Calibration of Gloss Measurements

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Abstract

Print gloss and attributes such as differential gloss and gloss uniformity are closely related to the specular reflectance characteristics of printed images. An instrument has been developed for the quantitative measurement of the specular reflectance of printed images based on gonio-photometric and micro-densitometric techniques. The device, called a micro-goniophotometer, can be calibrated to known reference materials and produce quantitative analytical information on the specular reflectance of printed materials. The reflectance factors are resolved both angularly, to yield a BRDF, and spatially to provide a measure of gloss variation resolved to the micro-scale. As a result, the causes of gloss differences can be parsed into differences in (a) angular distribution of reflected light, (b) optical constants of the materials, and (c) sub-structural reflectance factors. Examples of the application of the instrument to the characterization of different types of gloss phenomena will be presented along with a description of the configuration and calibration of the instrument.

Introduction

Calibration of an instrument should be a process of canceling out the properties of the instrument so that the measurement provides information only about the sample material under analysis. Traditional gloss meters have not achieved this level of calibration. As shown previously,[1] the calibration protocol for a traditional gloss meter, which involves a black glass reference of known refractive index, results in very repeatable measurements. However, a calibrated gloss meter does not fully cancel differences between instruments, and measurements with one calibrated gloss meter often does not agree with another calibrated gloss meter at the same specular angle.[1] Moreover, measurements from a traditional gloss meter have not been quantitatively related to optical constants of materials. Only qualitative experimental correlations have been observed between gloss meter readings and material properties such as surface roughness. As described below, the micro-goniophotometer can be calibrated to reference materials of known optical constants, and the resulting calibration provides a measure of the actual specular reflectance factor, ρ, of the material under analysis. The calibrated instrument enables one to distinguish between surface topographic effects and the intrinsic specular reflectance of the material.

Configuration of the Micro-Goniophotometer

Fig. 1 is a schematic illustration of the micro-goniophotometer used in the current work. Details of the instrument are described elsewhere,[2,3,4] and only a summary is given here. The printed sample is wrapped around a cylinder and illuminated with a line source that is collinear with the cylinder. A camera captures an image of the sample using a lens with a long working distance so that parallax from one side of the sample to the other can be ignored. Images are captured with both parallel and crossed polarizers, and a difference image is produced. The difference image contains only that light which maintains polarization when it is reflected. The bulk scattered light is randomly polarized and thereby eliminated by taking the difference between the two images. This leaves only the specular light in the image, as illustrated in Fig. 2. A horizontal scan of this image produces a bidirectional reflectance distribution function, BRDF. The specular lobe is centered at $\alpha = 0$, where α is the mean surface angle of the sample.

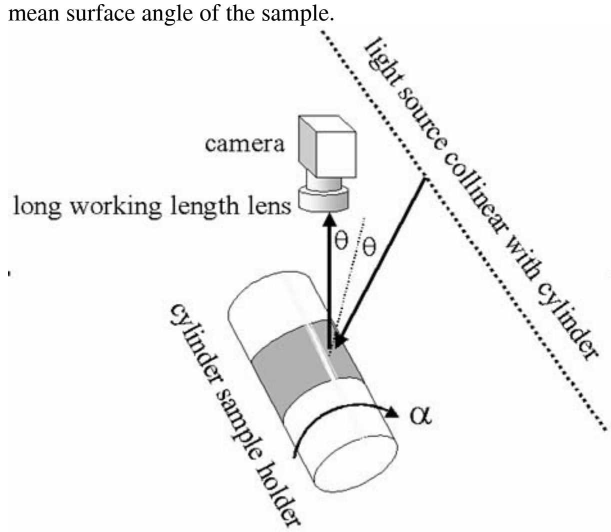

Figure 1. *Schematic diagram of the instrument with specular angle = 20o. The cylinder is 20 mm, and the camera and illumination distances are sufficiently long to minimize parallax.*

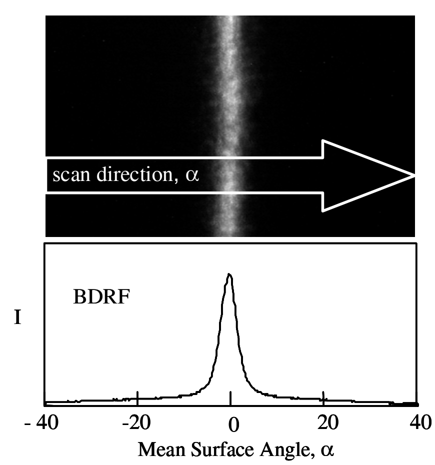

Figure 2: *Illustration of an image and a BRDF from the device shown in Fig. 1. The scan direction covers 5 millimeters of the sample.*

Calibration of the Micro-Goniophotometer

More traditional goniophotometric measurements involve scanning the detector through a range of specular angles, θ, around the sample in order to produce a BRDF. The specular reflection factor of a material, ρ, is a function of θ, so interpretation of a traditional BRDF in terms of the sample ρ is difficult. However, by scanning the sample angle, α, as shown in Fig. 2, the resulting BRDF can be interpreted much more easily. As illustrated in Fig. 3, the specular angle, θ, is a constant for all sample angles, α. This has been well described by the facet model of rough surfaces.[5,6,7,8] Since θ is constant, the area under this kind of BRDF curve should be proportional to the specular reflectance factor, ρ, of the material at the instrument specular angle, θ. This means that the BRDF area, A, can be calibrated relative to a material with a known specular reflectance factor, ρ_{ref}, as shown in Eq. 1, where A and A_{ref} are the measured BRDF areas of the sample and the reference, ρ_{ref} is specular reflectance factor of the reference, and ρ is the reflectance factor of the sample.

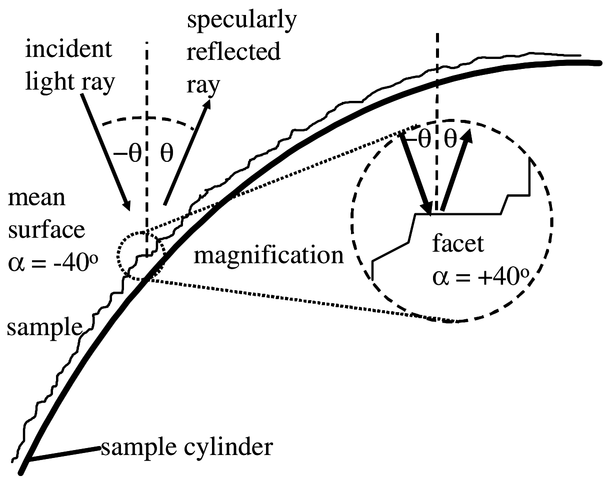

Figure 3: *Blow-up view of a section of the cylinder micro-goniophotometer illustrates that the instrument measures light as a function of sample angle, α. Magnification to show individual facets illustrates that specular light is always detected at a constant Fresnel angle, θ, regardless of the sample angle, α.*

$$\rho = \rho_{ref} \frac{A}{A_{ref}} \tag{1}$$

The reference material chosen for this instrument was a sheet of polyvinyl acetate. The optical constants, n and κ, of polyvinyl acetate and other common materials examined in this project are shown in the Table. Values of the specular reflectance factors, ρ(literature), were calculated from n and κ by applying Fresnel's laws,[9,10,11] and these values are also shown in the Table. The final column of the Table shows values of ρ measured by the micro-goniophotometer, as described above. The liquid samples were measured by wrapping a filter paper around the instrument cylinder and soaking the paper with the liquid.

Table of Optical properties[9, 10, 11] n=refractive index, k=absorption coefficient, ρ_L=reflection factor reported in literature, ρ_M=reflection factor measured with device in Fig. 1

Material	n	κ	ρ_L	ρ_M
water	1.33	0	0.020	0.020
teflon	1.36	0	0.023	0.035
PvOAc (ref)	1.49	0	0.036	≡ 0.036
olive oil	1.47	0	0.039	0.039
nylon	1.53	0	0.044	0.041
polycarbonate	1.59	0	0.051	0.054
stainless steel	2.49	1.38	0.58	0.051
aluminum	1.0	6.0	0.90	0.87

Fig. 4 shows the relationship between the experimentally measured values of ρ and the ρ values from the literature. It is evident that the micro-goniophotometer can be calibrated to provide a measure of the specular reflectance of materials over a very wide range of optical properties.

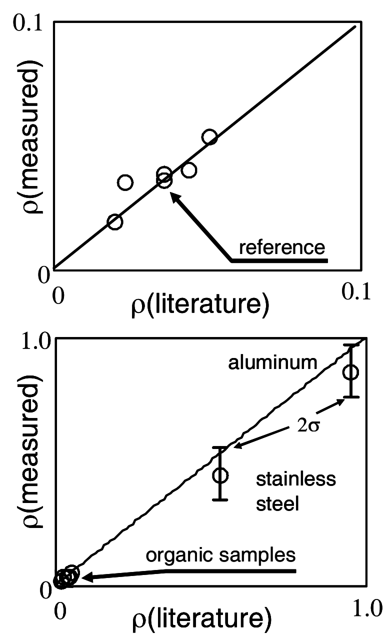

Figure 4: *Correlation between measured and literature values of the Fresnel reflectance values ρ.*

Differences Between Inks

Different inks show different specular reflection characteristics. Two different black toners printed with two different printers are illustrated in Fig. 5. The shapes of the two BRDF are very nearly the same, but the areas are significantly different. According to the facet theory, this can occur only if the reflectance factors, ρ, and therefore the material optical constants of the two black toners are different. In order to examine this difference further, a series of measurements of ρ were made at different Fresnel angles, θ.

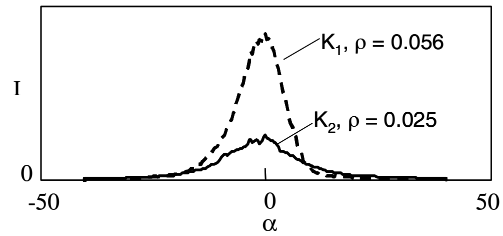

***Figure 5**: Black toner samples K_1 and K_2 from two different electrophotographic printers.*

As illustrated in Fig. 3, the measurement of the BRDF, and therefore of ρ, is made at a single, fixed value of θ. The value of θ is the so-called "gloss" angle and can be selected in the micro-goniophotometer. Values of ρ were measured for both black toners as a function of θ using p polarized light. The results are shown in Fig. 6.

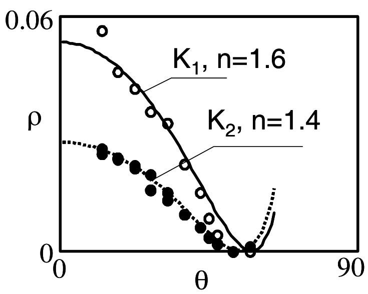

***Figure 6:** Black toner samples K_1 and K_2 from two different electrophotographic printers measured with linear polarized light in the p orientation. Fresnel's law is modeled in both cases with κ=0.*

The solid lines in Fig. 6 were constructed from Fresnel's law[9] for p polarized light. Fresnel's laws are summarized in equations (2) through (4), where n_c is the complex index of refraction and is a function of the two optical constants n and κ. It is notable that both black toners were well modeled with κ=0. This is indicated by the experimental values $\rho_p(\theta) = 0$ at the angle known as Brewster's angle. In other words, the gloss differences between the two inks are governed primarily by differences in the indices of refraction, n, and not by differences in surface roughness (width of the BRDF) or absorption coefficient, κ.

$$\varphi(\theta) = \sin^{-1}\left(\frac{\sin(\theta)}{n_c}\right) \quad \text{where } n_c = n\cdot(1-i\kappa) \tag{2}$$

$$\rho_p(\theta) = \frac{\tan(\theta-\varphi(\theta))\cdot\overline{\tan(\theta-\varphi(\theta))}}{\tan(\theta+\varphi(\theta))\cdot\overline{\tan(\theta+\varphi(\theta))}} \tag{3}$$

$$\rho_s(\theta) = \frac{\sin(\theta-\varphi(\theta))\cdot\overline{\sin(\theta-\varphi(\theta))}}{\sin(\theta+\varphi(\theta))\cdot\overline{\sin(\theta+\varphi(\theta))}} \tag{4}$$

The absorption coefficient, κ, can not always be ignored in the specular optics of printed images. This is illustrated by the behavior of a cyan sample printed by a commercial inkjet printer using a dye-based ink. The BRDF measured in white light indicated a very high value for ρ and prompted further measurements in red, green, and blue bands of light. The three BRDF for the cyan sample are shown in Fig. 7 along with the three values of ρ, and it is evident that the ρ values are significantly higher than the typical 4% to 6% observed for most common organic materials.

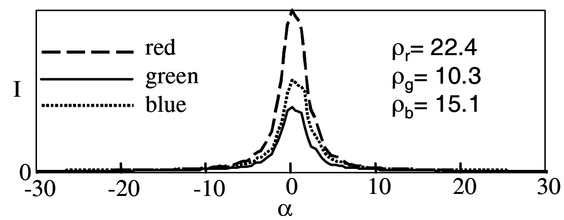

***Figure 7:** Cyan ink from an ink jet printer measured in red, green, and blue light.*

A previous report on the effect of RGB light on CMY samples printed by electrophotographic engines indicated that the light that is least strongly absorbed shows the greatest specular reflectance.[12] This was found to be a result of sub-surface specular reflections. Exactly the reverse of this sub-surface effect is evident in Fig. 7. The red light is the light most strongly absorbed by the cyan ink, and it is also the light that undergoes the strongest specular reflection. This behavior can be rationalized if either n or κ is a significant function of the extinction of light, and both effects are well known. To explore this effect in the cyan sample of Fig. 7, measurements of ρ were made in red, p polarized light as a function of the gloss angle, θ. The results are shown in Fig. 8 along with Fresnel's law modeled for $\rho_p(\theta)$. The model fits well with the data for n=2.1 and κ=0.5, and it is evident that both the increase in n and the significant contribution from κ result from a significant extinction coefficient of the cyan ink with red light.

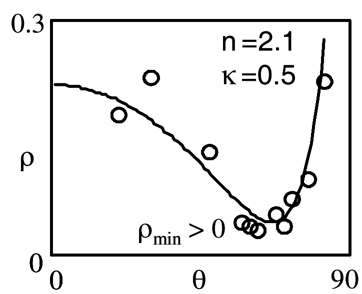

***Figure 8:** ρ vs θ for the cyan of Fig. 9 measured in red light as a function of θ. Note that ρ_{min} > 0 at Brewster's angle implies κ > 0.*

Conclusion

The results of this study show that the micro-goniophotometer described in previous reports can be calibrated to provide the provide measures of specular reflection factors, ρ, of samples. Analysis using the instrument can provide information about the relative importance of the surface roughness (width of the BRDF), the refractive index, and the absorption coefficient, κ, on gloss. Although not illustrated in this report, the analysis also can provide a measure of the spatial variation in the gloss. Thus, instead of measuring an arbitrarily defined index of gloss, this device provides a measure of the fundamental material properties that govern the gloss.

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