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Color change of printed surfaces due to a clear coating with matte finishing

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Abstract

When a clear layer is coated on a diffusing background, light is reflected multiple times within the transparent layer between the background and the air-layer interface. If the background is lit in one point, the angular distribution of the scattered light and Fresnel's angular reflectance of the interface induce a specific irradiance pattern on the diffuser: a ring-like halo. In the case where the background is not homogenously colored, e.g. a halftone print, the multiple reflection process induces multiple convolutions between the ring-like halo and the halftone pattern, which increases the probability for light to meet differently colored areas of the background and thus induces a color change of the print. This phenomenon, recently studied in the case of a smooth layer surface (glossy finishing) is extended here to rough surface layer (matte finishing) in order to see the impact of the surface roughness on the ring-like halo, and thereby on the print color change. A microfacet-based bi-directional reflectance distribution function (BRDF) model is used to predict the irradiance pattern on the background, and physical experiments have been carried out for verification. They show that the irradiance pattern in the case of a rough surface is still a ring-like halo, and that the print color change is similar to the one observed with a smooth interface, by discarding the in-surface reflections which can induce additional color change.

Introduction

When a halftone print is coated with a glossy clear layer, its color usually becomes darker and more saturated [1]–[3]. This color change is due to interreflections occurring within the transparent layer, between the diffusing substrate and the air-layer interface. These interreflections induce a very specific ring-like point spread function, of diameter proportional to the coating thickness, caused by the angular dependency of the Fresnel reflectance at the smooth coating-air interface [4]. This ring-like halo can be observed by pointing a thin light pencil on a diffusing substrate coated with a thick layer. It was particularly observed at the early age of astronomical photography as the interreflections inside the imaging glass plates, over-layered by a diffusing photosensitive emulsion, induced a halo around the brightest stars [5] as can be seen in Figure 1.A. This phenomenon has been fully modeled recently for glossy coating on halftone prints, with rather good accuracy in experimental verifications [6], [7].

The question that we would like to address here is whether the color changes observed with glossy coatings remains similar with matte coating, i.e. when the air-coating interface is rough. We often observe that the color becomes lighter and less saturated with a matte finishing than with a glossy finishing [8], as shown in Figure 1.B, due to the achromatic diffuse reflection due to the rough coating-air interface. But the fact that the interface is rough may also modify the ring-like point spread function observed with a smooth interface, therefore the convolutional multiple reflections process within the clear layer, and finally the color of the print.

A first section is dedicated to simulations of the halo effect for rough interfaces through a microfacet model, the simulation results are compared to an experiment in a second section. The third section simulates the effect of a matte coating on the appearance of printed halftones through a multi-convolutive model previously developed.

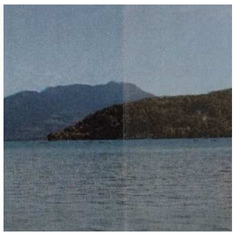
A)  B) 

Figure 1. *A) Halo around a bright star: adapted from* [9]. *B) Picture of a print coated on the left side with a glossy tape layer, and on the right side with a matte tape layer.*

Simulation of the ring-like halo with a smooth interface

Let us first summarize the optical phenomenon that happens when a diffusing substrate is capped by a clear layer with glossy finishing – full description can be found in [4]. Each point of the substrate, assumed Lambertian, scatters light in all directions towards the smooth interface. Let us specifically consider the point of coordinates $(0,0)$ and a small area A around it, whose exitance is M_0. Same radiance $L_0 = M_0/\pi$ flows in every direction across the coating until the interface, where it is reflected according to its orientation θ, in a proportion depending on Fresnel's angular reflectance $R_{n_1 n_0}(\theta)$ (where n_1 is the refractive index of the coating, often considered 1.5, and n_0 is the refractive of air equal to 1): it is weakly reflected at low incidence angles, and totally reflected beyond the critical angle $\arcsin(n_0/n_1)$, as illustrated in Figure 2.A. After reflection on the coating-air interface, the radiances re-illuminate the substrate and form an irradiance pattern $h_{smooth}(x,y)$, having the form of the ring-like halo similar to the one presented in Figure 1.A that depicts Fresnel's angular reflectance function, and whose diameter $\Phi = 4d/\sqrt{n_1^2 - 1}$ is proportional to the coating thickness d:

$$h_{smooth}(x,y) = \frac{M_0 A 4 d^2 R_{n_1 n_0}\left(\arctan\left(\sqrt{x^2+y^2}/2d\right)\right)}{\pi(x^2+y^2+4d^2)^2} \quad (1)$$

Each point of the substrate thus re-illuminated scatters again light according to its local reflectance $\rho(x,y)$ and produces again a ring-like halo, and so on. The multiple reflections of light between the substrate and the air-coating interface are modelled by successive convolutions and multiplications between the substrate reflectance function $\rho(x,y)$ and the halo function $h_{smooth}(x,y)$. Even if these multiple convolutions have an influence on the final point spread function (PSF) of the coated substrate, the first halo gives the main contribution to the PSF. When the substrate is not uniformly colored, i.e. $\rho(x,y)$ is not constant over the surface as in a halftone print, the multi-convolutive process increases the chance for light to be absorbed (the dot gain phenomenon well known in the printing domain is increased), to an extent that depends on the halftone screen period and the halo diameter Φ, and thus on the coating thickness d.

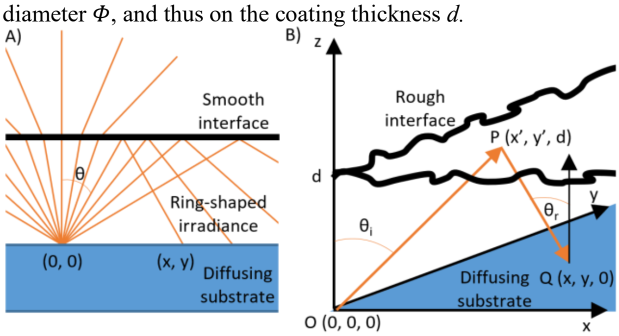


Figure 2. *A) Internal reflections inside the coating layer for a smooth interface. B) Scheme of the system for a rough interface.*

Simulation of the ring-like halo with a rough air-coating interface

We now want to estimate the irradiance pattern $h_{rough}(x,y)$ in the case where the print finishing is matte, i.e. the coating-air interface is rough. This roughness can be modelled by considering the upper interface to be composed of small planar areas, microfacets, of various orientations compared to the normal of the mean surface (assumed to be flat). The direction and proportion of light internally reflected by the interface not only depends on the angle of incidence of light on the interface, but also on the orientation of the local microfacet. This can thus have an impact on the halo phenomenon which can be simulated using a bi-directional reflectance distribution function (BRDF) model [10].

We consider an orthonormal system (x,y,z) where $(x,y,z=0)$ is the plane of the Lambertian substrate of normal parallel to the z axis, and $(x,y,z=d)$ is the mean surface of the rough interface between the coating layer and air, see Figure 2.B. We consider again a point O of coordinates (0,0,0) on the substrate and a small area A around it that has an exitance M_0. Same radiance $L_0 = M_0/\pi$ flows in every direction of the hemisphere and produces an irradiance $h(x',y')$ on a small area $dx'dy'$ of the rough interface around a point P of coordinates (x',y',d):

$$h(x',y') = \frac{L_0 d^2 G(x',y')}{dx'dy'} \tag{2}$$

where $d^2G(x',y')$ is the geometrical extent between areas A and $dx'dy'$:

$$d^2G(x',y') = \frac{A dx'dy' \cos^4\theta_i}{d^2} \tag{3}$$

θ_i is the angle between $\overrightarrow{\boldsymbol{OP}}$ and the normal of the substrate plane, and

$$\cos\theta_i = \sqrt{d^2/(x'^2+y'^2+d^2)}.$$

Therefore, the irradiance around P is:

$$h(x',y') = \frac{M_0 A \cos^4\theta_i}{\pi d^2} \tag{4}$$

The radiance $L(x,y,x',y')$ from the small area around P reaching a small area $dxdy$ around a point Q $(x,y,0)$ of the substrate can be described using a BRDF function f_r which depends on the direction of incidence $\overrightarrow{\boldsymbol{OP}}$ and of reflection $\overrightarrow{\boldsymbol{PQ}}$, and on a roughness parameter m:

$$L(x,y,x',y') = f_r(\overrightarrow{\boldsymbol{OP}},\overrightarrow{\boldsymbol{PQ}},m)\,h(x',y') \tag{5}$$

Function f_r, described in [11] pp.190-192, accounts for a gaussian microfacet slope distribution, and a roughness parameter $m = \sigma/\tau$ where σ is the r.m.s. height of the rough interface, and τ is its correlation length.

The irradiance around Q due to light reflected around P is:

$$d^2 h_{rough}(x,y) = \frac{L(x,y,x',y')\cos^4\theta_r}{d^2}\,dxdy \tag{6}$$

where θ_r is the angle between $\overrightarrow{\boldsymbol{PQ}}$ and the normal of the substrate plane:

$$\cos\theta_r = \sqrt{\frac{d^2}{(x'-x)^2+(y'-y)^2+d^2}}.$$

The total irradiance in Q coming from all points of the rough interface is then:

$$h_{rough}(x,y) = \int_{y=-\infty}^{\infty}\int_{x=-\infty}^{\infty}\frac{L(x,y,x',y')\cos^4\theta_r}{d^2}\,dx'dy'$$

$$= \frac{M_0 A}{\pi d^4}\int_{y=-\infty}^{\infty}\int_{x=-\infty}^{\infty} f_r(\overrightarrow{\boldsymbol{OP}},\overrightarrow{\boldsymbol{PQ}},m)\cos^4\theta_i\cos^4\theta_r\,dx'dy' \tag{7}$$

From this equation can be modelled the irradiance patterns (halos) due to rough interfaces. The irradiance profiles at the center of the halos for different roughness parameters, m, are displayed in Figure 3.

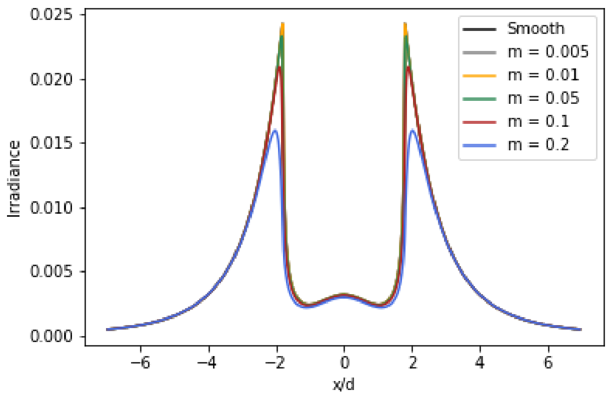


Figure 3. *Profiles of the modelled halos, with an initial exitance at the central point equal to unity.*

The striking information lays in the fact that the profile of the halo is very similar whether the interface is smooth or rough, the curves are almost superimposed for $m < 0.01$. The roughness of the interface tends to decrease the sharpness of the profile, but a halo of similar diameter is still clearly visible. However, the profiles described by the model for high roughnesses are in fact inexact as the BRDF model does not take into account multiple reflections between neighboring microfacets of the interface, which tend to artificially reduce the total fraction of light reflected by the interface (fraction often denoted r_i in classical print reflectance models, around 0.6 for $n_1 = 1.5$). This limitation has already been described and quantified in [12].

The multi-convolutional process evoked above in the case of a glossy finishing and detailed in [4] also occurs with a matte finishing. It can be modelled in the same way with successive multiplications and convolutions between the substrate reflectance function $\rho(x,y)$ and the halo function $h_{rough}(x,y)$. The only difference is that $h_{rough}(x,y)$ replaces $h_{smooth}(x,y)$. The consequence of the optical process on the reflectance of the coated substrate, and thereby on its color (excluding the light directly scattered at the air side by the rough surface) are therefore similar in case of glossy and matte finishing, as the two functions $h_{rough}(x,y)$ and $h_{smooth}(x,y)$ are comparable.

In a previous study [6], we showed that the appearance of printed halftones coated with a glossy transparent layer can be predicted both at the micro and at the macro scales using the optical model summarized above. This model also took into account the fractions of light transmitted by the interface between the coating and air, T_{in} and T_{out}, and the portion of light externally reflected by the interface in the air and reaching the sensor, r_s, visible in Figure 4. For a smooth interface, in the specular direction $r_s = 0.04$ at normal incidence, and $r_s = 0$ for any non-specular direction. For a rough interface, light is scattered externally in every direction and r_s depends on the measurement geometry and on the BRDF of the interface.

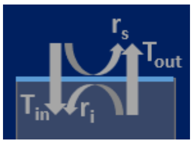


Figure 4. *Light fluxes at the upper interface.*

Experimental observation of the halo with a matte coating

The objective of this section is to observe experimentally the impact of a rough interface on the halo and compare it to the predictions by the model. An experiment was performed at the macroscale, where a laser beam illuminated a white diffuser alternately coated with a layer of smooth and rough interface with air. The resulting halos were captured with a camera. The scheme of the setup is displayed in Figure 5.A.

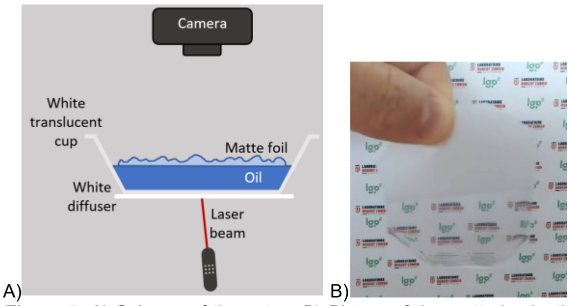


Figure 5. *A) Scheme of the setup. B) Picture of the matte lamination foil, the bottom part is covered by oil.*

The camera was a Sony ILCE-6000 capturing images in RAW format, with an exposure time of 1/3 s, an ISO of 400, and an aperture F/5.6. The laser was a red pointer illuminating the white diffuser from beneath to avoid disruptions due to the coating interface. The diffuser was a uniform white paper stuck to the external surface of the flat bottom of a translucent cup. The coating layer consisted of an oil layer, of optical index close to 1.5, which had a smooth interface with air. Oil was used in this experiment to obtain thicknesses high enough to observe the halo at a macroscopic scale. It is optically identical to any coating layer of similar optical index such as OPP (oriented polypropylene). The rough interface with air was generated by floating a matte lamination layer on the oil surface. The lamination layer thickness, measured with the micrometer from Adamel Lhomargy, was 27 µm, which is negligible in comparison to the millimetric thickness of the oil layer. Since the optical index of the lamination layer is close to the one of oil, the two layers are in optical contact, i.e. the interface between them is optically neutral. This optical index matching and the transparency of the lamination layer were checked by dipping the lamination layer in oil: the lamination layer then became transparent as its interface with air became smooth, as shown in Figure 5.B.

For both rough and smooth interfaces, the experiment was performed with two different oil thicknesses. The pictures, issued from the red channel of the camera, are displayed in Figure 6. The thicknesses were retrieved from the position of the maximal digital count of the halo of the smooth interfaces [13] p.92:

$$d = \left(\frac{\Phi_i}{2} - 0.4\Phi_{laser}\right)\left(\sqrt{n_1^2 - 1}/2\right) \quad (8)$$

where Φ_{laser} is the diameter of the laser spot, which was around 2 mm, and where Φ_i is the diameter of the ring of maximal digital count. The oil thicknesses were found to be respectively 3.4 mm and 6.8 mm. The pictures show that even though the interface with air is rough, there is still a ring-like halo. It only appears blurrier than the one with a smooth interface. This confirms the conclusions from the modelling of the first section: rough interfaces induce a similar halo phenomenon as smooth interfaces.

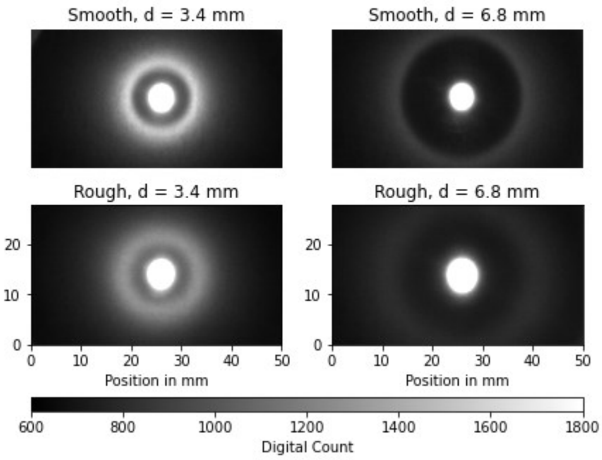


Figure 6. *Pictures of the halo induced by a smooth and a rough interface with air for two different coating thicknesses.*

From this experiment and the modelling, we can try to deduce the roughness parameter of the matte coating. Knowing the layer thicknesses, the theoretical function h_{smooth} related to the smooth interface can be retrieved for each thickness from equation (1). Amplitude factor and offset were manually fitted to get values comparable to the digital counts: the amplitude coefficient was set to $5.2 \cdot 10^5$, and the offset, linked to light diffusion on the substrate, was set to 645. Knowing these parameters and the thickness of the two layers, the halo induced by a rough interface can be calculated through the model presented in the first section. The roughness parameter, m, was then fitted to the experimental curve; m was found to be around 0.22, the resulting experimental and theoretical curves are displayed in Figure 7. This is a rough estimation which could be better evaluated by considering the actual laser beam diameter in the model, in place of a punctual illumination. The halos in the images also result from multiple interreflections between the substrate and the interface and are imaged through the interface which, in the case of the rough interface, can increase the blur of the halo (Figure 6 and 7). It is then likely that the roughness of the foil was overestimated. In any case, it has been shown that the halo phenomenon is similar whichever the roughness of the transparent coating. Previous studies on glossy finishing show that the color change of a print which is coated is mainly dependent on the ratio between the halo diameter and the halftone period. In the case of a rough coating, simulation and experiment show that the halo overall shape and diameter is unchanged as for a smooth coating, similar color prediction methods can then be used for both surface finishing.

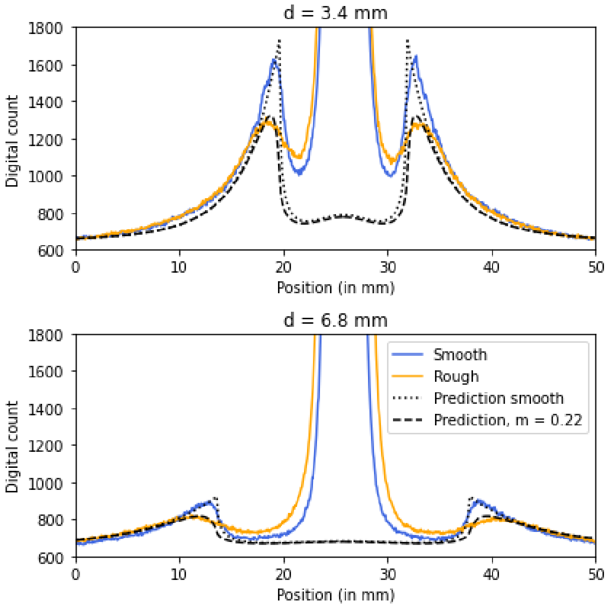


Figure 7. Profiles for each thickness, the black lines are modelled respectively through equation (1) for the smooth interface, and equation (7) for the rough one.

Simulation of the appearance of coated halftones

The objective of this section is to extend the appearance prediction of coated prints to rough interfaces. It has been shown that T_{in} and T_{out} are almost identical whether the interface is rough or smooth, [14]. The rough interface only has an impact on r_s (Figure 4) and, to a lesser extent, on the sharpness of the halo pattern. For these simulations, it has been considered that the roughness parameter was $m = 0.2$, which corresponds to a high roughness, an upper limit roughness value for a matte finishing, and that the thickness of the coating layer was $d = 20$ µm. A small component was added to each pixel of the rough halo image to compensate for the error on the simulated total fraction of light reflected by the interface, r_i, mentioned in the second section. The appearance for a smooth interface was also simulated with the same coating thickness for comparison purposes. The spatial and spectral reflectance factors of the non-coated prints chosen as inputs for the simulations were the one of a fulltone magenta patch and the one of a line magenta halftone patch of period 0.337 mm, presented in [6].

Even though the situation where $r_s = 0$ is usual for prints with a glossy coating by looking at them in the non-specular direction, it is far less usual for a print coated with a matte foil as light is scattered externally in every direction by the coating surface and eventually reaches the sensor. To evaluate r_s in the case of a matte coating for a d:8° geometry, the reflectance factors of both a glossy and a matte coating were measured with the spectrophotometer CM-2600d from Konica Minolta specular component excluded, with an aperture of 8 mm diameter. To avoid the influence of the bottom interface of the coating layers, it was colored in black with multiple layers and set in optical contact with a black paper. The parameter r_s was calculated as the average difference between the measured reflectance factors of the rough and of the smooth interfaces. It was found to be equal to 0.03 over the whole spectrum.

Figure 8 displays the resulting spatially averaged reflectance factors of the tested patches for the different interfaces and, in the case of the rough interface, for $r_s = 0$ and for $r_s = 0.03$. The blue lines correspond to the spectral reflectance factor of the non-coated prints. The yellow lines describe the simulated spectral reflectance factor of the prints coated with a glossy finishing layer. The accuracy of these predictions was detailed in [6]. The reflectance factor of the halftone decreases at the spectral bands at which ink absorbs the most, which results in a darkening and saturation of the color visually perceptible. The green lines correspond to the spectral reflectance factor of the prints predicted by the model by considering a very rough interface with air. It is shown that the prediction for the smooth and the rough interfaces are almost similar, which is explained by the fact that the prints are subject to similar ring-like interreflections within the coating layer. The red lines present the same prediction and includes the surface reflection component, $r_s = 0.03$. This increases the spectral reflectance factor uniformly over the whole spectrum, which lightens colors, making them comparable to the ones of the non-coated prints with a slight loss of saturation.

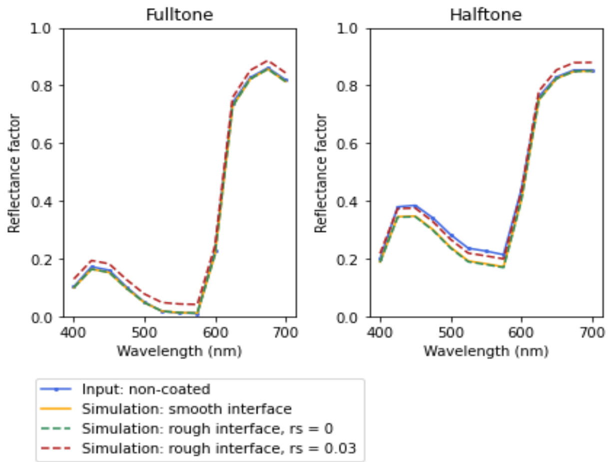


Figure 8. Modelling of the effect of matte and glossy coatings on the reflectance factor of magenta prints.

Conclusions

The optical model developed to predict the reflectance of a diffusing substrate coated by a clear layer with glossy finishing has been extended to a matte finishing (rough air-coating interface). The model is based on a halo function that describes how the light issued from one point of the substrate re-illuminates it after internal reflection of the interface. Thanks to a surface scattering model based on the microfacet theory, we could predict halo functions attached to rough interfaces, which are actually very similar to the one attached to a smooth interface. This has been verified by an experiment where the substrate is lit in one point by a laser beam and the halo captured by a camera for a smooth and for a rough interface. The multi-convolutive model initially developed for coated halftones printed with glossy finishing can therefore be used with matte finishing without major lack of accuracy. The main color change difference between a print coated with respectively matte and glossy lamination foils lays in the difference of light externally reflected by the interface. The matte laminated prints are subject to the same darkening effect caused by the halo interreflections for a rough as for a smooth coating, but they usually appear lighter with a rough coating due to the light externally reflected at the interface.

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