media Technologies
Rainer-Gruenter-Str. 21
D-42119 Wuppertal, Germany
E-mails: nahrgang@uni-wuppertal.de; ujung@uni-wuppertal.de; marzinko@uni-wuppertal.de

Abstract

Sustainable development is one of the most important and pressing topics in society, nowadays. Life Cycle Assessment (LCA) is a suitable instrument for assessing the environmental impact of products. The overall perspective in the LCA detects displacements of environmental burden and gives a comprehensive view on the environmental performance of products.

In this paper, results of a comparative cradle-to-gate LCA study of two different laminating films commonly used for coatings in the printing and packaging industry - polypropylene-based and cellulose-based films - are presented.

The LCA results show savings of non-renewable resources viz. oil in the product life cycle of cellulose-based laminating film. However the global warming potential is significantly higher than for the polypropylene-based type.

The research demonstrates the necessity of the life cycle approach to identify the environmental burden of products in the printing and packaging industry. The choice of impact categories in the LCA procedure is important for the communication of ecological sustainable products. The consideration of individual aspects, i.e. material consumption, is not enough. Furthermore, the uncertainty analysis of the data enables further information and provides the interpretation of the results. Statements about the environmental burden of products should be supported by a life cycle approach and a comprehensive impact assessment.

Keywords: life cycle assessment, renewable resources, global warming potential, coatings, laminating film

1. Introduction

Sustainable development is one of the most important and pressing topics in society, nowadays, and therefore 'sustainability' is a term often mentioned in communication. As a consequence, its meaning has become increasingly vague (Grober, 2010). The notion is broadly characterized in the Brundtland report (1987) and the UN Conference on Sustainable Development (1992) (Grunwald et al., 2006). Originally, 'sustainability' refers to the responsibility of society for following generations. Resources should be preserved so that the quality of life and global equality is possible, from generation to generation. Therefore, ecological, economic and social aspects should be considered equally (the three pillar concept). Thus, the term 'sustainability' involves all these three aspects.

The assessment of the sustainability of products, processes or companies requires an overall perspective. Taking this into account, the three pillars and all the aspects within each pillar have to be considered. In the following, the life cycle approach will be explained in the area of 'ecological sustainability'. Life Cycle Assessment (LCA) is a suitable instrument for assessing the environmental impact of products, processes or companies (Schulz, 2001). An extensive approach is necessary to detect displacements of environmental burden (Fava, 2002). Therefore, all of the life cycle stages have to be examined.

Additionally, sustainability is a term used increasingly in industry, including the printing industry, to promote marketing activities. This leads to a clearer picture of a product for end consumers without the relevant technical knowledge. As a result, background information has to be proven and reliable. The consideration of individual aspects and impacts could lead to inaccurate or wrong conclusions. Especially in the process of product development, the industry must consider that (1) the resources are utilized attentively, (2) they are procured fairly and (3) environmental impacts are minimized.

This paper focusses on the 'ecological sustainability' of a specific product in the printing and packaging industry. The product life cycle of laminating films used for coatings is assessed.

This research aims to demonstrate the necessity of the life cycle approach to identify the environmental hot spots of products in the printing and packaging industry. In this context, the utilization of renewable material for laminating films is discussed.

2. Methods

A comparative, cradle-to-gate LCA study of laminating films was carried out. To achieve this, the life cycle of two different laminating films, (1) oriented polypropylene film (OPP) and (2) cellulose-based film, were analyzed and assessed.

The product system involves all upstream processes of laminating film - from resource extraction to the production process of plastic film.

The software OpenLCA was used to model the product life cycle and assess the environmental effects. Inventory data were taken from the Life Cycle Inventory (LCI) database ecoinvent v2. For the impact assessment (LCIA), the EDIP2003 method was used. This LCA phase was focused on the impact categories 'resource consumption' of wood and oil and on the Global Warming Potential (GWP_{100}). The LCA study was conducted in compliance with the ISO standard 14040/44.

2.1 Product life cycles

In this section, the life cycles of conventional OPP film and cellulose-based film are described in detail.

2.1.1 Polypropylene-based laminating film

Polypropylene is a petrochemical polymer. There are various conversion processes for polymer granulates commonly in use. The extrusion process is employed to manufacture laminating films for the packaging industry. The main process steps are shown in Figure 1.

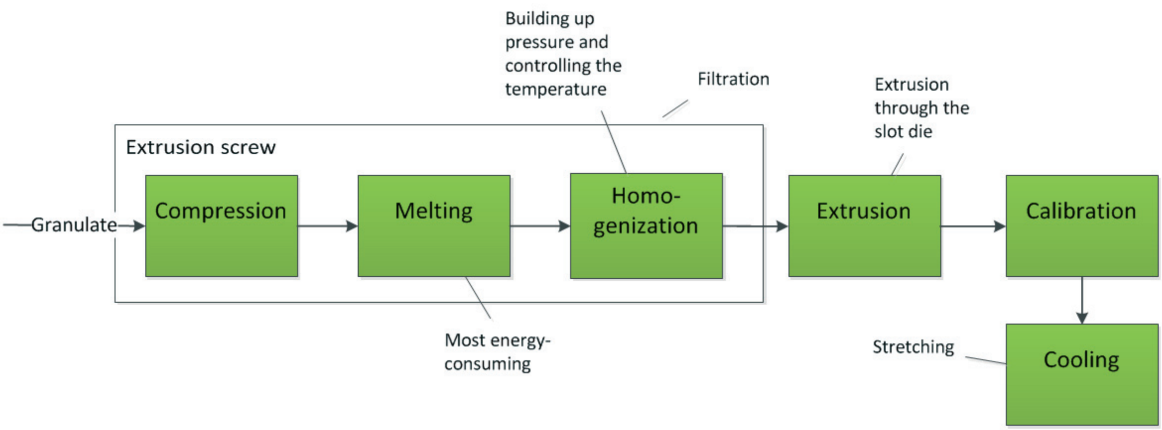

Figure 1: Model of the manufacturing process for extruded laminating film according to Habersatter et al. (1998) and Greif et al. (2004)

These inventory data include average data for the manufacturing process of polypropylene, polyethylene and polyvinylchloride, which are generally used in the extrusion process of plastic films (Hischier, 2007).

2.1.2 Cellulose-based laminating film

Cellulose-based polymer is a type of biopolymer. The manufacturing process that is chosen depends on the kind of industrial application. An overview of processing types is shown in Strunk (2012). Laminating films are generally manufactured from viscose. The production chain is presented in Figure 2.

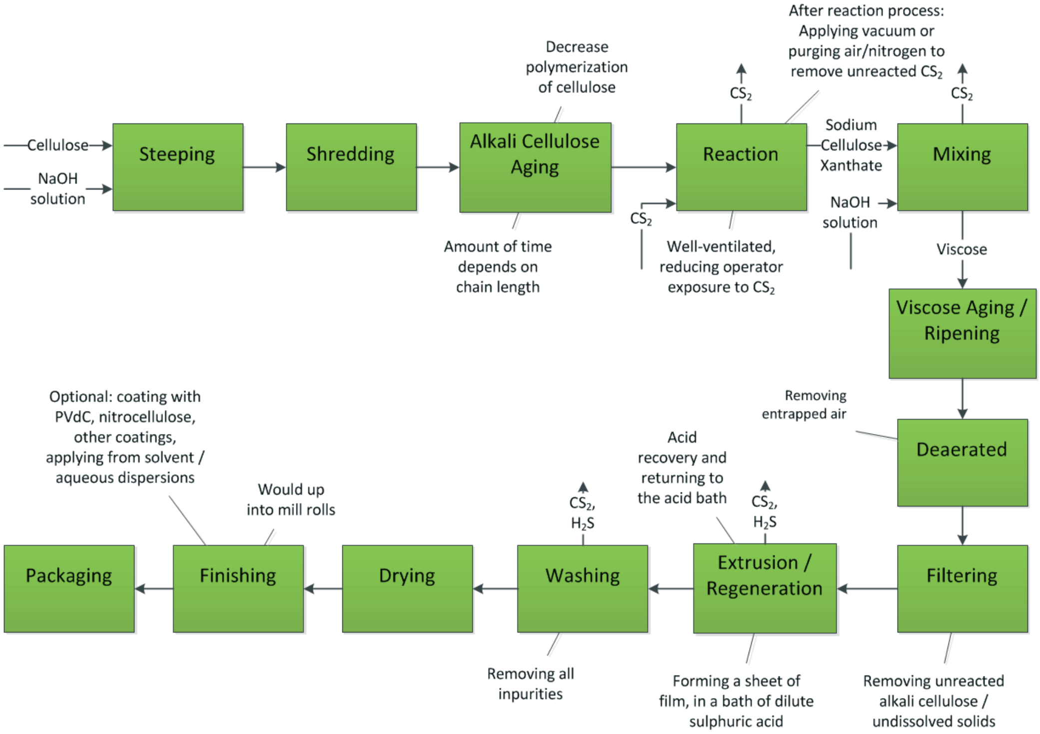

Figure 2: Model of the manufacturing process for cellulose-based laminating film according to Crump (2000)

Crump (2000) pointed out that the raw materials and processes involved are the same, irrespective of the industrial application. Viscose production is also common in the textile industry.

Due to the lack of sufficient inventory data for the production of laminating film in the packaging industry, the authors of this paper took inventory data from the viscose production in the textile industry (Althaus et al., 2007). Similar assumptions were made in Hermann et al. (2010).

The inventory data were verified whether they agreed with the manufacturing process described in Crump (2000). For this purpose, the inventory data were modified. The cellulose-based laminating film, considered in this LCA study, is manufactured from sulphate pulp of eucalyptus. In general, plastic wastes of renewable and non-renewable material are treated in the same way. Hence, the plastic waste is assumed to be burned to 100 % in a municipal waste incineration (cf. section 2.1.1).

For the transport packaging, the raw material was assumed to be transported in rolls. These inventory data of the packaging material were taken from the product system of corrugated boards.

2.2 Data uncertainty and availability

In this paper a Monte Carlo simulation is utilized to verify the data uncertainty. In the life cycle inventory, the uncertainty pedigree matrix of Weidema et al. (1996) was used as a measure of data uncertainty. The uncertainty of cumulative and aggregated input data, e.g. energy-related processes and the extraction and production process of the polypropylene granulate, were neither investigated nor considered in the Monte Carlo simulation of this study. The data uncertainty and error propagation is calculated in the simulation with 10 000 iterations.

3. Results

The cellulose-based laminating film could be seen as an alternative for the polypropylene-based one. The petrochemical raw material is therefore replaced by renewable wood to reduce the amount of oil deployed in the product life cycle.

The LCA results (Figure 3a) confirm the assumption: about 50 % of oil could be saved.

If the data uncertainty and the error propagation are considered, a great uncertainty in the LCA results can be recognized in both product systems (see Figure 3b). This could lead to a differentiated statement. In the impact category 'oil consumption', the LCA results show that a certain probability exists, which could lead to a reversal of the product ranking. In a best-practice scenario, a smaller rate of oil resources is needed in the product system of the cellulose-based laminating film. A clearer picture is shown for the impact category 'wood consumption': The ratio is significant, so that negligible uncertainty in the product ranking could be expected here.

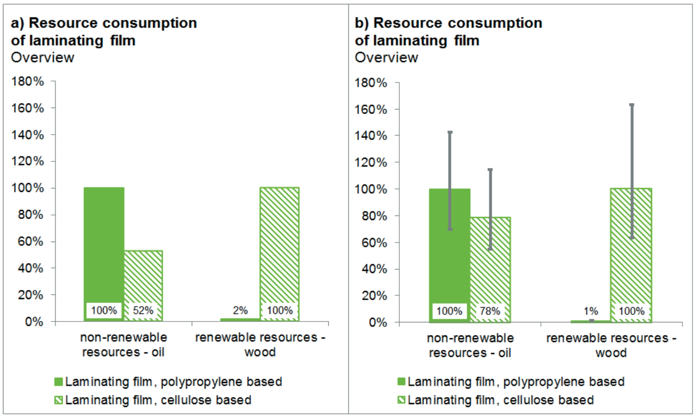

Figure 3: Environmental impact assessment of cellulose-based laminating film (29.5 g/m²) and OPP laminating film (18.2 g/m²); resource consumption of wood and oil (LCIA method: EDIP2003); a) LCA results without uncertainty analysis; b) LCA results with uncertainty analysis

In the dominance analysis, the life cycle stages 'raw material extraction/processing', 'distribution' and 'manufacturing' are investigated according to their contribution to the total consumption of oil and wood (see Table 1).

Table 1: Results from the dominance analysis of the life cycle stages 'raw material extraction/processing', 'distribution' and 'manufacturing' in the impact categories 'wood consumption' and 'oil consumption'

Contribution to wood consumption [%]	Raw material extraction/processing	*Distribution (transport and packaging)*	Manufacturing
Polypropylene-based film	0.2	*97.5*	2.3
Cellulose-based film	81.1	*0.5*	18.4
Contribution to oil consumption [%]	Raw material extraction/processing	*Distribution (transport and packaging)*	Manufacturing
Polypropylene-based film	97.9	*1.1*	0.9
Cellulose-based film	46.0	*4.7*	49.2

In section 3.1 and 3.2, the results of the dominance analysis of the life cycle stages (Table 1) are discussed intensively, together with the results from process flow diagrams.

3.1 Resource consumption of renewable material (wood)

The product life cycle of polypropylene-based film is mainly free of wood-based material (see Figure 4). The main contribution is located in the distribution stage of the raw material to the manufacturer (see Table 1).

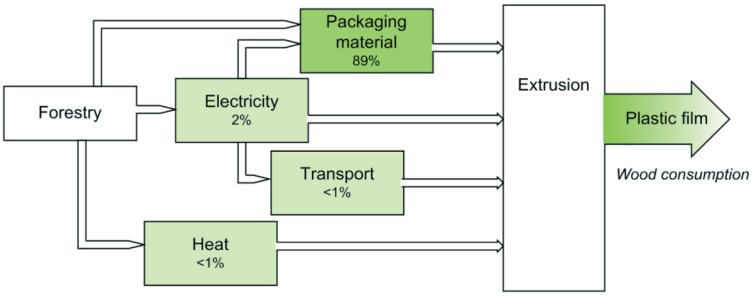

Figure 4: Life cycle analysis of polypropylene-based laminating film: Substance flow of wood-based resources; Infrastructure and disposal processes are cut off

89% of the wood consumption is used for transport packaging material. In the term 'packaging material', various packaging materials are summarized, assumed to be required for transportation (Hischier, 2007). Slight amounts of wood are consumed in the energy-related processes.

The product life cycle of cellulose-based laminating film is primarily based on wood. Thus, the extraction and production of the raw material broadly contributes to the impact category (cf. Table 1). The pulp production chain and its upstream processes lead to a wood consumption of 66% (see Figure 5). 14% is used for heating from wood chips during the manufacturing.

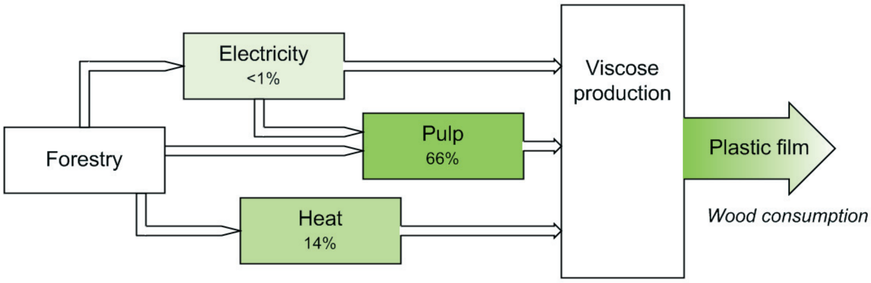

Figure 5: Life cycle analysis of cellulose-based laminating film: Substance flow of wood-based resources; Infrastructure, packaging material and disposal processes are cut off

In conclusion, these results were to be expected. The resource consumption of wood is significantly higher in the product chain of cellulose-based film, because the main material is pulp.

3.2 Resource consumption of non-renewable material (oil)

In the product system of polypropylene-based laminating film, 98% of the oil consumption is caused by the raw material extraction and processing (see Table 1, Figure 6).

The impact of the material extraction and the manufacturing process of the polymer granulate is only presented as a black-box system. Consequently, a hot spot analysis according to the process flows is not possible, in this part of the life cycle. Further process flows are neglectable.

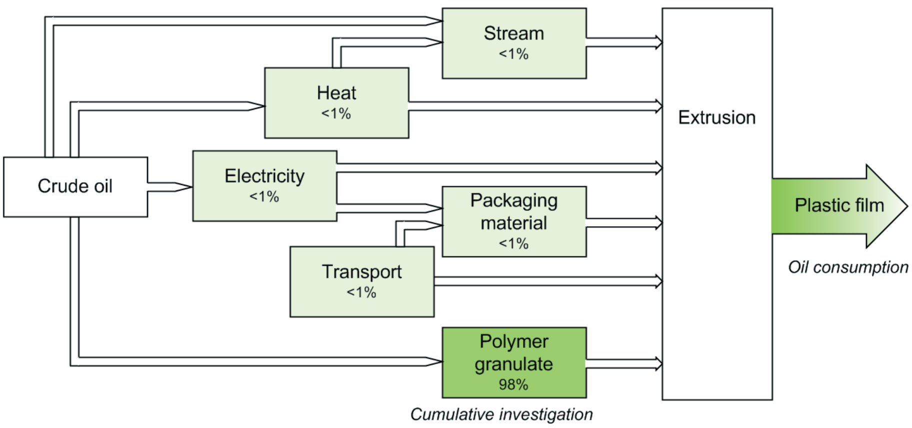

Figure 6: Life cycle analysis of polypropylene-based laminating film: Substance flow of oil-based resources; Infrastructure and disposal processes are cut off

In this product life cycle of the cellulose-based laminating film, 46% of the oil is spent in the production chain of pulp. The manufacturing process also contributes to the oil consumption (see Table 1). The process flows for the transportation and the chemical extraction/processing have a significant influence on this rate (see Figure 7).

In conclusion, the hot spot analysis shows a greater consumption of oil in the product chain of polypropylene-based laminating film. However, the product life cycle of cellulose-based laminating film has also a significant influence on the oil consumption.

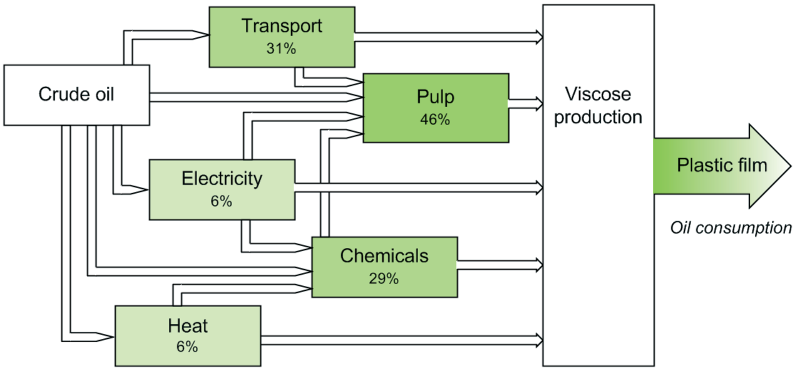

Figure 7: Life cycle analysis of cellulose-based laminating film: Substance flow of oil-based resources; Infrastructure, packaging material and disposal processes are cut off

3.3 Global Warming Potential, GWP_{100}

GWP is one of the best investigated and most common impact categories for describing the ecological sustainability of products.

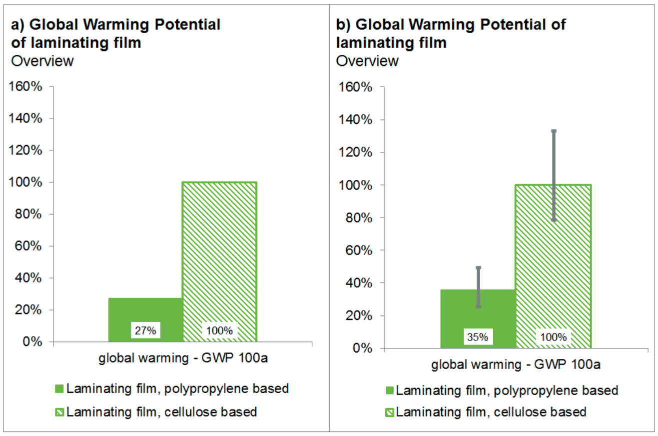

Figure 8: Environmental impact assessment of cellulose-based laminating film (29.5 g/m²) and OPP laminating film (18.2 g/m²); Global Warming Potential, GWP_{100} (LCIA method: EDIP2003); a) LCA results without uncertainty analysis; b) LCA results with uncertainty analysis

According to this LCA study, the cellulose-based laminating film reaches a three times higher level than the polypropylene-based type (see Figure 8a). The data uncertainty and error propagation are shown in Figure 8b. The amounts are significant but do not reverse the product ranking.

Table 2: Results from the dominance analysis of the life cycle stages 'raw material extraction/processing', 'distribution' and 'manufacturing' in the impact category 'Global warming potential, GWP_{100}'

Contribution to GWP_{100} [%]	Raw material extraction/processing	Distribution (transport and packaging)	Manufacturing
Polypropylene-based film	87.0	2.2	10.9
Cellulose-based film	19.6	1.3	79.1

The raw material extraction and processing has the main influence on the global warming in the polypropylene-based film. In the cellulose-based product system, the manufacturing process contributes decisively to the score.

The sankey diagram of the polypropylene-based laminating film indicates high contributions of the raw material processes (see Table 2, Figure 9). The manufacturing process of the laminating film from polymer is energy-consuming (11%).

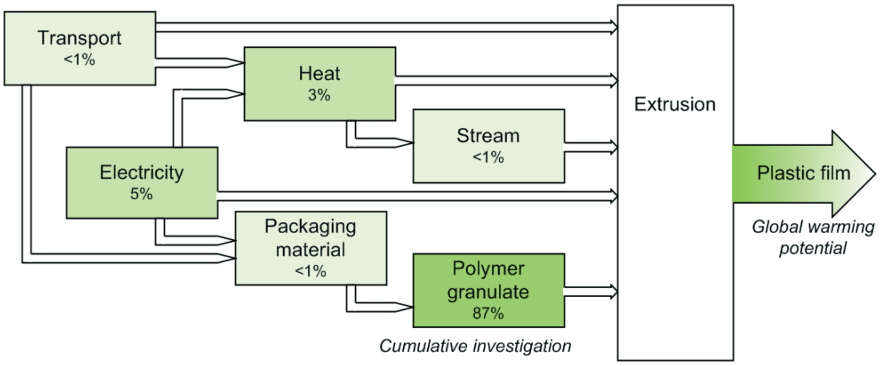

Figure 9: Life cycle analysis of polypropylene-based laminating film: process flow of GWP-related substances; Infrastructure and disposal processes are cut off

In the sankey diagram of the cellulose-based laminating film, the main contributor to the global warming potential is the chemical processing (see Figure 10). Together with a certain consumption of energy, the life cycle stage of the raw material (20 %) and the manufacturing process (79 %) broadly contribute to the total GWP (see Table 2).

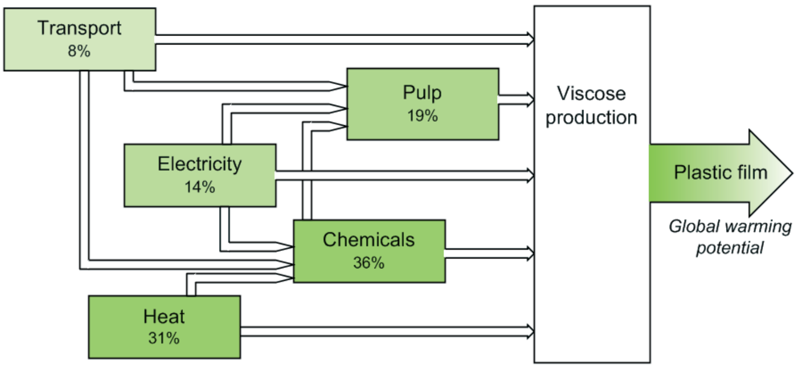

Figure 10: Life cycle analysis of cellulose-based laminating film: process flow of GWP-related substances; Infrastructure, packaging material and disposal processes are cut off

In conclusion, the detail analysis shows higher energy consumption and a significant chemical use in the manufacturing of the cellulose-based type, leading to a higher overall impact to the climate change.

4. Conclusions and discussion

The paper shows the environmental burden of two different laminating films commonly used for coatings in the printing and packaging industry. Therefore, a comparative cradle-to-gate LCA study was conducted. This view excludes the application processes in the finishing company and the disposal of the coated packaging. For this comparative analysis, this system boundary is sufficient. There are no differences in the processes outside the system boundary expected, which could affect the product comparison in this study. The life cycle impact assessment (LCIA) method EDIP2003 is choosen for the calculation of environmental impacts. This LCIA method includes categories to quantify the consumption of resources, e.g. wood and oil. The focus of recent research has been on these two categories, because these aspects are the reason for discussions in the community of the printing and packaging industry: The cellulose-based laminating film was developed to give an alternative to the petrochemical type. Thus, this kind of laminating film should reduce resource consumption of non-renewable oil. Non-renewable polypropylene is therefore replaced by renewable pulp.

The Global Warming Potential (GWP_{100}) is also taken into account, which is usually used as a representative of the environmental impact of products. The LCIA method of EDIP2003 refers to the global warming potentials developed by the Intergovernmental Panel on Climate Change (IPPC). This source is up-to-date and accepted in the LCA community (EC-JRC, 2010, 2011a, b; Hauschild et al., 2013).

Therefore, the EDIP2003 method is suitable for the LCA study presented in this paper.

Further impact categories are excluded. For the research goal - demonstration of the necessity of a life cycle approach to inform about environmental burden in the printing and packaging industry - this proceeding is appropriate for the analysis.

The LCA results are based on secondary inventory data from the ecoinvent database. Significant technological improvements or disruptive technology steps in this industry are not known. Thus, the data are assumed to be up-to-date even though the data are of high age.

The raw material process and its upstream processes for the polypropylene-based product alternative are integrated as a black-box system. This data aggregation complicated the interpretation of LCA results and limited the degree of information. In this study, the raw material extraction and processing is therefore treated as a black box in both product alternatives to reach the same point-of-view.

The LCA results show that a lower amount of oil is needed in the life cycle of cellulose-based laminating film. The uncertainty analysis presents a certain probability that these product ranking could be reversed. But if we assume a best-practice scenario, not the half but a smaller amount of oil could be saved by choosing the cellulose-based laminating film. However, the global warming potential of this laminating film type is about three times higher than the potential of the petrochemical type. These results do not allow a clear decision about the preferable alternative of laminating film. Nevertheless, these investigations show that the impact categories which are chosen for the communication of ecological sustainable products are crucial.

In this LCA study, the uncertainty of data and the error propagation was quantified by a Monte Carlo simulation. This additional information is necessary for the interpretation of the LCA results. In the case of oil consumption, the uncertainty could turn around the product ranking. However, uncertainties are not given for all input data in the product systems in question. This means, a higher uncertainty in the results as shown in the diagrams could be expected. As visible in the LCA of the cellulose-based laminating film, the cellulose production has a great influence on the LCA results. The inventory data considered in this study have a high uncertainty. Hence, inventory data from further sources (Gonzalez-Garcia, 2009; Gonzalez, 2011) were included in the sensitivity analysis of this LCA study. There are similar results reached in the impact category of global warming potential.

In conclusion, this paper confirms that a life cycle approach is necessary to give information about the environmental impact of printed products. The consideration of individual aspects, i.e. material consumption, is not enough for communication. Statements about the environmental burden of products should be supported by a life cycle approach and a comprehensive impact assessment.

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Novel surface preparation concept for improved deinking: bringing digital, functional and water-based prints into the mainstream recycling process

Patrick A. C. Gane[*]

School of Chemical Technology
Department of Forest Products Technology, Aalto University
P.O. Box 16300, FIN-00076 Aalto, Finland
Email: patrick.gane@aalto.fi

[*] Gane is also Vice President R&D, Omya International AG, CH-4665 Oftringen, Switzerland

Abstract

Recycling of printed paper and board is recognised as being both economically and environmentally advantageous, especially in large populated areas of conurbation. The procedures for deinking of printed products have become well established for the traditional rotogravure, offset and newsprint grades. Digital printing, however, delivers printed papers into the recycling chain with a wide variety of ink, pigments, dyes and toner types, which are often incompatible with the oleophilically-based separation technology of froth flotation agents. Increasingly, digital and flexographic printed packaging board and newsprint are presenting similar challenges to those of the already identified problem grades, namely office papers, due to their similarly dominant use of water-based ink formulations containing hydrophilic ink components. The expansion of printed functionality will also bring environmentally challenging ink components into the recycling stream, such as are used for conductive, light sensitive or capacitive effects. Electro-photography and inkjet, for example, adopt various colorant technologies ranging from dry fusible powder to liquid toners, and pigment and dyes, respectively. Whilst residual dyes in principle could be corrected for by bleaching, semi-hydrophilic ink pigment contamination of the recycled fibre stock is a major problem, degrading the quality and leading to potential deposits in the form of stickies and subsequent print quality defects in the following papermaking and printing processes. Instead of concentrating on the issue of deinking flotation chemical compatibility, the work presented in this paper illustrates a mechanism for the direct separation of ink from the paper surface using a specially designed exfoliating coating layer, exemplified by a calcium exchanged nanoclay in the form of a smectite montmorillonite, bentonite. Immersing the printed product in a caustic bath leads to the release of the applied ink layer together with a monolamellar mineral particle layer, which in turn could, in principle, be floated using silicate selective frothing agents well-known in mineral beneficiation technologies. In principle, this technology could be adopted for all printed media to enhance de-inked pulp (DIP) quality as well as opening the potential for recovering coating pigments in high bright form, instead of delivering to land-fill in today's standard deinking sludge waste.

Keywords: recycling, deinking, deinking of office paper, deinking of printed functionality, surface deinking exfoliating coating, recycling of digital prints, nanoparticle coatings, nanoclay

1. Introduction

In the UK alone, in 2011, 74% of all fibre used in the paper and packaging board industries was recycled (CPI, 2012). Recycling of printed paper and board is recognised as being both economically and environmentally advantageous, especially in large populated areas of conurbation. The movement toward recycling has achieved resonance in the community and forms a strong export good, in particular for fibre-strapped countries, such as China, which are growing at an extremely rapid rate in respect to the consumption of paper, tissue and paperboard.

The procedures for deinking of printed products have become well established based on flotation (Fuerstenau *et al*., 2007; Klassen and Makrousov, 1963; Finch and Hardie, 1999). The use of froth flotation relies on the attachment by adsorption of flotation chemicals, known as collectors, essentially frothing agents, onto the ink particles and pigment aggregates formed during the re-pulping or mulching of the delivered waste printed papers and boards. The principle of separation by flotation is based on the surface energy potential of hydrophobic species to collect at an air-water interface (Shen *et al*., 2006; Taylor *et al*. 1996, Du *et al*., 1993, Lee *et al*. 1984). The flotation agent attached to the oleophilic surface of the ink contaminant generates a consistent hydrophobicity, trapping the particle(s) at the interface of an air bubble, which in turn floats by buoyncy to the surface, and is subsequently removed by skimming the froth to form a dark sludge waste material.

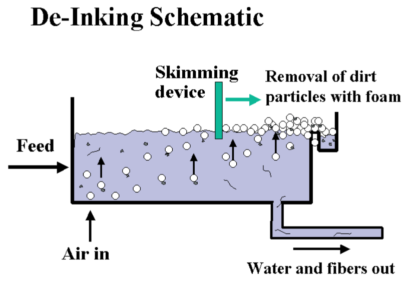

Figure 1:
Schematic of a flotation cell
(taken from www4.ncsu.edu)

The established flotation collector agents are well-suited for the traditional rotogravure, offset and newsprint grades, in which the oil-based ink formulations contain oleophilic pigment, resin and hydrophobic oil components. Digital printing, however, delivers printed papers into the recycling chain with a wide variety of inks, pigments, dyes and toner types, which are often incompatible with the oleophilic-based separation technology of the traditionally used froth flotation agents. Even 5-10 % addition of digitally printed papers could spoil the whole recovered paper mixture because the brightness of the recycled pulp decreases radically. Even more than 50 % decrease in the brightness is possible (Hanecker and Strauss, 2008; Fischer 2005; Carre and Magnin, 2004). Two problems exist in the ink removing process: either the ink layer does not come off at all or the particle size of the inks or toners is not suitable for flotation. Usually, the main problem is the poor ink removal. Inkjet and electrophotography are the most common digital printing methods used in the home and office environment. The problem when deinking inkjet paper is the small ink particle size which cannot be removed with flotation. The ink is also attached very tightly to the paper surface so the ink removal is not efficient. With laser printed paper the particle size of removed ink/toner is too large and soft and so is also difficult to remove. Toner removal from the paper surface is also only partial. Not all toners can be removed by using flotation.

Electrophotography and inkjet adopt various colorant technologies ranging from dry fusible powder to liquid toners, and pigment and dyes, respectively (Laden, 1997). Whilst residual dyes in principle could be corrected for by bleaching (Kipphan, 2001), it is also possible, when the contaminant is purely organic, to use methods such as critical oxidation, in which organics become soluble in water under critical conditions and can be readily oxidised and so removed from the system (Argyropoulos *et al*., 1988). The growing use of water-based pigment-containing inks, therefore, poses an enormous challenge in paper recycling in that the coloured pigment components are colour fast and do not respond to oxidation. Semi-hydrophilic ink pigment contamination of the recycled fibre stock can lead to potential deposits in the form of stickies in the papermaking process (Roberts, 1976), and degrades the paper quality by the appearance of dark agglomerates (specks) (Figure 2), additionally causing subsequent print defects (Byron *et al*., 1993; Fischer 2005), and cannot be corrected for without almost complete removal (Byron *et al*., 1993). A method of removing these independently from the waste pigment sludge could render the sludge reusable following critical oxidation treatment.

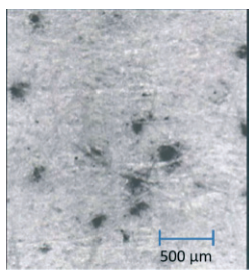

Figure 2:
Typical appearance of a paper sheet made from
recycled pulp containing retained ink specks
(taken from Byron et al., 1993)

Increasingly, digital and flexographic printed packaging board and newsprint are presenting similar challenges to those of the already identified problem office paper grades, due to their similarly dominant use of water-based ink formulations containing hydrophilic ink components (Sharma, 1991; Laden, 1997). The expansion of printed functionality will also bring environmentally challenging ink components into the recycling stream, such as are used for conductive, light sensitive or capacitive effects.

Instead of concentrating on the issue of deinking flotation chemical (collector) compatibility with the ink or toner type, or the separate removal of the remaining ink agglomerates, this work presents a concept for the direct separation of ink from the paper surface using a specially designed exfoliating coating layer.

2. Materials and methods

2.1 Smectite nanoclay

The properties of smectites centre about their layered crystal structure, as shown in Figure 3. Smectite is the general name given to layered silicates (hydrated aluminium silicate) of the montmorillonite family, which includes bentonite. Bentonites are used widely for chemical and industrial uses, for example in oil drilling, the paper industry and cosmetics. The layered nature allows for exfoliation into individual platelets, each with a thickness on the nano-scale, hence their recognised importance in the nanominerals (nanoclay) field.

Three most important properties of smectites are particle shape, size and charge. The shape of smectite is platy and it consists of many layers. The edges of the plates are positively charged and the faces are negatively charged. This charge difference is accentuated at reduced pH. The structure of the plates is described in Figure 3 (Stock-well, 1997).

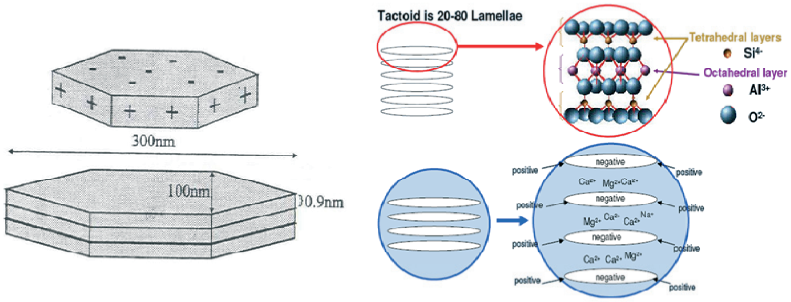

Figure 3: The crystal habit structure of the smectite plates (Stockwell, 1997, p179)

Bentonites are either used in their naturally hydrophilic state or artificially made hydrophobic. The most frequently commercially used bentonite is the sodium, or water-swellable, form. Especially, sodium bentonite has a high swelling capacity when it is in contact with water. Because of the swelling ability the surface area grows, frequently up to 700-800 m^2g^{-1}. Bentonite is also known for its high cation exchange capacity (CEC) and adsorption properties. Figure 4 shows the crystalline structure of montmorillonite (USGS).

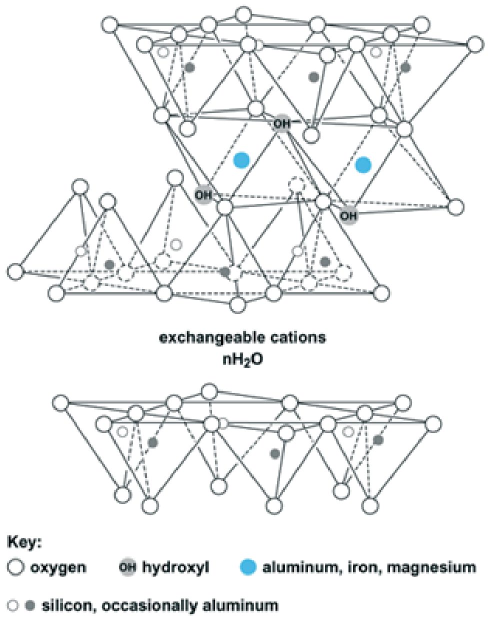

Figure 4: Structure of montmorillonite as example of a smectite nanoclay (taken from the US Geological Survey (USGS) open file Report 01-041)

The common exchangeable ions control the swelling ability of the bentonite tactoids consisting of 20-80 individual platelets. Every platelet has the same structure: in the middle is an octahedral layer of Al^{3+} and O^{2-} ions, which is surrounded by two tetrahedral layers of Si^{4+} and O^{2-}. This is the reason for the negative charge on the faces of the plates. Between the plates is a layer of cations, such as Mg^{2+}, Ca^{2+} and/or Na^{+}. This layer acts to counterbalance the negative charge. Bentonite can be readily dispersed in water in its calcium or sodium form. The sodium form results in a gel-like structure. A water-based coating or preprint could therefore be made prior to office or flexo printing. The nanoparticles upon drying film form and are self-binding, i.e. to themselves and to the paper/substrate surface (Figure 5). They can also be incorporated in organic solvent systems in the form of organo-clays allowing the possibility of forming an offset or rotogravure formulation such that a pre-print could also be made in these processes.

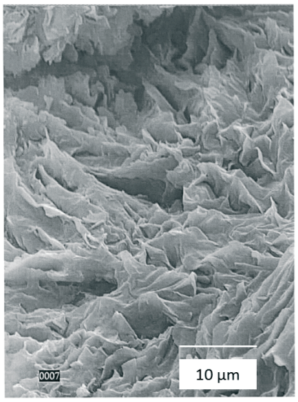

Figure 5: Electron micrograph of montmorillonite as it forms a film from its layered silicate lamellae

Smectite is removable by flotation using silicate attaching surface-active agents (Bell and Zefaratos, 1977). Although this is not selective to smectite alone, and so will include kaolin and talc, the potential for mineralogical separation would still favour high brightness species remaining in the mineral deinking sludge. Furthermore, the attachment of otherwise hydrophilic inks, as also ink pigments across the spectrum of ink types, to smectite could render the flotation process more efficient.

2.2 Exfoliation

Exfoliation can be made by exchanging the cations in the crystal inter-lamellar surface, for example from Ca^{2+} to Na^+ and then dispersing in water. If a process of exfoliation were to be included prior to flotation then a pre-separation of the ink layer from the coating surface might be envisaged.

2.3 Details of bentonite applied

The bentonite chosen was a commercially available product used primarily in the cosmetics industry, Gellant Optigel® CK1 (Rockwood Additives Limited, Moorfield Road, Widnes, Cheshire, UK). The product is hydrophilic and supplied in the sodium exchanged form. It can be easily introduced to water, having a high swelling capacity. Table 1 shows the relevant product technical data.

Table 1: Bentonite technical data

Product form	Powder
Moisture content / %	3-13
Colour	White
Brightness / ISO %	~ 60-65
Viscosity / mPas (5 % solids after 1 h)	> 400 (Brookfield 100 min^{-1})
Density / gcm^{-3}	2.6
Loose bulk density / gdm^{-3}	550-700
Median equivalent spherical diameter particle size by weight (d_{50}) at complete dispersion / µm	~1
pH (2 % suspension)	9-11

2.4 Coating colour

Many trials were made to find an optimal formulation for the bentonite coating colour. The bentonite was first dispersed in warm tap water, to aid the swelling of the tactoids. In the resulting gel form the dispersed bentonite platelets are surrounded by Na^+ ions. The mixture was stirred for 15 minutes to produce an even consistency. A convenient dosage level range of bentonite was found to be 0.1 - 3% solids content in the sodium form. With higher consistencies than these, the mixing of the bentonite with water was problematic. The pH of the bentonite gel was around 11. The gel was allowed to age overnight to avoid further post makedown thickening.

To initiate the calcium ion exchange effect, calcium chloride/calcium hydroxide was added to the gel. When adding Ca^{2+} ions to the mixture, an intercalation between the bentonite platelets occurs. In the early trials both calcium chloride and calcium hydroxide were used. Soon it was noticed, however, that calcium hydroxide led to ever increasing pH, after which only calcium chloride was used. When adding calcium chloride step by step, the gel finally collapsed and it became fluid. This phenomenon occurred when the pH was around 8 or 9. In this calcium form, solids levels of 7.5 - 8.5% solids could be used to get higher viscosity for coating. CMC (Finnfix 10, Cumberland Center II, 3100 Cumberland Boulevard, Suite 600, Atlanta, Georgia 30339 USA) with 10% dry solids content was added to rethicken the mixture suitable for the traditional coating methods employed. A picture of the bentonite coating colour is shown in Figure 6. The shade of the coating colour is offwhite-grey, and reflects the non-optimal light scattering cross-section of the bentonite in water.

Figure 6: Bentonite coating colour

Table 2 contains the details of the coating formulations. The bentonite is here used in the calcium form, and two coating colours were madedown: one with CMC and another without CMC. The viscosity of the coating colour was adjusted to between 600 and 3500 mPas for good runnability. The viscosity was measured with a Brookfield viscometer (Brookfield Engineering, 11 Commerce Boulevard, Middleboro, MA 02346 USA) using spindle number six. Dry solids content was also measured from the final coating colour according to standard SCAN-P 39:80.

Table 2: Coating colour formulations

		Colour 1	**Colour 2**
Bentonite solids consistency / %		7.5	8.5
Makedown	Bentonite / g	15	17
	Tap water / cm^3	200	200
	1 M $CaCl_2$ / cm^3	12	14
	CMC (Finnfix 10)	0	1.6
	Dry solids content / %	6.4	7.1

2.4 Coating application

Two uncoated paper grades were considered for the test coating: copy grade 80 gm^{-2} A4 sheets and LWC wood containing base paper, grammage 45 gm^{-2}, were used.

For the copy grade sheets, a laboratory rod coater was used to apply the novel nanoclay surface treatment. To apply a variety of controlled coating layer thicknesses eight wire wound rods with different coarseness can be used, and to achieve the desired coat weights, with the additional option of varying the application speed, rod numbers 2, 3, 4 and 5 were found to be suitable, producing coating layer applications of 1-4 gm^{-2} (Table 3).
Only coating colour number 2 was used as it attached better onto the paper. A tape strip was placed on the paper under and in front of the rod to avoid coating colour penetration into the paper prior to distribution on the surface. The coated paper was dried for 3 minutes using a hot-air dryer (air temperature 290° C).

Table 3: Coat weights with different rods and rod speeds

Rod number	Rod speed / mmin^{-1}	Average coat weight / gm^{-2}
2	3	0.8
3	3	2.1
3	4	1.8
3	5	2.4
4	5	3.3
5	5	4.2

The LWC basepaper was coated using a Cylindrical Laboratory Coater (CLC) high speed laboratory coating machine (SimuTech International, Inc., Hoodsport, Washington USA). The CLC coating speed was chosen to be 1 000 mmin^{-1}, and a range of blade pressures was initially used. The trial was made using coating colour formulations 1 and 2 (Table 2 - corresponding bentonite consistencies 7.5 and 8.5 %).

When using standard blade pressure, only very low coating amounts could be applied onto the paper. Although ultralow coat weight might have sufficed on an already coated sheet, the experiment set uncoated base paper as proof of principle, and so higher coat weights were sought to deliver an observable effect and to ensure even coverage. Setting the blade to grazing contact (just touching) a suitable amount of coating (3 gm^{-2}) was applied to the paper. It was found that coating colour 2 (8.5 % bentonite consistency) attached better to the paper partly due to the shear thinning action of CMC.

2.5 Printing and print evaluation

The coated paper samples were printed using two different printers: HP Colour Laserjet 2600n (Hewlett Packard, Palo Alto, CA, USA) and Epson Stylus S20 inkjet printer (Seiko Epson Corp. Head Office, 3-3-5 Owa, Suwa, Nagano 392-8502, Japan). Dry powder toners were used in the laser printer.

The printing method in the inkjet printer was a drop-on-demand, using Micro Piezo™ print head, with pigmented DURABrite™ Ultra-inks.

Figure 7 shows the printed colour scales as used for evaluation of print performance.

Figure 7: The printed colour scales

Variations in the print quality were evaluated by measuring rub-off, density and colour rendering. The samples were first stored at constant air-conditioned temperature (23° C, relative humidity 50 %) for 24 hours.

First, rub-off was measured using the Patra Rubproofness Tester. The measurement is based on rubbing printed paper against unprinted paper. The air-conditioned prints were prepared for the test by cutting them into suitable sized circular sheets, diameter 30 mm. The unprinted papers were cut into circles with diameter 110 mm. Smearing occurred when the printed sample was rotated against the unprinted paper under a pressure of 20 kPa. The rotation velocity of the device was 60 min^{-1} and the number of smearing contact cycles was 100. In these trials, the transferred ink amount was too small to be reproducibly recorded on a densitometer, illustrating excellent ink adhesion to the surface bentonite layer, and so ISO-brightness was measured instead with an L&W SE 070R El-repho Spectrophotometer.

Densitometry (Vipdens 2000: Viptronic Limited, 214 Moss Lane, Bramhall, Stockport, Cheshire, UK) was used to evaluate the transfer of inks onto the paper. Density describes the coverage of the print and the intensity of the colour. It measures how much the print on the substrate absorbs light of the colours other than that of the ink (complementary colours), and how much is reflected. The more the print absorbs the complementary colour light, the higher is the density (Kipphan, 2001, pp100-101). Density, D, is defined as:

$$D = -\log_{10}\frac{I_0}{I} \qquad [1]$$

where: I_0 is the intensity of incoming light

I is the intensity of reflected light at 45° angle

Colour rendering was measured using CIELAB colour space, based on CIE (Commission Internationale de l'Eclairage) standard three-dimensional colour space, Y, x, y, which measures colour difference corresponding as closely as possible to human colour perception ability. Colour values are converted into uniform scale values $L^*a^*b^*$, where L^* describes lightness, a^* and b^* being chromatic components, where a^* represents the red-green proportion and b^* the yellow-blue proportion (Kipphan, 2001, p74-77).

2.6 Caustic bath

The end application requires the printed paper samples to be dipped into 0.1 M sodium hydroxide solution to see if the ink comes off the surface as predicted by the exfoliation of the bentonite. The purpose of the trial is to remove the ink keeping it attached to a layer of the bentonite coating.

3. Results I

3.1 Print quality evaluation

A nanoclay application coat weight of ~4 gm^{-2} was used when making the quality measurements of inkjet printed copy grade paper samples. When measuring laser printed paper samples a lower coat weight, ~2 gm^{-2}, was used because of the subsequent better ink removal potential in the case of the laser toner compared with the inkjet penetration tendency.

The LWC papers had a fixed coat weight of ~3 gm^{-2}.

3.1.1 Rub resistance

The results of the rub-off measurements from the copy grade papers, evaluated in respect to lowered brightness level of the uncoated contact sheet, are shown in Figure 8.

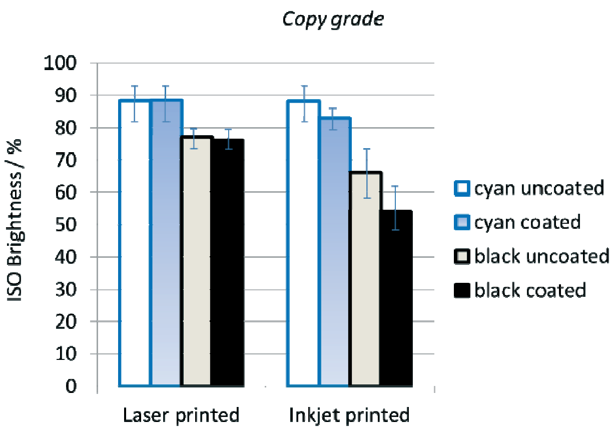

Figure 8:
ISO brightness of unprinted paper after rubbing contact with laser and inkjet printed papers: colour cyan and black

The data refer to the average values obtained across 4 analysed samples.When using laser printing, the difference in print rub between nanoclay coated and uncoated paper is minimal, but, as expected, for pigmented inkjet the increased surface closure in respect to reduced surface permeability results in increased ink pigment holdout and subsequently a greater propensity to print rub, which is more pronounced for black.

3.1.2 Print density

a) Laser printing

The print density values, exemplified by cyan and black as a function of dot size coverage, for the copy grade and LWC trials are shown in Figures 9 and 10, respectively.

The difference between uncoated and coated laser printed copy paper (Figure 9) is variable at higher print coverage levels for cyan, i.e. the density of cyan is somewhat lower on the coated paper at high coverage. When using LWC paper (Figure 10), the difference in densities is more noticeable than in the copy grade case.

Densities of cyan, magenta and yellow were all seen to be higher on the bentonite coated paper, whereas the density for black (LWC and copy paper) is almost the same across all ink coverage levels comparing the uncoated and coated papers.

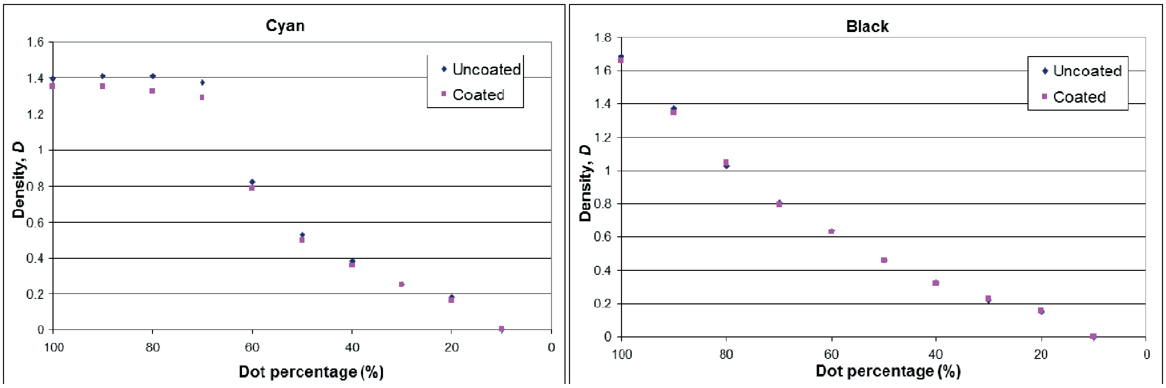

Figure 9: Print densities, D, of laser printed copy paper exemplified by cyan and black In both the uncoated state and with bentonite coating

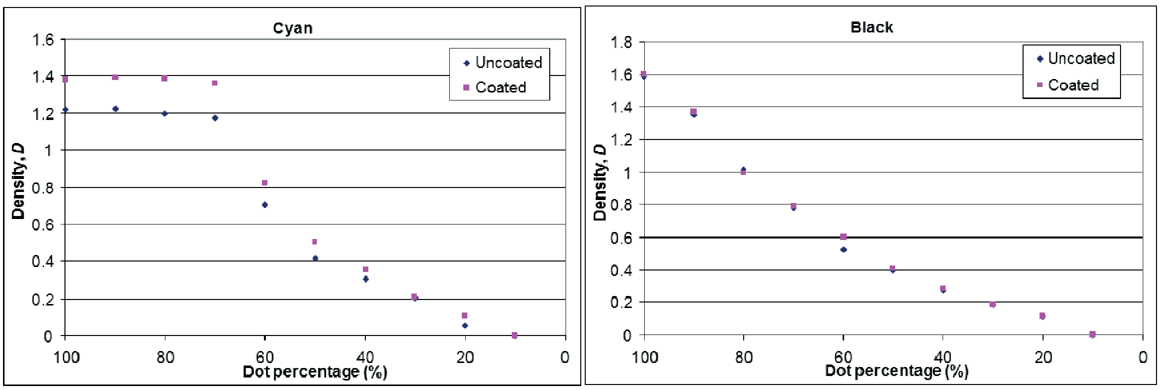

Figure 10: Print densities, D, of laser printed LWC paper in the uncoated and bentonite coated cases

b) Inkjet printing

The print density results of samples printed with the inkjet printer are shown in Figures 11 and 12, once again exemplified by cyan for the colours and by black. Print density response on the copy grade when using pigmented inkjet inks is opposite to that for the laser printed papers (Figure 9).

The densities of coated inkjet-printed copy papers are clearly higher, especially at higher ink coverage levels. This supports the expected holdout effect of the inkjet ink pigment. However, at lower dot percentages (0-50%) there is not such a clear difference between coated and uncoated papers.

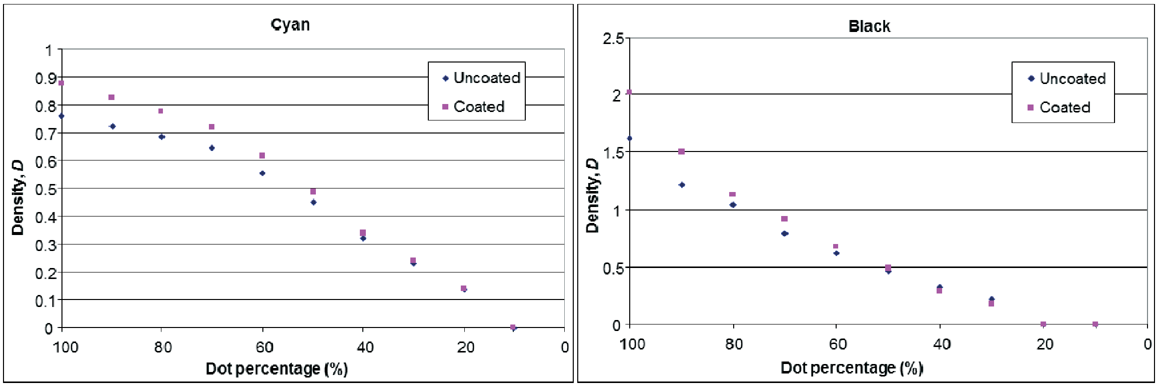

Figure 11: Print densities, D, of inkjet printed copy paper in both the uncoated state and with bentonite coating

When printing on LWC paper (Figure 12) the differences in densities are seen to vary depending on colour and dot percentage.

Density curves of magenta, yellow and black behave the same way as black (illustrated here). At high dot percentage coverage the densities are higher with bentonite coated paper but almost the same between the coated and uncoated with lower dot percentages. The density curve of cyan is a little different compared to the other colours. The densities of cyan are almost the same across all dot percentages, and the uncoated surface can on occasion show a tendency to be slightly higher at some dot percentages.

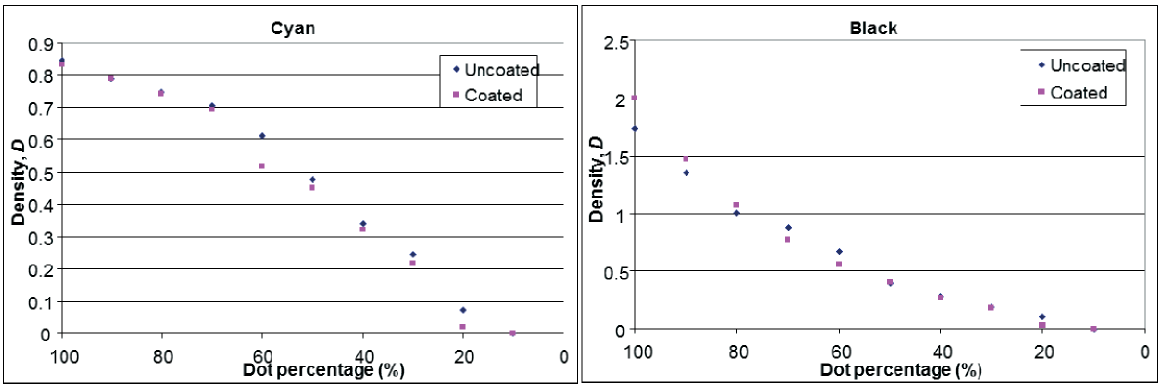

Figure 12: Print densities, D, of inkjet printed LWC paper in both the uncoated state and with bentonite coating

3.1.3 Colour rendering

Figures 13 and 14 show the results of colour gamut rendering for laser and inkjet printed copy paper and LWC basepaper, respectively, in both the uncoated and bentonite coated forms. Generally, the colour gamut of the printed coated copy paper (Figure 13) is similar to the uncoated one.

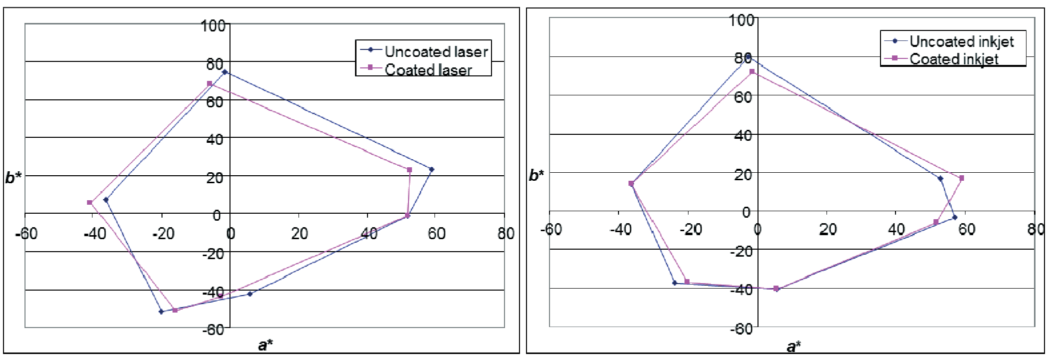

Figure 13: Colour rendering of laser printed (left) and inkjet printed (right) copy papers comparing the uncoated and coated trials

Only greenness of the laser printed and redness of inkjet printed copy paper are extended on the coated paper. This has to be considered also in the light of the nanoclay being of lower brightness than the copy paper itself. This has no big effect on the LWC paper because it is not highly white in the first place.

Colour rendering of bentonite coated LWC paper (Figure 14), especially in the case of inkjet printing, is better than uncoated because of the wider colour gamut supported by the improved ink pigment holdout.

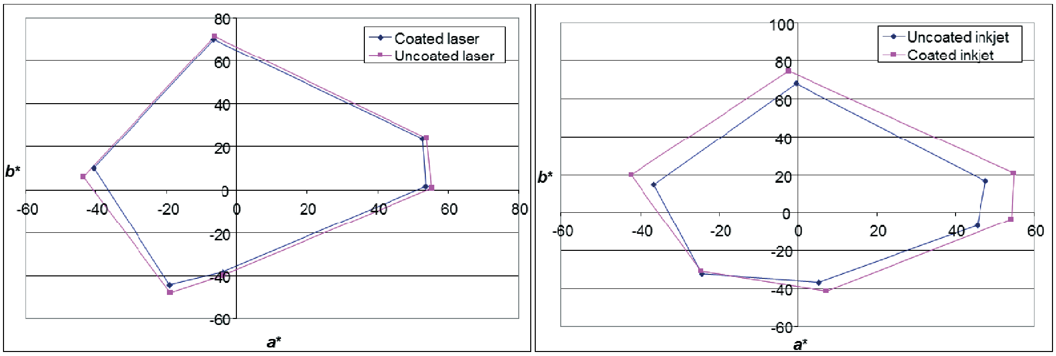

Figure 14: Colour rendering of laser printed (left) and inkjet printed (right) LWC paper comparing uncoated and coated trials

4. Results II

4.1 Removal of ink

4.1.1 Sodium hydroxide bath - nanoclay exfoliation

The calcium exchanged smectite bentonitic nanoclay coated samples were dipped into 0.1 M sodium hydroxide for 15-30 seconds. Immersing the printed product in a caustic bath leads to the release of the applied ink layer together with a mono-lamellate mineral particle layer.

As we see from the results of the copy grade samples, shown in Table 4, the lowest coat weight serves as a bridge with the uncoated control, i.e. between no ink removal from the uncoated surface and progressively improved ink removal as the amount of nanoclay applied increases.

Table 4: Results from the sodium hydroxide bath test for the copy grade papers

Average coat weight / gm^{-2}	Laser/inkjet printer	Ink comes off
0.8	Laser	Partly
2.1	Laser	Yes
1.8	Laser	Yes
2.4	Laser	Yes
3.3	Laser	Yes
4.2	Laser	Yes
0.8	Inkjet	No
2.1	Inkjet	No
1.8	Inkjet	No
2.4	Inkjet	No
3.3	Inkjet	Partly
4.2	Inkjet	Yes

Deinking was seen to be effective at coat weights >~ 1 gm^{-2} in the case of laser printing, and > 4 gm^{-2} for the pigmented inkjet. Upon dipping the laser printed paper into the sodium hydroxide solution, the toner came off in well-defined flakes.

When using pigmented inkjet inks, however, the ink did not come off the surface so cleanly and only the heaviest bentonite application weight gave almost complete ink removal in this inkjet case.

Figure 15 shows the actual fused laser toner removed from the coated copy grade remaining in the sodium hydroxide bath (on the left), and the difference of ink removal between uncoated and bentonite coated paper (on the right). There is no visible difference between black and colour toners. All fused toners are virtually completely removed.

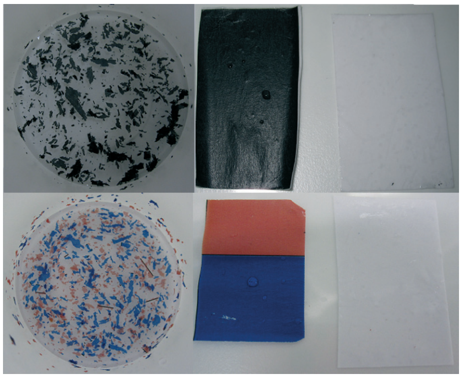

Figure 15: Ink removal from laser printed coated paper. The impact of the bentonite coating can be clearly seen on the right hand side image, where virtually all toner has been removed by the caustic bath, whereas paper without bentonite remains print fast (middle picture). Removed toner is seen floating in the caustic bath (left)

Inkjet inks, as expected, do not remove as well in the sodium hydroxide bath. Nonetheless, the advantageous effect is still marked, Figure 16. The difference is clear between the uncoated and bentonite coated paper.

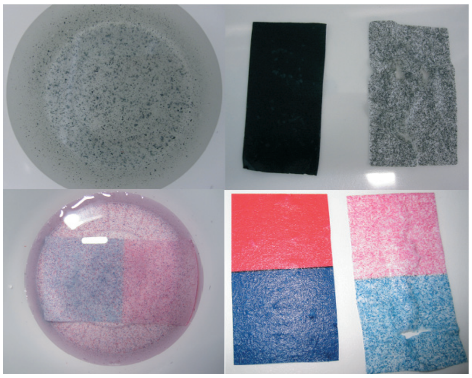

Figure 16: Partial ink removal of pigmented inkjet printed bentonite coated paper (right), printed uncoated paper showing no ink removal (middle) and removed ink in the caustic bath (left)

The results for the bentonite nanoclay coated LWC basepaper were similar. There were again significant differences in print layer removal when using toners and pigmented inkjet inks. Toners came off better than pigmented inkjet inks.

5. Discussion

5.1 Potential for ink removal and coating pigment recovery

According to the proposal by Gane (Gane, 2006), attachment of printing ink or toner to a layer of smectite montmorillonite, in the form of bentonite nanoclay on the printed paper surface, would enable two possible improved deinking process routes to be applied. These extend the potential use of the technology beyond the illustrated ink removal step alone, such that the overall recycling economy can be improved to include the recovery of coating pigment as well as the reduction of ink contamination in the recycled fibre:

- Firstly, the improved selective flotation of the ink-on-smectite by selective silica flotation aids. This could be applied either as part of the general flotation for improved recycled deinked pulp (DIP) fibre quality and/or by applying a secondary flotation of the normal mineral sludge waste from the deinking process to enhance coating pigment recovery potential rather than resorting to costly and environmentally questionable land-fill.

- Alternatively, if this concept were to be applied more universally an exfoliation process could be used either singly or before the standard deinking flotation, which could be especially advantageous potentially for water-based inks, but also for all pigmented inks and toners, allowing the resulting lower level sludge to be removed separately, sending an effectively white paper, including coated paper, on for repulping and/or coating pigment separation. This latter approach would also enable high brightness coating pigment recovery.

The basic mechanism behind the concept is shown in Figure 17.

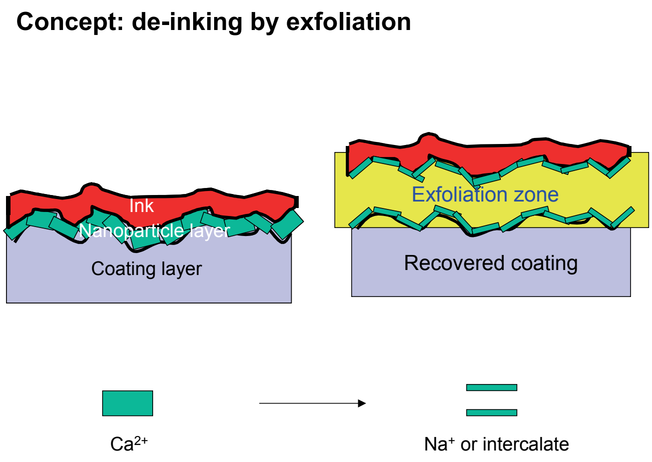

Figure 17: Nanoclay (smectite bentonite) and the proposed principle of ink adhesion plus exfoliation

We can formulate the above into an *hypothesis* - using a nanoparticle smectite clay treatment on the surface of paper two effects will be achieved:

- exfoliation of the smectite layer to provide a pre-separation of the ink layer from the paper surface, and
- continued adhesion of ink components to the nanoclay smectite in water suspension, to permit selective silicate flotation to remove the ink from the suspension, following well-known mineral beneficiation technologies, such as silicate removal from calcium carbonate in waste water treatment (Bell and Zefaratos, 1977). In principle, this technology could be adopted for all printed media, especially those with well-defined ink holdout.

In a first series of small scale trials we have seen that the proposed application of calcium exchanged bentonite onto a paper surface allows subsequent complete removal of electrophotographic laser toner when re-exchanged to the sodium form. Although not such a complete removal of inkjet ink could be achieved on these initially uncoated substrates, significant removal could nonetheless be achieved. Three possibilities as to why this is the case could be postulated: bonding and sealing by the inkjet ink preventing the exfoliation of the bentonite, penetration of ink pigment below the bentonite layer, presence of extra dyestuff in the inks which penetrate into the paper structure. The last point could be tested by bleaching.

It is, therefore, likely that ink formulation finds its way around the nanoclay edges, and it could be surmised that by using an already coated grade prior to the bentonite layer, reduced ink penetration into the substrate could be achieved. Alternatively, for the special case of inkjet, the bentonite layer could be used as a precoat followed by the specialised inkjet coating layer, and so removal of coating layer and absorbed ink could be achieved together to leave an improved quality fibre layer behind.

5. Conclusions

Application of an exfoliating layer onto paper, board or general print substrate supports a novel ink removal mechanism, which, if adopted, could lead to significant improvement in DIP quality. This concept could provide a solution to the growing challenges from digital printing, and not least the projected expansion of printed functionnality, in which "inks" frequently contain environmentally challenging materials in order to create specialised effects, such as printed electronics, phototronics, photovoltaics, conductive and capacitive functionnality etc.

If a smectite layered silicate is used as the exfoliating layer, the possibility to recover paper coating pigment could be realised either by selective flotation for silicate from the standard deinking sludge, since the ink is attached uniquely to the nanoclay layer, or by applying a pre-exfoliation deinking step, removing the reduced volume of inked material, i.e. ink plus a monolayer of nanoclay only, leaving high white pigment coating which could be removed during re-pulping.

The principle has been demonstrated for the improved recycling of office papers in the case of two digital printing methods, dry toner electrophotography and pigmented water-based inkjet. Toners were removed virtually completely from the surface as relatively large flakes, and although only an incomplete removal for inkjet could be achieved the improvement was also clearly shown. Further improvement was suggested by considering a multi-coating strategy.

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3

Quality in print

Effects of paper and printing press variability on the dynamics of linting

Rosiana Lestiani[1]*; Paul Banham*[2]*;Warren Batchelor*[1]

[1] Australian Pulp and Paper Institute
Department of Chemical Engineering
Monash University
PO Box 36, Clayton, Victoria 3800, Australia
E-mail: rosiana.lestiani@monash.edu
warren.batchelor@monash.edu

[2] Norske Skog Technical Support and Development
Boyer, Tasmania 7140, Australia
E-mail: paul.banham@norskeskog.com

Abstract

Linting is a common offset printing issue, occurred when loosely bonded fibres and fines detach from the surface of uncoated paper and accumulate on the printing blanket and possibly also on the printing plate, ink and water system. The dynamic of linting is complex and affected by both paper and printing press parameters.

In this paper, we have examined the effect on the transfer rates of lint particles of printing press parameters, especially ink tack and printing tone, as well as paper. As expected, the number of small particles removed is higher than the number of larger particles. The amount of lint removed by filtering the sample is higher than the amount of lint detected by the lint camera. Printing tone has the biggest effect on linting performance. Reducing printing tone from either 30% or 40% to 20% increased both the rate of removal of lint from the paper as well as the blanket. 20% printing tone could give higher or lower lint particles depending on the number of copies printed.

Keywords: linting, printing tone, ink tack

1. Introduction

During offset printing, uncoated newsprint paper has tendency to cause linting problem. All fibres, fines and other small materials are released from the paper surface due to the force at the exit of printing nip by the highly viscous ink. These lint particles get accumulated on the printing blanket and will eventually cause degradation in the printed image.

In earlier works (Wood & Karnis, 1990; Wood *et al*., 1998; Aspler 2003; Hoc, 2000), it is reported that pulp properties, paper machine operation and papermaking parameters affect paper surface linting. Mechanical pulp with lower specific surface area tends to bond poorly and thus, susceptible to linting (Aspler, 2003). One alternative to reduce linting potential is to increase the paper surface strength with guar gum (Mosbye *et al.*, 2008). It has also been suggested that the transition from Fourdriniers to gap formers machines can reduce linting because of better surface consolidation of the paper (Ionides, 1984 as cited by Batchelor *et. al.*, 2009).

Many printing press parameters have larger contribution to linting than the paper (Hoc, 2000). Some of them are ink tack, press speed, take-off angle and printing tone (Mangin, 1991; Moller et al., 1995; Hoc, 2000; Sudarno *et al.*, 2006). Increasing ink tack or viscosity generally leads to a higher level of lint. However, previous study (Mangin, 1991) indicated that linting is increased with ink tack only at low printing speeds. Sudarno has also shown that ink tack has a relatively small effect on the amount of lint (Sudarno, 2006). These studies have given inconsistent results. Other significant factor that has an impact on linting is the printing tone. The maximum amount of lint is typically occurred in middle range tone. One explanation offered to explain the trends with printing tone is the spreading of the dots that make up a halftone print (Batchelor *et al.*, 2009). Unfortunately, no results on dot gain measurements were provided in the study.

Linting problem can be difficult to solve due to the very small area of paper surface that is removed as lint. This makes lint measurement attempts become challenging. Previously, linting has been studies in the laboratory by pulling away the lint particles from the paper surface (Hoc, 2000; Gratton & Frigon, 2008) or by collecting the lint samples at the end of the printing run (Heintze & Ravary, 1993; Aspler, 2003; Mey

2003; Sudarno *et al.*, 2006). However, there is rarely any good correlation between the results of these methods and the actual linting in the commercial printing.

The dynamics of linting may also complicate the lint measurement. There are two rate constants to describe lint particle dynamics (Wiik, 2006). The first rate, k_1 is for the transfer of lint particles from paper surface to printing blanket. It specifies the number of particles shed per unit area of paper. The second rate, k_2 is for the lint particles that are transferred away from the blanket. It gives the probability, per copy of a lint particle being removed from the blanket. With the assumption of simple first order kinetics, the accumulation of lint on the blanket (L) is:

$$L = \frac{k_1}{k_2} \times \left(1 - \exp(-k_2 \times n)\right), \text{ where } n \text{ is the number of printed copies} \qquad [1]$$

For that reason, any lint measured after printing trial is only part of the lint that has been removed from the paper surface (Bachelor & Sudarno, 2010). Few studies have been done on the dynamics of linting (Wiik 2006; Hoc, 2009; Lestiani *et al.*, 2012). These studies looked at the development of a video camera technology to monitor the build-up of lint on the blanket.

Hence, the objectives of this research paper were to use the results obtained from printing trials, to examine the effect of paper and printing press parameters including, ink tack and printing form on the dynamics of linting.

2. Experimental method

2.1 Materials and printing trials

Four different grades of newsprint were tested in the trials: standard 42 gsm newsprint, standard 45 gsm newsprint, standard 48.8 gsm newsprint and an improved newsprint of 55 gsm with a brightness of ISO 80. There were eight paper samples in total and they were tested approximately 7 days from the date manufactured. The paper samples were produced on three different paper machines.

Two machines have horizontal twin-wire former and twinver press section and the paper is made at pH 4.8. The third machine is newer with a vertical twin-wire former and runs at pH 6.5 to 6.8. Most of these papers were made using thermomechanical pulp (TMP) from pinus radiata, with small percentages of softwood kraft and clay, except for the two samples (Roll A & D) of 42gsm newsprint which made from a mixture of 40% recycled fibre and 60% TMP. Improved newsprint has higher brightness compared to standard newsprint because of the bleaching of pulp and increased filler content.

Printing trials were carried out on Heidelberg GTO-52, a sheet fed single colour coldset printing press. We used a speed of 8 000 copies/hour and a nip pressure of approximately 3 MPa. Prior to printing, ink and fountain solution were first run for about 1 minute in order to achieve stable emulsification. A solid print density of 1 was targeted for each trial. The inks used in the trials were from two different manufacturers, DIC and Toyo. The tacks used were 4, 6, 9, 12.5 and 13.5. Fountain solution used was 2% Aquarius AC manufactured by Varn International. Three sets of printing trials were conducted using three different plates (Figure 1).

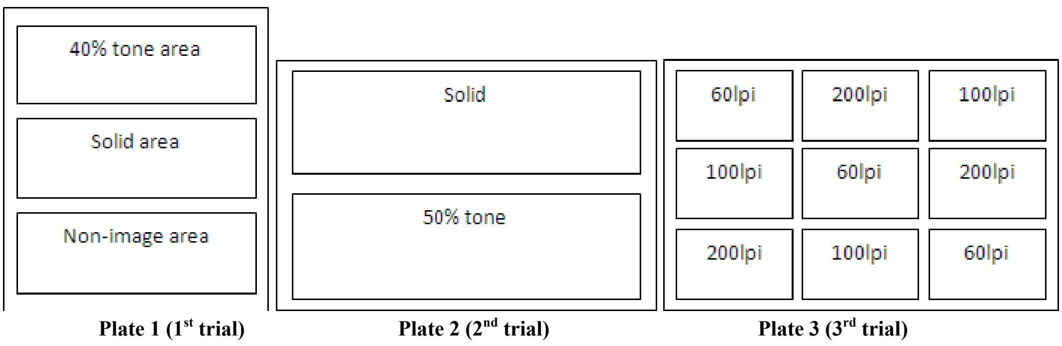

Figure 1: Different types of printing plates used in the trials

The first set of printing trial used a standard A4 test plate that was divided into three sections, consisting of a solid, a 40% tone at 150 lines per inch and a non-image area. This is a standard test pattern used during routine testing in Norske Skog Boyer mill.

The second set of printing trial used an A3 size plate with a solid in the top half and a 50% tone at 150 lines per inch in the bottom half of the plate.

The third set of printing trial used an A3 size plate that has been divided into nine area sections with varied screen ruling. The sampling scheme for this set of trial was described in Tables 2 and 3.

Table 1: Materials and Printing trials

Sample No.	Paper Grades	Plate	Paper Machine	Tack	Total No. of copies
1	Newsprint 42 gsm -Roll A	Plate 1-A4	PM3	12.5	7000
2	Newsprint 42 gsm -Roll B	Plate 1-A4	PM2	12.5	7000
3	Newsprint 45 gsm -Roll C	Plate 1-A4	PM1	12.5	7000
4	Newsprint 42 gsm -Roll D	Plate 1-A4	PM3	12.5	4000
5	Newsprint 42 gsm -Roll E	Plate 1-A4	PM2	12.5	7000
6	Newsprint 48.8 gsm-Roll F	Plate 1-A4	PM1	12.5	7000
7	Improved newsprint 55 gsm-Roll G	Plate 2-A3	PM1	4, 6, 9, 13.5	3000
8	Improved newsprint 55 gsm-Roll H	Plate 3-A3 (printing tone is varied: 20%, 30%, 40%)	PM1	6	500-3000 (interval 500 copies - 20% tone) 1000, 1500, 2500, 3000 - 30% tone 500, 1000, 1500, 2000, 3000, 4000 - 40% tone

Table 2: Lint collection method where three samples were collected from different section areas of blanket (as shown in Plate 3) for printing trial with 20% tone. The number of copies in the body shows that lint samples were collected from this area after printing this number of copies

Sample area	500 copies	1000 copies	1500 copies	2500 copies	3500 copies	4500 copies
1	500			2000		
2		1000			2500	
3			1500			3000
4		1000			2500	
5			1500			3000
6	500			2000		
7			1500			3000
8	500			2000		
9		1000			2500	

Lint samples were collected separately from three different section areas of the blanket each time the press was stopped. The heading line in the table indicates the number of copies before the printing press is stopped. The actual number of copies for lint accumulation is in the body of the table. The assumption made for this trial was that the sampling process removes all lint particles from the area sampled. Therefore, the samples taken after 2500 copies from the areas sampled after 500 copies actually means that the lint samples were taken after lint accumulation of 2000 copies. This sampling process however, takes a lot of time.

To minimise the time taken for sampling, it was decided that the samples for printing trial with 30% and 40% tone would be taken once either from top, middle or bottom row of the plate section. The number of copies printed was up to 3000 copies when printing with 30% tone plate and 4000 copies when printing with 40% tone plate.

Table 3:
Lint collection method for printing trial with 30% and 40% tone, where the samples were collected from either top, middle or bottom row of the plate section. The number of copies in the body shows that lint samples were collected from this area after printing this number of copies

Sample area	1000 copies	1500 copies	2500 copies	4000 copies
1	1000			3000
2	1000			3000
3	1000			3000
4		1500		
5		1500		
6		1500		
7			2500	
8			2500	
9			2500	

Sample area	500 copies	1000 copies	1500 copies	2500 copies	4000 copies	5500 copies
1	500			2000		
2	500			2000		
3	500			2000		
4		1000			3000	
5		1000			3000	
6		1000			3000	
7			1500			4000
8			1500			4000
9			1500			4000

2.2 Dynamic lint measurements

Measurement of linting dynamics can be done in two ways. First is by using a lint camera system, which consists of a CCD video camera, an optical sensor with polarized filter and a reflective tape, a LED ringlight and image analysis software for recording and measuring lint particles on the blanket (Lestiani *et al.,* 2013).

The camera was set in front of the press blanket to obtain images. Only images from a solid area were taken for these measurements. The dynamic images from solid area were collected for every revolution during the printing runs (Figure 2).

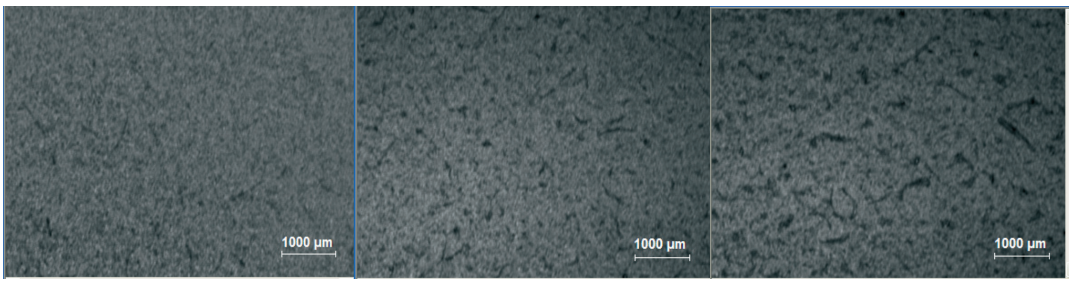

Figure 2: An example of lint build-up on the blanket captured by the lint camera during a press run (A) Dynamic images at the very beginning of run; (B) Dynamic images at 500 copies; (C) Dynamic images at 7000 copies. Press speed was 8000 copies an hour

At the end of the run, the press was stopped and the static images were taken. The acquired images were then analysed separately using ImagePro 4.5 software. This lint camera system was used to capture the dynamic images continuously for samples 1-7.

The second method to measure the dynamics of linting is using a static test undertaken by repeatedly stopping the press during a run, washing and collecting multiple lint samples from different areas of the blanket (Lestiani, *et al.*, 2013). The sampling protocol for sample 8 is described above.

2.3 Lint collection at the end of printing trial

Two methods were used to collect the lint samples at the end of each printing trial. The first method was sticking an adhesive tape onto the blanket with a roller, before being pulling it off. The weight of the tape before and after lint collection was recorded in order to calculate the lint weight per unit area of blanket (in gram/m^2). The second method was washing the blanket with 5% aqueous iso-propanol and a brush. For the first two trials, the suspended lint was captured in a 30x10cm curved frame which was held against the blanket area. In the third trial with the nine area sections of the A3 size test plate, the lint was collected using a smaller frame with an area of 10x8cm. Lint sample was collected separately from three different area sections of the blanket each time the press was stopped.

After collection, the lint sample was diluted with deionised water to 100ml. The sample was agitated vigorously before 2ml was drawn from it with a pipette and filtered through mixed cellulose ester filter paper for image analysis.

Image Analysis

An Olympus BX 60 light microscope at 5x magnification was used to capture the images of lint on the filter papers. 40 images were captured for each sample. Each of the images covered 7.66mm^2 out of 1134mm^2 of the total filter area. ImagePro 4.5 was used to process the acquired images from the filtered samples. To identify the lint particles, an automatic threshold was applied to each image (Sudarno *et al.*, 2006; Sudarno, 2006).

The lint particles were sorted into 16 area classes with a range of 1600µm^2. The final bin was set for particles with an area of 24,000 µm^2- 25,600 µm^2.

The dynamic and static images obtained from the lint camera were analysed using ImageJ. The image captured by the lint camera during the printing run was an 8-bit greyscale image. Any uneven illumination of the image was fixed by flattening the image background. For these images, a manual threshold on dark objects was applied by visual inspection to distinguish the desired lint particles from the background (Lestiani et al., 2013).

3. Results and discussion

3.1 First set of printing trials

The single measurement of a weight of lint removed at the end of a printing run is insufficient to predict the actual amount of lint accumulation.

An example is shown in Figure 3, taking lint weight measurement from different grades of newsprint, sampling from solid and screen area. There is approximate linear relationship between solid and screen lint, except for one marked outlier, which is circled in red. Looking from these results alone, it is difficult to understand the odd behaviour shown by Roll C as the transfer of lint particles that occurred during printing process cannot be analysed.

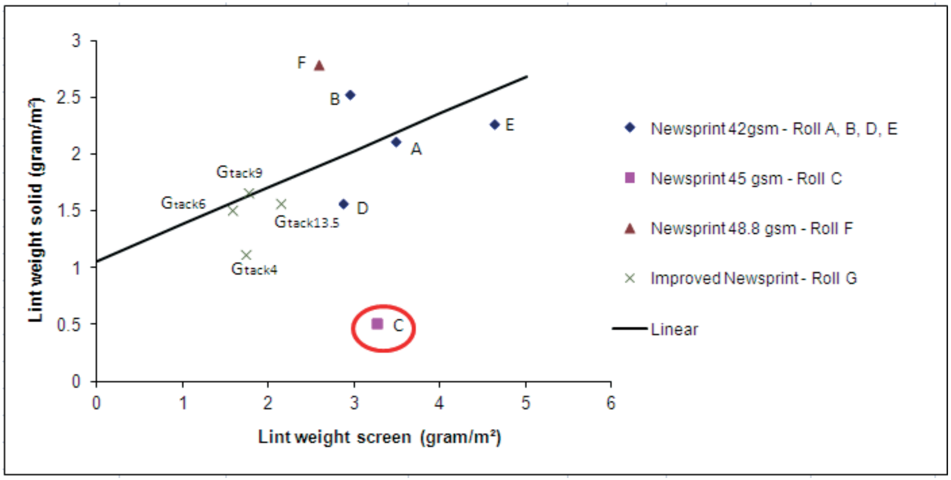

Figure 3: Lint weight measurement from the tape pulls. Lint weight from solid area vs. lint weight from screen area

The figure above indicates the importance of not relying alone on lint measurement after printing trials. Instead we use a lint camera system to measure the lint build-up on the blanket and measure the removal rate of lint particles.

Figure 4 shows that the lint increases with the increased number of printed copies measured by the lint camera for six samples (Roll A - Roll F). The initial slope of the number of lint particles per m^2 against the number of copies gives the rate of transfer of lint particles from the paper to the printing blanket (k_1). The number of lint particles will keep increasing until the rate of the lint removal from the blanket (k_2) approaches to the lint accumulation from the paper, then the curve starts to flatten out (Hoc, 2000; Wiik, 2006).

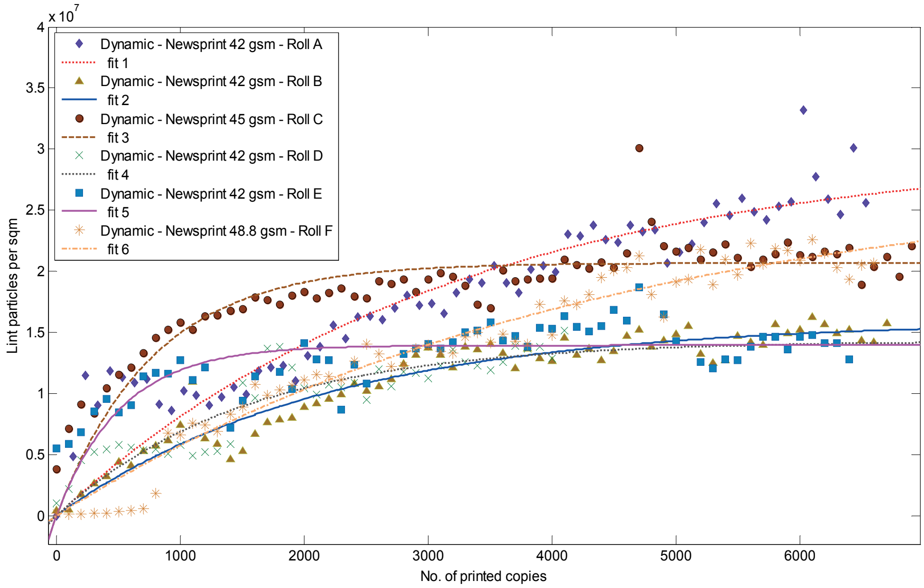

Figure 4: Dynamic lint model - lint accumulation on blanket during printing run

It is particularly interesting that five samples show that the number of lint particles on the blanket has stabilized by the end of the run, but for one sample (Roll A) the lint is continuing to increase at the end of the run.

For this sample, a measurement based on a single lint weight measured from tape pulls at the end of the run will greatly underestimate the lint accumulation in a commercial length print runs, which will be much longer.

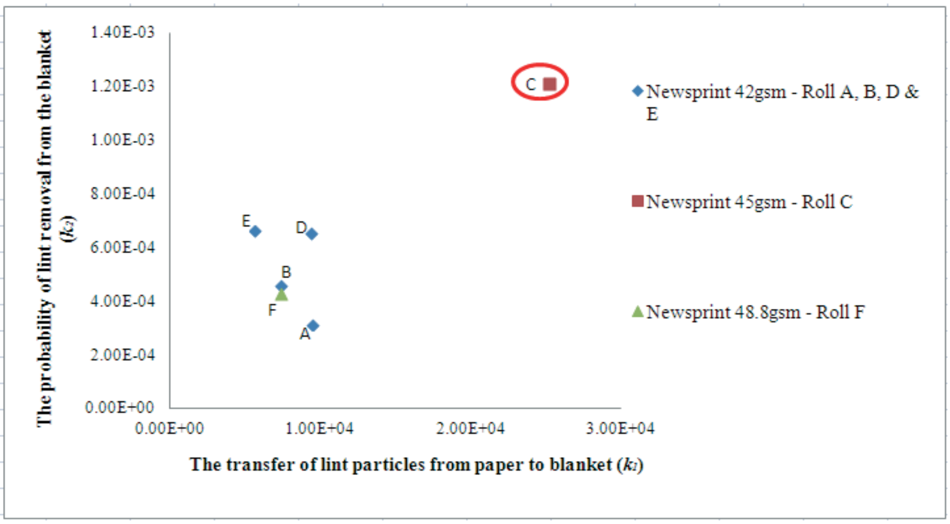

Figure 5: The transfer of lint particles from paper to blanket (k_1) vs. the probability of lint removal from the blanket (k_2)

Figure 5 illustrates the relationship between k_1 and k_2 for six samples (Roll A - Roll F), sorted by grade. The effect of the second transfer rate (k_2) seems to be relatively constant with variation in paper grades that were used in the printing run, except for one point which again pointed out to Roll C. As shown in Figure 4 and

Figure 5, this point is likely caused by local press variation that occurred during the printing run, resulting in both higher deposition as well as higher removal of lint materials on the blanket. As for Roll A, the value of k_1 is higher than all other samples except for Roll C, while the value of k_2 is the lowest among all the other samples. This suggests that when printing at the bottom side of the paper, Roll A does not remove much lint away from the blanket, resulting in the higher amount of lint being deposited on the blanket. This matches the finding by Gerli and Eigenbrood (2012), describing that linting is higher for the bottom side of the paper than for the top side.

Based on the dynamic lint model, the total number of lint particles at very large number of copies is given by k_1/k_2 and the number of copies at which the number of lint particles reaches 95% of the long equilibrium is defined as: $n = -\ln(0.05)/k_2 = 3/k_2$.

From the data in Figure 5, the number of copies required to reach 95% of long-run equilibrium ranged from 2480 to 9550 copies. This indicates that the relationship between the amount of lint measured by tape-pulls and a fixed number of copies and the equilibrium amount of lint at a very large number of copies will not be constant, and is likely to be pressroom, press and paper dependent.

3.2 Second set of printing trials

In the second set of printing trials, we measured the effect of lint transfer rate as a function of particle size and the effect of ink tack. Table 4 summarises all the lint transfer rate constants for improved newsprint - Roll G based on the area classes and varied ink tack. These results were obtained after analysing the dynamic images from the lint camera system.

The data show variation between sets, but most fits in Table 4 had reasonable fitting statistics. The lint transfer rate from paper to blanket ($\boldsymbol{k_1}$) is decreasing with increased particle size. With higher ink tack, more lint is being removed from the paper surface.

The total amount of lint produced with this improved newsprint are: 3784 lint particles/m² per copy at tack 4, 5765 lint particles/m² per copy at tack 6, 7223 lint particles/m² per copy at tack 9 and 14748 lint particles/m² per copy at tack 13.5.

Looking at Table 4, increasing tack also seems to have an effect on the removal of larger particle size, as larger force from the ink splitting film is applied on the paper surface.

Table 4: Lint transfer rate constants based on the size classes

Particle size (µm²)	Improved newsprint - Roll G											
	Tack 4						Tack 4					
	$k_1/10^4$		$k_1/10^4$		$k_1/10^4$		$k_1/10^4$		$k_1/10^4$		$k_1/10^4$	
0-1600	0.30	1.29	0.93	0.49	1.72	0.95	0.64	1.08	0.97	1.34	3.56	0.97
1600-3200	0.055	6.94	0.80	0.036	3.84	0.95	0.055	1.79	0.95	0.071	1.33	0.95
3200-4800	0.012	0.31	0.66	0.019	3.59	0.91	0.0088	9.35	0.99	0.019	5.54	0.92
4800-8000	0.0085	1.62	0.93	0.025	3.04	0.88	0.011	7.98	0.88	0.026	4.24	0.97
8000-11200	0.0020	4.55	0.58	0.0042	8.27	0.69	0.0074	5.86	0.98	0.0068	7.44	0.98
11200-16000	0.000018	23.4	0.97	0.00091	15.5	0.96	0.0001	23.7	0.86	0.012	2.44	0.89
16000-25600	0.00092	2.49	0.25	0.0014	11.3	0.98	1.32E-11	86.3	0.68	3.88E-6	37.9	0.94

The probability of a lint removal away from the blanket ($\boldsymbol{k_2}$) during one revolution is relatively constant for particle size up to 11200 µm². For larger particle size >11200 µm², the $\boldsymbol{k_2}$ data shown in Table 4 indicates higher amount of lint removal. The highest probability of lint removal from the blanket is occurred at tack 9 with total $\boldsymbol{k_2}$ value of 0.0136; while the lowest probability of lint transfer is happened at tack 4 with total $\boldsymbol{k_2}$ value of 0.0041.

These results of the lint on the blanket measured by the lint camera system at the end of the printing run are also compared with the results taken from the filtered sample. Figure 6 indicates that the filtered sample gives higher amount of lint on the blanket than the lint camera system. The reason for these differences in the data is because many small lint particles were being detected by the microscope. This will affect the overall amount of lint produced by the improved newsprint.

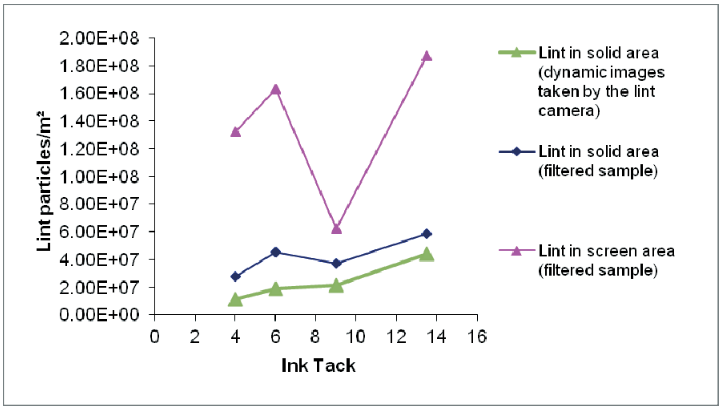

Figure 6: The results of lint produced in both solid and screen areas, measured using lint camera and filtered sample

The different regions between solid and screen areas also have different effects on the removal of lint from the paper surface. Figure 6 shows that the screen area releases higher amount of lint to the rubber blanket compared to the solid. These data are consistent with the general trends reported in the literature (Hoc, 2000). The explanation given was that the corresponding blanket areas of solid with high ink coverage will be completely covered with an ink film, thus resulting in lower amount of lint (Hoc, 2000).

3.3 Third set of printing trials

The third set of printing trials with plate 3 investigated the effect of printing tone and lines per inch (lpi) on the dynamics of linting. Nine sets of data with different printing tones and screen ruling are combined and shown in Figure 7. There are some spreads of the results when using different printing tone. There is possibly some indication that 100 lpi gives the highest amount of lint in comparison to 60 lpi and 200 lpi. However, these results need to be confirmed in future work. The biggest effect on linting performance is printing tone. 20 % tone has very rapid development, indicating much higher initial removal rates. Table 5 also shows that the initial transfer rate from paper to blanket (k_1) is lower for 40 % than for 30 % tone.

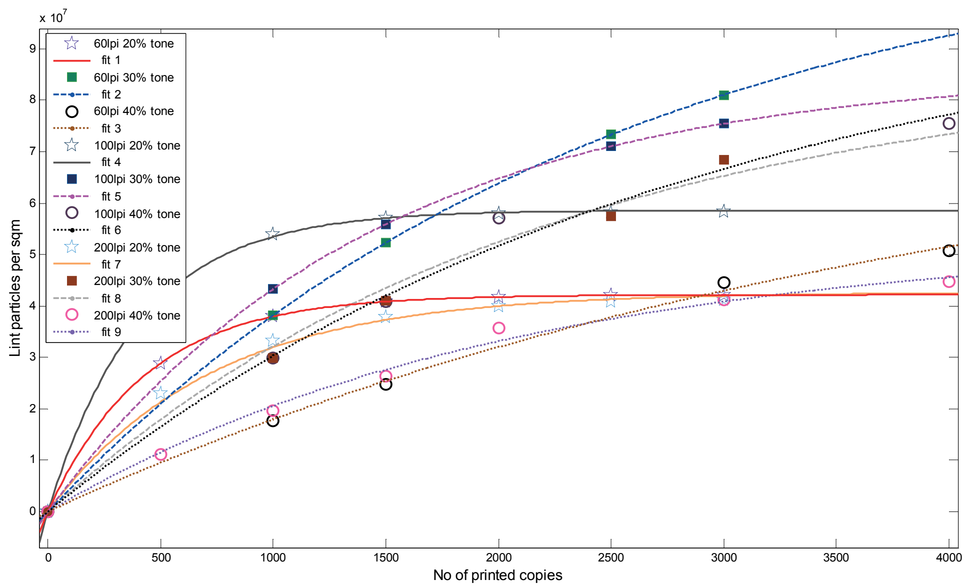

Figure 7: The amount of lint particles/m² released from an improved newsprint - Roll H when printing using different printing tones and screen ruling on the A3 plate

The result from Figure 7 shows that when printing at either 3000 or 4000 copies, the maximum amount of lint is occurred at either 30% or 40% printing tone. However, the 20% tone could also give higher lint than the 30% tone depending on the number of copies printed. This may be one reason for the contradictory results as to where the maximum lint with tone is.

Table 5: Lint transfer rate constants for all nine data sets

	$k_1/10^4$	$k_2/10^{-4}$	R^2
60 lpi 20% tone	9.72 (9.69-9.74)	23.05 (22.99-23.12)	1
100 lpi 20% tone	14.3 (13.4-15.2)	24.41 (22.64-26.18)	0.99
200 lpi 20% tone	5.91 (5.11-6.70)	13.85 (11.49-16.21)	0.99
60 lpi 30% tone	4.63 (4.62-4.64)	3.98 (3.96-4.01)	1
100 lpi 30% tone	6.02 (6.02-6.02)	7 (6.99-7)	1
200 lpi 30% tone	4.01 (2.51-5.51)	4.59 (0.82-8.37)	0.99
60 lpi 40% tone	2.03 (1.68-2.38)	2.47 (1.26-3.67)	0.99
100 lpi 40% tone	3.60 (2.50-4.70)	3.53 (1.06-5.99)	0.99
200 lpi 40% tone	2.60 (2.19-3.00)	4.91 (3.49-6.32)	0.99

4. Conclusions

The paper reports an investigation on the dynamics of linting. Lint measurement performed after printing trial was found to be insufficient to predict the actual lint accumulation and thus, the dynamic measurement using lint camera combined with image analysis is conducted. The effect of the transfer rate of lint with respect of their size classes are measured and correlated with the dynamic lint model. The removal of lint particles from paper surface is decreased with larger size of particles, while the probability of lint removal away from the blanket is relatively constant. Ink tack seems to have an effect on the amount of lint produced as well as on the removal of larger lint particle sizes from the paper. The lowest tone of 20% had the highest rate of both removals from paper as well as from the blanket.

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The impact of paper on tone value increase in heatset web offset

Rainer Klein [1], *Gerd Meder* [2], *Oliver Höhne* [1], *Jürgen Tomaszewski* [1]

[1] PTS Heidenau
Pirnaer Strasse 37
D-01809 Heidenau, Germany
E-mail: rainer.klein@ptspaper.de

[2] Mohn media arvato, Germany
E-mail: gerd.meder@bertelsmann.de

Abstract

Tone value increase (TVI) is an important performance characteristic of the results obtained in web offset printing, since it quantifies the increase in tone value (TV) of the printed product being tested. As there has been a lack of know-how about how to assess tone value increase based on fundamental paper properties, the approach employed up to now has been to empirically determine tone value increase curves that are specific to different types of paper (five paper types) and that have been established as the offset process standard. In view of the paper diversity that exists, this classification is not always representative, and more sensitive methods are being sought.

This publication provides a discussion of the influence of paper on tone value increase exemplified by heatset web offset (HSWO) printing and based on online measurement data for print density and tone value increase obtained from several web offset printing units. The data exhibited wide fluctuations in the course of time. Whereas the profiles for print density over the machine width were predominantly concave and symmetrical, the tone value increase profiles were convex in most cases and asymmetrical in some.

The printing unit and process control have the greatest impact on tone value increase. The latter is usually significantly higher in K than in CMY.

Keywords: heatset offset, tone value increase, chromacity

1. Introduction

The goal of printing is to economically produce printed products that correspond to the quality of the original. In fact, the results of heatset web offset (HSWO) are dependent on a number of factors such as layout, printing unit, printing parameters, printing ink, paper and others. The impact of these factors has not yet been clearly established in quantitative terms. Tone value increase (TVI) is of importance in this context. It describes the increase in tone value of the finished product compared to the tone value of the printing plate. If certain limits are exceeded, this increase results in an intolerable deviation between proof and print results. Colour management seeks to minimise this deviation in prepress by using calibration curves when producing the printing plate.

Due to a lack of knowledge or inadequate knowledge that is needed to be able to estimate the impact of paper on tone value increase based on fundamental paper properties, the approach employed up to now has been to empirically determine tone value increase curves that are specific to different types of paper. These empirical determinations, in addition to other characteristic paper parameters (grammage, chromaticity co-ordinates, gloss), are defined in the Process Standard Offset (PSO) - ISO 12647 [1] for five paper types. The Process Standard Offset is being used to an ever greater extent in print shops nowadays. These curves are not always representative of all paper types that have been combined into a single class owing to the huge diversity of paper types. For this reason, FOGRA and the bvdm proposed a more refined classification in the Media Standard Print 2010 [2].

This paper will present initial approaches to quantifying the impact of paper on tone value increase and thus on product quality using uncoated and coated web offset paper (paper type 3) as an example. In order to do so, it proved necessary to eliminate the impact of other factors or at least take them into account.

The studies were based on the zone-specific online measured data for print density and tone value increase obtained from several web offset printing units.

2. Printing performance characteristics - printing process and print product

2.1 General aspects

After having established a number of definitions (e.g. type of halftone screen, screen resolution and much more) prior to the printing run, the following performance characteristics are of interest for the printing process and for the print results for a given subject:

- print density and chromaticity co-ordinates (CIE L*, a*, b*),
- tone value increase (dot increase)
- grey balance.

Nowadays, most print jobs are controlled via print density. With the advent of modern online measurement systems, however, measurement and control via chromaticity co-ordinates is becoming ever more important.

2.2 Tone value (TV) and tone value increase (TVI)

In printing, tone value (TV) describes the percentage of the printed area (dots) compared to the total surface (unprinted paper + dots). Hence, a tone value of 30 % means that 30 % of the total surface is covered with dots. The tone values are related to colour in multi-colour printing. Due to the nature of the process, printing causes an increase in tone value (dot enlargement), compared to the proof. This is known as tone value increase (TVI) (Figure 1). The tone value increase shown in Figure 1 is caused by:

- optical components (light scattering; Yule-Nielsen effect) [3]
- geometrical (mechanical) components (dot enlargement),

which are based on different physical effects and which in some cases interact with one another. Figure 1 is an idealised dot with a tone value of 30 % including the tone value increase predetermined according to PSO and its tolerance range of ± 4 % (absolute).

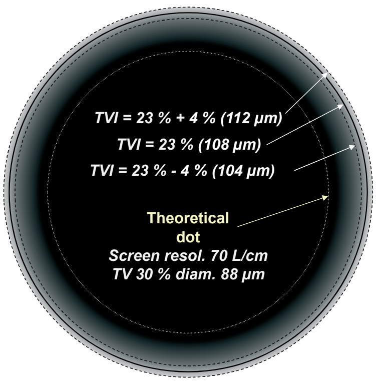
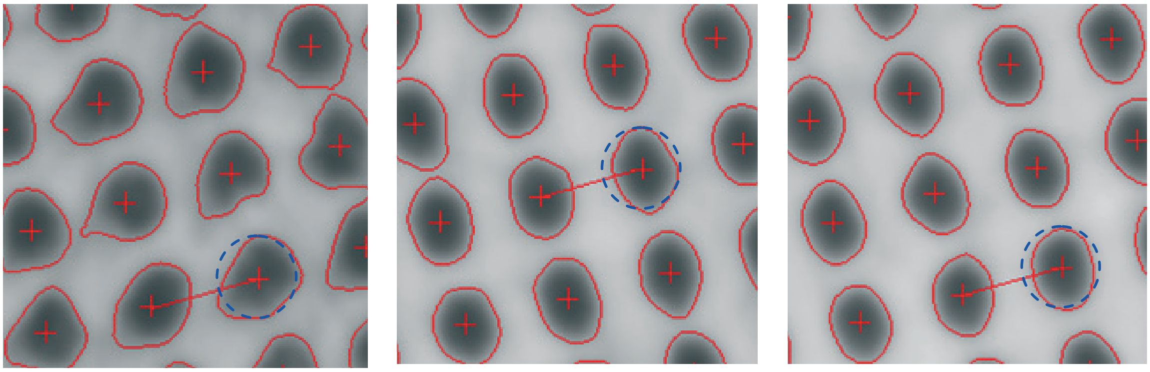


Figure 1: Idealised dot with 30 % tone value increase in K together with the plotted tone value increase and tolerance range according to PSO (screen resolution 70 L/cm; negative)

The inner circle reproduces the 30 % theoretical tone value. The ink spreading zone comprises the geometrical and optical tone value increase and is influenced by the paper to a not inconsiderable extent. Important paper properties and their fluctuation ranges play a role here. The paper properties include the optical properties of the paper, especially its scattering power and absorbency, as well as the wetting and penetration behaviour of the paper with respect to liquids (fountain solution, water emulsified in the ink, low-viscosity ink constituents - oil). Among other things, the formation of the paper, the variation in coat thickness in the case of coated papers and the pore system are important for the fluctuation range. It should be noted, however, that print shops can almost completely compensate for the impact of the paper with the help of plate calibration. Problems may still arise, however, if one type of paper exhibits different value levels as a function of time or the fluctuation range of important properties reaches above-average values.

Figure 2 shows high-resolution scans (9,600 dpi) of three actual print products (paper type 3, linear plate) whose tone value increase differs significantly. The images also contain the dot diameter which would be necessary to comply with the guidelines specified by the Process Standard Offset.



P03 TVI = 17 % diam. = 119 ± 16.9 µm | **P04** TVI = 13.4 % diam. = 114 ± 17.7 µm | **P08** TVI = 8.4 % diam. = 104 ± 2.7 µm

Figure 2: Actual dots on 3 papers (type 3) in the K_{30} field (30 % black screen) - target size after PSO tone value increase = 22.8 % (blue dot size) (screen resolution 70 L/cm; tone value = 30 %)

The use of a linear plate and compliance with PSO, however, are largely incompatible. On the contrary, the paper-related differences in tone value increase make themselves fully apparent here as illustrated by the range of the averaged tone value increases from 8 % to 17 %. These differences are caused by the value level of the optical properties of the paper as well as the dot size including light scattering.

Figure 3 is a detailed representation of the optical relationships, where the mean grey value curve (grey value 0 - black, 255 white) (corresponding to brightness according to ISO 2470-2) is displayed via the distance co-ordinates (dot centre to dot centre - see the connecting line in Figure 2).

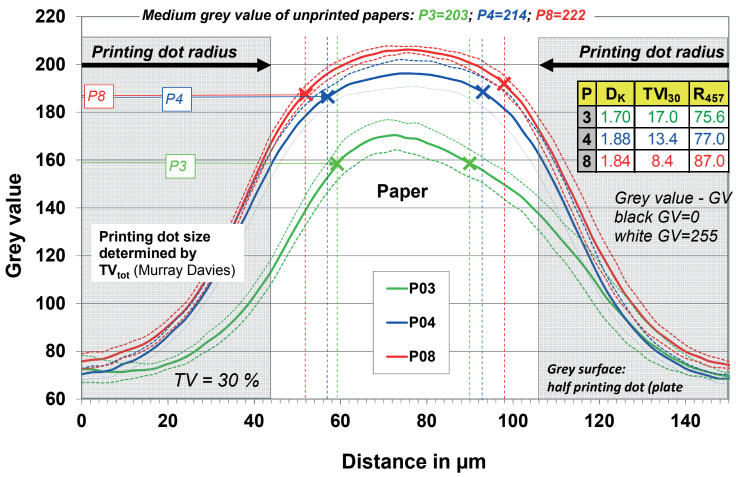


Figure 3: Detailed analysis of the paper-related optical relationships in print products (P - paper; D_K - colour density in black; TWI K_{30} - tone value increase in 30 % tone value black; R_{457} - ISO brightness)

The objective of paper manufacturers and printers must be to describe the paper-related tone value differences as accurately as possible in order to substantially eliminate the impact of the paper by printing plate correction. The following comments are a step in this direction.

3. Standardisation of the printing process - The Process Standard Offset (PSO)

The Process Standard Offset (ISO 12647-2 [2004]) [1] compiles the conditions based on paper types that ensure optimal print results (ΔE → min.). Tone value increase is one important component. Figure 4 is a graphical presentation of the nominal curves of tone value increase determined empirically by print trials for the currently defined five paper types for the four colours and the copy mode employed.

In some cases, undesirable deviations in tone value increase (and thus between the proof and print result) occur in practice owing to the fact that paper classification is fairly rough. An expanded paper classification scheme is proposed in the Media Standard Offset (bvdm) [2] to minimize such deviations.

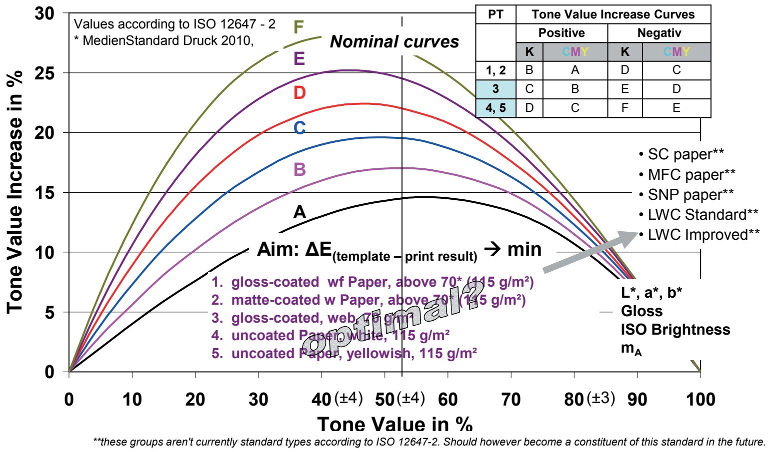


Figure 4: Tone value increase according to Process Standard Offset - ISO 12647-2

4. Factors contributing to tone value increase and economic importance

4.1 Factors contributing to tone value increase

The tone value increase of a print product is dependent on a number of parameters such as:

- plate layout (correction),
- printing process (printing parameters)
- printing unit,
  - machine characteristics,
  - machine width,
  - face printing, back-side printing,
- rubber blanket,
- printing ink, fountain solution,
- paper,
- time.

The degree to which these factors influence each other, however, is not entirely clear, especially due to the fact that several parameters exhibit mutual interaction.

4.2 Economic importance of tone value increase

As a rule, positive and negative deviations in tone value increase compared to the Process Standard Offset or the proof make it necessary to produce new printing plates and repeat the print run or continue the print job using the new plates. Both options incur additional costs such as:

- costs of plate material,
- costs of plate imaging,
- cost of machine downtime, including set-up time,
- costs of make-ready waste.

In addition, the print job may fall behind schedule which may also negatively affect costs. If a printing plate has to be replaced due to a tone value increase of 1 per cent of the print job, this results in average additional costs of approx. 100,000 €/a per printing unit. This is a significant cost item.

5. Tone value increase - a printing or paper phenomenon?

5.1 General aspects

As mentioned above, quantitative statements on the impact of the parameters listed in Chapter 0 on tone value increase are still barely known. Since paper is the largest cost factor of a print product, in-depth knowledge concerning this parameter is of utmost importance. Since the measuring technology outlay for manual tone value increase determination is very high on the one hand and considerable tone value fluctuations in a magnitude of ± 2 - 4 % (absolute) [4]occur during web offset printing, on the other hand, the authors resorted to the online data obtained from the process control system of the printing unit for these studies. Several heat-set web offset printing units were analysed to minimise the influence of the printing unit. Since the printing plates have to be calibrated for tone value increase due to the printing unit and paper used, these calibrations were recorded and taken into consideration in the paper analyses. Furthermore, the printing ink and rubber blankets used were recorded and also included in the paper analyses. The study included both uncoated and coated web offset paper that had been printed largely taking paper type 3 as the basis.

5.2 Online/offline measurement of tone value increase - Can they be compared?

Prior to evaluating the online data, comprehensive trials were conducted to determine how well the online data compared to the results of densitometric or spectrophotometric tone value determination. Both latter methods are regarded as the standard in tone value analysis. Absolute comparability of the results of measurement was ruled out right from the beginning owing to the differences in sensors, measuring conditions and deviating control elements (Table 1. The density and tone values were analysed across a number of individual measurements as a function of time for all four colours. It was established that a sufficiently good correlation exists between the offline and online data, i.e. the validity of the online data is representative when drawing conclusions concerning tone value increase.

Table 1: Compilation of measured variables and measuring conditions for online and offline measurement

	Offline	Online
	Spectrophotometer, densitometer	QuadTech [5] (CCD-based scanning spectrophotometer)
Measuring principle	Remission measurement	Remission measurement
Measured variable	Factor of reflectance	Factor of reflectance
Measurement area	model-dependent (z.B. diam. = 3.5 mm; diam. = 4.5mm)	Single measurement field < 2.5 x 1.7 mm; Simultaneous measurement of several fields (matrix camera)
Measurement conditions	DIN 16536 [6]; ISO 13655 [7]	absolute, black, no POL
Calculated values	Print density TV (depending on the check strip) TVI CIE L*, a*, b*	Print density TV (25 %, 50 %, 75 %) TVI CIE L*, a*, b*

Since the measuring head traverses the web, the density, tone value and tone value increase data are available during online measurement for approximately every 400^{th} ***n*** zones across the width of the printing unit. The number of zones ***n*** is dependent on the machine width and on the job-related machine utilisation. If no other information is given about the zone, it is assumed that it is the zone that represents the middle of the web.

5.3 The impact of time on tone value increase

Figure 5 plots the tone value increase of a tone value field of 50 % for black and magenta as a function of time for an SC paper during a print job lasting several days. It is evident that the tone value increase fluctuates considerably and in some cases tone value drifts even occurred (an extreme case).

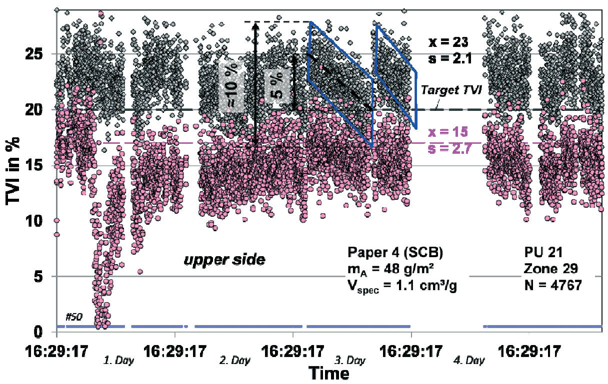


Figure 5:
Time dependency of tone value increase in a TV field 50 % back and magenta

The tone value drifts only became obvious because of the long-term evaluation that was carried out. The measured values illustrate that a fluctuation range for tone value increase in the σ-range amounting to approx. ± 2 % (absolute) occurred even in the case of a print job that used identical paper, although from a number of rolls. The maximal spread amounted to approx. 10 % absolute. This reported standard deviation occurred in most of the print jobs.

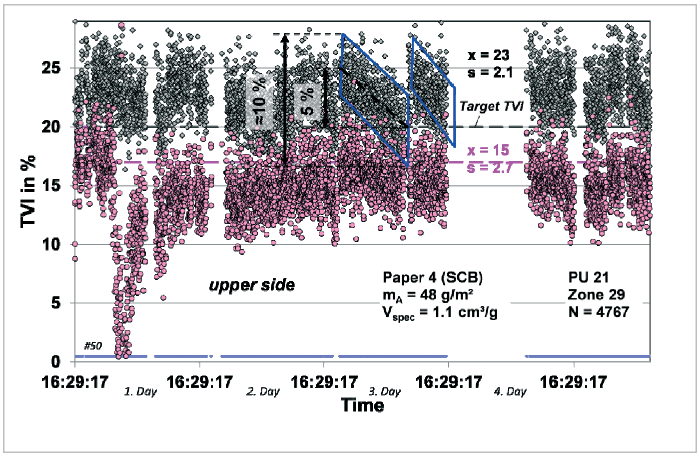


Figure 5: Time dependency of tone value increase in a TV field 50 % back and magenta

5.4 Print density and tone value increase

In most printing units, the supply of ink is controlled locally by the zone-related measurement of print density. It is obvious to assume that an increase in density (amount of ink) would go hand in hand with an increase in tone value increase due to an increase in the geometrical and optical components. To examine this question, the tone value increase in the tone value field 50 % for black (tone value increase K_{50}) has been plotted in Figure 6 across the printing density for all zones (52,000 measured values) that were recorded during the duration of the print job.

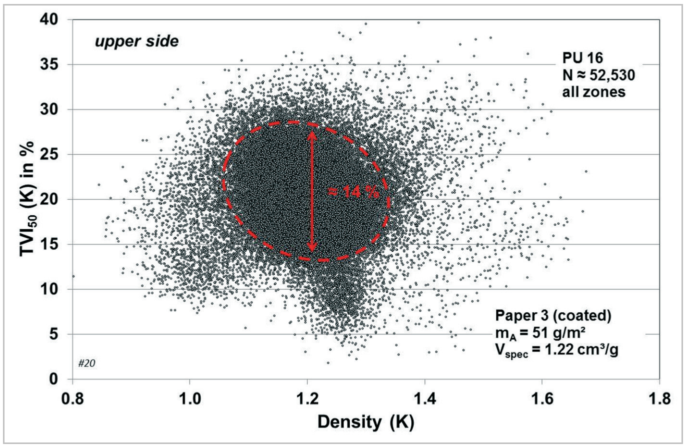


Figure 6: Tone value increase in black as a function of the print density (all zones); N-number of data sets

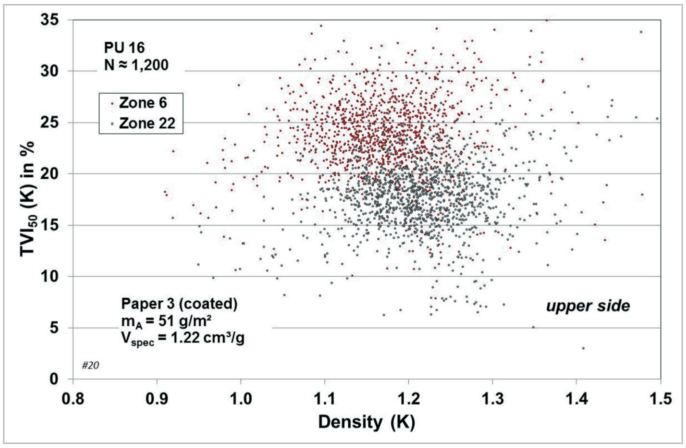


Figure 7: Tone value increase as a function of print density - zonal view; N - number of data sets

The cloud of dots in the graph indicates that there is no correlation between print density and TVI K_{50}, although a TVI core area does exist with a TVI diameter of K50 ≈ 14 % (absolute). This result was actually the impetus that led to in-depth studies. The relationships for a marginal zone (red) and the central zone (black) of the printing unit have been plotted in Figure 7. It is evident that the tone value increase in the marginal zone of the machine is significantly higher than in the central zone. A clear dependency of TVI K_{50} value on print density is not apparent.

On the basis of these results, the printing units were examined in more detail in the next step.

5.5 Consideration of printing units

Four printing units with a number of scheduled print jobs were used for the detailed studies. First of all, we analysed how print density develops across the width of the printing unit. For this purpose, all density data were collected for the specific zones and then averaged over the duration of the print job. Figure 8 shows the curves of the time-averaged, calibrated print density of the 24 print jobs from printing unit PU 20 as well as the extracted average calibrated curve (thick red line) across the machine width. The print jobs were calibrated based on the average value of the performance characteristic. This caused the positive and negative deviations with respect to the null plane.

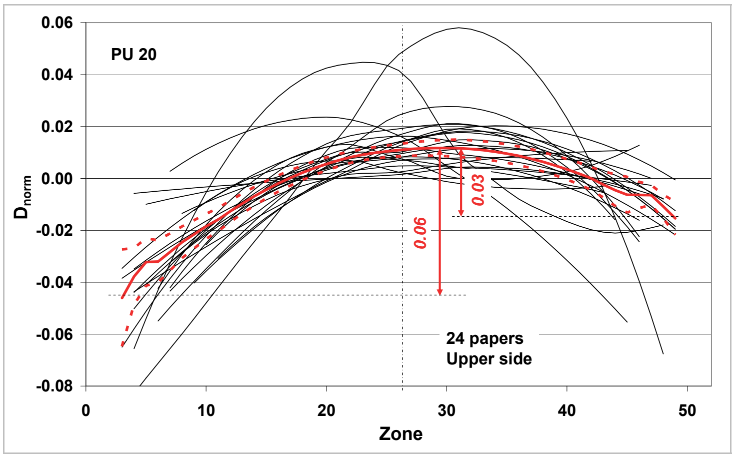


Figure 8: Standardised print density (K) as a function of machine width

The thick, dotted red lines document the fluctuation range of the print job from the average development. It is clear that print density drops significantly from the middle of the web to the front and back sides of the printing unit, no symmetry having been given for printing unit PU 20. There was a density difference of approx. 0.03 between both sides with a maximum density deviation of 0.06. As far as ink consumption is concerned, this means that the print jobs are being run with much more colour available in the middle of the web.

As far as tone value increase is concerned, the procedure used for print density was used here by analogy. The time-averaged, calibrated curve of the TVI K_{50} value from the individual print jobs as well as the calculated average values are contained in Figure 9.

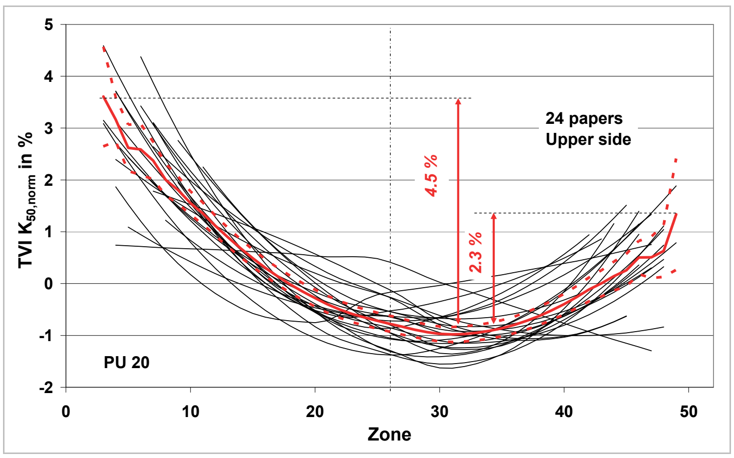


Figure 9: Standardised tone value increase (K_{50}) as a function of machine width

Tone value increase mirrors density. Both marginal sides of the web have significantly higher tone values compared to the middle of the web, the maximum distance being 4.5% absolute. What is surprising is that the highest tone value increase was recorded where print density was lowest (low zone number). It is mentioned in this context that the data material originated from production and that the printing plates were calibreted specifically for the printing unit and paper used in view of optimal tone value increase (PSO or proofs).

To elucidate the impact printing units have, Figure 10 illustrates the calibrated density curve and Figure 11 shows the calibrated tone value increase curve (50% tone value field) in black across the machine width for four printing units.

The dotted lines document the fluctuation range of the respective performance characteristic across the number of jobs. Since the printing units were manufactured with different widths, the zones were relativised, i.e. the middle zone (middle of the web) was set to zero. It should be noted that the zone breadth is identical for all printing units. With the exception of printing unit PU 21, all other printing units exhibit the concave density curve already described above. The absolute intensity and the degree of symmetry are specific to each and every printing unit. The convex development (bathtub curve) already explained above also results for the tone value increase across the machine width for all machines except for PU 21. Taking the specific characteristics of the printing units into account, the maximal average deviations across the width vary between 2% to 4.5% absolute and are thus not insignificant. If the fluctuations in tone value increase over time of approx. ±2% (absolute) in the 1-sigma range are taken into account, it becomes clear that considerable absolute tone value fluctuations are generated in the printing units, and these fluctuations are substantially independent of ink, rubber blanket and paper.

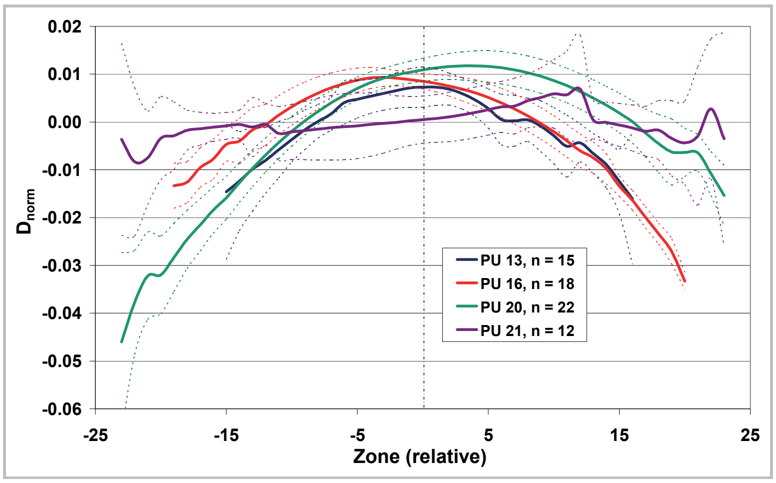


Figure 10: Printing unit characteristics - standardised print density D_{norm} for K as a function of machine width (zone); PU - printing unit; n - number of evaluated print jobs

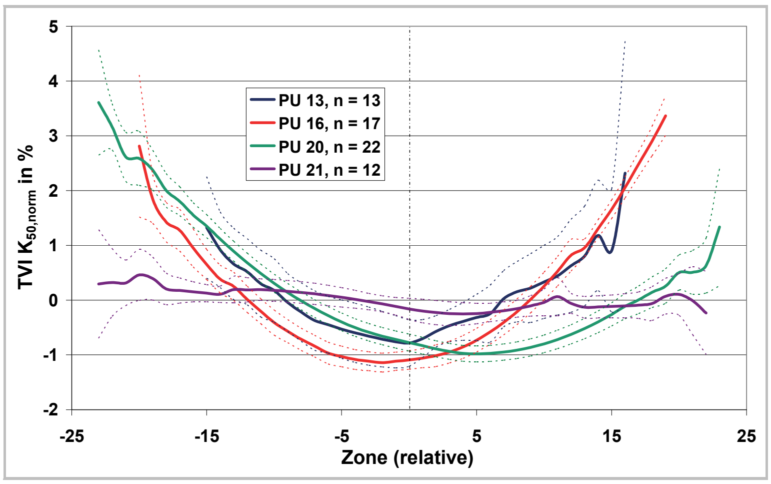


Figure 11: Printing unit characteristics - standardised averaged tone value increase (K_{50}) as a function of machine width (zone); PU - printing unit; n - number of evaluated print jobs

The curves shown above have complex causes. Possible causes may be:

- deflection and cocking of the cylinders,
- changes in the rubber blanket (swelling and/or shrinking) in the marginal zones due to different job-related paper widths,
- differences in the ink and water supply across the web width.

The percentage of these presumptive contributing factors cannot be quantified at present.

In addition to the statistical, printing unit-related evaluation of the many jobs, a constellation occurred in which a job and thus paper (n rolls) were printed in three printing units at the same time. The chronological development of print density and tone value increase can be seen in Figure 12 and Figure 13. It should be taken into consideration that the printing plates were calibrated for the specific machine taking the paper into account and thus were not identical. Whereas the target print density was the same in PU 12 and PU 14, it was chosen to be approx. 0.2 higher in PU 17. The fluctuation range of density was between 0.02 and 0.04 and thus within tolerance.

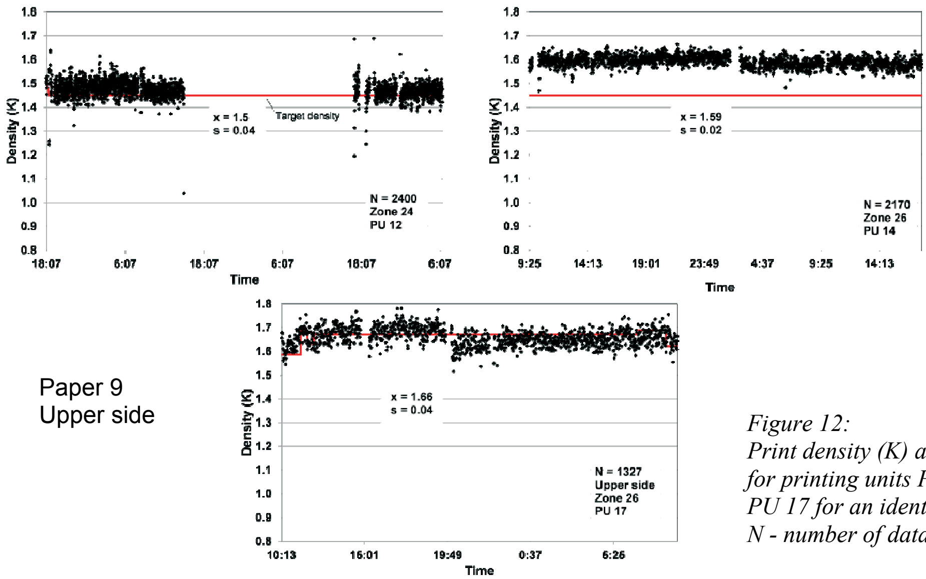


Figure 12:
Print density (K) as a function of time for printing units PU 12, PU 14 and PU 17 for an identical print job; N - number of data sets

The set point defaults for tone value increase K_{50} amounted to 15 % absolute for printing units 12 and 14 and 18 % for PU 17. Set point adjustments for density and tone value increase were also made on the last printing unit during the print job.

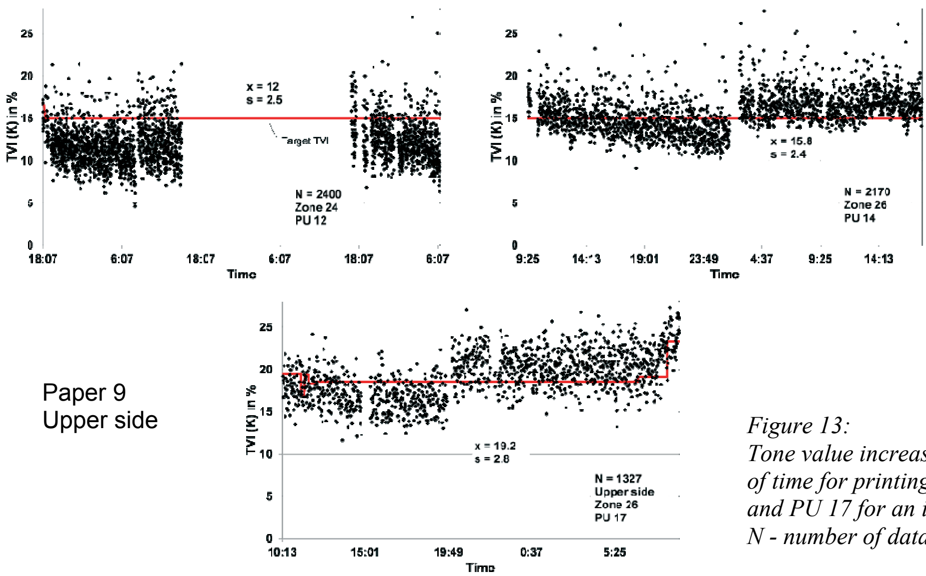


Figure 13:
Tone value increase (K_{50}) as a function of time for printing units PU 12, PU 14 and PU 17 for an identical print job; N - number of data sets

The above mentioned fluctuations in the measured values over time become very obvious in Figure 12 and Figure 13, although there are no extreme deviations (drifts) such as those seen in Figure 5. Analysis of the average TVI K_{50} value indicates that the target values were achieved for PU 14 and PU 17 (Δtarget value ≈ 3 % absolute). This is based on two approximately equally long periods with a greater or lesser tone value increase, however, i.e. approximately half of the print job was printed on these printing units with a positive or negative deviation in tone value increase. In the case of printing unit 12, the average tone value increase was generally about 3 % below the target value, although greater constancy over time is also noticeable. If all data in the zone are averaged together, the standard deviations for the tone value increase vary between 2.4 % and 2.8 % absolute. The analyses presented so far have been based exclusively on black ink which has the greatest tone value increase according to the PSO (Figure 4). The tone value increase of the colours is set one level lower in the standard, and this corresponds to approx. 3 % in the case of paper type 3 and a negative plate. The tone value increases for black and all other colours are graphically presented in Figure 14 for the print job that was carried out on three printing units.

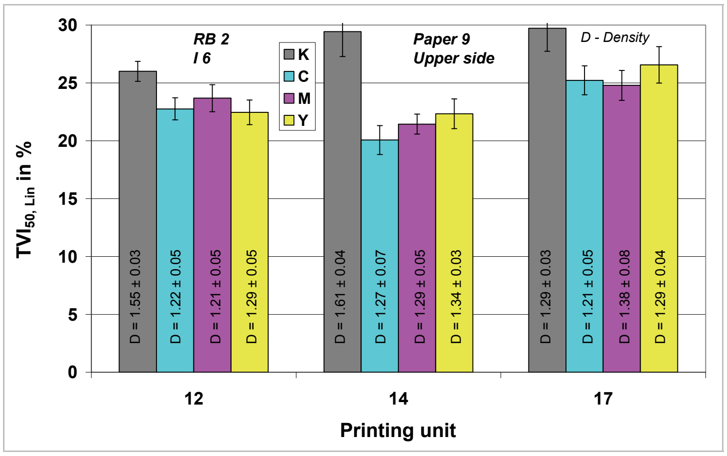


Figure 14: Tone value increase in CMYK colours (upper side of the paper measured; rubber blanket GT 2; printing ink F 6)

The slight tone value increase in colours that was expected was verified, although differences also occurred between the colours in one printing unit as well as between the different printing units. The differences between the printing units, however, were much greater.

5.6 The impact of paper

5.6.1 Uncoated paper

As already discussed above, it is not an easy task to quantify the absolute impact of the paper on tone value increase, since interaction occurs between the printing unit, the printing ink, the rubber blanket and the paper. One essential prerequisite for comparing paper is the consideration of the tone values and their increase in the case of a linear plate, thus substantially eliminating the impact of the plate calibration specific to the printing unit and paper used. The tone value increases in the K_{50} field scaled for eight uncoated reel papers can be seen in Figure 15. The papers used here were improved newsprint and type B SC paper. This graphic also plots the printing density achieved, the printing ink used (F1-F3) as well as the rubber blankets used (GT1 and S (sleeve)). The grammage and specific volume were noted on the paper side.

The total fluctuation width of the tone value increase in the K_{50} field of the analysed paper varies between 26 % (P7) and 41 % (P4), thus representing a considerable range. The consideration of one paper type (P4) whilst keeping all other contributing factors at a constant level (printing unit PU 21, among other things) apparently yields a reduced tone value increase range from 35 % to 41 %. At the present time, this does not ultimately settle the question of whether this tone value range can be traced back to the fluctuations in the paper alone. This would require comprehensive statistical analyses, since the printing parameters including the target parameters of printing density, tone value and time-related fluctuations are not comparable on a one-to-one basis.

A straightforward dependency between tone value increase and essential paper properties cannot be derived statistically in view of the fact that the existing database is rather limited, although a large range was covered with respect to specific volume (0.9 cm³/g - 1.5 cm³/g) and smoothness according to Parker Print Surf (1.2µm to 3.3 µm) (based on information supplied by the manufacturers in the internet). It will be necessary in this case to analyse the data material from a larger number of papers whose properties differ significantly and that have all been printed on one printing unit. It is assumed that this approach will yield at least a property-specific clustering of the papers with respect to tone value increase.

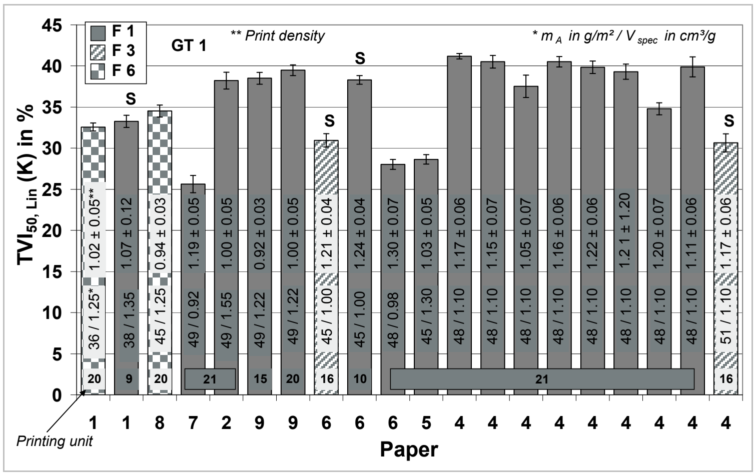


Figure 15: Linearised tone value increase ($K_{50,\ Lin}$) for uncoated paper (with varied colour, rubber blanket and printing unit)

5.6.2 Coated paper

The difficulty in extracting the impact of the paper also exists in the case of coated types. Figure 16 is a graphical presentation of the tone value increase for a linear plate in the K_{50} field for two glossy LWC papers from different manufacturers.

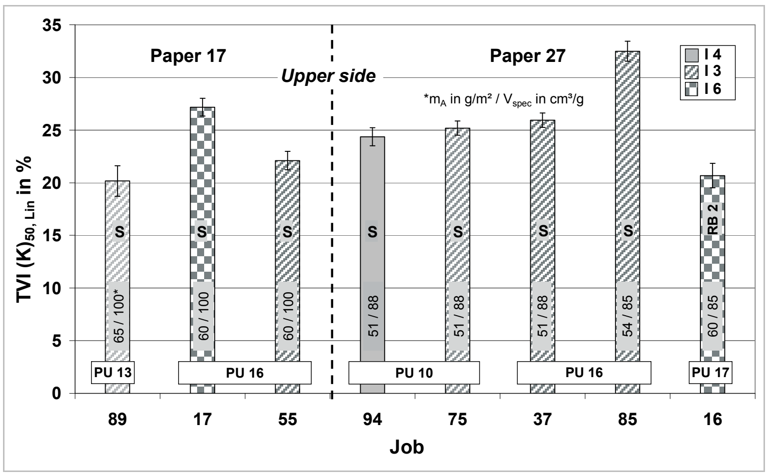


Figure 16: Linearised tone value increase ($K_{50,\ Lin}$) for coated paper (with varied colour and printing unit)

All print jobs were carried out on sleeve printing units with the exception of job No. 16. The tone value increase of the jobs varied between 20% and 25% with two exceptions. The reasons for the higher tone value increase in jobs 17 and 85 cannot be clarified sufficiently owing to the overlapping effects of the present data material. The impact of printing ink and rubber blanket cannot be quantified. We are inclined to assume that paper 17 exhibits a somewhat lower tone value increase than paper 27. This is indicated by comparing the $TVI_{50,\ Lin}$ of all colours in jobs 44 and 68 (70 g/m²) and jobs 28 and 67 (80 g/m²).

The linearised tone value increase for all colours and black have been plotted for a LWC paper type from one manufacturer in the form of bars for the printing unit PU 20 in Figure 17.

The grammage of the paper and the printing ink function as the parameters in this case. It is evident that the papers with somewhat higher grammage exhibit an increase in tone value increase, all other conditions remaining essentially constant. If it is assumed that the properties of the papers remain more or less constant, then it is logical to assume that the cause might be an enlargement of the geometric components - this however requires more comprehensive statistical studies.

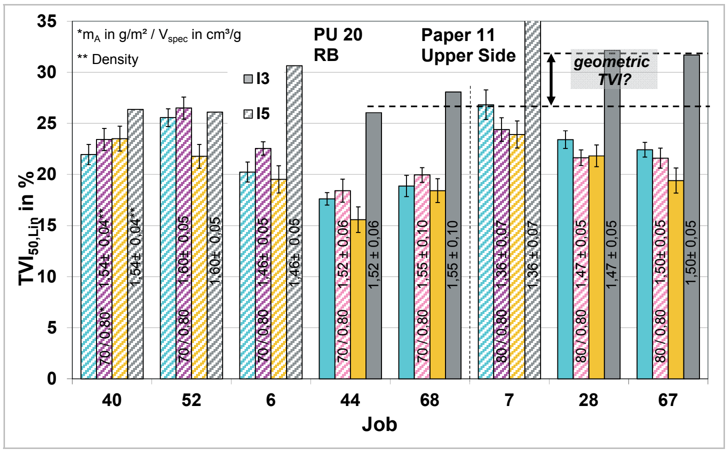


Figure 17: Linearised tone value increase (CMYK$_{50}$) of coated paper taking the grammage and printing ink into account

The results attained so far in quantifying the impact of paper on tone value increase are not entirely satisfactory. The studies, however, have shown that trends are evident. These must now be substantiated by selectively choosing the right print job and by providing an adequate statistical data base. Moreover, it must also be taken into account that the paper parameters are not constant during one and the same job as is clearly demonstrated by the lightness (Figure 18) and the chromaticity co-ordinates (Figure 19).

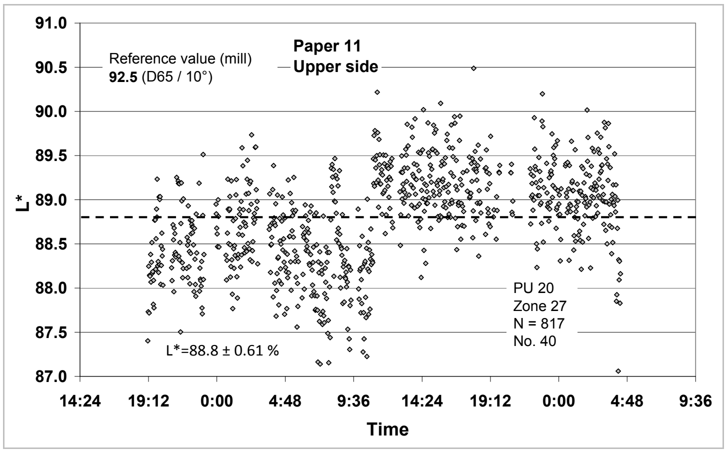


Figure 18: Lightness (L) of paper 11 as a function of time (time intervals without data are due to washing cycles or machine downtime); N - number of data sets; No.-job*

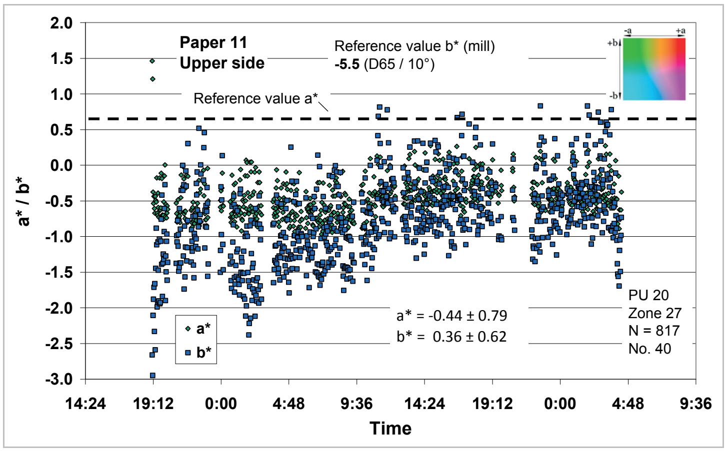


Figure 19: Chromaticity co-ordinates (a and b* values) as a function of time (time intervals without data are due to washing cycles or printing unit downtime); N - number of data sets; No -job*

These data were also recorded online using the QuadTech measurement system and should actually correspond to the data obtained from the online systems of the paper manufacturers. The closeness of agreement would be of interest in this case.

6. Summary and conclusions

The authors were able to prove that the zonal data obtained online for printing density, tone value and chromaticity co-ordinates correlate well with the data obtained by manual spectrophotometric measurement. They can therefore be used to study the impacts on tone value increase. The overall tone value increase, consisting of the optical and geometrical components, exhibits fluctuations amounting to approx. ± 2-2.5 % (absolute) over time during the actual printing process and is influenced by process control, the printing unit, rubber blanket, plate design, printing ink, fountain solution and the paper. However, a clear relationship between printing density (usually the control variables of the printing process) and tone value increase could not be veryfied owing to the many factors involved and their mutual influence. The quantification of tone value increase across the width of the printing unit is a noteworthy aspect. Although concave density profiles were detected ($\Delta PU_{ax} \approx 0.01$-$0.06$), a convex, partially asymmetrical tone value increase profile appeared in most cases, i.e. the tone values at the paper edges were as much as 5 % absolute higher than in the middle of the web. This was traced back to a geometrical dot enlargement. The results show that the printing unit (characteristics) and the printing parameters are crucial for tone value increase. It should also be mentioned that the tone value increase in K was significantly higher than that in the colours.

Nonetheless, the paper is a decisive factor in the level of tone value increase. The layering effects make it very difficult to quantify the impact the paper alone has on tone value increase. The authors have not been able to provide statistical verification for such quantification either based on the data material that exists. Until now, only the impact of grammage and specific volume has been verified.

The objectives of planned further studies will be the in-depth analysis of the paper by selectively planning the print job (printing unit, paper, etc.) and providing a statistical basis for the resultant findings. The evaluations shall also incorporate the lightness and chromaticity co-ordinates as well as other characteristics of the paper such as smoothness and gloss. The authors also intend to group the papers to provide greater detail with respect to tone value increase. Furthermore, the analytical examination of the impacts of process control and the printing units on tone value increase are to be continued.

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Investigation into the causes of marbling on PVC printed with water-based inks

Bertrand Quesne, Nadège Reverdy-Bruas, Davide Beneventi, Didier Chaussy

LGP2/Grenoble INP - Pagora/CNRS
461, rue de la Papeterie - CS 10065
F- 38402 Saint Martin d'Hères Cedex - France
E-mail: bertrand.quesne@pagora.grenoble-inp.fr

Abstract

Marbling is a recurrent print defect that can be observed on polyvinyl(chloride) (PVC) films prints. It can be defined as undesired irregularity in print, which gives a texture to a solid area. Unlike mottling, marbling is a high frequency and quite regular defect, which can have many causes, whose identification and removal rely on accurate and reliable quantification of marbling on printed PVC substrates. The first part of the present work highlights image analysis methodology developed to quantify mottle in order to assess marbling.

Then, the effects of plastisol formulation, process parameters and ink on marbling were investigated. It was proved that it is not possible to discriminate the printability of PVC with the contact angle measurement. Other tests carried out regarding the process indicate that new ways of research have to be investigated. Among them, the ink rheological properties such as viscosity, flow, relaxation time are identified as the possible more relevant parameters.

Keywords: print marble, rotogravure, PVC printing, plastisol, water-based ink

1. Research objectives

Plasticized polyvinyl(chloride) films are used in a multitude of print products. The constraints linked to the environmental protection impose the use of water-based inks. These inks, printed by rotogravure, may induce a defect called marbling. It is characterized by a recurrent irregularity of the print causing finger marks with variable densities (Figure 1).

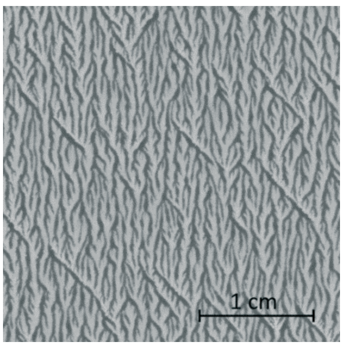


Figure 1: Example of marbling defect on a PVC substrate printed with water-based ink

Presently, this kind of defect is not deeply investigated and a lot of work is still needed to ascertain properly this feature. This defect can be associated to a poor substrate wettability, a plasticizers migration, topography irregularities of the substrate, ink formulation, and process settings [1][2]. In the present work, the influence on print marbling of physico-chemical interactions has been investigated.

Previous studies pointed out a migration of PVC additives on the film surface [1]. Affinity between these compounds and water-based inks is yet very poor. Therefore, additives migration can damage the film printability and generate ink dewetting and print marbling.

In order to investigate marbling causes, this defect must be quantitatively characterized. Based on models extracted from literature to evaluate print mottle ([4], [5]), the first part of the present work highlights image analysis methodology developed to quantify mottle in order to assess marbling.

Then, this study aims to investigate the plastisol formulation influence on surface free energy of films and consequently, on print marbling. In a third step, a special attention is paid on the identification of the relevant ink parameters with respect to marbling.

2. Materials and methods

Plasticized PVC films preparation

Sample media are composite films made of nonwoven glass-fiber embedded in a plastisol matrix. The plastisol is a dispersion of polyvinyl chloride (PVC) powder in plasticizers and additives. Samples were prepared by impregnating the nonwoven glass-fiber with the plastisol slurry using a blade coater and the subsequent composite consolidation by thermal treatment, as it is classically done for this kind of products [6].

Films studied have been made industrially with the plastisol formulation reference, and different films have been produced in laboratory to modify the film formulations. Ten different laboratory films have been made using a Werner-Mathis oven. First film was fabricated with the industrial plastisol formulation and was identified as the reference (named 'Ref'). For the other formulations, the reference formula has been modified removing or doubling the quantity of each additive (plasticizer, lubricant, heat stabilizer, co-stabilizer). The studied formulations are summarized in Table 1.

Table 1: Composition of the different plastisol formulations

	Ref	1	2	3	4	5	6	7	8	9	10
Plasticizer	$\frac{A+B}{2}$	A	B	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$	$\frac{A+B}{2}$
Lubricant	**C**	C	C	0	2C	C	C	C	C	C	C
Stabilizer	**D**	D	D	D	D	0	2D	D	D	D	D
Co-stabilizer	**E**	E	E	E	E	E	E	0	2E	E	E
PVC	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	$\frac{F+G}{2}$	F	G

Printability

Printing tests was carried out on IGT F1 laboratory rotogravure press.

A mechanically engraved cylinder with a 13.5 cm^3/m^2 volume and a 70 l/cm ruling has been used to print solid area. Print parameters have been chosen in order to fit with industrial conditions: a 0.5 m/s speed and a 250 N force.

Printing speed investigation was carried out on IGT Global Standard Tester 3H with the same engraved cylinder as previously described. This laboratory press allows speed variation up to 4 m/s.

Image acquisition and numerical treatment of data

Printed samples were scanned in RGB mode at 800 dpi with a calibrated scanner (Epson Perfection V700). TIFF image format was used to avoid data compression and modification.

From these data, RGB signals from the scanner were converted into CIE (L*, a*, b*) and the lightness layer was extracted with the software Adobe Photoshop Creative Suite 1. This method enables an exact color reproduction which is independent of the scanning device. An 8-bit grey level image of lightness was obtained. Marbling indices were then computed using Visilog 6.9.

Physico-chemical characterization

Contact angle measurements were carried out by depositing different solvents (water, formamide, ethylene glycol, glycerol and 1-bromonaphtalene) droplets at the surface of the studied substrates. The contact angle acquisition was realized with a goniometer DATAPHYSICS and performed 5 times for each liquid and substrate. Surface free energy of substrates has then been computed using the Owens-Wendt theory.

Representative panel of observation

In order to compare the calculated marbling indexes to the human perception of the defect, a panel composed of 54 persons was constituted.

3. Summary of results

Image Analysis

Different methods were investigated to quantify marbling [3]. The ISO standard and frequency analysis based on Fourier transform were selected because of the good agreement pointed out between visual perception and the calculated indexes. An example of established correlation with the band pass method is depicted on Figure 2.

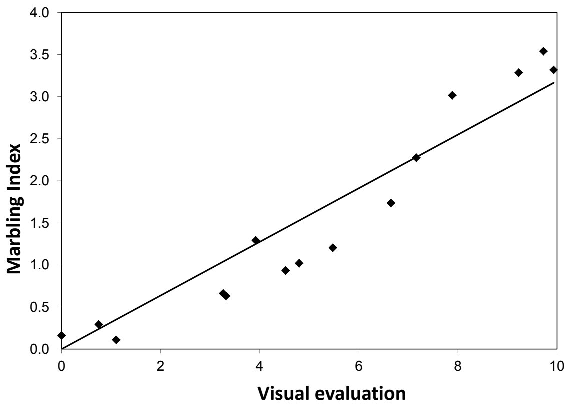


Figure 2:
Example of correlation between marbling index calculated with the band-pass method and visual evaluation of marbling performed by the panel - the higher the index, the lower the quality

Indexes based on frequency analysis are identified to be the best candidates to quantify marbling on PVC films. Indeed, a good correlation between marbling index and human perception can be pointed out (R^2=0.93).

This first step towards the evaluation of print quality of PVC films printed with water based inks allowed to define a quantitative index. It was established to be a useful tool to assess the impact of each process parameter on print defects. Consequently, it was used to investigate particularly modifications of PVC formulation and ink surface tension.

Effect of plastisol formulation on marbling

Additive migration is a well recurrent problem with plasticized PVC films. In terms of PVC printability, migration decreases the ink/substrate affinity and so the ink transfer. In order to study the impact of PVC formulation on printability and particularly on marbling, the surface free energy of the films were calculated from contact angle measurements. Polar and non-polar components of surface energy are exhibited on Figure 3.

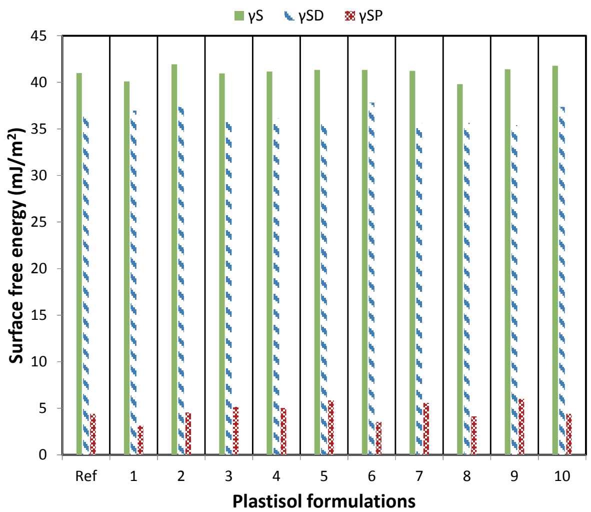


Figure 3:
Surface free energy of the different formulations of PVC films

The total surface free energy of the different formulations is about 40 mJ/m² with a polar componentclosed to 5 mJ/m² and a dispersive one near 35 mJ/m². Regarding these results, no difference of printability between these films can be predicted.

In order to assess the affinity between the different substrates and printing ink, contact angles of ink 1 were measured on each surface. Results are depicted on Figure 4.

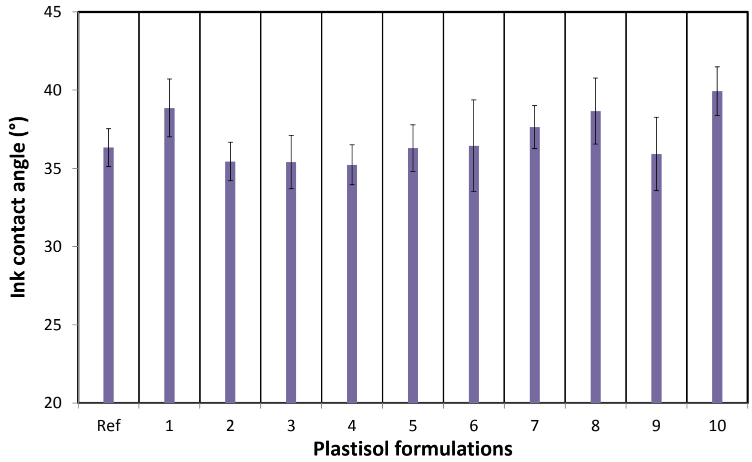
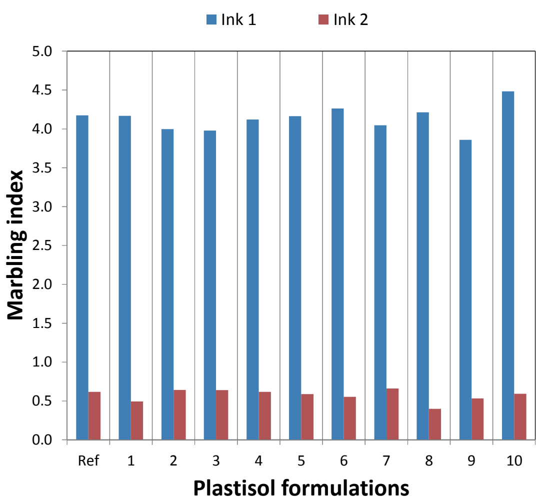


Figure 4: Contact angles of ink 1 on the different formulations of PVC films

Contact angles of ink 1 range from 35° to 40° whatever the plastisol formulation. This implies a good ink/substrate affinity and consequently a suitable ink spreading on substrates. As previously pointed out for the surface free energy, it is also difficult to conclude about a potential influence of the formulation on the ink contact angle, and thus on marbling. These films were printed with two PVC water-based inks, and then marbling indexes were measured on each sample. Surface tensions of ink 1 and ink 2 are respectively 27.8 mN/m and 28.0 mN/m. Marbling indexes are plotted on Figure 5.



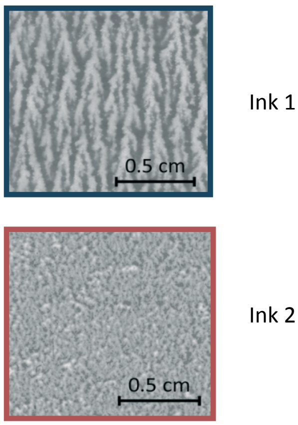


Figure 5: Marbling index of plasticized PVC films printed with two water-based inks

As presented beyond, marbling indexes are quite similar for a given ink on all films. But marbling levels are very different with ink 1 and 2. This suggests that ink properties are dominant upon film formulations.

Effect of ink surface tension on marbling

To assess the impact of ink surface tension on marbling, a PVC water-based ink with high surface tension (γ_{ink} = 38.3 mN/m) was used. Then, wetting agent was added to the ink to decrease its surface tension (γ_{ink}= 4.6 mN/m with 1 % wetting agent). The different inks with several wetting agent levels were printed on reference film and marbling indexes calculated.

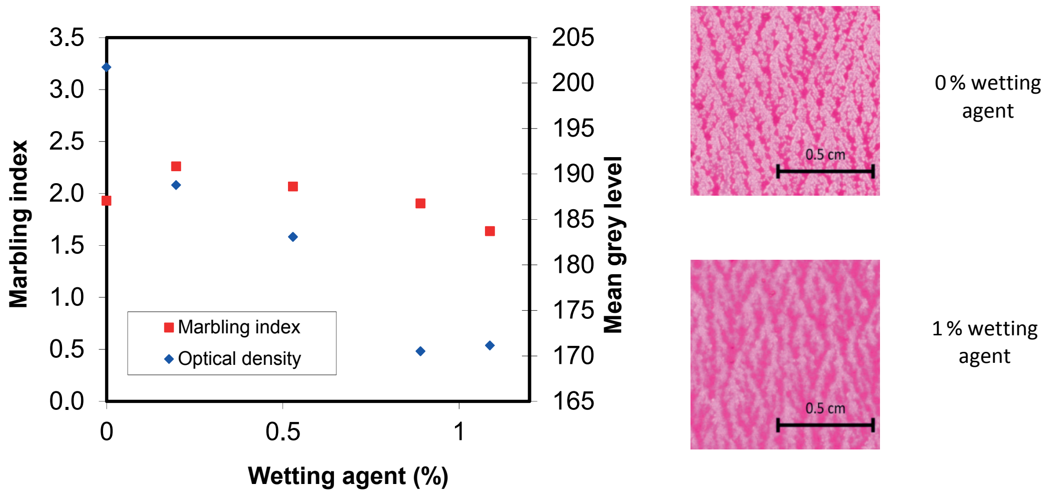


Figure 6: Effect of wetting agent adding on calculated marbling index and mean grey level

On Figure 6, marbling index and mean grey level are plotted as function of wetting agent level. Mean grey level decreases with the addition of wetting agent, reflecting for a higher ink transfer (the higher the mean grey level and the lighter is the print). But marbling index is not really affected by the wetting agent.

These results show that marbling is not a consequence of poor ink/substrate affinity like ink dewetting, but is more linked to process parameter or ink rheological behavior.

To confirm these results, industrial samples were printed before and after surface washing (with acetone). Washing substrate surface removes contaminant like additives and should improve ink/substrate affinity. Nevertheless, samples washed before printing showed similar marbling index as the others. Washing increased only slightly print density.

Others parameters should be predominant with respect to marbling. Process parameters were also investigated. Increasing speed decreases significantly marbling. Indeed, marbling index decreases from 2.6 at 0.2 m/s to 0.9 à 4 m/s, as depicted on Figure 7. Unlike most printing defects, it occurs at low printing speed and disappears with speed increase. It is crucial to be aware of this, because generally during production when a printing defect appears, machine speed is slowed down in order to minimize wastes.

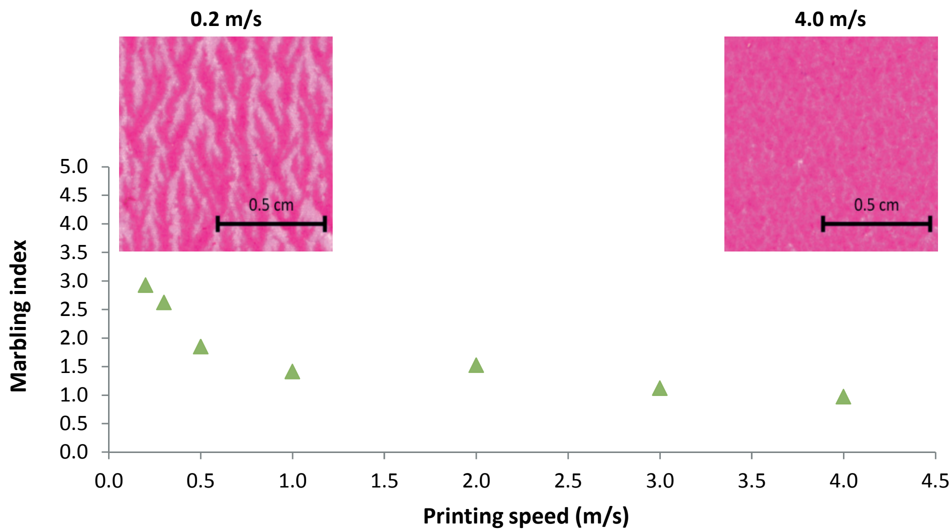


Figure 7: Influence of printing speed on marbling

Increasing the printing speed is the most influent parameter on marbling (observed with the same ink), and impacts mainly the rheological solicitation of the ink. This suggests that process times (shear rate, relaxation time of ink between blade and nip, dwell time of the substrate in the nip) may influence marbling.

4. Conclusion

Methods classically developed to quantify mottling were transposed with success to marbling evaluation. A panel of 54 persons was selected to evaluate human perception of marbling and a good correlation was established between the panel and the calculated indexes.

Based on this novel procedure, it was shown that substrate formulation had no sensitive influence on the calculated marbling indexes. In the same way, the addition of wetting agent on the ink - leading to its surface tension decrease - only slightly affected the calculated marbling indexes.

These results prove that it is not possible to discriminate the printability of PVC with the contact angle measurement. Other tests carried out regarding the process - increase of the printing speed - indicate that new ways of research have to be investigated. Among them, the ink rheological properties are identified as the possible more relevant parameter (viscosity, flow, relaxation time).

Acknowledgments

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Simultaneous determination of absorption mottle and white-top mottle in the same area on coated boards

Sofia Thorman, Li Yang, Anni Hagberg

Innventia AB
Box 5604, S-11486 Stockholm, Sweden
E-mails: sofia.thorman@innventia.com; li.yang@innventia.com; ann-catrine.hagberg@innventia.com

Abstract

The proposed measurement technique offers a number of advantages compared to other absorption methods. It enables one to study liquid absorption in a time period that is relevant to printing. Moreover, with this technique one can quantify the contributions of white-top mottle and absorption mottle at the same location and in a great detail. This makes this technique a useful tool for quality control of paper board products and for predicting print-mottle of flexographic printing. The reproducibility and reliability of the technique were very promising, as suggested by the Round Robin tests.

Keywords: absorption mottle, white-top mottle, liquid absorption, flexography

1. Introduction

Non-uniform print density, print mottle, is a frequently encountered quality defect in water-based flexographic printing. There are several contributing factors to print mottle that are closely related to board properties, ink properties and print settings. The initial source of print mottle is ink-transfer inhomogeneity, which is largely determined by the surface roughness of the paper/board and the hardness of the cliché (printing plate) together with the mounting tape, since it relies on the mechanical contact between the ink and the board surface (Aspler et al. 1998; Barros 2006; Woods et al. 2000). Ink-board interaction, in the forms of ink spreading and ink penetration, governs the (re-) distribution of the transferred ink, while being significant for print mottle. The interaction is dependent on the wetting and absorption properties, such as absorption rate and absorption uniformity. Additionally, the optical non-uniformity of the board, known as white-top mottle (WTM), may also add to the occurrence of print mottle, primarily due to an uneven distribution of material in the top layer(s) containing bleached pulp and various coatings. A substantial level of WTM can be disturbing in prints with light tones or even the solid tones of transparent inks. These factors often co-exist in a print, which makes it difficult to identify the main source of the problem. Therefore, being able to quantify separately the contributions from each of the factors would be a highly valuable tool. For example, it would be possible for board producers to identify the important board properties and to keep track of production control and product improvements.

When it comes to absorption characterisations, there are a number of widely used measurement techniques, e.g. the Cobb Test, which provides information about the volume of total absorption after quite a long period (60 seconds is often used) and for a large area (TAPPI 1998; Aspler et al. 1987; Elftonson and Ström 1995; Swerin et al. 2008). This time-scale might not be relevant to printing (Skowronski et al. 2005; Borch et al. 2002). The Bristow Test (Bristow 1967) is also commonly used, while there are other techniques based on this method, e.g. the Liquid Absorption Profilometer (Enomae et al., 1999). The Mutec PDA (penetration dynamics analyser) module PEA is a relatively new measurement technique (Daun 2006). It measures the transmittance of an ultrasonic beam that is attenuated, due to absorption and scattering, since transmittance changes while the liquid is penetrating the paper substrate. Using physical modelling, the transmittance values have been converted to depths of liquid penetration with time, enabling a detailed insight into the absorption process and the liquid-paper interaction (Yang, 2013). These measurement readings are, however, not relevant to the absorption uniformity across a surface area being measured.

There are other types of experimental methods that are often used for studying liquid-paper interaction and liquid absorption. The contact angle measurement indicates the trend of liquid spreading or wetting on the surface and liquid absorption (TAPPI 1997). The Micro Drop Absorption Tester (MicroDAT) estimates the rate of liquid absorption by the paper substrate (Svanholm 2007). Both methods rely on detecting the contour of a liquid droplet above the substrate surface and are therefore more suitable for studying coated grades instead of uncoated grades, whose rough surface and strong absorption property are often problematic in measurement accuracy. The MicroDAT test is rather time consuming and therefore mainly used in research work. There are several other techniques along this line, giving detailed and valuable information adapted for research work, e.g. liquid permeability through a stack of papers (Ridgway et al., 2003), resistivity changes in paper as liquid is being absorbed with the Clara device (Lamminmäki et al., 2010; 2011) and wicking in pigment tablets (Schoelkopf et al., 2000).

There are not many techniques available for the characterisation of lateral non-uniformities in absorption, particularly not for water-based ink absorption. Print quality defects, e.g. print mottle, are likely to be linked to non-uniformities in the substrate. Therefore, it is important to characterise absorption mottle (and WTM). While the staining technique suggested in this paper is based on a similar principle to the Bristow Wheel Test (Bristow, 1967), it includes the removal of excess liquid to limit the amount of the liquid absorption and to minimise the impact of surface roughness. The excess liquid is removed with a blotting paper in a similar way as in the Cobb Test. Then the innovative analysis method that enables us to quantify absorption non-uniformities of the stains clearly differentiates the new technique, from the Bristow Test.

We recently presented a technique to study the absorption non-uniformity (absorption mottle) using a small amount of liquid on coated boards (Thorman et al., 2012). While that technique was based on a principle similar to the Bristow Wheel Test (Bristow, 1967), it offered many more possibilities for studying liquid-paper interaction. For example, it enabled the short-time absorption of a coloured liquid, resulting in a stain. The non-uniformity of the stain pattern was linked to the absorption mottle and the WTM. However, the technique was not sufficiently reliable for obtaining the absorption mottle, which was equal to the difference between the total stain mottle and the WTM. The difference sometimes produced a negative result, hence physically incorrect. In this paper, we present an improved method that is reliable and enables a simultaneous determination of the absorption mottle and the WTM in the same area. Furthermore, we examined the reproducibility of the technique by means of a Round Robin test and validated important aspects of the testing procedure.

2. Methods

The instrumental setup is shown in Figure 1. As previously described (Thorman et al. 2012), the basis of this method is to allow the board to absorb a liquid for a brief and well-defined period of time. The liquid is coloured with a blue dye, methylene blue, and leaves a blue stain on the sample. The darker the stain, the greater the absorption. A uniform absorption across the surface creates a homogeneous stain, whereas local variations create reflectance disturbances.

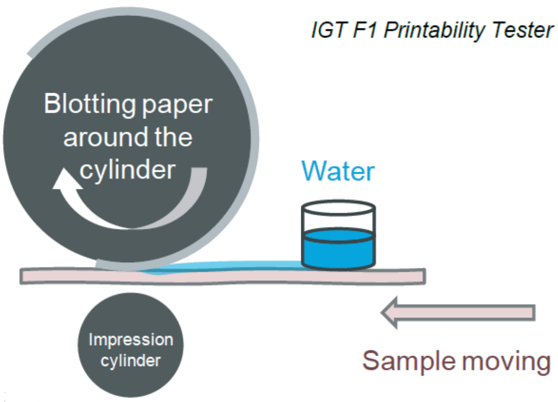

Figure 1: The IGT F1 Printability tester was used, which made it possible to achieve short absorption times, as little as 0.1 of a second. Any excess coloured water was removed using blotting paper

This method employs a slightly modified IGT F1 Printability tester (a laboratory-scale printing press whose inking unit had been disconnected). A specially constructed liquid container is placed on top of the sample and the open bottom enables contact between liquid and sample. A liquid film escapes when the sample passes the container and the sample can freely absorb liquid until entering the nip one tenth of a second later, which, in this set-up, contains a soft backing and blotting paper instead of a printing plate. Excess coloured water is removed by the blotting paper and the absorption from the reservoir of free water on top of the paper surface is stopped, while a certain redistribution of the liquid in the pore system may occur. During the short absorption phase, areas of the coating with a strong absorption potential, e.g. open areas with high surface energy, absorb more coloured liquid than areas with a low absorption potential, such as non-porous regions. The result is a mottled stain on the sample.

Since there is no external pressure involved in the process of applying the liquid, the non-uniformity in the stain can only originate from the non-uniformity of the capillary absorption and the WTM. The stain is uniform if the absorption is homogenous and the board is free of WTM.

2.1 Determining absorption and white-top mottle through different image channels

There are two factors contributing to the reflectance variation of the stain. Non-uniform liquid absorption by the board surface is one of the two factors, since it leads to the dye being distributed unevenly on the surface. The reflectance variation of the board itself (white-top mottle) also contributes to the mottled appearance of the semi-transparent stain. It is important to be able to evaluate separately the contribution from each of the origins. This was dealt with earlier in a method requiring two separate measurements, viz. the WTM in an unstained area and the total mottle (reflectance variations) of the stain.

The absorption mottle was calculated by subtracting the WTM from the total mottle of the stain. Since different areas were involved in the calculation, the method was not quite reliable. For example, the result after subtraction was sometimes negative, which is physically incorrect, since the absorption mottle should indicate positive or zero.

In this paper, we are proposing a new approach that relies on the measurement of only one area, namely the stained area. In this method, the absorption mottle and the WTM can be simultaneously characterised. First the stain is digitalised into RGB colour images, as shown in Figure 2. Working with the images of different colour channels, mainly the R and B channels, it is possible to calculate the WTM and the absorption mottle separately.

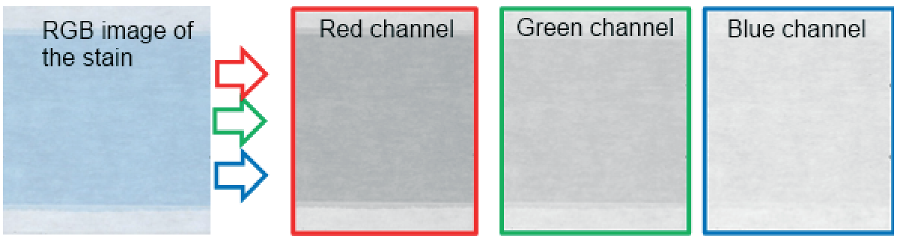

Figure 2: Illustration of the principle of the analysis method. The stain is digitalised by a scanner into RGB colour images. The B-channel image is dominated by the white-top mottle of the paper board, while the R-channel image is dominated by the absorption mottle

This new method utilises the spectral characteristics of the water that is dyed blue, which is almost transparent to blue light and absorptive to red light.

Figure 3 depicts the spectral reflectance value of the stain (dashed line) together with those of the board (dashed-dotted line) and the base of the board (solid line). Since the blue stain is almost transparent in the blue (B) band (short wavelengths), the B-channel image of the stain is virtually the same as that of the bare paper board. Hence it is not sensitive to the variation in liquid absorption. In other words, the non-uniformity in the B-channel is dominated by the white-top mottle. Additionally, the spectral reflectance of the base board exhibits spectral dependence, which favours this method.

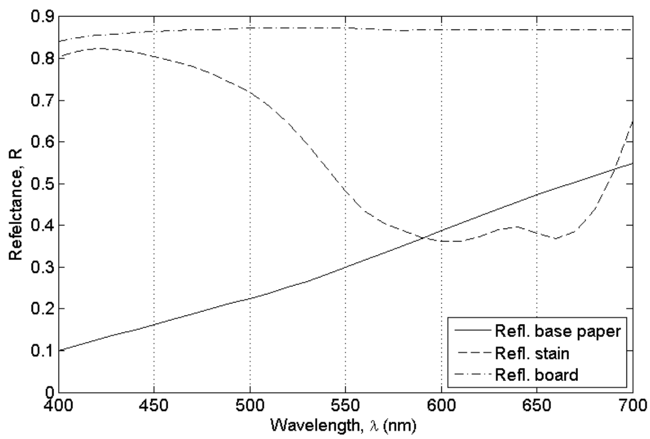

Figure 3: Spectral reflectance values of a blue stain, a white board and the base paper of the board. The spectra clearly indicate how red light is absorbed in the stain, whereas the white board gives a more homogeneous reflection. The brownish base exhibits a lower reflectance in blue and a higher reflectance in red

As already observed, the brownish base has the lowest reflectance (approx. 0.1) in the blue band and the highest in the red band (approx. 0.5). Since WTM originates from an uneven coverage of the white-top layer (bleached fibres and/or coating), through which the darker base becomes visible, this unevenness in the brownish base is most visible in the blue channel and least visible in the red channel.

Conversely, the blue liquid is strongly absorptive in the red (R) spectral band, which makes the R-channel image very sensitive to variations across the area of the stain. Hence, the variation observed in the R-channel is dominated by the non-uniform liquid absorption. However, WTM is not only visible in the B-channel image but, to some extent, it may also contribute to the mottled appearance in the R-channel image, depending on the optical density of the stain. Since the reflectance value of the board in each pixel is known in the B-channel image, it is possible to reduce/exclude the contribution from the WTM using Equation 1. This is done for each pixel and a new absorption image created (see Figure 4) without any significant impact from the WTM of the board.

$$R_{absorption} = \frac{R_{red}}{R_{blue}} x \bar{R}_{blue} \qquad [1]$$

where $R_{absorption}$ is the normalised reflectance of the R-channel pixel (of the stain), R_{red} the reflectance of the original R-channel pixel, R_{blue} the reflectance of the original B-channel pixel and $\bar{R}_{blue}$ the average reflectance of the B-channel image.

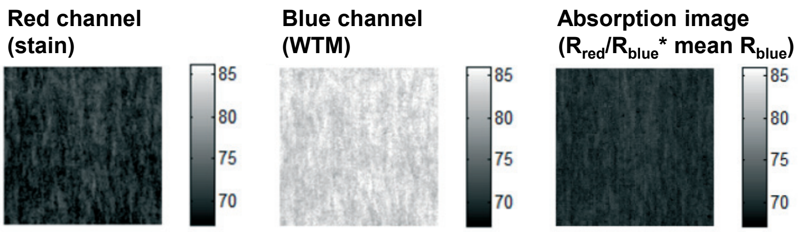

Figure 4: The left and the middle examples are the original images from the red (R) and the blue (B) image channels, while the right example is the one with the normalized reflectance obtained by employing equation 1

To quantify the different mottle values, each of the colour channels was calibrated to reflectance. The coefficient of variation in reflectance (CVR) was calculated using a Fast Fourier Transform. The emphasis was put on the spatial wavelengths between one and eight millimetres.

2.2 Experimental investigations

The substrates used in the experiments were all multi-coated duplex boards. The substrates used for validating the proposed method (Sec. 3.1) were a mix of pilot-coated and commercial boards. The pilot-coated boards had the same base but with coatings of different pigment blends (calcium carbonates and clay) and different types of latexes. In the Round Robin test, all the substrates were commercial duplex boards used for liquid packaging (labelled A-F). Since the detailed performance of the boards was not the focus of this report, no more information about the substrates is provided here.

The coloured liquid contained 12 % by volume of the condensed liquid dye, methylene blue, which was diluted in deionized water. The apparatus used for applying the coloured water was an IGT-F1 Lab press. Two stain areas were made for each board sample. After drying in a climate-controlled room, the stains were scanned as a colour image by the scanner, an Epson Perfection V750 PRO. The image was then evaluated by the STFI Mottling Expert software. The reported value presented was the average of 12 sampled subareas in the image. A high speed camera, a Nikon D200, was used for inspecting the coverage of the coloured liquid on the board surfaces.

3. Results

In this section, the results of the tests using the proposed method are presented first, in section 3.1. These results were also compared with those obtained from a previous method that was based on measuring two separate areas. The reproducibility of the method examined in the form of Round Robin tests is presented in section 3.2. The continuity of the liquid film and the stability of the stain pattern are shown in section 3.3.

3.1 Calculation of absorption and white-top mottle in the same area

The white-top mottle of a board was calculated by measuring the reflectance variation of the stain in the blue (B) image channel. The influence of the stain was expected to be marginal, since it is highly transparent in the B-image channel. This was validated by means of comparing measurements made of the WTM in the same area, before and after the stains were made. As shown in Figure 5 (left), the correlation was very high, indicating that it was definitely possible to measure WTM with a stain, using the blue channel in an RGB image.

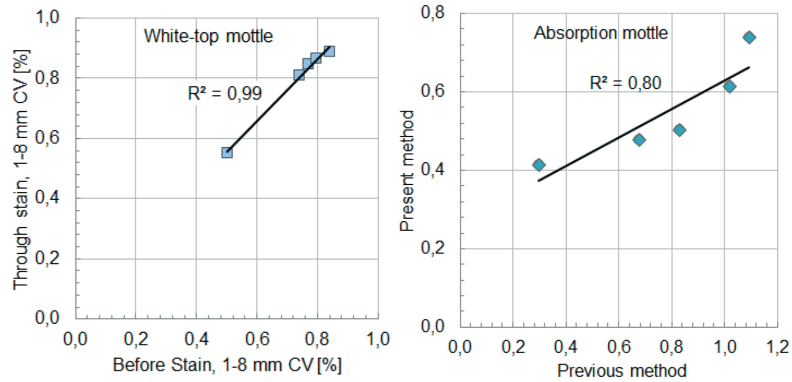

Figure 5: Validations of the present method for measurements of white-top mottle and absorption mottle. Left: Correlation between the white-top mottle in the same area (both from the blue channel images) before and after staining. Right: Comparisons between measurements of the absorption mottle, using the previous method and the present method

The absorption mottle of the stain was obtained by means of the exclusion of the WTM pattern from the stain mottle pattern, using the reflectance variations in the red and blue image channels. The absorption mottle measurements exhibited a fairly high correlation between the present method and the previously proposed method, as shown in Figure 5 (right). Nevertheless, it needs to be borne in mind that the absorption mottle calculated using the previous method was more of an indicative nature, since it was calculated by subtracting two separate measurements of the WTM of an uncoloured area (bare board) and the total mottle of a coloured area. The involving of two coefficients of variations, viz. the total mottle and the white-top mottle, corresponding to two different areas, meant that the estimated absorption mottle was less reliable. In some cases, it was not even possible to produce a calculation in such a case when the result of the subtraction was a negative one. In the present method, both the total mottle and the WTM were measured in the same RGB image, using the R and B channels separately. From these two image channels, an absorption image could be created, recalculating each pixel value. Therefore, reliable calculations of these two types of mottle are always achievable.

3.2 Reproducibility using the Round-Robin test

The reproducibility of the test method was evaluated using a *Round Robin* test with repeated measurements on six different duplex boards. Taking part were three laboratories (P1, P2, P3) at two board producers and Innventia AB, using their respective IGT F1 equipment and operators. Each laboratory used the same dyed water and the same board samples (six commercial coated liquid boards labelled A-F). To eliminate any impact from different image grabbing equipment, all the stains were scanned and analysed at the same laboratory.

The Round Robin test indicated a high level of reproducibility. The averaged values measured by different laboratories, for each paper board, were very close to each other, with an average standard deviation of 0.02, meaning that it was fairly easy to reproduce this test in the different laboratories. The standard deviation for each sample is listed in Table 1.

Table 1: Standard deviation for the three measurements of absorption mottle at separate laboratories

Sample	1-8 mm Average Mottle	1-8 mm Standard Deviation
A	0.46	0.03
B	0.56	0.01
C	0.50	0.04
D	0.44	0.01
E	0.53	0.04
F	0.42	0.01
Average	*0.49*	*0.02*

Furthermore, data from the tests made at the three laboratories correlated quite well with each other, considering that the samples showed quite similar absorption mottle levels. Figure 6 shows the pair-wise correlations of the absorption mottle in the wavelength range of 1mm-8mm, measured by the different laboratories. Each colour spot in the graph corresponds to one duplex board. There was also a similar correlation for the absorption mottle in the range of 0.5mm-1mm, where the average of R^2 was 0.77.

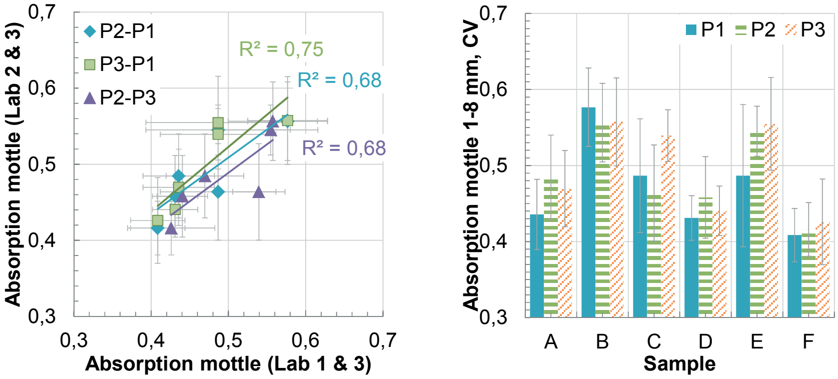

Figure 6: The correlation among the measurements of absorption mottle (1-8 mm) on all the paperboards (left). Data from each of the laboratories are also shown in a bar graph (right). The error bars indicate the standard deviation of the measurements for each board sample and at each labororatoty

3.3 Validation of the testing method

It was important that the availability of the liquid was not a limiting factor, when it came to absorption in any spot during the course of the absorption process. With a high speed camera, this was studied by observing the paper surface where the blotting nip would normally remove any excess liquid. That is, the liquid container was removed from its position for this test. It was confirmed that an unbroken liquid film covered the surface up to the nip, where the blotting paper removed the excess water. The illustration in Figure 7 shows the film after applying the liquid on to a very smooth coated board.

Figure 7: Liquid covering the surface of a sample after passing the liquid container

In addition, the stability of the absorption mottle pattern was investigated by measuring the absorption mottle on the six coated boards at two different moments, i.e. 10 minutes and 24 hours after the staining took place. The stain was found to be stable in both the longer (1 mm-8 mm) and shorter (0.5 mm-1 mm) wavelength ranges (see Figure 8), with a very high correlation between these two consecutive analyses (R^2 0.93 and 0.89). The ranking of the samples was not affected either.

The absolute levels were almost constant, indicating that the mottle pattern did not alter with time. To reduce the aging of the samples, they were kept in dark environments between the two measurements.

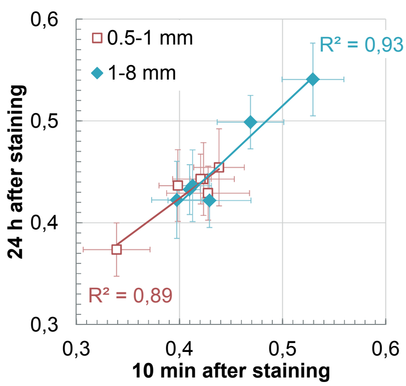

Figure 8: Comparison of absorption mottle data measured 24 hours apart on a set of coated boards. There were high correlations between the consecutive measurements, when analysing both wavelength ranges of 0.5 mm to 1 mm and 1 mm to 8 mm. The high level of correlation indicates stable mottle patterns in the stains

4. Discussion

A laboratory printing press was used in this experiment. However, the measurement technique was not intended to replace printing trials and did not imitate printing in all respects (e.g. pressure and viscosity). The aim was to find a reliable way to characterise the absorption uniformity of the samples to be used as a complement to other characterisations and to printing. Any equipment of similar design, sample transportation, a controlled nip for blotting and the possibility of adding the liquid application unit could have been used. The IGT F1 Printability Tester met these requirements and was available for the tests.

The proposed technique characterises the uniformity of liquid absorption, without the application of any external pressure during the application phase. This makes the liquid-flow very much controlled by the capillary pressure and the pore structure. When applying ink to the substrate in a printing press, however, there is a nip pressure. This changes the system and the preference of the liquid for certain pore sizes might differ. Without any external pressure, the capillary pressure is higher, the smaller the pore radius, whereas ink is more easily pressed into larger pores in the printing nip. The method at hand, rather indicated the possibility of ink redistribution (levelling) when exiting the printing nip, than giving an answer to how the ink is pressed into the pore-structure in the printing nip.

A water-based flexographic ink has a higher viscosity than the coloured liquid used in the absorption test with deionised water and methylene blue dye, which implied that it is more difficult for the flexographic ink to be absorbed by the boards. To use a flexographic ink as the test liquid may sound appealing. Unfortunately there are also drawbacks, for example, when removing the excess ink in the blotting nip, severe ink splitting patterns remained when there was an increase in viscosity.

The dye used, methylene blue, has a chromatographic effect and, hence, some preferential adsorption. A quick test, where a drop of testing liquid was placed on a sample of board with a calcium carbonate coating, clearly showed how the dye was deposited, while the water was more widely spread, see Figure 9. This was not fully mapped, although the action of being deposited in the top layer when liquid was being absorbed into the coating structure was positive. This reduced the risk of highly absorbing pores dragging the dye deep down into the structure and thereby giving a brighter appearance to the stain. This is regarded as an advantage, since redistribution of the colorant within the liquid was minimised.

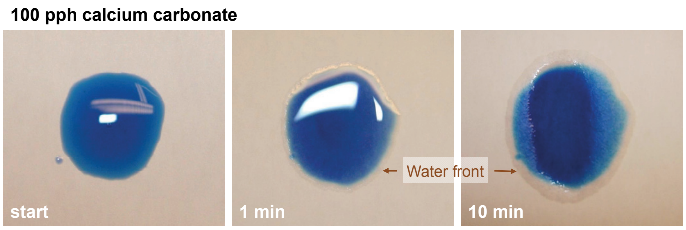

Figure 9: Drops of the aqueous solution with methylene blue were placed on the coating layers of a board. There was a chromatographic effect with water spreading in a wider circle than the dye, which had been deposited

5. Conclusions

This improved measurement technique offers a number of advantages. It enables the study of liquid absorption, especially absorption uniformity in time period and with an ink volume that is relevant to printing. Moreover, with this technique, the contributions of WTM and absorption mottle can be quantified simultaneously from one measurement. It is also possible to visualize both the WTM and the absorption patterns in the same stained area, which was not possible with the previous approach. This makes the technique a useful tool in the quality control of paper board products and for predicting print-mottle in flexographic printing. The reproducibility and reliability of this technique are promising, as suggested by the *Round Robin* tests.

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Improving the assessment of geometrical print image fidelity: Example using wide-format inkjet prints on various substrates

Martin Habekost and Rhonda Atkinson

Ryerson University
350 Victoria Street, Toronto
Ontario, M5B 2K3, Canada

E-mails: mhabekos@ryerson.ca; rhonda.atkinson@ryerson.ca

Abstract

A new method for the determination of inkjet wicking and intercolor bleed is introduced. The method is based on the thresholding concept of image analysis. The spread of a printed dot, instead of lines, is determined through the standard deviation of the mean pixel luminance. The larger the standard deviation the more wicking is occuring. A well-defined printed dot with not much variance in the pixel luminance will have a low standard deviation of the mean pixel luminance. The thresholding concept can also be used to determine intercolor bleed.

Known quality measures of paper topography and dot circularity were also used in conjunction with the newly introduced method to determine the quality of the printed dot and show how the substrate surface influences these quality parameters. Comparisons to standard print quality assessments are also made.

Keywords: inkjet, wicking, inter-color bleed, thresholding, image analysis

1. Introduction

Inkjet print technologies have become common in our lives. Beginning with the original home and office applications, today they are used in the production of many printed pieces ranging from direct mail and banners to large wide-format posters. Inkjet printing is used increasingly together with offset print technology. At DRUPA 2012 printing machine manufacturers displayed inkjet heads mounted on an offset press producing personalized printed pieces in a single step.

Due to Inkjet's speed and rapid set-up, application growth is certain. The inkjet print process is non-contact, and as such it differs from most other printing processes; to create the image, inks are propelled through the air as fine droplets to strike the medium. The electronic pump creating these droplets requires the ink be very low in viscosity, and as such, the droplets are at least partially absorbed by the paper. Ink absorption directly affects the image sharpness or visual clarity, which is often referred to as wicking or raggedness. Wicking occurs between printed characters, lines, and in half-tone images between the dots.

In the case of inkjet printing, dot sharpness and internal uniformity are affected not only by the formulation of the ink but also the properties of the paper; its surface treatment and the internal size, both of which affect the absorptive properties of the paper. A requirement for glossy inkjet paper coating is limiting the spread of the ink, i.e. to fix the inkjet colorants to the coating. In this study papers that have been specifically made for inkjet printing will be tested with water-based and UV inkjet inks.

Although the differences between two papers may be minimal in terms of wicking (i.e. raggedness and feathering), it can make the difference between a sharp, crisp looking print and a fuzzy looking print. This applies to text appearing fuzzy or too bold, and in half-tone areas that will darken as more wicking occurs.

The common test inkjet pattern contains lines but because scanners were used to acquire the test images, the authors chose to use dots as the primary test pattern, contrary to common practice. Using dots minimizes the possibility of the Moiré effect in the analysis: e. g. misalignment of the rectilinear printed line with the rectilinear scanner camera and the subsequent rectilinear image analysis. In addition, dots are the basis half-tone images, and the analysis program used in these tests was initially developed to analyze the quality of the offset/flexographic/gravure half-tone print; it was enhanced to handle non-contact inkjet tests as well. Practice has determined there is no difference between the perimeter wicking of a line and a dot. In this analysis the authors have chosen to use dots with a diameter of 2 μm printed in a range of colors.

2. Theory

Inkjet ink is, for the most part, solvent followed by the pigment or dye. There are a few other components in the inkjet ink as well, that control the evaporation rate of the ink as well as the inhibited growth of the micro-organisms. An exemplary inkjet ink formulation can be found in Table 1.

Table 1: Exemplary inkjet ink formulation (Stephenson, 2013)

Ink Component	Component Amount (%)	Ink Function
Water	50 - 90	Solvent
Colorant	1 - 15	Color
Co-solvent / Humectant	2 - 20	Ink Vehicle, Inhibits Evaporation
Fixative / Penetrant	0 - 10	Fix Ink to Substrate
Surfactant	0.1 - 6	Adjust Surface Tension and Wetting
Resin	0.2 - 10	Durability, Adhesion
Biocide	0.02 - 0.4	Prevent Bacterial Growth
Fungicide	0.05 - 1	Prevent Fungal Growth
Buffer	0.05 - 1	Control pH
Other	0.01 - 1	Corrosion, Contamination, etc

Table 1 above lists all the components and their function in inkjet ink. UV-inkjet inks contain monomers and oligomers for the solvent portion and there are also photo initiators present, which ensure proper curing of the ink and they absorb the UV-radiation based on the type of lamp (Hg-vapor or LED) that is used a source of UV light.

After knowing the general composition of an inkjet ink, it is important to know how well the inkjet ink agrees with the print media; what it will look like, not only from the layers present that form the substrate, but also how the substrates looks under a microscope. The following figure shows the general composition of three inkjet type media. The figure was adapted from Svandholm. Figure 1 bellow shows the substrate composition of inkjet media. From left to right: basic paper, photographic paper, transparent inkjet medium.

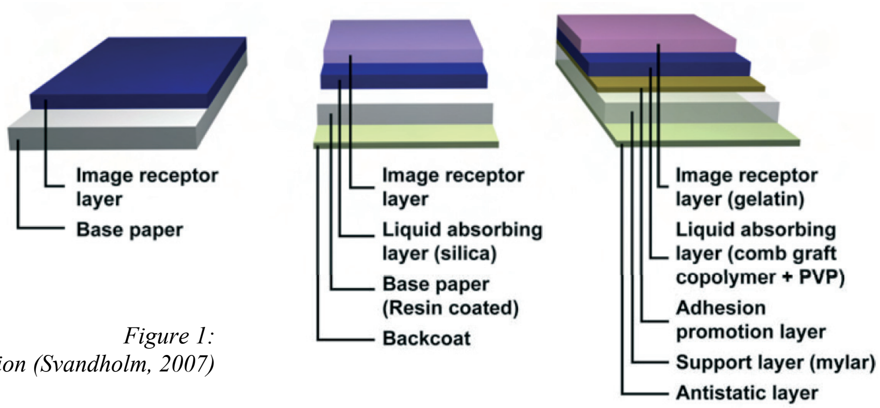


Figure 1: Substrate composition (Svandholm, 2007)

It can be seen from these images that all papers need an image receptor layer that helps to fixate the printed inkjet dot onto the paper. The next layer in all three substrates is there to absorb the liquid (water or monomers).

The images of the different surface structures help to understand why certain types of inkjet papers show more inkjet wicking and intercolor bleed than others. Before these images are shown it is necessary to see what is meant by wicking and intercolor bleed. The following figure is from Briggs (Briggs, 2002).

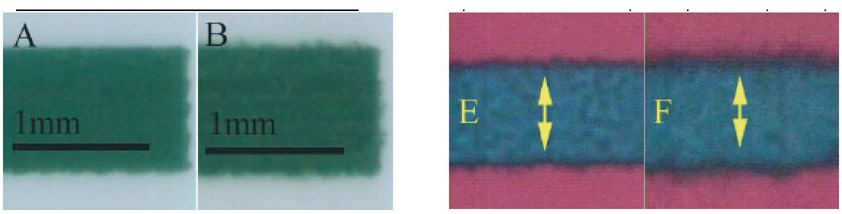


Figure 2: Images of inkjet wicking (left) and intercolor bleed (right)

From Figure 2 seen on previous page, it can be seen that wicking leads to the spread of inkjet ink into the surrounding area of the printed image. The edges become ragged and less defined when more wicking occurs. Intercolor bleed is in regards to the interaction of two inkjet inks neighboring onto each other. Depending on the ink composition and the wicking properties of the paper the intercolor bleed, this can be less or more severe.

In the Figure 3 below, SEM (scanning electron microscope) images of five different substrates are shown.

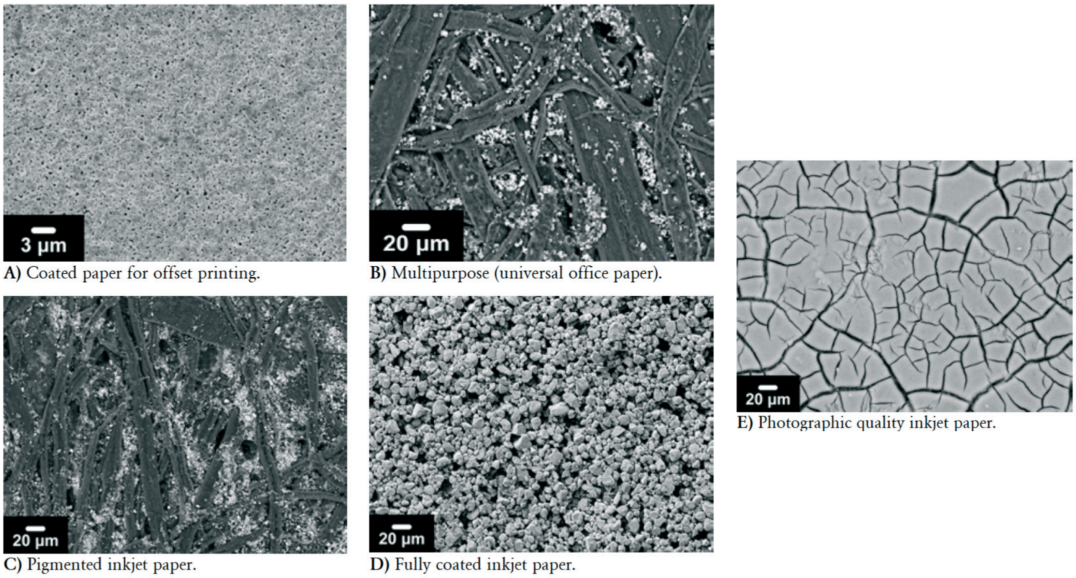


Figure 3: SEM images of different papers according to Svandholm (Svandholm, 2007)

The paper surfaces in Figure 3 show clearly how smooth the surface of a coated offset printing paper is. The paper fibers of a universal, uncoated office paper are also clearly visible. The most interesting image is the surface of a photographic inkjet paper.

Based on the great printed results that are achievable with this type of substrate one is astonished to see how many cracks and voids are in this paper.

3. Experimental and results

To measure ink wicking, the authors have chosen this pattern of dots, which is shown in Figure 4.

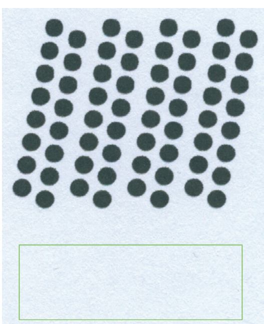


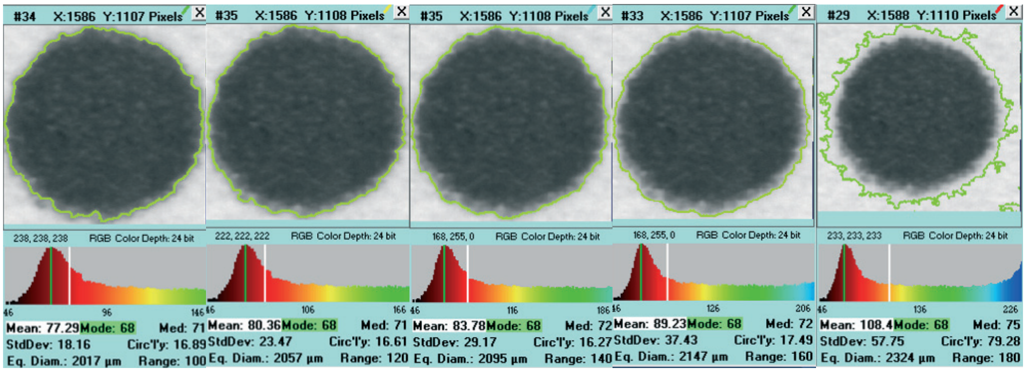
Figure 4:
Verity Dot Pattern used to determine inkjet wicking

These dots are uniformly 2 mm in diameter and may be printed in any color, within fields of any color. Dots offer many advantages to the image analyst, using as we have, a high quality scanner, because even at a low resolution of 600 ppi, dots cannot be misaligned.

Immediately below the dots is an unprinted area outlined in green. To prevent any contamination from ink over-spray on the original print, this area, with the dots above, is the final image on the page. In this unprinted area, defined by the green box, the analysis system measures the paper reflectivity and topography.

To measure the dots the software uses a concept known as "Thresholding". To understand the workings of a threshold one must first understand the image in which the measurement will be made is an 8-bit derivative of a full color 24-bit image. In an 8-bit image the pixel luminance (brightness) can have a value between 0, (pure black), to 255 (pure white). To see and to measure an object within the image it must contrast with its immediate surroundings. The degree of contrast is determined by the pixel luminance value (i. e. pixel or picture element brightness). The program extracts or identifies the object of interest based upon the threshold value; those pixels having a value less than or equal to the threshold value are identified as being of interest. The program measurement algorithm then associates the identified pixels to form the objects that are then measured and reported. The associated pixels forming the object of interest, in this case a dot image, are further analyzed to compute the mean luminance value of all the pixels within its perimeter, i.e. its brightness. The series of dots shown below illustrate how the software computes the mean luminance at five (5) progressively higher threshold values. These multiple thresholds are set using a rigid mathematic progression that measures the dot from its core or darkest value through to its fully wicked condition.

Figure 5 below shows the same single black inkjet dot printed on uncoated white paper measured by the software using the progressive threshold. It is the same dot in all the pictures taken from the system in an actual test.



(1) (2) (3) (4) (5)

Figure 5: Example images showing the thresholding process

Below each of the images in Figure 5, are data and the pixel luminance histogram derived from the application of progressively higher thresholds. The green line traces the perimeter of the dot. With the lowest threshold in Figure 5, the core or darkest portion of the dot is measured, as indicated by the equivalent diameter (Eq. Diam) measurement of 2.017 mm. As the threshold is changed the measured equivalent diameter becomes larger and the other property measurements change as well. Of primary interest is the variation in the pixel luminance value within the perimeter of the dot. The degree of variance in the dot mean pixel luminance measurement from low (core) to high threshold (maximum wicking) is the prime determinant of inkjet wicking. By computing the standard deviation of the mean pixel luminance value within each dot perimeter the program presents a measure of ink wicking and image quality. In the figure 5 the following values were obtained:

The mean pixel luminance within the perimeter:

1. 77.29 (The minimum or core of the dot)
2. 80.26
3. 83.78
4. 89.23
5. 108.4 (The maximum wicking into the inter-space)

The Mean Pixel Luminance Standard Deviation: $\sigma = 12.35$

The Mean Pixel Luminance Standard Deviation is proposed as the basis of comparative measurement of substrate quality for inkjet print.

Inter-color bleed is also an inkjet quality problem that is similar to wicking. This inter-color bleed depends on the colors that are being printed and can have an adverse effect on small colored text printed on a colored background. Line width and raggedness are defined in ISO 13660 and parts of this method will be used to evaluate the printed samples by substituting dots for lines.

For this research the following hard- and software was used to evaluate the printed samples:

- VerityIA MicroDot V 1.1 (now called Inkjet lines and dots)
- Epson Scanner, Model #
- Windows7 PC with 2GB RAM
- ImageJ version 1.45s
- Interactive 3D surface plot plug-in
- Curve 2 V 2.3
- X-Rite 530 spectrodensitometer

Prints made with large format printers from Océ, Epson and Fuji. Inkjet prints were made with water-based inkjet inks and UV-curable inkjet inks. There was also one UV-LED system tested. The other UV-curable prints were made with a mercury-vapor lamp as a source for the UV radiation. Figure 6 shows the scanner together with the sample weight to ensure that the sample is lying absolutely flat against the platen and that all samples have the same white background for measuring.

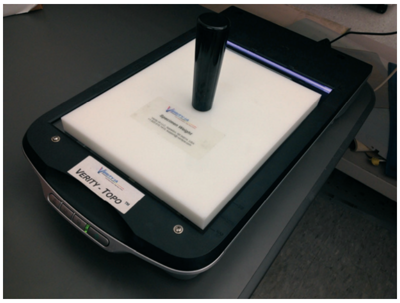


Figure 4:
Epson scanner with sample weight

The following figure shows the test pattern that was included in the testform, so all samples will be evaluated similarly.

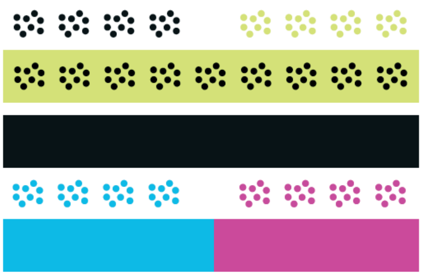


Figure 5:
Test pattern used for the determination of the inkjet wicking properties

Besides the determination of the "Mean Pixel Luminance Standard Deviation" for the inkjet wicking properties of the samples the topography of the tested samples and the dot circularity were also determined so that comparisons can be made to say how these two parameters correspond with the mean pixel luminance standard deviation.

The tested materials ranged from very smooth to quite rough. This is illustrated in the topography values that were obtained in this study. They ranged from 38.05 (very smooth) to over 3000 (quite rough). The following figure shows exemplary 3D-plots of some of the tested materials.

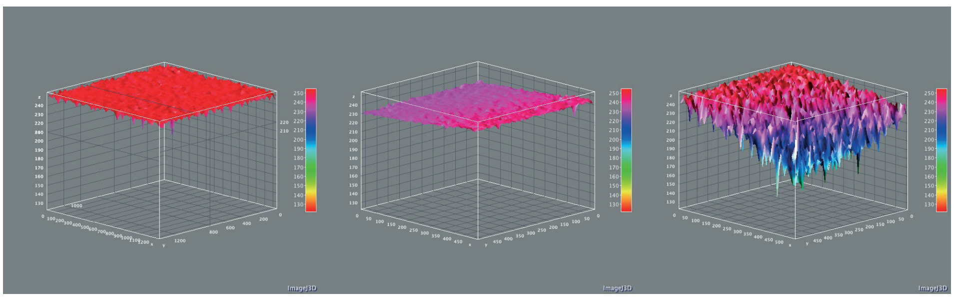


Figure 6: Exemplary 3D topography plots. Topography values were 38.05, 399.1 and 2561 from left to right

In the first analysis the obtained circularity values were plotted against the topography values of the tested substrates.

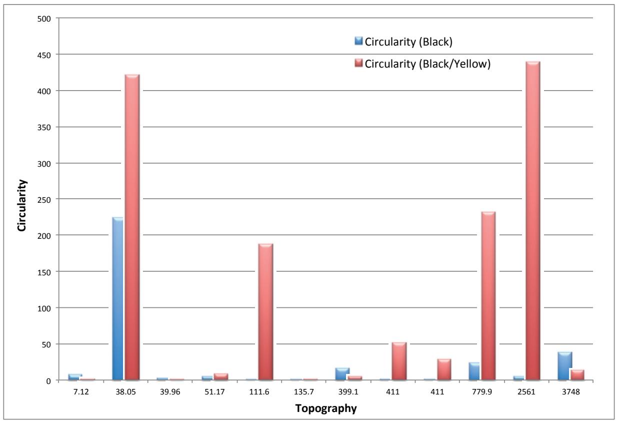


Figure 7: Circularity results of the tested substrates vs. the topography of the tested substrates

From figure 9 it can be seen that the circularity results vary drastically, independent of the topography values of the tested substrates. The red column shows any inter color bleed that is occurring between the black dots and the yellow solid shown in figure 7. The relatively smooth paper with a topography value 38.05 shows quite an irregular dot and a lot of inter color bleed, while the roughest substrate with a topography value of 3748 shows quite a round dot and very little inter color bleed. It needs to be seen how this comparison works in relation to the proposed mean pixel luminance standard deviation. This can be seen in the figure 10.

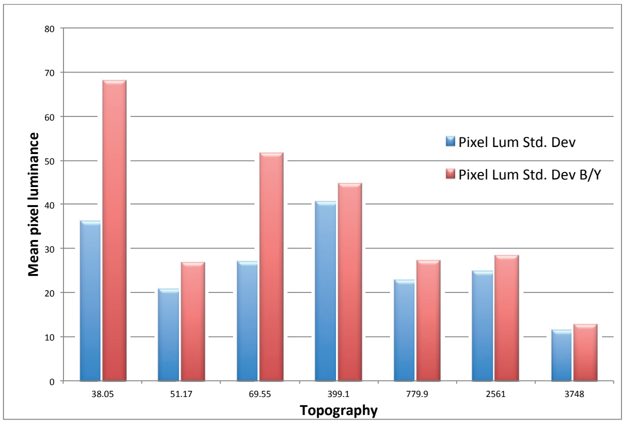


Figure 8: Mean pixel luminance standard deviation vs. topography of the tested substrates

Figure 10 shows a much clearer picture. All tested substrates show some inter color bleed, but the results are not as drastic as they were shown in figure 4. It is now possible to compare substrates over a wide range of surface topography values for their properties in regards to inkjet wicking and inter color bleed. The substrate with a topography value of 38.05 shows more inkjet wicking than the papers with a rougher topography. The last three substrates in figure 10 show less ink wicking and less inter color bleed than the substrates with smoother surfaces. A smooth substrate surface is not a guarantee for a superior print quality as revealed in the roundness of the tested dots.

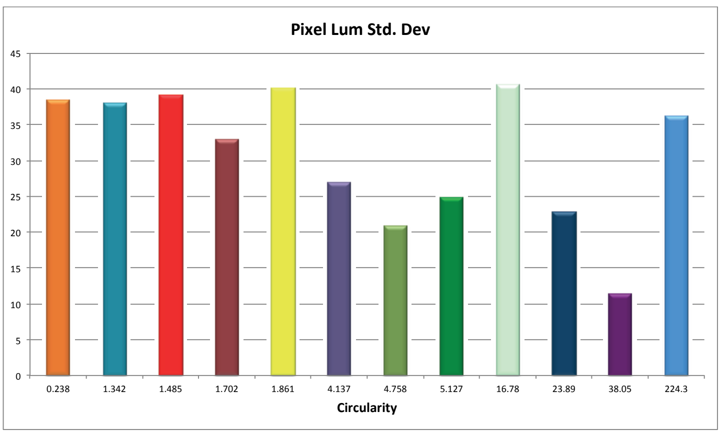


Figure 9: Mean pixel luminance standard deviation vs. dot circularity

Figure 11 and 12 show the results in regards to circularity and topography. They contain the results from all the tested prints on different substrates. The columns have been color coded to show how the order of the tested system changes. For example the light blue colored system in figure 11 has the highest dot circularity number, which means that the dot is not very round on a quite smooth substrate as can be seen in figure 12. The results from these two figures for this system mean, that the dots themselves are not very round, yet the paper shows a decent amount of ink wicking. There are substrates with a rougher surface, meaning higher topography values, yet the paper shows less ink wicking than a smoother substrate. This example can be seen in the olive green column in figures 11 and 12.

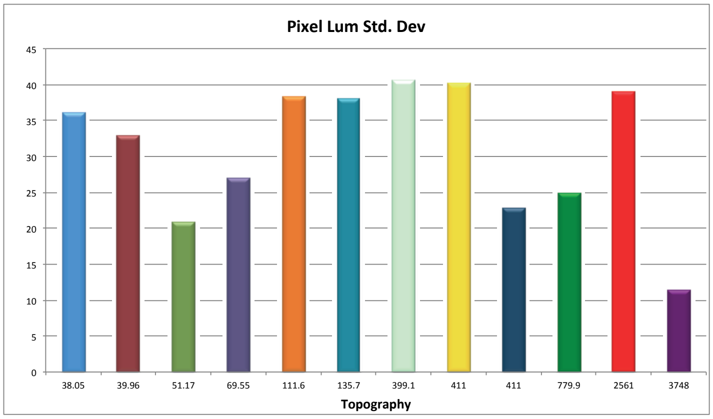


Figure 10:
Mean pixel luminance standard deviation vs. topography

In figure 13 and 14 the values for the black dots and the inter color bleed for black and yellow are shown.

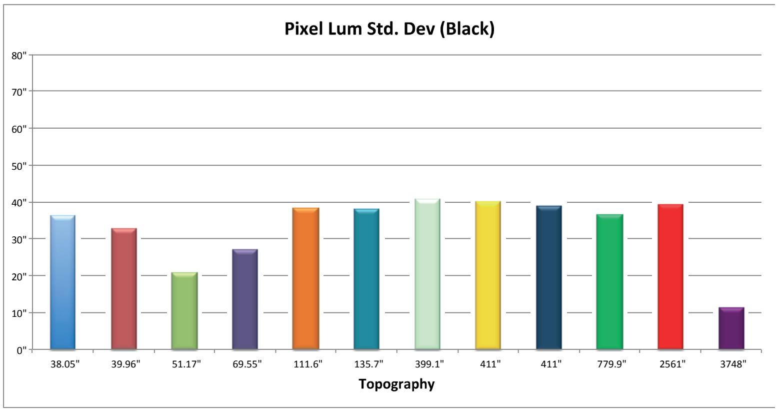


Figure 13: Mean pixel luminance standard deviation for black

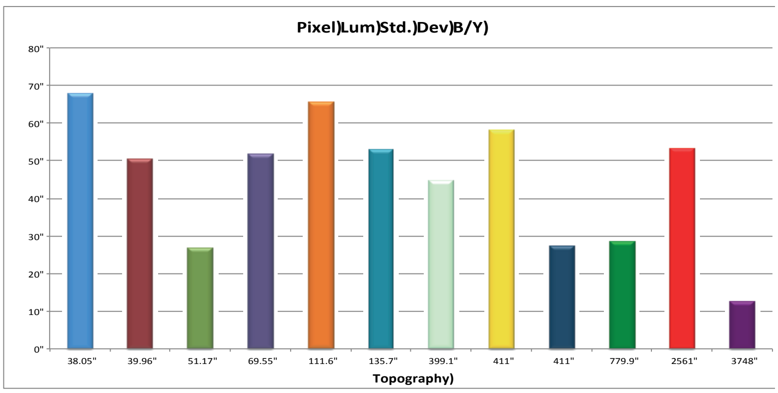


Figure 14: Mean pixel luminance standard deviation for black-yellow intercolor bleed

From the top part of figure 13 it can be seen that although the tested substrates get rougher and rougher the wicking properties remain quite stable. This is an interesting find, since it means that these substrates are cated systems, symbolized by the purple column was quite fascinating. The paper was of a bond type quality and the print was made with gelled water-based inkjet inks. The inkjet printer is geared towards the architectural market, so CAD-type drawings can be printed quickly and with very good quality, meaning a sharp dot and little or no inter color bleed. The results shown above demonstrate this.

Conventional methods of analysis can provide a further assessment of inkjet devices. TVI, Ink Trap, Print Contrast and Delta E were measured as means of a quality comparison. GRACoL sheet-fed offset recommended values were the basis of comparison.

Although inkjet capabilities differ from offset, the recommendded target values provide an effective visual indication of the quality achievable on inkjet devices. Table 2 below lists the recommended dot gain for CMYK at 50 % tint for GRACoL.

3.1 Tone value increase (dot gain) analysis

Table 2: Recommended Sheet-fed Offset Dot Gain for 50 % Tint (IDEAlliance, 2007, p.30)

BLACK	CYAN	MAGENTA	YELLOW
22 %	20 %	20 %	18 %

According to the IDEAlliance printing guidelines as shown in Table 2 above, recommended 50 % TVI values were not achieved for most samples. Samples 3 and 4 were the closest to target values and show good dot gain profiles compared to the rest of the tested samples. The high range and vast differences of the dot gains of CMYK reveal inconsistent calibration among the inkjet printers.

Figures 15 and 16 below show the dot gain profiles.

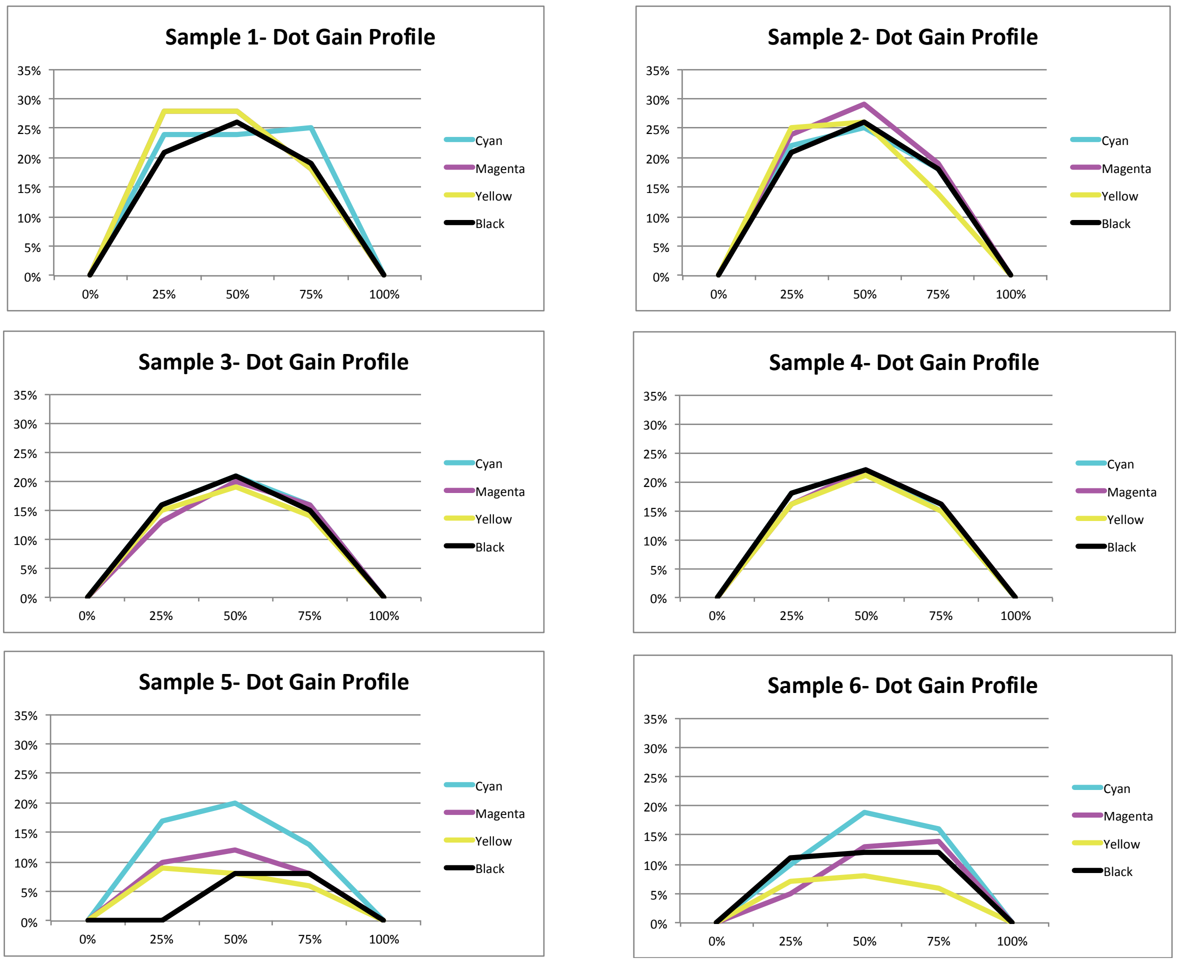
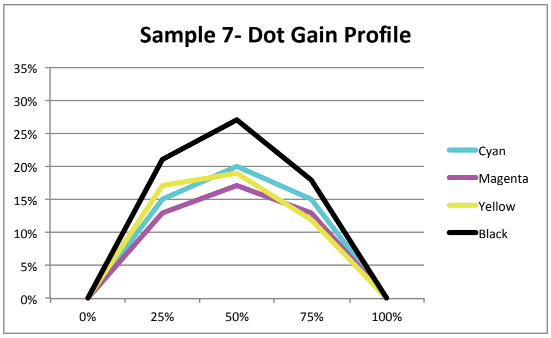
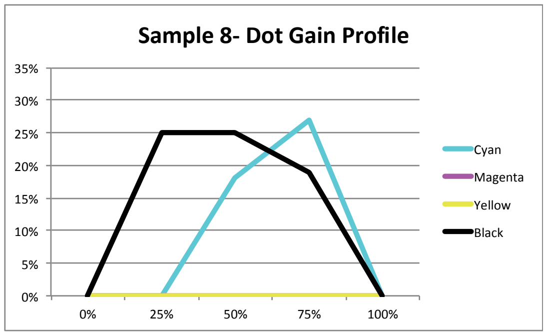
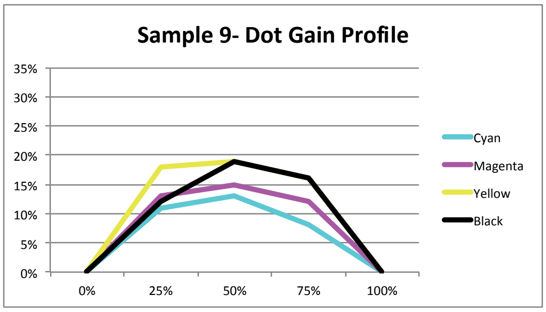
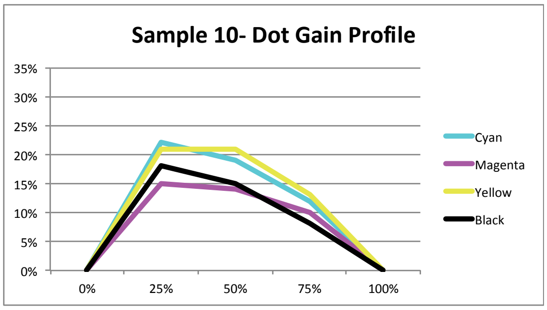


Figure 15: Dot Gain Profiles for samples 1 to 6









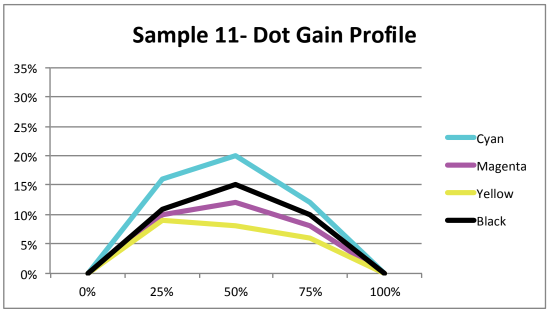


Figure 16:
Dot Gain Profiles for samples 7 to 11

3.2 Ink trap

The recommended GRACoL ink trap values from X-Rite are listed below in Table 3:

Table 3: Recommended Sheet-fed Offset Ink Trap Values for RGB (X-Rite, 2003, p.7)

RED	GREEN	BLUE
70	80	75

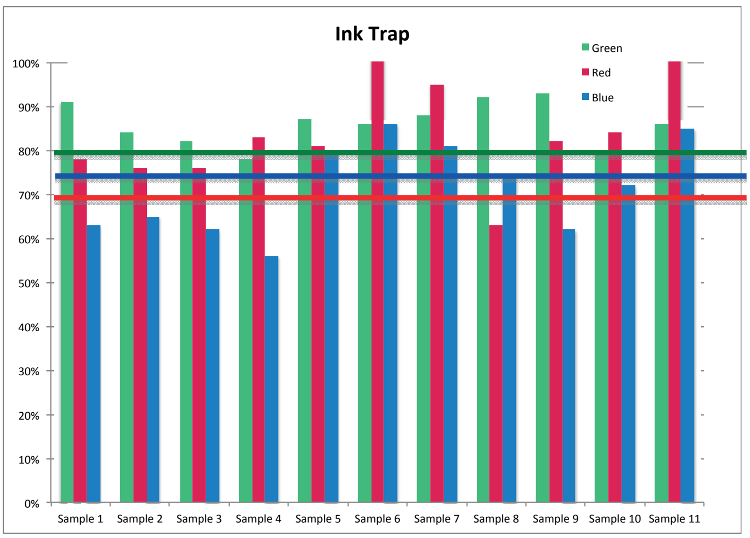


Figure 17:
Measured Ink Trap for RGB

The samples measured ink trapping both above and below the recommended industry trap values as shown in Figure 17. As shown, ink trapping at red for most devices is higher than the recommended value of 70. In contrast, ink trapping at blue is overall lower than the recommended value of 75.

3.3 Print Contrast

Recommended print contrast values from X-Rite at 75 % tint are listed in Table 4 below:

Table 4: Recommended Sheet-fed Offset Print Contrast Values for 75 % Tint (X-Rite, 2003, p.8)

BL ACK	CYAN	MAGENTA	YELLOW
43	38	38	33

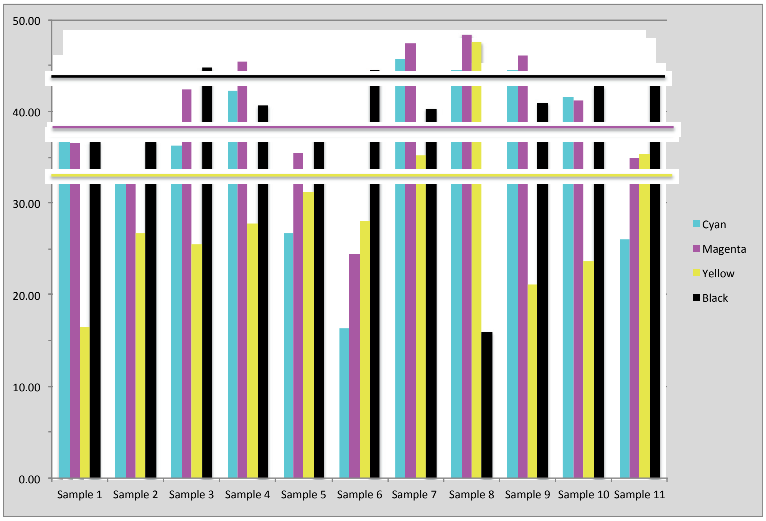


Figure 18: Measured Print Contrast Values

As seen in figure 18, there is a large range of print contrast among the samples. Sample 11 measured the closest target value for black.

The rest of the samples measured below the recommended value, except for samples 3 and 6, which measured slightly above. Print contrast for C, M, Y showed similar results, with only a rare few above the recommended values, but most below. Sample 6 interestingly showed poor contrast in C,M,Y but was too high in K.

3.4 Average Delta E

This evaluation stems from the Curve2 software that shows how far away the inks are from the ISO inks that are required for achieving neutral gray balance. Although the inkjet inks were not tested on the recommended stock, but on the material they were printed on.

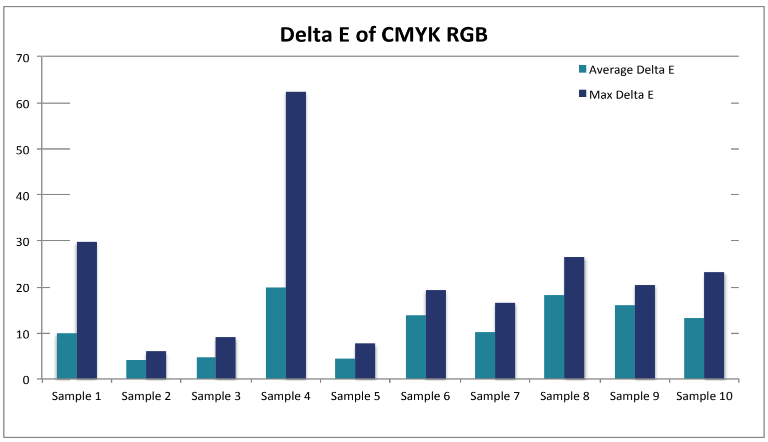


Figure 19: Average and Max Delta E of CMYK RGB as determined by Curve 2

Average and max Delta E values provided an interesting result for the tested devices. Samples 2, 3 and 5 were the only samples that values below 10.

Sample 4 showed especially a high Delta E value. The results as shown in Figure 19 reveal that color management software was not utilized in most cases.

The prints were made with the "high quality" or "art quality" setting of the software addressing the tested inkjet printers.

3.5 Calibration curve "wanted" values

For this part of the analysis the P2P25X target was measured with the EyeOne and the measurement values imported into the Curve2 analysis software that is used to determine the G7 compliance of a printing press.

The software will suggest changes that need to be made for the output curves, so the print will achieve a neutral grey balance.

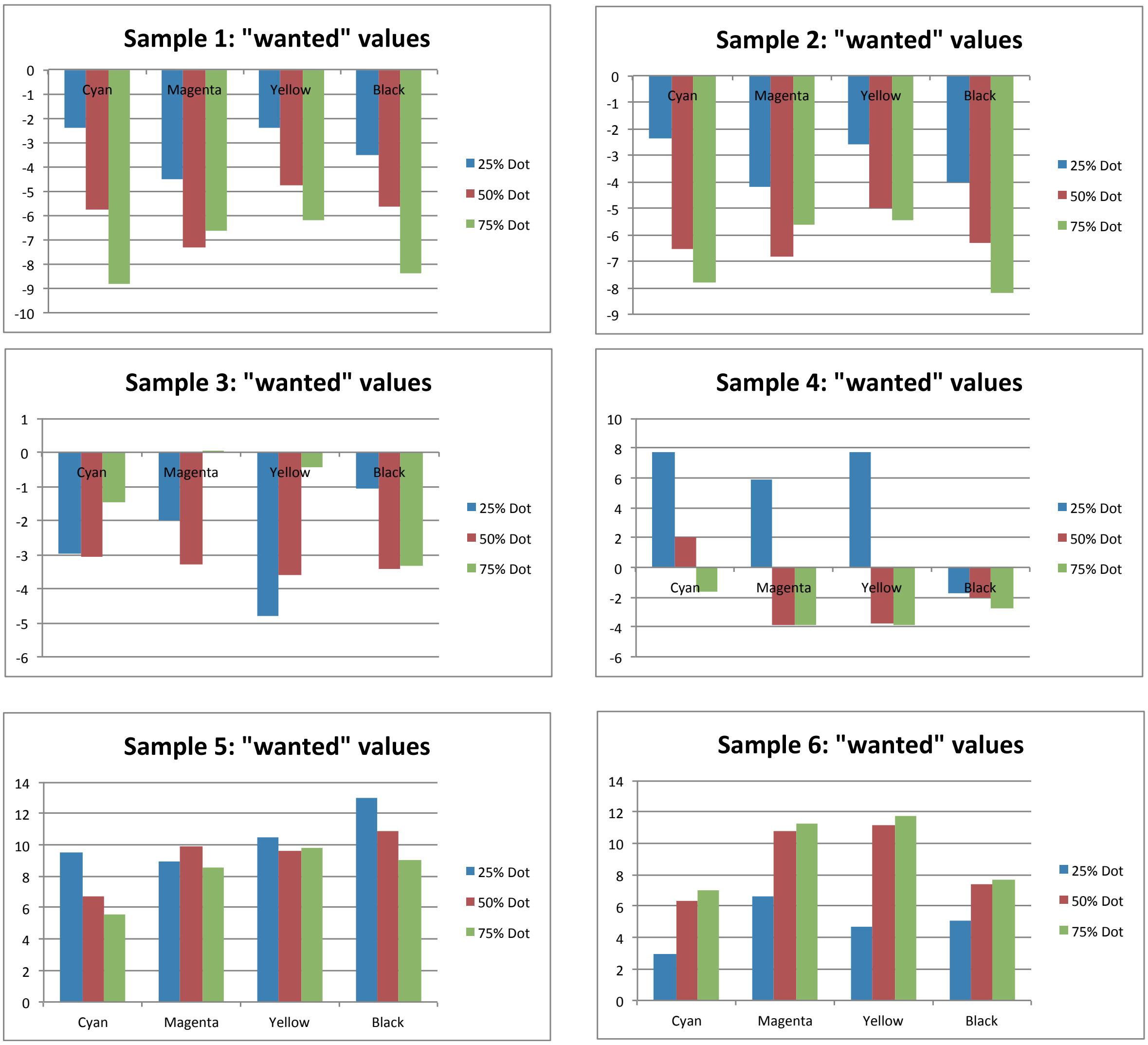


Figure 20: Calibration Curve- wanted values for Samples 1 to 6 as determined by Curve 2

As Figures 20 and 21 show, Curve 2 software suggested that the tested devices needed both increased, and decreased values, or in some cases both. Samples 1, 2, and 3 require cutting back C, M, Y, and K at all three dot percentages. While samples 5, 6, and 9 wanted increased dot values for all ink colors and dot percentages. Samples 4, 7, and 10 suggested some inks needed to be cut back, while some needed to be increased. The results of the Curve 2 calibration run revealed mixed results indicating calibration curves were not adjusted.

Figure 21: Calibration Curve- wanted values for Samples 7 to 10 as determined by Curve 2

4. Conclusions

Topography and circularity alone do not give a clear picture if one paper shows more wicking and/or feathering than another. The standard deviation of the pixel luminance shows that a paper with a rough surface can still have less wicking than a smooth paper. A combination of circularity, topography and standard deviation of pixel luminance is needed to assess the wicking properties of a paper and the inter color bleed that can take place between two colors. Since the prints were not made specifically to GRACoL recommendations there was a wide range of tone value increase, ink trap and print contrast results. The Curve2 software also showed that some of the inkjet inks differ dramatically from the recommended ISO process inks that are recommended for the neutral grey balance (G7) methodology. Since none of the prints were made using the G7 methodology it was not surprising to see large deviations from the optimum print conditions and that sometimes drastic changes to the output curves were suggested by the Curve2 software.

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Ink film opacity from reflectance and transparency

Paul D. Fleming[1], *Alexandra Pekarovicova*[1], *Veronika Lovell*[2], *Angel N. Allen*[1], *Gaurav D. Seth*[1]

[1] CEAS, A-231 Parkview
Western Michigan University
Kalamazoo, MI 49008-5462, USA
E-mails: dan.fleming@wmich.edu; a.pekarovicova@wmich.edu; angel.n.allen@wmich.edu, gaurav.d.seth@wmich.edu;

[2] Sun Chemical Corporation
1701 Westinghouse Blvd
Charlotte, NC 28273, USA
E-mail: veronika.lovell@sunchemical.com

Abstract

The goal of this work was to determine if the opacity, calculated from tristimulus values XYZ of ink film printed over black and white substrate, can be correlated with the ink film transmittance. A series of opacities and transparencies were calculated and correlated. A general regression was done, which specified a significant linear correlation between the opacities calculated from transmission and reflectance measurements of prints done on transparent PET film and Byko chart.

Keywords: opacity, transparency, reflectance, transmittance, flexo

1. Introduction

Incident light interacts with an ink film and light energy is transmitted, reflected, absorbed and scattered by the ink film, in reflection or transmission measurement mode. Multiple internal reflections (Fresnel reflections) may occur in the printing ink film. Surface reflection, also known as Fresnel reflectance of incident light also takes place. The ink transparency or it complementary value, opacity, affects the amount of light being reflected from the surface, which leads to more or less rich and saturated colors. Inks with high transparency enhance the visual sensation especially on foil or metalized substrates. On the other hand, single layer transparent inks do not add too much value to print on a white background (Leach, 2007; Gajadhur, 2007), thus transparent inks are employed in process color printing, while more opaque spot colors are used as single ink layers (Sangmule, 2012). Ink opacity or transparency is a very important issue for the graphic industry, especially when printing white inks. It requires about 10% more of white ink applied to enhance its opacity by 1% in opacity, which can increase the cost of ink by 10% (Argent, 2008). Prediction of reflectance and transmittance is becoming more complex for halftones, where one needs to account for tone value increase (Machizaud, 2012; Hebert, 2006; Bugnon, 2013)

Kubelka and Munk (1931) elaborated an equation, according to which light falling on a printed ink film is partially absorbed, and partially scattered. Scattered light can be measured as a diffuse reflectance R according to the formula [1]:

$$K/S = (1-R_\infty)^2/2R_\infty \quad [1]$$

where: K is absorbed light,
S is scattered light, and
R_∞ is diffuse reflectance of the infinitely thick film.

This model predicts the transmittance and reflectance of a single uniformly diffusing substrate layer (Kubelka and Munk, 1931). Later, ink concentrations were included into equation (1), K/S values for ink and substrate, as well as thickness of the ink film (Leach, 2012). The single constant Kubelka-Munk equation calculated the ratios of absorption to scattering coefficient in a way that the substrate color contribution was removed. The two- constant equation was also elaborated, which is mostly used for opaque ink formulations (Leach, 2007). Saunderson elaborated a correction of the Kubelka-Munk model computing exterior and interior reflectance, accounting for multiple internal reflections (Saunderson, 1942).

Spectral transmittance data of transparent prints were calculated using automated reflectance measurement (Cui, 2000). A transparent sheet was placed on a measurement table with paper backing. Transmittance of the same patches was measured for comparison and the data were used to calculate a transmittance model (Cui, 2000). A mathematical model between reflectance and transmittance was elaborated for stacked transparency and paper printed with halftone colors (Machizaud, 2012). Reflectance spectra were calculated from multiple reflections using Clapper-Yule (Clapper and Yule, 1953), or Williams-Clapper model (Williams and Clapper, 1953) depending on non-orientational or orientational attenuation of ink (Hebert, 2007). Most of these models were developed for halftone colors, but the Williams-Clapper model works with solid ink films.

Reflectance predictions of Opacity for Neugebauer primaries (solid ink and ink overprints) were done by using transmittance measurements. Only magenta gave accurate reflectance predictions, while yellow and cyan resulted in a less accurate predictions. It was proposed that the yellow and cyan ink films have different behavior in reflectance and transmittance mode (Razieh, 2012).

Our work aims to correlate opacity data gained by measured reflectance spectra of solid ink films, and XYZ values from it measured over white and black backing and XYZ data measured on a transparent substrate, using a transmission spectrophotometer, doing only one measurement, and calculating the opacity as supplemental value of transparency. The reasoning behind such measurements is to try to obtain opacity or transparency as a direct measurement instead of calculated one.

2. Materials and methods

2.1 Opacity calculation

A laboratory K-proofer in flexo mode was used to make flexo prints of single inks and two overprints. Water based flexo inks CMYK, orange, green and violet were employed (CCLV ECG WMU Series Sun Chemical Inks). The prints were taken on a coated Byko chart #PA-2811 (BYK-Gardner), which has white and black areas. Opacity from reflectance measurement was calculated as follows: The reflectance values over white and black backing were measured ten times each using i1iO Spectrophotometer attached to MeasureTool 5.0.8 (X-Rite). The XYZ values for (D50/2) illuminant/observer) were then calculated form the reflectance spectra. The percent opacity was calculated by using the standard test method ASTM D 2805-11). Contrast ratio C was calculated as shown in Equation 2:

$$C = 100R_b/R_w \qquad [2]$$

where: R_b is reflectance value from black area (Y tristimulus value)
R_w is reflectance value from white area (Y tristimulus value)

If the reflectance of the white area is measured, R_w can be calculated and the opacity (in percent) can be calculated by (Kubelka and Munk, 1931)

$$O = 100R_b/R_\infty \qquad [3]$$

R_w can be calculated from (Kubelka and Munk, 1931, ASTM D2805-11)

$$R_\infty = a-(a^2-1)^{1/2} \qquad [4]$$

where: $a=½(R_w +(R_b+W- R_w)/WR_b)$ and W is the reflectance of the white area.

The calculations of overprinting opacity due to the order of inks, ink drawdowns of two ink overprints were performed. Two inks were overprinted using the K-proofer in flexo mode on PET substrate as well as Byko charts (BYK Gardner). A tone step patterned flexographic plate was used with tone steps of 25 %, 50 %, 75 % and 100 %. The ink sequences that were compared were as follows:

- YM vs. MY
- YC vs. CY
- OM vs. MO
- OK vs. KO
- OC vs. CO
- GC vs. CG
- GK vs. KG
- MC vs. CM
- VK vs. KV

2.2 Transmission spectra

The transmission spectra were obtained from flexo prints done using a K-Proofer in flexo mode printed on transparent PET substrate in the exact same setting as used for printing samples for reflection measurement. Calibration of instrument was done including the transparent PET substrate. A SpectroScan T transmission spectrophotometer connected to MeasureTool 5 (X-Rite) was used to measure transmission spectra and calculate the XYZ for (D50/2) values of single inks and their overprints. Each sample was measured 15 times. The opacity from transmission spectra was calculated by subtracting the transparency (respective tristimulus value Y) from 100. Since the transmission spectrophotometer casts the light from the bottom, underneath the sample, transmission spectra were measured in both ways: PET/printed ink film and printed ink film/PET.

2.3 Analytical

Opacity and transparency correlation

A simple representation of correlation equation can be stated as Y = a + b*X; where 'a' & 'b' are the coefficients and 'X' & 'Y' are the variables. One of the most important aspects of correlation is the strength. The strength of the linear association between two variables can be quantified by the correlation coefficient C, or Pearson product moment correlation coefficient (Box, et al., 1978). The correlation coefficient directly relates to the regression line (Y = a + b*X) for any two variables because the regression line involving the least square values of 'r^2' passes through the means of X and Y.

The regression line can also represented completely by the means, standard deviations, and correlation of the two variables (Annon, 2012). In linear regressions 'r^2' is used more often and is termed as the coefficient of determination. The main purpose of 'r^2' is to take in to account the proportion of variability and to predict future outcomes on the basis of the related information.

The value of the coefficient of determination ranges between 0 and 1 (0% and 100%); a value of zero for r does not signify that there is no correlation; a correlation in such cases could be a nonlinear. However, even a nonlinear correlation will usually yield a non-zero correlation coefficient. The formula to calculate linear correlation coefficient C_{xy} is as follows: (Box, et al., 1978).

$$C_{xy} = \frac{n\Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{(n\Sigma x^2 - (\Sigma x)^2)(n\Sigma y^2 - (\Sigma y)^2)}} \quad [4]$$

where: x is factor and y is response

3. Results and discussion

A spectral reflectance curve can be defined as a curve that demonstrates the reflectance of light from a surface of a substrate. The reflectance curve is plotted wavelength-by-wavelength throughout the visible spectrum and servers as a means of determining the color of that surface. Spectral reflectance also aids in determining paper color, brightness, and whiteness and also vital optical properties that vividly affect the quality of material printed on the paper surface like color gamut in this case.

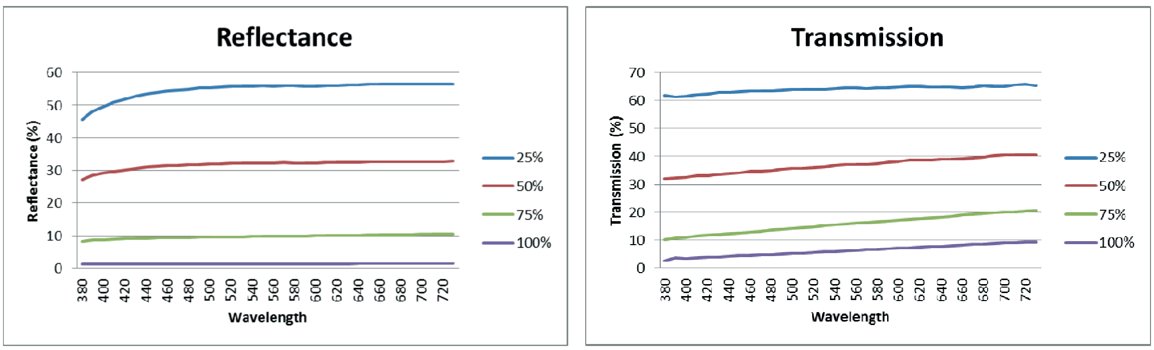

Figure 1: Reflectance curve of black ink (Left).
Transmission curve of black ink (Right)

Transmission curves of the same inks have values that are slightly higher or equal to the reflectance curves (Figure 1), (Seth, 2013).

In the reflection process some of the light is diffused into the substrate, which causes the recorded value to be slightly lower. Some reflection is also observed in transmission curves, but the diffusion of light in the substrate is much lower. Also, during the reflection process, the light involves two passes through the ink film, whereas in transmission the light only passes once through the ink film.

Opacity values, calculated from respective XYZ according to Equation (3), are shown in the Figure 2. Figure 3 shows the calculated values of opacities from transmission measurements of printed ink/PET direction.

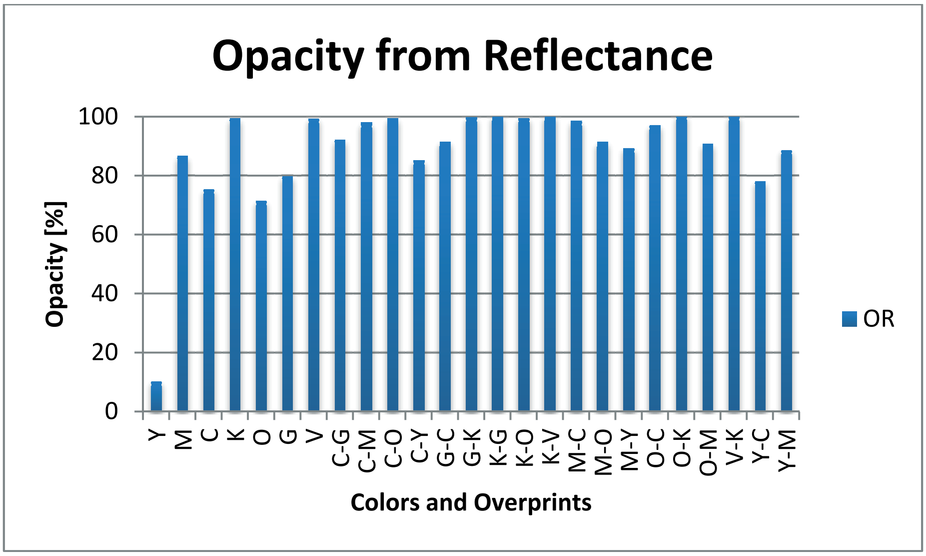

Figure 2: Opacity calculated from tristimulus values XYZ over black and white background. Only Y values were used

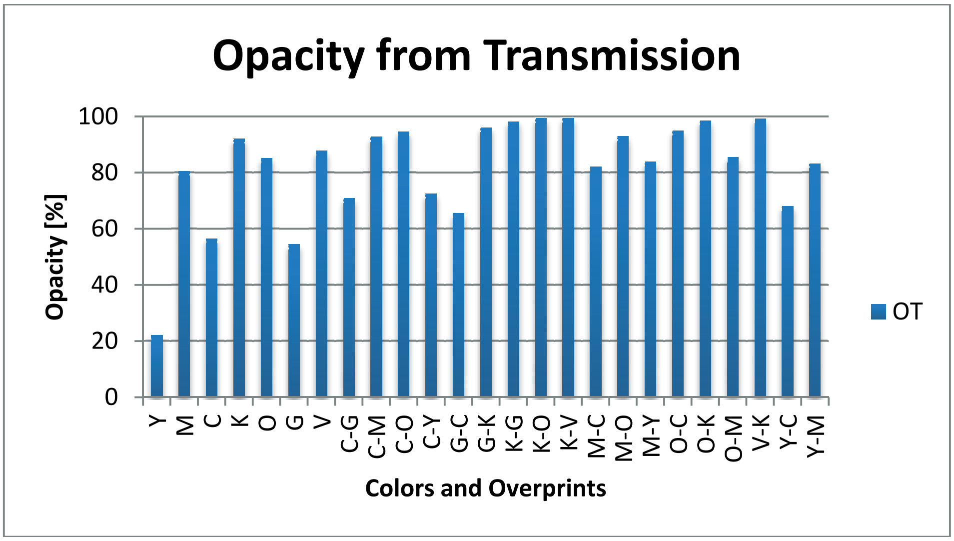

Figure 3: Opacity from transmission XYZ values measured by SpectroScan T. Only Y values were used

The opacities were measured for all the patches by both methods and a general regression was performed to obtain the correlation equation.

The transmittance was calculated by measuring the XYZ values from SpectroScan T. Both the opacities measured in reflection and transmission mode were treated as variables for the general regression. The opacity by reflection was termed as response and opacity by transmission was termed as factor. Correlation graph between opacity and transmission (Y tristimulus only) is illustrated in the Figure 4.

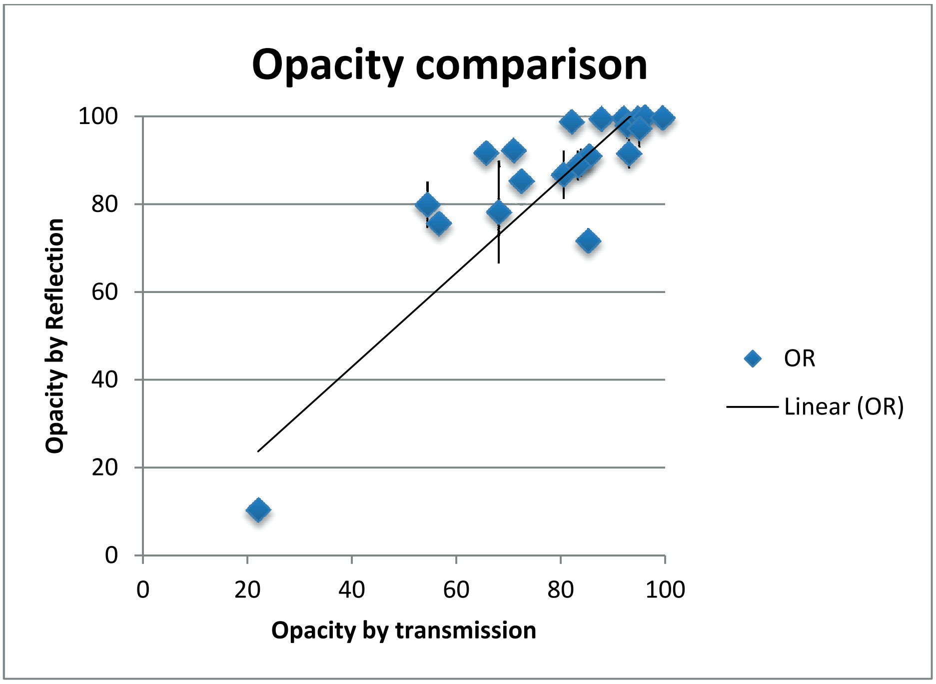

Figure 4: Correlation line between opacity from reflectance and transmission measurements

The correlation equation describes a linear relationship between the opacity calculated from transmission and opacity recorded from reflectance measurements. Thus, if one of the opacities is available then the other opacity can be calculated by using Equation 5 for Y tristimulus values.

Opacity (from reflectance) = 1.080 Opacity (from transmission) [5]

The calculation of correlation coefficient for the two Y value opacity estimates is .853. The coefficient in Equation 5 is well determined (1.080±.018).

We also can lump all of the corresponding tristimulus (XYZ) opacity into one regression formula. This yields

Opacity (from reflectance) = 1.027 Opacity (from transmission) [6]

The correlation coefficient for Equation 6 is .720. However, the coefficient is again well determined (1.027±.014).

4. Conclusions

A series of opacity values were calculated from XYZ values measured over black and white backing according to the ASTM D 2805-11 Standard test method. XYZ values of printed ink films were also measured with transmission spectroscopy and transmission was calculated from it. Opacity was calculated from transmission data by subtracting it from 100. The values obtained by both methods were correlated. General regression specifies a linear equation between the opacities calculated from transmission and reflection. The correlation coefficients that were obtained indicate significant linear relationship between the opacity by the two methods. It also makes it possible predict of the value of opacity for one method if one of the values for other method is known. It also provides a relation between ASTM D2805 Opacity and a direct measurement of opacity from transmittance.

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Artificial aging of outdoor prints

Ákos Borbély, Csaba Horváth, Rozália Szentgyörgyvölgyi

Óbuda University, Rejtő Sándor Faculty of Light Industry and Environmental Engineering
Insitute of Media Technology
Doberdó út 6., H-1034 Budapest, Hungary
E-mail: akos.borbely@rkk.uni-obuda.hu

Abstract

Outdoor advertising remained an effective and informative way of broadcasting a message to the receptive public. Poster advertising is still an important element of media campaigns. Large format inkjet printing technology has become one of the major technologies to produce posters in the last decade. Inkjet technology allows the use of wide range of substrates with solvent based, water based and UV curable inks. Outdoor printed products have to resist the degrading components of weather: solar radiation, moisture, rain, wind, etc. The estimation of the useful lifetime of the printed product for outdoor application is provides important information for the costumer. Expected lifetime of the printed products can be estimated by on site outdoor or laboratory testing. Laboratory test equipment is capable of providing the environmental effects and a controlled aging process. Our current research focuses on the apparent changes of visual quality of outdoor inkjet prints during the aging process. Two plastic and two laminated paper substrates were chosen, all of them recommended for outdoor use. We investigated how the optical parameters of our test prints change after equal subsequent doses of radiant exposure.

Keywords: accelerated aging, outdoor and laboratory weathering, fading

1. Introduction, research objectives

Outdoor advertising continues to be an important marketing tool since the second part of the 19th century, with the advance of large format and quantity printing. Today it is considered a favorite campaign medium, capable of influencing the decision of the buyer and providing aesthetic experience in the same time. Decades ago outdoor printed products were made by screen printing technology, nowadays, with the advance of digital technologies inkjet, electrophotographic and thermographic technologies are also applied. Billboards, together with large format printing opened new business opportunities in print industry. A wide range of substrates can be used for outdoor printing: paperboard, vinyl, canvas, etc. Plastic substrates are very popular because of their better resistance against weather than paper based substrates. Outdoor products are printed with water or organic based and UV curable inks, which resist weathering (solar radiation, moisture, rain, wind, etc.) to a certain extent. The general experience with outdoor printed products exposed to weather effects is that these products will fade, loose or change color. Deteriorated visual appearance is a crucial problem for high quality printed products. Outdoor advertisement needs to last until the validity of the message communicated holds (*Image Permanence Institute, 2007*).

Solar irradiation, temperature and moisture are the main weather factors that cause damage to outdoor products, but gases, contaminants, dust, etc. may also have a significant effect. The combined effect of the individual factors can be even more damaging. In outdoor or laboratory experiments the combined effect needs to be investigated (*Atlas Weathering Testing Guidebook, 2001*).

The durability of prints is determined by the substrate, the ink, and the other compounds alltogether. Aging is an irreversible physical and chemical process taking place over time. Durability depends mainly on the physical and mechanical properties of materials, affected by the factors of the micro-climate like heat, moisture and radiation, environmental ionic and gaseous pollutants, microorganisms (*Bolanča I. and Bolanča Z. 2004*). The process of aging starts immediately after printing, whether with digital or traditional technology. During aging the components of the substrate and the ink change simultaneously. Heat and moisture are the main factors affecting color prints, fading may also caused by the formation of chromophores upon ageing as a result of exposure to light and volatile gases (*Majnarić et al. 2010*). A common method of testing the resistance to aging of prints is artificial aging. During accelerated aging it is possible to control or measure variables, like the radiant exposure in a specific wavelength range, relative humidity, temperature. The aging of the printed product is testified by the changes of its physical, chemical and optical properties (*Debeljak-Karlović, Gregor-Svetec, 2011*).

Our research work focused on the objective evaluation of the gradual degradation of visual quality of test specimen. Two plastic and two laminated paper substrates were chosen, with two types of large format inkjet printers. We investigated how the colorimetric properties of our test prints change after equal subsequent doses of radiant exposure.

2. Experimental

In our discontinuous accelerated aging experiment inkjet prints of the test chart were irradiated in a laboratory artificial aging device. We used Atlas Suntest XLS+ material tester with ISO 4892-2 Method B6 without wetting. Irradiance was 45 W/m^2 in the 300 nm - 400 nm range. The temperature of the test chamber was 24°C - 65°C during the tests. Each individual test run lasted 48 hours, during which the specimen recieved approximately 7776 KJ/m^2 radiant exposure (Table 1).

Table 1: Operating time (t) and corresponding radiant exposure (H) values on the sample plane of the test chamber

t (hours)	0	48	96	144	192	240	288	366
H (kJ/m^2)	0	7776	15 552	23 328	31 104	38 880	46 656	54 432

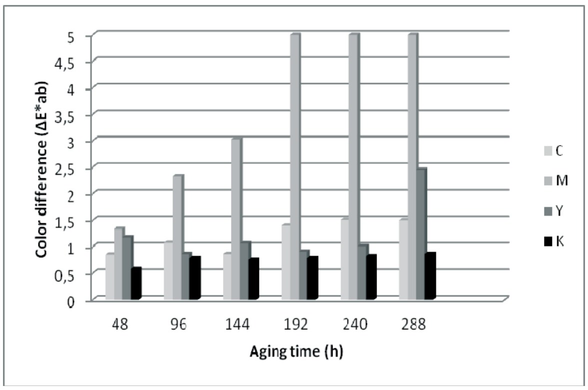
We aged 4 specimens in our experiment. Two of our specimens were plastic: Multifix Vynil HQ 500g/m^2 and Endotex Ex 500g/m^2, printed by Roland Soljet Pro III XC-540 large format inkjet printer. The other two, High Color Contrast paper 180g/m^2 and Zenith Photo Matt paper 180g/m^2 were printed with Canon imagePROGRAF iPF8000 large format inkjet printer, and laminated with heat activated glossy laminating pouch (80 microns) from manufacturer Eurosupplies.

After each 48 hour period of artificial aging optical density, tone value increase, color tri-stimulus values were measured and color gamut of the specimen were determined. A X-Rite SpectroEye spectrophotometer and an Eye-One IO automated scanning table has been used to obtain optical density and colorimetric data. In this paper we present the results of 6 and 8 steps of 48 hour aging of the laminated paper and of the plastic substrates.

3. Results

The measured optical properties are quantitative indicators of fading. In a previous research work we concluded, that the minor changes in optical density values may not be a sensitive indicator of the visual appearance of fading (*Á. Borbély, Cs. Horváth, R. Szentgyörgyvölgyi, 2012*). We found 0.0-0.04 units decrease in optical density of the full tone process colors as a result of the aging process. The magenta process color was the most sensitive to irradiation in all cases.

The magnitude of the changes on a perceptual scale can be best represented by the color shifts of the full tone process and secondary colors in CIELAB uniform color space and calculated color differences between the original and the aged specimen in CIE 1976 ΔE^*_{ab} units. Figure 2 and 3 demonstrate the color shift magnitudes in case of the paper and plastic substrates.



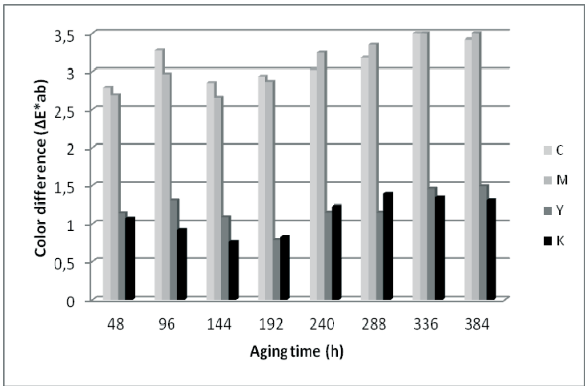


Figure 1: Color differences of solid patches of process colors (C, M, Y, K) at 48 hour steps of aging. Inkjet prints on Zenith Photo Matt paper (left) and Multifix Vynil HQ plastic (right) substrates

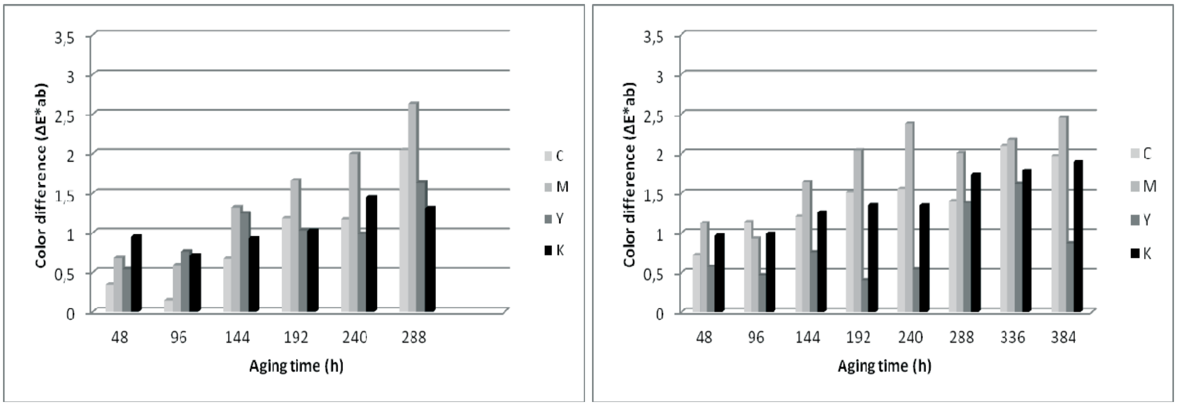


Figure 2:
Color differences of solid patches of process colors (C, M, Y, K) at 48 hour steps of aging.
Inkjet prints on High Color Contrast paper (left) and Endotex Ex plastic (right) substrates

Colorimetric shifts of the process colors are combined in case of secondary colors and CMY halftones. The magnitude of the shifts of chromatic grays at different tone levels (figures 3 and 4) remained in the range of that of the process colors for paper and plastic substrates as well.

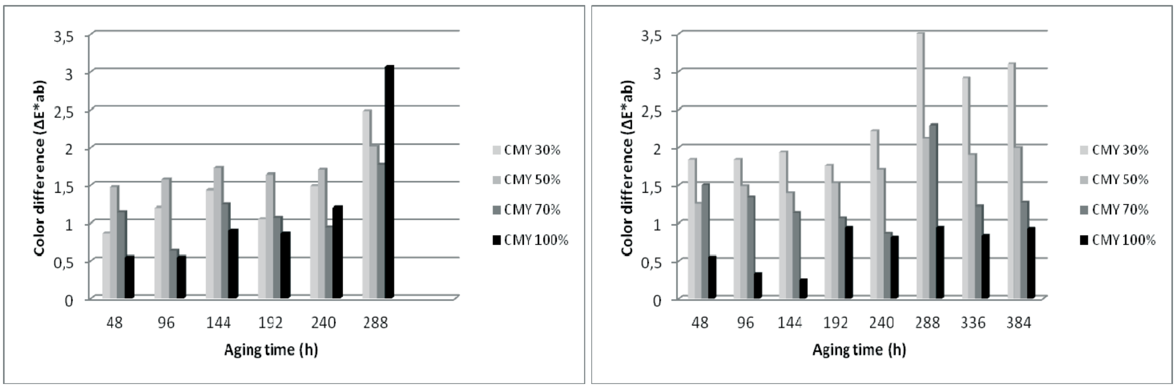


Figure 3:
Color differences of full tone and halftone patches chromatic grey (CMY) at 48 hour steps of aging.
Inkjet prints on Zenith Photo Matt paper (left) and Multifix Vynil HQ plastic (right) substrates

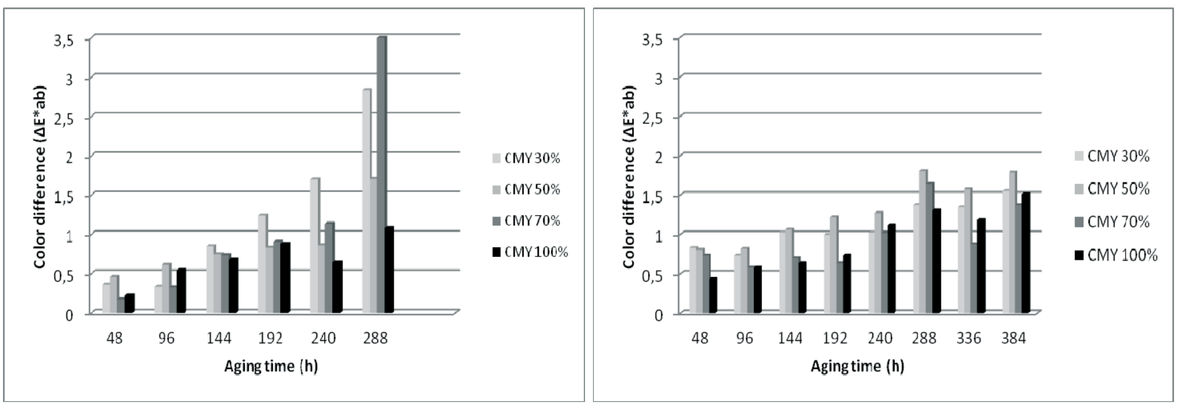


Figure 4:
Color differences of full tone and halftone patches chromatic grey (CMY) at 48 hour steps of aging.
Inkjet prints on High Color Contrast paper (left) and Endotex Ex plastic (right) substrates

The range of reproducible colors (color gamut) was determined using a 400 patch test chart, the standard profiling method, and profile analysis software. The measurement and computation process was completed after every 48 hours of aging, in order to obtain information on fading of the most saturated colors. The shrinking of the color solid volume with irradiation is shown on Figure 5.

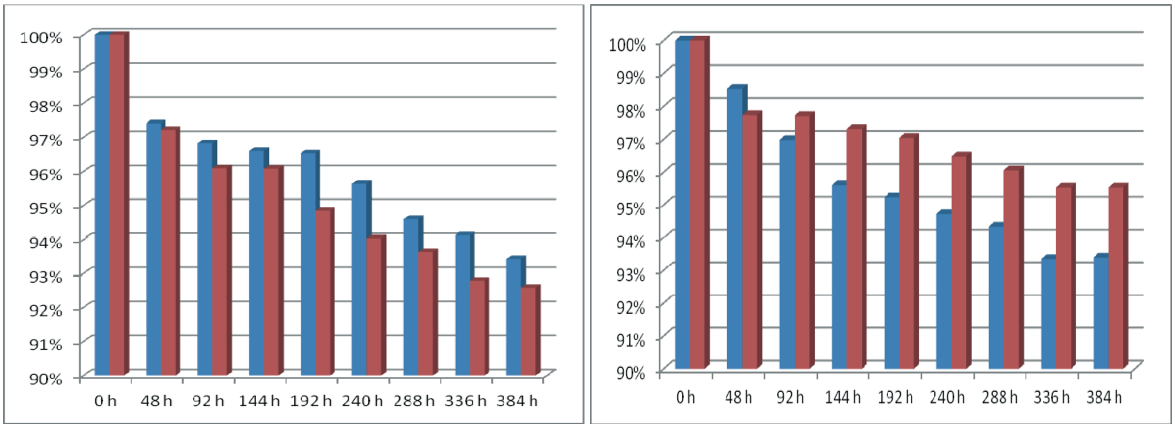


Figure 5: Color gamut changes of test prints after 48 hour steps of aging. Inkjet prints on Zenith Photo Matt paper (left, blue) and Multifix Vynil HQ plastic (left, red) substrates, High Color Contrast paper (right, blue) and Endotex Ex plastic (right, red)

4. Conclusions

We investigated the changes of optical properties of inkjet prints on laminated paper and plastic substrates during an accelerated aging experiment. Specimens were irradiated in a weathering testing instrument for 48 hour terms (equal doses of 7700KJ radiant exposure) under controlled conditions, optical properties were measured after each term.

Optical density was found to be a weak indicator of the magnitude of changes in appearance due to fading. We experienced color differences that were well above the threshold level on laminated paper and inkjet substrates. The magenta process color appeared to be the most sensitive to irradiation induced fading in all cases. The color gamut of the test prints decreased by up to 10% in case of all substrates during the whole experiment.

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A comparison of current approaches to predict the influence of Fluorescent Brightening Agents

Michael Dattner[1], *Daniel Bohn*[2], *Friedrich Böhme*[2]

[1] BST-International GmbH
Heidsieker Heide 53
D-33739 Bielefeld, Germany
E-mail: michael.dattner@bst-international.com

[2] Bergische Universität Wuppertal
Rainer Gruenter Straße 21
D-42119 Wuppertal, Germany
E-mails: bohn@uni-wuppertal.de; f.boehme@uni-wuppertal.de

Abstract

Optical brighteners - fluorescent brightening agents (FBAs) - in substrates have a major impact on the perception of color and particularly on the perception of halftone prints. The main objective of this paper is to present and compare several approaches to predict the influence of FBAs on the color perception of halftone prints.

Two approaches possess a spectral basis and another two a tristimulus basis. All approaches except the tristimulus based approach of CHUNG & TIAN belong to the authors of this paper whereby two of them are based on the backing correction approach of HANS OTT.

Namely, the following prediction-approaches will be presented and discussed:

S1) A Spectral Based Approach to predict the influence of FBAs for arbitrary illuminants, featuring a raster-tone specific weighting factor.
S2) HANS OTTs proposal to convert color values for different substrate backings and its transformation in terms of FBA-effects prediction.
T1) A Trisitmulus Based approach on the basis of S2.
T2) A Trisitmulus Based approach of CHUNG & TIAN.

In a first step all models are presented in the chapter "State of the scientific knowledge". The approaches S1, S2 and T1 are shown in their current development state for the first time in this publication.

The final mission of this paper is to compare all models (including the tristimulus approach of CHUNG & TIAN, T2), and to discuss all individual advantages- and drawbacks.

Keywords: optical brightening agents, perception of color, color stimulus, spectral reflection, halftones

1. Introduction

Optical brighteners - fluorescent brightening agents (FBAs) - in substrates have a major impact on the perception of color. This article describes solutions to consider the illumination-dependent interaction of brightened substrates with inks tailored to the print and media industry.

Measurements of identical samples printed on brightened substrate show significant differences in the visible spectrum, if different illuminations are used for measuring (cf. Figure 1). Factually, these effects cannot be compensated by solely considering the target-illumination - if different to the measurement-illumination - with the classical calculation of XYZ-values (tristimulus values) and the corresponding L*a*b*-values (coordinates in the CIELAB-color-space). Figure 2 shows occurring CLIELAB-color differences up to 7.02 ΔE*ab units for samples measured with illuminations A' respectively D65' (Dattner, 11). For the ΔE*ab calculation, the corresponding spectra are converted to L*a*b* values according to the established approach (CIE, 1971) using the 2° CIE standard observer and the CIE standard illuminant D65 without any adjustments.

The related dilemma in printing standardization (e.g. ISO 12647-2) is the more and more usage of production papers containing FBAs that cause an exceeding of ISO tolerance limits (ISO, 2010) if a sufficient substrate correction is not conducted in the workflow. For a physically founded substrate correction, the characteristic spectral behavior of FBAs and inks and related combinations in the UV wavelength range must be considered additionally to the well-known effects in the visible range. This provides a possibility to apply substrate correction to the aim and not to the measurement, which is an alternative solution to CHUNG & TIAN's for calculating substrate-corrected aims without (Chung, 2011) applying the ISO 13655 backing correction (ISO, 2009). In the chapter "State of the scientific knowledge" several current approaches to predict the influence of FBAs will be presented and finally compared to each other in the chapter "Results". Two approaches possess a spectral basis and another two a tristimulus basis. All approaches except the tristimulus based approach of CHUNG & TIAN belong to the authors of this paper whereby two of them are based on the backing correction approach of HANS OTT (Ott, 2013).

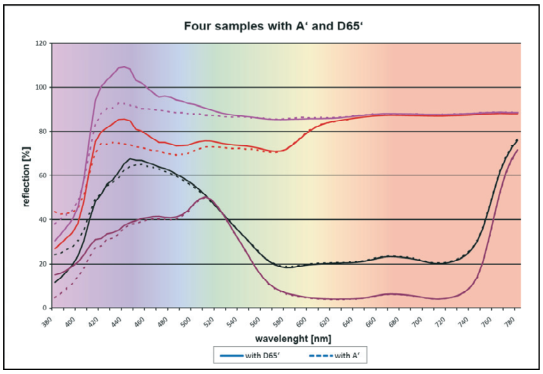

Figure 1: The influence of two illuminants on brightened samples shown concerning CIE-A and CIE D65 (Dattner, 2011a)

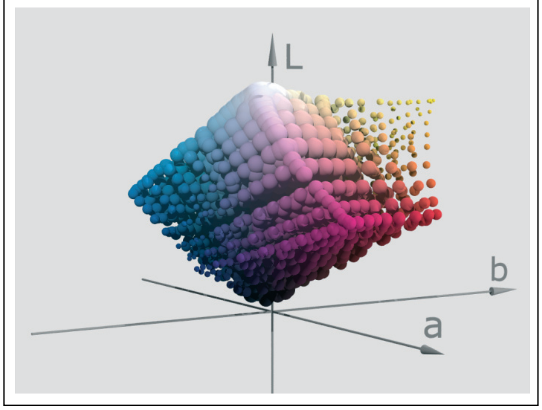

Figure 2: Visualized comparison of errors (ΔE_{00} up to 8.46 visualized by the largest sphere) occurring, if CIE-Lab-values are calculated for Standard illuminant D50 using spectral data measured with D50~ and UVcut-Filter respectively, if no adjustment is done

Namely, the following prediction-approaches will be presented and discussed:

S1) A Spectral Based Approach to predict the influence of FBAs for arbitrary illuminants, featuring a raster-tone specific weighting factor.
S2) HANS OTTs proposal to convert color values for different substrate backings and its transformation in terms of FBA-effects prediction.
T1) A Trisitmulus Based approach on the basis of S2.
T2) A Trisitmulus Based approach of CHUNG & TIAN.

2. State of the scientific knowledge

2.1 Existing approaches for considering the influence of optical brightener

It is documented and explored that the effects of different FBAs in various printing substrates lead to individual, illumination-dependent effects with unprinted and fully printed surfaces (Erhard, 2003), (Green, 2008), (Zwinkels, 2008). The optical behavior of halftone samples on brightened substrates is also empirically determined (Kraushaar, 2006), (Fiebrand, 2007), (Pertler, 2007). As mentioned, also the ISO 13655 backing correction is adapted to substrate correction in the context of FBAs (Chung, 2011). In TAGA 2012 Dattner & Bohn presented a physically founded model to predict the influence of FBAs for arbitrary illuminations. In this context Dattner & Bohn also showed that their spectral approach possesses a similar structured like the one of Chung & Tian (Chung, 2011).

In the following all four approaches are presented in detail.

2.2 Chung & Tian's adapted backing-correction approach (T1)

As mentioned above Chung & Tian adapted a backing-correction (as described in ISO 13655) to substrate correction in terms of FBA-compensation. Please notice that their approach is tristimulus based, which is needed for a sufficient integration in current color management processes.

Chung & Tian's solution starts with color data concerning samples printed on unbrightened substrate (APCO). This information is substrate-corrected by using the weighted difference of substrate relevant color data concerning APCO and the relevant brightened substrate. Equation 1 shows the initial formula of Chung & Tian.

$$X_2 = X_1 \cdot (1 + C) - X_{min} \cdot C$$

and

$$C = \frac{X_{w2} - Xw1}{X_{w1} - X_{min}} , \qquad [1]$$

Itemizing this formula provides in brackets a weighting of the associated base-value with "1 + a fraction", where differences in the numerator and also in the denominator consider FBA-affected and FBA-unaffected color information.

The consideration of arbitrary measurement-illuminants is not available, yet.

2.3 Hans Otts's proposal to convert color values for different substrate backing and its transformation in terms of FBA-effects prediction (S2)

In CGATS/SC3 N 627 Hans Ott presented an alternative backing correction approach to the one proposed in ISO 13655. In contrast, Ott's approach features a spectral basis.

Ott's initial formula is shown in equation 2.

$$R_{si} = R_{wi} \cdot \frac{R_s}{R_w} \qquad [2]$$

with R_{si} - *spectrum for ink on a black backing substrate*:

Blank Substrate:

R_w: Reflection-Spectrum for the white backing substrate
R_s: Reflection-Spectrum for the black backing substrate

Ink on Substrate:

R_{wi}: Reflection-Spectrum for ink on the white backing substrate

Ott's backing correction formula can be adapted to use it as an alternative substrate correction approach in terms of FBAs. This is done for the first time in this paper.

Equation 3 shows the adapted formula:

$$\widehat{\beta(\lambda)} := \beta^{UVcut}(\lambda) \cdot \left(\frac{\beta_{PW}(\lambda)}{\beta_{PW}^{UVcut}(\lambda)} \right) \qquad [3]$$

The R_{si}-value of OTT (spectrum for ink on a black backing substrate) is nothing but a measurement of the brightened substrate without an UVcut-Filter.

The R_s-value (Reflection-Spectrum for the black backing substrate) in terms of FBA consideration can be regarded as a measurement of the brightened substrate itself but with UVcut-Filter. Therefore the FBA-emission is suppressed. The fraction of these two values multiplied by any measurement of inks on the same substrate with UVcut-Filter (Δ^{UVcut}) can be used to predict the influence of FBAs.

As you can see this approach only needs measurement done one time with and one time without UV-cut filter of the unprinted substrate itself to predict the influence of FBAs for all measurements done with UVcut-Filter.

The main advantage of this approach is that it can be directly derived from the theory of Kubelka & Munk and features therefore a strong mathematical basis for future extensions.

Also for this approach the consideration of arbitrary measurement-illuminants not available, but because of the strong mathematical basis (derivation from the theory of Kubelka & Munk) this variant offers a good basis for future enhancements.

2.4 A Trisitmulus Based approach on the basis of S2 (T1)

While Ott only proposed a spectral variant for a substrate-correction the authors of this paper transferred it to a tristimulus-variant. This is an important step since current color management processes are mainly based on tristimulus values.

Equation 4 shows the corresponding formulas:

$$\widehat{X} := X^{UVcut}\left(\frac{X_{PW}}{X_{PW}^{UVcut}}\right)$$
$$\widehat{Y} := Y^{UVcut}\left(\frac{Y_{PW}}{Y_{PW}^{UVcut}}\right) \qquad [4]$$
$$\widehat{Z} := Z^{UVcut}\left(\frac{Z_{PW}}{Z_{PW}^{UVcut}}\right)$$

with R_{si} - *spectrum for ink on a black backing substrate*:

As you can see also, for this approach, only measurements one time with (εεεε X_{PW}^{UVcut}) and one time without UV-cut filter (X_{PW}) of unprinted brightened substrate are needed.

The consideration of arbitrary measurement-illuminants is not available, yet.

2.5 A Spectral Based Approach to predict the influence of FBAs for arbitrary illuminants, featuring a raster-tone specific weighting factor (S1)

Dattner & Bohn showed that a comprehensive FBA-effect-modulation can be achieved by using equation 5 (Dattner & Bohn 2012).

$$\beta\lambda = \beta_{APCO}(\lambda)\cdot\left(1 + B(\lambda)\cdot\frac{\Delta A_R\cdot(1+D_K)}{\Delta A_{PW}}\cdot\sum_{300nm}^{410nm}|S^{UVcut}(\lambda) - S\lambda|\cdot\varsigma\cdot\Delta\lambda\right)$$

with

$$\Delta A = \sum_{300nm}^{410nm}|\beta_{APCO}(\lambda) - \beta(\lambda)|\cdot\Delta\lambda \qquad [5]$$

Two parameters of this formula prevent a practical usage, since information of the invisible UV-range is needed (cf. Dattner, 2012). To get rid of this inexpedient demand it can be shown that only measurements one time with (β_{PW}^{UVcut}) and one time without UV-Cut filter (β^{UVcut}) of the particular (unprinted) substrate are necessary. Furthermore the halftone specific weighting factor ΔA is replaced by a halftone specific weighting factor which is reduced to spectral information the visible spectrum.

Equation 6 shows the new praxis orientated approach:

$$\widehat{\beta(\lambda)} := \beta^{UV\,cut}(\lambda) \cdot (1 + [B(\lambda) \cdot \Delta S] \cdot \Delta R) \qquad \forall \quad \lambda \in [380\,\text{nm}, ..., 780\,\text{nm}] \;.$$

with

$$\Delta R = 1 - \left([\beta_R^{UV\,cut}(\overline{\kappa}) - \beta_{PW}^{UV\,cut}(\overline{\kappa})] \cdot (1 + [\beta_R^{UV\,cut}(\kappa) - \beta_{PW}^{UV\,cut}] \right) \qquad [6]$$

as the weighting factor and with

$$B(\lambda) = \beta_{PW}(\lambda) - \beta_{PW}^{UV\,cut}(\lambda)$$

with $\lambda \in [380$ nm,. …, 730 nm]

as the actual brightener factor

The parameter ΔS remains unchanged including the former (Dattner, 2012) presented universal illumination-depending-weighting factor ε to predict the influence of the FBA for arbitrary illuminants, which is the main advantage of this approach. Please notice that this approach is the only one known to predict the influence of FBAs for arbitrary illuminants and that the full set of formulas will be discussed in upcoming publications (Dattner, 2012).

3. Method of evaluation

The data base of this paper is a large spectral dataset, which consist of 13 different paper-substrates, each containing 1617 halftone patches. This dataset has been measured using a prototype of X-Rites "Exact" spectral photometer, which takes spectral measurements with the CIE-Illuminant A (M0) as well as a physical build in D50 illumination (M1). It is proposed that this illumination conforms to ISO 3664:2009. Furthermore, each measurement is taken one time with and one time without UV-cut filter (M2).

Each substrate features a different FBA concentration and leads therefore to a varying FBA extinction in the blue region of the visible wavelength range (typically around 440 nm). The amount of FBA extinction can be described by formula 1 (Dattner, 2009) and is shown for all 13 substrates in Figure 3.

$$B(\lambda) = \beta_{PW}(\lambda) - \beta_{PW}^{UV\,cut}(\lambda) \qquad [6]$$

with $\lambda \in [380$ nm,. …, 730 nm]

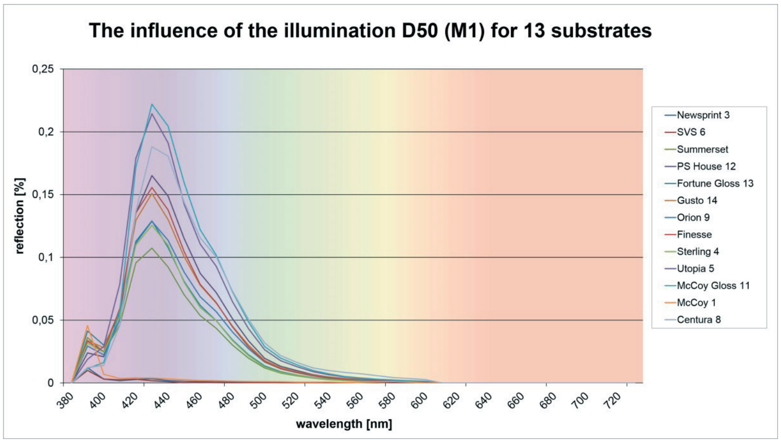

Figure 3: The influence of the illumination D50 (M1) for all 13 available substrates

Since the real relative spectral power distribution (RSPD) of the Exact is not accessible, the authors developped a method to interpolate it by making use of a laboratory UV/VIS-spectrophotometer. This spectrophotometer is able to determine spectral information in the visible and particularly in the UV-range (250 nm - 780 nm) of halftone prints. Several light sources and optical filters are used to generate measurements concerning various illuminations, including the simulations A', D50' and D65' of the CIE standard illuminations A, D50 and D65.

Table 1 shows the RSPD in the UV-range (ΔS) for several illuminations including the standard illumination D50. The column "FBA-Peak-Difference" shows additionally the peak difference (the amount of FBA excitation) of substrate 10 at 440 nm. This is done by once measuring the substrate with and one time without UV-Cut filter.

Table 1: Overview of different illuminations and their corresponding RSDP and Peak-difference

Illumination	RSPD in the UV-range (ΔS)	Peak-difference at 440 nm
Xenon	7.38	18.91
Xenon + ATM0 (Filter)	5.75	17.54
Xenon + NWG320_3 (Filter)	6.16	17.99
Xenon + GG395_1 (Filter)	2.18	7.62
Xenon + GG375 (Filter)	3.45	13.07
X-rite Exact	4.8 (Claimed to be CIE-D50)	15.90
CIE D50	4.12	X

By using this information in combination with a polynomial interpolation it can be reasoned that the actual RSPD of the Exact is 4.8 and not 4.12 as proposed for D50 in the CIE-Norm and is therefore used for illumination independent predictions of the S1-approach. On the basis of the previous work of the authors who described and modeled the effects due to FBAs on a spectral scale for a small amount of relevant test-patches, with many different physical light sources, such as A, D50 and D65, all presented FBA-prediction models are reviewed and verified by making use of the large dataset mentioned above.

The accuracy all approaches are finally compared to each other.

4. Comparison of all prediction approaches

The following figures illustrate the prediction accuracy for each approach. For a comprehensive comparison the occurring error, if no adjustment is done, is presented accordingly. The larger the size of each individual sphere, the larger is the resulting ΔE_{00}- value (The largest sphere equals 7.38 ΔE_{00}-units). Please notice that Chung & Tian (T2), as well as the approaches S2 and T1, need measurements done with the aim illumination. In contrast, the authors of this paper need for their spectral approach S1only measurements with *any* two illuminations. As shown above, only the RSPD of the aim illumination in the UV-range is needed for the prediction. In this example the illumination A as well as UV-cut measurements are used to predict how the FBA would affect the perception of color concerning the illumination of the Exact (with a RSDP in the UV-range of 4.8).

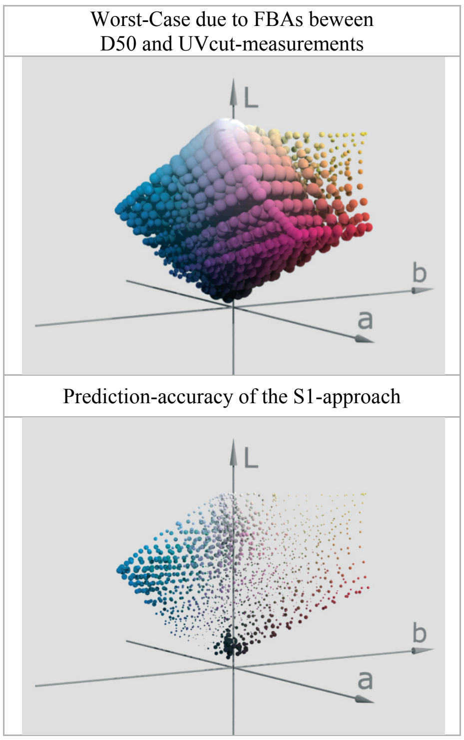

Figure 4:
*Visualized comparison of errors (ΔE_{00}) occurring, if no adjustment is done and the Spectral Based Approach to predict the influence of FBAs for arbitrary illuminants, featuring a raster-tone specific weighting factor **(S1)***

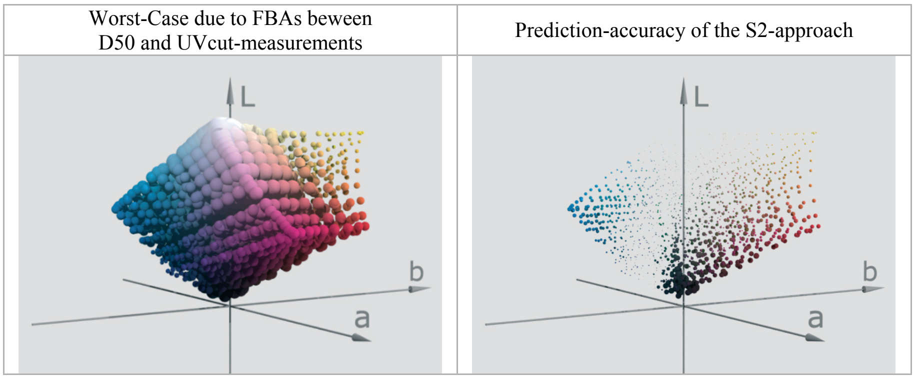

*Figure 5: Visualized comparison of errors (ΔE_{00}) occurring, if no adjustment is done and the Spectral Based Approach to predict the influence of FBAs derived from the theory of Kubelka & Munk (**S2**)*

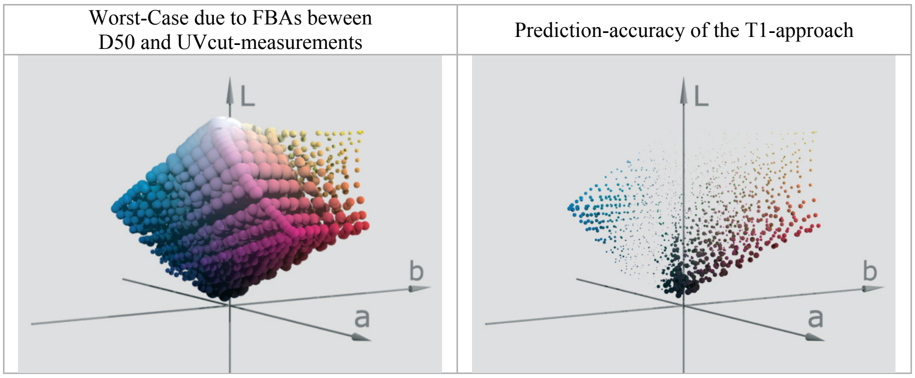

*Figure 6: Visualized comparison of errors (ΔE_{00}) occurring, if no adjustment is done and the Trisitmulus Based approach on the basis of the S2-approach (**T1**)*

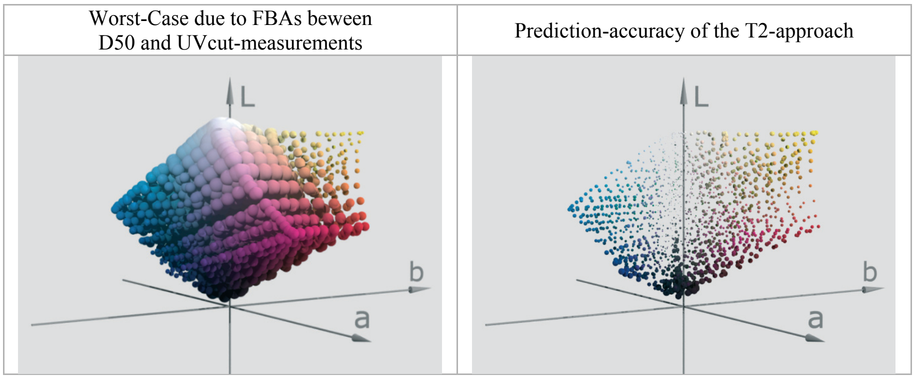

*Figure 7: Visualized comparison of errors (ΔE_{00}) occurring, if no adjustment is done and the Trisitmulus Based approach of Chung & Tian (**T2**)*

For a detailed comparison please notice the provided table, which contains detailed ΔE-error distributions for each approach.

Table 2:

ΔE_{2000}-Range	Worst-Case	S1-Approach	S2-Approach	T1-Approach	T2-Approach
< 0.5	**0.00%**	**42.80%**	**64.38%**	**62.09%**	**30.98%**
< 1.0	**0.68%**	**85.41%**	**91.96%**	**88.37%**	**79.16%**
< 1.5	**6.99%**	**98.52%**	**98.58%**	**97.53%**	**97.46%**
< 2.0	**15.21%**	**100.00%**	**99.32%**	**99.44%**	**99.26%**
< 2.5	**26.84%**	**100.00%**	**99.88%**	**99.94%**	**99.75%**
< 3.0	**48.24%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**
> 3.0	**51.76%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

ΔE_{2000}	Worst-Case	S1-Approach	S2-Approach	T1-Approach	T2-Approach
max ΔE_{00}	**8.46**	**2.00**	**2.77**	**2.68**	**2.90**
average ΔE_{00}	**3.35**	**0.63**	**0.47**	**0.49**	**0.71**

It becomes obvious that all approaches lead to significant improvements. If no adjustment is done a maximum ΔE_{00}-error of 8.46 can be found between the illuminations A and the D50 - simulation of the Exact. The average occurring error is 3.35 ΔE_{00}-units. All four presented models lead in contrast to a maximum error of less than < 3 and an average of less than 1 ΔE_{00}-units.

Taking the occurring ΔE_{00}-error range into consideration it can be determined that especially the two models which have been derived from OTTs baking correction model perform very well in terms of the average occurring ΔE_{00}-value (S2: 0.47 ΔE_{00}-units, T1: 0.49 ΔE_{00}-units).

In contrast, even the S1-approach shows a slightly higher ΔE_{00}-value of 0.63 in average but the maximum ΔE_{00}-value found is only 2.00 ΔE_{00}-units. Chung & Tian's (T2) approach shows compared to the other models slight disadvantages but still very good results regarding the maximum occurring ΔE_{00}-value (2.90) and the average ΔE_{00}-value (0,71).

The main difference can be found for different areas of the predicted color gamut. While the S1-approach shows a very good prediction accuracy in the yellow- and the magenta region of the color gamut, the S2-approach performs slightly better in the blue region, but also slightly worse in the magenta-region.

The tristimulus based approach T1 (derived from Ott's formula) shows nearly the same characteristic like the corresponding S2-approach (derived from Ott's formula), which implies that (at this point) no data is lost while reducing the spectra to XYZ-values. This offers great possibilities for future extensions of this approach.

The approach of Chung & Tian (T2) also performs very well, but shows slight disadvantages in the yellow as well as the blue region, compared to the T1-approach.

5. Conclusions

Several approaches are presented. It is shown that all, spectral as well as tristimulus based models, perform very well and lead to comparable results. All approaches are praxis orientated and offer in their current state a base for future, even more accurate prediction models. The main differences can be found in different areas of the color gamut. So far, only the spectral S1-approach enables the possibility to predict the influence of FBAs for arbitrary illuminants. The next big step will be the possibility to predict the influence for arbitrary illuminants solely on a XYZ-basis.

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Review and analysis of spectral characterization models and halftoning for multi-channel printing

Radovan Slavuj, Peter Nussbaum, Jon Yngve Hardeberg

The Norwegian Colour and Visual Computing Laboratory
Gjøvik University College, P.O. Box 191, N-2802, Gjøvik, Norway
E-mails: radovan.slavuj@hig.no, peter.nussbaum@hig.no, jon.hardeberg@hig.no

Abstract

In this paper, a comprehensive review and analysis of the spectral printer models will be conducted as well as an analysis of how different halftoning algorithms influence the performance of the models. These algorithms are usually developed independently from colour management and its performance is measured in image quality attributes. We will evaluate how two types of halftoning (AM and FM) influence parameters of the spectral printer models for multichannel printing. Here we target the dot gain modelling, ink spreading and ink limitation evaluation. Therefore, the first objective is to identify spectral printer models and to discuss its performance and shortcomings. The second objective is to determine whether different halftoning influence model and its parameters and to what extent.

Keywords: spectral modelling, multichannel printing, halftoning, dot gain modelling

1. Introduction

There has been a long tendency to accurately communicate colour from outside world to a print. Every object has the ability to selectively absorb and reflect certain wavelengths of the incoming light. As the Human Visual System (HVS) is performing its function through three-chromatic nature of its sensors, we build our system and devices that perform its colour information acquisition and reproduction based on this fact. Most of the imaging devices we use today are still three to four colour (channel) processes. Reducing the dimensionnality of the incoming light to three, we have established trichromatic colour management paradigm. The problem has always been that this reduced trichromatic information could be resolved of many of the spectral metamers, and this could occur not only when we change the illumination but also when we change the observer. Spectral information is therefore, the true and full information about an object's ability to selectively attune the light. Spectral printer models, takes this physical information of its primaries and with linear addition, they derive the spectral output. The models rely heavily to assumptions made to the physical behaviour of the ink, paper and light which is less than obvious and easy to model. With this difficulty to model the physical behaviour come the advantages of using spectral system: reduced metamerism, higher accuracy, convenience in incorporation of the other physical phenomena (gloss, textured surface), possibility to convey true appearance of the scene, etc. Although spectral imaging has been used in many industries for many decades (e.g. medicine, security), the attention in graphic arts is received around two decades ago. However, even till today, there has not been a real application of the spectral reproduction system. The reason is that with advantages come the shortcomings: complexity and computational intensity. The current ICC architecture is still not able to incorporate such system due to its shortcomings (ICC White Paper, 2010). Therefore, spectral reproduction or spectral printing is jet to see the light on the greater scale. It is however, one of the most researched areas in printing industry for the last two decades, as the computational power increases and the number of the researches are working around it (Taplin, 2001, Urban and Rosen, 2008, Tzeng and Berns, 1998, Gerhardt and Hardeberg, 2006). Introduction of the multichannel printing has occurred within the conventional printing where the standard CMYK printing processes were enriched by two more channels where the gamut of the conventional printing was simply not enough to satisfy the demanding needs. These ink configurations are almost a standard in today ink jet printing, as it is the technology that provides a high flexibility needed to incorporate such system. Spectral printing has the interest in using these multichannel processes in the sense of better sampling of the input spectra and producing the spectrally matched output. The logic behind this is that more colours will mean more degrees of freedom in reproduction of the right colour. Classical example of this is that there is only one CMYK four colour combination, but multiple one exists if we have a seven channel system. Same holds for three and two colour combination. Printer models convert the input to the output by modelling the behaviour of the printing system and its colorants. Physical or spectral models are relying on the physical information of the primary colours and make their approximation based on the assumption linear mixing of the colorants on the substrate.

The aim of this work is to provide a comprehensive review of the spectral characterization models used for multichannel printing and to evaluate how two major types of halftoning influence parameters of the models (specifically dot gain). Moreover, we have evaluated if the modelling process is halftone independent. The main contribution is going toward discovering controllable and the most suitable halftoning algorithm for multichannel printing.

2. Spectral printer models

First spectral - colour printer model was introduced for single colour print on substrate (Murray, 1936):

$$R_\lambda = a_i R_{\lambda,\mathrm{i}} + (1 - a_i) R_{\lambda,\mathrm{i}} \qquad [1]$$

This is Murray-Davies (MD) model for single colour on the paper. It assumes that the reflectance R_λ of the certain area is the product of the relative coverage of ink a_i, paper $(1 - a_i)$ and reflectance of the ink$R_{\lambda,\mathrm{i}}$ at full coverage. There are two types of dot coverage: theoretical and effective dot coverage. The former is the digital information sent to the printer and latter is the real dot on the paper. During printing process, ink penetrates to the substrate and phenomenon of dot gain occurs. It is called physical or mechanical dot gain as it is caused by printing system (contact or non-contact) and is resulting in physical spreading of the ink as it deviates from the desired shape. In order to calculate effective dot area one must invert the MD model:

$$a_{eff} = \frac{R_{min,meas} - R_{min,p}}{R_{min,i} - R_{min,p}} \qquad [2]$$

where subscript $\boldsymbol{p}$ is the reflectance of the substrate (paper), $\boldsymbol{i}$ is the reflectance of the primary ink and $\boldsymbol{R_{min}}$ is here to denote that the calculation is not performed with whole reflectance curve. Rather, it takes minimum value of the reflectance as it is the one that will be most affected with the dot gain. The estimated factor $\boldsymbol{a_{eff}}$ is the scaling factor for the input reflectance that translates the reflectance of primary ink after dot gain. If we are interested in how our dot gain is influenced by the change in spectra, we can rewrite the equation to a matrix calculation using least squared minimization:

$$a_{eff} = R_{m,p} R_{i,p}^T \left(R_{i,p} R_{i,p}^T\right)^{-1} \qquad [3]$$

Here, $R_{m,p} = R_{meas} - R_p$, $R_{i,p} = R_i - R_p$, where R_{meas}, R_p *and* $R_i$and are row vectors with spectral data. Other type of dot gain that MD model doesn't account for is optical dot gain. This phenomenon occurs due to the light scattering within the substrate. This implies that substrate near the dot does not have same reflectance value as pure substrate. It is actually a combination of the light that has passed to the ink filter, scattered inside the substrate and left out from unprinted area. Although this phenomenon is not necessarily unfavourable (it increases the colour gamut), it adds complexity into modelling.

2.1 Neugebauer model (NG)

Neugebauer extended MD model for multi-colour output by linear summation of the product of tone area coverage of each colorant and its reflectance (Neugebauer, 1989):

$$R_\lambda = \sum_i a_i R_{\lambda,\mathrm{i,max}} \qquad [4]$$

The model performs interpolation using so called Neugebauer primaries (NP) as a nodes in n dimensional space. For three colour case there are 8 NP's: substrate, cyan, magenta, yellow, red, green, blue and black (assumed when all three primaries are mixed together). Beside linearity that MD assumes, there is an assumption of randomness and independence of dot distribution where fractional dot coverage is represented by Demichelis equations (Demichelis, 1924):

$$\begin{aligned}
a_w &= (1 - a_c)(1 - a_m)(1 - a_y) \qquad [5]\\
a_c &= a_c(1 - a_m)(1 - a_y)\\
a_m &= (1 - a_c)a_m(1 - a_y)\\
a_m &= (1 - a_c)(1 - a_m)a_y\\
a_r &= (1 - a_c)a_m a_y\\
a_g &= (1 - a_m)a_c a_y
\end{aligned}$$

$$a_b = (1 - a_y)a_c a_m$$
$$a_k = a_c a_m a_y \qquad \textit{continued}\ [5]$$

This theoretical fractional coverage could be replaced with effective dot coverage calculated with inversed MD model. The condition of randomness that NG model assumes can be satisfied by using rotated screens or stochastic patterns, where for dot-on-dot printers has to be modified (Bala, 2003).

The NP's are only measurements that are required as an input for this model, where physical dot gain can be estimated for each printing primary and can serve as the input for Demichelis equations for better accuracy. However, the classical NG model does not account for optical dot gain and as that cannot provide a good estimate of printer output.

2.2 Yule-Nielsen n factor

The analysis of the measured and estimated reflectance showed that optical dot gain adds to the non-linearity of the ink-paper interaction (Yule, 1951). Yule-Nielsen n factor is empirically determined number to which the base reflectance is raised to give a better estimate:

$$R_\lambda = \left[a_i R_{\lambda,\mathrm{i}}^{\frac{1}{n}} + (1 - a_i) R_{\lambda,\mathrm{p}}^{\frac{1}{n}}\right]^n \qquad [6]$$

This factor is determined through mathematical optimization, although it could be derived with simple iteration process. Exponent *1/n* is transforming the reflectance space into one that is considered linear and then scaled back to the reflectance space by raising to the power on n. There has been attempts to assign a physical meaning to the n factor (Ruckdeschel, 1978, Pearson, 1980), but most of the authors came up with one conclusion: n=1 corresponds to the MD model, where for n=2 it is believed that represents highly scattered substrate. However, with ink-jet printing, the effect of the dot gain is significantly higher than with other printing technology.

There is a potential caveat in the process of determining and assigning n factor. Namely, the n factor could be used to model both optical and physical dot gain, which is not the ideal situation as we are relying on a single number. Much better option will be to apply the n factor to the already corrected reflectance for the physical dot gain. When we measure the single colour ramp to provide an estimate of the physical dot gain, the measuring instrument, being the area measuring device will effectively record the optical dot gain as well. The best scenario would be to separate physical and optical dot gain, which is not trivial process (Namedanian and Gooran, 2010) and not feasible to perform every time when new characterization model is needed. Potentially, determination of the n factor could be done as a function of the wavelength. This implies that the reflectance of the area is actually dependent on the dot gain, or that ink penetration will cause the reflectance attenuation. Although this approach provides better modelling of the n factor, it is not proven that the optical dot gain is wavelength dependent (Namedanian et al., 2008). This brings back the fact that the n factor does not represent a physical phenomenon.

2.3 Cellular NG

The main aim of the cellular model is to increase precision of interpolation by increasing number of the sampling points and this would lead to a more accurate printer model at the end (Heuberger et al., 1992, Rolleston and Balasubramanian, 1993). More sampling points will lead to the division of the printer gamut into cells, where sampled points serve as the nodes for lower and upper boundaries of the cell.

There are significant non-linearity introduced by paper ink interaction and those will reflect on interpolation precision in the process. This is in fact the main problem of the classical NG model where the cellular extension is much less prone to this.

If the dot gain has been accounted for, the sampling of the printer colour space for cellular model will than include the effective dot coverage. The search for the desired point is then performed equivalently to the inversed MD model with the exception of the end points which are in this case lower and upper boundary of the searched cell:

$$a_{eff} = \frac{R_{\lambda,i} - R_{\lambda,L}}{R_{\lambda,L} - R_{\lambda,U}} \qquad [7]$$

Here, $R_{\lambda,i}$ denote the reflectance of the ink, $R_{\lambda,L}$ denotes node on the lower boundary of the cell, and $R_{\lambda,U}$ is the upper boundary node.

The problem with this model is that it requires high number of training (measurement) patches. This number is the function of number of levels in the sampling along single colorant (3 for 0, 50 %, 100 % coverage), raised to the power of number of the colorants (channels). If we have 5 level sampling combined with 7 channel printing system we would end up measuring around 75.000 patches. Although this will provide highly accurate model it is simply not feasible bearing in mind that each change of the paper or a colorant would require new model. It is showed that by converting to the cellular model we can get improvements over classical YNSN model but to the extent of 25 % in RMS spectral precision (Taplin, 2001). There have been attempts to reduce number of patches (Chen et al., 2004) and measurement intensity by estimation of some nodes. There is also an assumption that some part of the space should be sampled with higher frequency than other. To determine what area is that, one must analyse spectral or colour error gradation throughout the printer space. There is also an issue of the cells search for interpolation process. As the printing relies on the metamerism to produce colour match, there are multiple cells that can map to the same colour. To obtain the "right one", one must set a condition for optimization process that is based on the particular requirement of the model usage. This constraint can be spectral difference or metamerism minimization as well as the colour difference under specified illuminant.

2.4 NG based models: improvements and extensions

There have been many attempts and improvements to the Neugebauer model and its extensions: YNSN and cellular. With assumption that ink spreading is not the same on paper and superimposed on another ink (Emmel and Hersch, 2002) the proposition is made to use calibration curves for each two and three colour overprint. This helps the model to perform better but requires additional measurement especially when it is applied to multichannel system. In fact, each two or more colour NP would have its own calibration curve and this is what makes this model similar to the cellular approach. Multiple attempts were also made to estimate the parameters for the NG model such are dot gain, n factor and primaries (Abebe et al., 2011, Agar and Allebach, 1998, Balasubramanian, 1999, Zuffi et al., 2005). Especially the physically non realizable primaries were addressed (where more than four colours need to be printed on an area) and although not printable, these NP's are very useful for sampling of the space for interpolation.

2.5 Continuous tone model: Kubelka - Munk model (KM)

Many types of coloration systems have used this model for prediction of the colour mixture. It is also widely used for various purposes in graphic arts where primarily halftone systems are usage. It is assumed that most of the scattering comes from the paper and therefore the single constant KM (Kubelka and Munk, 1931) theory was considered to be very useful for halftone printing. It bases its approximation by considering ratio of scattering and absorption coefficients of the mixture:

$$(K/S)_\lambda = \frac{(1-R_\lambda)^2}{2R_\lambda} \qquad [8]$$

Where R_λ is the spectral reflectance of the mixture, K is the absorption coefficient and S stands for scattering coefficient. To use this model for halftone printers, K/S factor is calculated for each ink at maximum coverage and for the paper:

$$(K/S)_{\lambda,i} = (K/S)_{\lambda,i,max} - (K/S)_{\lambda,p} \qquad [9]$$

For multichannel case, the previous equation can be expanded:

$$(K/S)_{\lambda,mix} = (K/S)_{\lambda,p} + \sum_i c_i (K/S)_{\lambda,i} \qquad [10]$$

Where c is the weighting on the unit K/S and is based on the concentration of the ink. In the K/S space, the additivity of the mixture is assumed and it is the space where the reflectance is behaving in linear manner. This fact was used by Chen for the model inversion where he used K/S space instead of the ink space where this linearity does not stand. Also, inversion of the model can be done analytically and it is straightforward process:

$$R_\lambda = 1 + \left(\frac{K}{S}\right)_{\lambda,mix} - \sqrt{\left(\frac{K}{S}\right)^2_{\lambda,mix} + 2\left(\frac{K}{S}\right)_{\lambda,mix}} \qquad [11]$$

There is also the cellular version of the KM model that performs the same operation like cellular NG model and also requires intermediate steps for measurements. The interest in using KM model is particularly strong in estimation of the physically non-realizable primaries that are needed for good space sampling and later interpolation. Also, estimation of the primaries can be used to reduce number patches needed for cellular NG model.

3. Halftoning for multichannel printing

Halftoning is the method of conveying the continuous tone information with binary devices. It performs the simulation and grey tone variation by either modulating the size (amplitude) or frequency of placement of binary dots. As the technology moves forward, the resolution that can be achieved with printers are increased in last two decades as it's the ability of the printers to simulate continuous tone image. Especially this is the case with ink - jet printers which are inherently FM type of printers, but resolution went so high that they have the ability to simulate the AM halftoning efficiently. Also, there are the ink-jet printers that employ multi-level halftoning, meaning that they can address more than one dot at the place.

The attributes of a halftoning are usually evaluated through the image quality measures such are: sharpness, number of grey levels, tone gradation, stability, etc. We are interested here in how different algorithms influence the precision of the spectral printer models and their parameters. As there are a division between AM and FM halftoning methods, we will evaluate one from each option with spectral Neugebauer model applied on seven channel printer. We are interested in how different influences the dot gain, ink-spreading, ink-limitations, and the final colour of the NP's. As ink-jet printers cannot vary the size of the dot, they effectively simulate AM halftoning by striking multiple dots to form a larger one. In such configuration, we can evaluate is the ink spreading the same when we print isolated dot on the paper or it varies when it is printed over another dot (same or different ink).

Spectral printer modelling has the interest in exploiting the possibility of different halftoning patterns as those can produce significantly different colour with the same input. This difference can go up to ΔE of 26 and can be exploited by releasing the restrictions imposed by ink-system (Morovič et al., 2012). Namely, if printer space is observed as NP's space, produced with different halftone patterns, the great variability in selecting so called "halftone metamers" opens up. Classic AM patterns are rosette, stochastic halftoning produces random distribution, iterative processes such as IMCDP (Iterative Method Controlling Dot Placement) (Gooran, 2004), DBS (Dynamic Binary Search) (Analoui and J. P. Allebach, 1992) produce same colour like previous two but less ink usage, due to dependent dot placement. They are taking into account previous separation and tend, through iteration process, to maximize the distance between adjacent dots. These algorithms are particularly interested for multichannel printing where ink-overlaps do not allow that for whatever reason we print more than four colours per area.

4. Method

The goal of the experiment is to evaluate how different are the halftoning types for determination of the input parameters for spectral modelling of multichannel printer. For this work, we used HP Z3200 ink-jet printer which is a twelve channel printer with CMYKRGB as independent channels. Primary purpose of the RGB channels is to increase the gamut where CMYK system shows shortcomings. For the purpose of spectral printing, these channels are treated as independent from CMYK. To perform spectral printing and modelling, one needs to establish full control over printer channels and bypass colour management. We have done it through the Onyx Production House RIP by sending seven channels TIFF file previously made with Matlab where RGB channels are treated as spot colours (Figure 1).

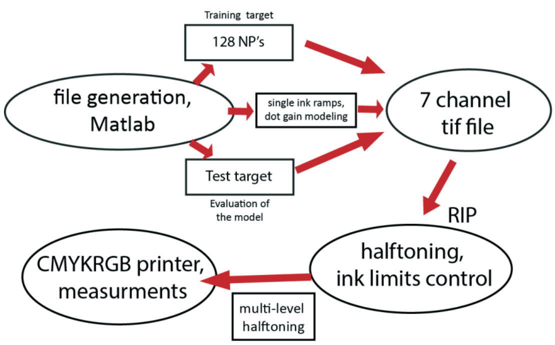

Figure 1:
Spectral printing framework

Halftoning algorithms are selected from the RIP. For modelling we used YNSN model which requires the test target made out of 128 patches that represent each possible combination of the seven channel system (Figure 2). As we printed full tone patches, the light channels were effectively excluded.

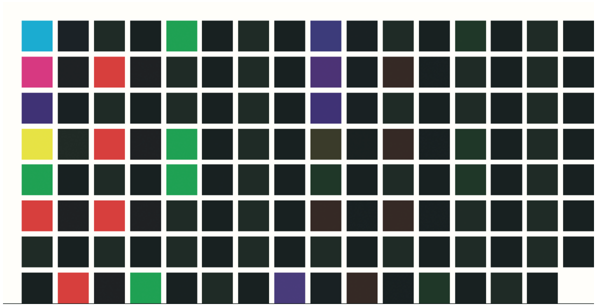

Figure 2: 128 Neugebauer primaries

To model the dot gain (for each type of halftoning), we output single color ramps with given halftoning as well as two color overprints in order to evaluate ink spreading both ink on paper and ink on ink (AM). We compute dot gain curves with spectral form of inversed MD model (Figure 3).

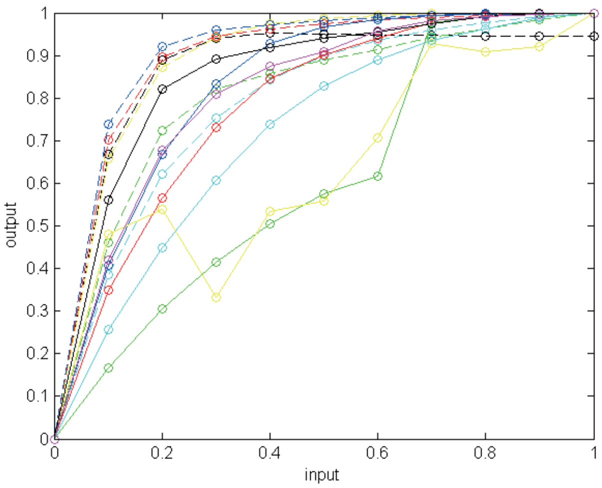

Figure 3: Effective dot gain for each channel where full line is AM and dashed FM halftoning

After obtaining dot gain curves, we have corrected the image of the NP's for each channel using Matlab. Compensated image in resolution 1200 x 1000 is sent to the printer and for this experiment we used HP Heavyweight Coated paper. As this printer employs multi-level haftoning, the amount of ink outputted to the paper is controlled with ink limits. With this, we are able to prevent ink bleeding and yet to have full tones NP's. To emphasize the difference in the halftoning, we employed YNSN model and select n factor of 2 globally (on each channel) for both type of halftoning which would otherwise be both halftone and channel specific. As the inputs we used effective dot coverage curves and target comprised of NP's. The accuracy of the YNSN model is performed with test set comprising samples from entire printer gamut. The space was sampled using three levels for each colorant (0, 50 %, and 100 %) and the combination thereof.

All together this target contained $3^{\wedge 7}$ or 6561 digital values that were compensated for dot gain prior printing the patches. We have selected a subset of this chart and for evaluation of the model and halftoning. This is to evaluate if we can used an AM halftoning based model to simulate the output made with FM or in other words, is the model halftone specific. All measurements were performed by following ISO 13655 methodology, with X-rite I1 instrument with UV cut filter mounted. As we are focused mainly on modeling of the colour properties of the printer, we have excluded the paper induced change caused by OBA's.

5. Results and discussion

We have evaluated the performance of the YNSN model on the 7 channel ink jet printer by using fixed n factor of 2 and the input image was corrected for the physical dot gain (Table 1). Sampling the colour space with NP's occurs in much higher frequency in the dark region and CIE ΔE_{00} was used as a colorimetric error metric since it more accurately estimates perceptual color differences in this region than ΔE_{ab}.

By analysis of the maximum colour difference, which occurs in saturated magenta, red and yellow region we could sample that area more frequently which would imply using the cellular NG model. This way we should improve interpolation process in the area where small changes are more perceptible.

Table 1: The performance of the YNSN model applied to the 7 channel printer using different halftoning

NG forward Printer model (AM)	sRMS (mean)	ΔE^*_{ab} (mean)	ΔE^*_{ab} (std)	ΔE^*_{ab} (max)	ΔE^*_{00} $(mean)$	ΔE^*_{00} (std)	ΔE^*_{00} (max)
	0.031	6.43	3.22	15.19	4.88	2.78	12.18
YNSN(test FM)	0.034	9.88	5.57	27.13	7.55	4.31	21.61
NG forward Printer model (FM)							
YNSN(test FM)	0.038	7.82	4.1	21.15	5.23	3.16	18.43
YNSN(test AM)	0.040	12.43	7.43	30.80	9.89	5.94	26.55

Different halftoning will produce significantly different dot overlaps and therefore different colour per patch and different NP's. It is true that we can compensate for this with different calibration curves, but in order to account for the difference in halftoning one must have ink-spreading curves (Figure 4) for each ink over other inks (assuming that printing order is in CMYKRGB). This would require usage of the IS-YNSN (Emmel and Hersch, 2002) model to account fully for the difference in halftone patterns.

Furthermore, it is known that AM is more prone to the optical dot gain than FM due to isolated dot placement. This would require halftone specific determination of the YN n factor.

Physical limitation of the ink per area challenges the whole concept as the trial and error test must be performed to find right amount of ink for a particular substrate. Currently we have no explanation for irregular curves with AM halftoned green and yellow ramps on Figure 3 as it may come from different factors like calculation process, measurement error or due to specific chemistry of the yellow and green ink.

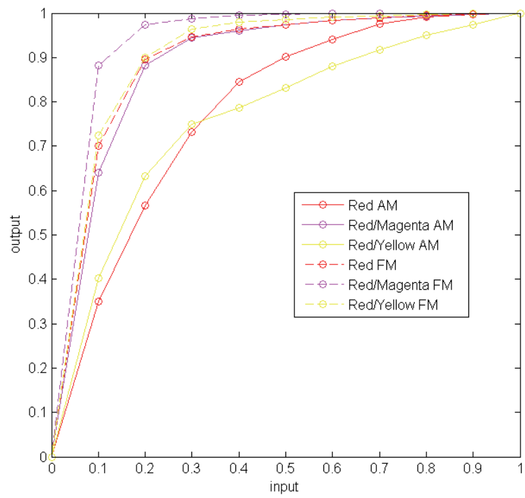

Figure 4: Ink spreading curves for Red channel superimposed to Magenta and Yellow for both AM and FM halftoning

6. Conclusions and further work

We have evaluated would it be possible and what are the factors that determine could the modeling of the multichannel printer be halftoning independent. As the halftone algorithms are developing apart from colour management, there has not been the one that is recommended to use for spectral reproduction workflow. They all have advantages and disadvantages. However, the fact is that different patterns produces different colour, and each one of them can be observed as a NP. According to this, we can obtain much higher subset of the primaries and their interaction which in return can increase spectral precision of the both forward and inverse model.

Each halftoning produces different type and amount of overlaps with other dots. In order to make modeling process halftone independent, one must use ink-spreading curves for each superimposing condition and specific optical dot gain modeling in addition to effective dot coverage curves for a dot on the substrate.

Precision of the modeling further might depend on the precision of measuring instrument in dark region as it is the area that is oversampled with NP's. Effectively this could result in much better sampled primaries and subsequent interpolation. As the over 70% of NP's are located in the dark region, it makes sense to estimate those using continuous tone mixing models like KM. These are referred as physically not realizable (not printable) colours. With estimation we could expand the printer space and have more accurate interpolation, especially in the area around dark end of the lightness axis where HVS is most sensitive.

Other improvements would be to investigate how dependent FM halftoning options work with spectral printing. They take into account previous separation for the dot placement and in that manner the less ink is outputted to the area.

All parameters that are included are specific to the model. Starting from paper selection, ink, halftoning, ink limit, printing order, measurement geometry, dot gain (both physical and optical) and ink spreading, all of this should be fixed and modeled accordingly.

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Matching proof and print under the influence of OBA

Robert Chung

School of Media Sciences
Rochester Institute of Technology
69 Lomb Memorial Drive, Rochester, NY-14623
United States
E-mail: rycppr@rit.edu

Abstract

Color proofing standard, ISO 12647-7, stipulates that the digital proofing substrate be the same as the production substrate and have similar UV responses. The reality is often the opposite. This is because the use of optical brightening agent (OBA) in papermaking yields the bluish white of the paper that print buyers prefer. Brightened papers cause two concerns: (1) they affect printed colors, including greys and solids, and (2) they cause color mismatch between non-OBA proofs and OBA prints. The former limits the usefulness of printing standards. The latter limits the trustworthiness of color proof between printer and print buyer. This case study, participated by four proofing solution providers, demonstrates the use of substrate-corrected dataset in M1 measurement conditions as a solution to bridge the above gaps. Substrate-corrected dataset or SCCA (substrate corrected colorimetric aims) is the adjustment of the color characterization data by means of tristimulus linear correction to account for the colorimetric difference between production paper and the reference substrate. When SCCA becomes the dataset and process control aims, printing by numbers are realistic goals. When SCCA becomes the proofing aims, proof matches print closely.

Keyword: proof, print, color management, conformity assessment

1. Introduction

ISO/DIS 15339-1 (2010) specifies the tristimulus linear correction method to reconcile color differences between the white point difference of the target dataset and that of the actual printing condition. RIT conducted a press run by using its Goss Sunday 2000 web offset press, Sappi Opus paper (containing OBA), and demonstrated printing conformity to substrate-corrected SWOP3 dataset and CGATS TR 016 tolerances (ISO/TC130/WG3 N1259, 2012).

Proofing to the substrate-corrected dataset is a new concept that addresses proof to print match under the influence of OBA. An RIT thesis experiment used the substrate-corrected characterization dataset as the common aims for proofing and printing. The psychometric analysis showed that substrate-corrected proof improved visual match to OBA print than ISO 12647-7 compliant proof where no substrate correction was applied (Carlos Carazo, 2012).

To further verify that proofing to the substrate-corrected dataset is a viable solution, RIT invited four proofing vendors (referred to as Vendor A, B, C, and D) to participate in this project. They were asked to produce three color-managed proofs with each proof conforming to a specified dataset varying in their white points, i.e.,

- Proof_1 conforms to the SWOP3 dataset as published, i.e., ignoring white point of the printing paper.
- Proof_2 conforms to the substrate-corrected SWOP3 dataset whereby the white point of Sappi Opus was measured by M0 illuminant.
- Proof_3 conforms to the substrate-corrected SWOP3 dataset whereby the white point of Sappi Opus was measured by M1 illuminant.

There are three objectives in this project: (1) to assess proofing conformity according to the CGATS TR016 tolerance, (2) to visually examine the proofs with the OBA print as the reference under the standard viewing conditions, and (3) to discuss what substrate-corrected dataset aims produces the best proof and print match under the Influence of OBA.

2. Methods

There are three steps involved in the study: (1) inviting proofing vendors to produce color proofs to match specified datasets, (2) assess proofing conformity according to CGATS TR016, and (3) discuss the relationship between visual assessment and colorimetric analysis. The first step is implemented by proofing solution providers. RIT carried out the second and the third step. These three steps are further elaborated below:

Step 1. Inviting proofing vendors to produce color proofs to match specified datasets.

Emails were sent to a number of proofing vendors explaining the objective of the study, i.e., color match between non-OBA proof and OBA print, and anonymity of their participation. Once there was agreement, RIT sent each vendor (a) test forms (.pdf), (b) a Goss 2000 web offset press printed sheet, (c) examples of printed images on paper with and without OBA, and (d) proofing instructions, including the Excel template that calculates substrate-corrected dataset (.xlsx), and submission deadlines.

The proofing instruction indicated that they needed to match three datasets with three different white points in each dataset. Table 1 shows CIELAB values of these white points. Proofing vendors would create three source ICC profiles or built-in substrate correction methods to produce these proofs.

Table 1: White points of the three source ICC profiles

Proof_ID	Source white point	CIELAB	ΔE_{ab}
Proof_1	SWOP3	93L*/0a*/0b*	---
Proof_2	Opus (M0)	93.1L*/1.8a*/-4.8b*	5.1
Proof_3	Opus (M1)	93.4L*/1.7a*/-6.5b*	6.7

Proof_1 represents the white point of the source color space as if OBA does not exist; Proof_2 represents the white point of the Sappi Opus under M0 measurement conditions, and Proof_3 represents the white point of the Sappi Opus under M1 measurement conditions.

A typical proofing substrate has a white point that matches the SWOP3 white point (93L*/0a*/0b*) closely. This is the only destination profile in the experiment. A proofing system uses its proprietary algorithm to modify the CMYK-to-CMYK transformation such that measured CIELAB values of the proof match the source dataset, including the white point of the source, closely.

Step 2. Assessing proofing conformity according to CGATS TR016

RIT used the following procedure to assess the proofing conformity according to the CGATS TR016: (a) measured the IT8.7/4 target of the proof with an i1 iSis (M0) spectrophotometer, and measurement data were saved as a .txt file, (b) the measurement file was assessed in a custom-built Excel template, for proofing conformity according to the CGATS TR 016.

Step 3. Discuss the relationship between visual assessment and colorimetric analysis

Proofing conformity assessment alone only answers the question if a proof passes or fails the established tolerances. More information can be obtained if we correlate visual assessment of pictorial printed colors with colorimetric analysis. In this regard, the ISO pictorial color reference image, Bar Set, was examined visually, and correlated with colorimetric analysis in terms of the five largest ΔE_{00} patches (out of 1,617 patches), white point, and grey reproduction.

3. Results and discussion

Four proofing vendors, i.e., Vendor_A, Vendor_B, Vendor_C, and Vendor_D, participated in the study. Results and discussion are highlighted in the following sections: (a) proofing conformity, (b) visual assessment, (c) white point analysis, and (d) grey ramp analysis between the proofs and press sheet.

3.1 Proofing conformity

CGATS TR 016 (2012) is a printing tolerance specification that (1) specifies substrate-corrected dataset and process control aims as conformity metrics, (2) defines three aspects of conformity assessment, i.e., deviation, within-sheet variation, and production variation, and (3) defines a multi-level tolerance schema with Level A being most stringent for critical color match, Level B for normal visual match, and Level C for pleasing color.

Table 2 is a summary of the conformity assessment by vendor according to CGATS TR 016. Amongst the four proofing solution providers, Vendor_A scored the best in terms of deviation conformity. All vendors achieved Level A conformity in within-sheet variation. What follow are observations regarding dataset conformance of the three proofs from each vendor.

Table 2: Deviation conformity of the three proofs by vendors

	Vendor_A	Vendor_B	Vendor_C	Wendor_D
Proof_1	A	B	B	A
Proof_2	A	C	C	A
Proof_3	A	F	C	B

Vendor_A - all three proofs achieved Level A in deviation conformity.

Vendor_B - (a) Proof_1 achieved Level B deviation conformance (100Y patch was less chromatic), (b) Proof_2 achieved Level C deviation conformance (100Y patch was less chromatic and 50C patch was darker and less chromatic), and (c) Proof_3 failed (50C patch was darker and less chromatic).

Vendor_C - (a) Proof_1 achieved Level B deviation conformance (both 100C and 100Y patch were darker and less chromatic), (b) Proof_2 achieved Level C deviation conformance (50Y patch was less chromatic), and (c) Proof_3 achieved Level C deviation conformance (100Y and 50Y patches were less chromatic; 100C and 50C patches were less chromatic).

Vendor_D - (a) Proof_1 and Proof_2 achieved Level A in deviation conformance, and (b) Proof_3 achieved Level B in deviation conformance.

3.2 Visual assessment

When the three proofs from Vendor_A and the offset print (reference) were placed randomly in the ISO 3664 (2009) compliant viewing booth, several observers were asked to pick a proof that was most different in color appearance than the print reference. The SWOP conformed Proof_1 was picked all the time. This was because the yellowness of Proof_1, made from SWOP3 as the source profile, is most noticeable. When asked again, observers were likely to place Proof_2, made from SWOP3_SCCA(M0) dataset, between Proof_1 and the offset print. Finally, Proof_3, made from SWOP3_SCCA(M1) was placed next to the offset print (Figure 1).

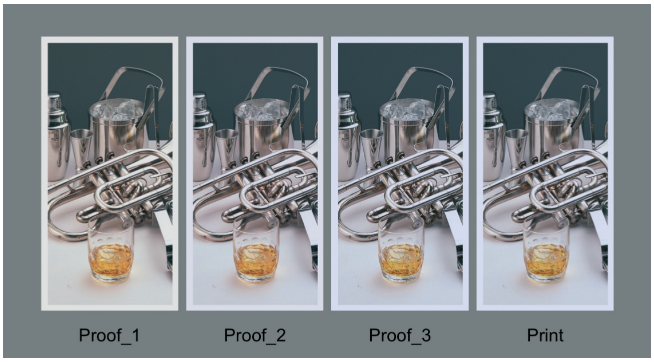

Figure 1: Simulation of the three proofs and the reference print

The procedure, described below, was used to simulate the appearance of the three proofs and the reference print (Figure 1):

Assign the legacy CMYK file (Bar Set) to four ICC profiles:

The SWOP3 ICC profile was assigned to the image (far left) and renamed as a tagged CMYK file, Proof_1.

The SWOP3_SCCA(M0) ICC profile was assigned to the image (second from the left) and renamed as, Proof_2.

The CMYK_SWOP3_SCCA(M1) ICC profile was assigned to the image (third from the left) and renamed as, Proof_3.

The Goss_Opus (M1) derived ICC profile was assigned to the image (far right) and renamed as Print.

These tagged files were converted to the Adobe RGB color space using the absolute colorimetric rendering intent, and placed in the Microsoft PowerPoint.

A screen capture of the PowerPoint (Figure 1) was placed in the Word document. If displayed in a calibrated display, these images resemble the hardcopy proofs and the offset print, including color of the substrates, closely.

If displayed in a calibrated display, these images resemble the hardcopy proofs and the offset print, including color of the substrates, closely.

3.3 White point analysis

The white point of the three proofs (measured in M0) and the offset print (measured in M1) help explain the result of the visual assessment. Vendor_A's data, shown in Table 3, indicates that there is a color difference of 6.20 ΔE_{00} between the unbrightened (non-OBA) Proof_1 substrate and the brightened (OBA) offset print. The color difference is visually seen as colorcast.

Table 3: White point comparison between Vendor_A's proofs and the print

Vendor_A	Proof White Point (M0)			Printing Paper(M1)			ΔE00
	L*	a*	b*	L*	a*	b*	
Proof_1	92.31	-0.25	-0.22	93.4	1.7	-6.5	6.20
Proof_2	92.83	1.71	-3.87				2.22
Proof_3	92.33	1.87	-4.75				1.63

The color difference of the white point reduced to 2.22 ΔE_{00} between Proof_2 and the print, and to 1.63 ΔE_{00} between Proof_3 and the print. We can conclude that the colorcast reduction is the result of substrate-corrected colorimetric aims.

The lesson learned is that color management can match colorimetrically specified color provided that the color is within the gamut of the destination color space. In this instance, Vendor_A's proofing system has done all it can to render Proof_3 with a bluish paper (-4.75 b*). This, being the proof that best resembles the offset print, still leaves the substrate as one of the largest color difference in relation to the SCCA dataset because of gamut clipping.

Appendix A lists the five largest color differences (ΔE_{00}), out of 1,617 colors, between a proof and a print by vendor. When there is visual difference between a proof and a print, viewed side by side, a major cause is the color difference between the two white points, i.e., substrate colors. Based on observations from the Appendix, a capable color proofing system can (1) conform to CGATS TR016 Level A tolerance, and (2) simulate the white point of the source substrate closely (less than 2 ΔE_{00}).

3.4 Grey ramp analysis

CGATS TR 015 (2011), based on a set of specific CMY triplets (also known as G7 grayscale), and an ink-paper-press condition (substrate color, CMY solid, and K solid), specifies tone reproduction and gray balance aims for that printing condition. When G7 adjustment curves are applied in raster image processing prior to CTP, different printing conditions will render the pre-defined CMY triplets the same, thus, makes the "shared neutral appearance" of printed colors possible across multiple substrates and multiple printing conditions.

We did not include the G7 triplets in the test form. However, we can simulate the gray reproduction of the G7 triplets using the A-to-B LUT of an ICC profile and the ColorThink Pro, a color management utility software. Figure 2 shows the gray reproduction of the SWOP3_SCCA(M1) reference (in dotted) versus the offset print (solid) measured under M1. Note that (a) there was an error in a* rendering of the gray ramp, and (b) the gray reproduction of the offset print deviates more towards the three-quarter tone.

Figure 3 compares grey ramp between the SWOP3_SCCA(M1) reference (dotted) and Vendor_A's Proof_1 (solid). Note that when Proof_1 ignores the printing paper, the starting point of the grey ramps are misaligned, and is perceived as a yellow cast in comparison with the brightened offset print.

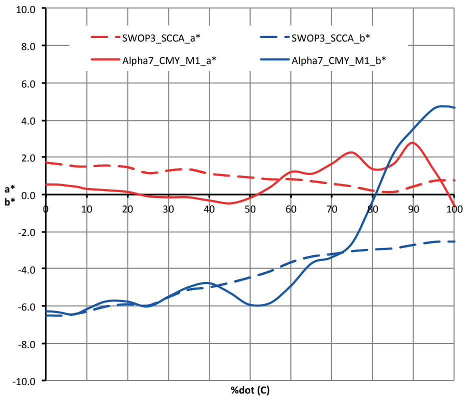

Figure 2: Grey ramp between the SWOP3_SCCA reference (dotted) and offset print (solid)

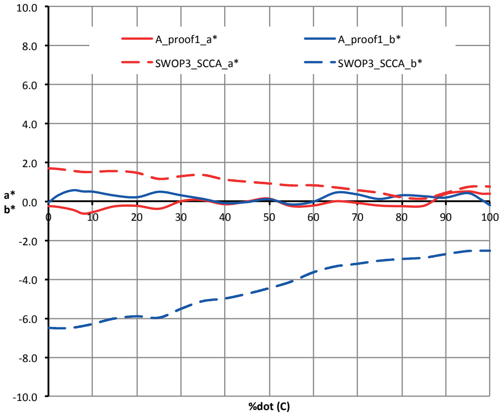

Figure 3: Grey ramp between SWOP3_SCCA reference (dotted) and Proof_1 (solid)

Figure 4 compares the grey ramp between SWOP3_SCCA reference (dotted) and Vendor_A's Proof_2 (solid). Note that Proof_2 was aimed at matching the white point of the printing paper, measured by M0. Thus, the yellow cast had diminished in comparison with Proof_1.

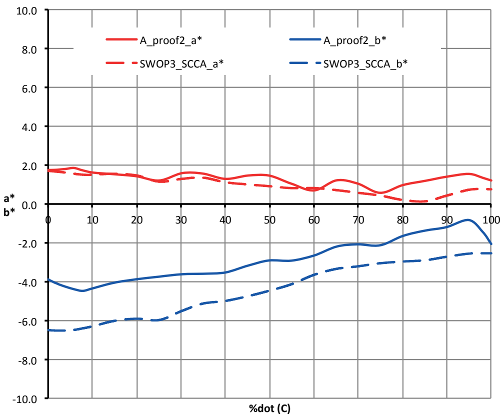

Figure 4: Grey ramp between and SWOP3_SCCA reference (dotted) and the Proof_2 (solid)

Figure 5 compares grey ramp between Proof_3 (solid) and SWOP3_SCCA (dotted). Not that Proof_3 is aimed at matching the white point of the printing paper, measured by M1. Despite the gamut clipping in the highlight region, it visually matches the brightened offset print the best.

The grey ramp analyses further indicate that (1) when printing and proofing to the same substrate-corrected dataset under M1 measurement conditions, visual agreement between proof and print in the ISO 3664 compliant viewing condition improves, (2) gamut clipping, e.g., paper and light cyan, causes colorcast, and (3) using a source ICC profile, constructed from a specific press sheet, instead of the substrate-corrected dataset, will further improve the proof-to-print visual match under the influence of OBA.

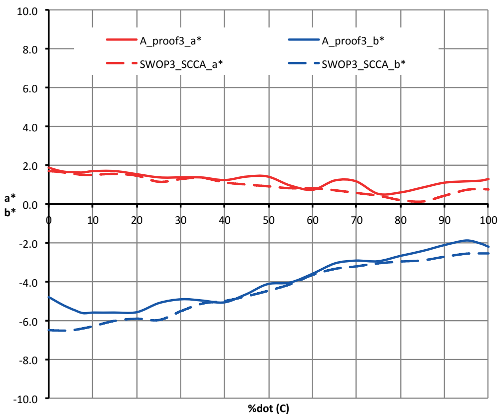

Figure 5: Grey ramp between SWOP3_SCCA reference (dotted) and the Proof_3 (solid lines)

The lessons learned are that SCCA (substrate corrected colorimetric aims) is the adjustment of the color characterization data to account for the colorimetric difference between production paper and the reference substrate. When SCCA is applied to printing conformance, it reconciles the color difference between the dataset white and the paper white. When SCCA is applied to proofing using M1 measurement, proof matches print closely under the influence of OBA. One caveat is that there should be no gamut clipping, particularly in the highlight region. In this case study, when the color difference between the OBA substrate and the dataset white point is greater than 6 ΔE_{00}, the user is cautioned that proof and press match may be compromised due to gamut clipping.

4. Conclusions

OBA is a blessing to print buyers who want brighter and colorful appearance of printed colors while controlling costs. OBA is a variable in paper that affects the appearance of printed color that causes two concerns to printers, i.e., print-to-numbers and proof-to-print match.

If the RIT thesis was a proof of concept (Carlos Carazo, 2012), this case study is a feasibility study to see if the problems of print-to-numbers and proof-to-print match can be implemented by today's color proofing technologies. In conclusion, printer can meet the challenges of printing on OBA papers that his/her customers prefer and, at the same time, print-to-numbers and proof-to-match-print with the following key steps:

- Use M1 color measurement mode (ISO 13655, 2009) for press sheet measurement.
- Use substrate-corrected printing aims to verify printing conformance (CGATS TR 016, 2012).
- Use substrate-corrected dataset as proofing aims.
- Use ISO 3664 (2009) compliant viewing booth to assess proof-to-print visual match.

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ISO/DIS 15339-1 (2012) Graphic technology - Printing from digital data across multiple technologies - Part 1: Principles and characterized reference printing conditions

ISO/TC130/WG3 N1259 (2012) Conformance to Substrate-corrected Dataset, a Case Study, Bob Chung

Appendix A. Five Largest ΔE_{00} Patches

When there is visual difference between a proof and a print, viewed side by side, a major cause is the color difference between the two white points, i.e., substrate colors. This Appendix lists the five largest color differences (ΔE_{00}), out of 1,617 colors, between a proof and a print by vendor. Vendor_A - These patches (Table A1) include outer gamut patches with 100K overprints in Proof_1 and Proof_2, and paper (Patch 1367) in Proof_3. The latter means that the bluish paper white of the source in Proof_3 is outside of the proofer gamut.

Table A1: The five largest ΔE_{00} patches in Vendor_A proofs

Vendor_A	Patch ID	C	M	Y	K	ΔE00
Proof_1 (SWOP3)	1271	0	100	40	100	1.95
	1281	40	0	100	100	2.42
	1273	40	40	40	100	2.66
	1261	0	40	0	100	3.20
	1262	0	100	0	100	3.98
Proof_2 (M0 SCCA SWOP3)	1265	40	100	0	100	2.32
	1282	40	40	100	100	2.61
	1247	0	100	100	80	2.64
	1273	40	40	40	100	2.91
	1262	0	100	0	100	4.31
Proof_3 (M1 SCCA SWOP3)	1367	0	0	0	0	1.74
	1399	100	85	85	100	1.75
	1284	100	0	100	100	1.98
	1268	100	100	0	100	2.04
	1269	0	0	40	100	2.12

Vendor_B - These patches (Table A2) include patches with 100C and yellow overprints in Proof_1; paper (Patch 1367 and Patch 1) and light cyan patches in Proof_2 and Proof_3. Again, the bluish white point of the print is 'clipped' by the limitation of the proofer gamut.

Table A2: The five largest ΔE_{00} patches in Vendor_B proofs

Vendor_B	Patch ID	C	M	Y	K	ΔE00
Proof_1 (SWOP3)	640	100	0	85	0	2.02
	649	0	0	100	0	2.02
	568	0	0	85	0	2.13
	478	100	0	55	0	2.28
	479	100	10	55	0	2.35
Proof_2 (M0 SCCA SWOP3)	1306	2	0	0	0	3.22
	1367	0	0	0	0	3.22
	1305	3	0	0	0	3.25
	1304	5	0	0	0	3.38
	1303	7	0	0	0	3.41
Proof_3 (M1 SCCA SWOP3)	1367	0	0	0	0	3.98
	1305	3	0	0	0	4.02
	1306	2	0	0	0	4.08
	1	0	0	0	0	4.09
	1303	7	0	0	0	4.11

Vendor_C - These patches (Table A3) include yellow highlight patches in Proof_1; paper (Patch 1367 and Patch 1) and cyan highlight patches in Proof_2 and Proof_3.

Table A3: The five largest ΔE_{00} patches in Vendor_C proofs

Vendor_C	Patch ID	C	M	Y	K	ΔE00
Proof_1 (SWOP3)	173	10	10	20	0	2.29
	1338	0	0	30	0	2.30
	1416	0	3	3	0	2.30
	1488	0	0	20	10	2.35
	1262	0	100	0	100	2.51
Proof_2 (M0 SCCA SWOP3)	1302	10	0	0	0	4.89
	1	0	0	0	0	5.11
	1367	0	0	0	0	5.14
	1305	3	0	0	0	5.19
	1306	2	0	0	0	5.30
Proof_3 (M1 SCCA SWOP3)	10	10	0	0	0	6.30
	1305	3	0	0	0	6.34
	1306	2	0	0	0	6.44
	1	0	0	0	0	6.51
	1367	0	0	0	0	6.56

Vendor_D - These patches (Table A4) include lighter patches with two or more overprints. It is interesting to note that paper white is not in the five largest ΔEs.

Table A4: The five largest ΔE_{00} patches in Vendor_D proofs

Vendor_D	Patch ID	C	M	Y	K	ΔE00
Proof_1 (SWOP3)	1577	40	40	10	10	1.81
	50	55	40	0	0	1.91
	1457	40	40	3	3	1.98
	384	70	55	40	0	2.00
	131	55	40	10	0	2.01
Proof_2 (M0 SCCA SWOP3)	281	40	10	30	0	1.63
	864	70	20	40	20	1.64
	632	70	10	85	0	1.64
	1432	0	0	7	7	1.74
	815	20	10	20	20	1.79
Proof_3 (M1 SCCA SWOP3)	1101	20	0	20	60	1.72
	1516	10	10	0	10	1.73
	1487	0	0	10	10	1.75
	553	85	30	70	0	1.85
	1512	10	0	10	10	1.97

Based on observations from Table A1 - A4, a capable color proofing system can (1) conform to CGATS TR016 Level A tolerance, and (2) simulate the white point of the source substrate (less than 2 ΔE_{00}).

The influence of defects in flexographic post-printing of corrugated board on register control

Kathrin Happel[1], *Constanze Ranfeld*[2], *Thorsten Euler*[2], *Edgar Dörsam*[2], *Thomas Walther*[1]

[1] Baumer hhs GmbH
Adolf-Dembach-Straße 7, D-47829 Krefeld, Germany
E-mails: khappel@baumerhhs.com; twalther@baumerhhs.com

[2] Institute of Printing Science and Technology
Technische Universität Darmstadt
Magdalenenstraße 2, D-64289 Darmstadt, Germany
E-mails: ranfeld@idd.tu-darmstadt.de; euler@idd.tu-darmstadt.de; doersam@idd.tu-darmstadt.de

Abstract

The applicability of different shapes was evaluated with respect to register control in flexographic printing on corrugated board. For this purpose, we printed a test-chart onto sheets of corrugated board with a flexographic laboratory printing press. Varying the printing parameters, printing defects were generated as they are typical for flexographic post-printing on corrugated board. Furthermore, the different shapes were tested concerning their detectability using an algorithm that detects geometric shapes in an image. We found, that an ellipse features the biggest advantages for register control on post-printed corrugated board.

Keywords: flexography; corrugated board; post-printing; register control

1. Introduction

When producing boxes made of corrugated board, production costs are the main factor. Nevertheless, customers increasingly ask for better quality. This includes multicolor printing, halftoning and varnishing, even when talking about post-printing, i.e. direct flexographic printing onto the corrugated board sheet. Modern flexo folder gluers (FFG) feature high printing quality and post-press processes. Quality control of the print includes a robust register measurement, i.e. the position of the printed inks relative to each other and relative to cut.

Controlling print register has been investigated extensively, especially for offset printing (HDM, 2011) or printing on web-fed machines (Mitsubishi, 2010). Here, the conditions are completely different. Homogeneous substrates and fine resolutions guarantee a steady process. Corrugated board has a slightly uneven surface due to the flutes. Furthermore, its mechanical behavior differs from a sheet of paper or a carton. Therefore, the register marks known from other printing techniques must be questioned when talking about post-printing on corrugated board. A condition for these new register marks is, that the operator is informed which printing unit is out of tolerance. Overlaying register marks can hardly feature this information, because differencing the first and second ink using a camera is a critical and time consuming evaluation. Visual inspection is more tolerant in this respect but it is also subjective.

2. Scope of the work

From literature (FTA, 1999), (Meyer, 2006), we know various defects occurring in flexography, some especially in post-printing of corrugated board. Nevertheless, little is known about how different geometries of the layout to be printed are affected by these defects. Therefore, we printed several basic geometric shapes such as lines, circles, ellipses, and rectangles in different angles (machine direction, cross direction, 45°) and sizes (cf. figure 1) on sheets of corrugated board with a B-flute. During these printing tests, we varied several printing parameters, e.g. printing pressure and speed. This way, we can evaluate the influence of these printing parameters on basic geometric shapes and also assess the susceptibility of these shapes to certain print defects. We anticipate some shapes being more prone to defects than others. Furthermore, we want to find a suitable shape of marks for register control for flexographic post-printing on corrugated board using a camera system. Therefore, the shapes will be judged concerning:

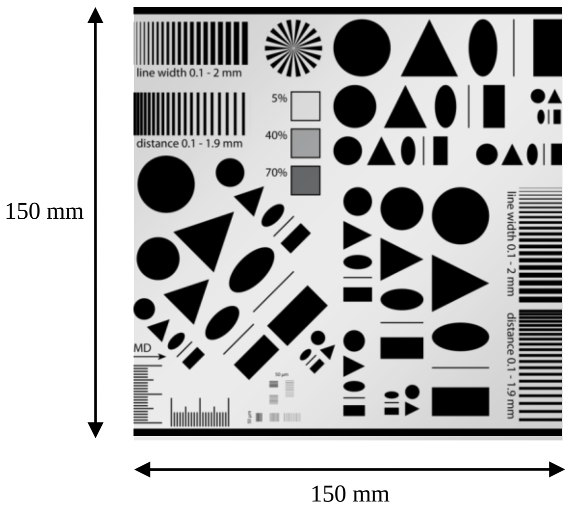

Figure 1: Layout with different shapes for register marks and control elements for evaluation of print quality

Tendency to defects and detectability

The dynamics of flexographic printing and the mechanical properties of corrugated board have big influence on the process stability of different shapes as lines, squares, circles, etc. Some of these defects prevent reliable position measurement while some can be eliminated by choosing a suitable algorithm.

Evaluation time

Given a chosen detection algorithm, different shapes require different evaluation times to find the elements in the search frame. The search frame defines the region, where the element is searched in. The rest of the sample is ignored. The evaluation time directly influences the maximum speed for register control. This speed must be high enough that production is not slowed down.

Size

The size has an important impact on the detectability, evaluation time, and process stability of the register mark. Nevertheless it should be as small as possible to be practicable in production.

There are three other aspects that influence the applicability of register marks. These are not analyzed in this work but restrict the analyzed samples. These are:

Available position parameters

The shape of the register mark should feature the measurement of its position in machine and cross direction as well as the measurement of angular displacements. Although a circle would not allow for angular measurements, we included this basic shape for a better understanding of the effects observed.

Precision of measurement

Given a fixed resolution for the detection with a camera, different geometrical shapes also feature different precision in position measurement. Choosing a suitable shape can increase the precision of the measurement to the subpixel range. In a previous theoretical study we found, that curved elements (circle and ellipse) show a better precision than linear elements (rectangle).

Possible integration of other measurements

A register mark becomes more practicable if its design allows for additional controls as densitometric or color measurements. For this purpose, a two dimensional shape is required, that features an area big enough for the measurement.

The outcome of this research can be used as design hints for register marks with respect to a camera based measurement system.

3. Experimental method

All printing trials in this study were conducted on a sheet fed laboratory flexographic printing press FLP21. The machine is based on the principle of a round plate cylinder printing onto a flat substrate. Therefore, it is suitable for post-printing of corrugated board as the sheets will not be bent during printing. Unfortunately, the FLP21 also has some disadvantages: As it was designed as a laboratory printing press, the printing and inking unit are not covered or encapsulated as in industrial printing presses thus allowing for faster evaporation of the solvent when using conventional (i.e. non-UV-curing) inks which will ultimately influence the ink viscosity and print quality. Also, the impression is altered manually without proper alignment to absolute values. Thus, we rely on the experience of the operator. The printing speed can be altered continuously with five different steps for guidance. It is not conclusively investigated how this translates into an SI derived unit (e.g. m/s).

As substrate, we used corrugated board with a testliner on B-flute and a thickness of 3.5 mm. Prior to the printing trials, the substrates were stored in a climatized room under standard conditions (50 % RH; 23.5 °C). The flutes were aligned in printing direction. To minimize the influence of the open printing unit regarding solvent evaporation and thus undesired viscosity alterations, we chose a water-based flexographic ink (Sun Chemical Blau B-1117/761) in favor of a solvent-based one.

The printing plate we used is a nyloflex FAH Digital from FlintGroup with a plate thickness of 1.14 mm and a shore hardness of 60° ShA. To mount the plate onto the plate cylinder, we chose two cushion tapes with different hardnesses.

Table 1: Printing parameters and their respective variations

Parameter	Range
printing speed	1 … 5
impression	kiss print (minimum) … maximum
anilox roller / pickup volume	Apex UniFlex S, M, L

For the printing trials, we varied the following parameters: printing speed, printing pressure, the pickup-volume of the anilox roller and the hardness of the adhesive tape. The range of variation can be obtained from table 1.

3. Evaluation method

Evaluating the applicability of the different shapes for register control, a custom program was used that utilizes the Matrox Imaging Library (MIL) for finding the defined geometries. First the printing samples were scanned with 600 dpi resolution on an Epson Perfection V750 PRO, without any imaging adjustments.

These images were loaded into the software. For each shape to be evaluated, a search frame was defined that measured 30 mm x 30 mm, where the shape of interest was approximately centered. Within this search frame, the model finder routine of MIL aimed to find the given shape with the given size. This routine is based on edge detection and geometry recognition. A scale variation from 90% to 110% of the original size was permitted, the angle was not restricted. If no shape was found, the routine terminated after a timeout of one second. For each finding, position, score, dimensions, search time, scale and other parameters were recorded. The score is a measure for the congruency of the shape found with the geometry searched. A score less than 60% was not interpreted as a finding.

The evaluation was restricted to the elements marked in Figure 4. These are:

- circles with diameter 5 mm, 10 mm, 15 mm, and 20 mm
- ellipses with 2.5 mm x 5 mm, 5 mm x 10 mm, 7.5 mm x 15 mm, and 10 mm x 20 mm
- isosceles triangles with height = width of 5 mm, 10 mm, 15 mm, and 20 mm
- rectangles with 2.5 mm x 5 mm, 5 mm x 10 mm, 7.5 mm x 15 mm, and 10 mm x 20 mm

These elements were printed in machine direction, cross direction, and diagonal, respectively. Thus, for each print sample, 48 measurements arise. Analyzing 24 samples, the total number of measurements was 1152.

4. Discussion of the results

As expected with such "difficult" substrates as we used with B-flute and testliner, we obtained printing results that show washboarding in every sample. The wave of the flute results in streaking of the printed image as the printing plate is not in contact with the complete width of the substrate in the printing nip. The ink will therefore hardly or not be transferred into the hollows of the flute (cf. figure 2). We deliberately chose the substrate in anticipation of this phenomenon. We wanted to obtain those samples in order to test the algorithm for finding shapes under difficult conditions. If the algorithm works correctly with these samples, it should work with any sample, especially ones with high-quality substrates such as coated paper. Note that the washboarding is hardly influenced by variation of the printing parameters as explained above. Merely a slight change in its markedness can be observed.

Figure 2: Detail of printed sample with obvious washboarding. The alignment of the flute is indicated by the arrow

As is clearly visible in figure 2, the shapes show a darker edge on their outline at the end of the print. Contrary to the arrow shown in figure 2, the left side of this image went into the printing nip first. We attribute these darker edges to both the halo effect due to too much ink transferred and also to plate plugging as introduced by (Boluk, 1991). Generally, this phenomenon occurs when either the impression is too high or too much ink is transferred because of a too high pickup volume.

We could not keep to our initial intention to deliberately produce certain print defects to investigate their correlation to specific printing parameters regarding post-printing of corrugated board due to the strong washboarding overlaying other defects. An example is given in figure 3: it shows the rating of different defects with varying impression. With these parameters, we would expect the halo effect to increase with increasing impression. As obvious, no distinct correlation or trend can be obtained. This is exemplary for other parameters and print defects.

Nevertheless, we determined by visual inspection that rectangles and triangles are more prone to show waviness of their edges due to the underlying flute than circles or ellipses.

We attribute this to the curving of their outlines and its perception by the human eye. To consolidate our observations, we used the algorithm explained above.

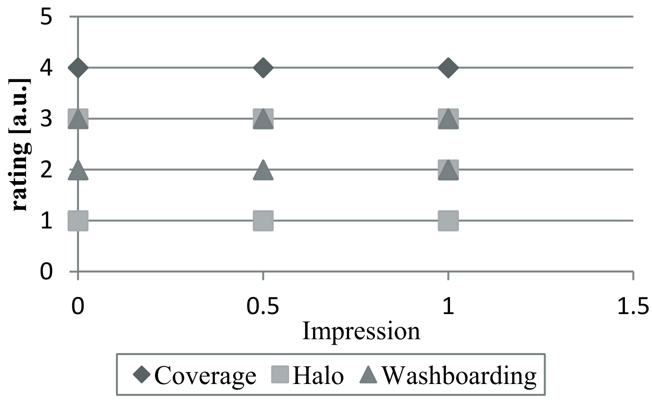

Figure 3: Rating of different print defects with varying impression

Figure 4 shows the scan with the black search frame and the white ellipse of 5 mm x 10 mm found. If the algorithm finds more than just one shape with a score greater than 60 %, the result with the highest score is interpreted as the finding. This can lead to errors, as it can be seen in Figure 5. Here, all findings are marked with a small dot. Usually, these dots lie in the center of an element that should be detected. The dots marked with arrows, are false findings. Here, other printed elements resembled the search model with a higher score than the shape that was intended.

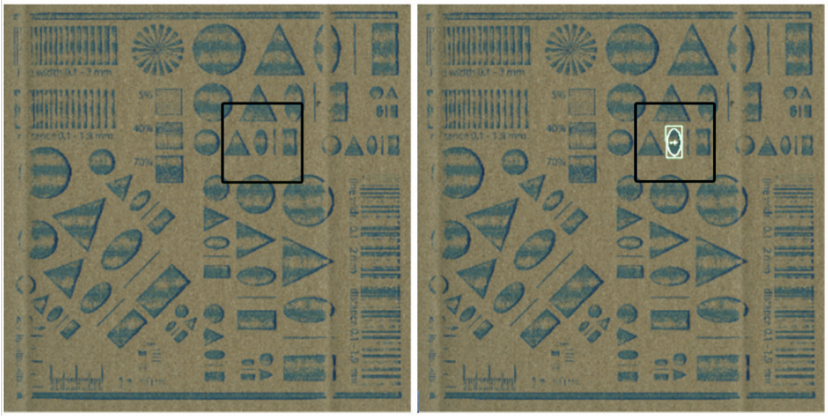

Figure 4: Search frame (left) and ellipse found (right) within the search frame

The differences in the detected positions can be explained by the different image sections from scanning the samples. These could not be calibrated. Therefore, the accuracy of the detected position could not be evaluated. But from a previous theoretical study, we know that the curved ellipse and circle outperform the rectangle by more than factor 10. The triangle was not tested.

In a statistical review, the robustness of the element detection can be determined, see figure 6.

On the left hand side, the diagram shows the frequency, that the algorithm found exactly one element in the search frame. This is the desired performance for register control. The frequency decreases over the elements circle, ellipse, triangle, rectangle. Also, searching for smaller elements, the algorithm more often found more than just one shape, as it is plotted in the center graph. Nevertheless, this is not true for the circle. Here, no multiple findings occurred. This error was frequently observed for rectangles, followed by triangles and some ellipses. If the quality of the printed element was too poor, in some cases no element was found. This happened more frequently with triangular and rectangular elements than with circles and ellipses. Obviously, these shapes are more robust for geometry detection on post-printed corrugated board with the algorithm used.

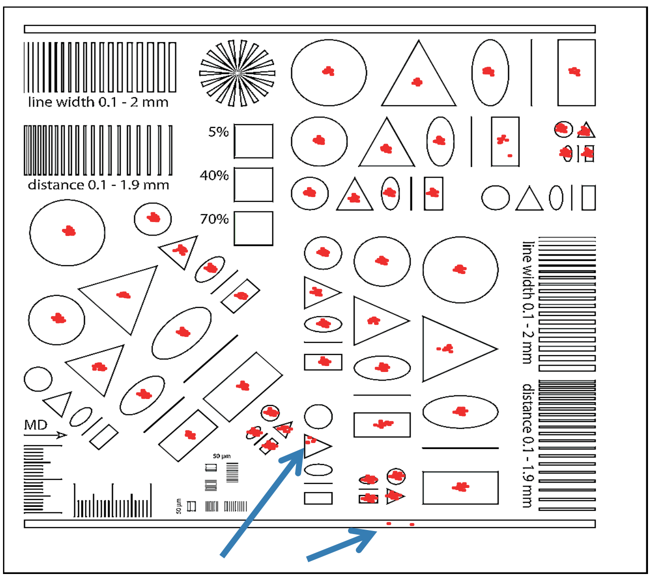

Figure 5: Position of the findings on the printing layout. Arrows indicate false findings

Of course, these result depend on the chosen score limit of 60%. Increasing this limit would result in less "multiple element" cases and more "no element" cases. Decreasing the limit might obliterate the "no element" cases, but the "multiple element" cases would be more numerous.

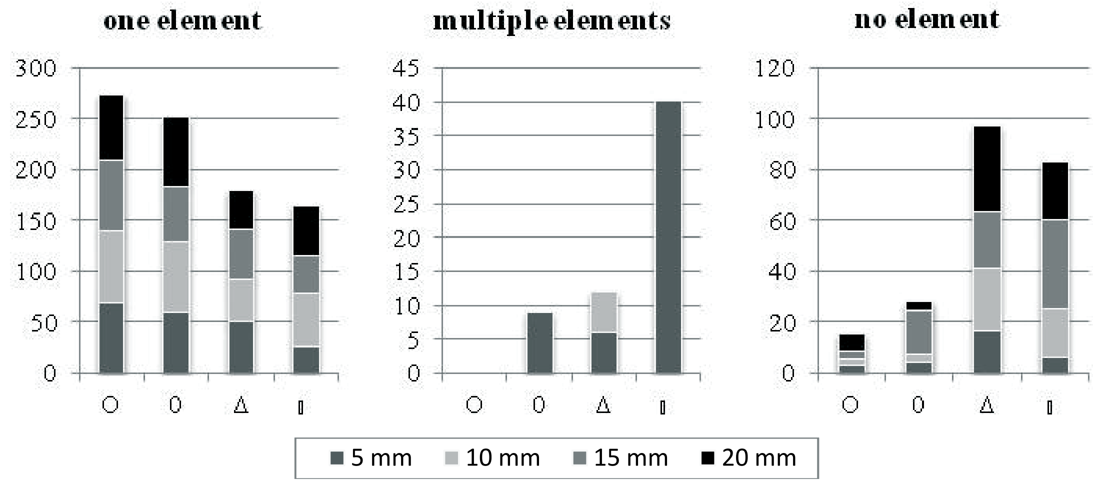

Figure 6: Frequency of findings in the search frame for the different geometries (abscissa) circle, ellipse, triangle, and rectangle. Left: The algorithm found exactly one element. Center: The algorithm found more than one elements. Right: The algorithm did not find any element

Figure 7 shows the frequencies of the scores for the findings and for the unwanted additional elements. Higher scores of the findings and lower scores of the additional elements are preferable. Concerning the score of the findings, the ellipse shows the best performance, followed by circle, rectangle, and at last triangle. The score of additional elements could not be rated for the circle, since this case did not occur for this shape. From the three remaining geometries, the ellipse outnumbers the others. The rectangle is the least in this aspect. With a score of up to 80% additional rectangular shapes were found, that were not intended. A reason is that resembling shapes are quite frequent in printing layouts. An example is the lower line in figure 5 where parts of it were interpreted as small rectangles.

In contrast, a compromise score of 65% for the ellipses would eliminate additional elements, while only a small number of findings would be ignored.

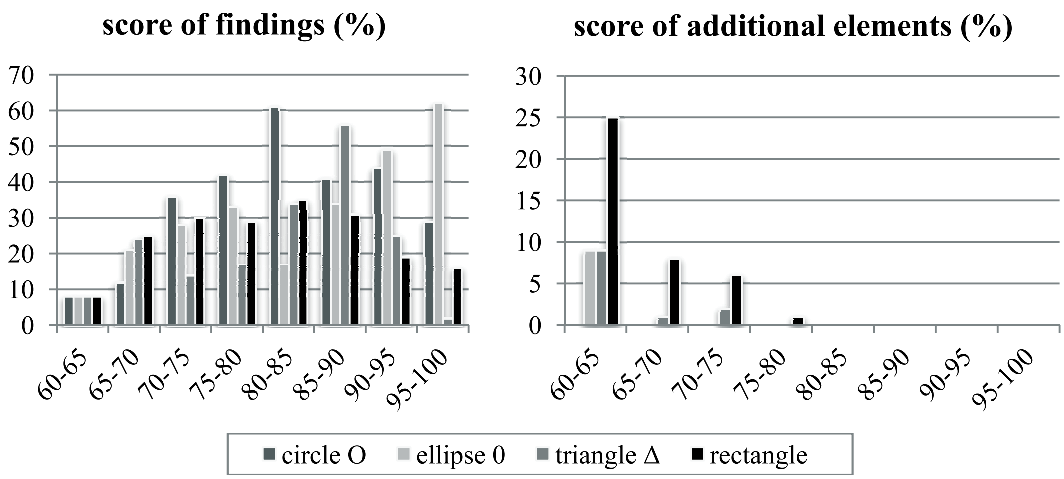

Figure 7: Frequency of the score for the findings (abscissa) and the score for the unwanted additional elements

An example of the good detectability of ellipses is illustrated in figure 8. The corrugated board had a notch that affected the print noticeably. Nevertheless, the algorithm found the elliptic shape with a score of 62%. Similar results could not be found for rectangles or triangles. A reason is, that with the curved shape of the ellipse, its contour is not so much affected by printing defects and the fitting of the geometry has a higher certainty than that of shapes with linear contours.

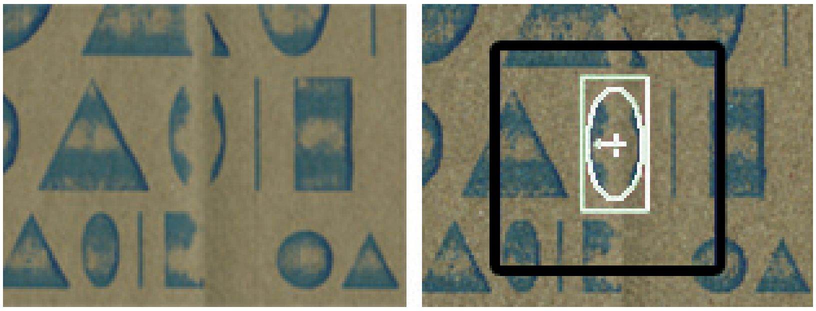

Figure 8: Printed sample (left) and ellipse shape found by software (right). The score of the finding was 62 %

For the following analysis of the evaluation time, the scope was set to ellipses only. These showed the best applicability with respect to score and detectability. Circles will not be considered, since they feature no skew detection.

An important aspect for register control is the evaluation time, i.e. the time that is necessary that the algorithm finds the element. Figure 9 shows the frequency of evaluation times (abscissa in milliseconds) for the different sizes of the ellipses. The ellipses with a height of 10, 15, and 20 mm perform quite similarly. Only the smallest ellipses tend to a higher evaluation time. In terms of printing layout, designers prefer control elements as small as possible. Nevertheless, the detectability and production speed are not to be affected.

For reasons of testing feasibility, we chose a fixed size of the search frame. Although it was not tested, we anticipate that adjusting the search frame to the dimensions of the element searched would decrease evaluation time.

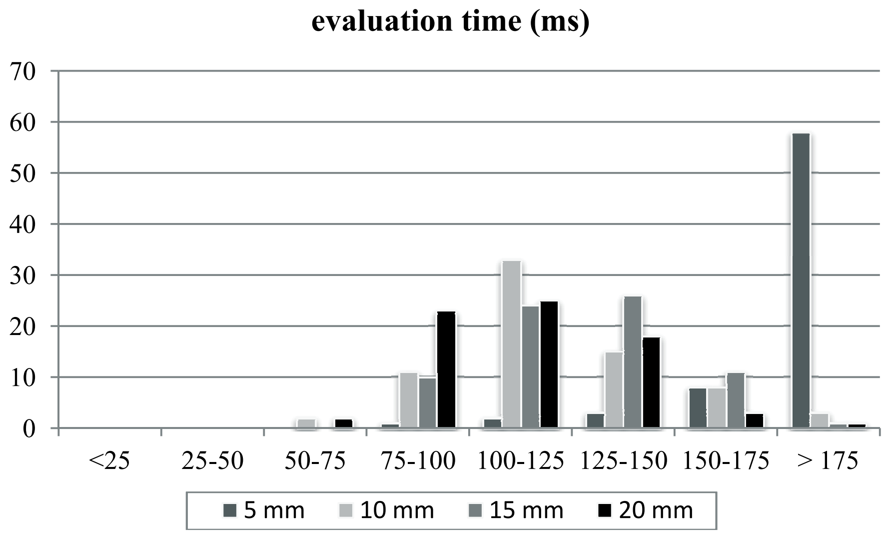

Figure 9: Frequency of evaluation times (abscissa) in milliseconds for the different element sizes

5. Conclusions

The printed samples did not show the desired print defects we wanted to achieve. Washboarding obscured most other defects except for halo effects and plate plugging. We attribute this to the very strong markedness of the B-flute on the surface of the substrate. Thus we conclude that printing trials on corrugated board are not appropriate for reconstruction of certain print defects and their correlation to specific printing parameters.

We analyzed the printed samples in terms of applicability for register control on corrugated board. For the calculations we chose a model finder algorithm that is based on edge detection.

We found, that ellipses are more robust for the detection than rectangle or triangle. In terms of evaluation time, we found that the ellipses are not to be designed too small. Here, adjusting the search frame to a smaller size might still enhance the calculations.

Acknowledgement

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The effect plate exposure on ink transfer in flexographic halftone printing

Simon M. Hamblyn, Glyn R. Davies, David T. Gethin, Timothy C. Claypole

Welsh Centre for Printing and Coating
College of Engineering
Swansea University
Swansea, SA2 8PP, UK

E-mail: s.m.hamblyn@swansea.ac.uk

Abstract

The majority of flexographic printing plates are produced using a photo exposure process. Insufficient control of the plate processing parameters will lead to colour matching problems on the print. This investigation evaluated how the quantity of UV energy supplied to the plates during front and back exposure affect the geometry of halftone dots on the plate and how this subsequently affect the ink transfer to the substrate and the colour. Plates were produced using the range of exposure conditions used within the printing industry. These were characterised using white light interferometry to determine the geometry of the halftone dots and printed using an IGT F1 printability tester. The prints were measured using white light interferometry to examine the area and volume of the dots and a spectrophotometer to evaluate the colour.

The effect of exposure was most significant on the shoulder angles of the dots. On the prints, the highlight and midtone regions were the most affected by the changes in the exposure resulting into tone gain increases of up to 10% at the lowest printing force considered which translated to colour differences of over 6 units (delta E_{1976}). The differences between the plates increased with increasing print force. Increasing the front exposure had the most significant effect on the shoulder angle of the dots on the plates and on the prints due to greater ink transfer from the shoulders of the dots.

Keywords: flexography, halftone, dot geometry

1. Introduction

Brand owners are standardising the colour reproduction on their packaging worldwide and the print companies are expected to match to a colour standard. For many print companies, printing plates are produced by external repro houses, with some print companies using more than one repro house to supply plates. Since the plate making process is not standardised across the industry or between countries, this can lead to problems with colour matching on the press and therefore production waste.

The majority of flexographic printing plates are currently produced using a photo exposure process. The depth of the dots is determined by exposing the back of the plate to UV light for a fixed period of time to cure the photopolymer to a fixed depth. A laser is then used to ablate the negative image as halftone dots and solid areas into a black mask incorporated into the top layer of the plate. Alternatively in older systems a negative film is produced of the image and this is laid over the plate surface under a vacuum. The front of the plate is then exposed to UV to reproduce the image in to the plate. The unexposed areas of the plate are removed using a washing process leaving only the exposed solid areas and halftone dot structures. The power of the UV lamp and the exposure time has a significant effect on not only the dot areas on the plate but also the geometry of the dots such as depth and shoulder angle (Hamblyn et al, 2005).

Previous studies (Warfford, 1997), (Galton, 2002), (Galton, 2003), (Galton, 2004), (Galton, 2005) have evaluated how the exposure process effects the dot areas on the plates, however, little is understood on how this relates to the ink transfer from the plate to the substrate and ultimately the colour of the print. This investigation examines the effect of the plate exposure on the geometry of plate halftone dots and how this affects the physical dot area and colour on the print.

2. Methodology

Photopolymer plates used were manufactured by Asahi under controlled conditions. The exposures of the plates were controlled by the quantity of UV-A energy applied to the plate:

UV-A Energy (mJ) = UV quantity (mW/cm^2) x Exposure time (seconds) [1]

To impart different relief heights onto the different plates, two different exposure energies of 270 mJ and 810 mJ were used for the back exposures, while exposure energies of 3300 mJ and 16200 mJ were used for the front exposure of the plates to control the shoulder angle of the dots. The lamp powers used were within the typical ranges used within the industry. The test image consisted of a halftone gradation scale, with nominal coverages ranging from 2 % to 100 %. Plates were produced at two line rulings: 39.4 lpcm and 59.1 lpcm.

2.1 Plate characterisation

The study focussed on the highlight and midtone dots. The dot areas, shoulder angles and dot depths were obtained using white light interferometry (Hamblyn, 2004); these are tabulated in Table 1 for the 39.4 lpcm line ruling.

Table 1: Dot areas, depths and shoulder angles on the plates

Plate	Back Exposure (mJ)	Front Exposure (mJ)	Nominal Coverage (%)	Measured Dot Area (μm^2)	Actual coverage (%)	Maximum Dot Depth (μm)	Maximum Shoulder Angle (degrees)
1	270	3300	5	3261.5	5.1	186.5	26.0
			10	5874.2	9.1	170.7	27.5
			30	17496.2	27.1	121.1	28.7
2	810	3300	5	3642.3	5.6	-	-
			10	6197.0	9.6	-	-
			30	18229.3	28.3	116.5	30.2
3	270	16200	5	3757.6	5.8	177.5	30.2
			10	6796.4	10.5	155	32.5
			30	19138.4	29.7	108	36.0
4	810	16200	5	4590.5	7.1	-	-
			10	7583.4	11.8	144.3	34.8
			30	19951.5	30.9	100.0	36.0

Increasing the front exposure from 3300 mJ to 16200 mJ produced an increase in the dot areas and shoulder angles, but also decreasing the depth of the dots. This was due to light leaking around the dots on the negative, exposing and polymerising a greater area of the plate. Increasing the back exposure of the plates from 270 mJ to 810 mJ decreased the overall dot heights and also increased their shoulder angles and areas.

2.2 Experimental printing conditions

A laboratory printing trial was performed on an IGT F1 printability tester using cyan UV ink and a polypropylene substrate. The anilox had a volume of 2.7 cm^3/m^2 with a screen ruling of 236 lpcm. Three printing forces of 10 N, 35 N and 75 N were used to evaluate how the geometry of the dots interacted with the nip pressure.

The printed samples were measured using spectrophotometry to obtain the optical densities and colour, and white light interferometry to quantify the topography of the dots (Hamblyn, 2004).

3. Results

Figure 1 shows the difference in tone gain between the prints for plates 2, 3, and 4 calculated relative to Plate 1 for a 10 N print force. As expected, the tone gain increased with as the front and back exposure UV energy was increased. The largest differences between the plates occurred in the highlight and midtone regions, where the range of dot areas between the plates was approximately 10 %. This study therefore focuses on these halftone regions.

The overall colour difference between the plates for selected highlight and midtone dots is plotted in Figure 2. These were calculated relative to the plate with the smallest dot areas (Plate 1). There were significant differences between the plates in terms of their colour reproductions, which dots during the deformation process in the anilox and printing nips, which was evaluated using numerical modelling.

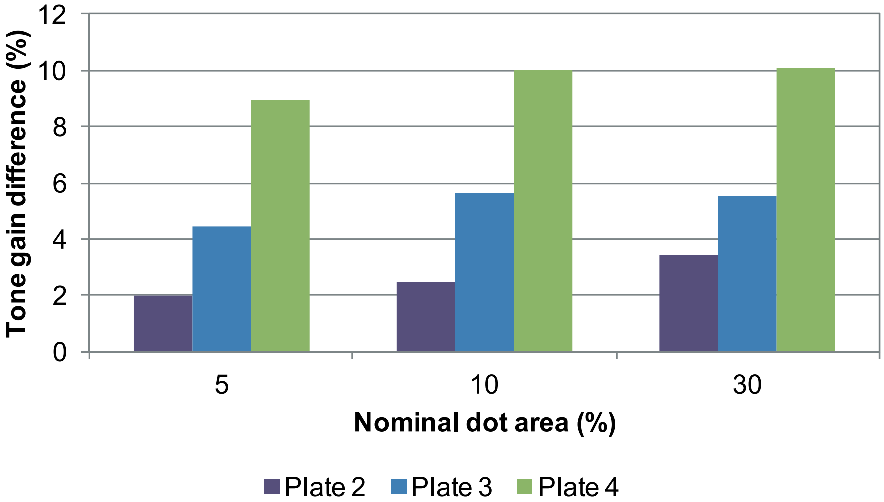

Figure 1: Differences in printed tone gain between the plates relative to Plate 1

The colour reproduction showed that increasing the exposure produced a linear increase in the saturation of the colour with no change in hue. The range in saturation between the plates was significant, with the 5% dot from Plate 4 reproducing nearly identical hue and saturation as a 10% dot from Plate 2. The differences in colour reproduction between the plates would be magnified when printing using multiple colours affecting not only the saturation but also the hue (Hamblyn et al, 2005). The differences between the colour reproductions from the plates increased with increasing print force.

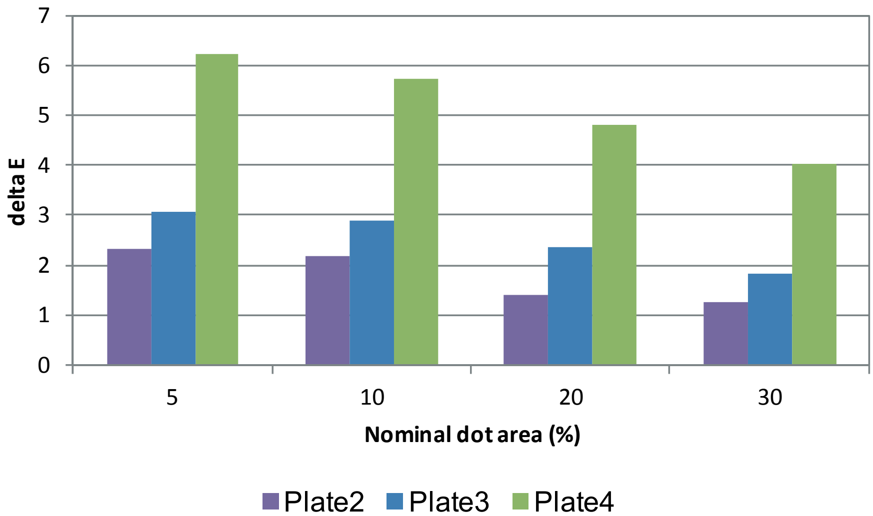

Figure 2: Colour difference between the plates printed at 10N relative to Plate 1

The printed dots were characterised using whitelight interferometry to determine their lateral surface area. These are plotted against the measured dot areas on the plate for the 30% dots in Figure 3 for the prints at 10N. The dot areas on the prints were over 50% larger than the dots on the plate due to the dot deformation mechanisms and ink spreading. Increasing the front and back exposure increased the dot area on the plate, which in turn lead to an increase in the printed dot area. Increasing the dot area on the plate increased the volume of ink that could be carried, which would result in a greater ability to spread due to the squeeze forces between the plate and the substrate. Larger dots would also produce a greater contact area between which the ink could spread. However, the relationship between the dot areas on the plate and the resultant printed dot areas was non-linear. For the plates with a 3300 mJ front exposure, increasing the back exposure from 270 mJ to 810 mJ increased the dot area on the plate by 4% but the printed dot area increased by over 10%. However, when the using a 270 mJ back exposure and 16200 mJ back exposure the dot area on the plate increased by 5% but produced only a small increase in printed dot area. For the plates with a 16200 mJ front exposures, where the shoulder angles were much shallower, these produced larger amounts of tone gain than the

3300 mJ plates and were more sensitive to changes in print force. This therefore indicated that in some circumstances the shoulder angle could have more influence on the print quality than small changes in plate dot area.

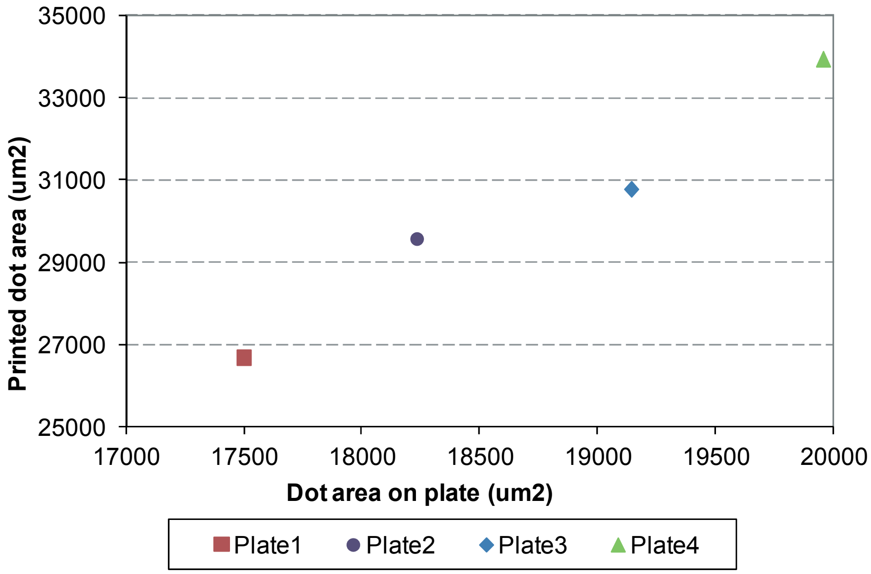

Figure 3: Lateral surface area of the 30% printed dots

4. Discussion

This study has investigated how the typical range of plate exposure conditions used within the industry effect the geometry of the dots on the printing plates and how these impacted on the ink transfer and colour of the prints. A change in the shoulder angle and area of the plate dots affected the volume of ink carried by the plate and affect the manner in which the dots interact with the anilox cells. This interaction would therefore be dependent on the specifications of the anilox roll. Differences in dot areas between plates result in differences in how the ink is squeezed between the plate and the substrate; a larger dot area provides a larger contact affecting the pressure within the contact, and the area of the printed dots. This would also be dependent on the quantity of ink carried by the plate and the engagement applied.

Differences in the geometry of the dots between the plates also result in differences in the way they deform and hence the volume of ink transferred to the substrate and the printed dot areas. This has been investigated in other studies (Hamblyn, 2004). The differences between the plates increased as the printing force was increased which was due to greater ink spreading and transfer of more ink from the dot shoulders. This would also be affected by the anilox cell geometry as well as the properties of the mounting tape and ink rheology. In order to compensate for a plate that has been underexposed compared to normal it might be possible for a printer to increase the printing force to achieve a desirable colour match, although this is also likely to have an impact elsewhere on the print. However, if the plate was overexposed compared to normal it is usually not possible to reduce the print force as this often leads to incomplete solids and problems with low spots on the plate.

5. Conclusions

This investigation has highlighted the importance of controlling of the plate making parameters during the processing of the plates in order to minimise job-to-job variations in colour and reduce the time on press spent trying to match colours. Standard operating procedures covering all stages of the plate making process need to be in place and enforced as well as maintenance procedures to ensure consistent UV output and temperature during the processing. The finished plates should also be measured to ensure of compliance before being used on press. Printers and plate makers also need a better understanding of how the processing affects the geometry of the plate features and how this subsequently affects the print. Where plates are supplied by multiple repro houses, the print companies need to work with the repro houses in order to obtain similar results from the different suppliers.

Although the experiments were aimed at graphics printing the findings are also applicable to the printing of functional inks where the geometry of the features on the plate and hence different amounts of ink transferred would influence the functionality of the print.

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Effect of the printing speed on the uniformity of the thickness of the ink layer flexographic printing

Rostislav Moginov and Yaroslav Dmitriev

Moscow State University of Printing Arts (MSUPA)
St. Pryanishnikova 2 A, Moscow, Russia, RU-127550
E-mails: tpipp@mail.ru; yarky2006@mail.ru

Abstract

This paper discusses the influence of changing the speed printing on ink film thickness, which is applied to the flexographic printing elements form. We developed the model of the transfer of ink from the anilox cells on the surface of the printing plate. We determined theoretically time of spreading of ink drops on the surface of the printing plate and on uncured ink layer on the surface of the printing plate. We obtained experimental results of spreading of ink drops on the surface of the printing plate and on uncured ink layer. Obtained results showed that the ink drops do not have time to spread on the surface of the printing plate before printing and the ink layer on the printing form is uneven in thickness.

Keywords: flexographic printing, ink layer, spreading, anilox roll

1. Introduction

The inking is one of the main problems for quality of the raster flexo printing. Function of gravure shaft is not only in transferring a sufficient amount of ink, but also in ensuring its uniform ink layer peal. Effect of basic parameters of anilox shaft on printing quality considered in the scientific work by Christopher Harper (Харпер, 2003). Further developments of anilox shaft are presented in the scientific work of David Atkinson (Atkinson, 2009).

The article's material concerning the question of the ink layer application on the flexographic printing elements form. The thickness and uniformity of the ink layer are determined by the parameters of the anilox roll: cell width, jumber's width, screen shaft ruling. The ratio of cell / jumper indicates how much of the shaft surface is occupied by cells.

2. Methods

Ink certain capacity or theoretical amount of ink determined by the shape and depth (height) h cells (Meyer, 1999). Thus, the volume is equal to (Figure 1a):

$$V_{\text{cell}} = S \cdot h \,, \qquad [1]$$

where: S - the surface area of the cell,
h - depth (height) of the cell.

On the printing form surface of the ink layer is applied as droplets, the amount of which is determined by various authors as 0,4 ÷ 0,6 V_{cell}. For our calculations the volume of the cell is assumed equal to $0.5V_{\text{cell}}$ (Figure 1b) (Харпер, 2004). In the process of ink transferring from the anilox roller to the printable area the ink spreads over the printing elements (Figure 1c) and forms an even layer. However, as follows from Figure 2c, to achieve a uniform continuous layer of ink droplets must to merge not only with edges, but at a point most distant from the centers of drops. Otherwise, the profile of the ink layer on the surface of the printing plate in front of the print zone may be shaped wavy surface. This will affect the uniformity of distribution of the ink layer applied to the printed surface.

It is necessary to determine the time of spreading ink on printed form.

As one of parameters to characterize the uneven transfer of ink can be used amplitude coating thickness on the form A_f, which defined as follows:

$$A_f = \frac{h_{max} - h_{min}}{h_{av}} \cdot 100\% , \qquad [2]$$

where: h_{max}, h_{min}, h_{av} - respectively, the maximum, minimum and average thickness of the ink layer on the form within one revolution of the plate cylinder, before it enters the print zone.

To characterize the significance of the deviations of this kind is introduced special parameter - thickness step of layer ink coating (step coating thickness) on the form.

Thickness step of layer ink coating on the form (step coating thickness) S_{hf} calculated by the formula (Раскин, 1989):

$$S_{hf} = \frac{\Delta h_{max}}{h_{av}} \cdot 100\% , \qquad [3]$$

where: Δh_{max} - the maximum deviation of the thickness of ink on the form.

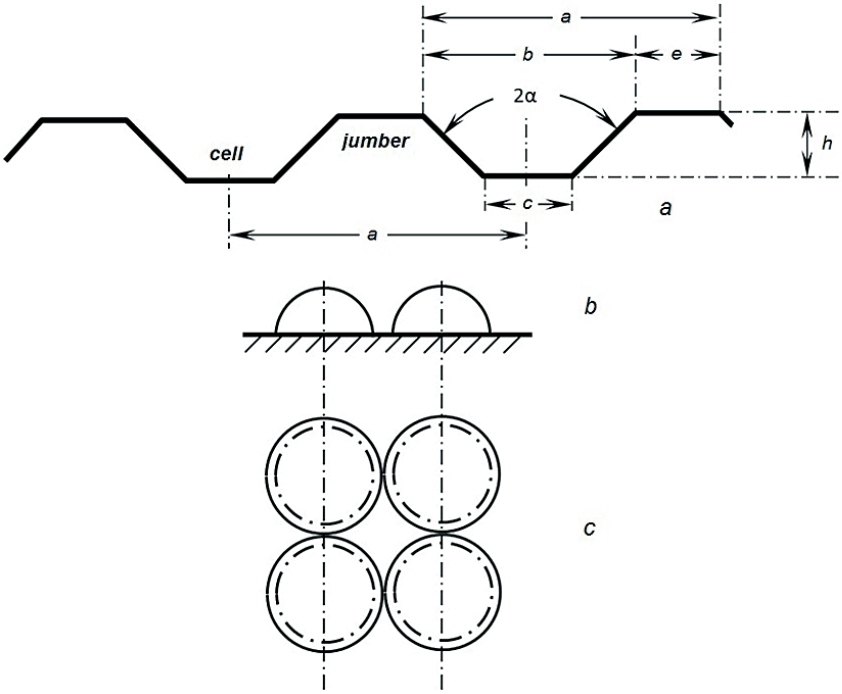

Figure 1: Diagram of ink transfer from anilox to the surface of the printing plate.
a - raster step, *b* -step the cells, *c* - width of the cell, *h* - depth (height) -he cell,
e - jumber's width, 2α - opening angle

For experimental studies were selected flexographic printing inks brand Flintgroup Flexocuresigma II, the said viscosity of the supplier - 200-600 cps (at 20 º C).

As the printed surfaces are used polyethylene and polypropylene films on self-adhesive and polyethylene terephthalate film. Characteristics of printed surfaces are shown in Table 1.

Table 1: Characteristics of printed surfaces

Type of material	Manufacturer	Thickness, mm	Weight of 1 m^2, g	Substrate
Polyethylene	Fasson	0,063	66,5	Paper; acrylic adhesive
Polypropylene	Fasson	0,58	54	Paper; acrylic adhesive
Polyethylene terephthalate	Exxon mobil	0,88	92	No

For the manufacture of printed forms were used thin flexo printing plates Dupont DPU, thickness 1,14 mm.

To study the kinetics of spreading UV-curable flexographic printing ink used device Easy Drop DSA 20E.

The surface topography anilox viewed by optical and scanning electron microscope (SEM) Stereoscan-360 company Cambride Instruments. The image on the screen is digitized with the number of pixels in the horizontal - 1536 and in vertical - 1124. Distances between markers are automatically calculated and the results are displayed in the lower right corner of the screen.

3. Results

The surface topography, which was photographed from ceramic shaft firm ZECHER with parameters: linearity 100 lines/cm; ink certain capacity 10 cm^3/m^2. The image on the photography (Figure 2) is performed at 400 multiple of magnification. In Figure 2 major cell parameters *a*, *b*, and *h* can be easily seen.

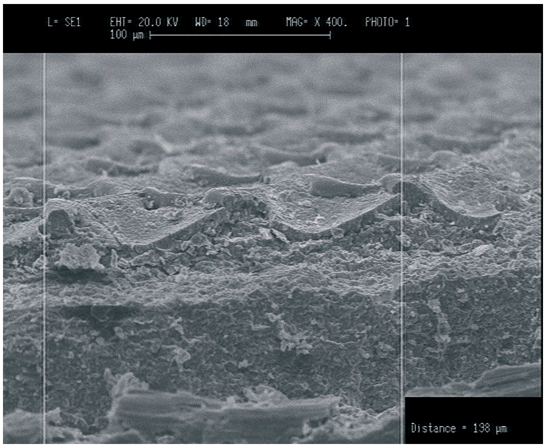

Figure 2:
The surface topography anilox

On the device EasyDrop DSA 20E was measured surface tension by the hanging drop method for the four test colors. Results are presented in Table 2.

Table 2: The surface tension of flexographic inks Flintgroup Flexocure sigma II, measured by the hanging drop method

Ink	The surface tension σ, mN/m
Yellow	43,84
Cyan	43,82
Magenta	44,13
Black	46,78

Figure 3 shows photographs of ink droplets (yellow) which was deposited on the uncured surface of the ink layer at different points in time *t*: 0 seconds, 1 second, 1,8 seconds, 20 seconds. The results were obtained from the experiment.

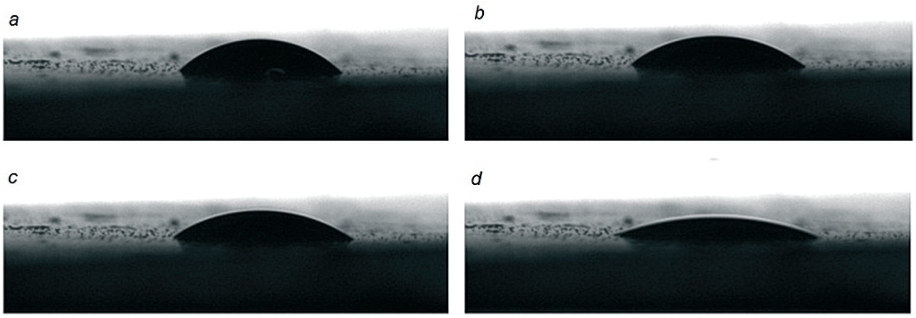

Figure 3: Photographs of ink during different moments of drops spreading
a - 0 sec, b - 1 sec, c - 1,8 sec, d - 20 sec

The first cycle of the printing process is different from all subsequent fact that the ink is applied on printing form the first time, i.e. interacts directly with the dry surface of the printing elements. The uniformity of the paint layer formed on the surface of the printing elements is determined by a flow rate of ink droplets on the surface. Plot the contact angle and the area of ink drops from time to time drop spreading over the surface of the printing plate, Figures 4 and 5.

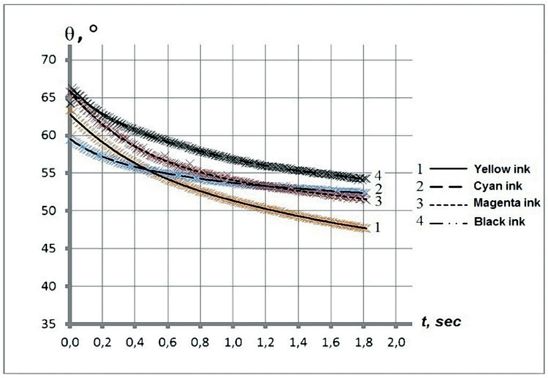

Figure 4: Dependence of the contact angle θ drops of ink from time to time t, during the spreading on a dry form

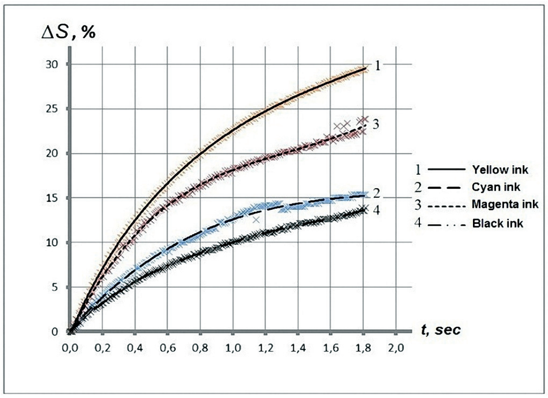

Figure 5: Graph of the increase area ΔS of ink drops from time to time t during the spreading on a dry form

The graphs show that over time, the contact angle decreases and the drop size increases, and, if the trend of these changes is the same for all colors, the rate of change - different. The fastest on the dry form spreads yellow ink, black ink has the lowest rate of spreading. However, the absolute value of the increment of the area for the smallest drops of black ink.

This may be due to the composition of inks, particularly the characteristics of the pigment used, as well as the technological characteristics of the paint, especially suitable photo initiator which may be reactive in the presence of daylight, especially for cyan ink. That is, under the influence of ambient light blue paint can display the ability to cure, which should increase its influence on the viscosity and reduce the spread ability. In (Могинов, 2013) provides the timing data transferring ink from the anilox roll to the printing material printed on the form for flexographic printing machine Arsoma Gallus EM280, are given in Table 3.

Table 3: Time of transferring ink from the anilox roll to the printing material according to the printing

Print speed *V*, m/min	Print speed *V*, m/sec	The transfer time $t_{tr.}$, sec
30	0,5	0,143
60	1,0	0,072
90	1,5	0,048
120	2,0	0,036
150	2,5	0,029

As can be seen from Table 3, the most interesting analysis graphs plot is from t = 0 sec t = 0,143 sec - limit the time spent on the surface of the printing ink to form the entrance to the printing nip. In this area the maximum increase in the area of ink does not exceed 5 %, and the area to t = 0,0725 sec (half of the analyzed range) - not more than 2,8 %.

For all subsequent cycles of the printing ink will not be applied to the printing form surface, and the uncured layer of the same colored ink. Plot the contact angle and the area of ink drops from time to time drop spreading on the surface of the uncured paint layer, Figure 6 and 7.

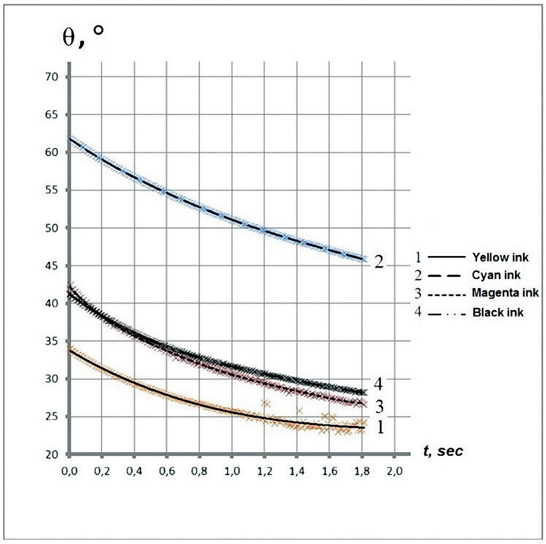

Figure 7:
Graph of the increase area ΔS of ink drops from time to time t, during the spreading on uncured layer of ink on the form

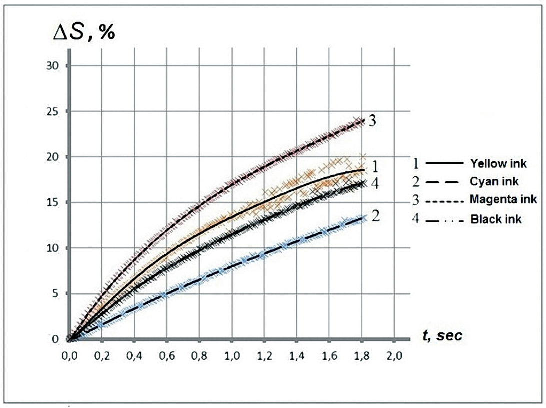

Figure 6:
Graph of the contact angle θ drops of ink from time to time t, during the spreading on uncured layer of ink on the form

The graphs show that during the spreading of ink on the surface of non-negative assertion of the ink layer contact angle decreases and the droplet size increases. Most rapidly spreads purple paint on a layer of uncured purple ink, then its speed is reduced, the blue ink has the lowest rate of spreading.

The absolute value of the increment of the area drops to lowest blue ink. The values of the contact angle for cyan ink significantly greater than for all other colors, this may be due to the ink composition, particularly the characteristics of the pigment used, as well as the technological characteristics, especially suitable photo initiator which may be in reactive the presence of daylight, especially for cyan ink.

That is, under the influence of ambient light blue ink can display the ability to cure, which should increase its influence on the viscosity and reduce the spread ability. Small contact angle for the yellow ink may be associated with the lack of significant changes in the structure of ink, ie the lack of solidification, unlike in the cyan ink, and to a lesser extent for the magenta and black inks, such an assumption is consistent with the characteristics of the yellow ink color: light pigments are reflective and less susceptible to actinic radiation.

4. Conclusion

1. Analyzing the graphs in Figures 4-7, it should be noted that when the contact angle on the spreading of uncured ink layer (Figure 4-5) for the majority of inks considerably less than when the spreading on a dry form (Figure 6-7). The exception is the blue ink, whose absolute value is less than during the spreading on a dry form, but the rate of spreading on uncured layer above it. Increment of the area during the spreading of droplets on the uncured layer is smaller than the dry form. This can be explained as follows: during the spreading on a dry form of the contact angle for most of the ink is great, and so is in store a considerable range to lower it. At distribution for uncured layer is less than the value of the contact angle, and therefore the range of possible reduction of these values already. Given that the motion curves to the x-axis (i.e., the full spreading), the rate of spreading is reduced, and then the increment of the area during the spreading should decline. In this case the dye molecules are not necessary to overcome the energy barrier

at the paint-solid as spreading surface is already thin ink film. At distribution for the dry form such a need is there, and so on viscous regime accounts for most of the observed process of spreading. Consequently, in the experiment conducted to compare only the increment space drops caused by spreading a viscous regime, which begins to drop compared with the various reference points.

2. Analyzing the graphs in Figure 4-7, the area from t = 0 sec to t = 0,143 sec, we obtain the maximum increase in area drops of 3,5 %, while the area to t = 0,0725 sec - no more than 1,6 %.

3. Given these results, it is obvious that the printing speed (not less than 90 m / min) for transferring ink droplets from the anilox roll to the printing nip melt is less than that required for their fusion with neighboring drops to obtain a uniform inking on shape.

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Evaluation of quality of flexographic print with UV inks on PLA film

Joanna Izdebska and Mateusz Nesterowicz

Warsaw University of Technology, Faculty of Production Engineering
Institute of Mechanics and Printing, Department of Printing Technology
Konwiktorska 2, PL-00217 Warsaw, Poland
E-mail: j.izdebska@wip.pw.edu.pl

Abstract

On the market there are various biodegradable materials among which PLA is the most important. UV inks are more widely used to print non-absorbent substrates in flexographic technic. The article is an attempt to answer the question, what is the quality of copies printed on the PLA film with use of different UV inks. PLA film and two samples of UV, black inks were used as the object of investigation.

The studies comprised the inks and film tests, and preparation of copies and their research. The most important measured properties were: adhesive of ink film to the substrate, resistance to abrasion and scratching, optical density of full tone, values of colour coordinates L*, a*, b* and gloss. It has been found that UV inks enable to obtain on PLA film copies of good quality. The ink composition determines the quality of printing on PLA film, but available on the market inks dedicated to plastic materials after the properly selection allow to get the satisfactory quality of prints. The gloss of such prints is very high and density and colorimetric values suitable. In case of the both inks printed on PLA film the mechanical properties of the dry ink film are relatively good, and for most applications of copies are acceptable.

Keywords: polylactide, biodegradable films, flexographic printing, copies quality

1. Introduction

The lifetime of the products are still reduced, which also entails shorter and shorter life of the packaging. Therefore the number of generated waste greatly increases. Biodegradable plastic seem to be an alternative to traditional plastic. They become degraded within the time of several months to several years depends on the condition, where the traditional synthetic, petroleum-based plastics need hundreds or thousands years (Intertech Pira, 2010).

The share of biodegradable packaging in the packaging market is still growing rapidly. The use of plastics in those segments, for which they are an alternative, is also growing. At present on the market there are various biodegradable materials which characterize different properties. Polylactide (PLA), starch and cellulose are the most important polymers among them (Rudnik, 2008).

PLA is the most common biodegradable plastic with a market share of 42 % in 2010 (Intertech Pira, 2010). It is produced by converting sugar or starch obtained from natural sources such as: corn, wheat, rice, etc. Available on the market PLA films have been found to provide mechanical properties better than polystyrene (PS) and comparable to poly(ethylene terephthalate) (PET). Appropriately obtained PLA materials can be also the alternatives of polypropylene (PP), polyethylene (PE) and polyamide (PA) (Garlotta, 2001; Jamshidian, 2010).

Flexographic printing technique is commonly used to print non-absorbent substrates such as films. Three kinds of inks: water based, solvent based and UV are used to printing. Nowadays UV inks are more widely used. This is due to the possibility of eliminating such problems as: ink fixation, use of flammable and explosive solvents, change of ink color intensity on the copies during the printing process, etc. Other principal benefit for using of UV ink is their fast and quite easy drying (Walker, 2010).

The prints made on packages and their quality have very high importance. This is due to the marketing role of the packages, which is intended to gain consumer attention. It is allow to achieve for packages which have interesting shape, distinctive graphics, deep colors and resistant to abrasion and deterioration during transport, storage and display, and a high gloss.

The article is an attempt to answer the question, what is the quality of copies printed on the PLA film with use of flexographic UV inks. The studies comprised the inks and film tests, and preparation of copies and their research. It has been found that UV inks enable to obtain on PLA film copies of good quality.

2. Materials and methods

Polylactide films are environmentally favorable alternative to those produced from conventional plastics. Biodegradable and compostable PLA film - conforming to the standard EN 13432 - were used as the object of investigation. A4 sheets of PLA EarthFirst BCP film from Sidaplax, each of thickness 20 μm were cut for halt for printing process.

Two samples of UV inks from different producers were used. The first one was Zeller+Gmelin UVAFLEX Y77 named in the article Ink 1. The second one was Huber UV flexo (Ink 2). Both of them were black. These printing ink are recommended for flexographic printing on plastics films.

Viscosity of inks were studied before the printing process. The rheological characteristic of the flexographic printing inks were specified by the flow time in a flow cup (volume 100 ml, Ø 4 mm) according to the standard (ISO 2431, 1993). The measurements were performed at 20 ± 0,5°C. The kinematic viscosity of Inks were respectively average 34,5 and 58,0 s.

Surface free energy of the film was determined according to the Owens/Wendt method. For that purpose the contact angel of water and methylene iodide were measured. The calculated value of surface free energy was 48 mJ/m^2.

Copies were printed on the Flexiproof 100 (RK, UK) device with keeping constant printing parameters and were also prepared with hand coater. It allows to applying varied wet film thickness. The ambient condition during both parts of copies preparation were: temperature 23,0 ± 1,5^{o}C, RH 45 ± 5%. Laboratory, handy printing was carried with a rod applicator nr 2 (RK prints, UK). The deposition of wet ink film thickness was 10 μm. Printing process on laboratory printing machine were realized with constant speed and pressers between cylinders. The printing speed was 60 m/min. The printing plate containing the full covered field was prepared by digital laser-photochemical method from BASF photopolymer. Its thickness was 1,7 mm. The plate was mounted on the print cylinder using the soft tesa plate mounting tape with thickness 0,5 mm. The ceramic anilox roller with two screen frequency was used for printing; the rulings screens were properly 315 and 472 l/cm.

The prints were dried immediately after printing process in a UV laboratory compact dryer Aktiprint mini (IGT, Netherlands). The drying speed was 40 m/min.

The mechanical properties of dried copies were investigated. Such tests as: adhesion of ink film to the substrate and resistance to abrasion and scratching were done. Adhesion of dried ink film to the PLA film was performed by tape test according to the standard (PN EN 1538, 2009). The slice of tape was attached to the copies and rapidly peeled off by hand in three different areas of each sample. The tests were done 15 min. after printing and curing.

The resistance of the printed films to abrasion was studied using an Ink Rub Tester (TMI Machines, Canada). An offset paper strip (80 g, Arctic Paper Kostrzyn, Poland) was attached to a weight (0,5 kg) and it was automatically rubbed with speed 99 cycles/min along the overprinted sample. The color fastness was quantified by analyzing the color of the paper strip after 10, 50, 100, 200, 300, 500, 1 000, 1 500, 2 000 and 2 500 rubbing cycles. To facilitate the analysis of the results eleven point scale describing the changes of rubbing paper was developed and used. According to that, 10 means the absence of any changes on the stripe of white paper, while 0 indicates the intense color on its surface. Tests were performed under controlled environmental condition such as: temperature 22,5 ± 0,5 ^{o}C and RH 52 ± 3 %, at least one week after preparation of copies.

The resistance to scratching of the copies was tested by a pencil test using a pencil hardness tester (BYK, Germany). Pencils from 9B to 9H degrees of hardness were used to draw over the coating surface to determine which pencil causes indentation. Five scratches were made on each sample. The hardness of the hardest pencil that did not mark the coating is named pencil hardness.

Also optical density of full tone and values of colour coordinates L*, a*, b*, as well as gloss were measured. A Gretag SpectroEye spectrophotometer (GretagMacbeth, Switzerland) was used to assess the optical densities of copies and for the determination of the color coordinates values. Both of them were done in reflective light after the placing of prints on the Matchprint Proofing Paper as a white base. The measurements of optical density were performed with the following settings: polarized physical filter, DIN measuring geometry and relative white based. Whereas the measurements of L*, a*, b* color coordinates were carried out with the settings: D65 illuminant, 2° observer, without a polarization filter and absolute white based. The reported results are the average of five measurements.

The gloss of copies was measured with the use of a micro-TRI-gloss glossmeter (BYK, Germany) according to standard (ISO 2813, 2001). All tests were done at 20° geometry due to the high value of this parameters.

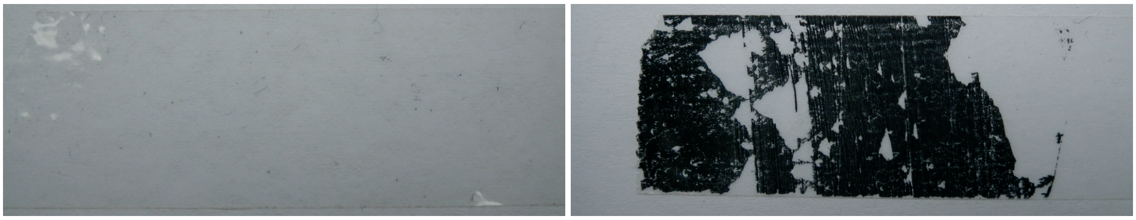
Data collection was performed at six places in two different directions on each sample. The reported values are the average of these measurements.

3. Results

In this work some mechanical properties of the prints (adhesion of ink film to the substrate as well as abrasion and scratch resistant) were studied. The examples of the adhesion test results for both inks are shown in Figure 1.

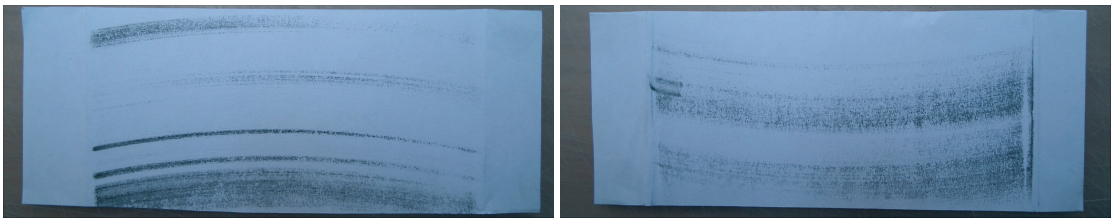
The results represent the worst case. The abrasion test results are presented in Figures 2 and 3.

The photos of the paper stripes (Figure 2) illustrate the effects received after 2500 rubbing cycles which number is extremely high. The scratch resistant according to the pencil test was 9H for Ink 1 and H for Ink 2.



a) b)

Figure 1: Tape strips from the ink adhesion test a) Ink 1, b) Ink 2



a) b)

Figure 2: Surfaces of the paper after 2500 cycles of rubbing a) Ink 1, b) Ink 2

The most important optical properties of copies such as: optical density of full tone fields, L*, a*, b* color coordinates values and gloss were investigated. Measurements of the optical density of fully coated fields depended on the kind of ink and procedure of the printing are displayed in Figure 4.

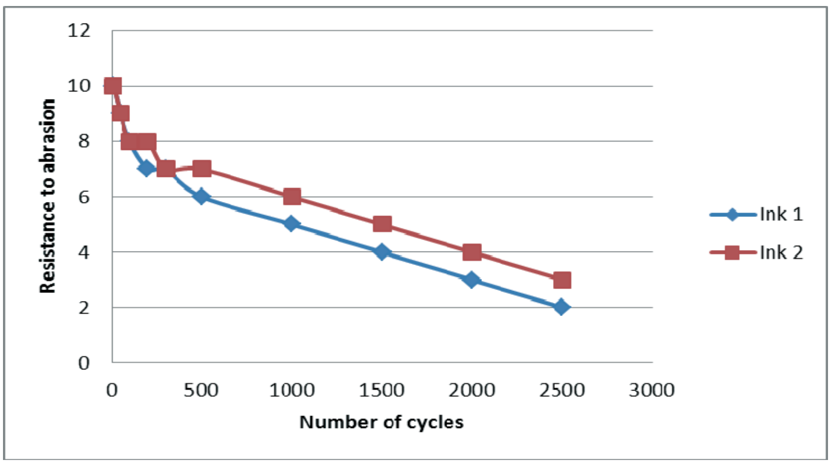


Figure 3: Changes of abrasion resistance

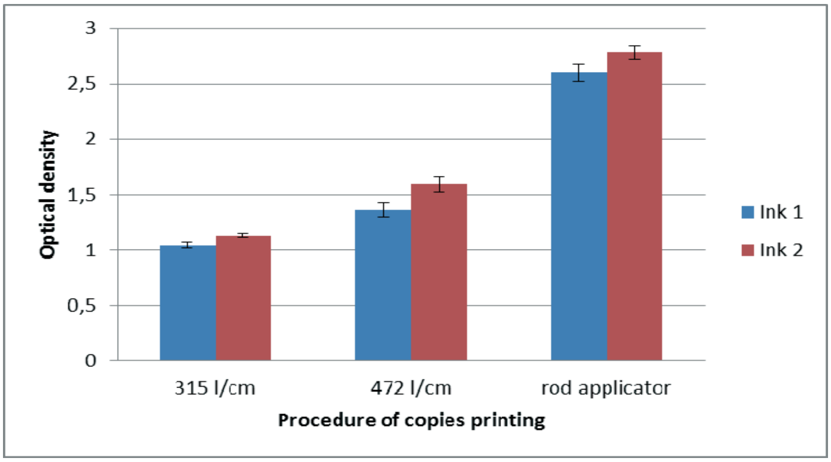


Figure 4: Values of the optical density

The changes of color coordinates values according to the ink used in printing process are showed in Figure 5.

All tested copies, regardless of the printing procedures used in their preparation, are a very high gloss prints. The values of gloss amounted respectively 11,34 ± 3,25 for Ink 1 and 15,24 ± 6,58 for Ink 2.

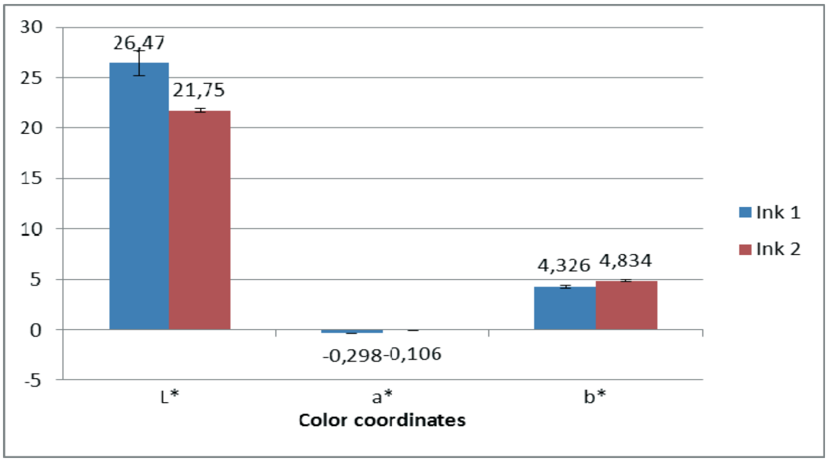


Figure 5: Values of color coordinates of copies printed with anilox with screen frequency 472 l/cm

4. Discussion

Despite the fact that both inks are dedicated for printing plastic substrates, the adhesion to the printed film for Ink 2 was very low. In case of Ink 1 full adhesion to the PLA film were observed. For Ink 2 it was almost completely detached from the PLA film (Fig. 1), which shows that without changes in the surface layer of the substrate it is not recommended its use on that substrate. It should be emphasized that Ink 2 has good adhesion to various plastic films including for example the activated PET film, which the authors found in other studies carried out by it. Therefore, it can reasonably be expected that the activation of PLA film surface before printing improve the adhesion of this ink. Different matter is the fact that, according to curing may actually continue for a number of hours after exposure to the UV source. It can explain good abrasion resistance.

The scratch resistance of copies made with Ink 2 was lower than those printed by Ink 1. Ink 1 gave the maximum resistant. Nevertheless for Ink 2 it was also not so poor.

Copies printed with Ink 1 showed slightly lower abrasion resistance than those prepared with Ink 2 (Figure 3). The difference were observed when the number of the cycles up to 200. The first changes on the paper used to rubbing was observed after 50 cycles of abrasion, but it did not cause visible changes in the printed copies. In case of copies printed with Ink 1 significant damages of the printed surfaces were visible after 500 cycles of abrasion. Slightly better results were obtained for the Ink 2. In that case after 1000 cycles were visible the first changes on the prints, as well as quite intensive, dark streaks on the abrasive paper. Carried out of the resistance to abrasion tests allowed to state a quite good resistance for both printing inks. Despite the fact that all copies after 2500 cycles of abrasion were damaged (Fig. 2), this number of rubbing cycle is much higher than typical resistant requirements (Schmalzl, 2001).

The values of optical density of the full tone coming to those recommended in the literature sources (FFTA, 2003; Czech, 1993) were obtained for prints made using Flexiproof device and anilox cylinder with 400 lpi screen ruling. While there were significant differences for the different inks. Higher values were obtained for the ink 2, which resulted from the higher viscosity.

A very high gloss were observed for copies printed by Ink 1 as well as Ink 2. In all cases the measurements were done with geometry 20^o. Both inks used for printing gave the high-gloss copies what was in accordance with the manufacturers' description. In addition, the high-gloss of PLA film surface has a positive impact on the value of prints gloss.

5. Conclusions

It has been found that UV inks enable to obtain on PLA film copies of good quality. The ink composition determines the quality of printing on PLA film, but available on the market inks dedicated to plastic materials after the properly selection allow to get the satisfactory quality of prints. The gloss of such prints is very high and density and colorimetric values suitable. In case of first ink printed on PLA film the mechanical properties of the dry ink film are good where for the second one relatively low, but still in some applications of copies could be acceptable.

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Effect of under print on subsequently printed colours in UV flexo

David Beynon, Timothy C. Claypole, David Gethin

WCPC
University of Wales
Welsh Centre for Printing and Coating
Singleton Park, Swansea
SA2 8PP, Wales, United Kingdon

E-mails: d.g.beynon@swansea.ac.uk; t.c.claypole@swansea.ac.uk; d.t.gethin@swansea.ac.uk

Abstract

In order to improve print quality, minimize wastage and maintain print quality through the run it is important to understand the effect of process parameters on ink transfer and therefore print quality. In this investigation the effect of previously printed ink on transfer of subsequently printed ink is investigated through a printing trial at full press scale. Using cationic UV inks various coverages were over printed using a banded anilox roll. Plate design included full tonal strips of various line ruling therefore a wide range of press parameters and dot geometries have been investigated.

Changes in ink transfer were found to be due to physical interaction between ink layers and different trends were observed dependent upon the coverage of both ink layers. Previously printed halftones act as a barrier to ink spreading. When printing onto a solid ink area the ink is spread further by the increased impression however with increased surface roughness there is a reduction in print density for highlight areas. Therefore achieving ultimate flexographic print quality at kiss contact printing will also require consideration of the coverage of previous ink layers for colour separation during plate making.

Keywords: flexography, ink transfer

1. Introduction

In order to improve print quality, minimize wastage and maintain print quality through the run it is important to understand the effect of process parameters on ink transfer and therefore print quality. Previous investigations have studied ink transfer from the anilox to the plate [1] and the effect of process parameters such as anilox volume, engagement, viscosity and geometry [2-7]. These investigations have isolated the process parameters and determined the ink transfer mechanisms when only printing a single process colour. That is, the interaction between ink, plate and substrate alone however this situation is only true for the first colour printed. For the majority of process printing the ink is printed onto a combination of previously printed ink and substrate the ratio of which is dependent on the previous print layer. In this investigation the effect of previously printed ink on transfer of subsequently printed ink is investigated through a printing trial at full press scale. The effect of previously printed ink layers is investigated with reference to the process parameters of anilox volume, engagement and print geometry.

2. Materials and methods

Printing was conducted using 2 units of a narrow web packaging press (Timsons T-Flex 508) using a chambered ink delivery system, the first unit was used to print white ink the second to print magenta over the white ink layer. The inks used were commercially available cationic curing UV inks. The first printed layer (under print) was printed on the first unit of the in-line press using a 6.40cm^3/m^2 anilox. Four coverages of 25 %, 50 %, 75 % and 100 % were printed and dried before reaching the second print station. At the second print station magenta ink was printed onto each of the white ink coverages with varied line ruling (65, 85, 120, 150 and 175lpi) with 16 coverage patches from 1 % to 100 % coverage (1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95 and 100 %), therefore a wide variety of dot shapes and geometries were included in the study. In addition a banded anilox roll was used to print the magenta ink with six volumes (1.63, 3.04, 4.18, 5.49, 6.59 and 8.31 cm^3/m^2) and engagement varied at 3thou, 4thou and 5thou.

The substrate chosen was a white biaxiallyorientated polypropylene film (BOPP). The film ensures that ink transfer only occurs through ink splitting and not absorption into the substrate. This allows the ink transfer due to film splitting to be characterized independently and the white film and white ink allow for easy distinction of the magenta overprinted ink.

The printed samples were measured using spectrophotometry and image analysis techniques. A Gretag Macbeth Spectrolino spectrophotometer was used to measure CIE Lab and density values using D50 illuminant and 2° observer angle in accordance with ISO 12647-1.

Physical dot size and shape was measured using image capture through a computer linked microscope. The captured images were analysed using Image J software to threshold the image isolating the magenta print area. The thresholded image was then anlysed to output the area and circularity of individual dots. Coverage of the under printed ink was measured using whitelight interferometry and a large degree of ink spreading found therefore the actual under print coverages are as shown in table 1.

Table 1: White under print coverage measured using white light interferometry

Nominal Coverage (%)	Measured Coverage (%)
25	62.2
50	90.2
75	100
100	100

3. Definitions

During this investigation it is necessary to discuss ink coverage for different inks and both theoretical and measured coverage therefore to avoid confusion the following definitions are supplied:

Under print: The first ink layer printed directly onto the substrate.

Over print: The second ink layer printed on top of the under print.

Nominal coverage: The coverage value specified in the PDF supplied for plate making.

Physical coverage: The ink area coverage as measured using image analysis.

4. Results and discussion

The results of both density and coverage measurements show two distinct trends dependent upon the coverage of the white under print layer (figures 1 and 2).

The magenta printed onto the 62.2% and 90.2% coverage show a decrease in both density and coverage when compared to samples with no under print with the decrease greater as the nominal coverage increases. When printed onto 100% under printed ink there is a different trend observed. The density is decreased at lower coverages and is unchanged at coverages above 50%, the physical coverage however shows a slight increase.

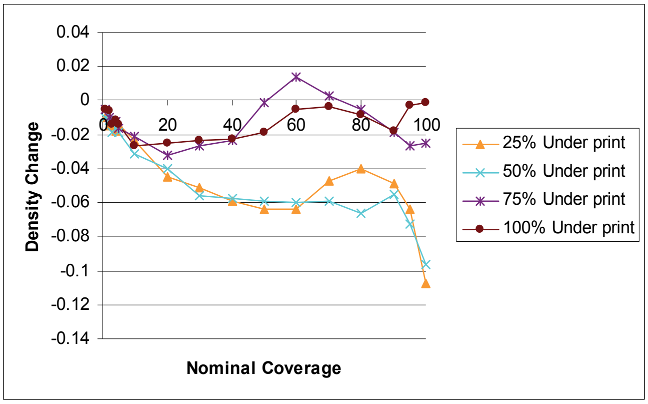

Figure 1: 5.49 cm^3/m^2 anilox, 175 lpi density change with addition of under print at 3thou engagement

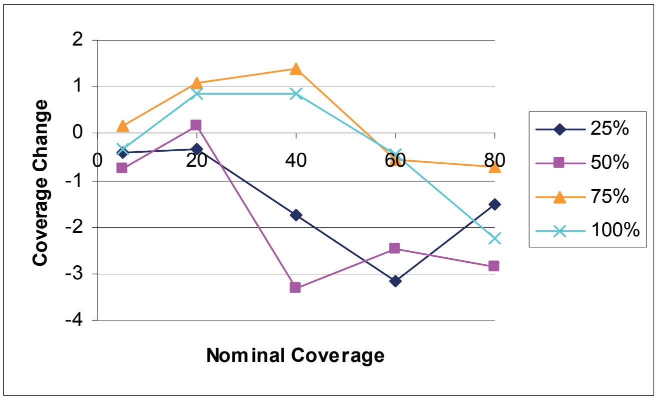

Figure 2: Coverage change with the addition of under print for 5.49 cm^3/m^2 anilox, 175 lpi, and 3thou patches

The change in density, coverage and circularity could be due to surface energy differences between the substrate and printed ink however when measured using a FibroDat 1100 contact angle tester the surface energies were found to be similar (BOPP film 18.4 Dynes/cm, White ink 16.2 Dynes/cm).

It would also be expected that if a chemical interaction between previously printed ink and over printed ink is affecting ink transfer the change would be progressively larger with increasing under print coverage. The coverage and density changes are therefore due to physical mechanisms induced by the surface texture change. Where the under printed ink is a halftone the texture of the previously printed surface acts as a physical barrier to ink spreading, figure 3, reducing the coverage and also the density. The effect will be greater for dots with larger perimeter and therefore higher coverages are affected to a larger degree.

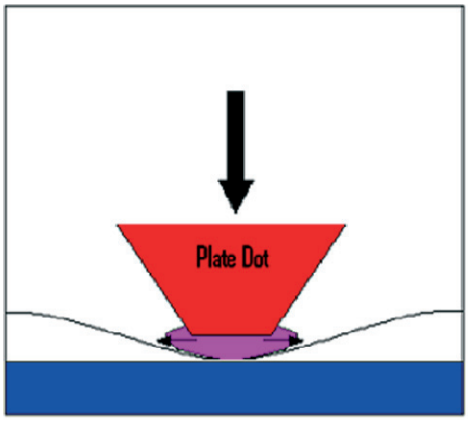

Figure 3: Schematic of ink spreading limitation by previously printed ink

If the ink coverage increase was caused by ink dot spreading on the roughness of the 100% under print it would be expected that there would be a decrease in circularity, there was however an increase in circularity at all over print coverages for the 100% under print samples. The dots therefore are not spreading on the roughness of the under print. Instead it is the thickness of the under printed ink effectively increasing the engagement between plate and substrate, this brings about the increase in both coverage and dot circularity.

As the coverage is in fact increased by the addition of under print the decrease in density at low coverage (1-20%) must not be due to spreading limitation by the roughness of the under printed ink. The roughness of the under print ink is the cause of the density decrease however it is the reduction in film thickness this causes that actually reduces the measured density. Above 20% coverage the larger volume dots are able to cover the peaks of the roughness and therefore the density of these samples is not affected.

The changes in both density and coverage caused by the under printed ink are relatively small when compared to the changes that can be made by altering other parameters such as impression pressure and anilox volume. The changes are however visible to the human eye, especially in the highlight areas, as indicated by the ΔE colour difference, figure 4. These colour differences have been found for a single colour and the effect could be multiplied for each additional colour.

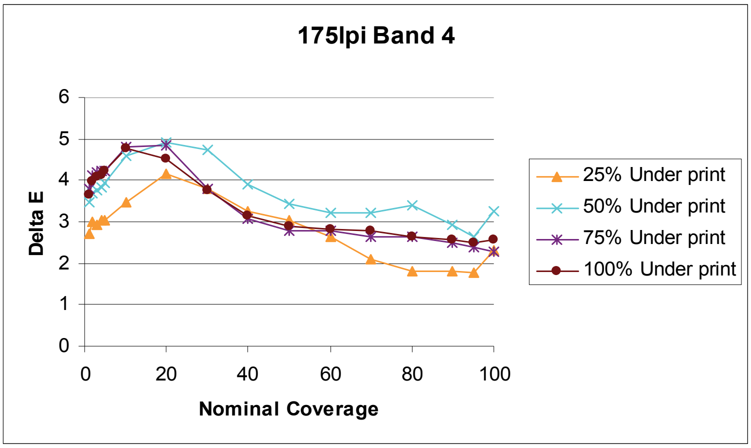

Figure 4: 175 lpi, Band 4, 3thou bottom patches, ΔE for different levels of under print

5. Conclusions

The effect of previously printed ink on transfer of the next ink layer has been investigated at full press scale by printing two layers of UV curing ink onto BOPP film. A full tonal range of magenta ink was printed on to a white ink at 60, 90 and 100% coverage this colour selection allowed the use of spectophotometry and image analysis measurements to characterize changes in ink transfer.

Changes in ink transfer were found to be due to physical interaction between ink layers and different trends were observed dependent upon the coverage of both ink layers. Previously printed halftones act as a barrier to ink spreading, this has a greater effect on dots with larger perimeters and therefore affects higher coverages to a greater degree. When printing onto a solid ink area the ink is spread further by the increased impression. When combined with increased surface roughness there is a reduction in print density for highlight areas.

The changes in ink transfer observed are small compared to those of other process parameters but would be visible and could be expected to multiply with additional ink layers. Improvements in flexographic printing have been made through understanding of ink transfer mechanisms and improved materials and the aim of kiss contact printing. This work has shown that ultimate flexographic print quality will also require consideration of the coverage of previous ink layers for colour separation during plate making.

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Media development and the consumer

Agile development of a new tablet newspaper concept and a heuristic evaluation model for tablets

Helene Juhola[1], *Harri Heikkilä*[2], *Merja Helle*[2], *Kennet Härmälä*[2]

[1] Finnmedia
Lönnrotinkatu 11 A, PL291, FIN-00121, Helsinki, Finland
E-mail: helene.juhola@vkl.fi

[2] Aalto University, School of Arts, Design and Architecture
Hämeentie 136 C, FIN-00560 Helsinki, Finland
E-mails: name.surname@aalto.fi

Abstract

Rapid and efficient development of digital media concepts that fullfil user needs and preferences requires new ways of organizing the development in the publishing houses and new methods for evaluation and testing user experience.

This paper describes an agile development of a new type of a tablet newspaper concept (HBL+) together with an Aalto University research group and a Finnish media company KSF media 2010-2013. The daily newspaper Hufvudstadsbladet developed first a tablet version for a Windows tablet in 2010 and discarded if after user tests, then in 2011 a pdf-version and a iPad version of the printed newspaper. At the end of 2012 it published a completely new concept: weekly HBL+ which contains also material from several other Swedish-language newspapers in Finland. All the stories are edited and designed for the tablet by two full-time journalists.

The development of the tablet product and the testing in different phases was an iterative and incremental process and *applied the logic of agile product development. Several different sets of tests and heuristic analyses were conducted* during the development. A model for new heuristic evaluation tool specially designed for tablet publications was developed.

Keywords: agile development, digital newspapers, tablet publication, heuristic evaluation

1. Introduction

The purpose of the developmental research project between Aalto University's Media Concepts Research Group and the daily newspaper Hufvudstadsbladet was to develop a new and innovative tablet newspaper concept. The starting point of the project was to improve the service for the readers of the Swedish language newspaper in the Åland Islands. The printed newspaper was delivered to the mailboxes only in the afternoon on weekdays and the Sunday issue on Mondays. Another objective was to test and create a method for agile product development in the digital publishing context consisting of iterative processes, so that based on heuristic evaluation and user experience tests of the tablet, software, visuality and content were developed further.

We utilized the principles of agile product development (Doz & Kosonen, 2008; Larman, 2004). According to the Manifesto for Agile Software Development (Beck et al. 2001) the focus in software development should be on:

1. Individuals and interactions over processes and tools
2. Working software over comprehensive documentation
3. Customer collaboration over contract negotiation
4. Responding to change over following a plan

Innovation and design of new digital products is approached in this paper from the background theories of Social Studies of Technology (Bijker, Hughes, & Pinch, 2012), Actor Network Theory (Latour, 2005) User-centered Design (Beyer & Holtzblatt, 1997; Hyysalo, 2010) and innovation research (Henderson & Clark 1990; Teece & Pisano 1997; Tushman & Anderson 1997; O'Reilly & Tushman 2004). Media use and adaption of new technology depends on how the new products fit the daily media practices, what needs they can fulfill and the cultural contexts and media economics (Grönroos, 2010; Perez, 2002; Verganti, 2009). We employed several qualitative methods like media diaries, ethnographic observation, focus groups and semi-structured, videotaped usability tests, interviews as well as questionnaires and laboratory tests.

We present the process of development during 2010-2013 focusing mostly on the usability of the tablet, content and navigation. In the second part we describe the development of a new heuristic model for evaluation of tablet devices and the media content.

Several different sets of tests and heuristic analyses were conducted during the development. We found out that the heuristic evaluation models developed for printed media products were not adequate as they did not address issues specific to small screens and touch screen usage. Nielsen's (1994) heuristic rules are a solid resource when evaluating the device, operating system or the programs, but they are difficult to utilize with evaluation e.g. of media content and its presentation. However, it is important to realize that the technical or visual details are not the most important factors for the success of technological innovations. Our research also shows how the cultural context had a great influence in explaining the use of Hufvudstadsbladet's (HBL) print and tablet versions.

Finland has two official languages, Finnish and Swedish, but the Swedish speaking population is less than 10% of the citizenship. For the HBL readers it was very important to know what happened in the Swedish-Finnish communities and HBL was the best product for that information. Many of the respondents also emphasized that they wanted to pass their cultural heritage to their children by subscribing and reading HBL.

Another important issue relates to the everyday media practices. The HBL tablet content was available early in the morning without the need to walk to the post box or shovel snow to get there - one could just grab the tablet and read the news in the comfort of a warm bed.

The development of the tablet versions of the Swedish language Hufvudstadsbladet, published by KSF Media, started from the initial planning of the first version of tablet newspaper in 2010 and resulted in the public launch of HBL+ concept in November 2012. After that there have already been several iterations of the design of the content. The first version of the tablet paper was running on Windows 7 tablet called Hanvon with HBL Newsreader software. The first set of user tests were conducted spring 2011 and we utilized a wide range of research methods with 25 families. After this first round of user experience the publisher decided to ditch the Windows version and the Hanvon tablet. They released a pdf version of the printed paper for the web and an app for iPad summer 2011 and started to develop a new HTML5 based tablet paper that differed strongly from the earlier concept.

After several development cycles the new concept of a weekly newsmagazine HBL+ for the iPad was released in November 2012. It was a weekly news magazine based on the articles published in HBL and other Swedish language newspapers published by KSF media. It was targeted at younger non-print readers and persons who had given up reading daily printed newspaper. Heuristic evaluation was conducted by researchers from the beginning fall 2010, and the second and third sets of user tests were conducted in the winter of 2011/2012 and fall 2012. Spring 2013 a questionnaire was used to evaluate how the tablet readers reacted to the new redesign based on heuristic evaluations. Fall 2013 another set of user tests will be conducted as some interactive features have been added to HBL+.

In the next chapter we present the methods and results of our user tests with the different versions of the HBL tablet product 2010-2013. In chapter three we introduce the new heuristic evaluation model developed in this project and how it evolved during the user experience tests. In chapter four we conclude with the evaluation of the results, development process and how it could be improved.

The research project was funded by the Finnish Technology Fund (TEKES) as part of the Next Media project 2010-2013. The Finnish Next Media research program (2010-2013) is supporting the industry in transforming the media business to digital platforms. It is aiming at innovations for new business models, media concepts and technologies providing completely new types of media experience (Juhola, 2012) and developing co-operation between media companies, universities and research institutes.

2. Methods and results

2.1. Testing the Windows tablet in the Åland Islands spring 2011

The first user tests for HBL with the Windows based Hanvon tablet and the Newsreader product were conducted in the Åland Islands spring 2011. Fall 2010 only Windows based color tablets were available for testing with an automated feed from the newspaper's editorial system. The main reason for choosing Åland

Islands was that the postal home delivery fee was higher than the yearly subscription. Also with the tablet the readers would have the content ready on their tablets early morning. The printed newspaper arrived into the post box early afternoon and the Sunday newspaper was delivered Monday afternoon.

We used several methods in our research. Initially 41 adult members of 25 families answered a questionnaire about their media use and media habits. All 25 families were asked to keep a media diary for one month about their use of the tablet HBL and printed HBL. After the first week of the trial, all families answered a short e-mail questionnaire about the initial experiences of using the tablet paper. At the end of the test period members of the 25 families answered an online questionnaire about their use of the tablet paper. Finally the families were also gathered into three focus group interviews in Mariehamn, the capital of the Åland Islands.

Figure 1: Screenshot of the HBL Newsreader application on the Hanvon tablet

Within this group of 25 families, four families were chosen for interviews and observation. Nine people from the four families, participated in an interview about media use. Media use in these families was also observed during one morning in April. The four families were also interviewed about the tablet paper at the end of the trial period. In addition, they took pictures of situations and places where the tablet was used.

The Newsreader tablet version included all the content of the printed newspaper. The navigation was available on the first page where the paper was divided into three main sections of News, Sports and middle, which, however, did not work properly and so people had to scroll one story after another. This created a lot of complaints about poor navigation and the impossibility to differentiate between big and small events, which is the strength of a traditional printed newspaper layout.

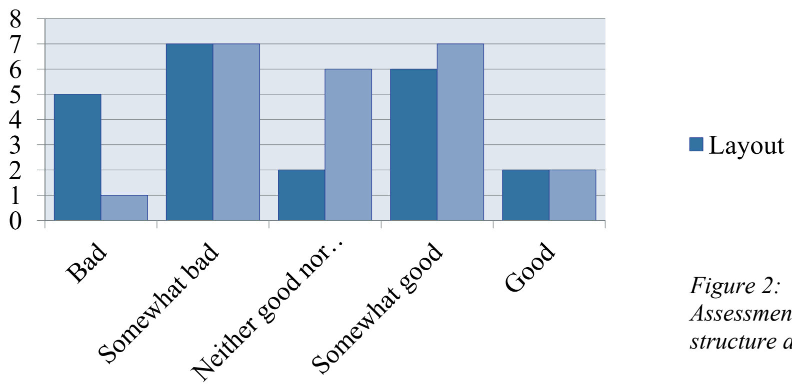

Figure 2: Assessment of HBL Newsreader's layout, structure and navigation among participants

The first set of tests revealed that the tablet was considered clumsy and technologically unreliable, but the possibility of getting the content automatically into the tablet for early in the morning outweighed the perceived problems.

The layout and navigation of the tablet newspaper were criticized - especially the impossibility to get an overview of the news and their relative importance. Local events and the Fukushima power plant accident were the same size in the tablet. In spite of these facts 42% of the test users would have been willing to substitute the printed paper with the tablet version.

After the first round of user tests HBL decided not continue with the Hanvon tablet and the Newsreader concept. The first iPads became available in Finland late 2010 and summer 2011 HBL released a pdf-version of the newspaper for the web and also print replica version packaged as an iOS application for the iPad.

2.2. User tests and heuristic evaluation of the new HBL+ concept in 2011-13

User test findings of the first trial encouraged the development team at HBL to come up with a new innovative concept of HTML5 based tablet paper HBL+, a weekly newsmagazines compiled from stories of the daily newspaper HBL and other Swedish-speaking regional newspapers published by KFS media. The stories were chosen by the newsroom and redesigned for iPad. The product had a clear thematic structure and navigation as well as strong visual emphasis.

A demo version of HBL+ was completed in December 2011 and the user tests were completed next January. Ten university students and ten former subscribers of Hufvudstadsbladet participated. Before the interview, each test subject completed a questionnaire about their media habits. After this, the participants used freely the demo version of HBL+ and a semi-structured interview was conducted about the user experience. An interview lasted typically about 40 minutes. After the interview the participants filled a questionnaire evaluating the software's visuality and usability.

Most participants quite quickly expressed that they liked how the software looked. Some pointed out how similar HBL+ felt to the print version of Hufvudstadsbladet, and this was perceived as a positive feature. The look of photographs in the application were especially praised. The participants liked the vertical article view better than the horizontal view and many participants found switching between horizontal and vertical navigation confusing at first. All except for one of the test participants said they would like a simple function that would take them back to the cover page or table of contents.

The content in this version was divided into three separate parts, which could also be purchased separately. The three categories of Lifestyle, Culture and Society proved problematic, as only one of the participants wanted to subscribe to the lifestyle section. A reasonable price for a monthly subscription of HBL+, on average as said to be 12 € for the entire newsmagazine and 7 € for one content category. Fifteen of the participants said they could imagine subscribing to HBL+ at some point in the future.

On the basis of the results from the user tests, Hufvudstadsbladet decided to fund the further development of the HBL+ application in 2012. The product was redesigned in accordance with the feedback from the user tests and heuristic evaluations. HBL+ was still to be an html5-based weekly magazine for iPad; however, the idea of three separate sections was abandoned. HBL+ was still going to include articles from not only Hufvudstadsbladet, but also other regional Swedish-speaking newspapers.

The second set of HBL+ user tests were conducted in October 2012, again at our eReading lab. Ten current and former subscribers of HBL+ participated in the test. The test design was similar to the first set of HBL+ user tests. However, the media use questionnaire the evaluation questionnaire at the end of the user test had some additional items based on the changes in design. During the interview itself, the test participants were asked to first use the HBL+ application on their own for 10 minutes before the interview began.

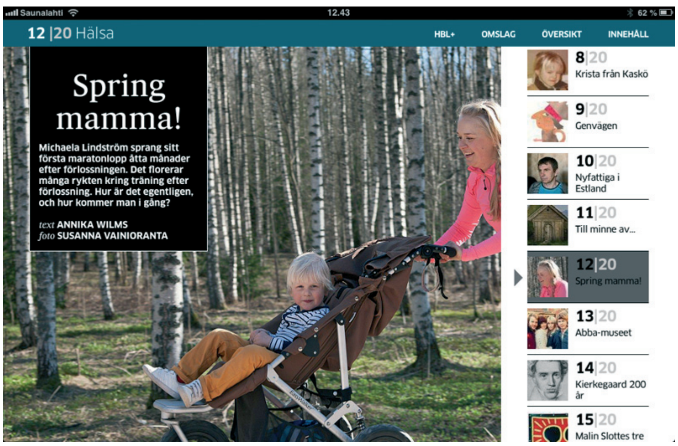

Figure 3: Example of navigation in the HBL+ version 2013

The participants liked the visuality of the HBL+. The feedback about navigation was clearly more positive than before. The two pop-up overlays with the magazine content were widely appreciated and utilized. The scrollbar at the bottom of the screen was generally more liked than disliked. Seven out of the ten test participants said they could imagine subscribing to the magazine sometime in the future. When asked about a reasonable price for HBL+ the respondents again answered 12 € on average for a monthly subscription and 2,50 € for a single issue.

The new HBL+ was released for finally in November 2012 as a HTML5 based downloadable web application for iPad.

2.3. HBL+ user experience survey 2013

An electronic survey was conducted among the readers of HBL+ in April and May 2013. 104 readers participated in the survey, which dealt with both the usability and content of HBL+. The actual readers of HBL+ were not the intended target audience. First, the average age among the respondents was 57 years, with the oldest reader being over 90 years old. Secondly, almost all of the respondents were readers of the printed Hufvudstadsbladet who got to read HBL+ for free. Only two of the respondents had paid to read HBL+ specifically. This was in stark contrast to the intended target audience, which was young adults who did not want to subscribe to the paper edition of Hufvudstadsbladet. This result is likely due to the fact that marketing of the tablet HBL+ had been done almost only in the printed newspapers.

The respondents were pleased with both the content and usability of HBL+. None of the issues about bad navigation, which were raised during the user tests earlier, were mentioned by the respondents and the readers seemed to navigate the newspaper without any problems. Some of the items in the questionnaire were designed to address issues raised after the heuristic evaluation conducted spring 2013. The readers were, for example, asked to rate the different navigation options in the navigation bar.

3. Development of new tablet publication heuristic evaluation tool in the HBL-project

The first heuristic evaluation of the Hufvustadsbladet's (HBL) tablet design project was conducted by Aalto Arts in February 2011using the classic Nielsen heuristics. The "Nielsen usability heuristics" were originally developed 1990 and revised in 1994 after factor analysis of 249 usability problems (Nielsen 1994). Nielsen's "10 principles" is a general list, like heuristics tend to be, and offers broad categories like "user control and freedom" and "aesthetic and minimalistic design". Our choice was Nielsen since it is the most used evaluation method.

For the HBL-case the standard Nielsen evaluation was further developed by dividing problems into different categories according to the origin of the problem to make report more usable and to facilitate distribution of work when fixing the problems. The device, the operating system (OS), the reader software and the publication itself were assessed separately.

Usability problems
related to publication

PROBLEM	COMMENT	Broken heuristic	Severity
Too much space between chapters	If chapters are not indented, space is required but never a full chapter space	8	cosmetic
Return to home page is not clear		1,7,2, 11	major
Not possible to enlarge pictures easily		6	minor
Just one column in a wide screen device is not optimal		1,8	major
Generally very basic, even unimpressive typography	Typography lacks contrast of size and form.	1, 8	major
Mediocre quality of pictures		8	cosmetic
All pictures almost same size, generally too small size		1, 8	minor
Too little inner marginal in several text boxes on home screen		8	cosmetic
Lay-out lacks variation and emotion.	Feeling of quality absent	8	major

Twelve interface heuristics used in the evaluation. 1. Match system-real world (familiar words, intuitive layout)
2. Consistent interface/follows interface standards (words, objects, operations, behaviors) 3. Visible system status (provides constant feedback)
4. Error prevention 5. Error recovery (clear messages) 6. User control (provide exits/undos)
7. Visual clues for user action 8. Aesthetics/minimalistic design (relevant info, aligned, consistent placement)
9. Recognition over using memory (don't have to remember info) 10. Makes the user smart (reduce need for memory, calculating, relating)
11. Flexibility/efficiency of use (novice/expert use, tailoring) 12. Help/documentation (task focused, not too large, easy to search)

Figure 4:
A section of the Nielsen report for HBL describing problems Hanvon version

The heavy weight, clumsiness and lack of home button as well as non-functional dimensions were considered as major and severe device problems. Confusing start-up, instability and lack of help and error messages and empty dialog boxes were criticized at the OS-level. Unresponsive interface and inconsistent forward/backward - navigation were considered major problems in the reader-software. Finally, there were lots of quite obvious problems in navigation and in hierarchy, from "layout lacking variation and emotion", "typography lacks contrast of size and form" "return to home page is not clear" to more lay-out oriented issues like "too much space between chapters", "just one column of text in a wide screen device is not optimal". We found out that Nielsen's heuristic rules fit quite well when evaluating the device, operating systems or programs, but they are difficult to utilize with evaluation of media content and its presentation.

3.1. Shortcomings of commonly used heuristics in tablet publications

In addition to Nielsen, other well known heuristics include Norman's (1988) "7 principles" Shneiderman's "8 golden rules" (Shneiderman and Plaisant, 2005), Tognazzini's (2003) "First principles of user interface design". They basically redefine and reorder the same principles, as is also the case with other less known heuristics from Brown (1999), Aaron (1992), Johnson (2008) and Stone (2005). Most common heuristic rules are "strive for consistency", "need for feedback" and "visibility of system status" and "reversibility".

All current heuristics give quite scant guidance for necessities like navigation, affordances, perceivability and readability even though these variables can be seen as quite obvious building blocks of accessibility, usability and user-experience (UX). And this is true also in software and webpages. But in digital magazine/newspaper design they can be considered crucial. Our tests with HBL showed that Nielsen and other heuristic evaluation schemes perform very well when assessing the hardware and traditional software (OS and the reader), but fall short with the publication-part.

From the viewpoint of tablet magazines and publications in general another problem in the traditional heuristics originates from their background in software engineering and in WIMP (windows, icons, mouse and pointing device) approach. Tablets (defined here as touch screen devices with over 6" display) build on a fundamentally different paradigm than WIMP-computers. In iOS and Android world, there is no mouse, nor cursor, no hovering or tool tips in the interface, no multi-windowing and very restricted file management.

Files are integrated and accessed with programs. This already requires a different approach from traditional heuristics. For example, the places where the reader is supposed to touch the screen should stand out clearly, since there is no hinting.

Thus we concluded that there really is a need for a new kind of heuristics. On one hand it covers the platform change from WIMP devices to touch-screens, and on the other emphasizes issues like navigation, readability and hierarchy, which are important from the user point of view. For example, loosing ones place when browsing a digital book or magazine is quite common and greatly affects the attitude towards the product (Heikkilä 2011).

In the future, there is even a more important place for a new kind of heuristics in digital books, newspapers and magazines. This is because the users from the print tradition confront the digital version with an expectation that it works like its Gutenbergian equivalent and on the other hand because the publishers are confronted with the world of added interactivity in digital publishing.

3.2. Constructing the new heuristic evaluation tool

The new tablet heuristic evaluation tool developed in this project was done by combining relevant parts of older heuristics with new categories relevant for touch screen devices. We started by comparing existing heuristics to find out common categories and to categorize what is missing. It was challenging to make exact comparisons, because same variables were often present in several categories and were expressed in different terms.

The main problem in the research project was how to create content for tablets, which would appeal to the readers. We studied research articles, conference papers and attended seminars on digital publishing. We also made a study of newspaper websites and tablet products to find what kind of interactive features were used (Heikkilä, 2012). We filtered expert recommendations from various articles, and used experiences from our usability experiments within the Finnish Next Media project 2010 - 2013. The new heuristic model has gone through several iterations and has been tested also with products from WSOY, Bonnier, OtavaMedia, Sanoma Magazines and University of Helsinki.

In order to make the heuristics more comprehensible, we divided the model into three categories: accessibility, usability and user experience. Accessibility is understood in this paper as the very basics of usability - not as rigorous accessibility standards like alternative texts for images meant for special groups. The accessibility category in this new heuristics model covers all "entry level" things that make accessing the content possible within the publication. Usability is about how easily and effectively the publication can be utilized, and how pleasant it is to use.

Table 1: Comparison of variables in the most used heuristics. Only Tognazzini (2003) mentions readability

Author/ Category	Visibility of ys.status	User control	Consistency	Guidance	Efficiency	Feedback	Mapping/Navigation	Memory	Simplicity	Aesthetics	User language	Percievability	Affordances	Readability	Reversability
Nielsen	x	x	x	x	x	x		x	x	x	x				x
Norman	x		x			x	x								x
Stone	x					x			x				x		
Johnson			x								x				
Tognazzini	x		x		x		x					x		x	
Schneiderman		x	x			x		x							x

Table 2: Categorization and hierarchy of the rules in the new heuristic model

CATEGORY					
ACCESSABILITY (A)	Legibility and Readability AI	Guidance A2			
USABILITY (U)	Touch screen ergonomics U1	Perceivability U2 • *Visibility* • *Affordances* • *Natural mapping*	Orientation U3 • *Sense of place* • *Sense of directions* • *Memory load*	Consistency U4	Responsiveness U5
USER EXPERIENCE (X)	Flow X1	Interestingness, playfulness, arousal X2	Mood and brand X3	Interactivity X4 • *Interface* • *Social* • *Adaptive* • *Creative*	

In order to make the new model easier to use in practice these heuristics are constructed with rules or claims (roman-text) and questions (in italics) as well as "what-to-look-for" questions that define the rules better and make them easier to implement. The method is explained in detail in the report "Towards tablet publication heuristics" (Heikkilä 2013).

In addition the method also introduces new way of reporting. It is a commonly known problem in usability reporting that often the reports tend to be not very agile.

The chunky reports are time consuming to compose, and they are often just forgotten on the shelves and do not lead to the practical improvement of the products. In order solve this problem more light weighted models have been presented, by for example by Krug (2006).

In order to emphasize the agility, a method was created where reporting consists just of a self-contained visual presentation and a list of the problems found. The list can be used as a reference when following the presentation of an evaluation or as a to-do-list when making corrections. Self-contained model means here that the report has the necessary explanations and visuality to be presented also without a researcher or consultant.

HBL+ ASSESSMENT WITH TABLET HEURISTICS

AFFECTED HEURISTICS	EXPLANATION/SUGGESTION	SEV.	PICTURE
FLOW (X1) "Keep it simple" ORIENTATION (U3) Sense of direction	*Is it necessary to have two overlapping navigations? "Innehåll (content)" and "översikt (overview)" have redundant function in navigation bar. Maybe "Översikt" with would be enough?*	2	
FLOW (X1) "Keep it simple" ORIENTATION (U3) Sense of direction	*In navigation bar, there is link "omslag" (cover). It is this necessary, since cover can be reached from "översikt".*	2	
PERCIEVABILITY U2 "use natural language"	*In navigation bar, there is link "HBL+" which leads to archive. It is not evident what thise means without testing, why can't we say "arkiv" (Archive) or home or main view?*	2	
FLOW (X1) "Keep it simple"	*Black download-window is redudant and gloomy. This window could be combined to archive view where differnet weekly numbers could be a bit smaller and preview of downloadable number larger with progress bar and more*	2	

Figure 5: Segment of the minimalistic style of reporting. The report consists of a list of problems, with affected heuristics (first column), explanation of the problem and the suggestion (second column) and assessment of the severity (third column) and a picture of the incident

The new HTML5 concept of HBL+ was developed fall 2011 and spring 2012. During the development phase we visited HBL regularly to give feedback of different iterations and details like how the navigational icons should look like. Collaboration resulted in changes both in the design of the tablet publication and in developing the new heuristic tool. For example, proprietary icons that were designed by the HBL+ team for accessing content were dropped, because users first need to learn what their functions are. Heuristics evaluation recommended that icons should be self explanatory and existing design models should be preferred in order to create clear understanding of the meaning of each icon.

Major findings in the evaluations were combined into three major recommendations:

1. Constructing a more logical and simple navigation bar would enhance the user experience.
   - Two important navigational components "Innehåll (content)" and "översikt (overview)" have redundant functions and are placed near each other in the navigation bar. Removing the other would simplify the navigation bar.
   - There is also link "HBL+" but it is not evident that this leads to the archive. Placing it in the top left corner, where the "home"-buttons are usually located, would help, as well as naming it according to its function: archive or main view.
   - In navigation bar, there is link "omslag" (cover). This is unnecessary, since cover can be reached from "översikt". There should be navigation available in cover page.

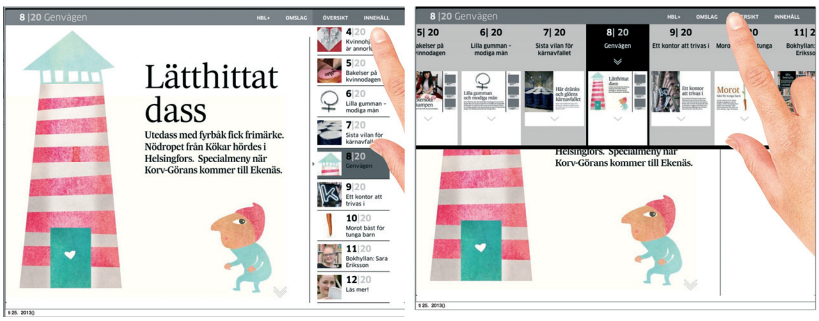

Figure 6: Heuristics guide for "simple and clean" design HBL+ navigation bar has many redundant and unnecessary options

2. Navigation needs to be improved elsewhere also
   - Changing font-size requires scrolling to the beginning of the body text. / Font-size adjustment should be placed somewhere it is always available. Hints for navigation are missing, navigation is not working as expected, for example some arrows can be tapped, some can't.
   - Clickable elements are unclear.
   - No indication of article length. This is especially a problem in long articles. Use scrollbar to show progress in the right edge of the screen.

3. UX would benefit from more coherent door views (the archive view, the view before entering the publication)
   - Interactive parts of door view have no similarity in appearance. Hierarchy is missing.

Figure 7: In perceivability (U2) heuristics advise us that "if something is clickable, make it look like it"

And "if something is not clickable, do not make it look like it is". HBL+ uses the plus symbol as a decorative element, it is not interactive, yet it looks like it.

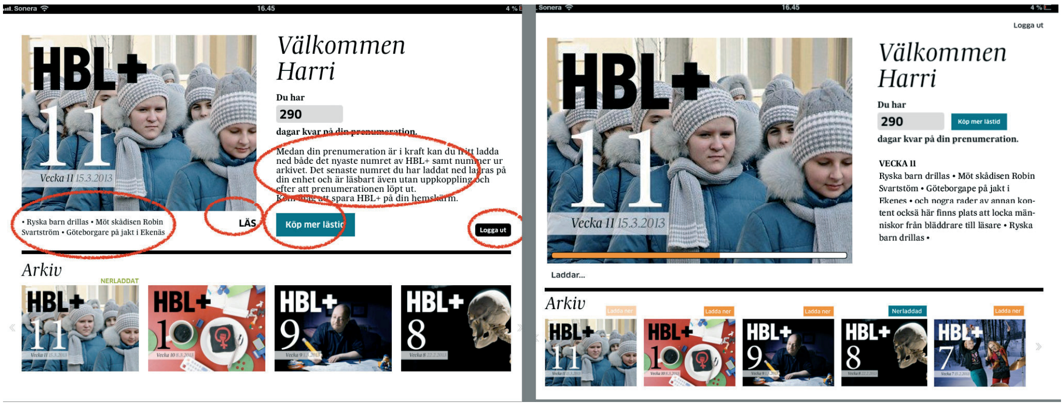

Figure 8: In the door view heuristics emphasize that "visual cues should be consistent with each other" and "information should appear in a natural and logical order" and that Gestalt laws from gestalt psychology should be respected. On the right hand side there is a suggestion derived from those principles

Some of the findings and our recommendations were included into the next reader survey to test them with the users. Results supported the heuristic evaluation and our recommendations: The Omslag cover link in the navigation bar, which we suggested to be removed as an unnecessary, was rarely used by the readers.

The survey results also indicated that the "innehåll" (content) label was favored over the "översikt" (overview) and that navigation should be available already in the cover view - as suggested by the heuristic evaluation.

Since the navigational issues were quite difficult to explain to the respondents, even with using pictures in the questionnaire (we had pictures of menu bar and navigation for example), we have decided to do additional interviews before final suggestions about navigation and door view issues for the next developmental phase.

4. Discussion and conclusions

Even though the principles for agile software development are not at all new, few Finnish media companies have utilized them in trying to track the reader responses throughout the developmental process. The HBL Newsreader and HBL+ research processes have highlighted the possibility and importance of a swift and agile research approach for the development of digital media products. Due to the fast pace in which the media landscape and technology change research results are needed quickly to meet the demands of the development. It is also important to embrace a flexible approach to study media products and their design, as rapidly changing situations may demand quite different designs than initially planned.

HBL+ case shows the results of the fundamental important principle of agile development: test and try out, and learn and try again with the real users with real products. However, designing a new media product and testing it with users is not enough, as it also has to be produced in the atmosphere of declining revenues for traditional media companies and diminishing resources in their editorial offices and technology departments. The new HBL+ weekly news magazine concept is presently produced by two full-time journalists, but they have said they would need more help and ideas from the print journalists. We have also followed changes in the work practices at HBL with the tablet content production since 2011. We will continue to study it until the end of 2013 and also make some recommendations for the editorial management. Previous research has shown how difficult it is for print journalists to embrace web journalism. It seems often to threaten their identity as journalists (Domingo, 2008; Helle, 2010; Singer, et al., 2011).

Even though we focused in this paper mainly on the design of the tablet content and its details no single factor determines the success of a media product: even with a clumsy device and lacking visuality and navigation the convenience of having the content first thing every morning can outweigh the negative features.

For usability evaluation there is clear need for new kinds of heuristic evaluation guidelines as publishers and designers are confronted with new publishing platforms and their demands, and because the touch screen media products are novel to many producers and users. There is an important need for new evaluation guidelines also for digital newspapers, books and magazines, because users from print tradition first expect that they work like the printed products. For example, loosing one's place when browsing a digital book or magazine is quite common, and it greatly affects the feeling towards the product.

HBL+ project illustrated also the need to re-think what kinds of media concepts new publishing platforms like tablets can lead to. There is no need to stick to the content or form of a traditional printed newspaper, or to only the content of one media title. The weekly interval for news can be enough (combined with web and mobile content services) for the hectic work life timetables, and therefore there is also a need for content that is evaluated, summarized and arranged into an easily navigable structure by trusted media professionals.

Agile manifesto (2001) emphasizes the close and daily cooperation between the business people and development, this is also true between research partners and media companies. In fact, in order to succeed, the whole organization should embrace the principles of agile development, so that there is a favorable attitude towards constant feedback from users and the preparedness to act quickly, so that the findings will be effectively implemented and re-designed without too much delay.

Small companies might be more agile in their development of new products, but on the other hand they are often constrained with smaller financial resources and lacking internal competencies. This was also evident in our project with the HBL, but this did not stop them from creating and producing a new and innovative concept for tablet publishing, and which was tailored according to their production resources. The project also showed how university research, which is often criticized for being too theoretical and slow, can adapt to more agile research methods, and produce results which benefit both academic knowledge and publishing as well as the media field and media companies.

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EPUB 3 on current e-readers - drawbacks and opportunities

Christin Götz and Ulrich Nikolaus

HTWK Leipzig University of Applied Sciences
Gustav-Freytag-Straße 42, D-04277 Leipzig, Germany
E-mail: nikolaus@fbm.htwk-leipzig.de

Abstract

In recent years the International Digital Publishing Forum's ePUB format has become one of the major data formats for the production of electronic books (e-books). With the publication of its most recent version, ePUB 3, several new features have been added to the standard, which now allow for the inclusion of multimedia objects (audio, video), additional interactive elements (media control buttons, drag-and-drop functionality etc.), and of reading system-specific layout (CSS 3 media queries). In theory, these new features could be the key to present an enhanced viewing experience that cannot be achieved with printed books in a comparable way. However, ePUB 3 being a markup language based format (relying heavily on HTML 5 for content description), its success depends on whether the corresponding e-book reading systems (from here on referred to as e-readers) are able to interpret the markup code in the intended way. In this paper, we present the results of a study analyzing the ePUB 3 support (and especially the support of the new multimedia features) in current e-reading technology. The results suggest that many of these innovative functions are not fully implemented yet, and that for some features, diverging implementations exist - leading to incompatibilities in e-book-production.

Keywords: e-book, e-reader, ePUB, electronic publishing

1 Introduction

The emergence of electronic publishing has considerably changed the publishing industry. Publications no longer appear only as paper book versions such as hardcover and pocket editions, special editions or limited book editions. Since e-readers, tablet computers and other reading devices become more popular, more and more titles also appear in electronic form.

At present, e-books are produced in different formats such as the Amazon Whispernet Format (AZW), the Mobipocket Format, the Microsoft Literature Format (LIT), the Portable Document Format (PDF), and the Electronic Publication Format (ePUB). Although there is no uniform e-book standard in the e-book market today, the International Digital Publishing Forum's ePUB format is becoming increasingly popular (Börsenverein, 2012; Oldendorf & Patzig, 2011).

According to the International Digital Publishing Forum (IDPF), ePUB was developed as a general-purpose document format for the production and representation of publications in a reflowable digital form, e. g. magazines and newspapers, journals, office documents, books and so on (Garrish, 2011; IDPF, 2011a). ePUB was standardized in September 2007, superseding the *Open eBook Publication Structure* (OEBPS), which was developed in 1999. In April 2010, just as the ePUB 2.0.1 maintenance update was approved, new reading devices such as the iPad brought significant changes to the media market and electronic publishing. As a reaction to this, ePUB 3 was presented in October 2011 - "*handling rich media, complex layouts, scripting, global language support, MathML, synchronizing text and audio, and a host of other new features*" (Kasdorf, 2011; Wang, 2011).

Technically, ePUB 3 is a non-proprietary standard for distributing digital publications in a single-file format. The standard defines not only a container for structured content, but describes also how reading systems display it to the reader. More specifically, ePUB 3 consists of a set of four specifications:

- *EPUB Publication 3.0*: This specification uses the eXtensible Markup Language (XML) to define publication-level semantics (metadata information) about the ePUB publication. It is used in the package document. The EPUB Publication 3.0 specification also defines conformance requirements for ePUB 3, including required content types, the format of the Package Document and rules for combining the package document and other publication resources to a valid ePUB publication (Garrish, 2011; IDPF, 2011b).

- *EPUB Content Documents 3.0*: This specification defines profiles needed for the representation of content in ePUB Publications - such as the eXtensible Hypertext Markup Language (XHTML) or the Hypertext Markup Language 5 (HTML 5), respectively (for the structured rendition of text), Scalable Vector Graphics 1.1 (SVG 1.1, for vector images) and Cascading Style Sheets Level 2 Revision 1 plus Level 3 (CSS 2.1 and CSS 3, for the description of presentation semantics). Furthermore, a format for in-document navigation and the table of contents (toc) is specified as well - the EPUB Navigation Document (Garrish, 2011; IDPF, 2011c).

- *EPUB Media Overlays 3.0*: This section of the specification is new compared to ePUB 2.0.1. IPDF defines it as a "*format and a processing model for synchronization of text and audio*" (IDPF, 2011a), based on the Synchronized Multimedia Integration Language (SMIL) (Garrish, 2011; IDPF, 2011d). For instance, this feature can be used for synchronized audio narrations or for accessibility purposes.

- *EPUB Open Container Format (OCF) 3.0*: This section defines a format to bundle all resources of an ePUB publication into a single-file zip-container; using *.epub as file extension (Garrish, 2011; IDPF, 2011a).

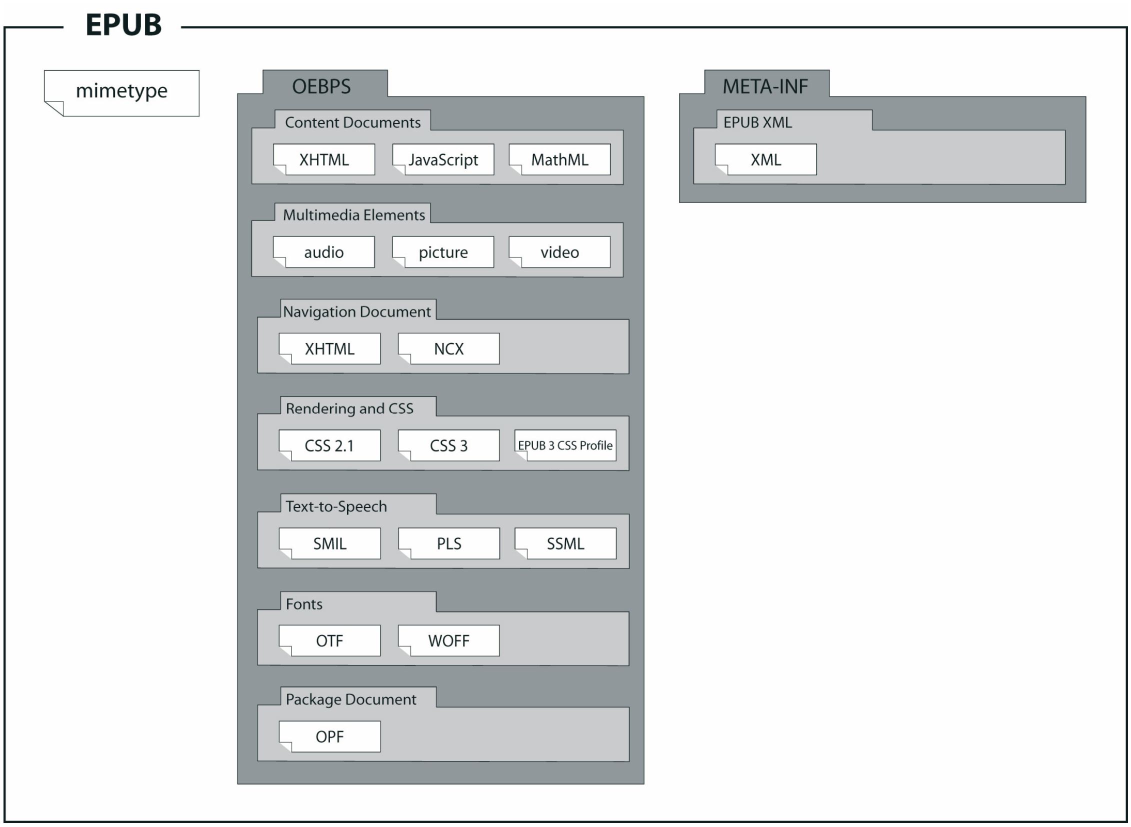

Figure 1: Basic structure of an ePUB 3 publication
(inspired by Matrisch, 2011; Völker, 2012)

All in all, an ePUB book is a zip-container with a special file and directory structure (cf. Figure 1). All resources of the e-book have to be collected within a directory named OPS or OEBPS. This directory has to be followed immediately by another directory named META-INF. This directory has to include the xml container file identifying the point of entry for this publication (i.e. the first file to be loaded while opening the e-book; usually named container.xml).

Optionally, META-INF may contain information on digital signatures (signatures.xml), on the encryption of the ePUB publication (encryption.xml) or on digital rights management (rights.xml). It may store additional meta-data (metadata.xml) and the file manifest.xml may give e-book readers additional information on the internal document structure. The root directory of the `*.epub` folder has to include another file named mimetype, used by reading systems to identify the zip container as an ePUB file (IDPF, 2011e).

2. Methods

As it can be seen in the previous section, the ePUB 3 standard relies heavily on XML based markup languages such as HTML 5, XHTML and XML. Hence, all of these files have to be parsed and rendered by the respective user agents while opening an e-book. The new features that ePUB 3 provides are, thus, only applicable in e-book production if the respective reading devices offer full support of the corresponding semantic elements. Unfortunately, this cannot always be taken for granted[1].

Hence, the objective of this publication is to explore, to which extent the new possibilities of the ePUB 3 standard are supported by current reading systems. In order to achieve this aim, a constructional approach was used: first, a sample e-book that implemented all of the new features of ePUB 3 was produced. This sample document was then validated using IDPF's EpubCheck tool to assure the conformance of the test book with the ePUB 3 specification (for a more detailed description cf. Götz, 2012). Because the ePUB 3 specification permits alternate renditions (also named "fallbacks") for optional features or in cases where a reading device does not (yet) fully support the standard, content may be included in different ways. Mathematical formulas, for instance, can be included in MathML format, as a vector graphic (in SVG format) and as a bitmap (in PNG format) to give e-readers a greater choice to find a compatible data type.

Next, the test document was tested on several e-book reading devices, currently available on the German market. As there are, in general, several ePUB reading applications available for most reading devices, two different e-reading programs (and wherever possible: one proprietary and one third-party application) were tested for each type of device (e-ink readers, tablets, smartphones and PCs) (cf. Table 1).

Table 1: Overview of e-reading devices and applications tested

	E-ink Readers		Smartphones		Tablets		PCs
Reading Device	Sony Reader PRS-T1	Kobo eReader Touch Ed.	Samsung Galaxy Note	Apple iPod Touch 4	Apple iPad 2	Acer Iconia Tab A200	Personal Computer
Operating System	Proprietary	Proprietary	Android	iOS	iOS	Android	Windows 7
Reading Application	Proprietary	Proprietary	eBookS Reader	iBooks	iBooks	Aldiko Book Reader	Infogrid Pacific Azardi and Google Chrome with Readium add-on

3. Results

In comparison to ePUB 2.0.1, ePUB 3 allows for the production of functionally enhanced and interactive e-books and lets e-book layouts resemble more closely to the design of a printed book. The new functionalities can be classified in four main categories - *interaction and multimedia*, *macro* and *micro typography* and *accessibility* (for a more detailed explanation of this categorization cf. Götz, 2012).

For each of these categories, a short overview of the new functions will now be given. Next, the results of the e-reader tests will be described. Last, an illustrative example will be given occasionally, and all results will be presented in tabular form.

Interaction and multimedia

Since HTML 5 is used for content description in ePUB 3, the new features this markup language brings to web design can also be used to produce functionally enhanced and interactive e-books. Among these new features are for instance, the `audio` and `video` elements (for the integration of audio and video files) (Castro, 2011), or `canvas` (for the creation of interactive media objects inside the electronic books; in combination with JavaScript, `canvas` can, for instance, be used to create Flash-like animations) (Garrish & Gylling, 2013). The elements `meter` or `progress` can be used to create scales for diagrams and progress bars for multimedia

[1] In (Nikolaus, 2010) for instance, it has been shown that accessibility functions included in the ePUB 2 standard were largely ignored by the corresponding reading devices (not one single e-book reader was able to render the whole sample document according to specification).

objects without having to use a scripting language. The element `epub:trigger` is used to create markup-based controls for multimedia objects (IDPF, 2011c; W3C, 2011). Furthermore, it is possible to include pop-up me-nus, picture galleries, or slideshows into an ePUB `3 e-book`, to include the HTML 5 drag-and-drop function-nality (W3C, 2011) and to synchronize word highlighting and text to speech audio output by using the ePUB `3 media overlay` function (Garrish & Gylling, 2013; IDPF, 2011d).

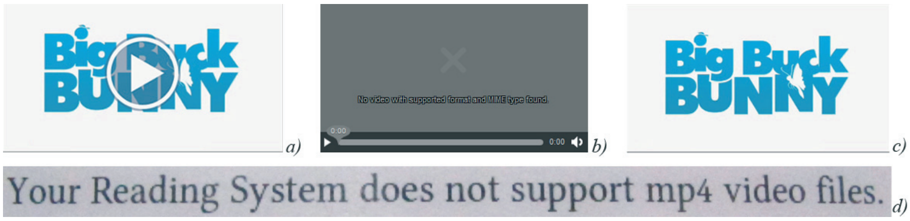

Figure 2: Support of video playback and fallbacks on different reading systems - a) video playback is fully supported for this file format (iBooks, iPad 2); b) video playback unsupported and no rendition of fallback image included in the ePUB 3 book, but a native error message of the reading system is displayed ("No video with supported format and MIME type found"; Azardi); c) video file format is not supported; no rendering of the integrated textual fallback, only the poster-image is displayed (iBooks, iPad); d) video file format is not supported, but the textual fallback included in the ePUB 3 e-book is reproduced correctly (Sony Reader PRS-T1)

All in all, interaction and multimedia support was best for PC-based e-reading applications and almost non-existent on e-ink readers. Audio and video playback was partially supported by Apple Smartphones and Tablets and the Azardi and Readium reader software on Windows 7 - but even there, only a small number of video and audio codecs were supported. In fact, the authors were not able to find one single audio video con-figuration that would allow a playback of the same e-book on all e-reading devices that supported any audio and video playback at all. To make bad matters worse, some reading devices did not even support the ePUB 3 fallback functionality (which is either supposed to display a text like "This reading system does not support …" or to render a static picture instead of a video player; cf. Figure 2).

Another feature of ePUB 3, the integration of additional information as pop-ups, was more or less supported by all tested reading systems, although only iPad, iPod Touch, and Readium had the ability to display a real pop-up window. The other devices included the pop-up information on additional pages at the end of the ac-tual e-book and inserted links to this position into the actual text. Since picture galleries were also imple-mented using the pop-up technology, the test of slideshows led to similar results.

All in all, the Google Chrome add-on Readium at present supports the most multimedia and interactive fea-tures of ePUB 3 (cf. Figure 3). This reading system is currently the only one which supports video playback of not only one, but of several file formats such as MP4, OGG or WebM, is able to synchronize text/audio out-put using the ePUB 3 `media overlay` function (although without visual text highlighting) and supports the elements `track, epub:trigger, details, meter` as well as the drag-and-drop function. The next best rea-ding system in this test category is the iBooks app on the various Apple devices. In comparison to Readium, iBooks has some weaknesses in displaying Media Overlays (which is only supported for e-books that have so-called fixed layouts optimized for one specific reading device; whereas ePUB 3, in principle, was designed to be a re-flowable format). At present, all other e-reading devices and applications in the test offer only a very limited support of ePUB 3 interaction and multimedia functionality. An overview of the test results are shown in Figure 3. For a more detailed test evaluation cf. Götz, 2012.

Macro and micro typography

The layout and the overall design of an ePUB 3 e-book can be controlled using the Cascading Style Sheet (CSS) language. According to the specification, ePUB 3 implements the complete CSS 2.1 standard and some modules of the CSS 3 standard. Additionally, IDPF defines own layout profiles to enhance the resemblance of e-book layouts to the design of printed books. New macro typography features and elements of ePUB 3 are: media queries (to tailor the e-book layout automatically to the pixel ratio and screen resolution of the various output devices; W3C, 2010), alternate style sheets (IDPF, 2011f), multi-column layouts (W3C, 2011), footnotes and sidebars (IDPF, 2011c, o. J.), header and footer (IDPF, 2011c) and support for various interna-tional wri-ting modes - e. g. left-to-right (Latin), right-to-left (Arabic), bidirectional (mixed Latin and Arabic) or verti-cal (Asian; W3C, 2012). Furthermore, it is now possible to indicate how to represent the first page of the EPUB Content Document of a two-page spread - on the left-hand or on the right-hand side (IDPF, 2011b) - and to use various HTML 5 elements to improve the document structure, such as `article` and `aside` (W3C, 2011).

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
Interaction and multimedia								
Audio	○	○	○	◐	◐	○	◐	◐
Video	○	○	○	◐	◐	○	◐	●
Track element	○	○	○	○	○	○	○	●
Pop-up menus, picture galleries and slideshows	◐	◐	◐	●	●	◐	◐	●
Interactive media objects (canvas)	◐	◐	◐	●	●	◐	○	●
Buttons and controls	○	○	○	◐	◐	○	◐	◐
Non-scripting scales	○	○	○	○	○	○	◐	◐
Media Overlays	○	○	○	○	○	○	○	◐

Figure 3: Test results interaction and multimedia (for a more detailed description cf. Götz, 2012)
[legend: ● full support, ◐ partial support, ○ no support]

The test results show that the macro typography features of the ePUB 3 standard is the category supported least by current reading devices (cf. Figure 4). Except for the HTML 5 elements used for content structuring and media queries, there is only a very limited support of these new functions. Largely unsupported (the iBooks app being the only exception) is, for instance, the new way of defining footnotes by using a set of attributes of the `epub:type` element (instead of using standard linking technology to simulate footnote behavior).

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
Macro typography								
Media Queries	○	○	○	●	●	○	●	●
Alternate style sheets	○	○	○	○	○	○	○	○
Multi-Column Layout	○	○	○	○	○	○	○	○
Footnote and marginal	○	○	○	◐	◐	○	○	○
Display Property Values	○	○	○	◐	○	○	○	○
Text writing mode / Text layout	○	○	○	◐	◐	○	○	◐
Page-spread-left / -right	–	–	–	–	○	○	–	–
Structure elements	●	●	●	●	●	●	●	●

Figure 4: Test results macro typography (for a more detailed description cf. Götz, 2012)
[legend: ● full support, ◐ partial support, ○ no support, - no double page view]

Among the new features that the ePUB 3 standard includes in the micro typography category is the embedding of OpenType Fonts (OTF) and Web Open Format Fonts (WOFF) into an e-book (IDPF, 2011c). Besides, there are new ways to influence text decoration, e. g. underlining and shadowing, and to emphasize text by coloring (W3C, 2011). For the production of non-Latin (esp. Asian) e-books, the new support for emphasis marks[2] (Castro, 2010; IDPF, 2011c; W3C, 2012, 2013) and the HTML 5 element `ruby`, which use short runs of text along-side the base text to indicate the correct pronunciation[3] (IDPF, 2011c), are valuable additions.

[2] In Japan, Taiwan, Hong Kong, and mainland China, characters are emphasized by attaching emphasis dots rather than italicizing them (Garrish & Gylling, 2013).

[3] In Japanese, for instance, this pronunciation help is named *furigana* and is positioned centered over the main characters.

Compared to the rather limited support of macro typography functions, the test results for the new micro typography features that the ePUB 3 standards includes are definitely better. Apart from the `ruby` elements which are not rendered correctly on any of the tested reading systems (cf. Figure 5) , all other functions are at least partially supported by some of the analyzed devices (cf. Figure 6). Especially high is the support of text decoration and text highlighting functionalities on all tested reading systems.

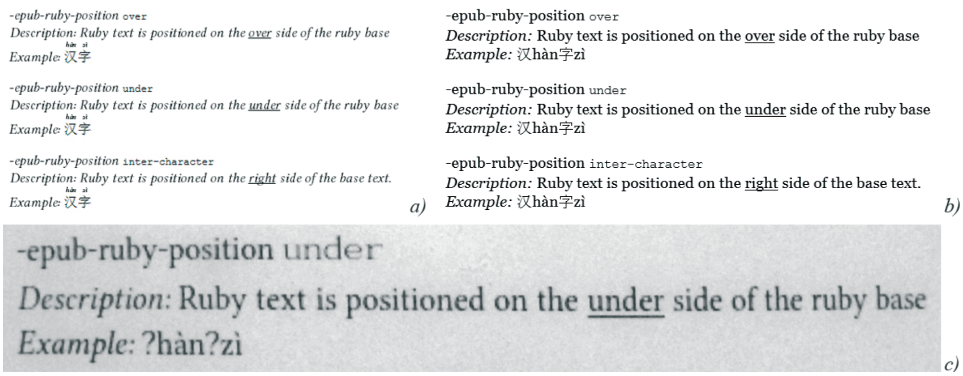

Figure 5: Support test of the ruby element and its attribute set - displayed incorrect on any tested reading system a) ruby text for pronunciation always above the base text (Readium); b) ruby text for pronunciation only on the left-side before the base text (Azardi); c) incorrect rendering of ruby symbols (Sony Reader PRS-T1)

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
Micro typography								
Fonts	○	◐	◐	●	●	◐	○	◐
Properties for text manipulation	○	○	○	◐	◐	○	◐	◐
Ruby	○	○	○	○	○	○	○	○
Text decoration and text marking	◐	◐	◐	●	●	◐	●	●
epub:switch element	●	●	●	○	○	●	○	●

Figure 6: Test results micro typography (for a more detailed description cf. Götz, 2012) [legend: ● full support, ◐ partial support, ○ no support]

As for the font embedding, reading devices such as the tested e-ink readers, tablets and smartphones (but not the reading software for personal computers) were able to render embedded OTF. Integrated WOFF characters, however, were only displayed correctly on iBooks (iPad as well as iPod Touch), Azardi and Readium. Micro typography properties for text manipulation, e. g. text emphasis, word-breaking and line-breaking, were almost unsupported. Some of these features displayed appropriately on Apple's reading devices and on reading software for PC's, like for instance the features `word-break` and `text-emphasis`.

The support of the `epub:switch` element proved to be unsatisfactory as well, because it was not interpreted correctly by iPad, iPod Touch and Readium. Hence, instead of choosing the content element that was suited best for the corresponding reading device[4], *all* possible variants were, more often than not, displayed at once, so that the same content was displayed up to three times in varying quality.

Accessibility

The inclusion of accessibility features in electronic books has changed significantly from ePUB 2.0.1 to ePUB 3. Instead of using specialized DTBook content documents to generate accessible e-books (a feature that was largely ignored by commercial e-reading systems, cf. Nikolaus 2010), ePUB 3 now uses the markup

[4] In the sample document, a MathML formula was supplemented by an SVG vector graphic and a PNG bitmap image as possible fallbacks.

languages SSML, PLS, and the IDPF CSS Speech Profile to implement accessibility functions. SSML and PLS generate synthetic speech (IDPF, 2011c), and the speech profile controls specific aspects such as pronunciation, pronunciation alphabet, volume, pitch, or rate (IDPF, 2011c).

A closer examination of these accessibility features showed that only the iBooks reading software on iPad 2 and iPod Touch had a Text-to-Speech (TTS) engine that could be activated for synthetic speech output - providing that the VoiceOver function was activated in the main preferences of the iOS operating system. But even this TTS engine ignored ePUB 3 pronunciation instructions completely (cf. Figure 7)

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
Accessibility								
SSML	–	–	–	○	○	–	–	–
PLS	–	–	–	○	○	–	–	–

Figure 7: Test results accessibility [legend: ● full support, ◐ partial support, ○ no support, - no TTS engine]

Global functions and components

Finally, some global e-book functions and components were tested as well - e. g. the support of book cover illustrations, the correct and exhaustive rendition of metadata or the support of the new EPUB Navigation Document as table of contents.

In the test, the included book cover illustration was displayed correctly on all e-reading systems. The support of basic metadata functionality (such as title and author) and CSS styling was acceptable as well. However, all reading systems had some trouble showing meta element sub expressions, which may be used to further refine the primary meaning of a `meta` tag, e.g. to assign different roles to a collaborative group of creators or to distinguish between main titles and subtitles (IDPF, 2011b).

As for the implementation of the table of content (toc), it has to be stated first, that in the new ePUB 3 standard, the HTML 5-based EPUB Navigation Document supersedes the older Navigation Center eXtended (NCX) file (as defined in the ePUB 2.0.1 standard). This new EPUB Navigation Document is now mandatory, *"ensuring increased usability and accessibility [of e-books] for the User"* (IDPF, 2011c).

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
General criteria								
Book cover	●	●	●	●	●	●	●	●
Metadata	◐	◐	◐	◐	◐	◐	◐	◐
Table of content	○	○	○	●	●	○	●	●
Landmarks	○	○	○	○	○	○	●	●
Gerneral CSS support	●	●	●	◐	◐	●	◐	●

Figure 8: Test results general test criteria, such as support of book cover and metadata [legend: ● full support, ◐ partial support, ○ no support]

For reasons of downward compatibility, it is still possible to include an NCX file in ePUB 3 e-books (IDPF, 2011c). This, however, was not done in the sample e-book in order to test the full and correct reproduction of the EPUB Navigation Document, including its new features such as landmarks[1] for an easier reading position relocation.

As it turned out, only half of the tested devices were able to show entries in the toc at all; the others displayed empty pages - and the landmarks functionality was only supported by Azardi and the Google Chrome add-on Readium.

	E-ink Reader		Smartphones		Tablets		Reader Softwares	
	Sony Reader PRS-T1	Kobo eReader Touch Edition	Samsung Galaxy Note (eBookS Reader 1.2)	iPod Touch 4 (iBooks 3.0.1)	iPad 2 (iBooks 3.0.1)	Acer Iconia Tab A200 (Aldiko Book Reader 2.1.0)	Azardi 11.4 (Win 7)	Readium 0.5.5 (Win 7)
General criteria								
Book cover	●	●	●	●	●	●	●	●
Metadata	◐	◐	◐	◐	◐	◐	◐	◐
Table of content	○	○	○	●	●	○	●	●
Landmarks	○	○	○	○	○	○	●	●
Gerneral CSS support	●	●	●	◐	◐	●	◐	●

Figure 9: Test results general test criteria, such as support of book cover and metadata [legend: ● full support, ◐ partial support, ○ no support]

4. Discussion

At present, there is an increasing demand for electronic books; especially for interactive and enhanced ones that can be read on tablets and smartphones. Hence, there is a need for the new functions IDPF's ePUB 3 standard offers.

This survey has shown that the ePUB 3 standard offers a lot of new features to create electronic books without the limitations of printed books - way beyond a simple reproduction of words and pictures. It is as Matt Garrish, ePUB expert and accessible publishing advocate, once said: *"EPUB 3 will forever change what a book can be"* (Garrish, 2011). But for now, the test results are sobering. The test shows that only a few of these new available possibilities for e-book production are supported by all the different reading systems. Only basic functions were supported properly and reliably.

In the interaction and multimedia category, the missing audio and video playback certainly is one of the most important drawbacks. Similar to the situation in the World Wide Web, there is a general disagreement as to which codecs and file formats should be used for audio and video playback. Commercial applications tend to favor proprietary formats such as MP4 (for audio and video support) and MP3 (audio), whereas open-source solutions prefer the open container format OGG (a container for both audio and video data) and WebM (for video only).

Due to this discrepancy, IDPF does not recommend one single file format in the ePUB 3 standard. Instead, it states that reading systems should at least support one of the H.264 (the video codec of MP4) or VP8 (a royalty-free, open video compression codec for the container format WebM) video codecs.

If the reading systems have the capability to render audio files, they must support the audio file format MP3 and should support MP4 and AAC LC audio files (Garrish & Gylling, 2013; IDPF, 2011b). Due to this ambiguous specification, it is rather the rule than the exception that video or audio files are only supported by some of the tested e-reading devices.

Macro typography and accessibility support was equally disappointing, whereas the micro typography category came off a little better. An interesting observation is that the feature support is not homogeneous amongst e-reading devices to the effect that all devices support the same subset of ePUB 3 functions. Instead, in most cases at least one reading device could be found that rendered the corresponding content at least partially correct. Nevertheless, the overall support was weak for most of the innovative functions of ePUB 3.

Certainly, it has to be kept in mind that features like JavaScript support or the implementation of media overlays are only optional in the ePUB 3 standard, too - but a concentration on the mandatory functions of ePUB 3 would mean at the same time to forego the key advantages that ePUB 3 has over ePUB 2.01.

5. Conclusions

Today, ePUB 3 can certainly be used for the production of simple texts that use only standard paragraphs or headings and only basic CSS features. Support for this is already available on most reading systems - older and modern ones.

If, however, one decides to use the new multimedia features to include audio, video, or animation into an e-book; if one tries to produce books with a more complex internal structure or if mathematical formulas, side-bars, columns, and so on are to be included, major rendering problems must be expected. Some features are not rendered at all on some devices, others are displayed only partly or incorrectly. Sometimes, non-standard workarounds are necessary to implement a specific function on a certain reading system. These workarounds, however, are in general incompatible with other reading systems and can cause severe rendering problems there. Thus, these workarounds might be a short-term solution to implement features on a certain, comer-cially important reading device. In the long run, however, this is no permanent solution, because it forces the e-book publisher to produce several non-standard e-books. This is not only expensive and hard to keep up as more and more reading devices enter the market, but it is also inconvenient for the readers, preventing the transfer of e-book collections from one reading device to another. Hence, in the long run, producing e-books strictly according to the IDPF standard is without any alternative.

Therefore, reading systems (and especially their rendering engines) have to be upgraded to get a full and standard compliant ePUB 3 support - in general, current devices already fulfill most of the corresponding hard-ware requirements. Yet, comparing ePUB 3 support from the time the IDPF specification was finally ap-proved to the situation today, it can be said that the situation is slowly but constantly improving. Thus, it is to be hoped that it is only a matter of time until the advantages of ePUB 3 will be available for every e-book reader - although the progress might certainly be a little faster.

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User evaluation of eBook service in Finnish public library

Olli Nurmi

VTT Technical Research Centre of Finland
P.O. Box 1000, FIN-02044 VTT, Espoo, Finland
E-mail: olli.nurmi@vtt.fi

Abstract

The work described in this paper deals with the digital book library system, eBib, developed for the Helsinki Metropolitan Area Libraries in Helsinki, Finland. The purpose of this work is to study the user experience of the eBib and compare the lending, reading and returning options of book steaming and two offline reading softwares.

The user feedback was gathered by a web questionnaire. The library patrons were asked to evaluate the overall system and lending, reading and returning functions of two offline reading softwares (Adobe Digital Editions and Bluefire Reader) and a book streaming software (Streaming) developed specially for eBib. The majority of patrons evaluated the overall user experience as positive and were even willing to recommend the system to their friends.

If the digital library provides pleasant user experience it may also increase the commercial market. The study showed that those users that were happy with the system are intending to buy digital books also in the future.

Keywords: eBooks, libraries, online and offline reading, user experience

1. Introduction

Public libraries are on the front lines of the unresolved situation between book publishers, ebook vendors, and libraries. The demand for ebooks is surging and the library patrons expect seamless access to the ebooks using mobile devices both offline and online. However pricing, restrictions on access, DRM and a multitude of formats and devices present challenges to public libraries.

The Finnish book publishers are cautious giving their books to public libraries because of fear of piracy and how this would influence in commercial market. In this research it was possible for the first time to get a reasonable collection of popular Finnish literature in ePub-format to large scale library.

The work described in this paper deals with the digital book library system, eBib, developed for the Helsinki Metropolitan Area Libraries in Helsinki, Finland. The purpose of this work is to study the user experience of the eBib and compare the lending, reading and returning options of book steaming and two offline reading softwares.

The user feedback was gathered by a web questionnaire. The library patrons were asked to evaluate the overall system and lending, reading and returning functions of two offline reading softwares (Adobe Digital Editions and Bluefire Reader) and a book streaming software (Streaming) developed specially for eBib.

The majority of patrons evaluated the overall user experience as positive and were even willing to recommend the system to their friends. The results showed that in Streaming book lending was evaluated to be the most fluent. However in Streaming the actual book reading was not at same level as with offline software. The book returning after the loan was evaluated to be on the same level in all of the tested softwares.

If the digital library provides pleasant user experience it may also increase the commercial market. The study showed that those users that were happy with the system are intending to buy digital books also in the future.

2. Libraries in Finland

There are 836 public libraries in Finland (2011), which equates to 1.5 libraries per 10 000 population, compared with an average across the 17 EU countries of 1.3 libraries per 10 000 population. Finland is known for its comprehensive library network, high user and lending rates and effective use of ICT technology and information networks in libraries. Both public and research libraries are open to all. No fee is charged for either borrowing or the use of collections at the library. [1]

In Finland, library and information services promote equal access to education and culture, reading and art appreciation, constant development of knowledge, skills and citizenship skills, internationalization and lifelong learning.

HelMET network (Helsinki Metropolitan Area Libraries) consists of the city libraries of Helsinki, Espoo, Kauniainen, and Vantaa. Staffed by 900 library and media professionals, HelMET circulates nearly 17 million items a year and provides 64 libraries and six bookmobiles to the metropolitan community. The HelMET Web library (www.helmet.fi) is the most frequently used library Web site in Finland. HelMet is actively developing new electronic services for the library patrons.

In this project it was possible to agree between book publishers and libraries license models that are not too expensive for the libraries and at the same time are economically feasible for the book publishers and writers. This co-operation project allowed offering a reasonable collection of popular modern Finnish literature in HelMet to test and promote the digital library services in public libraries.

3. Usability of evaluation framework for digital libraries

Usability is a multidimensional construct that can be examined from various perspectives. The International Standards Organization (ISO 9241) defines usability as "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use." According to this standard, measurement of system usability consists of three usability attributes:

1. Effectiveness: How well do the users achieve their goals using the system?
2. Efficiency: What resources are consumed in order to achieve their goals?
3. Satisfaction: How do the users feel about their use of the system?

Nielsen (2) writes about a framework of system acceptability, where usability is a part of usefulness and is composed of five attributes: learnability, efficiency, memorability, low error rate and easy error recovery, and satisfaction. Subsequently, many other studies in different areas have mentioned various other attributes of usability. However following attributes are commonly applied: effectiveness, efficiency, subjective satisfaction and learnability. Effectiveness is related to the completeness at which users achieve specified goal, efficiency refers to the resources used in completing a task and subjective satisfaction refers to positive attitudes toward using the system. Finally learnability measures how easy it is for casual users to learn a system.

Usability has several aspects, including interface design, functional design, data and metadata, and computer systems and networks. Usability is a property of the total system. All the components must work together smoothly to create an effective and convenient digital library.

Usability of a digital library primarily relates to its accessibility, i.e. how easily users can interact with the interface of the digital library, how easily they can find useful information, how easily they can use the retrieved information, etc. In general if information can be accessed easily then the digital library will be used frequently.

Usability of a digital library depends on a number of factors, such as the effectiveness and efficiency of the information access system, the ease of use and friendliness of the user interface, users' needs, usage patterns, etc. The heterogeneity and distribution of information resources is also a factor.

Digital library is a space where users engage with the information infrastructure, and hence usability problems, user attitudes, specific use situations and work practices are of importance.

To date there are no standard evolution models for digital libraries. Although researcher are working to develop a common evaluation framework, standardized criteria for digital library evaluation is still missing [3].

Basically two types of usability evaluation methods have been applied to the digital libraries: inspection methods and empirical methods. Inspection methods involve mainly two strategies, a usability experts' judgment and authorized guidelines and principles, whereas empirical methods test digital library systems through an analysis of data on potential or actual users. Inspection methods include heuristic evaluations, checklists, cognitive walk-throughs, whereas empirical methods include formal usability tests, interviews, focus groups, questionnaires, and others [4].

Previous research has identified some usability evaluation criteria for digital libraries. Most of this research deals with the usability of academic libraries. In this context the items of efficiency and effectiveness dimensions focused on resource searching considering that the main purpose of digital library uses lies in academic resource finding. Thus, most of items in efficiency and effectiveness dimensions include the wordings such as "find", "search task" or "searching resources" [5]. This kind of approach is too narrow on public libraries where the service function of the library is much broader.

In Finland, library and information services promote equal access to education and culture, reading and art appreciation, constant development of knowledge, skills and citizenship skills, internationalization and lifelong learning. According to the recent EU study the core service of 'books to read/borrow' is considered the most important in Finnish public libraries. This is why the usability testing in this work dealing with digital public libraries put special emphasis on testing and comparing the book borrowing, reading and returning options.

4. Methodology

In this work a digital library service for HelMet (eBib) was specified and developed using agile software development methodology. The usability of the digital library was tested empirically designing an electronic questionnaire and presenting this questionnaire after the first usage session to the library patrons.

4.1 Specification and development of the digital library system

Following top level specifications were made for the digital library system in the discussions with the book publishers, service providers and public libraries.

1. Book must vanish after the loan: no copy of the digital book must remain after the loan period in users end device
2. Clear instructions for user: the user guidelines must be so clear that only minimum amount of technical support is needed
3. Clear licensing conditions: the applied licensing model must allow the reimbursement of the library license to the copyright holders
4. Interesting book collection: The book collection should consist of new Finnish books that are of high interest to the patrons of Helmet public library
5. Both online and offline reading: The system should allow both online reading using standard browser and offline reading with different reading softwares supporting Adobe DRM scheme
6. Loan and user statistics: The system should collect statistics for both the users and books to allow analysis of the digital library system
7. Management of loan: An electronic book shelf should be provided allowing user to manage his loans, make reservations and return online loan

Based on these specifications a test system was build and integrated to the Millenium library system of Helmet. Adobe DRM with Adobe Content Server was applied for book downloading for offline reading and a special content server system and content protection scheme was developed for book streaming and online reading.

Special effort was put for development of HTML5 web application allowing online reading of books. The web application runs on standard browser and allows seamless reading even during temporary internet connection breaks. Two consecutive chapters of the book are downloaded to local memory and new material is automatically downloaded whenever the internet connection is restored. Downloaded chapters are segmented and encrypted so that is practically impossible to restore an unauthorised copy of the book. Copying or printing of the ebooks was not allowed. However the library patrons were allowed to make bookmarks or annotations. The digital library system offered possibility to browse few pages of the books without borrowing.

It is very essential for the reader to know on which place he is while reading and how much is there still to read. This need was answered by offering a slider showing the reading progress and allowing also to navigate to different places in the book.

Figure 1 shows the concept used to inform the reading position to the reader in the developed web application and in one commercial reading software, Bluefire Reader The offline reader, Bluefire Reader, shows also the page numbers but this concept has both technical and semantic challenges in the web application. The amount of pages depends among other things on the font size, page marginals, screen size and browser window. Because the book is downloaded by chapters to the browser local memory complicated techniques would have been applied to calculate the total amount of pages. For this reason the page number concept was not applied in the developed web application.

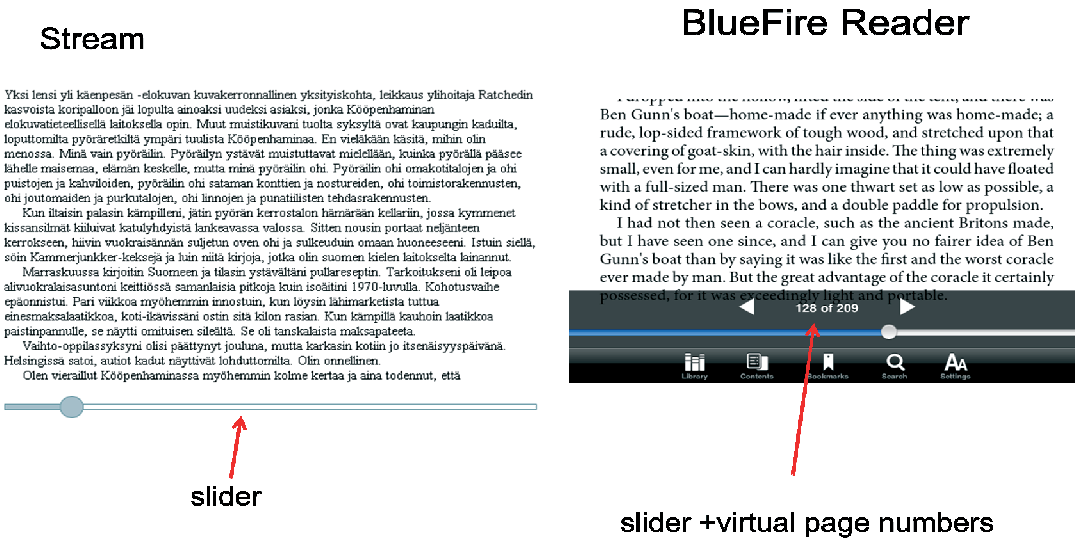

Figure 1: Concept used to show the reading position in the web application (Stream) and in commercial offline reading software (Bluefire Reader)

Book publishers Otava and Edita selected the ebooks from their recent production that were included into the library collection. There were 25 books from 15 writers from Otava and 11 books from Edita. HelMet libraries purchased different amount of licenses for the books, altogether 490 licenses. To offer ebooks to as many as possible only one loan was allowed at a time for single user. The loan period was either 1 day or 7 days after which the book is automatically returned to library. It was naturally possible to return the book earlier.

The digital library system included also different administrative tools that allowed management of collection and gathering of detailed statistics. Linux, Apache, MySQL and PHP were used in the technical platform. The usage of Ebib-service was analysed by using Google Analytics.

4.2 Usability measurement design

Different dimension of the usability were measured by Likert scales and questionnaires. An electronic questionnaire was developed, with questions drawn from the identified key measures (see Table 1). The questionnaire consisted of statements which the respondents were asked to evaluate according to subjective criteria and the level of agreement or disagreement was measured.

Table 1: Measurement dimensions and items

Dimension	Item indicator
Efficiency	It was easy to find what your were looking for
Effectiveness	I could use the service the way I wanted
Satisfaction	It is pleasant to use the service
	The service was encouraging to read more
	It was pleasant to read digital books
	I will continue reading digital books
	I recommend the service to my friend
Learnability	The user guidelines were clear
	It was easy to establish Adobe user Id
	It was easy to install the reading programs
	It was easy to create a reservation for the book

The background questionnaire collects demographic data, including gender, age, reading habits, previous experience of digital library services and digital book reading and ownership of PC's, ereaders or tablet devices. The subjects were asked to rank satisfaction with the system after the first usage session and to write down comments.

In addition, there was a post-test questionnaire that specifically examines satisfaction in the areas of book borrowing, book reading and returning the loan comparing online reading and offline reading. In addition, the users were asked to compare the issues of user lostness and navigation disorientation of different reading options.

4.3 Experiments and background information of the users

Ebib was opened for all HelMet customers for a test period of 15 October 2012 - 31 December 2012. The patrons having valid library card could lend and read Finnish books with PC's, tablets or mobile devices both offline and online. The collection consisted of 36 books in epub-format and there were 490 book licences altogether.

During the test period there were 3 146 registered users and roughly half of them actually borrowed a book. Altogether 2 705 loans were made and 40 % of the books were read using book streaming. The average utilisation rate of the books was 47 %. The number of visitors and loans in the first weeks is shown in the Figure 2. The marketing action carried out at 6th November 2012 increased the amount of new visitors. The most popular mo-bile device was Appls' iPad which was used by 67 % of the mobile visitors. Other mobile devices included iPhone (10 %) and Samsung Galaxy Tab (14 %).

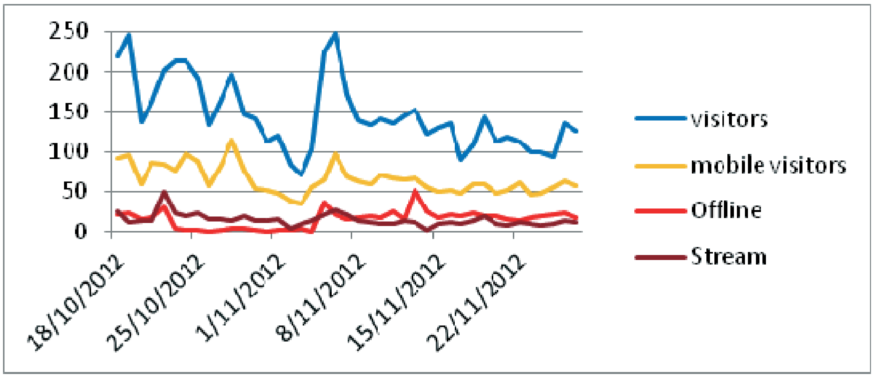

Figure 2: The number of visitors and offline and online loans during the first month of the experiment

Figure 3 shows the age and gender distribution of the users. The largest user group of the digital library was young women. The user group included however large variety of age group and the oldest user was 88 years old. 62 % of the users have already borrowed a book during last month. Typically the users borrow 2 to 3 books per month.

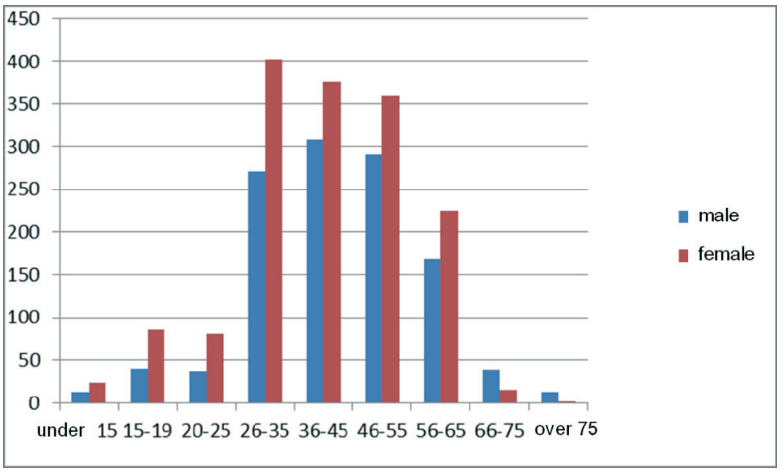

Figure 3: The age and gender distribution of the users

After the first loan the Ebib patron was asked to answer a web questionnaire. Totally 569 answers were received which was about 40 % of those borrowing a book. 55 % of the respondents were female. The respondents can be characterised to rather active readers who are used to use the digital services of the library. Almost all of the respondents have PC or laptop, 70 % smartphone, 60 % tablet PC, but only 16 % have ereader. The respondents were accustomed to use internet, read digital books, magazines or newspapers.

5. Results and discussion

The user experience of eBib library system was generally evaluated to be good. The use of service was evaluated to be pleasant and increasing patrons' willingness to read digital books. Most of the respondents are going to continue using eBib also in the future and recommend the service also to their friends. The result of the evaluation is shown in the Figure 4.

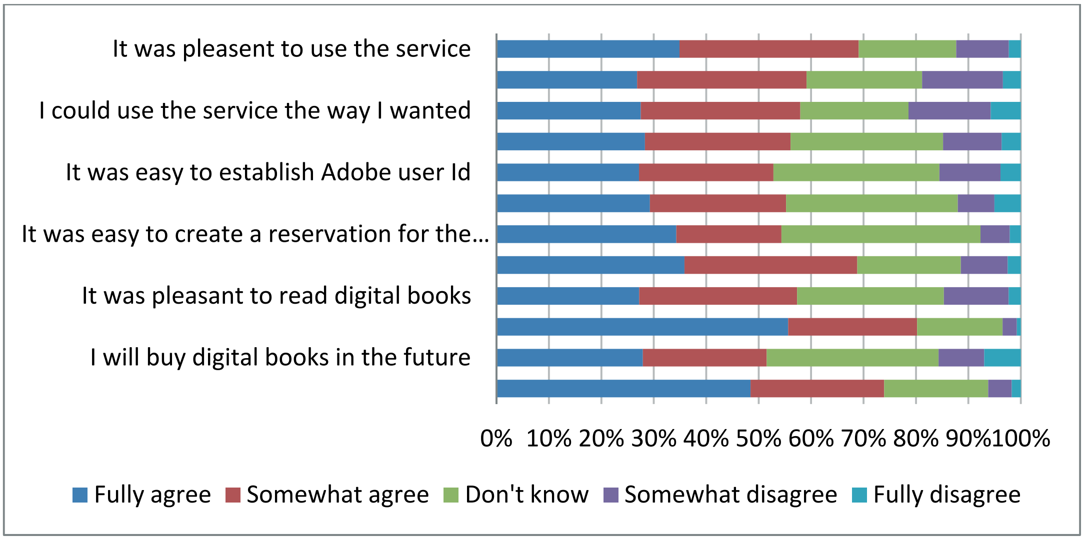

Figure 4: General evaluation of the eBib service

Previous experience of reading digital books had positive effect on how easy the installation of the necessary offline reading software or creation of Adobe Id was considered. Those who felt that the service was encouraging to read more answered also that they will continue reading digital books or buy digital books also in the future.

Especially the young readers gave most positive evaluation for the service. Figure 5 shows the evaluation given by different age groups.

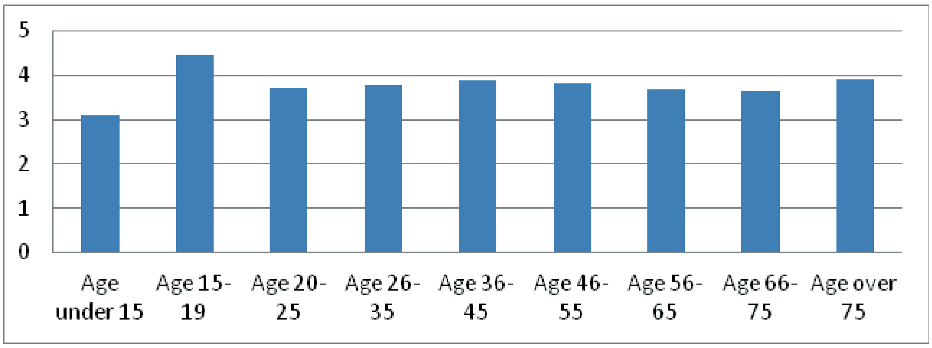

Figure 5: General evaluation (score 1-5) of the eBib service for different age users

The digital library can also increase the commercial digital book market. The data showed that intension to buy digital books from commercial books shops increases if the digital library service encouraged patrons to read more. 65 % of those that felt that the system encouraged them to read more intended to buy digital books in the future.

Table 2: Dependence of how the system encouraged reading more on intention to buy digital books

the service encouraged to read more	I intend to buy digital books					Total
	fully disagree	somewhat disagree	don't know	somewhat agree	fully agree	
fully disagree	3	4	3	2	1	13
	23,1%	30,8%	23,1%	15,4%	7,7%	100,0%
somewhat disagree	7	7	7	11	14	46
	15,2%	15,2%	15,2%	23,9%	30,4%	100,0%
don't know	11	3	62	8	18	102
	10,8%	2,9%	60,8%	7,8%	17,6%	100,0%
somewhat agree	8	21	51	54	34	168
	4,8%	12,5%	30,4%	32,1%	20,2%	100,0%
fully agree	7	10	46	46	76	185
	3,8%	5,4%	24,9%	24,9%	41,1%	100,0%
Total	36	45	169	121	143	514
	7,0%	8,8%	32,9%	23,5%	27,8%	100,0%

The book lending was evaluated to be easiest with streaming. However the actual book reading was slightly more difficult with Streaming as with ADE and BFR. This can be caused by several reasons.

The sense of place is provided in ADE and BFR by page numbers. This option was not possible in book streaming due to technical issues. Instead a progress bar showing the place in the book was provided but this turned out to be insufficient. Reading experience of streaming application could be enhanced even further by providing two page reading view and allowing users change the background colour and side marginal. A small portion of respondent regarded book returning as difficult in streaming. This can be improved by adding a response message conforming accepted book return.

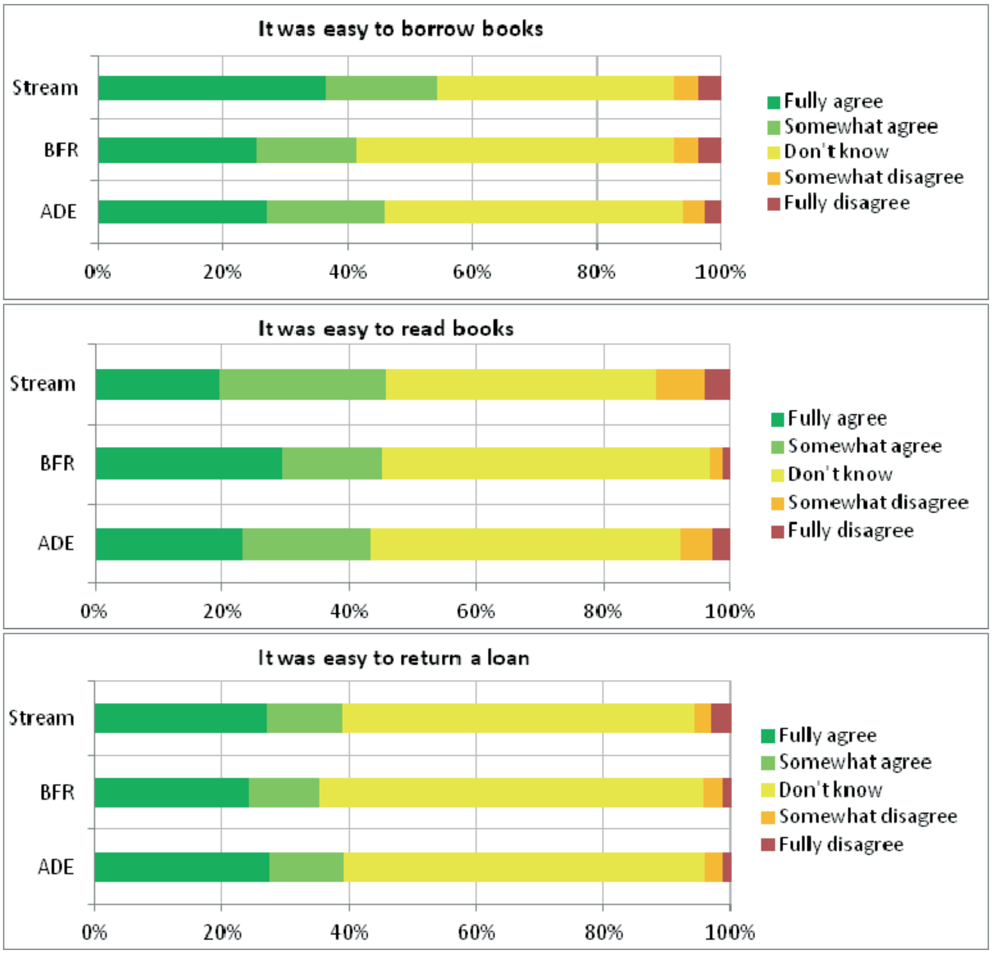

Figure 6: The summary of the user evaluation of the ebook lending, reading and returning in the three options of the eBib-library system

6. Conclusions

The difference in user experience of lending, reading and returning ebooks online and offline were studied in the public libraries. A test service eBib was developed and web questionnaire conducted. The new digital library system was evaluated as good and especially the young patrons liked the service. Analysis of the questionnaire showed some differences between streaming, BRF and ADE. More information about the place has to be provided in order to reach comparable results as BFR or ADE while reading a book.

The user feedback can be used to develop the system even further. Following development areas have been identified: integration of the Ebib system to the library system of HelMet more tightly, services that allow management of the patrons own virtual library and adding new features to the web application including management of the background color and marginal's. Suprisingly the Adobe DRM scheme didn't provide any major problems for the user. The reason for this can be that the users of the Ebib-service were rather advanced user with good knowledge of modern internet services.

If the digital library provides pleasant user experience, it may also increase the commercial market. The study showed that those users that were happy with the system are intending to buy digital books also in the future. This finding supports earlier observations that heavy readers both loan and buy books. Yet, all library patrons are not potential book buyers.

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The development of an improved speed of reading test for measuring legibility

Saskia Kraft, Michael Reiche, Diana Tillmann

Faculty of Media, University of Applied Sciences
Postfach 301 166, D-04251 Leipzig, Germany

E-mail: kraft@fbm.htwk-leipzig.de; reiche@fbm.htwk-leipzig.de; diana.tillmann@stud.htwk-leipzig.de

Abstract

In this paper, the methodology to measure the legibility of a text-design discussed. Along with an overview of the advantages and disadvantages of the most relevant methods of investigation, requirements for a method for measuring the legibility are defined. Based on these requirements, an improved speed of reading test was developed and is described in this paper. To evaluate the method, an experimental study was carried out, which considered all identified variables that could possibly influence reading speed.

Keywords: typography, legibility, speed of reading

1. Introduction

Legibility is fundamental for text-design and an important prerequisite for a successful transfer of information. From the late nineteenth century, a great amount of experimental legibility research was carried out, mainly in the English-speaking regions. This research was done by scientists who mainly had a psychological background and who were trying to develop conceptions of what "good" typography is. These studies, little known to today's designers and typographers, describe how people respond to written text. Ideally, these research results should provide a useful data base for designers and typographers. But today most designers consistently work without knowledge of or without consulting this academic literature. Furthermore, the typographic field is dominated largely by convention and intuition, with most designers and typographers basing their work on their own personal experience and/or the publications of well-known typographers.

This leads to the question, how academic research can support design decisions?

Definitions of legibility

One reason for this lack of communication between scientists and designers could be related to non-sufficient knowledge about what legibility actually means. Scientists often distinguish "legibility" and "readability" as the objective and subjective sides of typographic perception. In this regard, "egibility" describes the ease with which a letter or word can be recognized, whereas "readability" describes the ease with which a text can be understood (reading comprehension). However, scientists and designers often use the terms "legibility" and "readability" synonymously.

The empirical researcher Miles A. Tinker uses the term "legibility" to describe both perception and comprehension: "Legibility […] is concerned with perceiving letters and words, and with the reading of continuous textual material. […] Optimal legibility of print, therefore, is achieved by a typographical arrangement in which shape of letters and other symbols, characteristic word forms, and all other typographical factors such as type size, line width, leading, etc., are coordinated to produce comfortable vision and easy and rapid reading with comprehension." (Tinker 1963, pp. 7–8) Also Zachrisson defines legibility in terms of the measurement process "[…] as the speed and accuracy of visually receiving and comprehending meaningful running text." (Zachrisson 1965, p. 25) Accordings to Tinker and Zachrisson, criteria of legibility are both perceptibility and comprehensibility.

The described confusion between the terms legibility and readability can lead to a communication gap between academics and designers. To avoid this confusion, the term legibility has to be defined exactly. Based on the recommendation of the DIN 1450 (2013) standard, which provides the most practicable orientation in that regard, the term "legibility" describes several factors in typography and layout which influence the speed and accuracy with which information can be read. In contrast, the term readability will refer to the rate of comprehension (DIN 1450 2013).

Methods of past investigation

Another reason for the ignorance of legibility research results by many designers and typographers could be a lack of a typographic basic knowledge concerning experimental testing. For the experimental testing of legibility, different methods are used, depending on the different criteria of legibility. Beier (2009) gives a detailed overview of the most important methods. Basically these methods can be divided into two groups. One group refers to visibility and perceptibility of individual characters and words. The other group refers to the influence of a typographical parameter in a continuous text. Visibility and perceptibility of individual characters and words are often measured by speed of perception, visibility under reduced illumination, perceptibility at a distance or in peripheral vision. Common methods which refer to perceptibility and comprehensibility of continuous text measure fatigue, eye movement, time to solve a task or readers' preferences.

To examine the influence of a typographical parameter in a continuous text, measuring reading speed is the most relevant method (Tinker 1963, p. 20). This method refers to the movement of the eyes along lines. The reading process is characterised by saccadic movements and fixation pauses. During the saccadic movements, no clear vision is possible, it is only in the fixation pauses, lasting approximately 50 to 500 milliseconds, that the reader can process visual information. At a normal reading distance of 40 cm (15,7 inches), about seven to ten letters can be recognized in a fixation pause (Rayner 1998). Yet short exposure experiments (using a tachistoscope) have shown that briefly presented words can be recognized as rapidly as briefly presented letters (Wagner 1918, p. 17). These experiments have also shown the so-called "word superiority effect", which "suggests that letter identification follows word recognition rather than preceding it" (Reynolds 1979, p. 312).

However, the role of eye movement in the reading process cannot be explained exactly today and is still subject of present research. However, it has been shown that the frequency of fixations and regressions (backward movement) can be influenced by typography factors, which can be investigated by measuring reading speed (Tinker 1963; Rayner et al. 2010).

The reading speed can be measured in different ways. The most important methods for measuring reading speed were carried out by Miles A. Tinker from the 1920s to the 1950s (reviewed in Tinker 1963) and by Gordon C. Legge from the 1980s to present (overview in Legge 2007). "The method applied by Miles A. Tinker when testing speed of reading, was to have participants read a series of short paragraphs. Each of these paragraphs would contain one phrase towards the end that confused the meaning of the context; the task was then to identify this phrase." (Beier 2009, p. 28).

Although the method of measuring reading speed was developed already in the 19th century (e.g. Weber 1881), Tinker and his colleague Paterson were the first to define several criteria for more valid measuring instruments (Tinker 1963, pp. 19-23). One criterion describes the problem of text content influence. Previous investigations measured the reading speed of texts that were not comparable. Therefore, stylistically and grammatically comparable texts seem to be necessary to retain valid results. Among the first studies using such texts were the "Studies of Typographical Factors Influencing Speed of Reading" published by Paterson and Tinker in 1928. This report contains an analysis of different font parameters, e.g. type size, line length and typeface. For their investigations, Paterson and Tinker used the Chapman-Cook Speed of Reading Test, which consists of syntactically similar texts (Tinker & Paterson 1928). These comparable test texts provide a good base for measuring reading speeds of different typographical parameters. Still, another problem is the comprehension check. Hartley et al. found that asking comprehension questions is the least reliable method to measure legibility. "The lack of consistent performance can be an outcome of many things: e.g. the non-standardization of the treatments between and during different testing sessions; the expectations of the experimenter and the readers; levels of motivation and the social situation generally."(Hartley et al. 1975, p. 291).

Legge (2007) used several methods to measure reading speed. For example the flashcard method, which consists of a participant reading aloud short passages which are exposed only for a short time, as quickly and accurately as possible. A disadvantage in oral reading is that the situation is non-natural for most adults and the measure is not reliable.

Another problem is that studies can be hardly compared because of the different definitions of type size (Legge & Bigelow 2011). Legge, who collaborated with the American type designer Charles Bigelow, points out defects in Tinker's study considering the definition of character size. Tinker (1963) measured body size - the distance from the ascender line to the descender line. "For a given body size, the apparent sizes of typefaces are influenced by their x-heights: Faces with larger x-height fractions appear to be bigger than those with smaller fractions […] Conversely, types with the same x-heights but different body sizes appear to be approximately the same size." (Legge & Bigelow 2011, p. 4) Therefore they recommend using x-height of a typeface as a basic measure.

To sum up, studies investigating the influence of typographical factors on continuous reading proves problematic because of the countless numbers of variables to be controlled. The results of the overview over past investigations measuring reading speed indicate that researchers should be careful in experimental designs (1) to use stylistically comparable texts (2) to examine readers constitution and (3) to control the interacting font parameters.

Based on the aforementioned knowledge about various defects and different variables affecting the reading speed, an experimental study which considers these aspects was been designed.

2. Methods

The aim of this experimental study was to determine the influence of a typographic parameter on reading speed using an improved method.

In this study, the hypothesis that reading speed is influenced by a slightly increased letter spacing in small print size was evaluated. Very close settings can cause confusions in letter recognition and spatial interaction between characters (crowding phenomenon), especially in the parafoveal and peripheral areas (Pelli et al., 2007) and in the fovea, according to texts viewed from distance. Research into the crowding phenomenon has been a popular subject in recent years. Past investigations suggest that the spacing of letters in a text influences reading speed in normal central and peripheral vision (Chung, 2002; Subbaram et al., 2004; Tai et al. 2006; Yu et al., 2007). Although increasing letter spacing decreases the effect of crowding, it slows down reading speed (Legge et al., 1985; Chung, 2002; Subbaram et al., 2004), which is very surprising. Therefore, experiments investigating this phenomenon can give designers important information in terms of possible improvements in legibility.

On the basis of these previous studies, the current study indicates that reading speed decreases with increased character spacing. To examine this hypothesis, the reading speed for normal (standard) and increased letter spacing was measured.

3. Experimental study

Subjects

The sample group of this study comprised 42 subjects. Experimental subjects were students of Printing Technology and Publishing Technology in their first semester at the University of Applied Sciences Leipzig. The study was realised in two groups (study I and study II) with 21 subjects each. With a portion of 60 %, the number of female subjects was higher than that of male subjects. The subjects were between 18 and 32 years old. More than half of the subjects (53 %) were between 21 and 23 years old. All subjects had normal visual acuity ascertained with the "Freiburg Visual Acuity Test" (Bach, 1996).

Material

The most fundamental prerequisite to construct a speed of reading test is an applicable test text. In this study, twelve test texts of the Radner Lesetafel® were used. These reading sheets were developed by Wolfgang Radner (1998) with the utilization of findings from the fields of linguistics, psychology and ophthalmology. They were designed for the examination of reading capability and reading speed and consist of short sentences (14 words) that resemble each other in syntactic structure, word and sentence length as well as lexical level (Figure 1).

Vor der Einfahrt stand lange
der Kleinwagen, der auch uns
gute Dienste geleistet hatte.

Figure 1: Example for a sentence from the Radner Lesetafel ® (Radner 1998)

Six of the twelve test sentences were manipulated for this investigation. This means that in six test sentences the typographic parameter "tracking" was extended by a value of "50" with the DTP program InDesign® CS5.5. Non-manipulated sentences remained unchanged with a value of "0".

The primary typographic design of the test sentences followed the development of the Radner Lesetafel®, where the type face "Arial" was used. The type size was, differing from the Radner Lesetafel®, not in 12pt, but chosen to be in the print size 8pt with a x-height of 1,46 mm. The line distance in this study was 120 % of the type size. This equals 9.6pt. The DIN 1450 (2013) recommends for the consultation size a line spacing of ≈120 % of the type size. The line width followed the Radner Lesetafel®. The line breaking remained the same as specified by the author. Due to the varying word spacing in centre justification, the left justification was used.

Every test sentence was positioned at the optical centre of a DIN A4 paper (Figure 2). Between every test sentence, a white paper with a black dot positioned at the optical centre, was included. This dot served as a visual fixation point for the orientation of the eye (Figure 2). In the first position, there was a white paper with a black frame. The latter also served as an orientation regarding which position the test sentence would be located.

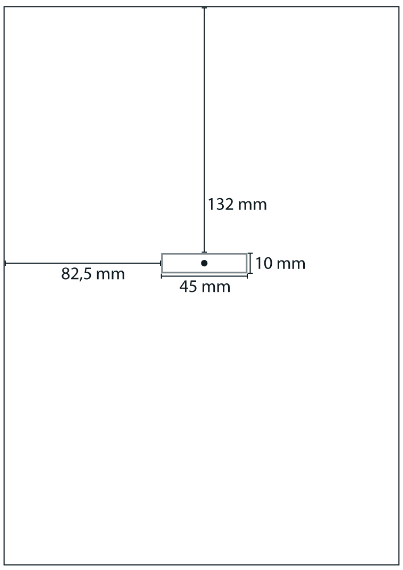

Figure 2: positioning test sentence and fixing point

Characters were presented as high-contrast and printed with black colour on white, wood-free paper of size DIN A4 with a grammage of 80 g/m². The test sentences were printed on a Konica Minolta bizhub C203, which uses Simitri® HD polymerised toner (Konica Minolta, 2008).

Via a questionnaire, sociodemographic data (age, gender, profession, native language and eye disorders) was gathered. Furthermore, the questionnaire included a decision question: "Could you perceive changes in the font of the sentences and if any, which ones?"

Procedure

In the beginning, the first part (sociodemographic data) of the questionnaire was filled out through an interviewer in the framework of a direct survey. After measuring the visual acuity, the speed of reading test followed. This was carried out at the standardised color matching box *mega normlicht 98,* which provides color matching light in standard light quality D50 (mega-stahl, 2013). The subjects were requested to stand in front of the table. They were allowed to stand free or lean on the table. The experimental setup was then explained by the examiner. The task for the subjects was to read out loud as fast and consistent as they could. It was emphasized that it is not important who is reading the fastest, because that can cause the subject to misread due to the fast reading. Each person should read individually fast. Subsequently, the recorder was placed at the color matching box and switched on, in a way that did not distract the subject. The subject then started to read. Twelve test sentences were separately uncovered by the researcher. After the subject had read a sentence, the next one was uncovered. The operationalisation of the reading was realized with a digital recorder. This procedure proved to be suitable, in contrast to measuring the reading time with a stopwatch like in past studies. To record the reading digitally proved to be a very exact method, since measuring errors, e.g. delays by the researcher when pressing the start button of the stopwatch, could thus be avoided Influences of subjective nature were completely prevented. Capturing the reading times with an audio editor proved to be uncomplicated, and values were measured down to millisecond precision. After completion of the reading, the subject was requested to fill out the second half of the questionnaire. After this, the speed of reading test for the current subject was finished.

Results

At first, a statistical data analysis was performed. The mean value (of *n* data points) of the reading time and its empirical divergence *s* were calculated. The value of a measurand is denoted by *y*. The arithmetic average is defined, with a series of *n* measured data points $y_1, y_2, \ldots, y_n$, as

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \qquad [1]$$

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2} \qquad [2]$$

The empirical divergence (standard deviation) is used as a measure of the distribution of data around its average value. To be able to compare the average value with the distribution, a calculation of the standard deviation must be done.

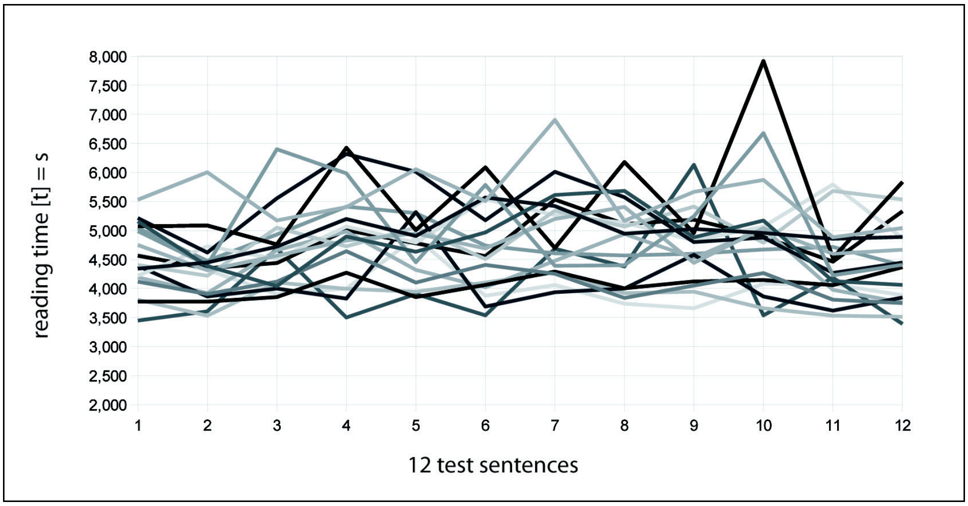

Figure 3: Visualisation of reading times study I

Considering the averages of study I, they resulted in a mean reading time of 4.685 ± 0.546 sec for manipulated sentences and in a mean reading time of 4.727 ± 0.519 sec for non-manipulated sentences. The average difference of manipulated to non-manipulated sentences is 0.042 sec.

Considering the averages of the second study iteration, they resulted in a mean reading time for manipulated sentences of 4.691 ± 0.586 sec and for non-manipulated sentences in a mean reading time of 4.709 ± 0.947 sec. The difference of manipulated to non-manipulated sentences is 0,018 sec.

A complete averaging over both, study I and II with 38 subjects in total, results in a mean reading time of 4.688 ± 0.566 sec for manipulated sentences and in a reading time of 4.718 ± 0.733 sec for non-manipulated sentences. The difference of manipulated to non-manipulated sentences is 0,030 sec.

The determination of the reading speed of the 38 subjects yields a mean reading speed of 183,6 ± 20,9 w/min for manipulated and 183,7 ± 24,7 w/min for non-manipulated sentences.

$$\text{reading speed} = \frac{14\ \text{words}}{\text{seconds}} \cdot 60 = \frac{840}{\text{sec}} = \text{words/minute (w/min)} \qquad [3]$$

Taking the average of the reading time in relation to gender, the data for manipulated sentences shows a mean reading time of 4.456 ± 0.595 sec for female and 5.043 ± 0.595 sec for male subjects. Manipulated sentences were read by women within 4.476 ± 0.901 sec on average and by men within 5.088 ± 0.629 sec. There does not seem to be a clear correlation between the test sentences, but it emerges that on average women read 0.6 seconds faster than men (Figure 4).

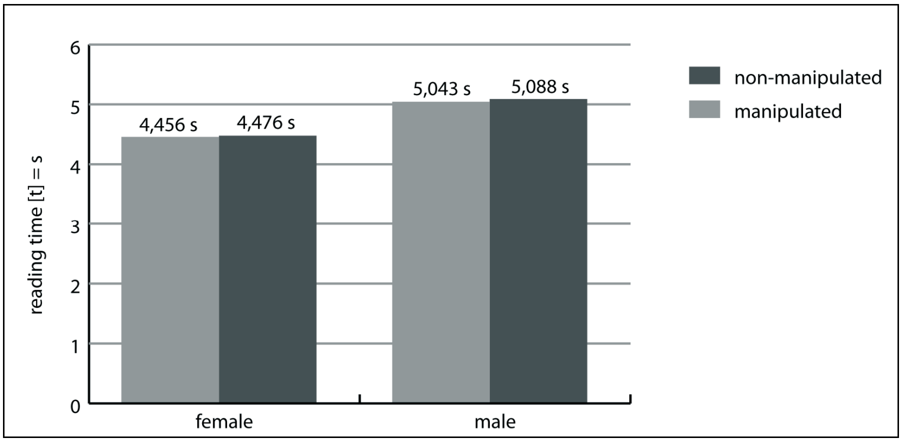

Figure 4: Reading time in relation to gender

The mean reading speed for manipulated sentences of females is 185,6 ± 22,2 w/min and of males 180,3 ± 18,9 w/min. On average, non-manipulated sentences were read with 186,6 ± 27,3 w/min by women and by men with 179,2 ± 2,10 w/min. Women read 5-8 words per minute more than men.

The subjects 11 and 28 were no native speakers and errors occurred during the recording process of the reading time of subjects 14 and 22 so that their data needed to be excluded from the evaluation.

4. Discussion

In most previous studies, the average reading speed was evaluated as the main criteria for legibility. When comparing the average reading speed results of this study, no significant differences between the normal and the manipulated tracking were found. In contrast to the average values of reading speed, the results of each person show that there are significant differences between the reading speed of the manipulated and normal texts. The evaluation of the results also suggests a correlation between reading speed and the gender of the individual persons.

Besides considering the averages of the reading times, an individual analysis was also carried out. In this, the averages of every subject of both test sentences were compared and analysed. For this, the absolute differences between the reading times of manipulated and non-manipulated sentences were calculated. For this, three divergence levels were defined.

A - no divergence: difference of average value < 0,1
B - minimal divergence: 0,1 ≥ difference of average value ≤ 0,5
C - maximal divergence: difference of average value > 0,5

Figure 5 illustrates the three defined divergence levels dependent on gender. More than half (53 %) of the test sentences show a minimal divergence (level B) between manipulated and non-manipulated sentences. The fraction of women in this level is 34 % and that of men 19 %. In divergence level C the genders are evenly distributed with 8 % each. 11 % of the subjects read manipulated sentences slower than non-manipulated, whereas the opposite is the case for the other 5 %. Barely one third of the test sentences shows no divergence. Of this percentage, 18 % are women and 13 % are men. It is interesting that the figure shows that in level B and C only women read manipulated sentences faster than non-manipulated sentences.

The aim of the second part of the questionnaire was to assess whether the subjects had perceived the variations in the type face. 19 of 38 subjects (50%) answered the text question with *YES* and commented on which variations they had perceived. Two subjects noticed that the tracking or pitch was manipulated. Eight subjects perceived a variation of the type size. Three persons observed a different line distance. Another three noticed differences, but could not identify them. Furthermore, the subjects of the 19 perceived variable stroke widths, different word distances, sans-serif fonts, size differences, vanishing serifs, letter spacing and varying fonts.

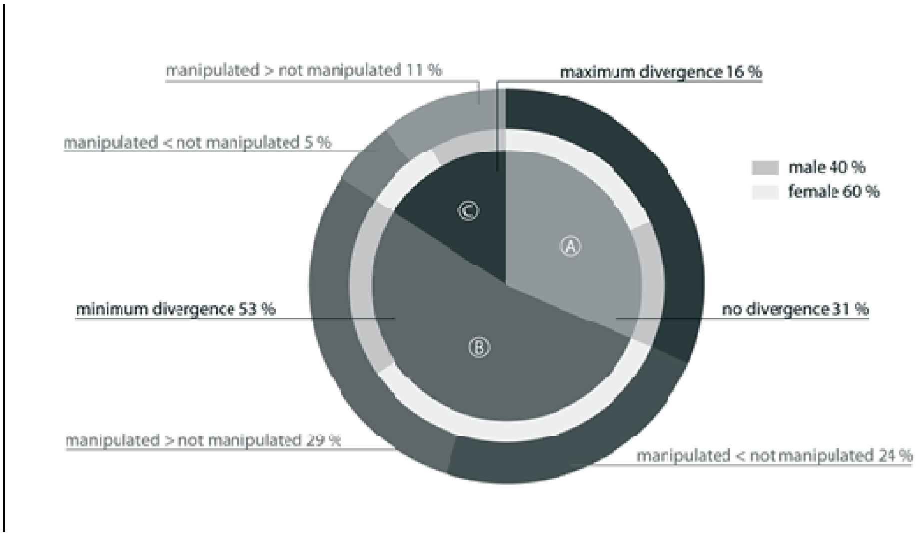

Figure 5: divergence levels

This shows that the subjects could conclusively identify neither the fact that manipulated and non-manipulated sentences were used nor the kind of manipulation. This could be traced back to the fact that the subjects concentrated on reading only. Due to the reading task, the attention of the subjects was primarily lead to reading. Additionally, there is also the fact that the study was realized in a laboratory. The subjects had to accommodate to this artificial situation since this reading environment did not conform to reality. Additionally, it was observed that subjects with previous typographic knowledge were able to recognize modifications in the typeface more often than persons without this previous knowledge.

5. Conclusions

The method used in the experiment was selected after its analysis proved it to be a reliable instrument to measure legibility of a text-design, but may not be sensitive enough: The choice of the manipulated typographic variable was arbitrary, because the primary task was to evaluate the method. To investigate the influence of the typography on legibility, the tracking in one of the two reading samples was changed. With a tracking value of 50, a significant change was made. However, the outcomes of the reading speed evaluation do not allow a sound statement about the question whether the tracking has any influence on legibility. This raises the question, whether the chosen parameter was the decisive factor or if the modification was too small.

Another problem which emerged already in the beginning was the choice of suitable test sentences. The content plays an essential role, because the reading samples must be similar in style and grammar. The Radner Lesetafel® remedies this problem. Considering the resulting reading times, it is obvious that the sentences are very short, tentatively too short for the recognition of clearly noticeable differences of reading speeds. It appears advisable to use longer reading samples in order to be able to measure a clearer correlation between the values. Another weakness of the method is the fact that only German native speakers can participate in the test. This excludes a variety of subjects and information about the statistical population can not be fully gathered by an empirical sample. For each language, different test sentences would have to be developed, thus taking into account the differing grammatical structures and word lengths.

At first, it was assumed that, starting from the idea of measuring just effects of signal transmission with an averaging over the reading times, the individuality of each subject could be deliberately excluded. To gather evidence for this, a statistical data analysis ensued. One result of the experiment is that the results of the statistical work have no exclusive expressiveness: Other boundary conditions, like "reading biography" and social background, need to be considered as well. This finding will be incorporated into the planning of the next experiments.

The personal constitution of the subjects must come more to the fore, because, as can be seen from the influence of gender on reading speed demonstrated in this study, individual characteristics play a large role in measuring legibility.

This method evaluation pointed out some deficiencies of past studies. Further studies are required to evaluate these findings and to investigate data that can provide valid and reliable results for designers and typographers.

Legibility research might question the use of the classical experimental paradigm and make use of other methods in combination.

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How do Swedish online newspapers respond to the increased significance of social media?

Cecilia Teljas

KTH - Royal Institute of Technology Stockholm
Department of Media Technology and Interaction Design
Lindstedtsv. 3, SE-100 44 Stockholm
E-mail: teljas@kth.se

Abstract

This paper explores how traditional media institutions such as online newspapers meet the increasing popularity of social media. A case study of Aftonbladet.se was conducted in order to understand how one of the main Swedish online newspapers uses social media and relates to this new media form. The most important verification of the influence of social media on Aftonbladet is shown by the way its role as an online newspaper is expressed: "Aftonbladet wants to be a meeting place (…). The whole experience builds on interactivity and community." The case study results of Aftonbladet's social media use are interesting because they offer indications of Sweden's leading newspaper's take on new media development and of the reasoning within the newspaper around the changing user relations.

Keywords: convergence, interaction, online newspapers, social media, users.

1. Introduction

Social media have become increasingly popular and compose a growing part of the total daily media use. During a typical day in Sweden in 2010, among people aged 9-79 years 19 percent read online newspapers and 35 percent used social media (Nordicom, 2011). This relation raises the question of how traditional media institutions such as online newspapers meet this new competition on their audience time. Accordingly, Nygren and Zuiderveld (2011) state that there is cause to discuss the roles media companies will play in the network society.

Previous research indicates that the amount of interactivity offered by Swedish online newspapers websites has increased since mid 2000 (Karlsson, 2010; Nygren and Zuiderveld, 2011). However, research by Chung (2008) shows that online audiences do not extensively use interactive features. In a Swedish context, Bergström (2008) also found that the general audience shows little interest in participating in creating content on news sites. The same study found the active group to be small, as only 16 % had commented on a news article during the past 12 months. According to Picard (2010) the use of many social media and new technologies in traditional media online in most cases only serves 5-20 percent of the entire digital audience. Furthermore, Swedish media companies have been claimed to lack strategic plans (Alström and Hedman, 2008; Picard, 2010). According to many media representatives it is no longer possible to plan more than six months ahead, due to the continuous technological and behavioral changes (Alström and Hedman, 2008). Although possibly lacking strategic plans, or perhaps as a result of this, Swedish media companies have been early in implementting new innovations. Deuze et. al. (2007) point out the Scandinavian countries as suitable for identifying emerging practices in the area of participatory media-making. Altogether, several aspects of previous research indicate a relevance for further research on social media use and strategies of Swedish online newspapers.

This paper aims to present an overview of the social media use of the leading online newspapers in Sweden. The study has a newspaper perspective and its main focus is on the social media use for conversational interaction on online newspaper websites.

The general research question of this paper is: *How do Swedish online newspapers respond to the increased significance of social media?* In order to answer this, the following four underlying questions are to be answered: First, *what kinds of social media features do the most visited Swedish online newspapers offer?* Second, *in what ways does the most visited Swedish online newspaper Aftonbladet use social media for conversational interaction with its users?* Third, *in what ways have social media affected online newspapers and their editorial content?* And fourth, *how and to what extent does Aftonbladet work strategically with social media?*

A mapping of social media features on the websites of the five most visited Swedish online newspapers *Aftonbladet*, *Expressen*, *DN*, *SVD* and *GP* (Orvesto, 2011) was conducted in the spring 2011. This initial, condensed study was followed by a richer case study with focus on the social media use of the newspaper *Aftonbladet*. The website *Aftonbladet.se* was chosen as a case study object partly because it is the most visited Swedish online newspaper (Orvesto, 2011) and partly because of *Aftonbladet's* past record of being early in introducing new technology and services. An example of such early moves by *Aftonbladet* could be seen when the online newspaper responded to the increasing popularity of social media services such as Facebook and YouTube abroad, by launching an own community and video service for its users in 2008. The *Aftonbladet* case study was also conducted in the spring 2011 and is based on a review of the online newspaper's social media use on its website and two interviews.

The interviews were held with the acting manager for reader contribution and a media analyst at *Aftonbladet,* in March and April 2011. These provide additional information about the social media (related) features and complement the analysis of function and content. They gave insights into the discussions, ideas and experiences surrounding the social media use within *Aftonbladet* in terms of motivations, identified problems and goals.

In the interviews, questions were raised about how Aftonbladet's works with social media in a more strategic way: Have social media affected the journalistic work or the role of the online newspaper? How is the development of social media features on the website planned, given the fast changes in digital media? How and why does Aftonbladet use social media? Is the UGC used editorially?

After the terrorist attacks in Oslo and Utoya, Norway in the summer 2011, a major public debate arose in Swedish media on how online newspapers should manage abusive behavior in their commentary features. The consideration resulted in modifications of several online newspapers' commentary features intending to raise the quality of the discussions. This example showed that the use of social media features on their websites has forced online newspapers to reassess their management of these features and also to consider their role in the context of user-generated content (UGC) on their websites. The debate uncovered uncertainties surrounding the social media use in Swedish online newspapers and thus indicated tendencies typical for Jenkins' theories on media convergence (2006).

The next section contains a brief discussion of the concept *social media*. Then follows a section describing earlier research on social media use of traditional media and news site producers', and related theory. Subsequently, the study results are presented starting with the results from the mapping of the main Swedish online newspapers' social media use, followed by results from the *Aftonbladet* case study. The last section consists of discussion and conclusions.

2. Social media

The concept *social media* is not consistently defined in academic literature. Generally, some sort of user participation or interaction is central to the concept. Social media typically allow many-to-many communication and often combine different features of previous computer mediated communication forms (Hogan and Quan Haase, 2010). Currently, social media may include all of, or different combinations of the following digital features: blogs, social networking sites, forums/chat rooms, media sharing sites, podcasts, videocasts, livecasts, wikis, social news, social games, social bookmarking, collaborative project spaces.

The concept social media may also be understood by individually defining the composing terms *social* and *media*. The concept *media* can be interpreted conventionally. However, the term *social* in social media is problematic, since all media have a social element (Hogan and Quan-Haase, 2010). Furthermore, *social* can in this context refer either to *the situation*, or to *the effects* of social media. In the former sense, it is meant that the user is *being social,* whereas the latter sense implies that social media are being used to *strengthen or maintain social bonds* between users. As opposed to traditional mass media (print, radio and television) social media enable many-to-many communication. Furthermore, the content is typically produced by its users and published online. However, despite all these social affordances social media may also be used in a private, closed and non-social manner. In this paper, the concept social media is understood in a technology-oriented sense as *web-based applications, enabling many-to-many communication that is published online.*

What is here described as *social media features* are by some researchers instead referred to as *interactive features*. For instance, Deuze (2003) relates interactivity dimensions to news website design, and uses three types:

navigational interactivity, which refers to site navigation affordances (such as menu bars and links, for example); *adaptive interactivity*, which means that the users' actions have consequences on the site content (such as allowing upload of content, offering chatrooms, etc.); and *functional interactivity* that allows users, at least to some extent to participate in the production process of the site by interacting with producers or other users (for example through email-links to journalists and moderated discussion lists). However, while conducting the study, it emerged that some of the studied features were only indirectly related to the described interactivity classifications. Therefore Deuze's interactivity model is not used in this study. Instead, the more open expressions *social media features* and *social media related features* are used to describe the affordances studied at the Swedish online newspapers. In this context, *social media features* include e.g. commentary features allowing users to publically comment on articles. *Social media related features* typically include hyperlinks to external social media platforms and information about related social media activities, etc.

3. Traditional media and social media

This section presents some previous research on traditional media's use of social media and UGC relevant to this study. Since this study has a focus on online newspapers, the emphasis of this section is on this industry.

A study of user participation on American and European (but not Swedish) newspaper websites by Rebillard and Touboul (2010) shows that the websites studied did little to invite page visitors to participate. Only one in four of the studied newspapers published users' reactions on their website and the authors concluded that their study supports the claim of journalists and editorial staff maintaining their domination and control in news media, and thus contradicts the conception of a digital revolution in journalism.

In his study of the British tabloid *The Sun* and the Swedish online newspaper *Aftonbladet,* Örnebring (2008) finds that the only UGC that was given similar status as material produced by the news organization was user photos of breaking news events. Holt and Karlsson (2011) discover tendencies of traditional patterns even in citizen media production. For instance, their study shows that much of the "citizen" contribution can actually be traced to professional journalists, lobbyists and organizations. In an overview of earlier research, Bergström (2008) finds that user participation mostly means feedback from users to producers, not content creation. All these studies indicate that the way content is produced and presented in online newspapers has not changed remarkably. This can be explained by previous research stating that news organizations are still working out whether and how to integrate user participation within existing norms and practices and how to implement and utilize such features (Hermida and Thurman, 2008; Chung, 2007). Chung (2007) also describes that several site producers had explored interactive features facilitating interpersonal communication, but then drawn back from fully incorporating such features because the conversational environment was difficult to control.

In recent media discourse two main standpoints can be recognized regarding the general impact of social media. On one hand, social media are regarded as revolutionary and democratizing tools because they offer anyone the possibility to publish their own thoughts and ideas (Benkler, 2006; Gillmor, 2004). On the other hand, criticism of Internet's democracy effects is also raised. Challenges of participatory culture mentioned by Jenkins (2006), include racist and sexist contributions and deep-rooted hostility between different groups. In parallel, news organizations have on one hand been criticized for conservatism and slow adoption of interactive publishing techniques (Bergström, 2008). On the other hand criticism has also claimed the opposite, that news media should reassess their use of social media and consider their actual benefits for journalism and the business for journalism (Picard, 2010).

Regarding problems and concerns related to social media features, the following aspects are commonly mentioned in previous research: Legal and quality issues, increased workloads, costs and fear of being marginalized. The concern about *the quality* of the UGC is commonly raised as a problem with social media features (Bergström, 2008; Chung, 2007). *Legal issues* are also considered important. In Sweden, e.g. the editor-in-chief is legally responsible for what is published on the website, including the UGC (Bergström, 2008). The fear that these features will lead to an *increased workload* typically refers to the need of quality control, editing and moderating of UGC (Bergström, 2008; Chung, 2007). Moderating is considered important to keep the quality of discussions high (Paulussen and Ugille, 2008; Chung, 2007; Hermida and Thurman, 2008). *The costs, both* for implementing and maintaining social media features are also declared a problem (Bergström, 2008; Chung, 2007; Hermida and Thurman, 2008). Lastly, the *fear of being marginalized* is identified as a factor that seems to affect decisions on social media use. A study of British online newspapers integration of UGC shows that fear of being marginalized by user media is one reason for an increase in adopting such features (Hermida and Thurman, 2008). In a recent Swedish study, Nygren and Zuiderveld (2011) similarly note a fear among online newspapers of not keeping up with trends, of doing wrong or missing important arenas. Despite the perceived challenges described above, previous research also shows that there is a general awareness of the importance of UGC and user participation (Paulussen and Ugille, 2008; Chung, 2007).

According to Bergström (2008) comments on news sites are typically written by frequent online news users who tend to be interested in new technology. However, overall Bergström (2008) found "*little general interest in the kind of participation demanding more activity and creativity from the users when it comes to news sites*". From their assessment of past work on online news consumption, Mitchelstein and Boczkowski (2010) state that during the past few years the user habits of online news consumers have not changed drastically, despite the increase of sites and technologies. As mentioned in the introduction, according to Picard (2010) only 5-20 percent of the total audience is served by social media and services based on new technology in news media. Interestingly, previous research also shows that user contributions are appreciated by the more passive users (Bergström, 2008; Larsson, 2010). Nevertheless, an example from the television industry shows that viewers of user-generated videos broadcasted by traditional media find the content quality to be crucial for the experience. The conclusion is that participation is not enough, media consumers demand high quality, also for user contributions (Carpentier 2009). Jenkins' theory describing convergence culture (2006) as a transition period is relevant when studying the uses of social media by news site producers, and may help understand the development occurring around social media. Jenkins maintains that this period is among other effects characterized by unclear directions and unpredictable outcomes. Furthermore, he emphasizes that convergence refers to a process, not an end point and states that convergence involves a change both in the way media is produced and in the way media is consumed. One of the central characteristics in his idea of convergence culture is *"increased contact and collaboration between established and emerging media institutions"* (Jenkins, 2006). Furthermore, Jenkins (2006) presents the concept of "affective economics" used in marketing research, which is much related to the matter of companies' social media use. According to this theory, engaged consumers are believed to be the most loyal, and an ideal consumer is described as active, emotionally engaged, and socially networked.

4. Social media features on Swedish online newspaper websites

This section gives an overview of the use of social media and social media related features on the websites of the five most visited Swedish online newspapers (Orvesto, 2011): *Aftonbladet, DN, Expressen, GP* and *SvD*. The reason for including this description is the ephemeral nature of new media features online. Both the social media related features offered and their uses most likely evolve continuously. Therefore, this part both serves as an overview and a snapshot of the social media features available on the websites of the studied online newspapers in the spring 2011.

Figure 1:
The typical newspaper website contained most of the social media related elements marked in the screenshot (Aftonbladet.se, 2011)

The studied newspaper websites contained several social media features and related elements. Although the layouts and styles of the websites studied varied, the features and elements numbered from 1 to 5 in Figure 1 were used by all of the studied online newspapers at the time of the study.

1) The amount of Facebook recommendations made to the articles is displayed. Articles that allowed users to add comments sometimes also showed the number of comments made.
2) Links to blog posts about the articles were published in the article fields.
3) Facebook recommend buttons enabled Facebook users to easily show the articles to their friends.
4) Links for article sharing via external social media platforms e.g. Facebook or Twitter were also used.
5) Below the articles there were forms for adding comments and a field with posted user comments.

Comparisons of the studied online newspapers' uses of social media related features showed that all five newspapers offered Facebook sharing of articles. Some of them also offered content sharing through other services such as Twitter, the social bookmarking service del.icio.us and the Swedish link sharing website Pusha. *Expressen* was the only newspaper to offer a long list of possibilities for article sharing with links to Bloggy, Digg, FriendFeed, MySpace and other services. However, overall the similarities in the social media related features offered by the studied websites were striking. Email is not regarded as a social media but is included in table 1 for comparison.

Table 1: Possibilities for the newspaper consumers to share and save article content

Online newspapers	Share by email	Share on Facebook	Share on Twitter	Share on Pusha	Add to del.icio.us
Aftonbladet.se	X	X	X		
Expressen.se	X	X	X	X	X
DN.se	X	X	X	X	X
SVD.se	X	X	X		
GP.se	X	X		X	

At the time of the study, *Aftonbladet* and *SvD* both belonged to the media company Schibsted and used the same Content Management System (CMS), Escenic. *Expressen* and *DN* were parts of the Bonnier media company and used EPiServer and Bink respectively, whereas *GP* was owned by the media company Stampen and used the Polopoly CMS. The selection of affordances offered by the newspapers shown in Table 1, indicates that ownership, rather than CMS did impact which features were offered. This observation implies that some differences may be explained by corporate level strategic decisions. In contrast, a comparison of Facebook features offered (seen in table 2) showed significant similarities based on genre rather than ownership.

Moreover, table 2 shows that all of the five online newspapers allowed article comments, which is remarkable if compared to the results of Rebillard & Touboul (2011), showing that only one in four online newspapers published users' reactions on their websites.

Table 2: An overview of online newspapers use of the following social media related features

Online newspaper	Comment	Facebook like box	Facebook interaction	Links to tweets	Links to blog posts
Aftonbladet.se	X	X	X		X
Expressen.se	X	X	X		X
DN.se	X				X
SVD.se	X			X	X
GP.se	X				X

Only the evening papers *Aftonbladet* and *Expressen*, used boxes for "Facebook like" and "Facebook interaction". The "Facebook like box" had a hyperlink to the newspapers' Facebook page, a "Facebook like button" and information about the number of people liking the page. Users being logged in to Facebook while visiting the online newspaper could see a personalized box showing news content shared by their Facebook friends; here called the "Facebook interaction box". Table 2 shows that all five newspapers published links to blog posts written about their articles and enabled user comments to at least some of their content. Some of the newspapers allowed anonymous comments whereas others demanded some form of registering in order to use the feature.

After the attacks in Norway, in July 2011, a major publicist debate arose on the commentary features in Swedish online newspapers. Although discussions about the occasionally harsh tone in the commentary feature had been ongoing prior to these events, they now became intensified. This public debate resulted in a closing down of all commentary features of many major online newspapers. In September 2011, *Aftonbladet* re-launched its commentary feature with a mandatory Facebook login for users wanting to post comments. The acting manager for reader participation at *Aftonbladet*, found the new system to have improved the debate climate (Westin, 2011). Almost two years later, in June 2013, *Aftonbladet* still used "Facebook comments", *Expressen* had closed all commenting, *SvD* and *DN* offered commenting after login (Facebook, and other options), and *GP* had just closed down commenting again due to recent legal unclarities.

5. The use of social media and its effects on *Aftonbladet*

As was seen in the previous section, the studied online newspapers were in many ways remarkably similar in terms of their social media use. The subsequent separate description of *Aftonbladet's* social media use is based on a review of the website and material from the two interviews described in the introduction. In spring 2011, *Aftonbladet* used different social media features. Four such features, commentary, *Debatt-live* (live debate), *Cover-It-Live* and *Superlive* were found on its website. *Aftonbladet* also held social media services outside the own website: *Aftonbladet Blogg*, *Snack,* and *Mitt Klipp*. Lastly, *Aftonbladet* used the external social media services *Facebook* and *Twitter* to communicate. All the mentioned features and services are described in this section. Lastly, interview results in terms of the respondents' reflections on the online newspaper's social media use and the perceived effects of this on the online newspaper are presented.

Most of the articles on *Aftonbladet.se* allowed commentary. The comments made were published in a thread, visible for all page visitors. However, in order to add a comment the user had to register with an email address. It was possible for *Aftonbladet* editorials to follow discussions and delete remarks that were believed to spoil the discussion or break against the rules. However, the majority of the moderating was done by an external company post-moderating all comments. In spring 2011 about 6000-7000 comments were made daily on the website. Overall, politics and sports raised most comments.

According to *Aftonbladet's* acting manager for reader participation (Stockholm, 17 March 2011) - henceforth referred to as Interview A - *Aftonbladet* had *"self-evident rules such as that one is not allowed to degrade ethnic groups, threaten anyone, etc."* But *Aftonbladet* also tried to keep the discussions on a reasonable level *"so that one criticizes opinions and not people."*. The respondent had also learned from experience that the discussions in the user comments were improved when the newspaper's journalists were active and asked the commentators to keep a proper tone.

In 2011, *Aftonbladet* introduced the feature *Debatt-live*. Every weekday a topic was raised for discussion, and the users were encouraged to participate with questions and comments. The matters discussed in *Debatt-live* were typically related to articles about some current issue. A live debate might consist of a debate between two experts with different standpoints and a moderator lifting users' questions and comments to the discussion during the debate. Alternatively, the users were invited to discuss a topic together with an invited guest or expert and thus contribute more actively to the discussion.

Aftonbladet also held a *Cover-it-live* feature in which a journalist followed a course of events live whereas the users were invited to participate by asking questions or making comments. This feature was used in different ways: users could be invited to chat with experts, interact with reporters or use the chat as a tool for referencing. In March 2011, *Cover-it-live* sessions were held to report news from Fukushima in Japan. In this case, a journalist followed news about the catastrophe in Fukushima while reporting these in a live chat. Meanwhile, users could ask questions and share information and links in the same chat window.

The *Superlive* feature was introduced by *Aftonbladet* in 2010 and was used to present large events live. During the first year, it covered a royal wedding in Stockholm, the Swedish Idol finale, the Nobel banquet, the parliamentary election and other media events. During *Superlive* events the whole *Aftonbladet* website was topped with live TV, chats, Twitter feeds, *Cover-it-live* coverage and interactivity. *Superlive* may be described as an extended version of *Cover-it-live*. The interactive aspect of *Superlive* was emphasized in one of the interviews (Interview A, 2011): *"Much focus is put on live feeling and contact with our readers"*. *Superlive* aimed to offer a common experience for the users, and social aspects were prominent.

In addition to the *Aftonbladet* website, at the time of the study the newspaper also held two major social media platforms; the community *Snack*, and the blog service *Aftonbladet Blogg*. *Snack* allowed its users to create a profile page, send/receive messages, discuss, and share photo/video content. *Aftonbladet Blogg* offered the general public to create and run a blog but was also used by reporters, chroniclers and invited guest bloggers. However, both these services were closed down in June 2011. The community *Aftonbladet Snack* had been introduced in 2008, with the ambition to create stronger bonds to users and make them increasingly participatory. The goal had been to aggregate UGC from *Aftonbladet's* blogs, its forums and *Aftonbladet's* UGC video-service *Mitt Klipp (My Clip),* which was closed down earlier in 2011. Moreover, *Aftonbladet* also had external activities on Facebook, i.e. the *Aftonbladet* Facebook page was introduced in 2010. Wall postings made by *Aftonbladet* typically consisted of a question connected to an article link to *Aftonbladet.se*. The link comprised a header, an image and a short text describing the news article. In spring 2011, *Aftonbladet* typically posted content on the Facebook page twice a day during weekdays. Responses to these postings, in terms of comments and likes varied. Wall postings made by page visitors were intermittent and overall non-editorial postings consisted of possible news topics, event recommendations and questions about *Aftonbladet's* digital features and services.

Aftonbladet also held separate Facebook pages for several of its editorial departments. Furthermore, some departments as well as some individual employees used Twitter, more or less representing *Aftonbladet*. These activities were based on individual initiatives and *Aftonbladet* had no general policy for Twitter use. At the time of the interviews, the users were believed to primarily use Facebook, whereas Twitter was considered to be narrower.

The most important verification of the influence of social media on *Aftonbladet* was shown by the way its social role was emphasized: *"Aftonbladet wants to be a meeting place, it could be in terms of comments or Cover-it-live coverage (...) The whole experience builds on interactivity and a sense of community"* (Interview A, 2011). This identification was the result of a branding project at the online newspaper, and is thus closely related to strategic aspects of the company's social media work. This turned out to be a key description of how the social media use was reflected on within *Aftonbladet*. In spring 2011 *Aftonbladet* had started to let go of their community-like services because *"it is not the role of Aftonbladet to directly compete with Facebook and YouTube."* (Interview A, 2011). Instead, *Aftonbladet* decided to focus on what was identified to be its strength, professionally produced news content. However, since people spend much time on Facebook, the importance of being mentioned there had been reflected within the company. It was believed that in the future much would be centered on social media but without knowing exactly how. The question how much *Aftonbladet* should do outside the own site had been raised. At the time of the interviews, *Aftonbladet* used social media to drive traffic, get user contact and input, make inquiries, ask people of their opinions and strengthen the brand.

The commentary feature had become very successful and had exceeded all expectations. The manager for reader contribution at *Aftonbladet* said that it is evident that *Aftonbladet* has a lot of discussion on the site, but it could be discussed if they should work more with raising the quality of the discussions or do this in a different manner (Interview A, 2011). A focus group project conducted by *Aftonbladet* showed that users want to know what others think, even those not taking part in the commentary discussions. However, the same project also showed that too much fuss is detrimental for the experience. In terms of news production, the discussions in the commentary feature had given *Aftonbladet* some good cases and ideas leading to breaking news. There was at the time of the interview no systematic way of working with those examples, although it had been identified as a way of working to develop. Overall, social media were believed to have affected the journalism to some extent, but otherwise the changes were still considered rather small.

The manager highlighted that it is problematic for a mass media company to enter the social media arena, as it is not possible to start talking personally with everyone. Instead they have to find a middle way: *"At the moment Facebook works rather well for us, but if we start having five million readers there…"* (Interview A, 2011). Moreover, the *Aftonbladet* Facebook pages were initially created by enthusiasts in the editorial staff and not based on strategic decisions. After some more or less successful efforts to try new ideas a need for guidelines started to emerge. This need also arose from the growth of users on the Facebook pages, which made it increasingly important to have some idea of how to act and what to do there. However, the guidelines were still quite rudimentary and there were plans on continuing to sort out how to work with these aspects.

Regarding the fast changes in technology developments and user behavior, *Aftonbladet* tried to keep up with what happened, but also had some long-term thinking around how they wish to work (Interview A, 2011): *"Much is uncertain as behavioral patterns change quickly for media consumption and online activities. Furthermore, the constant introduction of new devices for media use also makes predictions complex."*. Generally, *Aftonbladet* used to experiment with new ideas and see how they turned out, whereas they today increasingly have a more structured way of working, with proper goal statements. The general condition was that they worked according to present circumstances, with the reservation that in two years it might be quite different.

6. Discussion and conclusions

As described earlier, Rebillard and Touboul (2010) found that European and American online newspapers did little to invite users to participate and only sparsely published users' reactions. The continuous development occurring in online media practice makes asynchronous comparisons difficult and uncertain, and there may also be cultural variations. Nevertheless, the results of this study of Swedish online newspapers offer a rather different picture and indicate a development towards more interaction and increased use of social media features on the websites.

The mapping of five major Swedish online newspapers and the Aftonbladet case study in particular, both show features supporting several levels of user participation. The concept of social media can be understood as media used to support and manage social relations. However, the social media features found on the studied online newspapers' websites, e.g. the commentary feature, primarily seemed to afford the act of being social. Yet, some of the social media related features such as the article sharing feature for Facebook indirectly supported existing social relations.

Generally, the five online newspapers studied showed significant similarities regarding social media use on their websites. This clear tendency may be explained by several factors. As found by Nygren and Zuiderveld (2011) there seems to be both an uncertainty among many Swedish media companies regarding how to use social media and a fear of being left behind. By offering the same portfolio of social media features as the main competitors, the online newspapers reduced the risk of losing users to competitors due to lack of features. Overall, in accordance with earlier research (Hermida and Thurman, 2008; Chung, 2007) this study indicates that the social media uses of the studied online newspapers were still rather explorative in 2011.

As mentioned before, Hogan and Quan-Haase (2010) maintain that all media have a social element. It seems *Aftonbladet* had taken its social function one step further by its social media use and particularly its aim to be a meeting place and deliver an experience built on interactivity and community. This development is in accordance with Jenkins' (2006) description of affective economics. Particularly the blogs, the commentary feature and the live chats offered by *Aftonbladet*, encouraged and even depended on user commitment. In the long term, getting users to participate may create a stronger brand loyalty. In a shorter timeframe, participation results in users spending more time on the websites and thus generating increased advertising revenues. After some hesitation and internal discussions, *Aftonbladet* formally decided to invest in activities outside its own site, specifically by working with the *Aftonbladet* Facebook page. The aim was to drive traffic, interact with users and strengthen the brand. Jenkins (2006) identifies "increased contact and collaboration between established and emerging media institutions" as a central characteristic of convergence culture. Such trends were distinctly seen in Swedish online newspapers' use of social media, e.g. by using Facebook boxes on their websites, linking to external blog posts and tweets, sharing opportunities through external social media services, and of course by holding Facebook pages. *Aftonbladet's* introduction of a Facebook login for its commentary feature is a distinct example of such increased proximity between established and emerging media institutions.

Chung (2007) found that several news site producers had experienced interpersonal communication difficult to control. This case study indicates that regarding social media use and UGC, the quality issue was one of the most emphasized concerns at Aftonbladet. A balancing between allowing users to contribute versus maintaining the gatekeeping role was found in the different social media features offered by *Aftonbladet*. The commentary feature could be regarded as a compromise: users were allowed to participate by sharing their opinions, however journalists rarely joined these discussions and it was still relatively unusual that they resulted in news content. The Cover-it-live and the Debatt-live features were both more co-creative, as users could to some extent contribute to the content production. On the other hand, the filtering was more extensive in these features. However, by introducing Facebook login for commenting, *Aftonbladet* and other online newspapers aimed to enhance the quality of the discussions and improve the debate climate. The aim to raise the quality of user contributions is supported by previous research concluding that the quality of UGC is crucial for users and that merely allowing participation in traditional media is not enough (Carpentier, 2009). Correspondingly, *Aftonbladet's* focus group study had shown that the quality of user contributions affects the overall experience of the website. Thus, it seems as the need for professional filtering and polishing will remain and that traditional media's gatekeeping role is at least to some extent supported by the users' demand for high quality content.

As mentioned in the introduction, Nygren and Zuiderveld (2011) state a need to discuss what roles traditional media will take in the network society. The results of this case study show that previously unclear directions indirectly seen at *Aftonbladet* had in 2011 been countered by a distinction of the newspaper's strengths. The discussions taking place on the Aftonbladet website - around its journalism - were identified to be the "big thing" at the newspaper. This identification appears to mirror a reconsideration of what the *Aftonbladet* product should be. *Aftonbladet* decided to focus on its core business: professionally produced news content and combine this asset with social media features enabling and encouraging users to interact about the news content in order to emphasize the social role of the newspaper. This clarification is probably an important step in the process of defining a new role of the online newspaper in the network society.

According to Jenkins (2006), convergence involves a change both in the way media is produced and consumed. This study shows that whereas social media did affect consumption related aspects in conventional Swedish online newspapers, they did not (yet) affect the news production significantly. The perceived limited effects of social media at *Aftonbladet* were perhaps related to the external moderating of the commentary feature. Although the journalists were encouraged to take part in the commentary debates by the department for reader contribution, placing the moderating on an external actor meant that the journalists could keep focusing on producing news content in a traditional way. This result is in line with previous studies of online newspapers (Bergström, 2008; Örnebring, 2008; Holt and Karlsson, 2011) displaying traditional patterns in news production and publishing. As mentioned above, this case study of *Aftonbladet* shows that user contributions still infrequently lead to news.

Jenkins (2006) states that an age of media transition is mainly characterized by unclear directions and unpredictable outcomes. Such signs are recognized in the results of the *Aftonbladet* case study. The claimed lack of long-term strategies within news organizations (Alström and Hedman, 2008; Picard, 2010) could at *Aftonbladet* most clearly be seen in the continuous policy changes regarding its social media features. It may be asked if it is fruitful to state long-term strategies in an unpredictable and continuously changing media environment. At *Aftonbladet* they mainly tried to keep up with the development in technology and media use and try to stay flexible. Nonetheless, some long-term strategies could be distinguished, e.g. in the identification of what *Aftonbladet* should be. Long-term strategies can sometimes become manifest as responses to perceived phenomena, e.g. testing new ideas may help identify what is and is not in line with what the newspaper should do or be. This could be seen when the services MittKlipp, Snack and Aftonbladet Blogg were closed down only a few years after being introduced. Closing these social media features was an act based on the strategic decision that *Aftonbladet* would place its journalism in focus. These closed down features were not directly connected to the editorial content and it seems they aimed to attract a target group broader than the one of the newspaper. The more recently introduced social media features Cover-it-live, Superlive and Debatt-live all used social media to support and extend the news content. The Debatt-live feature is a concrete example of a social media feature with explicit proximity to the editorial content and showed how journalism can be used to generate commentary discussions. By cutting off social media features not strongly related to journalistic content, *Aftonbladet* had found a way to refine its product and distinguish it from external social media services. Perhaps such adaptations of new media forms could be one key to more long lasting strategies for online newspapers' social media use.

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Comparing media use habits in Finland and Germany

Anu Seisto[1], *Anna Viljakainen*[1], *Juliane Kirchner*[2], *Joachim R. Höflich*[2]

[1] VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland
E-mail: firstname.surname@vtt.fi

[2] University of Erfurt
Department of Media and Communication
Nordhaeuser Strasse 63, D-99089 Erfurt, Germany
E-mail: firstname.surname@uni-erfurt.de

Abstract

This paper presents the results of a web survey carried out in Finland and Germany in combination with quantitative data of media use. Our findings indicate that looking only at the quantitative data on reading and time spent with media does not portray a full picture of how and why people use media. With the exception on magazine reading, both Finland and Germany are fairly similar when it comes to time spent with print media. Also, similar consumer segments were found in both countries. The most important difference between Finland and Germany observed in this study was that there was a wider variety of use contexts for which books were found suitable in Germany than in Finland. On the other hand, newspapers appeared to have several important roles in Finland. In both countries more attention should be paid on creating services for consumer segments that use both print and digital media side by side. These consumers are not traditional print users but instead very naturally shift between print and digital. It is clear that the markets for printed products are slowly but inevitably declining in both countries. Consequently, it is of utmost importance to find new attributes to characterize the consumer segments based on their needs for media products and services, and thus, to enable innovative solutions for the future, including print media.

Keywords: print media, digital media, consumers

1. Introduction and background of the study

There are many simultaneous forces shaping the magazine and newspaper markets and changing the core business logics. On one hand we experience media convergence, where the traditional media industry is integrating with the telecommunications industry and information technology (Küng, Picard, & Towse, 2008). It is shaping consumers' media use habits and opening up the markets for new competitors causing media and audience fragmentation (Napoli, 2003). On the other hand the advertising markets react to the changing economic climate and increasing amount of online media content, causing traditional media companies to experience a gradually deteriorating source of income. The power is shifting from media companies to people. Consumers have an ever increasing selection of content which they can consume when and where they want. Consequently, the basic quantitative exposure-based metrics used for selling media audiences for each media separately are no longer sufficient portrayal and justification on the media impact. (Napoli, 2011; Viljakainen, 2013a, 2013b)

In an increasing competitive environment it has become vital for traditional media to better understand consumers' attitudes and behavioural responses to media content and advertisements (Napoli, 2011, 2012), and on the role of different media in consumers' lives (see e.g. Viljakainen et al. 2010). In effect, the basic demographics (such as age and gender) seem to have a lesser explanatory power in media use. The thinking is shifting from provider-centricity to customer-centricity in both business models and audience research, because media convergence sets pressures on media firms to enter into service business and adopt new value creation perspectives. Service researchers (see e.g., Vargo & Lusch, 2004, 2008) have repeatedly argued that companies ought to understand the needs and circumstances of their customers in order to be able to develop economically sustainable offerings. Customer needs and wants are dynamic, changing over time, and therefore they are a driving force for innovation. However, the changing needs present a challenge for companies' capability to maintain customer understanding. Understanding what customers value goes beyond the obvious needs and wants into the less obvious criteria of valuation. This includes, for example, how customers value and experience the relationship or what kind of emotional needs they have. Such customer insight helps companies anticipate the changing needs and create innovations that break out of traditional conventions. (Korhonen et al., 2010) In recent studies, the significance of *customer experience* has been highlighted in particular (see e.g. Payne et al., 2008; Kaasinen et al., 2010). Helkkula and Holopainen (2011), emphasize that understanding the user experience is often crucial to launch successful new services. The key in collecting and analysing experimental data is the recognition that data on user experiences is multidimensional and relates to lived practices rather than to specific technical features or to the process between the user and the provider. (Ibid.) Furthermore it seems to be relevant not only to consider the socio-demographic information about the users, but also other data like individual value orientations or lifestyles. As an example, the presented German long-term study uses such data in form of so-called sinus milieus (Best & Breunig, 2011). Moreover, there is also a well-known German typology of media users based on the individual program and genre preferences as well as the interest for media reception and intensity of use. Examples for individual types are the "active family-oriented people", the "people with a wide range of interests" and so on (see the whole typology, Oehmichen, 2007).

According to Bengtsson (1995) the broad field of media use research may be summarized into three principal questions:

1. *How do we use the media?*
2. *Why do we use media?*
3. *How do we interpret and respond to the media?*

In this study we have mainly concentrated on the first two questions and used them to identify different user segments and their reasoning for using print and digital media in two European countries, namely, Germany and Finland. With the segmentation we aimed at finding data that would supplement demographic data in explaining media use choices and for making it possible to move towards a better understanding of how the consumers respond to different media. Results from the two countries are presented to point out similarities and differences in media use habits in two countries. Finland and Germany make an interesting comparison as both being Protestant/Lutheran countries, the printed book has a very important historical meaning for these nations. However, Germany is a considerably larger market with about 82 M inhabitants compared to the about 5 M in Finland. In addition, there are differences in the use of digital content based on e.g. the speed with which smart phones have penetrated the market and how people use social media. In Finland the penetration of smart phones per capita is above 80% whereas in Germany it is 30% based on data from 2013 (http://communities-dominate.blogs.com/brands/smartphone/). Hence, a considerably larger proportion of Finns have a device that enables the use of digital media content via a mobile phone. In social networking the difference is smaller, with 50% of frequent social media users (use social media services every day or almost every day) in Finland compared to 34% in Germany in 2010 (http://www.kantar.com/media/social/tracking-social-media-growth-in-europe/), and nearly 50% of internet users having a Facebook account in Finland compared to nearly 40% in Germany in 2012 (http://www.internetworldstats.com/stats4.htm).

1.1 Print media markets in Finland and Germany

The following section is divided into two parts. It starts with profiling the individual situation of print media markets in Finland and Germany, and ends with a discussion on the similarities and differences of the two countries.

1.1.1. Finland

The first decade in the 21st century was a highly successful era for printed media in Finland. During these ten years newspapers, magazines and books were published and sold more than ever in the history of print media. Since then, printed media has experienced a downward development trend and its share from the total mass media market has shrunk approximately ten per cent. Consumers and advertisers are increasingly investing resources in digital media. Despite these unfavourable developments, print media, especially newspapers, have a strong foothold in the Finnish media markets. There is a strong reading culture and an efficient morning delivery system that supports it. At present, the majority of newspaper and magazine revenue is still drawn from traditional print products. (Antikainen & Kuusisto, 2012; Statistics Finland, 2012) However, the production and delivery of high quality content to multiple platforms while confronting the increased competition from global players is a challenge for all traditional Finnish media because of the small language area. The business models for profitable digital publishing are yet to be established in magazine, newspaper, and book publishing.

There are over 200 newspapers published in a country that has only slightly over 5.4 million inhabitants, and when comparing the total circulations of daily newspapers to per capita, Finland ranks third in the world statistics (after Norway and Japan; World Press Trends, 2012). Over 90 per cent of Finns read a printed newspaper during an average week, and over two thirds read online papers (from PC, smartphone, or tablets/e-reading devices). Two thirds of Finns consider newspaper content and advertising trustworthy. (Finnish Newspaper Association, 2013) Even if newspapers have lost almost 100 million euros advertising revenues in years between 2000 and 2010 (Antikainen & Kuusisto, 2012), they still represent the biggest advertising medium in Finland with the share of 34 per cent (462 million euros) of the total 1.4 billion euros investment (TNS Media Intelligence & Finnish Advertising Council, 2012). However, as the newspaper business is moving to the web it is more difficult to sustain the current level of profitability because online advertising and subscription revenues are far lower than those of printed papers (Antikainen & Kuusisto, 2012).

Finland in also one of world's leading countries in magazine consumption, and there are around 3000 magazine titles published in Finland (Finnish Periodical Publishers' Association, 2013). However, very similar to the newspaper business, also magazine markets are experiencing a downward development trend. In effect, until year 2007 magazine publishing was a stable and growing business, after which the total volume of paid magazines started to decrease. At the same time magazine readerships and circulations are declining. However, when compared to world magazine markets, Finland has a strong tradition of subscribing magazines that are home-delivered.

Thus, the revenue models of magazine publishers rely heavily on steady standing order income, and less on advertising revenue that is highly sensitive to market economy fluctuations. (Antikainen & Kuusisto, 2012; Statistics Finland, 2012) Advertising revenue for magazines in 2012 was 146 million euros, which is only less than four per cent of the total annual media advertising investment in Finland (TNS Media Intelligence & Finnish Advertising Council, 2012).

Similar to the reading of papers, the reading of books has been declining in the past 20 years in Finland. Especially the younger generations read fewer books than in the early 1990's. However, reading is still one of the most common hobbies in Finland. (Statistics Finland, 2009) There are around 260 000 books sold annually in Finland, out of which less than 20 000 are digital publications (Finnish Book Publishers' Association, 2012). The sale of books has similarly experienced a slight downward trend since year 2006. Internet and the changed leisure time habits are the main reasons for the decrease in book sales in Finland. (Antikainen & Kuusisto, 2012).

1.1.2. Germany

There are very similar developments concerning the print market in Germany as in Finland, especially considering the shift of newspaper business to the web and the shrinking number of editions and loss of advertising in the last decade. Actually the German print media is still fighting with a strained economical situation. The sad climax of this development was the publication stop of the German issue of Financial Times in December 2012. In view of failing income through advertisements, other newspapers partially use new pay-models beside the normal subscriptions, where users can pay voluntarily for articles in their online presence (e.g. the campaign of the *taz*, one of the daily appearing newspapers, see Schlütz et al. 2012). In the field of so-called consumer or special-interest press (magazines) there is a similar situation. Of the 1 450 magazine titles published in Germany (Vogel, 2012), only nine still have an edition of about million copies. Symptomatic for this kind of press genre is the fact, that the sales figures of weekly or 14-day titles shrink continuously, but new titles (e.g. with content of new lifestyle concepts) which are published in a lower frequency (e.g. every three months) have been more successful.

Nevertheless, the addition of traditional print offers with an online presence (mostly with same contents) ensures a long range of potential readers (Röper, 2012). Accordingly, nowadays the web is seen more as a chance for the print market than as a threat. Various studies, especially in the field of news reception, confirm that web offers are used complementarily and not substitutively to the traditional media (Eimeren & Ridder, 2011). Also the so-called "ARD/ZDF Long-term study of mass communication", which collects empirical data about the use and evaluation of media of the German population since 1964, confirms this. The latest data from 2010 shows, that the use of the internet dominates with 86 minutes out of the daily media budget (if we disregard the values for TV and radio use) and only 23 minutes are attributable for reading newspapers and 22 minutes for reading books. In comparison the reading of magazines nowadays plays only a marginal role in the daily lives of consumers (6 minutes/day). From the previous survey in 2005 the amount has decreased by at least 50 %. Despite the dominance of daily internet use it must be noted that a considerable part of the activity of surfing within the web is for reading news, including, e.g. homepages of a traditional newspapers (Eimeren & Ridder, 2011). But even if the newspaper has the general image to be credible, objective and critical, only 44 % of the Germans have daily access to a printed newspaper (ibid.).

Besides the rise of the internet also the loss of interest for reading the newspaper within the age group of 14-29 year olds is often mentioned as one of the reasons for the strained situation of the print market. Having a look at this special group, the generation of digital natives, it is not surprising that the web use within this group is relatively high (144 minutes/day) while there is less time for reading the newspaper (only ten minutes/day) (Eimeren & Ridder, 2011).

1.1.3. Media-use statistics from Finland and Germany

To summarize the status quo of Finnish and German print media markets it is useful to make a comparison of the time spent on media in both countries. Obviously there are already differences concerning the total time spent on media on an average day. The Finns dedicate to media for 8 hours and 39 minutes a day (TNS Atlas Intermedia, 2012), whereas the Germans use media for 9 hours and 43 minutes (ARD/ZDF Long-term study on mass communication, 2010 see results in Eimeren & Ridder, 2011). The following table (Table 1) gives an overview of general media use in both countries and shows the proportion of the single media offers.

Table 1: Distribution of different media on the total media-use time in Finland and Germany on an average day (TNS Atlas Intermedia, 2012; ARD/ZDF Long-term study on mass communication, 2010 see results in Eimeren & Ridder, 2011)

	Finland (2012, %)	Germany (2010, %)
Television	30	38
Internet	26	14
Newspapers	7	4
Radio	19	32
Magazines	4	1
Books	6	4
DVD and video	2	1
Audio (incl. CDs etc.)	6	6

The internet use in Finland is more relevant during an average day, whereas in Germany especially the parallel reception of radio is distinctive (Best & Breunig, 2011). However it has to be emphasized that the German study is only conducted every five years. In all probability there is also a growing internet use in Germany as well as in Finland. When comparing to the audio-visual media of television, radio and internet, the time used on print media is lower in both Finland and Germany. The share of TV and radio from the total time spent on media is far bigger for the Germans than the Finns.

For a particular view on the use of print products, Table 2 shows the total time spent in minutes on newspapers, magazines and books distinguishing the gender and age groups for both Finland and Germany. It is important to note that the surveys are not fully comparable since the samples in the surveys cover Finns in the age of 15-69 years and Germans in the age of 14+. The Finnish survey on newspaper and magazine reading was conducted in TNS Gallup's internet panel involving circa 21 000 persons (TNS Atlas Intermedia, 2010). The German long-term study is based on a representative computer-assisted telephone survey with 4 500 persons, whereby the number of participants refers to the basic population of all German-speaking people in the age of 14+ (Germans, members of European Union or other foreigners) in German private households who have a landline phone (Eimeren & Ridder, 2011).

With a view on the reception of newspapers there are no surprising differences between the two countries, between the genders or the age groups. In total, Germans spend only three minutes more for reading the newspaper on an average day than Finns. However, the German data covers only data from print editions, and the data from Finland print and digital editions combined. Thus, the difference with comparable metrics would be even higher. Even though per capita the Finns are among the world leaders in subscribing and reading newspapers, the total time spent on reading is in fact not so different compared to the Germans.

Concerning the reading of magazines the data draws a completely different picture about the two countries. The time spent on reading magazines in Finland is more than three times higher than in Germany - in all age groups. This corresponds with the number of published magazine titles. As already stated in the previous section, within the Finnish market there are over 3000 magazine titles published, whereas in Germany there are only 1450 titles. Of course at this point the question about hen and egg could follow, but the results clearly show that magazines are not as important to the German consumers as they are in Finland.

Reading of books seems to be a common hobby in both Finland and Germany. Not surprisingly, the younger generation, reads more books than the middle-aged people, and women read more than men. There seem to be no dramatic difference between the two countries. However, it is worth noticing that compared to Finland the pensioners in Germany spend much more time on reading books. In effect, the data suggests that the Germans pick up their reading habits after passing the very busy years.

Table 2: Time spent (in minutes per day) in newspaper, magazine, and book reading in Finland and Germany in 2008 and 2010 (Statistics Finland, 2010, 2011; & TNS Atlas Intermedia, 2008,2010; ARD/ZDF Long-term study on mass communication, 2010 see results Best & Breunig, 2011)

		Finland (min. per day)		Germany (min. per day)
Newspaper readership in 2010[1]				
	Total	20	Total	23
Gender	Women	19	Women	21
	Men	21	Men	25
Age	15-24	9	14-29	10
	25-44	14	30-49	18
	45-59	24	50-64	27
	60-69	38	65+	41
Magazine readership in 2010[2]				
	Total	21	Total	6
Gender	Women	23	Women	7
	Men	19	Men	6
Age	15-24	14	14-29	4
	25-44	15	30-49	4
	45-59	21	50-64	8
	60-69	38	65+	11
Book readership in 2008, 2010[3]				
	Total	24	Total	22
Gender	Women	29	Women	27
	Men	18	Men	17
Age	10-24	38	14-29	30
	25-44	21	30-49	15
	45-59	19	50-64	18
	60+	19	65+	27

[1] Print and digital editions combined in data from Finland and only print editions in data from Germany
[2] Only print editions in data from both Finland and Germany
[3] Year 2008 data for Finland and 2010 data for Germany. The research method and target group for newspaper and magazine reading in Finland differ. Figures for book reading come from a telephone survey involving circa 20 000 persons aged 10+ (TNS Atlas Intermedia, 2009)

To summarize these statistics it can be mentioned that Germans spend more time with media during an average day, but the reception is more concentrated on audio-visual offers such as television, radio and internet. Nearly the same amount of time is spent for reading books (fiction and non-fiction) as wells as newspapers, but less time is spent on reading magazines. In contrast, the Finns have a strong reading culture, which can be seen in the time spent on daily media use. However, in the present media environment this kind of comparison based on a fixed viewing of single media is becoming outdated. As already mentioned, we must not forget the growing media convergence and the increasing number of cross-media and mobile offers (e.g. print newspaper and additional online presence or apps). Therefore it is very important to realize that also a consistent cross-media perspective is necessary if we want to explain motives for media use (Hasebrink & Schmidt, 2013). Especially in the context of mobile use the situational needs of a user influence the media choice.

2. Method

The study was carried out as a web survey in April-December 2012. The survey is part of a larger European consumer study carried out for the Print Power organization. The objective of the survey was to find out the role of printed media in the everyday life of consumers as well as their attitudes towards advertisements through different channels.

Web survey is a research method where respondents are invited to visit a website to complete an online questionnaire. This type of method enables the reach of large audiences that are spread across the world economically and fast, but it may lack generalizability of results due to a biased sample of a population. (Bryman & Bell, 2011). In this case, the respondents were mainly recruited through professional (such as newspaper publishers and trade magazines) and university networks. The aim was to attract respondents, whose media use was not limited by capability to use different platforms or by economic issues. Hence, it would be possible to introduce media use situations that are slightly futuristic. Thus, the aim was not to replace existing audience information systems and collect data that is generalizable to the population as a whole, but rather, to foresight possible development trends. Slightly over 200 replies were collected from Finland and Germany altogether. The resulting data was analysed with the use of PCA (Principal Component Analysis) in order to reveal any respondent segments based on how they evaluated the stories related to their media use habits. PCA is used when the amount of data and interrelated variables is vast, and the aim is to reduce the diversity to find new sets of uncorrelated variables (see e.g., Jolliffe, 2002).

The questionnaire was divided into three parts: (1) background information of the respondents, (2) reading, evaluating and commenting six narratives describing an imaginary person's media use habits, and (3) evaluation of the importance of advertising in different channels. The survey asked consumers to comment on different media use situations and ascertain how well these stories described their own media use. They were also asked to estimate the advertising channels that worked to grab their attention, were seen as trustworthy and useful, and where they would look for information to support their buying decisions. Especially the second part of the study seems to be of particular relevance considering the combination of quantitative and quailtative research elements. Therefore the evaluation included a quantitative scale ranking the narrative descrybing the respondents media use habits very well, quite well, quite poorly or very poorly as well as the possibility to give individual comments with own words. Using narrative media use situations and habits instead of direct questions about the individual media use make it easier for the respondents to reflect their own media use. In a broader sense they could compare their own behaviour with the one presented in the narrative and evaluate this. The combination of quantitative and qualitative elements within the study seems to be useful in view of research on the meaning of daily media use. Especially the possibility to give open answers allows more openness and flexibility for the respondent and helps the researcher to get an insight in the preferences and habits of the respondents. Furthermore in this way information will be delivered which helps to identify possible various types of users (segments) and describe these in detail (Berg, 2007; Meyen et al., 2011).

3. Results

The demographic profile of the respondents is presented in Figure 1. A larger proportion of young respondents could be attracted in Germany than in Finland. The largest age group was 25-34 in Germany compared to 45-54 in Finland. This resulted in a larger proportion of families with children living at home in Finland (42 %) than in Germany (21 %). In both countries more than half of the respondents had moderately money to spend after the essentials.

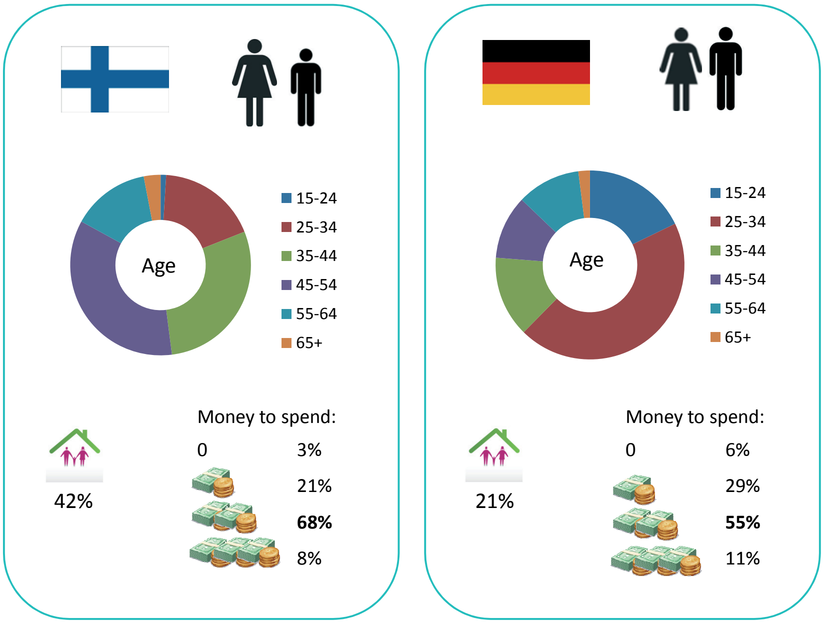

Figure 1: Demographic profile of respondents from Finland and Germany

According to the PCA analysis, four main consumer segments could be found in a sense of a typology elaborating differences in consumers' media use habits. These consumer segments were: (1) Slow bons vivants, (2) Busy mix-and-matchers, (3) Tolerant surfers, and (4) Youthful digilovers. Within these four segments, any possible correlations with the background information of the respondents were searched for. Our findings suggest, that in consumer segments that prefer and regularly use print media products, people in older age categories are over-represented. This is a general finding in literature that the heavy users of printed products are ageing, since the younger digital native generation appreciates less printed media (see e.g. Küng et al., 2008; OECD, 2010). However, this study also suggests that *age alone does not explain the choice of media and the role of advertising in print in the everyday lives of consumers*.

3.1. The four consumer segments

People in the *Slow bons vivant* -consumer segment have a very traditional way of using print media. Respondents in the Slow bons vivants segment are on average older than people in the other groups. Reading a printed newspaper is an important part of their daily routine. These people spend much of their day working with the computer, thus, they make a clear distinction between using print and digital media. Both mediums have their own roles and purposes. In effect, as these people live a hectic and stressful life, digital devices are not so commonly used in free time, since they remind of work. Slow bons vivant want to relax and enjoy their free-time, and a glass of wine while reading a book is not an uncommon activity. Also, magazines are quite often read in this segment. Along with newspapers, magazines, and books, people in this group find printed catalogues and direct mail enjoyable. Thus, as printed products are a common element in their lives, also print advertising is found trustworthy and useful. As a result, print advertisements - along with internet - are important sources of information to support purchase decision making.

People in the *Busy mix-and-matchers* -consumer segment live a busy family and working life, with children still living at home. For consumers in this group digital media is part of the everyday life, but at the same time they are strongly attached to print media which is considered a valuable part of everyday life. In effect, this group is very similar to the Slow bons vivants, with the exception that internet has a more important role in their lives, especially for finding information to support purchase decisions. The internet is used at home, but Busy mix-and-matchers also enjoy the quiet time being offline and reading. Tablets and e-reading devices are seen as useful for both working and relaxing. People in this segment use several different media channels, mainly based on what is most convenient for the purpose. Newspapers and magazines that are chosen to be read are trusted. Also, the advertisements in print are paid attention to and found useful. Information seeking to support purchase decisions is found in print, but also from digital media since digital devices are commonly used in this group.

People in the *Tolerant surfers* - consumer segment are on average younger than people in the first two segments. They are starting their careers after studies and living a very active life. They are heavy cross-media and cross-platform users. They are constantly online, but they also read magazines, as well as newspapers and catalogues. However, print media is not as actively used as in the first two consumer segments. Tolerant surfers often have a smartphone, which they use for various purposes: calling friends, listening to music and chatting with friends through social media services. Attitudes toward social media are much more positive in this group than in any other group. Tolerant surfers say they would read a book, if they only had more time. They are very omnivorous with many media types and notice and feel comfortable with advertisements in them. In effect, different media ads are found useful depending on the situation and circumstances. However, advertising on the internet and social media is not trusted in the same degree as print media advertisements. Internet as a medium is highly valued, but having several media channels to choose from is very important to this group.

Youthful digilovers, as the name describes, are young and constantly online. People in this consumer segment do not have specific needs for using print media and print is not a part of their everyday lives, even though it might be occasionally used. Interestingly, print media - magazines and newspapers - is however still regarded as the most trustworthy advertising channel. Digital media is an important part of relaxations, and as such, this group often plays online games or watches a movie from their laptops. Magazines, newspapers and catalogues are used very randomly, for example, while waiting in a dentist or with nothing to do if there is one at-hand that interests them. But generally, everything they need is found in the internet. Advertisements are not commonly paid too much attention in this group, because of lower purchasing power due to the young age. However, advertisements in print, TV, and internet can be useful. The role of internet search and recommendations from friends are very important for Youthful digilovers in making purchase decisions.

Regardless of the younger age of the German respondents, the proportion of respondents belonging to different consumer segments was very similar in both countries, as shown in Figure 2. The ways how Slow bons vivants and Busy mix-and-matchers described their media use were very similar in Finland and Germany. In these groups print media was highly valued and also actively used especially for relaxing. In the Tolerant surfers and Youthful digilovers groups some differences could be observed. Even though in these groups use of print media was not active, in Finland the respondents still valued advertising in magazines and newspapers quite highly. They mentioned paying attention to advertising in these channels and found the ads trustworthy and useful. This finding confirms with earlier studies which elaborate the strong relationship between Finns and the printed media. For example the Finnish Newspaper Association (2012) has found that even if the younger generation reads less printed media, 83 % of Finns under 35 years of age still consider newspapers valuable, 79 % credible, and 73 % trustworthy. According to the German data, the Tolerant surfers and Youthful digilovers groups find advertising in newspapers and magazines trustworthy, but in general printed advertising has a clearly less important role. Also, in general the German respondents in all segments pointed out the role of printed books more than the respondents in Finland.

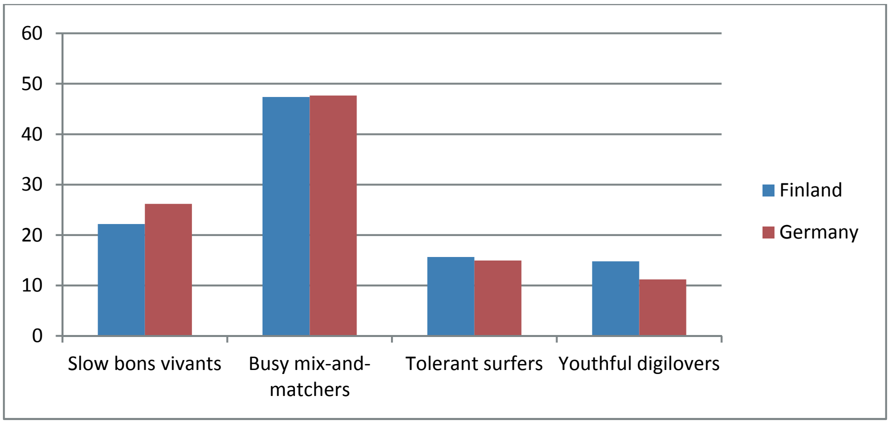

Figure 2: Proportion of respondents in different consumer segments in Finland and Germany

Even though the PCA analysis showed that the proportion of older respondents was higher in Slow bons vivants than in the other groups and the Tolerant surfers and Youthful digilovers were in general younger, all age groups were present in all four segments as shown in Figure 3.

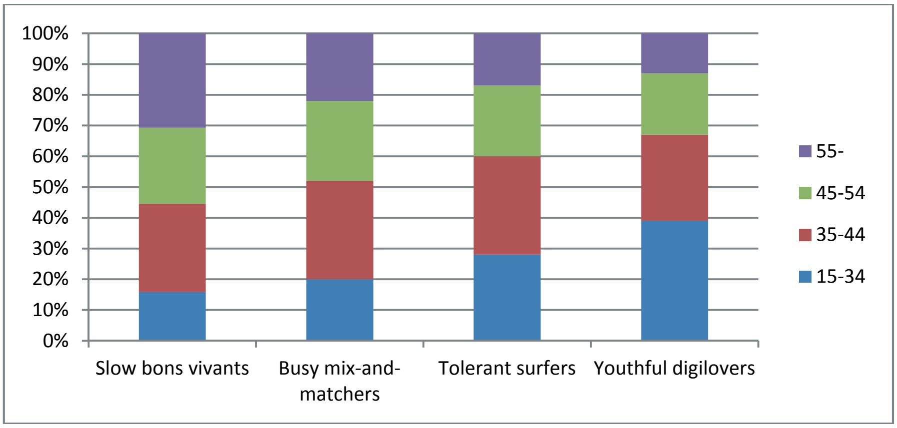

Figure 3: Proportion of different age groups in the four consumer segments

4. Discussion

Understanding the attitudes of the consumers towards advertising is crucial to the media business as media convergence and the audience evolution is very much blurring the traditional ways of consuming media. Consumers are gaining more power because they are faced with more choices in terms of both platforms and content. The new media empowers audiences to serve as both receivers and senders of mass communication. New technologies are changing media consumption habits. Consequently, consumers are getting less attentive to mass media vehicles. Legacy media companies and marketers are looking for better understanding on how to reach and impact consumers with media content and advertisements regardless of the platform from which it is consumed. In this development target group definitions are shifting from mere demographic portraits (such as age or gender) into something much deeper, looking at consumers' engagement to the media. Traditional measurement systems that see a passive audience are unable to measure audiences' behaviour and media use. In effect, not only is it important to understand how many people have exposed to a certain media and its advertising, but also, and more importantly, what was the response to the message (see e.g. Napoli, 2003, 2011; Viljakainen, 2013a, 2013b). More profound ways rather than demographic data should be used to understand consumers' media use habits. Based on these premises, the aim of this survey was to explore differences in consumers' media use habits. The findings suggest a typology with four consumer segments:

1. ***Slow bons vivants.*** People who consider themselves as traditional print users, and who make a clear distinction between using print or digital media for certain purposes.
2. ***Busy mix-and-matchers.*** People who enjoy and appreciate print media, and very naturally shift between print and digital. Interactivity in print is considered as a positive feature.
3. ***Tolerant surfers.*** People who use digital media more than print but have a positive attitude towards print. They also appreciate the possibility to choose from a large variety of media. Especially in Finland, use of social media services is frequent and valued in this group.
4. ***Youthful digilovers.*** People who consider themselves as digital users. This group sees no benefits in the use of print media.

Even though age correlations could be found, the data showed very clearly that all age groups were present in all consumer segments, and that *lifestyle and situation in life are very important factors guiding the media choices*. It is important to note that even though the German respondents were in general younger than the Finnish respondents this did not have an effect on the proportions of the four consumer segments. Based on the way the respondents evaluated the storylines representing examples of media use and the open answers that they wrote, printed products play an important role in the lives of the Slow bon vivants and Busy mix-and-matchers, they are present in the lives of Tolerant surfers, and fairly much absent in the Youthful digilovers' lives. Furthermore, the results of this study appear to strengthen the observations on the multiple roles of newspapers in Finland and books in Germany based on how they were valued by all consumer groups in the two countries respectively. In an earlier study of the attitudes of Finnish and German consumers to different media (Leinonen et al. 2009; Leinonen 2009), it was found that books had a special position among the German respondents. There was a wider variety of use contexts for which books were found suitable in Germany than in Finland. On the other hand, newspapers appeared to have several important roles in Finland.

Interestingly, the more important role of magazines as seen in the time spent on reading them (as presented Table 2) was not highly reflected in the open answers obtained in this survey. According on Leinonen (2009), the strengths of magazines are experiences differently in Finland and Germany. Finns tend to value the concept of magazine, i.e. the way it doesn't require concentration, offers short articles and plenty of photographs and colours whereas the Germans tend to value the content, i.e. interesting themes, background information and analytical content. One reason for the difference may be in the purchasing culture. In Finland magazines are mainly subscribed and in Germany mainly bought as single issues. Magazine reaching a reader at the home environment appears to result in a more personal relationship, as the Finns relate magazines to "I'll have a moment for myself" and "I want to reward myself" more than the Germans (Leinonen 2009). In this study, the respondents mainly commented whether they in general read magazines or not, but in the Finnish data it was also common to state how many magazines the respondent subscribed for. This more probably reflects the first responses to the narratives more than actual feelings towards magazines.

For being willing to pay for digital content, a recent study by Kuula (2013) suggests that a habit of purchasing or subscribing professional journalistic content in printed form plays an important role. In his study of the same group of young adults in 2006 and 2012, Kuula noticed that the group that had the most positive attitude towards print media was ready to invest some money for it as a student. This group also wanted to keep the tradition of reading professional journalistic content later in life. However, the platform will not necessarily remain the same. This group may be just as pleased with a tablet version of their favourite newspaper or magazine as they are with the printed version. Hence, they resemble very much the Busy mix-and-matchers segment of this study. Also a group that had a positive attitude towards professional content and print products as students but not enough time to spend with magazines or newspapers had started to subscribe them later on in life (Kuula, 2013). This would imply that, a segment such as the Tolerant surfers in this study could potentially start a habit of consuming print media.

From the print media value chain viewpoint, the Busy mix-and-matchers and Tolerant surfers would be very interesting groups to study in more detail. In these groups the attitude towards print media and professionally produced content was positive, which would imply that they would already have a habit or they would be ready to build a habit of purchasing magazine or newspaper content either in printed or digital form. In Finland, both groups also valued advertising in the print channels. In the German data, the position of print media was not quite as strong, but they were found as valuable advertising channels alongside with the Internet. Further studies with the Busy mix-and-matchers and Tolerant surfers could reveal more detailed knowledge of the similarities and differences between these groups and shed more light to the future of print media. In these two segments the consumers have a positive attitude towards print media, but their media use habits differ from traditional Slow bons vivants. Therefore, future print products should be designed to fit into the lives of these consumer segments better than they do today.

5. Conclusions

When considering the future of print media the media use habits of the consumers need to be taken into account. Also, as the fragmentation of consumers' media use continues, it is increasingly important to carry out studies which give new insight on how and why people use different media for different purposes. This makes it possible to identify potential audiences for print products as well as for chargeable digital content. It seems evident that dividing the consumers to digital immigrants and digital natives based on their media use habits is much too simplistic. In many cases, the consumers actually use print and digital content side by side, regardless of being more fond of print or digital products and services. Therefore future newspaper, magazine and book services should also be designed with a combined vision of the print and digital sides.

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The consumer perception of AR applications in Finland and Canada

Aino Mensonen[1], *Natalia Lumby*[2], *Maiju Aikala*[2]

[1] VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland
E-mails: aino.mensonen@vtt.fi, maiju.aikala@vtt.fi

[2] *Natalia Lumby*
Ryerson University
350 Victoria St., Toronto, ON, Canada M5B 2K3
E-mail: nlumby@ryerson.ca

Abstract

This research strives to identify the consumer attitudes towards augmented reality (AR) in two countries: Finland and Canada. In addition, the study explores whether these attitudes differ from one another.Focus group interviews and Q-methodology are used as research methods. First, focus groups are used for investigating consumer opinions, views and hesitations connected with AR applications. Derived from them are 25 statements describing attitudes towards AR to be used for the Q-sort. The results of focus groups indicate that AR was found useful, beneficial, attractive, interesting, fascinating as well as having a futuristic feel. The Q-sort analysis revealed six groups of shared attitudes towards AR based on the similar rankings of the statements: Techno Believers, Pragmatics, Entertainment Seekers, Sceptics, Marketers and Non-committals. Each group is described in the research to help guide decisions around the implementation and use of AR technology. Lastly, minor differences between countries are observed. The study indicates that, although some cultural differences in attitudes toward AR technology may exist, both countries show promise for future uses of AR that extend beyond how we are using it today.

Keywords: augmented reality, consumer perception, Finland, Canada

1. Introduction

Augmented Reality (AR) is a technology that augments virtual information on top of a camera view of the real world. The benefits of utilizing AR technology, as well as the user experience and acceptance towards this new way of presenting information are still unclear. While most studies in the area are case based and not as generalizable, a user-centric study by Seisto et al. (2012) focused on the technology acceptance of magazine advertisements that utilize AR technology. In this study, positive feedback was obtained from the users. There are few studies, where the user attitudes toward AR applications are studied across countries. Olsson and Salo (2011) have conducted an on-line survey on mobile augmented reality applications. They concentrated on applications without a link to print media, and the user group they studied was made up of early adopters. The results showed that the early adopter group had quite a positive experience with currently available AR applications. Gauzente et al. (2011) studied consumer perception of AR in shopping context including packaging applications in France and Russia. The study revealed that perceived usefulness is the main driver to use AR. In both countries it appeared that the younger the users are, the more likely they are to perceive AR positively and to use it in their lives.

This research paper extends the study completed by Gauzente et al. (2011) to other geographic regions, namely Finland and Canada, in order to interrogate the similarities and differences between the user perceptions of AR in additional countries and cultures, improving the generalizability of the findings. Further, including a variety of media applications, rather than focusing on packaging alone widens the scope. Similar methodology has been used, while adjusting the procedures to meet the needs of Finnish and Canadian consumers.

The aim of the research was to interrogate, what kind of attitudes consumers in Finland and Canada have towards augmented reality applications. In addition, the study anecdotally explored whether the Finnish and Canadian attitudes towards augmented reality applications differ from one another. Lastly, given the research methods used, the data was able to categorize user types into comprehensible groups. It is hoped that this contribution will allow companies that use AR technology to better focus their efforts to specific groups identified.

2. Research methods

The study was conducted in two parts. First the attitudes towards augmented reality applications were studied at the Nordic level. The statements of consumer attitudes towards augmented reality applications were then derived from the transcripts of the focus group interviews and tested by q-sort methodology among the interviewees. Secondly, the process was repeated with Canadian professionals. The q-sort statements derived from part one were kept consistent for the Canadian study to allow for easy comparison. The progress of the study is presented in the Fig. 1.

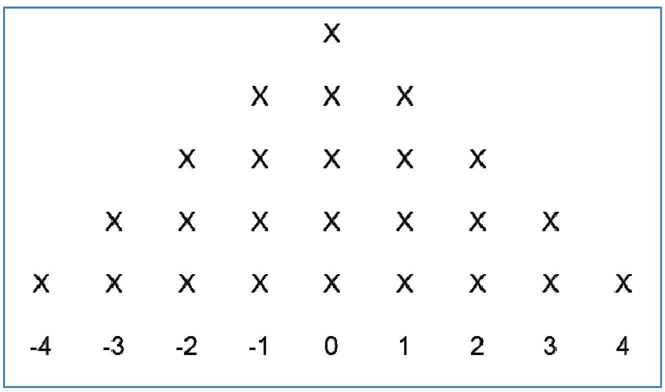
Figure 1: Progress of the study

Focus group interviews and Q-methodology were used as research methods. The aim of focus group interviews was to investigate consumer opinions, views and hesitations connected with AR applications. The interviews also served as occasions for giving a short briefing about AR to participants. The interview sessions consisted of four steps as follows:

1. Interviewees filled out a background information questionnaire concerning the communication devices they were using and their use habits
2. Interviewees were shown three examples of augmented reality applications
3. Trying on eyeglasses with mobile augmented reality (http://www.youtube.com/watch?v=agwFbTwg9HA)
4. Looking inside a box (http://www.youtube.com/watch?v=PGu0N3eL2D0)
5. Interacting with print media utilizing AR (http://www.youtube.com/watch?v=AjDjsmr0G14)
6. Interviewees wrote down their first impressions of AR based on the examples
7. Interviewees discussed their first impressions, sharing their thoughts on the mixture of virtual and real images, practicality of AR applications, and other application ideas.

Based on the focus groups, 25 statements describing interviewee attitudes towards AR were identified and tested using Q-sort methodology. A list of statements was presented to each study participant and the participant was requested to indicate to what extent he/she agrees with each statement. The convention in Q methodology is that the statements are sorted into a quasi-normal distribution, i.e. a bell-shaped curve (Fig. 2). Thus, the respondents may agree and disagree completely on only one statement and be neutral on several statements (Davis & Michelle, 2011).

Figure 2: Ranking of the statements into a Q-sort. Value -4 denotes 'most strongly disagree' and value 4 denotes 'most strongly agree'. 'X' denotes a statement



This has the additional benefit of avoiding answers that lack decisiveness and allow an overly neutral position. As an example, if people were asked to give a score between 1 and 5 to each statement, they might give the score 3 to every statement. However, in Q methodology this is not possible. Factor analysis by-person is then run from the Q sorts in order to identify a set of factors that represent inter-correlated groups of Q sorts. The groups of similar Q sorts typically have a shared and uniform point-of-view on the topic of interest (Davis & Michelle, 2011).

Based on their backgrounds, the participants formed three subgroups: professional groups in Finland and Canada, and a student group in Finland. The professionals represented mainly brand owners. There were 25 participants in each of the subgroups.

3. Results

3.1. Focus group interviews

The results of Nordic focus groups indicated that AR was found useful, beneficial, attractive, interesting, fascinating as well as having a wow factor. Some participants thought that AR usage was time consuming, while others deemed it time saving. In Canada the impressions of AR technology were primarily positive. The study participants felt that the technology was interesting, has potential value, and has a futuristic feel. In particular, there was a general agreement that there is a potential for the technology to improve the online shopping experience. Some participants also pointed out that AR could serve as a learning tool.

The need for a universal AR code reader is commonly sited as a key requirement for continued success. Costs from different perspectives were seen as an obstacle by the attendees of the focus groups in all Nordic countries. The applications must be easy to use and fast. The mobility aspect was also highlighted as the applications and content would primarily be designed for mobile use. In Canada, cost was not an area of focus, however ease of use was important. Further, there was definitely a type of user associated with AR; the young tech savvy individual who enjoys online shopping. Likewise, the group was interested in the mix of physical and digital content, but seemed to also find it a bit intimidating (always referring to the tech savvy persona) and very futuristic.

In the Nordic countries, there was a distinct willingness to try this AR technology, test its usefulness and value, and reap its benefits. AR was considered to encompass both information complexity as well as being ideal for leisure activities such as games. Further AR was considered to be win-win for both consumers and brand owners. In Canada on the other hand, the emphasis was on the consumer applications of AR. Over 80 % of participants agreed that AR has the potential to be practical and to offer some value. While over 90 % agreed that it has the potential to be fun. The practical application was most commonly sited as shopping (online or in-store) with the value-add being additional and more engaging information for the product. From an entertainment perspective AR was also seen positively, however some participants thought that it is a bit simplistic for gaming, and that there is a challenge to create return visits to the application once users had tried them.

There were also discussions about the motivation of the use of AR. Some of the participants commented on the cumbersome task of needing to download a separate application to us AR, as oppose to the technology existing built-in to the phone. We have seen this with other mobile technologies such as near field communication (NFC) chips and mobile visual search (MVS) (Lumby, 2012). While participants in Canada were very technically capable, only about half of them had ever personally tried AR technology before.

In the Nordic results, the group of printers was sceptical about the business potential of AR technology in relation to print media applications. One concern was that the AR application would shift the users' focus to the phone, thus keeping them on their mobile devices instead of returning to the printed product. However, the interactivity was seen as a clear benefit and AR was considered a plausible extension of printing. Also AR was seen valuable for the advertising industry in both geographical areas.

Based on the interviews, 25 statements concerning the attitudes towards AR were identified. The statements were categorized into six classes, which describe the different aspects of user experience: (1) instrumental experiences, (2) cognitive and epistemic experiences, (3) emotional experiences, (4) sensory experiences, (5) motivational experiences, and (6) social experiences. *Instrumental experiences* are pragmatic experiences, which originate, for example, from utility, user's accomplishments, and product performance. *The cognitive and epistemic experiences* are related to thoughts, human information processing and rationality. These experiences originate from the semantic features of the product or service and the abilities to arouse interest and fulfil the need for knowledge. *Emotional experiences* are related to the subjective emotional reactions stemming from the use of the product or service. *Motivational experiences* are created when the use of a product or service causes a particular behaviour in the users. *Sensory experiences* relate to product's or service's ability to arouse sensory and physical pleasure. *Social experiences* originate from interactions between humans, which are intermediated by technology. (Buccini & Padovani, 2007; Olsson, 2013) The statements and their categories are presented in Table 1. The main focus was on instrumental, cognitive and epistemic, emotional and motivational experiences.

Table 1: Statements concerning the attitudes towards AR

Instrumental experiences	Cognitive and epistemic experiences	Emotional experiences	Motivational experiences	Sensory experiences	Social experiences
Using AR with a webcam is too complicated. With a phone, it is ok.	I want to use AR to familiarize myself with products that I am not already familiar with.	AR is not surprising. I've already seen things like this before.	I don't understand how it works, it's too complicated. I don't want to try it.	One needs to be able to touch the product.	The combination of AR and social media would strengthen the effect of an ad.
The threshold for using AR is too high; you have to find it, and then install it, and after that you are able to use the application. You must have a strong motivation to do this.	Seeing an object through AR, it's good in store when you can neither see the object nor open the box.	It's playful and fun.	There is a risk that AR apps in a magazine will cause a focus shift and that the reader stays using the mobile phone after using the apps and does not come back to the printed magazine.		
AR needs to give added value to the readers of print media to be interesting for the publisher.	AR applications must involve all senses before I would use them for purchasing on the web.	AR is not a problem solver for print media but may increase consumers' interests towards magazines	I wouldn't have time to use AR.		
In the future AR would help consumer to see something concrete already in its planning stages (for example in interior design).		I like the way AR can be used to tell stories: it makes me interested because it stimulates a variety of senses.	AR is a great possibility for innovation; we have not seen the best ideas yet.		
One would use AR more, if the applications were accessible through screens inside stores.			Seeing a product through AR is not enough to make me buy it.		
AR gives print media the potential of interactivity which is a clear benefit.			AR is too expensive for me.		
AR would be helpful in assembly and installation application areas.					
Some articles are not commonly sold in web shops because consumer needs to try them on. If one could "try on" an article with AR, this could increase sale of those articles.					
Everyone is able to use AR.					
AR will be popular in the near future.					

3.2. Q-Sort Analysis

In the factor analysis of the Q-sorts six factors were identified. Each factor depicts a group of shared point of view on AR based on the similar rankings of the statements. The factors and the most important statements describing the factors are presented in Table 2.

Table 2: Six factors describing the viewpoints towards augmented reality based on the shared ranking of statements Abbreviations in the Table: SD is strong disagreement with the statement, D is disagreement, A is agreement, and SA is strong agreement

	Factor 1				Factor 2				Factor 3				Factor 4				Factor 5				Factor 6			
	SD	D	A	SA	SD	D	A	SA	SD	D	A	SA	SD	D	A	SA	SD	D	A	SA	SD	D	A	SA
Using AR with a webcam is too complicated. (…)		X											X											
I don't understand how it works, it's too complicated (…)	X								X				X				X				X			
AR is not surprising. I've already seen things like (…)							X		X								X					X		
I wouldn't have time to use AR.	X									X											X			
The threshold for using AR is too high; (…)		X						X								X			X					
There is a risk that AR apps in a magazine will cause (…)																X		X						X
AR needs to give added value to the readers (…)																								
AR gives print media the potential of interactivity (…)			X																X					
AR will be popular in the near future.												X								X				
I want to use AR to familiarize myself with products (…)											X				X			X						
Seeing an object through AR, it's good in store (…)				X			X																X	
One would use AR more, if the applications (…)														X					X					
It's playful and fun.											X				X									
One needs to be able to touch the product.					X							X											X	
In the future AR would help consumer to see (…)				X				X				X				X								
AR would be helpful in assembly and installation (…)			X				X																	
AR is a great possibility for innovation; (…)				X				X							X					X				
Seeing a product through AR is not enough (…)					X																			X
Some articles are not commonly sold in web shops (…)			X							X														
The combination of AR and social media would (…)						X					X									X			X	
I like the way AR can be used to tell stories: (…)																								X
AR is not a problem solver for print media but (…)										X				X										
AR applications must involve all senses (…)		X				X			X					X								X		
Everyone is able to use AR.					X								X					X			X			
AR is too expensive for me.	X					X											X					X		

Once the factors were identified, descriptive names were added to each of the 6 groups to more easily establish meaning in the results. The groups were named as follows: (1) Techno Believers, (2) Pragmatics, (3) Entertainment Seekers (4) Sceptics (5) Marketers and (6) Non-committals. Each factor represents a shared attitude towards AR. A description of each group follows.

Techno believers

The motivational aspects of experience are the most important for Techno Believers. They think that *"AR is a great possibility for innovation"*, and, they disagree with negative statements like "*I don't understand how it works, it's too complicated. I don't want to try"*, *"AR is too expensive for me"*, and *"I wouldn't have time to use AR"*. For techno believers technology is not an obstacle. They do not have a problem using and reusing mobile applications. However, the Techno Believers are neutral on emotional, sensory and social aspects of experience.

This group consisted of all three subgroups within the study: professionals in Canada and Finland, and students in Finland.

Pragmatics

For the Pragmatics the instrumental aspects of experience were the most important. They voiced doubts about the ease of use of the applications and of AR more generally. They strongly agree with the statement *"The threshold for using AR is too high; you have to find it, and then install it, and after that you are able to use the application. You must have a strong motivation to do this."* and strongly disagree with the statement *"Everyone is able to use AR."* However, they believe that *"AR is a great possibility for innovation; we have not seen the best ideas yet"*, and *"there are benefits that AR brings along, for example in assembly and installation applications."*

Interestingly, the Pragmatics group was represented only by the Finnish professionals subgroup.

Entertainment seekers

For the Entertainment Seekers group the emotional and sensory elements of experience are important. They find AR *"surprising"*, *"playful and funny"*, and they *"like the way AR can be used to tell stories: it makes them interested because it stimulates variety of senses."* They believe that AR will be popular in the future. They have rather neutral attitudes towards the instrumental and motivational aspects of experience.

The Entertainment Seekers consisted of Canadian professionals and Finnish students.

Sceptics

This group was the most sceptical towards the benefits that AR could bring to print media, as well as having very neutral opinions more broadly. They find it difficult to start using AR applications, but on the other hand, they are not worried about the ease of use in general. They have neutral attitudes towards the price, spending time with AR applications as well as the general future of AR.

The Sceptics viewpoint was based on the evaluations of Finnish professionals and students.

Marketers

This group was the only one that agreed with the statement *"The combination of AR and social media would strengthen the effect of an ad."*

They also believe that AR will be a successful technology in the future and they did not find technology acceptance or the ease of use as obstacles to achieving the goals of AR.

In this group there were representatives from each subgroup: professionals in Canada and Finland, and students in Finland.

Non-committals

Non-committals find AR applications as a possible risk for print media, because the applications might *"cause a focus shift and that the reader stays in the mobile phone after using the apps and doesn't come back to printed magazine."*

While they *"like the way AR can be used to tell stories: it makes them interested because it stimulates variety of senses,"* they have a neutral attitude towards instrumental experiences. In addition to the motivational aspects of experience, the non-committals group find that the emotional experiences are also relevant. The Non-committals viewpoint was based on the evaluations of Canadian professionals and Finnish students.

4. Discussion

The purpose of this study was to clarify, what kind of attitudes consumers in Finland and Canada have towards augmented reality applications. In addition the study explored whether the Finnish and Canadian attitudes towards augmented reality applications differ from one another. Based on focus group interviews in Nordic countries, a variety of attitudes towards AR applications could be identified. The attitudes were rephrased in the form of statements, which were ranked utilizing Q methodology.

In the analysis of the results, six viewpoints towards AR applications were identified. According to the results, the pragmatic aspects of experience were clearly more important for the participants than the hedonic ones. This is typical for new technologies. Augmented reality is still a new technology in applications targeted toward consumers. Such technologies tend to be evaluated based on their novelty value, as well as their pragmatic aspects such as ease of use (Olsson & Salo, 2011).

In the result minor differences between countries were identified. There were two viewpoints, namely 'Pragmatics' and 'Sceptics', were solely based on evaluations of Finnish participants. In addition, the viewpoints 'Techno Believers' and 'Marketers' were based on evaluations of all three subgroups. The other two viewpoints, 'Entertainment Seekers' and 'Non-committals', were based on the rankings of Canadian professionals and Finnish students. Thus, the results indicate that there probably are some cultural differences but they are not the only explanation. The results of cultural differences are in line with findings of the study by Gauzente et al. (2011). They studied perceptions towards AR in France and Russia, and identified six viewpoints towards AR, of which three were common to both countries, two were typical for Russian participants and one was typical for French (Gauzente et al., 2011).

It is interesting that there were two viewpoints in which Canadian professionals and Finnish students displayed the same attitudes. This may indicate that in Canada, companies are less likely to think of AR technologies as a professional marketing tool. This could be because not many professional applications currently exist, or because of the novel nature of interactive technologies. The European market has certainly been quicker to absorb some of the potential uses of this technology, and the results of this study indirectly support this.

The benefit of the Q methodology is in quantification of qualitative data. Based on the focus group interviews different attitudes towards the AR applications were identified and Q methodology was then used for evaluation of the importance of the attitudes. As an example, people in focus groups were uneasy about the costs, however when they filled in the Q-sort formula, costs were seen as a minor issue. Interestingly, the Q-sort results showed that the costs were not seen as an obstacle. Here we can see the benefit of using this methodology as it allows us to prioritize the results of the less structured focus group data.

5. Conclusions

For AR technology to succeed a business model for digital advertisements needs to be developed. Further AR should be developed for a variety of technological platforms, extending beyond focusing on mobile phones. For example, while the Canadian results showed that today most participants felt that AR offers shopping advantages, many saw the future of AR in the medical field. Interestingly the suggestions for future, were moving away from combining print and AR, and rather moving into a world that is augmented through the use of some device (like a mobile phone or glasses). This indicates that consumers are media agnostic, looking at what the technology could achieve independent from the media platform it is currently utilizing.

The results thus far show exciting theoretical and practical implications for AR technology, that are not limited to its use for entertainment alone, but rather to be integrated into our media providing some usefulness. Further, this research has contributed to our understanding of AR, while maintaining a culturally sensitive perspective. As many brands in today's world are global, this knowledge will be very useful. In particular, it is interesting to note that the attitudes of Canadian professionals closely match to those of Finnish students, rather than aligning with Finnish professionals. The two viewpoints for which this is the case are ‘Entertainment Seekers' and 'Non-committals'. One could presume that students are less likely to interact with AR in a professional capacity, with a majority of the applications for this target market being entertaining in nature. Thus one could then extend that the Canadian market has had a stronger focus in this area as well. In a sense, this means that there is opportunity to extend the use of AR in Canada. This is further supported by the 'Marketers' and 'Techno Believers' viewpoints being represented by all three subgroups. Very optimistically, the study thus shows that, while some cultural differences in attitudes toward AR technology may exist, both countries show promise for future uses of AR that extend beyond how we are using it today.

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Familiarity and color effects on consumer reactions to packaging design

Ulrich Nikolaus and Anne Geißler

Leipzig University of Applied Sciences (HTWK Leipzig)
Gutenbergplatz 2 3 4, D-04103 Leipzig, Germany
E-mail: nikolaus@fbm.htwk-leipzig.de

Abstract

As a part of an ongoing study analyzing consumer reactions to packaging design, in this paper, we present the results of an eye tracking study, exploring the influence of familiarity and color in packaging design. The results suggest that consumer reactions to well-known and unknown designs differ, but to a lesser extent than might be assumed. The importance of color in packaging design is confirmed, and properties that consumers associate with a certain color (at least in the realm of chocolate packaging) are discussed in detail.

Keywords: packaging design, eye tracking, familiarity, color

1. Introduction

Packages have to fulfill multiple functions. From an informational point of view, they have to relay a wide range of information (cf. Berndt & Sellschopf, 2011), ensure brand recognition and product differentiation (cf. Hinz & Weller, 2011). From a marketing perspective, it is desirable to guide the consumer's attention, perception and information processing (cf. Munzinger & Musiol, 2009, 50 f; Wedel & Pieters, 2006, 37 ff.) - thereby possibly influencing the consumer's behavior, motivation and (buying) decisions (cf. Bittner & Schwarz, 2010, 18, Munzinger & Musiol, 2009, 16).

In order to create efficient and effective designs, packaging designers use visual stimuli such as the size or shape of a packaging, graphic and surface design, color or typography (cf. Hinz & Weller, 2011, 236; Hinz & Weller, 2011, 263). To do this, it is helpful to understand the attentional impact visual stimuli have on the average consumer as accurately as possible. Eye tracking has recently become one possible tool to measure such consumer reactions (cf. Wedel & Pieters, 2006, 45; Piqueras-Fiszman et al. 2013, 329).

In a previous eye tracking study on packaging design (cf. Nikolaus & Lipfert, 2012), text-based, reduced designs of pharmaceutical packaging had been compared to richly illustrated, colorful designs of chocolate boxes in order to find out how the different use of visual stimuli influenced viewer's reception and infomation processing. This study led to some unexpected results.

First, it had been assumed that pictorial elements like product shots and other graphic elements would highly influence the viewer's attention, at least when looking at the more emotionally designed chocolate boxes. Eye tracking results, however, had shown that *text elements* were looked at longest and attracted the interest of the test participants most - particularly product and brand names. This was unexpected, because pictorial elements are thought to have a high tendency to attract attention (Wedel & Pieters, 2006, 50) and a higher emotional impact on consumers than textual information (Munzinger & Musiol, 2009, 67). Therefore, it might have been expected that product shots or other images would serve as eye catchers that attract the viewers' attention first.

One possible explanation for this reduced attentional impact of images in the previous test might be familiarity: In order to find premium quality samples, only commercially successful (and rather well-known) designs had been chosen. Wedel and Pieters (2006, 60 ff. and 77) note that in the context of print ads, familiarity led to a drop in attention of as much as 50% and to an increased attention to text elements. Assuming similar effects in packaging design, it is quite possible that mere recognition takes less time and requires other viewing strategies than a first time viewing. Therefore, in a second test described in this paper, designs unknown to the test participants were used.

A second interesting result of the first test was the importance of color. When asked to name visual stimuli that, in their opinion, had a high emotional impact, viewers attributed top values to the *coloring*. This, again, is consistent with results from ad design that showed that color ads were scanned more quickly, more often and longer than black and white ads (Duchowski, 2007, 263). Unfortunately, this aspect could not be studied in detail during the previous test, because color is evenly distributed across the package, and therefore difficult to analyze with eye tracking data alone. By using both visual stimuli that only varied in their coloring and a more detailed questionnaire, we wanted to obtain additional information on the attentional impact that color has on viewers.

2. Research methods

The eye tracking tests described in this paper consisted of two parts. In the first part, effects of familiarity on the test viewer's perception and information processing were analyzed; the second part was focused on the influence of color. The test was performed at the Leipzig University of Applied Sciences (HTWK Leipzig) in November 2013. The research design was as follows:

Subjects: Seventeen fourth-year students (10 males, 7 females) studying Media Technology at the Leipzig University of Applied Sciences (HTWK Leipzig) were recruited for the experiments. They had normal or corrected vision, and their ages ranged from 22 to 37 years (26 on the average). Although they all attended basic lectures on visual media design in their first year, none of them had special knowledge in packaging design.

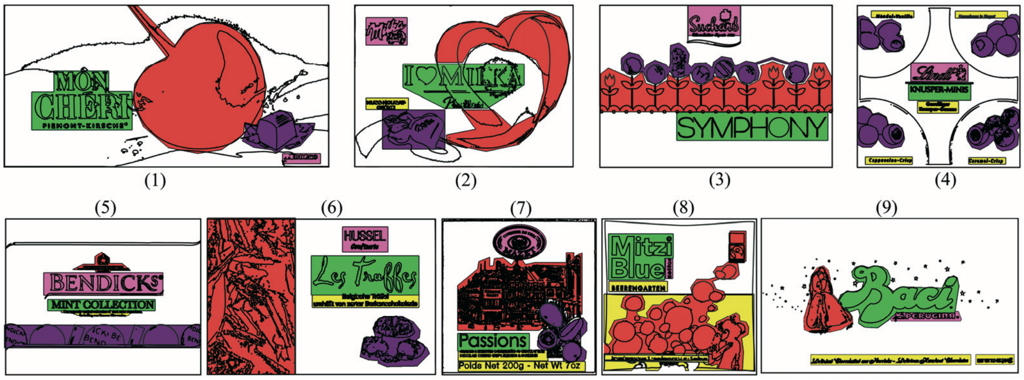

Figure 1: Outline rendering of the test samples and Area of Interests (AOI) for well-known (nos. 1 and 2) and unknown chocolate boxes (nos. 3 to 9) used in the first part of the test. Color coding for the AOIs: Brand and logo elements: pink; product name: green; body text: yellow; product shot: violet; other images: red

Stimuli: Because the eye tracking system used for this test was computer-based, two-dimensional reproductions of the chosen packages were shown to the test participants on a 17" LC display in random order[1]. To use the screen resolution to its full capacity, all samples were in landscape format (cf. Figure 1 [2]). All packages were reproduced photographically and then retouched using an image processing program to obtain a realistic re-creation. All designs were then shown to the subjects on a dark background; one sample at a time, each display lasting five seconds. The stimuli were displayed in random order. Using eye tracking technology, the overall distribution of attention was recorded for each participant and sample.

For the first part of the test, two well-known designs that had already been used in the previous test were supplemented with seven lesser-known designs. These new designs were chosen from a set of originally 24 chocolate box designs that were listed on a website giving a brand overview of chocolate products available on the German market (Weblike, 2013). As in the previous test, seasonal goods and packages with obtrusive discount markers, transparencies, holograms, embossment or other effects were excluded, and the packages had to be similar in shape to the two preselected designs (i.e. made of cardboard, rectangular or square). This original set was then narrowed down to seven designs that were rated both as unknown and well designed by fifteen randomly chosen friends and colleagues of the authors (none of whom participated in the actual test). A post-test survey at the end of the eye tracking test ascertained that test samples (1) and (2) in Figure 1.in were indeed well-known and samples (3) to (9) mostly unknown to the actual eye tracking test participants.

[1] For a more detailed discussion on using digital images instead of real packages for the visual assessment of visual packaging designs, please cf. (Laine et al., 2010).

[2] In the actual test, full-color reproductions of the packaging designs were shown. In Figure 1, outlines are only used to facilitate the identification of the Areas of Interest (AOIs).

For the second part of the test, visual stimuli were used that only varied in coloring. For this purpose, sample (9) of figure 1 was used as basic layout, because it was largely monochrome and gave no specific infomation on the taste or the appearance of the products included therein. Using Adobe Photoshop, red, green yellow, brown and light blue variants of the original design (which was dark blue in color) were created (cf. Figure 2).

Figure 2: Slices of the six samples used in the second part of the test. The packaging designs were identical except for their color. Next to the original (dark blue, left), brown, green, light blue, yellow and red variants were presented

Apparatus and procedure: The stimuli were presented on a monocular, desktop based NYAN 2 XT/EDGE eye tracking system produced by Interactive Minds, Dresden (Interactive Minds, 2013). A Samsung Sync-Master 17" TFT display with 1280 × 1024 pixel resolution was used at a sampling rate of 60 Hz rate and 0.45° accuracy. The samples were slightly enlarged in order to compensate for the lower resolution of coputer screens.

Then, user reactions were recorded and their visual scan paths analyzed. In order to assess the relative importance of the main visual components on the sample packages (brand name, logo, product name, product shot etc.), Areas of Interest (AOIs) were defined beforehand for each of these elements in order to compare hit rates, the time to first fixation, gaze durations etc. These Areas of Interest are shown in Figure 1.

After the test, the participants were asked to complete two questionnaires. The first one asked the test subjects to name designs that were already known to them prior to the test and to rate the display time (too short/too long). Furthermore, they were asked to assess for each design, whether it was rather informative than emotional.

For the second part of the test (analyzing the effects of color), an additional questionnaire had been prepared, were participants had to assign certain flavors and properties to the different-colored packages. First, participants had to assess which chocolate flavor (like milk chocolate, dark chocolate, strawberry flavor etc.) corresponded best to each color variant. Next, they were asked to assign various properties - for instance basic tastes (sweet, sour, bitter), texture (crunchy, creamy, fluffy), mildness and pungency (mild, delicate, strong, pungent (hot), heavy) or on the assumed quality level (classic, high-quality, exclusive). If they wished to, test participants could add properties of their own.

3. Results

For the two well-known chocolate boxes, previous results could more or less be reproduced. Again, the product name was the first stimulus to be observed, and its gaze duration was higher than that of any of the pictorial elements (cf. the first and second column in first and second column of Figures 3 and 4). The seven new packaging designs were indeed unknown to the test subjects, with the exception of sample (4), which was known to 4 out of 17 test viewers (3 others were not sure), and sample (3), that was known to one participant (and another one was not sure). As to sample (6) and (9), two and one participant were not sure if they had seen it before, respectively. In the post-test survey, viewers stated that the viewing time of five seconds was rather too long for the first two designs, whereas it was considered to be rather too short for the unknown designs.

Interestingly, the emotional impact of the well-known chocolate boxes was higher than that of the unknown - although the packages where not specifically chosen that way. The only unknown package that got high emotional values was the one that was used as color sample in part two of the test.

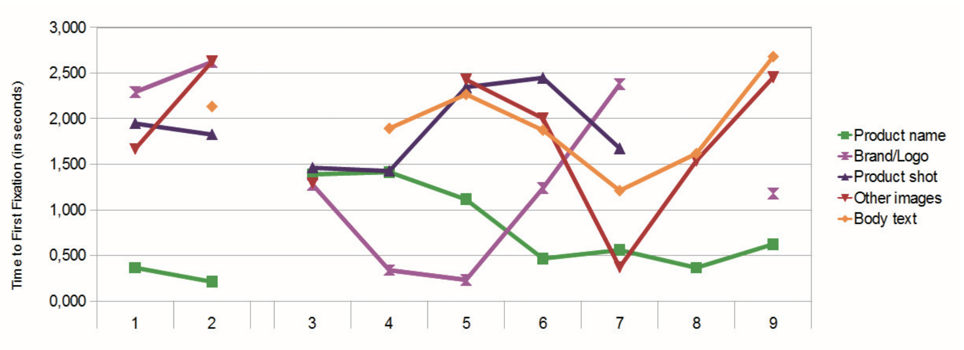

Figure 3: First Fixation results for familiar (no. 1 & 2) and unfamiliar packaging designs (nos. 3 to 9; average of all individual results). The Time to First Fixation (in seconds) indicates when a certain Area of Interest (AOI) was first focused; earlier is better. Missing values indicate that such a stimulus does not appear in the corresponding design

Apart from that, the differences between known and unknown designs were less significant than assumed. Particularly, the viewing patterns recorded via eye tracking did not differ as much as expected. Again, brand/logo elements and product names got the lowest Time to First Fixation (cf. column 3 to 9 in Figure 3), whereas pictorial elements were mostly looked at almost at the same time or even later. The dominance of the product name was less significant than it was for the two well-known samples, but the general order was more or less the same. Contrary to our assumption, pictorial elements (product shots and other images) were *still* looked upon comparatively late. The only sample that got an exceptionally low Time to First Fixation for an image was sample (7), where the background image was on average the first element to be looked upon.

The analysis of the gaze durations yielded similar results. Again, pictorial elements did not get substantially higher viewing times than the product name or the brand/logo elements, although the difference was less than it was for the well-known designs. Product shots got higher gaze durations if they consisted not only of one single object but of several pieces (cf. no. 3, 4 and 5 inFigure 4), see also the scan paths in Figure 6.

Besides, a certain influence of size could be detected: Pictorial elements that were quite large and located at the very center of the package, got higher gaze duration values; for instance the background images in no. (7) and (8) of Figure 4. On the other hand, comparatively big images that were positioned off-center, got considerably less attention (cf. no. 5 or 6 of Figure 6). Beyond that, even comparatively small textual elements like the brand names in no. (3) and (7) of Figure 4 got quite high attentional values compared to their size. Even the small body text elements in the very corners of no. (4) got almost the same attentional values as the considerably more prominently placed product shots (cf. heat map (ii) in Figure 5.

Text elements that got a somewhat bigger size and a better position like the product names in no. (6), (8) and (9) of Figure 4 got the highest gaze duration values. The heat maps in figure 5 show this dominance of textual elements visually.

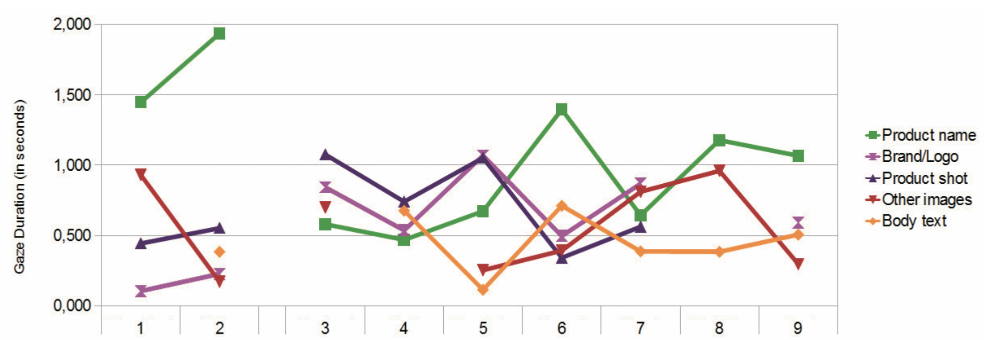

Figure 4: Gaze Duration results for familiar (no. 1 & 2) and unfamiliar packaging designs (nos. 3 to 9; average of all individual results). The Gaze Duration (in seconds) indicates the average viewing time for a certain Area of Interest (AOI); longer is better. Missing values indicate that such a stimulus does not appear in the corresponding design

An analysis of the color questionnaire in the second part of the test showed that color seems to convey rather specific information to the viewers. As aforementioned, dark blue, brown, green, light blue, yellow and red color variants of the packaging design shown in Figure 2 were presented to all participants. The designs in red, green and yellow were considered to be stimulating, whereas dark blue and brown were rather calming. The red design was rated as emotional, brown and light blue as rather non-emotional.

The test viewers first had to assess which chocolate flavor corresponded best to each color variant (apart from dark, milk and white chocolate, the suggested flavors were: almond, banana, blueberry, chili, coffee, hazelnut, marzipan, mint, orange, nougat, raisin, strawberry, toffee and yogurt). As it turned out, certain flavors were repeatedly assigned to the same designs: the brown-colored variant was associated with a nougat flavor by 16 out of 17 test subjects, the green design with mint (14/17), and the yellow one with banana (13/17). Dark chocolate, chili and marzipan flavors were associated with the color red by 7, 12 and 10 out of 17, respectively, and milk chocolate was generally considered to be blue (dark blue: 12/17; light blue: 10/17). Somewhat predictable, blueberry, orange and strawberry flavors were most often associated with dark blue (10/17), yellow and red (both 8/17); and hazelnut was sometimes associated with the color brown (7/17). As for the other six flavors (almond, coffee, raisin, toffee, white chocolate and yoghurt), no unambiguous assignment could be found - but as 17 flavors had to be assigned to only 6 color versions, it is quite possible that stronger color associations for the other flavors were simply dominant here.

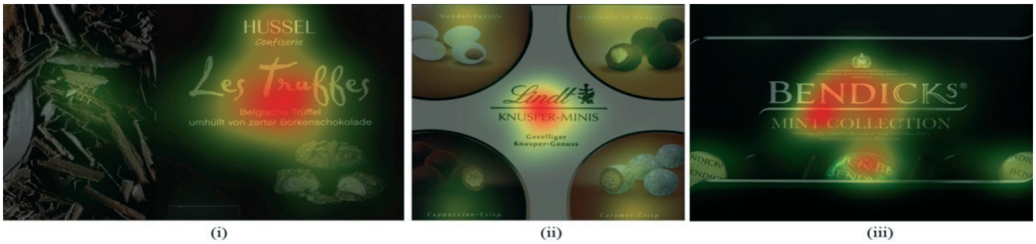

Figure 5: Sample heat maps from packaging design analysis. Those areas of the stimuli that received most attention from the test participants are marked with colored spots (red means high levels of attention, followed by yellow and green) Areas that got only minor attention are darkened.

After the attribution of flavors, the participants were asked to assign certain properties to the products - describing basic tastes (sweet, sour, bitter), texture (crunchy, creamy, fluffy), mildness and pungency (mild, delicate, strong, pungent (hot), heavy), freshness (chocolaty, fruity, fresh) or an assumed quality level (classic, high-quality, exclusive). Again, it can be stated that some of to the above-mentioned properties were seldom associated with any color at all (less than 4/17 associations); such as bitter, crunchy, heavy and exclusive. Others, however, were quite distinctly associated with one single color, such as chocolaty and creamy with brown (14 and 10/17, respectively), fluffy and mild with light blue (11 and 10/17), fresh and fruity with green and yellow (12 and 10/17), and classic with dark blue (10/17).

However, unambiguous one-to-one-relations between colors and properties could not be found. For some properties, several colors provided similar results; on the other hand, the same color was sometimes assigned to different colors (cf. results in Table 1). Grouping the three properties most often named for each single color, however, led to quite distinct characterizations for each of the six colors. Thus, brown was characterized as chocolaty, creamy and sweet; both yellow and green as fresh, fruity and sour; light blue as fluffy, mild and sweet or red as high-quality, pungent and strong. Dark blue was considered to be classic and mild, and (with 5/17 associations each) as high-quality, chocolaty and creamy.

Table 1: Results showing the participants' associations of gustatorial properties to certain colors. Properties that were assigned most often (i.e. the three highest values in each row) are marked for clarity

	sweet	sour	bitter	crunchy	creamy	fluffy	mild	delicate	rich/strong	pungent	heavy	chocolaty	fruity	fresh	classic	high-quality	exclusive
brown	**8**	0	1	3	**10**	0	3	4	1	0	4	**14**	0	0	**8**	3	2
green	3	**7**	3	4	0	0	0	1	2	3	0	2	**7**	**12**	1	0	2
dark blue	3	0	4	1	5	2	**6**	4	4	0	4	5	2	0	**10**	5	3
red	**6**	0	2	2	2	1	0	3	**6**	**6**	0	3	5	0	1	**7**	4
yellow	6	**7**	1	4	2	2	2	0	2	0	0	0	**10**	**8**	0	0	2
light blue	**8**	0	0	1	5	**11**	**10**	6	0	1	0	6	2	5	5	0	0

4. Discussion

Summarizing the results for the influence of familiarity, it can be stated that familiarity effects can be observed, but that its impact was smaller than assumed. In the post-test survey, viewers stated that five seconds viewing time was too long for known, but too short for unknown designs: This is an indication that it does indeed take more time to process completely unknown layouts, texts and graphical elements than familiar ones.

The higher rated emotional impact of the well-known chocolate boxes and of the color sample in the second part of the test may indicate that familiarity does increase the emotional attachment to a certain product as well.

Wedel and Pieters (2006, 60 ff. and 77) note that in the context of print ads, familiarity led to an overall drop in attention of as much as 50 % and to an increased attention to text elements. Assuming similar effects in packaging design, it had been expected that consumer reactions to unknown designs would show higher attentional values for pictorial elements.

However, eye tracking results showed that, for unknown and well-known designs alike, *text elements* attracted the interest of the test participants most - particularly product and brand names. Product names, in general, got high gaze duration values as well. For brand/logo elements, in contrast, first fixation time was comparably low and the gaze duration rather high for unknown designs, whereas for the familiar designs, the results were exactly the opposite. This might indicate that the importance of brand/logo elements decreases with an increase of familiarity, whereas product names tend to have a high importance regardless of the familiarity level.

Comparing the attentional impact of text and pictorial elements, a preference of textual information could be detected, even though it was somewhat reduced for the unknown designs. As to the Time to First Fixation, sample (7) is an exception to the rule, as its background image was looked at slightly earlier than its product name (the gaze duration values for this background image are also comparably high).

On closer inspection, however, it becomes apparent that this pictorial element is not only quite large and very detailed, but also located at the very center of the package, whereas all the textual elements are somewhat off-center at the very top (brand element) or in the lower left corner (product name; cf. (iv) in Figure 6).

(i) (ii) (iii) (iv)

Figure 6: Sample scan paths that show the eye movements of selected test participants. Each circle visualizes a fixation of the viewer. The numbers in the upper half of the circle specify the order in which the fixations were made, the number in the lower half and the size of the circles visualize gaze duration

Thus, test viewers shifting their attention from the product name to the brand element or vice versa, inevitably have to cross the pictorial element in the center, which might lead to some additional fixations. Besides, considering the difference in size and positioning between the texts and this background image, the pictorial element still got comparably low attentional values. Apart from sample (7), the stimuli (3) and (4) were the only other cases where product shots got attentional values that were similarly good as the text elements. Interestingly, in both cases, the product shot consisted of several elements (whose gaze duration values were summed up, and the earliest fixation time for any of these truffles was entered as the Time to First Fixation for the product shot as a whole).

Thus it can be stated that all over all, the primacy of text over images has been affirmed for unknown packaging designs also, although the attentional impact of visual stimuli depends on other factors as well, such as the level of detail of the visual stimuli, the number of elements they consist of, their size and positioning. Elements that are very detailed or consist of several elements seem to get higher attention than homogeneous ones, stimuli at the center probably get more fixations than those in corners and bigger stimuli tend to get more attention than smaller ones (compare, for instance, the product names in figure 5). But even if all these factors are taken into account, a dominance of textual elements might still be detected (for instance, the tiny body text elements at the very top and the very bottom of sample (4) - cf. Figure 5 (ii) and Figure 6 (i) and (ii) - get more attention than the corresponding product shots - although these are bigger and positioned nearer to the center).

The results of the second part of the test show the influence of color. When asked to name those visual stimuli that, in their opinion, had the highest emotional impact, viewers attributed top values to the *coloring* of the package. This, again, is consistent with results from ad design that showed that color ads were scanned quicker, were looked at more often and longer than black and white ads (Duchowski, 2007, 263).

Besides, color obviously serves as an information carrier, too. In our test, the participants repeatedly assigned similar properties and flavors to each of the tested colors. All in all, the correlation with flavor seemed to be quite strong for some of these colors (like, for instance, dark brown or green). At least for chocolate packaging on the German market, there seems to be a quite distinct color coding of chocolate flavors. However, as color-related associations are depended of cross-cultural differences, fashion, trends and individual preferences, it cannot be ruled out that the findings in this paper might be time-dependent or restricted to a certain cultural area.

As far as association of color with certain gustatory properties is concerned, the findings do not suggest that one single area of taste (like basic tastes, texture, pungency etc.) has a stronger connection to color than the others. Besides, there was no full coverage for any of those areas, for as though there were recurring attributions for some color-property pairings (and some of these even quite strong), associations were rather faint for others.

Thus, it cannot be said that the whole area of human gustatory properties can be mapped exhaustively on human color perception. However, if all associations one certain color evokes are taken together, they form quite different characterizations for each of the tested colors: Light blue, for instance, was said to be mild, fluffy, sweet, delicate, chocolaty - whereas red was perceived as pungent, strong, high-quality and sweet or yellow as sour, fresh and fruity. Thus, though colors might not be suited to precisely describe discrete gustatory properties, they might nonetheless be able to describe multifaceted, complex taste experiences that help consumers to choose a product according to their liking.

5. Conclusions

The findings in this publication once again underline the importance of textual elements in packaging design. One key result of the eye tracking tests is that even for unknown packages, the attentional impact of pictorial elements was lower than originally assumed (as was the influence of familiarity both on eye movements and the distribution of attention). An interesting result is that, in the post-test survey, the test participants stated that images were very important for the emotional impact of packaging designs. Thus, visual elements that got only low attentional values in the eye tracking test were considered to be of high emotional importance (a similar effect has been reported in Piqueras-Fiszman, 2013, 333).

A possible explanation for this apparent contradiction could be that product identification is a rather rational task, and is therefore achieved quite easily by using textual elements (such as product or brand names) with a well-defined, distinct meaning. Coming to a buying decision, on the other hand, might be a subsequent step more strongly influenced by emotional factors (at least as regards to chocolate). Possibly, pictorial elements might be of higher importance in this part of the process.

An alternative approach to explain the above contradiction might be found in human cognition. It is a well-known fact (discussed, for instance, in Paivio, 1986, 53 f.) that images and texts are perceived and processed differently by the human mind. This might account for some of the differences in eye tracking results, as it might be possible that it takes viewers less time to view, recognize and process pictorial information than textual information, or that the role of focused attention might be a different one (as might be derived from Treisman & Gelade, 1980). In short, the impact of these differences in human cognition on eye tracking analysis in general and the role of pictorial elements in packaging design still needs some further analysis.

As for the importance of color in packaging design, it can be stated that the color of a packaging did provide additional information to our test viewers, specifically on chocolate flavor and on gustatory properties of the corresponding product. Although no systematic and exhaustive correlation between color and gustatory properties could be found, color did convey quite complex and self-contained taste experiences. As the color variants used in the second part of the test did not represent real products, but artificial ones created especially for this test, familiarity effects can be ruled out in this case. Nonetheless, these designs conjured up some quite specific associations - which might reflect an existing color coding for real-life chocolate products on the German market.

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