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Modeling and investigating the dynamic gloss of flexo printed UV-inks containing aluminum pigments

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Short abstract

Various factors affect the dynamic gloss development after printing such as the amount of ink applied, the ink viscosity or different properties of the substrate. When using metallic inks that contain aluminum leafing pigments, also these leafing properties are crucial. In this study, the micro-tri-gloss, a specular gloss meter that measures gloss at the angles of 20°, 60° and 85° is used to study the dynamic gloss of metallic inks on different substrates. The two types of inks used contain vacuum metallized pigments and cornflake pigments. It is shown how the dynamic gloss of these inks behaves differentially and how the dynamic gloss differs according to the substrate used. Further, it is shown how the dynamic gloss curves can be modelled using the Kohlrausch function or a summation of two exponential functions. Finally, it is discussed why the dynamic gloss curves measured simultaneously at different angles can behave in a contrary manner.

Keywords: gloss measurement, aluminium pigments, dynamic gloss, UV-inks, flexo printing

1. Introduction and background

In the label and package printing industry metallic embellishments can be produced with a range of different printing methods as described by Weber, Spiehl and Dörsam (2022). One of these methods is based on flexo printing with UV-curable inks containing aluminum pigments. The visual quality of a metallic embellishment is determined by various indicators. A primary one is the gloss: often metallized surfaces are targeting to have a glossy, or mirror-like appearance. This is especially the case for packaging for high quality products. The print gloss of inks is dependent on various factors. As stated by Preston, et al. (2003) who made investigations on the dynamic gloss of non-metallic printing inks, the ink formulation, paper properties such as roughness, porosity, or type of coating play a decisive role.

As stated by Rich, et al. (2017), Wheeler (1999), Wißling (2013), and Pfaff, Bartelt and Maile (2021), there are three different types of aluminum pigments used in metallic printing inks. If applied on a smooth surface, so-called cornflake pigments result in a faint or minor mirror effect. Using silverdollar pigments improves the result in terms of gloss. However, only the application of vacuum metallized pigments (VMPs), which have the highest quality and a very smooth surface can result in a mirror-like appearance. According to Wheeler (1999) and Maile, Pfaff and Reynders (2005), cornflake and silverdollar pigments typically have a thickness of about 0.1–1.0 µm. VMPs, however, can be as thin as 40 nm. It can be distinguished between leafing and non-leafing pigments. While leafing pigments float to the top of the ink film after printing, non-leafing pigments stay evenly distributed in the ink film as shown in Figure 1.

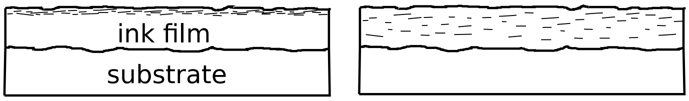

Figure 1: Distribution of leafing (left) and non-leafing (right) aluminum pigments in ink (Weber, Spiehl and Dörsam, 2022)

Beside the substrate, ink formulation and pigment type, also print settings such as the speed of the printing machine, or the amount of ink applied influence the print gloss. Another important factor is the time between application of the UV-inks on the substrate and UV-curing of the ink. After printing the ink, a change of gloss takes place, which is called dynamic print gloss or simply dynamic gloss. As stated by Koivula, et al. (2009), the measurement of dynamic gloss can be a useful tool to study paper-ink interactions after printing and can help papermakers and printers to understand why different papers lead to different print gloss. In this study, the dynamic gloss of two UV-inks containing VMPs and cornflake pigments was investigated. The metallic ink was printed on different substrates with different properties such as roughness, porosity, and pre-treatment using a laboratory flexo printing machine. A commercially available gloss meter measuring gloss continuously at three different angles was used to investigate the dynamic gloss.

2. Materials and methods

Printing trials were carried out using the laboratory flexo printing machine IGT F1. Gloss measurements were conducted using the micro-tri-gloss from Byk Gardner. As described by Weber, Spiehl and Dörsam (2021a; 2021b) in detail, this gloss meter can measure specular gloss at the specular angles of 20°, 60° and 85°. In continuous measurement mode, it measures gloss in intervals that can be adjusted from zero to nine seconds in steps of one second. For the gloss measurements made in this study, the interval was adjusted to one second. Both, the laboratory printing machine and gloss meter are shown in Figure 2.

Figure 2: Laboratory flexo printing machine IGT F1 printability tester and micro-tri-gloss (in blue in the bottom left) on a printed substrate

As explained by Weber, Spiehl and Dörsam (2021b), when measuring the specular gloss, a LED flashes light that passes a lens and an aperture with an inclination of θ on the surface of a sample. There, the light is reflected and scattered and partially absorbed. A part of the reflected light passes an aperture on the receiver side of the specular angle. It is important to note that according to ASTM D523-14, the light source aperture is the same for all three angles (American Society for Testing and Materials, 2018). The receiver aperture however, differs and is larger for the receiver aperture at 60° compared to the receiver aperture at 20°. The aperture sizes are listed in Table 1. Figure 3 shows a schematic of a specular gloss meter with the angles associated to Table 1.

Table 1: Angles of the light source aperture and receiver aperture for the measurement of specular gloss at 20°, 60° and 85° after ASTM D523-14; the angles α and β correspond to Figure 1

	In plane of measurement (α)	Perpendicular to plane of measurement (β)
Light source aperture (for all angels)	0.75° ± 0.25°	2.5° ± 0.5°
20° receiver aperture	1.8° ± 0.05°	3.6° ± 0.1°
60° receiver aperture	4.4° ± 0.10°	11.7° ± 0.2°
85° receiver aperture	4.0° ± 0.30°	6.0° ± 0.3°

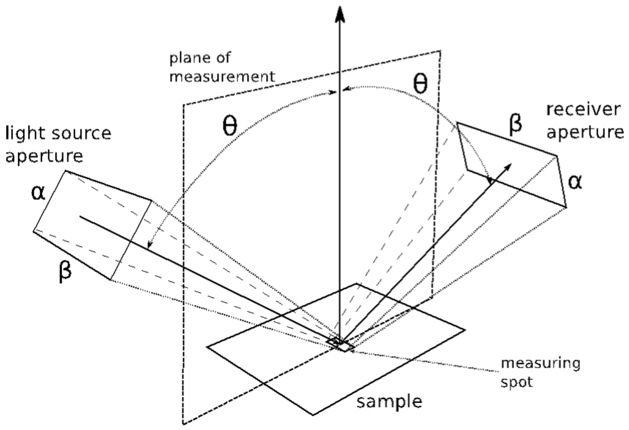

Figure 3: Schematic of a specular gloss meter with the angles associated to Table 1; after Westlund and Meyer (2001), cited from Weber, Spiehl and Dörsam (2021b)

The print settings of the printing machine as well as the anilox rollers used for the experiments are listed in Table 2. Three different substrates were used for this study. These were Chromolux paper from Zanders with a grammage of 100 g/m^2, Chromolux board from Zanders with a grammage of 400 g/m^2, and LumiArt paper from Stora Enso Oyj with a grammage of 115 g/m^2. Both Chromolux substrates are super calendered, which makes their surface extremely smooth and glossy. LumiArt paper is multicoated art paper that is rougher than the Chromolux types. The company Siegwerk produces the primer used for two series of the experiments. The metallic printing inks used for this study were UV low-migration printing inks, which were provided by the company Schlenk. According to the datasheets and additional company information, the pigments of the ink containing VMPs have a d_{50} size of 7 µm and a d_{99} size of 10–12 µm, a metal content of approximately 3 % and a viscosity of 300–900 mPas. Pigments in the ink containing cornflake pigments have a d_{50} size of 6 µm and a d_{99} size of 11–12 µm, a metal content of 15 % and a viscosity of 800–1 600 mPas.

Table 2: Print setting of the laboratory flexo printing machine IGT F1

Anilox force	60 N
Printing force	75 N
Printing velocity	0.50 m/s
Anilox roller volume for printing metallic inks	16 ml/m^2
Anilox roller volume for printing primer	8 ml/m^2

Between printing the samples with the printing machine, placing the gloss meter on the sample and starting the continuous measurement a time lag of about 2 seconds occurred, which was measured repeatedly using a stopwatch. Continuous measurements were made until no significant further change of gloss after printing was observed. Hereafter, the UV-curing of the inks was carried out. Each of the three different substrate types was printed with the two different metallic inks without prior pre-treatment using a primer.

For one series of trials, the LumiArt paper was additionally primed and then printed with the metallic inks. In total, this gave eight different combinations of substrate, pre-treatment and metallic ink.

Before the experiments were carried out, the gloss meter was checked according to its measurement stability under continuous measurement mode. To do so, the device was calibrated on a black glass calibration tile. Afterwards, 500 measurements were carried out using the continuous measurement mode with one second in between the measurements. After each 100th measurement, a measurement on the black calibration tile was taken. From the results shown in Table 3 it can be concluded that the device measurements were stable, and no internal device drift due to possible heat development during measurements could be expected. The used paper substrates were characterized in terms of gloss. The results can be seen in Table 4. Each measurement value is the average of five measurements on different positions and directions on the regarding paper substrate.

Table 3: Stability of the micro-tri-gloss at continuous measurement mode; measurement values in Gloss Units (GU); $gloss_{xx}$ denotes the specular gloss measured at the specular angle of xx°

Number of measurements	$gloss_{20}$[GU]	$gloss_{60}$[GU]	$gloss_{85}$[GU]
0 (calibration values)	92.9	95.4	99.3
100	92.8	95.3	99.3
200	92.5	95.2	99.2
300	92.6	95.2	98.9
400	92.8	95.3	98.9
500	92.8	95.3	98.6

Table 4: Gloss measured at the specular angles of 20°, 60°, and 85° with the micro-tri-gloss on the substrates used in the experiments; the average values and standard deviations are calculated from five measurements on each sample

	Chromolux board	Chromolux paper	LumiArt paper	LumiArt primed
$gloss_{20}$[GU]	57.5 ± 0.4	50.9 ± 1.0	3.4 ± 0.4	15.9 ± 0.9
$gloss_{60}$[GU]	77.9 ± 0.2	80.1 ± 0.2	29.9 ± 0.5	58.7 ± 1.6
$gloss_{85}$[GU]	97.0 ± 0.1	91.2 ± 0.4	79.9 ± 0.5	85.0 ± 0.8

3. Results and analysis

Figure 4 shows one sample of each of the eight combinations of the printing trials, which are Chromolux paper, Chromolux board, LumiArt paper and primed LumiArt paper printed with UV flexo inks containing VMPs and cornflake pigments after UV-curing. The picture was taken with samples placed in front of a checkerboard to give an impression of the glossiness and mirroring capability of the samples. It can be seen that combinations printed with inks containing VMPs give a clearer and sharper reflection of the checkerboard and have a higher gloss than the combinations printed with inks containing cornflake pigments. Further, the reflection of the printed Chromolux paper and board is superior compared to the LumiArt paper and the primed LumiArt paper. The imprint that is visible on some of the samples comes from the gloss meter that was placed on the uncured ink for dynamic gloss measurements.

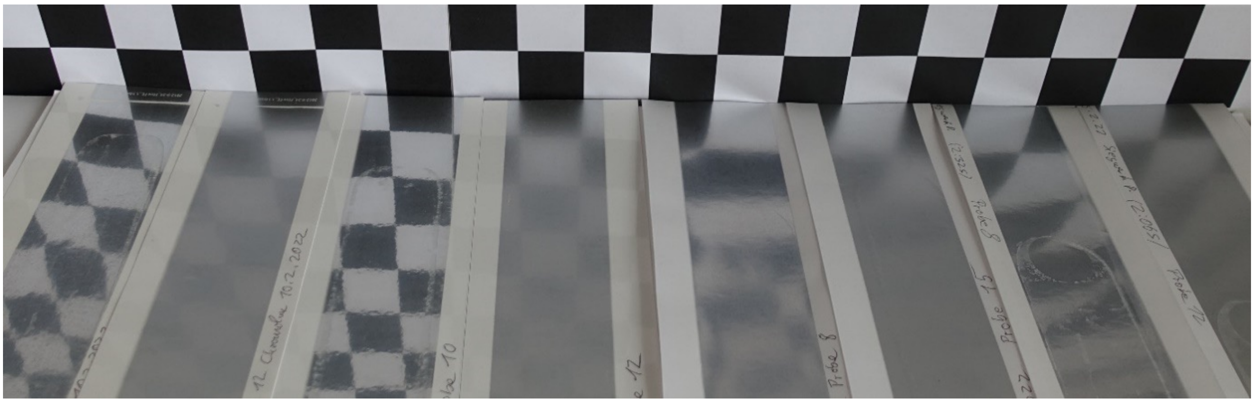

Figure 4: Collection of samples printed in the experiments photographed in front of a checkerboard; from left to right: Chromolux paper (VMP), Chromolux paper (cornflake), Chromolux board (VMP), Chromolux board (cornflake), LumiArt (VMP), LumiArt (cornflake), LumiArt primed (VMP), LumiArt primed (cornflake)

Figures 5–8 show exemplary dynamic gloss curves for each of the eight combinations. The first measurement for each trial started about two seconds after printing. Figure 5 shows the dynamic gloss measured on the uncured ink on Chromolux board. While the specular gloss of inks containing VMPs at 20° and 60° rose rapidly in the first 20 seconds, inks with cornflake pigments exhibited only minor changes in specular gloss. Figure 6 shows the dynamic gloss on Chromolux paper. Compared to all the other combinations, dynamic gloss changes can be measured for a very long time on this substrate using inks containing VMPs. It is also important to note that the specular gloss measured at 20° first decreases slightly before it goes up. Interestingly, dynamic gloss changes could be measured for a longer time on Chromolux paper compared to Chromolux board for both types of metallic inks. In Figure 7, the dynamic gloss curves for unprimed LumiArt paper can be seen. For inks containing VMPs it is interesting to see that the specular gloss measured at 60° rose for more than 60 seconds while the specular gloss measured at 20° only rose for a short instant, and then decreased. When comparing the dynamic gloss on LumiArt paper with dynamic gloss on primed LumiArt paper it is striking that the time during which the gloss rose after printing was shorter while the total gloss measured at the three angles was higher compared unprimed LumiArt paper. Overall, the rise of the gloss values measured at the three angles always took longer, and the maximum gloss levels were always higher for inks containing VMPs compared to cornflake pigments.

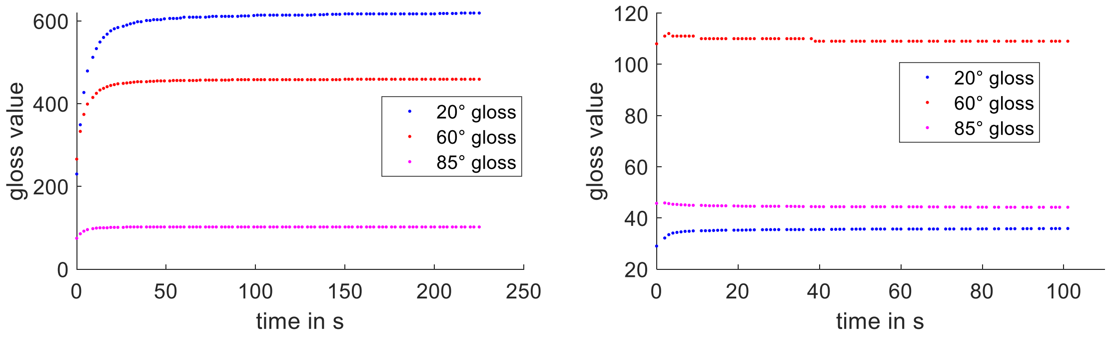

Figure 5: Dynamic gloss measured on Chromolux board with inks containing VMPs (left) and cornflake pigments (right)

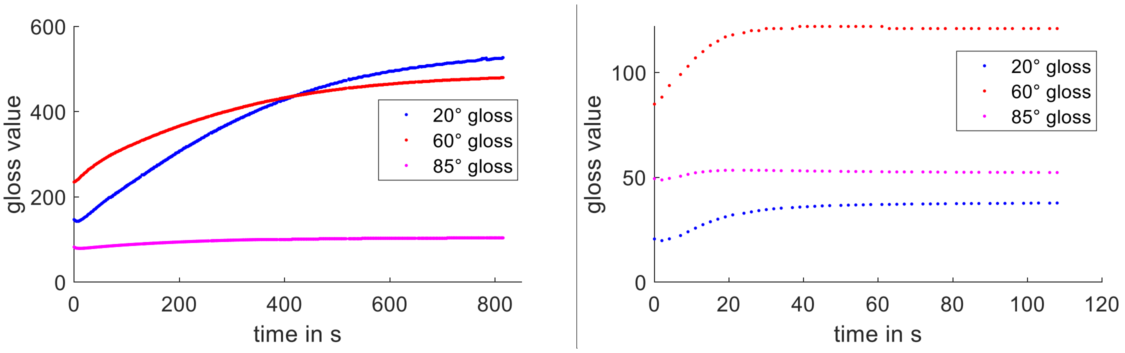

Figure 6: Dynamic gloss measured on Chromolux paper with inks containing VMPs (left) and cornflake pigments (right)

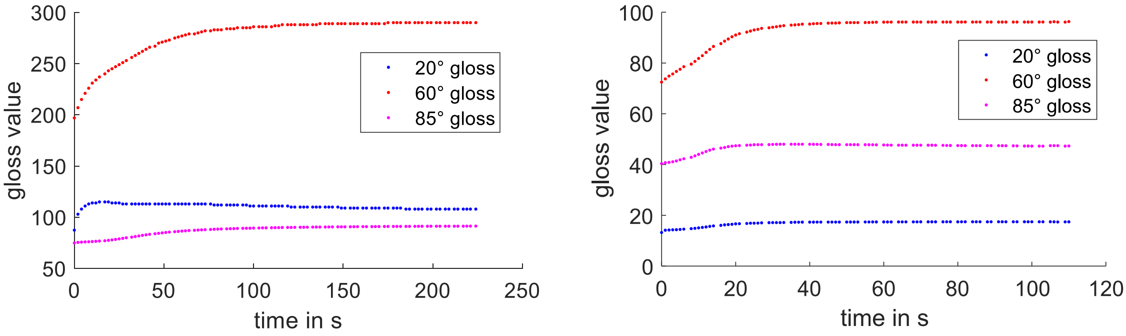

Figure 7: Dynamic gloss measured on LumiArt paper with inks containing VMPs (left) and cornflake pigments (right)

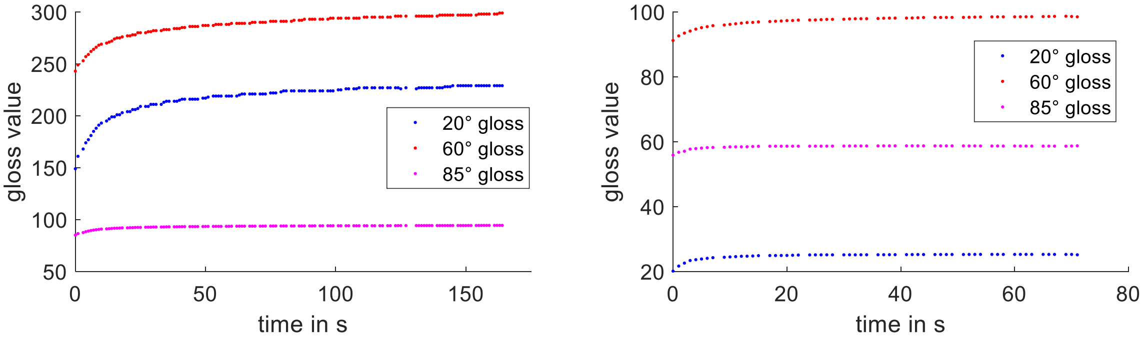

Figure 8: Dynamic gloss measured on primed LumiArt paper with inks containing VMPs (left) and cornflake pigments (right)

Figure 9 shows two microscopic images taken from metallized Chromolux board after UV-curing. On the left, VMPs and on the right Cornflake pigments of the metallic inks used can be seen. The light areas in the respective pictures are the pigments. It can be seen that the VMPs appear to align better to each other, while the cornflake pigments appear to have a greater size distribution, more edges, and a higher surface roughness. Thus, light reflection becomes more diffusive, and gloss is generally lower for substrates metallized with cornflake pigments than with VMPs.

There are three factors that could lead to a higher mobility of the VMPs in the ink compared to the cornflake pigments. First, VMPs are much thinner than cornflake pigments, second the metal content of the VMP ink is lower, and third the viscosity of the ink containing VMPs is lower. Hence, gloss changes are measurable for a longer time when using the ink containing VMPs.

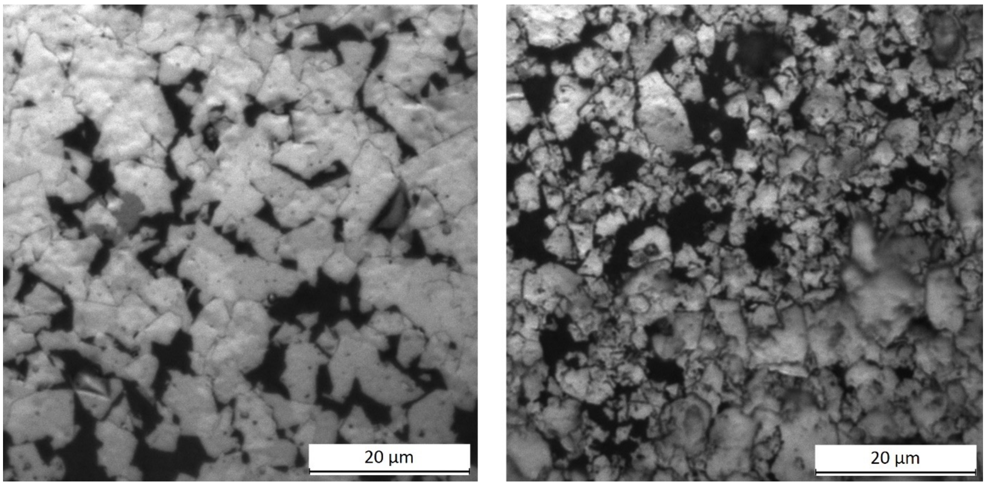

Figure 9: Inks containing VMPs (left) and cornflake pigments (right) printed on Chromolux board

In the following, only the dynamic gloss measured on Chromolux board and on unprimed LumiArt paper are analyzed in greater detail and it is shown how the dynamic gloss trends can be modeled using mathematical functions. When using inks containing VMPs, dynamic gloss curves for Chromolux board and Chromolux paper can be modeled best with a Kohlrausch function 1. The t is the time of measurement, a, b, c and d are non-negative fit parameters. $c - a$ is the gloss delta from the start of the measurement until the steady state gloss value, given by c. The b reciprocally correlates with the time needed to reach the steady state gloss value, and positively correlates with the initial incline. The d is the stretching exponent that is usually between 0 and 1.

$$f(t) = -\,a * exp(-(b * t)^{d}) + c \tag*{[1]}$$

This Kohlrausch function (Kohlrausch, 1854) describes the distribution of attachment energies of electric charges at the dielectric between capacitor plates. The stretching exponent $d = 0 \ldots 1$ is characteristic for the material and its influence on the capacitor discharge process. The case $d = 1$ corresponds to ordinary exponential relaxation. If applied to dynamic print gloss, the stretching exponent d could describe the feature that pigments float up with size-dependent rates. For the VMP relaxation on Chromolux board, e.g., one finds $d = 0.70$ and 0.74 for gloss angles of 20° and 60°, as shown in Figure 10. This could describe the feature that larger pigments float up faster than smaller ones.

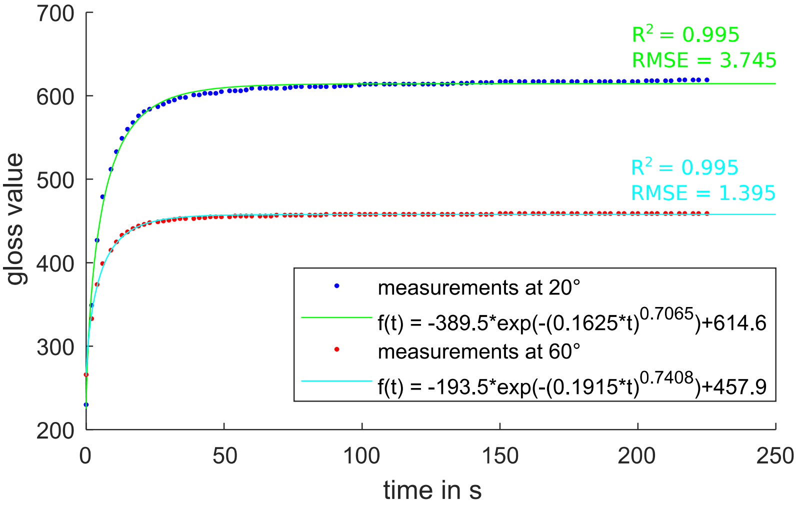

Figure 10: Fitting of function 1 on the dynamic gloss measured on Chromolux board when printing with inks containing VMPs

When fitting function 1 on the dynamic gloss trends measured at 20° and 60° resulting from unprimed LumiArt paper and inks containing VMPs, it is striking that the function does not give a good fit for the trend measured at 20°. However, for the trend measured at 60° a Kohlrausch fit with $d = 1$ appears adequate, which is shown in Figure 11. Function 2 is a better model of the gloss curve measured at 20°. It is the sum of two exponential functions. One of them describes the rising, the second one a slow and steady decrease of the gloss level.

$$f(t) = -\, a * exp(-b * t) + c * exp(-b' * t) + h \qquad [2]$$

Where $h + c$ gives the gloss maximum that is reached, a gives the delta between the first measurement and the gloss maximum. b is the rising rate of the initial incline, and $b' << b$ describes the slow decline after the gloss maximum has been passed. The description of the dynamic gloss with the summation of the two exponential function shows that basically two different processes happen after printing, of which one is responsible for the incline of the curve and one for the decline. To explain these different behaviors of dynamic gloss measured at 20° and 60° both the process that happens after printing as well as the construction of a gloss meter has to be considered.

After printing, the gloss influencing processes are first the levelling of the ink film, the alignment of the pigments to the ink surface as well as the floating up of the pigments in the ink. Secondly, the binder of the ink penetrates into the substrate. For this reason, the ink film that is still present on the paper surface together with the pigments aligns more and more with the paper surface texture. This leads to a rising roughness of ink film. A schematic of this process can be seen in Figure 12. The decreasing interspace between the pigments leads to the effect that total amount of reflected light increases. The increasing roughness of the ink film surface caused by the comparatively slow binder penetration into the paper leads to an increasing scattering of light.

Since the receiver aperture of the gloss meter at 20° is smaller than the receiver aperture at 60°, the increasing scattering of light results in a decreasing fraction of incident light at the photodiode behind the aperture. Thus, the measurement signal decreases when scattering becomes more apparent. The larger receiver aperture at 60° however, is not so sensitive to the scattering of reflected light. From the amount of scattered light, a greater amount can pass the receiver aperture without attenuation. Hence, the amount of light passing the receiver aperture increases as the interspace between the pigments decreases.

According to ASTM D4039-09, haze that makes statements about the scattering of light can be calculated by taking the subtraction of 20° from gloss measured at 60° (American Society for Testing and Materials, 2015). For reasons unknown to the authors this is only specified for nonmetallic surfaces. However, if that is applied here not only the dynamic gloss is measured but also statements about a dynamic haze that changes with time after printing can be made.

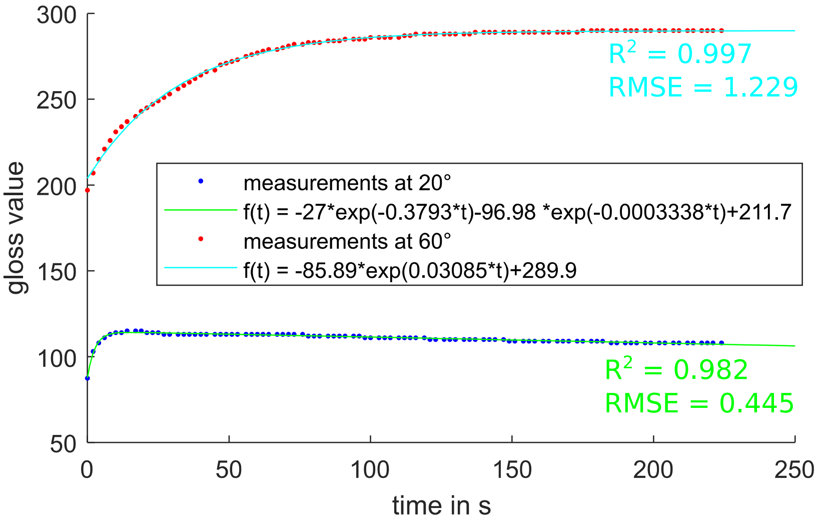

Figure 11: Fitting of function 1 and function 2 on the dynamic gloss measured on unprimed LumiArt paper when printing with inks containing VMPs, with b = 0.3793 and b' = 0.0003338 at a gloss angle of 20°

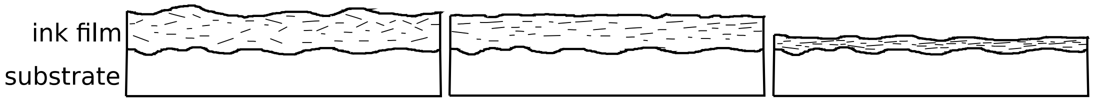

Figure 12: Schematic of ink levelling of metallic inks on a rough substrate with a relatively high porosity and roughness

4. Conclusion and outlook

In the present study, the dynamic gloss after printing metallic inks on different substrates was investigated using specular gloss measurements made at three different angles. It was shown that inks containing different sorts of aluminum pigments behave very differently, and that the substrate also has a major impact on the dynamic gloss. Further, it was shown how some of the dynamic gloss trends can be modeled using exponential functions and how the meaning of the fit parameters of these can be explained. A major finding was that the dynamic gloss trends measured at different angles can have opposite directions. An explanation of this phenomenon was given by referring to the construction of the gloss meter as well as by referring to the processes influencing the gloss and the scattering of light after printing. The difference of the trends of gloss measured at 20° and 60° can also be referred to as dynamic haze.

In further studies the process of the change of dynamic gloss will be interrupted in different time intervals. By doing so, we will be able to investigate the changing positions of the pigments and the correlating gloss in a steady state and hence in more detail. Further, we will examine the pore structure and water absorptivity of the substrates to relate them with the dynamic gloss and to find out why e.g., Chromolux paper and Chromolux board behave very different in terms of dynamic gloss. Additionally, experiments are planned using a different gloss meter that enables to make continuous gloss measurements and to make investigations on the light distribution around the specular angle and gives not only a single gloss value for every angle.

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