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Cold foil transfer technology for functional printing

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Abstract

Since some years, several research institutes, institutions and companies are working on the realization of electronic components by innovative methods, which can lead to cost-effective, simplified and flexible production of such products. Among other low-cost technologies such as coating and vapor deposition, printing as an additive structuring process is one focus of research. Another interesting additive printing-related method is cold foil transfer technology or also so-called cold foil stamping. The cold foil transfer technology is conventionally used in the finishing step for various, mostly decorative, printing products. For a real metal effect to be obtained in graphic arts printing so-called cold foils are used, which in most cases have an aluminium layer. The metal is applied by vapor deposition with high demands on the polyester foil properties, so that the metal particles are close together and thus set up a thin homogeneous conductive aluminium layer in the nanometer range. The fact that the cold foils have a metal layer has led to the idea of using this printing method for electronic applications using its conductivity. The following criteria are important for using cold foil transfer processes for printed electronics: electrical conductivity, reproducibility and reliability of such metal layers, especially depending on different printing process settings. In this research, the cold foil is transferred to a substrate in a sheet-fed offset printing press. The samples are measured by using a contactless measurement method. The experiments show a medium to low sheet resistances of the transferred aluminium layer. Furthermore, the conductivity of the aluminium areas on the substrate depend on their location on the much larger substrate sheet. The objective of this research – application of the cold foil transfer technology and determination of its process boundaries for the use in the electronics field – could be confirmed.

Keywords: hot stamping, sheet-to-sheet process, mass production, electric conductivity, printed electronics

1. Introduction

Functional printing has shown a rapid development in the last years. Optimized functional fluids enable the production of the various functional layers and this even with instruments and devices beyond the laboratory scale. Functional fluids that have the suitable electrical properties can be processed with established industrial mass manufacturing processes, amongst others, with printing processes, investigated by Organic and Printed Electronic Association (OE-A, 2013).

In flexographic printing, the printing plate is compressible. Therefore, it is suitable for rigid substrates such as glass and also for surfaces, which are sensitive to mechanical stress (Kipphan, 2001). Gravure printing offers benefits in the production of very thin functional layers down to the nanometer range. Screen printing provides advantages for high laydown of ink material (Rausch et al., 2011). The latter is useful, for example, in the production of electroluminescent devices. With the development in chemical industry, the functional fluids are also optimized to be printed by inkjet printing. Inkjet in graphic arts industry is mainly used for short-run and personalized print production. Further specific advantages of inkjet arise due to its modularity and flexibility allowing integration into various architectures ranging from desktop printers to print production systems and even into existing printing presses as imprinting solutions (Leenders, 2005).

In addition to conventional printing methods, it has been tried to produce functional layers using the hot stamping technology. The Paper "Hot Stamping Technology for Functional Printing" (Lyashenko, Salun and Doersam, 2012) investigates hot stamping processes for the production of electrical components. It was confirmed that hot stamped metal layers exhibit reasonably good conductivity. Furthermore, it was shown that the electrical conductivity of these metal layers depends on the properties of hot stamping foils (Lyashenko, 2014).

Based on these findings, an investigation of the production of the electricaly conductive layers using cold foil transfer technology was conducted as well. With cold foil transfer technology, the functional layer can be manufactured on highly productive presses with some advantages for mass production at lower cost. The cold foil transfer is a well-established process in graphic arts industry mainly used for inline decorative refinement. The differences between the cold foil basic material composition and the hot stamping foil are shown in Figure 1 and Figure 2.

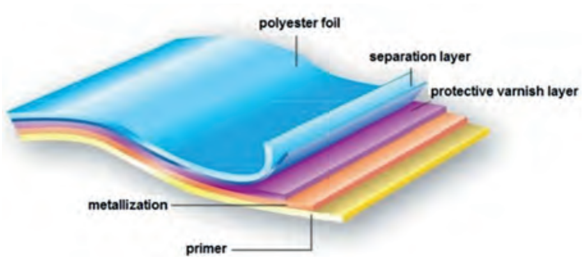


Figure 1: The layer composition of a cold foil (Kurz, 2011)

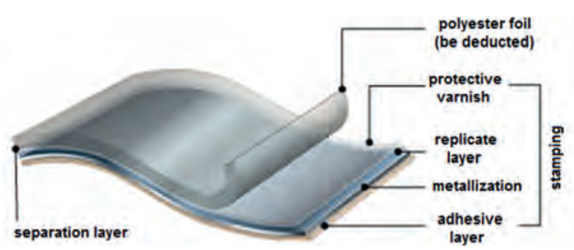


Figure 2: The layer composition of a hot stamping foil (Kurz, 2011)

The main difference is the primer layer in cold foils (Figure 1) and the adhesive layer in hot stamping foils (Figure 2) as these layers have to be adapted to the substrate. In case of cold foil, the primer layer has to meet the requirements of the preprinted glue and, in case of hot stamping foil, the adhesive layer will be activated by heat and has to stick to the surface of the substrate.

The external glue in case of cold foil is applied by printing methods such as offset and flexographic printing like a conventional printing ink. In the next step, the cold foil is pressed onto the substrate in a special cold foil transfer unit. In those areas where the glue is located, the metal cold foil is transferred as shown in Figure 3. The other layers of both foils are similar and play almost the same role. There are a polyester foil, a separation layer, a protective varnish layer and a metallization (usually aluminium) by vacuum-deposition (Figure 1 and Figure 2). Replicate layer is typically used in hologram stamping foils only.

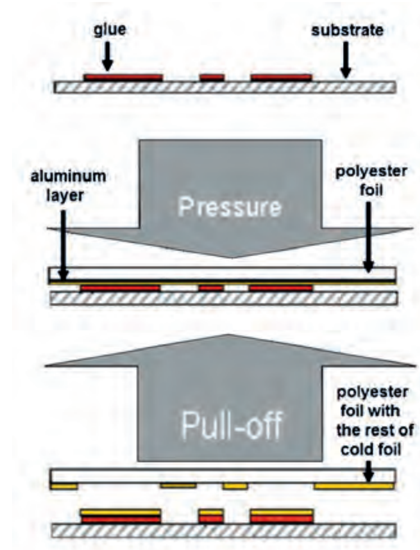


Figure 3: Working principle of cold foil transfer process (Heidelberg, 2012)

Besides the advantage of a high-speed mass production, the cold foil transfer technology has substantially lower manufacturing costs and flexibility in the layout as opposed to the hot stamping. (Remark: cold foil can be applied not only for the full areas, but also for screened areas. In the graphic arts industry, cold foil is transferable for areas with screen ruling lower than 40 l/cm and halftone areas between 20 % and 90 % (Heidelberg, 2012).) Visual and tactile effects, however, are not mentioned here since they are not aimed for in electrical applications.

2. Printing experiments

The printing experiments were carried out on an offset printing press Heidelberg Speedmaster XL 105-5+L. Printing units 1 and 2 were used for cold foil transfer. In the first offset printing unit, the glue was printed as usual in standard graphic arts applications. The second unit was equipped with a cold foil transfer unit, in which the cold foil is pressed onto the printing sheet. All other subsequent printing units were off (no pressing). For the experiments, a standard gloss paper BVS (manufactured by Scheufelen GmbH) in format 1050 × 750 mm with the grammage of 135 g/m² was used. As cold foil material, two similar types of foils were applied, for short named Type 1 and Type 2. The regular thickness of the aluminium layer for the cold foil process, which is usually used in the graphic industry, is between 10 and 20 nm. As this is a very thin layer, the sheet resistance is not expected to be very low. Both types of cold foil materials are without a coloring above the metallization (aluminium). The glue material GLUE FoilStar 100 (Heidelberg Saphira®) similar to a conventional oil-

Table 1: Settings of the printing experiments on Heidelberg Speedmaster XL 105-5+L

Test run	Type of cold foil material	Color density of glue	Dampening [%]	Speed [sheets/h]	Tension of foil web (out and up side) [N/cm]	Engagement [mm]
1	2	0.3	25	8000	1.0/1.5	0.15
2	2	0.3	25	8000	1.0/1.5	0.25
3	2	0.3	25	10000	1.0/1.5	0.25
4	2	0.3	25	12000	1.0/1.5	0.25
5	2	0.3	25	14000	1.0/1.5	0.25
6	2	0.3	25	10000	0.4/1.5	0.25
7	2	0.3	25	10000	2.0/1.5	0.25
8	2	0.22	25	10000	1.0/1.5	0.25
9	2	0.35	25	10000	1.0/1.5	0.25
10	2	0.3	40	10000	1.0/1.5	0.25
11	2	0.25-0.3	15	10000	1.0/1.5	0.25
12	1	0.25-0.3	15	10000	1.0/1.5	0.25
13	1	0.3	40	10000	1.0/1.5	0.25
14	1	0.35	25	10000	1.0/1.5	0.25
15	1	0.22	25	10000	1.0/1.5	0.25
16	1	0.3	25	10000	2.0/1.5	0.25
17	1	0.3	25	10000	0.4/1.5	0.25
18	1	0.3	25	14000	1.0/1.5	0.25
19	1	0.3	25	12000	1.0/1.5	0.25
20	1	0.3	25	10000	1.0/1.5	0.25
21	1	0.3	25	8000	1.0/1.5	0.25
22	1	0.3	25	8000	1.0/1.5	0.15

For each test run, 100 sheets were printed (after initial set-up running), which were dried at room temperature 2 days in the pressroom.

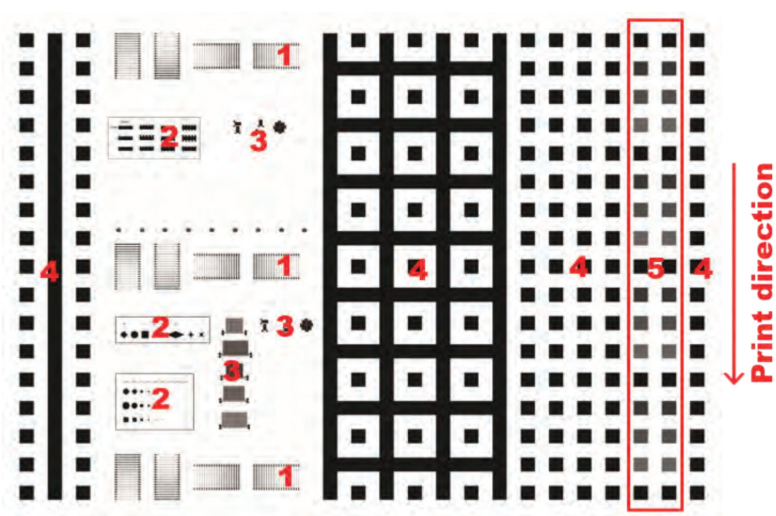


Figure 4: Sheet layout in format 1050 × 750 mm for printing experiments: 1 – circuit paths; 2 – visual control elements; 3 – sensor elements; 4 – full tone fields; 5 – half tone fields (10–100 %); print direction shows direction of sheet running in the offset printing press, in other words, the leading edge of the print sheet is shown in the lower edge of the image

based ink for offset printing (including dampening) was used. The printing layout is shown in Figure 4.

To proof the different visual and functional properties, different printed elements were included into the layout: sensor elements, circuit paths, full tone fields and lines, half tone fields (10–100 % in 10 % step) and some elements for visual control of the print quality (Figure 4).

Four speeds were applied on the printing press: from 8 000 to 14 000 sheets/h in steps of 2 000 sheets/h. To avoid any additional stress effect on the metal layer, the dryer was off. To analyze the influence of glue amount and dampening on the conductivity of cold foil areas, the supply of glue and dampening was varied. The tension of the cold foil web was defined between 0.4 N/cm and 2.0 N/cm. The engagement between the pressure cylinders in the cold foil transfer unit were chosen between 0.15 mm and 0.25 mm (line width of engagement). The value of powder was constant at 5 % as well as the draw-off angle of the cold foil roll during the manufacturing process. The exact settings of the printing experiments are listed in Table 1.

3. Measurements of electrical sheet resistance

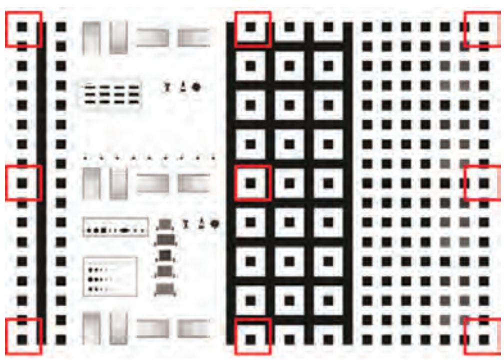


Figure 5: Layout of the printed sheets; fields selected for the measurements are marked with red frame

Figure 6: Designation of position selected fields on the printed sheets

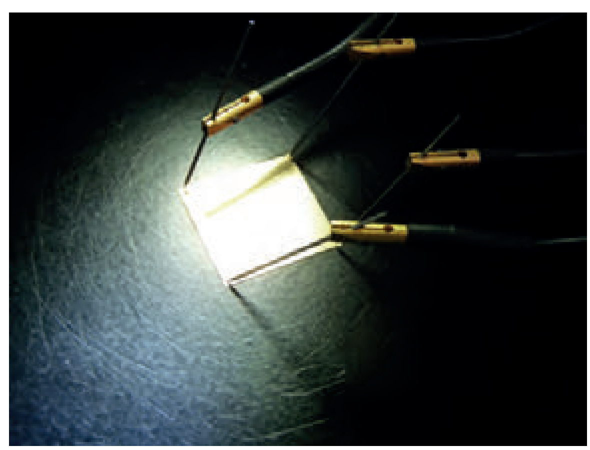


Figure 7: Sheet resistance measurement of a printed cold foil sample on the 4-point measurement station

To investigate the electrical conductivity of the printed cold foil samples, each 10th printed sheet was taken from each test run (in total 10 printed sheets/test run). On each printed sheet nine areas were defined: three on the leading edge of the printed sheet (gripper side, C-positions), three in the middle (B-positions) and three on the outside edge (A-positions) (see Figure 5 and Figure 6). In total, 1 980 samples 2 × 2 cm in size were taken for the analysis.

As the printed cold foil elements are provided on the upper side with a protective insulating layer, the challenge was to measure the electrical resistance of the aluminium layer in spite of this protective layer. Etching of the protective layer of the cold foils (Egitto, 1990) similar to the hot stamping foils in a plasma system (Lyashenko, Salun and Doersam, 2012) proved to be less practical because of long etching times needed (more than 120 minutes) and also because of the large number of samples. In addition, there is a problem with the electrical sheet resistance measurements based on a 4-point measurement method (Van der Pauw, 1958) that were not plausible by reason of the sharpness of sensory needles of the measurement station and because of the very thin metal layers of the cold foils (Figure 7) that were frequently destroyed by the sensory needles (Lyashenko, Salun and Doersam, 2012).

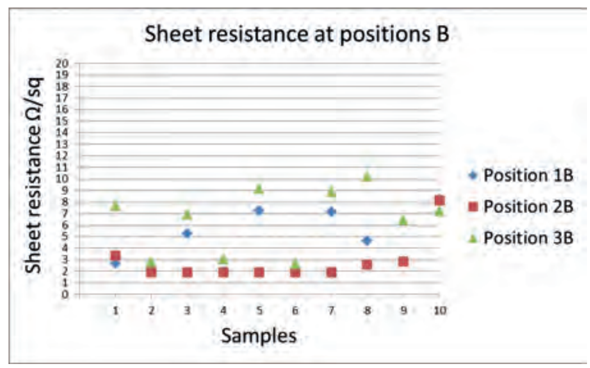
As an alternative to the 4-point measurement method, the eddy current measurement method was selected, which is often used in semiconductors industry (Claeys et al., 2006; Schroder, 2006). The contactless sheet resistance measurement system SRM-14TSS of company NAGY Messsysteme GmbH (Figure 8) works on the eddy current principle, in which the test object is placed in the magnetic field of the coil of a high-frequency circuit. As a result, both the specific electrical resistance and the sheet resistance of the measured object can be determined. In addition, the special manufactured NAGY system SRM-14TSS allows a visual inspection of the homogeneity of the samples and the metal layer of the cold foils through a built-uniformly illuminated field.

With the NAGY system SRM-14TSS the printed cold foil samples were measured without contact and without removing the protective layer. The sheet resistance was determined for each sample using a circle measurement area with a diameter of 15 mm. The measurements of the sheet resistance were performed once for each sample.

Figure 8: The contactless sheet resistance measurement system SRM-14TSS of company NAGY Messsysteme GmbH (NAGY, 2014)

4. Statistical analysis

For the evaluation, 1 980 printed cold foil samples with eight input variables (settings of the printing experiments) were measured. This is a high amount of data, which is most useful to judge by a statistical method of analysis. The analysis was performed using the software Cornerstone version 5.1. Using such an analysis it is possible to determine the influence of individual input variables, the square of the input variables and the influence of the combination of the input variables on the conductivity of the cold foil metal layers (output variable). In the investigated case, the conductivity was measured indirectly by measuring the sheet resistance values (Figure 9).



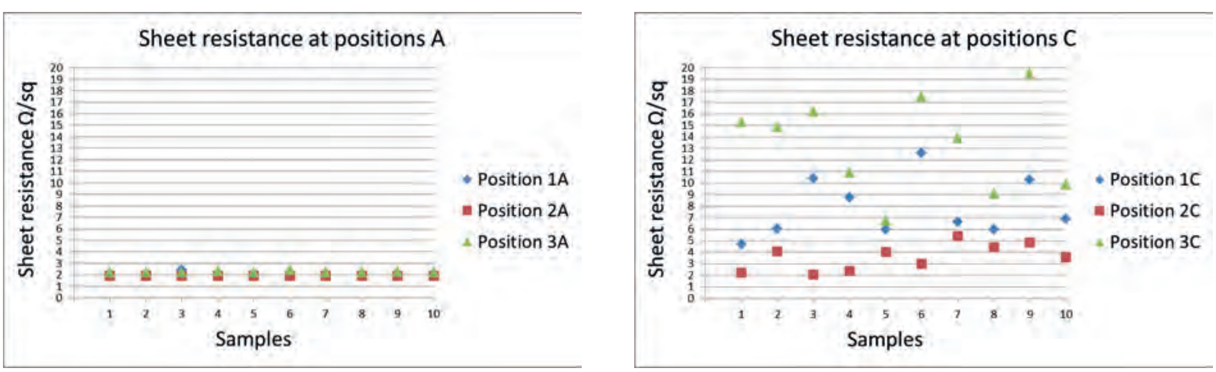


Figure 9: Sheet resistance values of cold foil samples for test run number 14 at positions A, B and C (Type 1 cold foil material); for the positions 1A to 3C see Figure 5 and Figure 6

5. Results

The sheet resistance values of 1 980 printed cold foil samples were distributed between 1.76 and 38.15 Ω/sq with a mean value of 4.52 Ω/sq. In Figure 9 the measurement results of the sheet resistance for test run number 14 (see Table 1) at positions A, B and C of printed cold foil samples of the Type 1 cold foil material are shown.

Ten different samples for every position were measured. By regression analysis using Cornerstone 5.1, a coefficient of determination (Jann, 2005) of 0.7380 was obtained after data transformation. This value shows that 73.8 % of the sheet resistance values can be explained with the help of the achieved regression model. In other words, the coefficient of determination of 0.738 is the ratio between the variation of the regression model and the variation of measured values of the sheet resistance; 26.2 % of the variation of sheet resistance values cannot be explained by the regression model.

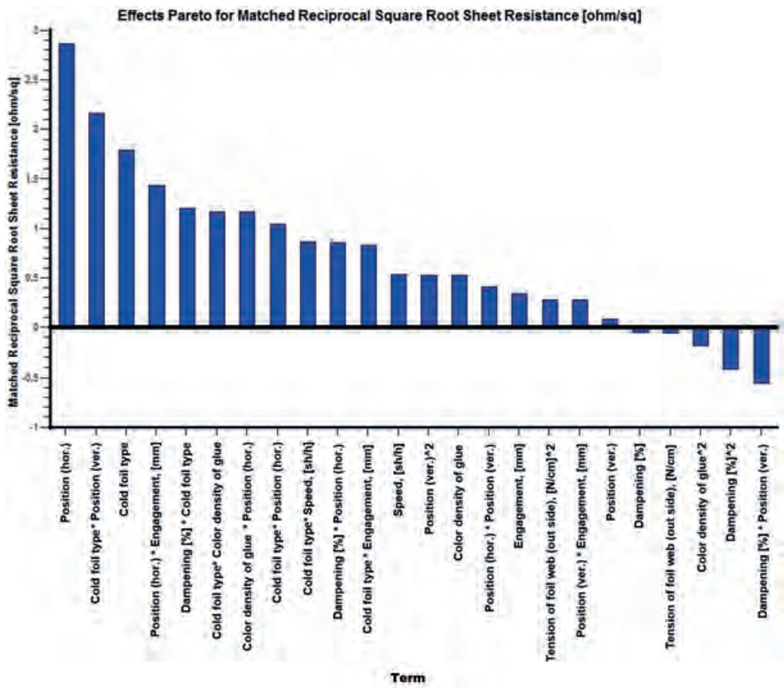


Figure 10: Chart Effects Pareto for the influence of input variables (printing setting) on the examined output variable (electrical sheet resistance of printed cold foil samples)

To examine the influence of input variables on the examined output variable the chart "Pareto Effects" (SAS, 2012) was created (Figure 10). The highest positive values indicate the greatest influence among the input variables measured on the sheet resistance values. From left to right, the influences of the input variables drop. The lower the absolute height, the lower the influence on the output variable. Negative values mean an inverse influence on the output variable. From the regression analysis a total of 53 terms were created; 29 terms in the regression model were not taken into account because the probability of error exceeded 10 %, as described is SAS (2012).

Following the rules of statistical analysis, terms in the model with an error probability of over around 10 % were eliminated. Amongst those were linear, quadratic and interaction terms, e.g. the tension of the foil web (upper side i.e. incoming web) and other inputs.

The diagram in Figure 10 shows the following results. The terms such as horizontal position of the printed cold foil samples on the printed sheet and cold foil material itself, have the highest influence on the sheet resistance values. If the cold foil material is changed, the sheet resistance is strongly affected. The term "vertical position" has a minor influence on the sheet resistance values. The variation of this term results in a small change in the sheet resistance. Similarly, the sheet resistance can be reduced only slightly when the dampening or the tension of foil web (outer side) are slightly increased. This means a small increase in the conductivity.

The statistics histogram was used to check the normal distribution of the measured values (Figure 11).

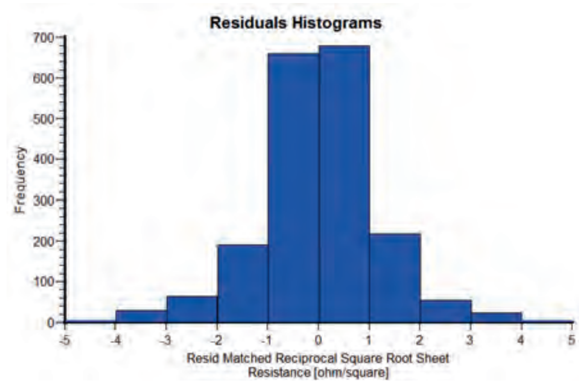


Figure 11: Residuals Histogram for distribution of the measured sheet resistance values of printed cold foil samples

In addition, a so-called Residuals Probability Plot was created (Figure 12). This plot resolves the weak spots of the histogram. It shows the distance between the measured values and the standard normal probability distribution. By performing this evaluation, the measurement data were transformed in order to reduce the outliers of the measurement values and to produce a meaningful Residuals Probability Plot.

The central range of the regress values fit very well to the normal probability distribution. The values at the beginning and end of the curve, however, depart from normal distribution. In this case there is the so-called

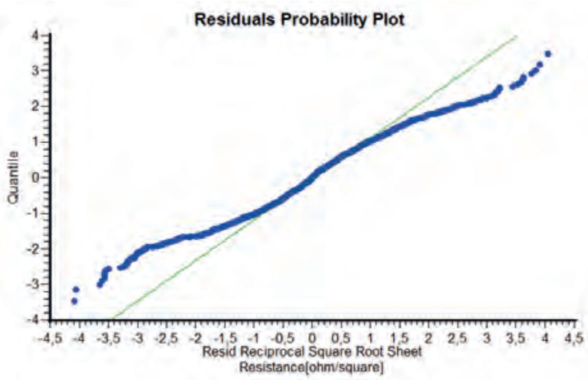


Figure 12: Residuals Probability Plot for distribution of the measured and then transformed sheet resistance values of printed cold foil samples

"heavy tails" (poor fit), since the extreme residuals are higher than expected in the case of the normal distribution. The extreme residuals can be explained by the measurement error, which could arise from various causes. One of them is the layer homogeneity of the printed cold foil samples that was checked on the additional illuminated field of the NAGY system SRM-14TSS. In some samples some cracks in the metal layer could be seen (Figure 13), which strongly depended on the position of the samples on the printed sheet. The horizontal positions A, at the gripper edge, provided stable and smaller sheet resistance values, while in the horizontal positions B and C they were up to 23-fold higher.

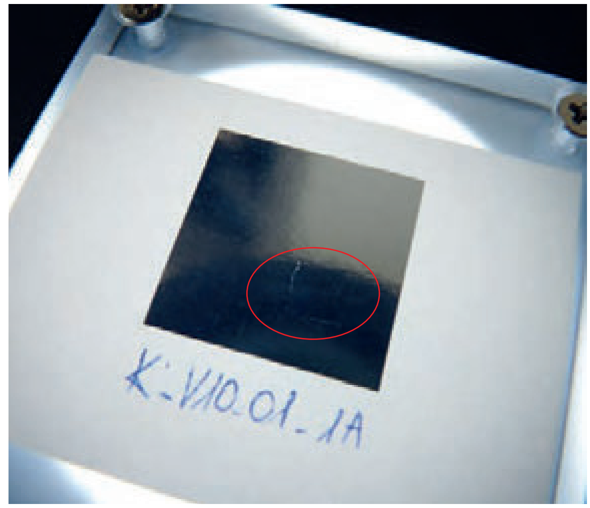


Figure 13: A printed cold foil sample on the illuminated field of the NAGY system SRM-14TSS with a marked position of a crack in the metal layer

6. Discussion

The following criteria are considered to be important for using cold foil transfer processes for printed electronics: first, the electrical conductivity (in the investigated case, sheet resistance values in Ω/sq) and second, the reproducibility and reliability of such metal layers, especially depending on different printing process settings.

The experiments and the statistical analysis have shown several interesting points that should be considered in future research and applications:

- The sheet resistance values were distributed inhomogeneously over the printed sheets depending on the horizontal position of the samples. The samples on the trailing edge (A-positions) of the printed sheet had low and homogeneous sheet resistance values (around 2 Ω/sq). On the contrary to this, high and varying sheet resistance values were recognized in the middle and on the leading edge of the printed sheet (B- and C-positions). It should be noted that this was depending on the printing process. Probably, the engagement was distributed inhomogeneously over the sheet. This influenced the distribution of the adhesive layer as well as the quality of the transferred cold foil material. The visual quality of the printed cold foil layer with regard to the homogeneity was to a certain extent influenced by tiny cracks in the metal layer that were observed in almost all cold foil samples mainly located on the leading edge and in the middle of the printed sheet (B- and C-positions). Additionally, influences such as deformation of the printed sheet during the printing process can be a reason for the layer cracks. In contrast to the horizontal position of the cold foil samples, the vertical position on the printed sheet had a small influence on the sheet resistance values.
- Another important parameter in the analysis of the measurement results is the cold foil material itself. The measurement results indicate that the Type 1 cold foil material shows more stable and smaller sheet resistance values and less metal layer defects such as cracks. The basic electrical resistance value was highly dependent on the type of the cold foil material. Parameters such as homogeneity, thickness and density/porosity of the metal layer can be enumerated that might influence conductivity as well as the ease of transfer under the influence of the glue. One has to admit that such transfer materials are made for graphic applications only and are by far not intended to manufacture electronic devices.
- Almost any change in the printing setting has resulted in a change of the measured values. The color density of glue corresponding to the glue layer thickness and the printing speed continue the list of the most influential parameters by cold foil transfer process. An increase of these parameters has led to an increase of sheet resistance.

7. Conclusion

In summary, it can be said that cold foil transfer technology is an additional candidate for applications in functional printing. The printed metal layers exhibit reasonably good conductivity and sheet resistance values in Ω/sq-range at least for applications where electric current is not that crucial (e.g. for capacitive-related systems). Furthermore, a way to optimize the homogeneity of the cold foil printed samples over the printed sheets should be found. Therefore, the investigation of different glue types for the printing process and different cold foil engagements on the out and up side of the printing unit could be helpful. To understand the role of the cold foil materials themselves, a systematic investigation of the cold foils currently available on the market needs to be performed.

At this time, only cold foil materials for graphic arts applications with a thickness in the range of 20 nm and below are available. Therefore, another option for the cold foil manufacturers might be to develop further quality grades (e.g. aluminium layers with higher thickness) optimized for electronic functions to achieve higher values of conductivity for a broader range of electric applications. In parallel one then has to investigate and optimize the transfer process for thicker aluminium layers anew.

A further interesting point is the investigation of various applications of electronic components such as circuit tracks, capacitors or sensor elements manufactured using cold foil transfer technology. Because of the given measuring system, only solid areas could be investigated in this research. In case of circuit tracks, however, one might study the currently achievable resolution of the printed elements with special pattern designs without using the contactless measuring method that is suitable for areas elements only.

Acknowledgements

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