Effect of gloss and colorant mass on color

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Abstract

Maintaining color consistency within print and from print-to-print is important for all the marking industry, whatever the marking technology. The fluctuation in color for a given colorant comes mainly from the variation in surface smoothness (image gloss) and pigment (or dye) mass per unit area (PMA). In this study, orange xerographic prints were used to understand the effect of these two factors on the measured color. Results of the print evaluation show that gloss and PMA affect the reflectance spectra in very different ways. Based on these measurements a simple model was developed to account their effects. The predicted colors calculated based on this model agreed well with the experimental data. The developed model is general and can be used to predict color fluctuations within a range of gloss and PMA values for other colors.

Introduction

In general, printing is about making marks on substrates. For a typical four-color (Cyan, Magenta, Yellow and Black) printer, the colorant (pigment or dye) is laid down in certain ways to produce single or mixed colors. The color human eyes perceive will depend not only on the colorant, but also on the substrate and light source. However, even with a fixed substrate, light source and colorant type, there will be color variations observed during printing from print-to-print or within a single print. In this article, we tackled this important practical problem by studying the effect of pigment mass per unit area (PMA) – the amount of colorant; and image gloss – surface smoothness on solid colors with fixed paper substrate and light source.

It is obvious that the amount of colorant affects color. The more colorant we put down, the more intense (darker) color we generally get (up to some limit that depends on the colorant). Before we go any further, let us first explain a few color terms. In this paper, we used the CIEL*a*b* color system, where each color corresponds to a unique set of (L*, a*, b*). Here L* stands for lightness, a* and b* are for the color. The difference between two colors can be calculated in terms of ΔE^* or improved version ΔE^*_{2000}. The three axis in the (L*, a*, b*) coordinate system are perpendicular to each other. Another common way to describe colors is to use a cylindrical coordinate system. If we connect a color dot to the origin, the distance between the color dot and the origin is called Chroma and the angle between the line and the a* axis is called Hue angle. Figure 1 shows the a* vs b* plot for some Cyan prints at different PMA (triangle dots) around similar gloss and at the same PMA but different gloss (circles). The dashed line shows the effect of increasing PMA (about 2 times) and the dotted line shows the effect of increasing gloss (about 15 gloss units). The L* difference between the lowest and highest PMA is about 10 units and the color difference in terms of ΔE^*_{2000} is about 4.5 units, which is more than human perception limit ~ 3 ΔE^*_{2000} for most people.

People also noticed that the gloss – the smoothness of the colored surface, also affect the perceived colors. Matte objects (less smooth) appear less intensely colored (low Chroma); while corresponding glossy objects can have very vivid colors (high chroma). As shown in figure 1, the high gloss print (solid circle) is further away from the origin than the low gloss print (open circle), thus the former has higher Chroma. For this reason, many people have studied the gloss effect on color and its application such as in security printing [1,2]. In 1999, E.N. Dalal and K.M. Natale-Hoffman developed a model for the effect of gloss on reflected color, taking the measurement geometry of the color measuring device into account [1]. Their model considers the total front surface reflectance of a given sample to be independent of gloss and determined only by its refractive index and the angle of the incident beam. The predicted and measured color of all their prints was found to be about 3 CIEL*a*b* ΔE^* units. However, their model did not look at the spectral reflectance spectrum, which we have found to be important in explaining the effect of both the amount of colorant and gloss.

This paper has two main parts – experiments and theory. Firstly, orange xerographic prints were used to understand the effect of PMA and gloss on the measured color. Results of the

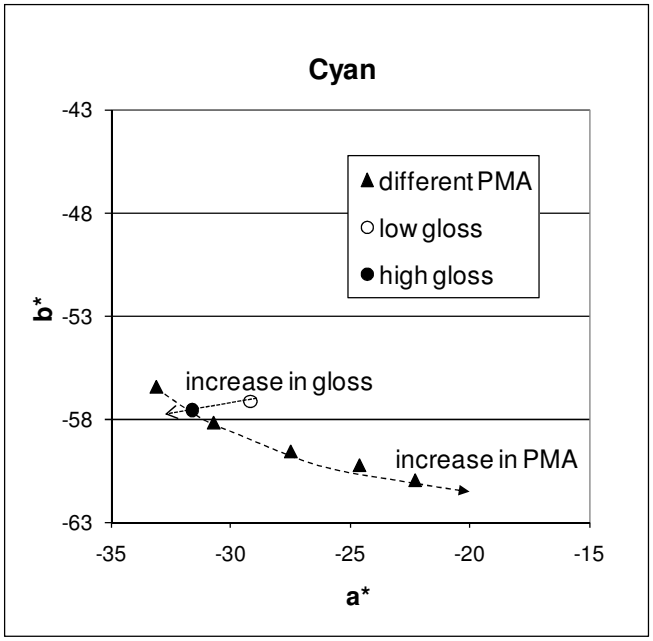

Figure 1. a* vs b* for Cyan prints at different PMA and two prints at low and high gloss. The dashed arrow shows the trend with increase in PMA and the dotted arrow for the increase in gloss.

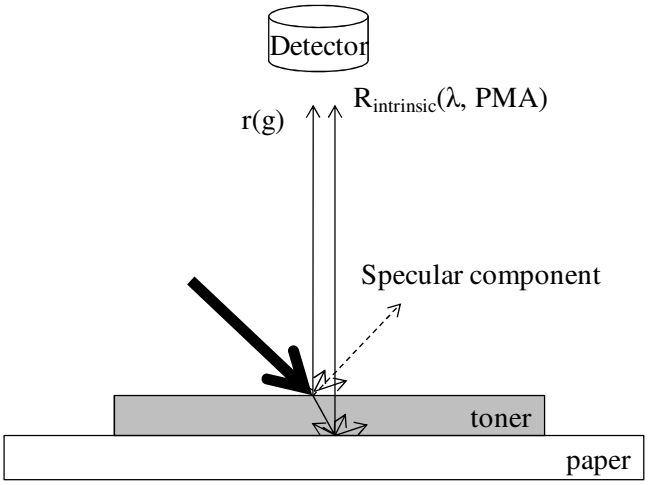

Figure 2. Schematic illustration of the front reflection at the toner surface and the reflection at the toner and paper interface for the case of 45/0 spectrophotometer geometry.

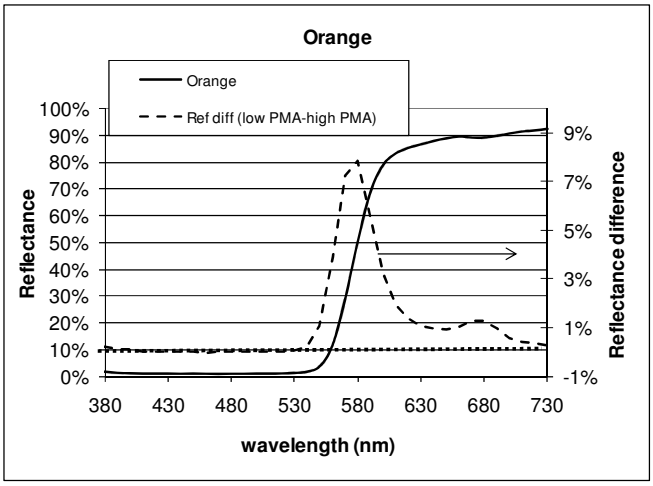

Figure 3. The reflectance spectrum (solid line) of an Orange print and the difference spectrum (dashed line) between a low PMA print and a high PMA print (y-axis on the right).

print evaluation show that gloss and PMA affect the reflectance spectra in very different ways. Secondly, based on these measurements a simple model was developed to account their effects. The predicted colors calculated based on this model agreed well with the experimental data. We believe that the developed model is general and can be used to predict color fluctuations within a range of gloss and PMA values for other colors.

Experiment

What happens when a beam of light shines on a print? As shown in figure 2, part of the light will get specularly reflected (specular component), part will scatter, and the rest will go inside the toner layer, go through absorption and scattering and then come back outside as diffuse light. The specular reflection component closely retains the spectral properties of the in-coming light. Clearly the detector (or the eye) only collects a small part of the scattered light from the surface and small part of light comes out of the toner layer. To be consistent with reference 1, we call them r(g) and $R_{intrinsic}$ respectively. Reference 1 states that the total front surface reflection, the sum of the specular component and r(g), is a constant. The smoother the surface is the higher the gloss, the larger the specular component, and thus the smaller r(g) will be. The $R_{intrinsic}$ depends on the PMA and wavelength, as pigment absorption is wavelength dependent. In our study, we focus on the light collected by the detector (sum of r(g) and $R_{intrinsic}$) as that is the portion viewed by the eye.

The color of all the prints were measured with the 0/45 measurement geometry using a GretagMacbeth Spectrolino using D50 illuminant and 2 degree observer. The gloss was measured with a 75 degree micro gloss meter from BYK Gardner. The toners were lab prepared EA (Emulsion Aggregation) toners at the Xerox Research Center of Canada and the substrates were standard coated paper - Xerox digital color elite gloss (DCEG).

Figure 3 shows the typical reflectance spectra of one of the orange prints (solid line) and the difference spectrum between prints with low and high PMAs (dashed line) but the same gloss. The reflectance spectrum corresponds to the y-axis on the left and the difference spectrum corresponds to the y-axis on the right, which was blown up for easy viewing. The dotted line indicates the zero line for the difference spectrum. Clearly, for the orange pigment used here, we have three very different parts in the spectrum. From 380nm to 550nm, the pigment has a strong absorption and very little light get measured – dark region. From 620nm to 720nm, the pigment has very weak absorption (transparent) and lots of light get measured – bright region. From 550nm to 620nm, it is a transition range between these two extremes – half transparent. In terms of the difference spectrum, it is interesting to see that the difference is mainly in the transition range. And the difference seems to depend on the corresponding

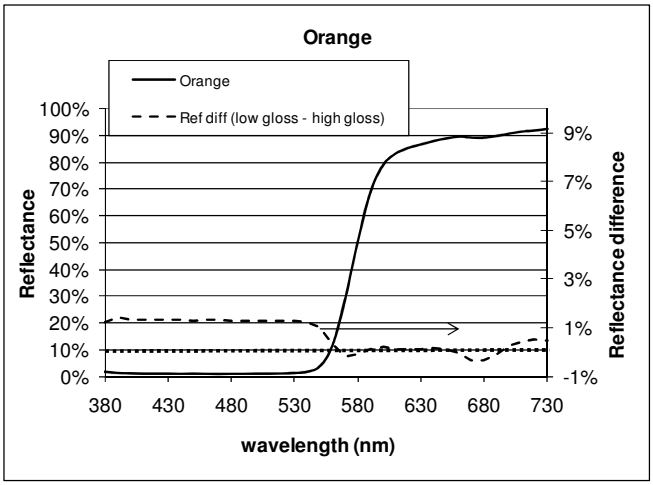

Figure 4, The reflectance spectrum (solid line) of an Orange print and the difference spectrum (dashed line) between a low gloss print and a high gloss print (y-axis on the right).

spectral reflectance value which depends on the pigment absorption intensity at that wavelength. This means the PMA fluctuation will mostly affect the reflectance spectra in the half transparent region.

Figure 4 shows again the reflectance spectrum and the difference spectrum between prints with different gloss but the same PMA. Again, the dotted line is the zero reference for the y-axis on the right. On the contrary to the earlier case, the spectral difference is mainly in the dark region. Also it is a constant in dependent of the wavelength. This means the fluctuation in gloss will affect the reflectance spectrum in the dark region. The questions now are why PMA and gloss have this very different effect and what this means in terms of color consistency, e.g. corresponding CIEL*a*b* values?

Theory

Because pigment has very different absorption at different wavelength, we will take a look at the dark region and transparent/half transparent regions separately.

For the dark region, the pigment has very strong absorption. We can expect that after we have sufficient pigment, any light gets into the toner layer will be totally absorbed, thus what the detector senses will be only r(g). Because of the sum of r(g) and specular component is a constant, as the gloss becomes higher, more light gets directed to the specular direction and less light gets detected. In other words, the smoother the surface is, the "darker" the image will be. This effect is especially strong for black prints because of the strong black pigment absorption across the whole spectral region. We did see this with our black prints - after certain amount of pigment density, gloss is the only factor affecting the reflection optical density. For the orange data in figure 4, it is easy to understand that the difference between two prints with different gloss value is a constant in the dark region. No shown here, but this gloss effect is also true for other colors that we looked, namely Cyan, Magenta, Yellow, Green and Violet.

For the transparent/half transparent region, much of the light can go inside the toner layer and come out again. Because r(g) is generally quite a bit smaller than $R_{intrinsic}$, we can ignore the r(g) term for now. Thus, what the detector senses will be only $R_{intrinsic}$, which depends on both PMA and wavelength, and can be expressed as shown in equation 1.

$$R_{measured}(\lambda, g, PMA)=A(\lambda)e^{-PMA*\eta(\lambda)} \quad (1)$$

Here $A(\lambda)$ depends on the incoming light, $\eta(\lambda)$ is the attenuation coefficient. If we make further approximation - $A(\lambda)$ is a constant with a value of 1, equation 1 can be simplified to equation 2.

$$R_{measured}(\lambda, g, PMA)=e^{-PMA*\eta(\lambda)} \quad (2)$$

Thus, the unknown spectrum at another PMA (e.g. PMA_1) can be written as function of the known spectrum of PMA_2 as shown in equation 3.

$$R_{measured}(PMA_1)=R_{measured}(PMA_2)^{PMA1/PMA2} \quad (3)$$

And the difference between these two PMAs can be written as a function of the spectrum at PMA2 shown in equation (4)

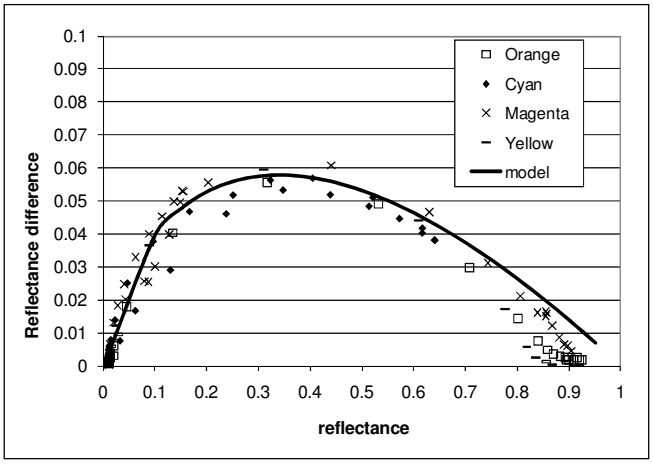

Figure 5, The reflectance difference vs. corresponding reflectance values for 4 different colors (Orange, Cyan, Mangenta and Yellow). The dots are experimental data and the solid line is from the model.

$$\Delta R_{measured}=R_{measured}(PMA_2)^{PMA1/PMA2}- R_{measured}(PMA_2) \quad (4)$$

Figure 5 shows the difference spectra between prints with different PMA but the same gloss vs. corresponding reflectance spectra for four different colors. The scattered dots are experimental data and the solid line is from the model calculated based on equation 4. For all four colors, the data agree fairly well with the model especially in the half transparent region. This means that the effect of PMA is mostly in the half transparent regions. The model also shows that the strongest effect happens at the reflectance value of 0.35 or 35%.

Now we understand that gloss mostly affects the spectra in the dark region but the PMA affects the spectra in the half transparent/transparent regions. We need to answer the second question - what this means in terms of color consistency, e.g. corresponding CIEL*a*b* values? In other words, if we know the reflectance spectrum of a print at a certain PMA and gloss, how can we get the corresponding L*, a*, b* values and how much will those values change at other PMA and gloss? For the first part of the question, there is a set of well known formulas to convert the spectrum to corresponding L*, a*, b* values [3,4]. For our calculation, we used a homemade Excel template which covers from 400nm to 700nm - most of the visible spectrum region and

Table I. Color parameters.

		TMA (mg/cm^2)	gloss	L*	a*	b*	dE_2000
Orange	exp	0.46	76.6	62.2	66.2	89.3	4.15
	calculated	0.61	76.6	58.6	68.7	83.4	
	exp	*0.61*	*76.9*	*59.9*	*68.4*	*85.5*	
Cyan	exp	0.45	76.9	48.4	-31.6	-57.6	5.45
	calculated	0.55	76.9	43.4	-25.7	-60.2	
	exp	*0.55*	*74.1*	*44.9*	*-27.3*	*-59.4*	
Magenta	exp	0.45	73.2	43.4	79.1	-5.1	4.18
	calculated	0.55	73.2	40.7	77.5	3.5	
	exp	*0.55*	*70.0*	*41.2*	*77.9*	*2.2*	

has all the equations built in [5]. For the second part of the question, we first obtain the reflectance spectra at other PMA and gloss based on the learning in this article; and then calculate the L*, a*, b* values using the converting Excel sheet.

For simplification, we will only give some examples about the PMA effect here. Because there can be multiple pigments in a toner, we use the toner mass per unit area (TMA) in the examples below. It is easy to see that PMA equals TMA times the pigment loading. Suppose we know the reflectance spectrum of an Orange print at TMA 0.46 mg/cm^2 at gloss 77, we can calculate the L*, a*, b* values as listed in the first row of table 1. What if printer decides to make prints at higher TMA, e.g., 33% more, to TMA 0.61 mg/cm^2? What are the L*, a*, b* now at TMA 0.61 mg/cm^2? Because gloss is the same, we keep the reflectance spectrum in the dark region from 400nm to 550nm the same as at TMA 0.46 mg/cm^2 and calculate the spectrum from 550 to 700 using equation 3. Then we use the Excel template to calculate the L*, a*, b*. All the calculated results at TMA 0.61 mg/cm^2 are listed in the second row. The color difference due to this TMA/PMA change is listed as dE_2000 (ΔE^*_{2000}). For comparison, the experimental data at TMA 0.61 mg/cm^2 is listed in row #3. We can see that the calculated results agree with the experiment fairly well. The same results were found for other two colors (Cyan and Magenta) as well. This means that the simple model works fairly well around this TMA range.

Summary

In summary, we looked at the effect of PMA and gloss on the reflectance spectra. We found that gloss mostly affects the dark region while PMA affects the half transparent/transparent region. Based on the learning, a very simple model was developed and it gives a fairly good prediction of color variation due to variations of gloss and PMA during practical printing runs.

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Suxia Yang received her BS in honor physics from Nanjing University in China (1998) and her PhD in physics from Hong Kong University of Science and Technology (2002). She then worked at the Center for Advanced Nanotechnology on photonic crystals and optical characterization of nano-structures. In 2007, she joined the Xerox Research Center of Canada and has worked on the research and development of various consumables such as toners, additives and carriers for xerographic printing.

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