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Quality control of embossed holograms by measuring gloss and color values

Pauline Brumm[1], *Edgar Dörsam*[1], *Duy Linh Nguyen*[1] *and Martin Schmitt-Lewen*[2]

[1] Technische Universität Darmstadt,
Institute of Printing Science and Technology,
Magdalenenstr. 2, 64289 Darmstadt, Germany
[2] Heidelberger Druckmaschinen AG,
Alte Eppelheimer Str. 26, 69115 Heidelberg, Germany

pauline.brumm@stud.tu-darmstadt.de
doersam@idd.tu-darmstadt.de
martin.schmitt-lewen@heidelberg.com

Abstract

Embossed holograms are increasingly often used for the decorative refinement of printed products. So far, there has not been much scientific research about quality control of embossed holograms as well as research about the influence of the background color on the quality of embossed holograms. For this purpose, hologram samples with different background colors were produced in a laboratory setup, using the principle of UV embossing. At first, the quality of the samples was evaluated through a visual experiment. The conceptual design of that experiment was part of this research. Second, gloss and color values were measured with conventional hand-held measuring instruments used by the graphics industry. Color measurements were conducted with an X-Rite MA98 multi-angle spectrophotometer and measurements of gloss values with a BYK micro-TRI-gloss gloss meter. The comparison of the results of the visual experiment and the color measurement led to the conclusion that conventional color measuring instruments can evaluate the influence of the background color on the quality of embossed holograms. It was found out that calculating the color difference ΔE^*_{ab} between background color and sample can be used to recreate the results of the visual experiment, whereas the samples' chroma C^*_{ab} is not suitable for evaluating the influence of the background color. The number of provided measuring geometries is a limitation of this approach. Moreover, the comparison of the results of the visual experiment and the gloss measurements showed that conventional gloss meters cannot evaluate the influence of the background color. However, conclusions concerning the UV embossing process can be drawn from a sample's gloss. This suggests the usage of gloss measurement for process control.

Keywords: micro embossing, UV curing, visual experiment, nickel shim, multi-angle color measurements

1. Introduction

Embossed holograms are well known from banknotes, identification cards or other security documents where they serve as complex anti-counterfeit elements, but they are also used for decorative refinement, e. g. for the refinement of product packaging. Production processes for embossed holograms have become high-speed mass production processes. Consequently, a need for quality control arises.

Another reason for an upcoming need for quality control is the following. For some years, a new scope for design is available through the production process UV embossing, which allows the choice of an arbitrary background color for the embossed hologram (Masuda, 2006). Before this, only metallic background colors were possible, which provide the desired brilliant effect of the classical embossed hologram. The free choice of the background color opens up new possibilities but also new challenges. Which background color can be used to achieve a strong holographic effect? How can the quality of an embossed hologram be measured?

So far, there has not been much scientific research about quality control of embossed holograms and the influence of the background color. In general, one can say that quality control of holograms is difficult because of the great angle-dependency of the holographic effect. Similar difficulties can be found when investigating effect coatings (Hupp and Dörsam, 2007; Kehren, Dörsam and Hupp, 2009).

The goal of this research is to find out, if conventional hand-held measuring instruments for gloss and color values used by the graphic industry can evaluate the quality of embossed holograms. A part of the research was presented at the 43rd International Research Conference of iarigai held in Toronto, Canada (Brumm et al., 2016).

For this research, several experiments are conducted (section 2). We prepare hologram samples with different background colors in section 2.1 and conduct a visual experiment, which has the aim to evaluate the samples' quality, in section 2.2. The development of the visual experiment is also part of this research. In section 2.3, we conduct gloss and color measurements and in section 3, the results of the visual experiment and the measurements are presented and compared to each other. Finally, conclusions are drawn in section 4.

2. Experimental

2.1 Sample preparation

This chapter is about the production of hologram samples with different background colors, using the principle of UV embossing.

2.1.1 Pre-printed substrates

Five types of pre-printed substrates in the colors blue, red, black, white and silver with a size of approximately 135 mm × 330 mm were used (Figure 1).

For the blue, red, black and white pre-printed substrates, Fasson MC Offset 2S-90 (SV4565) with a thickness of 71 µm and grammage of 90 g/m^2 was used as paper substrate. For the UV coating, Saphira UV-Coating U8730 (Heidelberger Druckmaschinen AG) was used. The silver pre-printed substrate differs from the others, because it is produced by cold foil transfer using silver cold foil. Moreover, another paper substrate with a grammage around 180 g/m^2 was used. Table 1 shows CIELAB color values and gloss values (measured in GU-gloss units) of the five types of pre-printed substrates.

2.1.2 Embossing master

To produce an embossing master, we poured a conventional transparent silicone onto a nickel shim (Iliescu, Necşoiu and Comănescu, 2011) and then hardened it in an oven (Vötsch Industrietechnik VTL 60/90) at 42 °C for about three hours. Afterwards, we left it at room temperature for about 60 hours, before gently peeling of the replica (Figure 2). Thus, we produced a transparent silicone shim (thickness approximately 3 mm), which we later used as an embossing master for the UV embossing of our hologram samples.

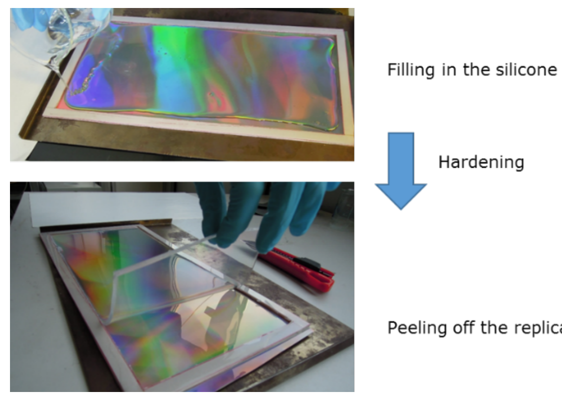

Figure 2: Production of transparent silicone shim

There do not exist clear specifications for nickel shims. They are chosen by visual characteristics like the 'rainbow effect'. We used a commercially available 'rainbow effect' nickel shim, provided by Heidelberger Druckmaschinen AG. It has a double sine wave surface microstructure that creates a rainbow effect due to light diffraction. That means that in different viewing angles different colors of the rainbow (red, orange, yellow, green and blue) appear. We chose the rainbow effect, because it is a simple holographic effect, which is the base of many complex embossed holograms. The depth of the surface microstructures is approximately 130 nm to 140 nm and the period length is approximately 1.02 µm in one direction and approximately 1.25 µm in the perpendicular direction. We measured these values with an atomic force microscope (Nanosurf Nanite

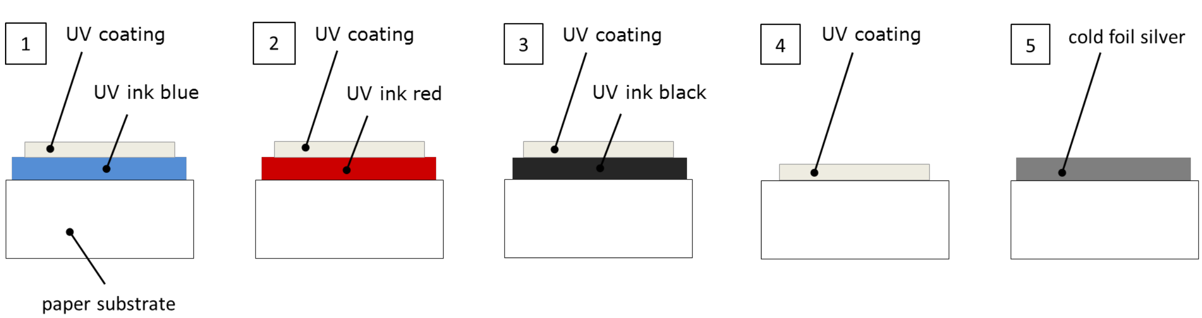

Figure 1: Types of pre-printed substrates. 1 – Blue, 2 – Red, 3 – Black, 4 – White, 5 – Silver

Table 1: CIELAB color values L, a* and b* of pre-printed substrates (X-Rite MA98, measuring geometry 45°/0°, illumination D65, 10° observer, n = 10) and gloss values of pre-printed substrates (BYK micro-TRI-gloss, 20° and 60° measuring angle, n = 10) measured on one pre-printed substrate*

Pre-printed substrate	*L**	*a**	*b**	Gloss (GU)	
				20°	60°
Red	31.3	61.9	40.2	57.3	91.4
Blue	31.2	−15.2	−44.9	45.2	83.9
Black	7.4	−0.1	−1.8	49.6	91.3
Silver	12.8	−0.6	−3.4	1056.7	669.8
White	88.1	−0.2	−0.9	60.1	93.9

B System). Since direct measurements on the nickel shim are technically difficult, we measured the surface structure of one of our hologram samples, which theoretically shows the identical surface structure of the nickel shim.

2.1.3 UV embossing

For the production of our hologram samples, we used the principle of UV embossing (Figure 3). To produce one hologram sample, we coated one of the pre-printed substrates with UV lacquer (holographic lacquer from Heidelberger Druckmaschinen AG) using an automatic film applicator coater (Zehntner ZAA 2300) and a doctor blade (Zehntner ZUA 2000) with the gap height of 50 µm. Then, our transparent silicone shim was pressed into the still wet UV lacquer and exposed to UV light, using an UV curing system (IST Metz M-40-1-URS-WIR-TR-SLC). Lastly, the transparent silicone shim was removed. Before using the transparent silicone shim again, we cleaned it from UV lacquer residuals with a strip of strong adhesive tape.

For each type of pre-printed substrate (background color blue, red, black, white and silver), ten hologram samples were produced and numbered in the order of their production (sample #1, #2, #3, ... #10). Preliminary tests had shown that each silicone shim could only be used 12 times on average for UV embossing before it becomes brittle and eventually gets torn. In the following, this behavior is referred to as the aging of the silicone shim. A similar behavior is known from Theopold et al. (2012) where the influence of solvents on flexo printing forms is investigated. Fine cracks already appeared after approximately eight times of use and could be detected in the sample surface as well (Figure 4). For this reason, we used a new silicone shim (100 mm × 140 mm) of the same properties for each background color.

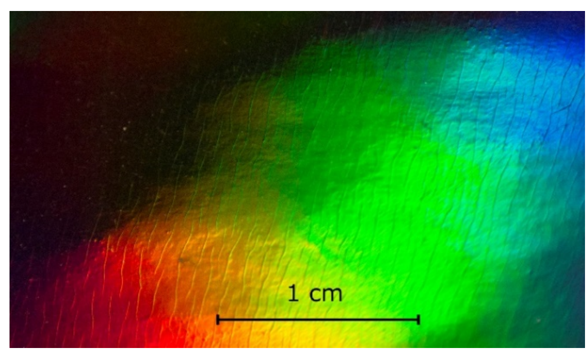

Figure 4: Cracks in the surface of black sample #10

We would like to emphasize that we prepared the hologram samples in a laboratory setup. There also exists an industrial process for the UV embossing of holograms,

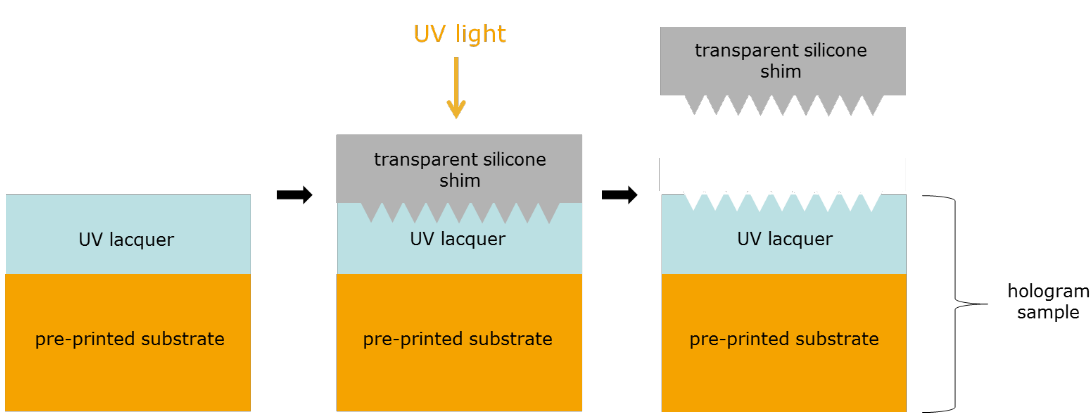

Figure 3: UV embossing of hologram samples

which is commercially referred to as 'UV Casting'. Other names are 'UV Film Casting' or 'Cast and Cure'. Instead of using a transparent silicone shim as in this research paper, the industrial UV embossing process uses a transparent plastic film which has a transparent lacquer coating with imprinted micro- or nanostructures on one side (Kaule and Grauvogl, 1999). It is to mention that the contact time of embossing master and UV lacquer is much shorter in the industrial UV embossing process than in our laboratory flatbed setup.

2.2 Visual experiment

There hardly exist any scientific approaches for the visual inspection of embossed holograms, yet. For this reason, we developed our own visual experiment.

2.2.1 Equipment

Samples #1 and #10 of each background color were used. For better handling and a uniform look, a black frame (70 mm × 70 mm window size) made from cardboard was added to each sample. Besides, we used a viewing booth Macbeth SpectraLight III covered with black velvet inside, a self-made sample display, which can be tilted ± 5° around its basic adjustment of 45° to the horizontal (Figure 5), and a chin rest.

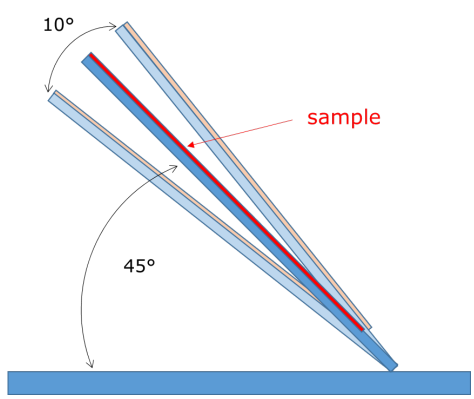

Figure 5: Sample display

2.2.2 Assessment criteria

Aiming to evaluate the quality of our samples, we first had to find appropriate assessment criteria. To start with, the reader needs to know that embossed holograms produced by UV embossing – like our hologram samples – are rather used for decorative refinement than for security applications. This is due to their easily damageable open holographic structure. Often, the purpose of decorative refinement is to attract the viewer's attention. Presuming that quality is the fitness for a special purpose (Teschner, 2010), we therefore assume that the samples' quality depends on certain sample properties that are responsible to attract the viewer's attention, e. g. color properties.

In this research, we choose the sample properties 'intensity' and 'variety of colors' as assessment criteria for our samples' quality, assuming that great intensity and great variety of colors notably attract the viewer's attention. Please note that the visual experiment is conducted in German language, using the German terms 'Leuchtkraft' (intensity) and 'Farbvielfalt' (variety of colors) as assessment criteria, whereby the German and English expressions may have slightly different meanings.

2.2.3 Subjects

26 test persons participated in this research, 17 of them male and 9 female, from age 22 to 65 (average 32). All were normal or corrected-to-normal sighted. No color vision deficiencies were found according to the Farnsworth-Munsell 100 Hue Color Vision Test. Ten of the test persons were classified as experts, which have experience in colorimetry or visual experiments.

2.2.4 Procedure

The experiment is part of a broad series of visual experiments. Only the experiments directly relevant to the topic of this research paper are described further. All visual experiments are conducted in the so-called 'Black Room' at the Institute of Printing Science and Technology, Darmstadt, Germany. This room is almost entirely furnished black, so that as little scattered light as possible gets into the viewing booth. The viewing situation in the viewing booth is shown in Figure 6.

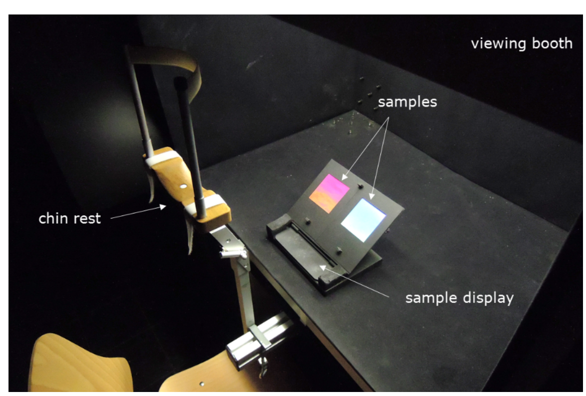

Figure 6: Viewing situation in the viewing booth

To create a ranking of the different samples, paired comparisons are conducted. We chose this approach, because the human eye is better in comparing simultaneously than successively (Hunter and Harold, 1987). The order of the paired comparisons and the samples' arrangement on the sample display is random.

In the first experiment, each sample #1 is compared to every other sample #1 with respect to intensity and variety of color, which means that ten comparisons must be done by each test person. The sample with the highest intensity scores one point and the sample with the highest variety of color scores one as well. In Figure 7, you see a scene from the first experiment from the view of a test person.

Figure 7: First experiment from the view of a test person (exemplary scene; left – red sample #1, and right – silver sample #1)

In the second experiment, sample #1 and sample #10 of the same background color are being compared. The test persons must decide, whether they see a difference between the two samples and if yes, they shall describe it. They do not know which is #1 and which is #10. The purpose of this experiment is to find out if the quality of the samples is visibly changing within the production process.

In both experiments, the test persons were told to tilt the sample display back and forth several times so that they could see the rainbow effect in its full range. At this point, we want to emphasize that the test persons were always asked to compare solely the samples' rainbow effect and not their background colors. Besides, all test persons were told to decide spontaneously and subjectively. All instructions to the test persons were given orally.

2.2.5 Illumination and geometry

The first experiment was conducted twice, once with illuminant TL84 and once with illuminant D65 aiming to simulate the viewing conditions in a shopping mall (TL84) and in daylight (D65). Both illuminants are built into the Macbeth SpectraLight III viewing booth by default. The second experiment was conducted with illuminant TL84 only.

The height of the chin rest, where the test persons had to lay their chin on during all experiments, and the position of the sample display within the viewing booth determine the geometry of the visual experiment. The experimental setup was chosen so that the light of the selected illuminant strikes the sample approximately at an incident angle of 45° to the sample's normal and the emergent angle is approximately 0° to the sample's normal (45°/0°). We chose this geometry according to the recommendation of the nickel shim manufacturer. Of course, the viewing geometry changes by the tilting of the sample display in its tilting limits. To create a reproducible visual experiment, we preferred this relatively specified geometry to a free geometry.

2.3 Measurements

For the measurements of gloss and color values, we used conventional hand-held measuring instruments used by the graphic industry. All samples (sample #1 to #10) of each background color were measured.

For the gloss measurements, we used the following equipment: gloss meter BYK micro-TRI-gloss, software Easy-Link for data handling and black cardboard as a measuring underlay. We measured each sample ten times on random spots (measuring angles 20°, 60° and 85°). The measuring instrument was always oriented longitudinal to the sample to eliminate possible anisotropy.

The following equipment was used for the color measurements: multi-angle spectrophotometer X-Rite MA98, software X-Color QC for data handling and black cardboard as a measuring underlay. Just like at the gloss measurement, we measured each sample ten times on random spots and we always oriented the measuring instrument longitudinal to the sample. Measuring angles, illumination and CIE standard photometric observer were chosen consistent with the visual experiment (see section 3.2.2).

3. Results and discussion

In this chapter, both the results of the visual experiment and the measurements are presented and compared to each other.

3.1 Results of the visual experiment

3.1.1 First experiment

In the first experiment, each sample #1 is compared to every other sample #1 with respect to intensity and variety of colors. The maximum total score to be reached by a sample is 4 × 2 × 26 = 208, since every sample is compared to four other samples, gains maximum two points per comparison for the two assessment criteria and is assessed by 26 test persons in total.

Figure 8 shows the results of the first experiment at illumination TL84. It displays the score reached for the criteria ‘variety of colors’ and ‘intensity’ as well as the total score reached by samples of all background colors. The silver samples gain the highest score, closely followed by the black samples. The red and blue samples are ranked third and fourth, as they gain rather similar scores for their variety of colors. However, the red samples were given twice the score for their intensity than the blue samples. The white samples gain the lowest score since they gain no points for their intensity and only a few for their variety of colors.

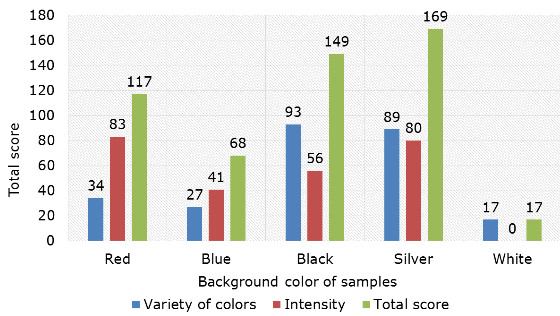

Figure 8: Results of the first experiment at illumination TL84 and geometry 45°/0°, where the maximum total score is 208

The results of the first experiment conducted at illumination D65 are shown in Figure 9. In comparison to the results in Figure 8, similar scores and nearly the same ranking of the samples can be found. Only the first and second placing are inverted, since the black samples gain a slightly higher score than the silver samples. Thereby we would like to add that those test persons who were considered as experts on average still assigned more points for the silver samples than for the black samples.

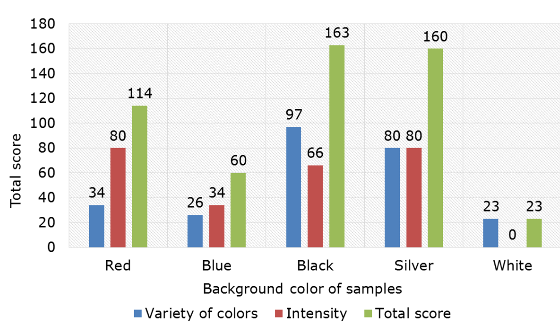

Figure 9: Results of the first experiment at illumination D65 and geometry 45°/0°, where the maximum total score is 208

3.1.2 Second experiment

In the second experiment, sample #1 and sample #10 of the same background color are being compared. The major results of the second experiment are presented in Figure 10, which shows how many test persons saw a difference between sample #1 and sample #10 of the same background color. We want to remind the reader that the samples were named in the order of their production. It appears that for all background colors most of the test persons saw a difference between the samples #1 and #10. While all test persons saw a difference between the white samples, a difference between the silver samples was most seldom discovered. This implies that the appearance of the silver samples is most constant during the production process.

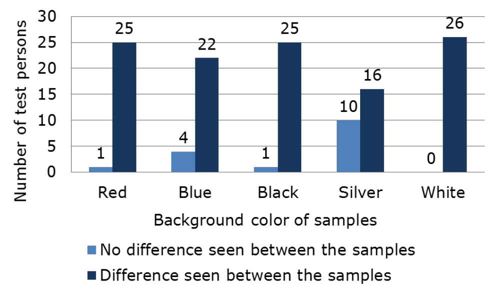

Figure 10: Results of the second experiment at illumination TL84 and geometry 45°/0°

Other results of the second experiment are the following. Those persons who named ‘intensity’ or ‘variety of colors’ as a difference between the samples, always – except once – related the greater intensity and the greater variety of colors to sample #1. This means that the samples #1 are of a better quality than samples #10. Moreover, it became apparent that a very frequently named difference between the samples was the shape of the rainbow, which is influenced by the samples’ waviness (Figure 11).

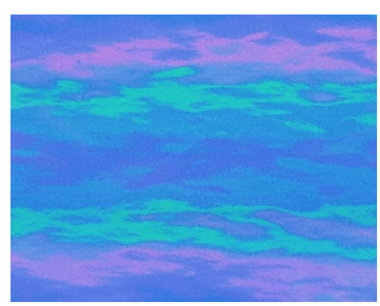

Figure 11: Detail of a blue sample with wavy surface structure that influences the shape of the rainbow

3.2 Results of the measurements

3.2.1 Results of the gloss measurement

In the following, the blue, red, black and white samples will be referred to as non-metallic samples. The 60° measuring angle is chosen for evaluation, because the non-metallic samples’ gloss values at a 60° measuring angle lie between 10 GU and 70 GU (Deutsches Institut für Normung, 1982). Figure 12 shows the gloss values from sample #1 to sample #10 of all background colors at 60° measuring angle. The silver samples take on a special position concerning gloss measurement since they have more than six times higher gloss values than the non-metallic samples. In contrast, the non-metallic samples nearly all have the same gloss values.

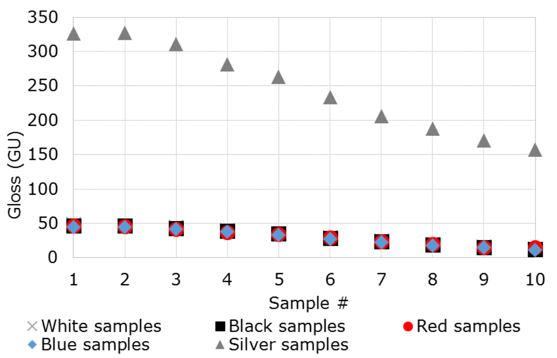

Figure 12: Gloss measurement of samples at 60° measuring angle

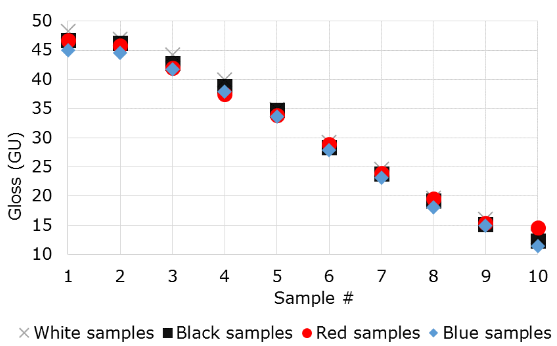

Figure 13: Gloss measurement of samples at 60° measuring angle without silver samples

Taking a closer look at the non-metallic samples' gloss values (Figure 13), it can be detected that the imaginary gloss curves, which are the imaginary connecting lines between the measuring values of one background color, cross each other. Consequently, the gloss measurement is not able to provide a ranking of the samples. This implies that gloss measurement is not able to evaluate the influence of the background color on the quality of embossed holograms.

However, Figure 12 clearly indicates that conclusions concerning the UV embossing process can be drawn from a sample's gloss. Irrespective of the background color, gloss values are constantly decreasing with increasing sample number. In total, the silver samples lose about 75 GU and all non-metallic samples about 35 GU. Comparing this to the results of the visual experiment (second experiment, see section 3.1.2), which showed that the samples #10 are of worse quality than the samples #1, we conclude that the loss of quality is accompanied by decreasing gloss values. Therefore, gloss measurement can be used for process control of the UV embossing process as conducted in this research. For example, gloss measurement can be used as an early warning system for the aging of the silicone shim. This can be realized by defining a lower limit of gloss that indicates that the silicone shim must be replaced.

3.2.2 Results of the color measurement

The multi-angle spectrophotometer X-Rite MA98 offers different measuring geometries (Kehren et al., 2011). Due to the angle-dependency of the holographic effect, analyzing several measuring geometries is reasonable. We chose to analyze the measuring geometries 45°:as25°, 45°:as45° and 45°:as75° because these are the measuring geometries provided by the X-Rite MA98 spectrophotometer that lie closest to the geometry used for the visual experiment. The first number, 45°, represents the incident angle in respect to the surface normal. The second number represents the viewing direction in respect to the specular angle. Accordingly, 45°:as45° represents the geometry used for the visual experiment (45°/0°). As illuminant, we chose D65 and as CIE standard photometric observer, we selected the 10° observer because in the visual experiment the samples are regarded at an aperture angle of more than 4° (Deutsches Institut für Normung, 2009).

Figure 14 shows three chromaticity diagrams, one for each of the selected measuring geometries, where the CIELAB color values a^* and b^* of sample #1 to sample #10 of each background color are plotted. It is to notice that the displayed colors in the chromaticity diagrams serve only for visualization purposes and do not conform to the real colors of the samples. This is because the value of the lightness L^* is chosen as 60 within the chromaticity diagram although each sample has a different L^*-value. The dotted lines between the measuring values serve as a guide for the eye only. Samples #1 are marked with the number '1'. As can be seen in all diagrams, samples of different background color show distinctly different color values a^* and b^* although they were prepared with the same holographic surface structure. This implies that the background color has influence on the holographic effect.

Taking a closer look at the samples' color locations (Figure 14), it becomes apparent that at all measuring geometries the red samples' color locations rather lie in the red area whereas the blue samples' color locations rather lie in the blue area. In contrast, the silver samples appear rather blue at 45°:as25° and rather red at 45°:as45° and 45°:as75°. This leads to the conclusion that chromatic background colors (blue, red) in contrast to non-chromatic background colors (e.g. silver)

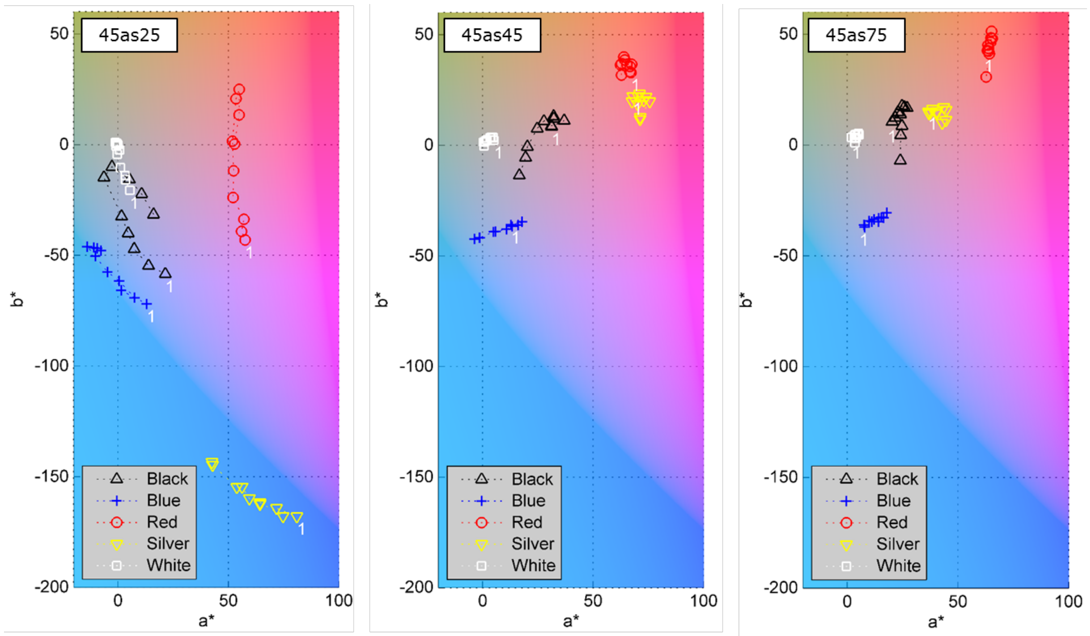

Figure 14: Chromaticity diagrams of hologram samples at L = 60 (illumination D65, 10° observer); measuring geometries from left to right: 45°:as25°, 45°:as45°, 45°:as75°*

overlay with the colors of the rainbow effect so that they shift them into the direction of the background color.

Moreover, Figure 14 shows that the color measurement is not able to characterize the rainbow effect in its full range, since the three selected measuring geometries represent only bluish and reddish parts of the rainbow. However, the rainbow of the applied rainbow effect contains more than these two colors. To represent all colors of the rainbow or at least more than two colors, ideally, a color measuring instrument with continuously adjustable measuring geometries must be used.

In Figure 15, we investigate the development of the chroma C^*_{ab} from sample #1 to sample #10. In general, the dipping and rising of chroma values can be explained by the aging of the silicone shim and by the waviness of the pre-printed substrates which negatively influences the preciseness of the color measurement. Taking a closer look at the development of the chroma values, it becomes apparent that, at measuring geometry 45°:as25°, the chroma values of all background colors tend to go down with increasing sample number. This fits to the results of the second visual experiment, which shows that the samples' rainbow effect loses intensity from sample #1 to sample #10. However, at the other measuring geometries (45°:as45° and 45°:as75°), we cannot recognize any evident trend regarding the samples' chroma values.

Investigating the samples' chroma C^*_{ab} and comparing it to the visual experiment, one could assume that the samples' chroma values represent the samples' quality, since the white samples have the lowest chroma and the silver samples have a rather great chroma at all measuring geometries (Figure 15). However, it contradicts the

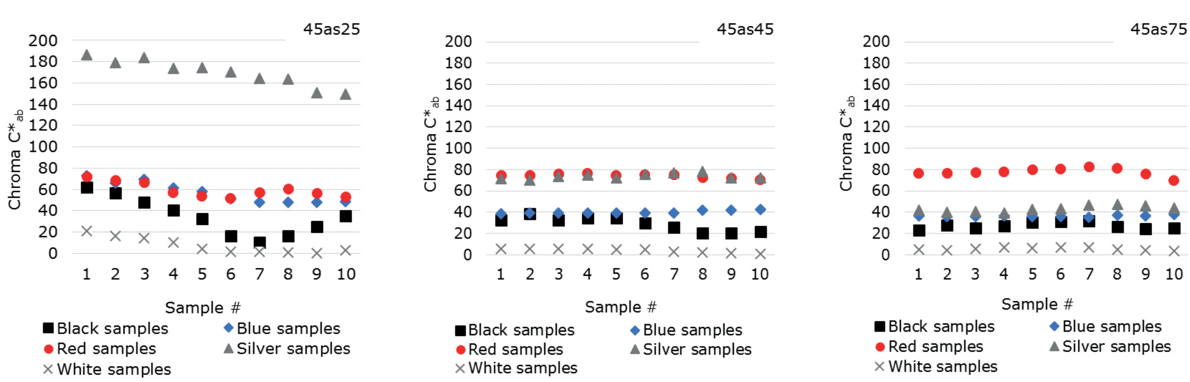

Figure 15: Chroma C^*_{ab} of all samples at measuring geometries 45°:as25°, 45°:as45° and 45°:as75°, at D65/10°

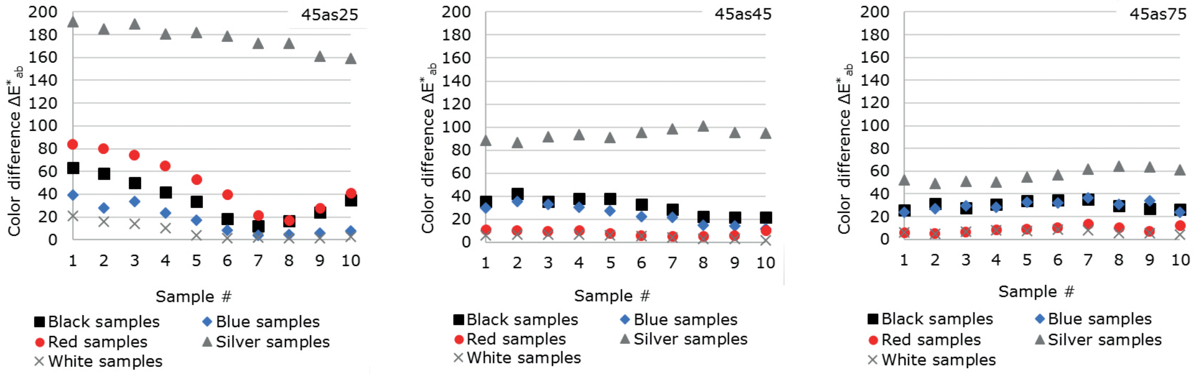

Figure 16: Color difference ΔE^*_{ab} between pre-printed substrate and hologram sample at measuring geometries 45°:as25°, 45°:as45° and 45°:as75°, at D65/10°

visual experiment that the black samples have only the second lowest chroma, whereas they gained a rather high scoring at the visual experiment. Consequently, the investigation of chroma values is not a suitable method to evaluate the influence of the background color on the quality of our samples.

In the following, we therefore chose another approach; we calculate the color difference ΔE^*_{ab} between the pre-printed substrate and the hologram sample (Figure 16). The consideration behind that approach is that color appears in interaction with its surrounding (Berns, 2000) – in our case the background color, which appears at some viewing angles alongside the rainbow effect. Whereas the chroma C^*_{ab} is an absolute measurement variable, the color difference ΔE^*_{ab} is a relative measurement variable which can consider the background color. Assuming that a greater color difference stands for a stronger holographic effect, Figure 16 clearly states that the black samples have a rather strong holographic effect. This fits better to the results of the visual experiment than the results from Figure 15.

To make a combined statement about the color difference, we calculated the arithmetic mean of the color differences at all three analyzed measuring geometries (Figure 17). This step is reasonable since the measuring geometry 45°:as45° – which is the geometry used for the visual experiment – represents only one color of the rainbow effect.

However, the test persons saw the full rainbow because the setup of the visual experiment (size of samples, tilting of sample display) was chosen according to that. Consequently, using only the measuring geometry 45°:as45° does not lead to a sufficient statement. Taking a look at the combined statement in Figure 17, it becomes apparent that – except the relative positioning of the red and blue samples and the big gap between the silver and black samples – Figure 17 well represents the results of the visual experiment.

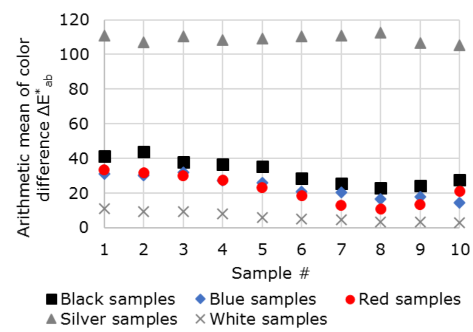

Figure 17: Arithmetic mean of color difference ΔE^*_{ab} between pre-printed substrate and hologram sample at measuring geometries 45°:as25°, 45°:as45° and 45°:as75°, at D65/10°

3.3 Accuracy of the measurements

Statistical data for the gloss measurement can be found in Table 2, which shows that the standard deviation of gloss values lies in the same scale, both for the 'normal' pre-printed substrates and the hologram samples. This means that the gloss measurement of hologram samples can be regarded as a rather precise measurement. However, the hologram samples' relative standard deviation tends to be a little higher than the pre-printed substrates' relative standard deviation since the hologram samples' gloss values are at least about two times lower (samples #1) and up to seven times lower (samples #10) than the pre-printed substrates' gloss values.

In Table 3, statistical data for the color measurement – using the blue sample #1 and a blue substrate as an example – is provided. As can be seen, the standard deviation of the hologram sample is about one or two magnitudes higher than the pre-printed substrate's standard deviation. Consequently, the color measurement of our hologram samples cannot be considered as precise as a measurement we know from the printing industry. The reason for the high standard deviation is the waviness of the samples, which changes the appearance

Table 2: Gloss (GU) values with standard deviation and relative standard deviation (in brackets) at 60° measuring angle, for an exemplary pre-printed substrate of each background color and for all hologram samples #1 to #10, measured ten times (n = 10) on different spots

Background color	Red	Blue	Black	Silver	White
Pre-printed substrates	91.4 ± 1.5 (± 1.6 %)	83.9 ± 1.0 (± 1.2 %)	91.3 ± 1.7 (± 1.8 %)	669.8 ± 8.4 (± 1.3 %)	93.9 ± 0.9 (± 0.9 %)
Hologram samples					
#1	46.7 ± 0.7 (± 1.4 %)	45.0 ± 1.5 (± 3.3 %)	46.7 ± 0.6 (± 1.3 %)	326.4 ± 6.1 (± 1.9 %)	48.3 ± 0.6 (± 1.3 %)
#2	45.7 ± 1.0 (± 2.1 %)	44.6 ± 0.4 (± 0.8 %)	46.2 ± 0.9 (± 2.0 %)	326.8 ± 8.1 (± 2.5 %)	47.0 ± 0.4 (± 0.9 %)
#3	42.0 ± 0.5 (± 1.1 %)	41.7 ± 1.1 (± 2.8 %)	42.8 ± 0.5 (± 1.2 %)	310.7 ± 11.4 (± 3.7 %)	44.2 ± 0.4 (± 1.0 %)
#4	37.5 ± 2.8 (± 7.5 %)	37.9 ± 0.5 (± 1.3 %)	38.8 ± 1.0 (± 2.5 %)	281.9 ± 7.3 (± 2.6 %)	40.0 ± 0.9 (± 2.3 %)
#5	33.9 ± 1.1 (± 3.2 %)	33.6 ± 0.7 (± 2.1 %)	34.8 ± 0.5 (± 1.5 %)	263.2 ± 5.7 (± 2.2. %)	34.9 ± 0.6 (± 1.8 %)
#6	28.9 ± 1.0 (± 3.3 %)	27.9 ± 1.5 (± 5.3 %)	28.4 ± 0.6 (± 2.1 %)	233.8 ± 4.7 (± 2.0 %)	29.2 ± 1.0 (± 3.4 %)
#7	23.9 ± 0.8 (± 3.1 %)	23.1 ± 0.8 (± 3.4 %)	23.8 ± 0.5 (± 2.1 %)	206.3 ± 3.0 (± 1.5 %)	24.6 ± 0.6 (± 2.6 %)
#8	19.5 ± 0.8 (± 4.1 %)	18.1 ± 1.6 (± 8.9 %)	19.2 ± 1.0 (± 5.1 %)	187.5 ± 3.2 (± 1.7 %)	19.7 ± 0.8 (± 4.0 %)
#9	15.4 ± 1.6 (± 10.2 %)	15.0 ± 0.5 (± 3.5 %)	15.1 ± 0.4 (± 2.6 %)	170.6 ± 4.1 (± 2.4 %)	16.1 ± 0.3 (± 2.1 %)
#10	14.6 ± 1.4 (± 9.3 %)	11.5 ± 0.8 (± 6.8 %)	12.3 ± 0.6 (± 5.1 %)	157.4 ± 1.7 (± 1.1 %)	13.1 ± 0.3 (± 2.7 %)

Table 3: CIELAB color values with standard deviation at 45°:as25° and D65/10° for both the pre-printed substrate and the blue hologram sample #1, measured forty times (n = 40) on different spots

Parameter	L^*	a^*	b^*
Blue pre-printed substrate	31.2 ± 0.4	−14.7 ± 0.2	−45.0 ± 0.5
Blue hologram sample #1	42.3 ± 3.0	0.3 ± 16.2	−66.3 ± 8.5

of the holographic effect and thus the measured color values. Please note that the measurements in Table 3 were conducted for closer examination, irrespective of the other color measurements. We did forty measurements instead of ten like in the other examples because of the rather high dispersion of the measuring values.

Regarding the rather high measurement errors of the color values, it is important to investigate, if the measurement error influences the samples' ranking as given in Figure 17. Therefore, a Gaussian error propagation was done exemplarily for samples #1, based on the measuring values in Table 4. The pre-printed substrates' standard deviations for L^*, a^* and b^* were neglected. Please note that the measuring software X-Color QC, which was used for the color measurements, provided only the standard deviations for L^*, a^* and b^* for one defined illumination/observer combination for each background color.

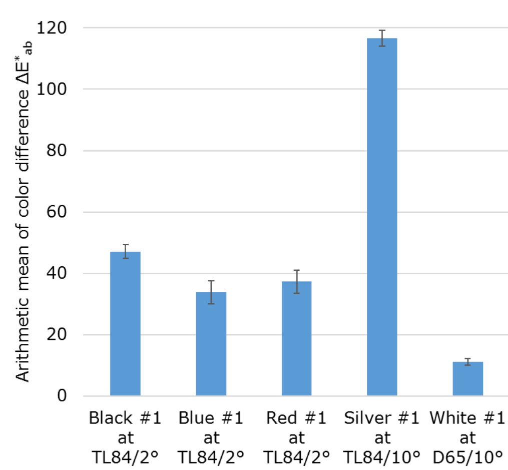

Figure 18: Standard deviations for arithmetic mean of color difference ΔE^*_{ab} for samples #1 resulting from Gaussian error propagation

Table 4: CIELAB color values and standard deviations (n = 10) at 45°:as25°, 45°:as45° and 45°:as75°, used for the Gaussian error propagation

Background color **Illumination and observer**		**Red** **TL84/2°**	**Blue** **TL84/2°**	**Black** **TL84/2°**	**Silver** **TL84/10°**	**White** **D65/10°**
Pre-printed substrates						
*L**	45°:as25°	35.5	17.4	7.1	34.7	89.0
	45°:as45°	35.3	17.6	7.2	12.6	88.1
	45°:as75°	35.7	17.3	7.8	10.8	87.4
*a**	45°:as25°	59.9	14.6	0.2	−1.1	−0.1
	45°:as45°	60.1	13.8	0.2	−1.1	−0.2
	45°:as75°	60.4	15.0	0.0	−0.8	−0.3
*b**	45°:as25°	45.7	−67.2	−2.4	−5.0	−0.5
	45°:as45°	46.1	−67.1	−2.3	−3.8	−0.9
	45°:as75°	47.8	−67.6	−1.9	−1.9	−0.9
Hologram samples #1						
*L**	45°:as25°	39.6 ± 0.6	24.7 ± 1.6	18.3 ± 1.3	76.3 ± 3.0	91.5 ± 0.3
	45°:as45°	40.9 ± 1.5	29.2 ± 3.5	21.4 ± 1.3	65.6 ± 3.7	89.6 ± 0.2
	45°:as75°	41.9 ± 1.9	28.3 ± 2.3	18.9 ± 2.0	42.9 ± 1.5	88.9 ± 0.3
*a**	45°:as25°	66.3 ± 5.8	42.2 ± 10.5	32.4 ± 5.5	71.5 ± 6.6	5.3 ± 2.1
	45°:as45°	63.3 ± 1.6	34.2 ± 6.1	28.3 ± 2.5	57.1 ± 3.8	5.1 ± 0.8
	45°:as75°	63.7 ± 1.4	32.9 ± 5.4	22.7 ± 3.3	39.0 ± 2.7	4.0 ± 0.9
*b**	45°:as25°	−48.1 ± 11.0	−99.7 ± 7.4	−73.4 ± 5.6	−198.9 ± 6.2	−20.6 ± 3.2
	45°:as45°	37.6 ± 3.3	−48.8 ± 6.8	9.3 ± 2.4	25.4 ± 6.1	2.3 ± 0.6
	45°:as75°	48.5 ± 2.1	−48.5 ± 3.2	12.1 ± 2.7	18.2 ± 2.2	3.2 ± 0.6

The result of the Gaussian error propagation carried out in this research is the standard deviation for the arithmetic mean of the color difference ΔE^*_{ab} for all samples #1, shown in Figure 18 in form of error bars. Figure 18 demonstrates that the measurement error has no great influence on the samples' ranking. Only the blue and red samples' measurement error slightly influences the ranking.

4. Conclusion and outlook

The visual experiment conducted in this research serves as a guideline for the design of UV embossed holograms. We found out that the background colors silver and black achieve the strongest holographic effect. In comparison, red and blue background colors only evoke a mediocre and white background colors evoke the weakest holographic effect. Besides, we learned that the waviness of the pre-printed substrates influences the samples' appearance.

The comparison of the visual experiment and the gloss measurements leads to the following conclusions:

- Conventional hand-held gloss measuring instruments cannot evaluate the influence of the background color on the quality of embossed holograms.
- However, the samples' gloss steadily decreases within the UV embossing process due to the aging of the embossing master. Besides, the gloss measurement is very precise. This suggests the usage of gloss measurement for process control of the UV embossing process as conducted in this research.

The comparison of the visual experiment and the color measurements leads to the following conclusions:

- Conventional hand-held color measuring instruments can evaluate the influence of the background color on the quality of embossed holograms.
- Calculating the color difference ΔE^*_{ab} between pre-printed substrate and sample is a method to recreate the results of the visual experiment.
- The number of provided or analyzed measuring geometries is a limitation of color measurements; in this research three measuring geometries (45°:as25°, 45°:as45°, 45°:as75°) lead to useful results, but other holographic effects may require far more measuring geometries.
- Besides, the waviness of the pre-printed substrates strongly limits the precision of color measurements; the results of color measurements are rather imprecise in comparison to the results of gloss measurement.

In future research, the following questions may become important:

- What does the quality of embossed holograms need to look like? Are ‘intensity’ and ‘variety of colors’ useful and sufficient assessment criteria?
- Does the method also work for more complex holographic effects than the rainbow effect?
- Can the results of this research be equally applied to the industrial UV embossing process?
- Would we get similar results if we calculated ΔE_{00} instead of ΔE^*_{ab}?
- What could a control strip for embossed holograms look like?

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