Journal of Imaging Science and Technology® 50(6): 567–571, 2006.

Interpretation of Gloss Meter Measurements

J. S. Arney▲, Ling Ye and Steve Banach
Rochester Institute of Technology, Rochester, New York 14623
E-mail: arney@cis.rit.edu

Abstract. *Gloss meters are commonly used to measure characteristics of the specular light reflected from materials. Such meters are based on illumination and detection at equal, opposite angles. The particular angle, θ, and other parameters of instrument geometry, are well known to play major roles in the results produced by a given meter, so several standards have been developed for gloss measurements that specify the geometry and optical characteristics of gloss meters (TAPPI T480; ISO-2813 (1994); ASTM-D523-89 (1999)). Nevertheless, the reason why gloss meter readings change with θ, and the reasons why meters of the same θ produce different readings seem not to be well understood. The focus of the study described in this paper has been on exploring these two effects. A quantitatively model of a generic gloss meter was constructed from Fresnel's law of surface reflection combined with empirical models of bidirectional reflectance distribution function (BRDF). Comparison of the model with experimental data strongly indicates that the width of the BRDF, and therefore the roughness of the surface, plays the major role in governing the reading from a gloss meter. Differences in index of refraction, by comparison, appear to play only a minor role. In addition, differences in gloss readings produced by instruments of the same angle, θ, were found to be the result of differences in the instrument angles of acceptance. The results of these studies suggest that it may be possible to make better use of conventional gloss meter measurements by making measurements at multiple angles, θ, rather than just a single angle. © 2006 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.(2006)50:6(567)]

INTRODUCTION

Many excellent gloss meters are available commercially that provide repeatable measurements of gloss indices, *G*. However, the relationship between *G* numbers and underlying material properties remains a difficult problem in spite of a large body of literature about gloss. Gloss is well known to involve the first surface, specular reflection of light from the surface of a material. Such reflections are well described by the refractive index of the material and Fresnel's law of reflection.[1–3] However, recent work indicates that Fresnel type reflections from subsurface interfaces can also contribute to gloss.[4–6] In addition, extensive research has shown that surface roughness is a major factor in determining the gloss of a material.[3,7,8] In spite of an extensive literature on gloss, much of the gloss phenomenon and the instrumental measurement of *G* are still not entirely understood.

The work described in this paper was undertaken in an effort to extend our understanding of two particular phenomena commonly observed with gloss meter *G* numbers. First, increasing the gloss angle, θ, increases the value of the gloss meter reading, *G*. Second, two gloss meters at the same angle, θ, often give different *G* readings even though both are manufactured to conform to the same gloss standard.[1] Work described below indicates that the shape of the bidirectional reflectance distribution function (BRDF) plays the major role in both these phenomena. We begin with a generic description of a gloss meter.

A GLOSS METER MODEL

A gloss meter such as illustrated in Fig. 1 produces a gloss index, *G*, defined as the detector signal divided by the signal measured for a reference material. The most common reference specified in standard methods is a polished black glass of refractive index $n=1.567$.[1]

Gloss is well known to involve a specular reflection from the front-surface of a material.[2,3] Such front-surface reflections are well described by Fresnel's law. However, recent work clearly indicates that subsurface reflections can also play a significant role in the gloss of some materials.[4–6] In addition, extensive research has shown that differences in surface roughness, rather than differences in refractive index, play the dominant role in the gloss differences between most materials.[3,7,8] In order to develop a useful model for the gloss meter of Fig. 1, we begin with Fresnel's law, illustrated in Fig. 2.

A Fresnel reflection is governed by the difference in the indices of refraction at the surface, n and n_o, as shown in Fig. 2. For common organic materials, most of the incident light is transmitted into the material and refracted at an angle ϕ. This refracted light, I_t, is then either absorbed or transmitted through the material. A small fraction of the light, I_r, is reflected at the equal, opposite angle, θ. The Fresnel reflection factor is defined as the ratio $\rho=I_r/I_o$, where I_o is the light incident on the interface and I_r is the reflected light.

Figure 2(b) shows reflection factors calculated for an interface using Fresnel's Eqs. (1)–(4). The specular reflection

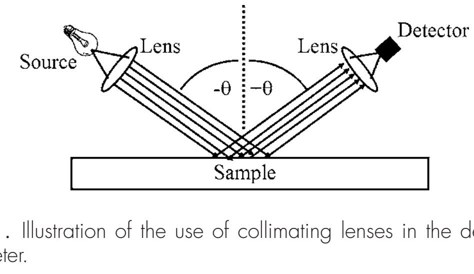

Figure 1. Illustration of the use of collimating lenses in the design of a gloss meter.

▲IST Member

Received Aug. 4, 2005; accepted for publication Mar. 9, 2006.
1062-3701/2006/50(6)/567/5/$20.00.

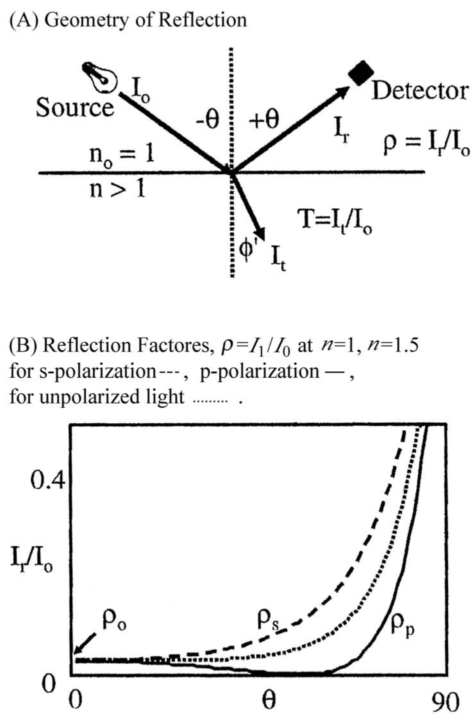

Figure 2. Fresnel's law of specular reflection.

factor, ρ, depends on the specular angle, θ, the indices n and n_o, and on the direction of polarization of the light. Equation (2) describes the reflectance factor for light with the electric field perpendicular to the incident plane. Equation (3) describes the parallel component, and Eq. (4) is the total reflectance factor for randomly polarized light.

$$\varphi = \mathrm{Arcsin}\left(\frac{n_o}{n}\cdot \sin(\theta)\right), \tag{1}$$

$$\rho_s = \left[\frac{\sin(\theta-\varphi)}{\sin(\theta+\varphi)}\right]^2, \tag{2}$$

$$\rho_p = \left[\frac{\tan(\theta-\varphi)}{\tan(\theta+\varphi)}\right]^2, \tag{3}$$

$$\rho = \tfrac{1}{2}\rho_s + \tfrac{1}{2}\rho_p. \tag{4}$$

If the output from a gloss meter were governed only by the refractive index of the material, n, and the specular angle, θ, then Fresnel's law could be used to model G as shown in Eq. (5). In order to test this model, experimental data were collected for a variety of materials with a wide range of gloss values. The materials included 45 paper samples, both coated and noncoated, and several organic materials commonly found in an office environment. These included plastic and cloth materials as well as printed images. All of these samples were measured at 20°, 60°, and 85° with a BYK-Gardner gloss meter designed to measure at

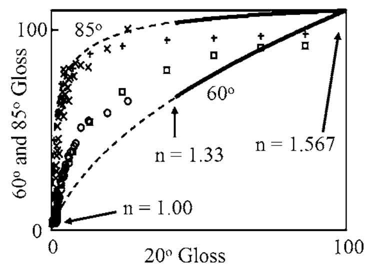

Figure 3. G values at 60° and 85° versus G values at 20°. Data for papers (× and ∘) and plastics (+ and □). Equation (5) for $n>1.33$ (solid line) and $n<1.33$ (dashed line)

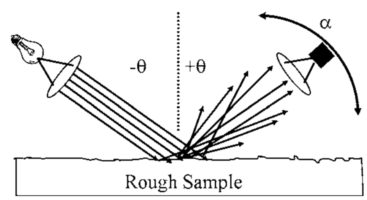

Figure 4. Roughness distributes the specular light around the specular direction and decreases gloss.

these three angles. Figure 3 shows the experimental G values measured at 60° and 85° versus the G values at 20°. As is commonly observed, the G values increase significantly as θ increases

$$G(n,\theta) = \frac{\rho(n,\theta)}{\rho_{\mathrm{ref}}(n_{\mathrm{ref}},\theta)}\cdot 100\ \% . \tag{5}$$

Equation (5) was used to model the data in Fig. 3 by assuming $n_o=1.00$ (air), $n_{\mathrm{ref}}=1.567$ (black glass) and varying n from 1.00 to 1.567 to simulate differences in material properties. The calculation was performed at $\theta=20°$, 60°, and 85°, and the results are shown as the lines in Fig. 3. The general shapes of the model lines appear to agree closely with the 85° data but less closely for the 60° data. However, the key assumption of this model is that G values are determined only by the material index, n. In order to fit the data, n is required to range from 1 (air) through 1.33 (water) up to 1.567 (black glass). This is not a reasonable assumption for most commonly encountered papers and organic materials, which means Eq. (5) does not provide a sufficient explanation for the higher G values observed at higher θ angles.

GLOSS AND THE BRDF

Surface roughness is well known to influence the results of gloss meter measurements.[3,7,8] As illustrated in Fig. 4, roughness disperses specular light about the specular angle, θ. The distribution of the light around the specular direction is called the bidirectional reflectance distribution function, BRDF. The complete BRDF is a function of two angles, α_1 and α_2 as shown in Fig. 5, where α_1 is the deviation from θ in the plane of the incident/reflected light, and α_2 is the deviation perpendicular to this plane.

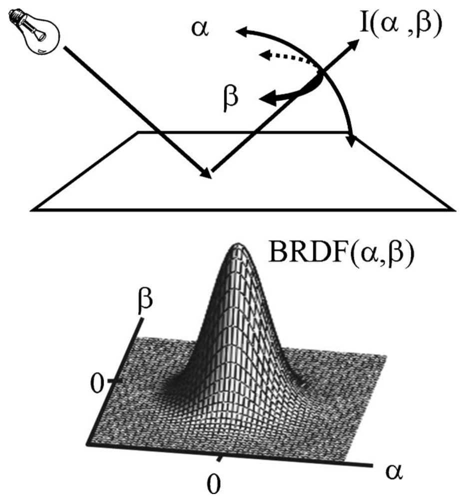

Figure 5. Illustration of the a BRDF, which is defined as the reflected light intensity, I, in watts per steradian.

Several examples can be found in the literature that suggest gloss can be modeled by an integral of the BRDF around the acceptance angle of a gloss meter, as shown in Eq. (6).[2,9–12] The subscript on BRDF_0 is used to distinguish between different BRDFs

$$G(\delta) = \frac{1}{K} \cdot \int_{-\delta}^{\delta}\int_{-\delta}^{\delta} \mathrm{BRDF}_0(\alpha_1,\alpha_2)d\alpha_1 d\alpha_2, \tag{6}$$

where $K=\int_{-\delta}^{\delta}\int_{-\delta}^{\delta}\mathrm{BRDF}_{\mathrm{Ref}}(\alpha_1,\alpha_2)d\alpha_1 d\alpha_2$.

The BRDF model of G in Eq. (6) can be simplified by assuming that the angular acceptance is circular with a radius δ. This appears to be true for some gloss meters, but not for all. We also assume that the BRDF is identical in the, α_1 and α_2 directions. This assumption is also not true in many cases. Nevertheless, we make these approximations to simplify the model. This enables the Gloss model to be expressed in one angular dimension, α, as shown in Eqs. (7) and (8)

$$\alpha = \sqrt{\alpha_1^2 + \alpha_2^2}, \tag{7}$$

$$G(\delta) = \frac{1}{K}\int_{0}^{\delta} \mathrm{BRDF}_0(\alpha)d\alpha. \tag{8}$$

Equation (8) implies a detector with a circularly symmetrical opening that detects light from the sample over an acceptance angle of 2δ. It can be shown that a $\mathrm{BRDF}_1(\alpha)$ function exists such that Eq. (9) is true. In other words, a symmetrical, two-dimensional BRDF can be modeled as if it were a one-dimensional BRDF. Modeling gloss, G, now only requires a model for the BRDF

$$G(\delta) = \frac{1}{K}\int_{-\delta}^{\delta} \mathrm{BRDF}_1(\alpha)d\alpha. \tag{9}$$

There is evidence that most papers, both coated and noncoated, have BRDFs that are approximately Lorentzian in shape.[4,13,14] We model the BRDF with the Lorentzian function shown in Eq. (10), where w is the width of the BRDF at half height, and ρ is the Fresnel reflectance factor of Eq. (4). The width, w, is governed by the roughness of the surface

$$\mathrm{BRDF}_1(\alpha) = \rho \cdot \frac{w}{w^2 + \alpha^2}. \tag{10}$$

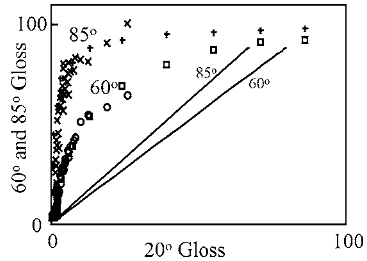

Figure 6. The Lorentzian BRDF model of gloss with constant n and varying w.

In this model, we assumed that all materials have the same index of refraction, $n=1.5$, and the same shape BRDF, Eq. (10). This model assumes that gloss is governed only by the sample roughness, so a range of gloss is modeled by varying w from very narrow to very wide, and we applied Eqs. (9) and (10) assuming the gloss meter has an angle of acceptance of $\delta=2°$. Figure 6 shows the result. This model clearly does not provide a useful rationale for the observed behavior.

Varying only the index of refraction, n, or varying only the roughness, w, as described above, did not lead to a quantitative rational for the effect of θ on gloss meter readings, G. One might try modeling gloss as a simultaneous change in both n and w. However, we have found no evidence in the literature to suggest that material roughness is correlated with refractive index. However, another optical characteristic of the BRDF has been reported to vary in concert with surface roughness. This characteristic is often called shadowing and obscuration.[7,14,15]

GLOSS, BRDF, AND SHADOWING

The phenomenon of shadowing and obscuration has been described schematically as the blocking of some regions of a rough surface by nearby topographic features of the surface.[7,14,15] This shadowing and obscuration effect has been suggested as a rational for the observation that the BRDF width decreases as the angle of measurement, θ, increases in goniophotometric measurements.[13] Attempts have been made to model the effect a priori, but in most cases the phenomenon is modeled empirically.[16,17] We have chosen the latter option. Figure 7 contains data reported in the literature[7] and measured in our laboratory[18] that show the change in BRDF width as a function of the Fresnel angle, θ. The data is shown as a fraction $F=w(\theta)/w_o$ where $w(\theta)$ is the BRDF half peak width at θ and w_o is the half peak width at $\theta=0°$. Equation (10) was then expressed as shown in Eq. (11).

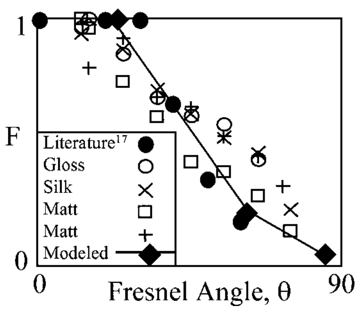

Figure 7. The fractional width of the BRDF versus θ.

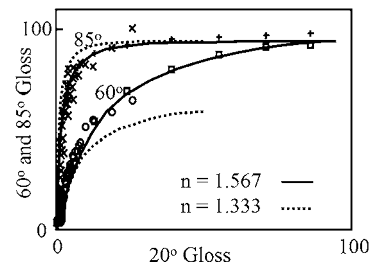

Figure 9. The Lorentzian BRDF model of gloss with varying w_o, F as a function of θ, and with $n=1.33$ (dotted line) and $n=1.567$ (solid line).

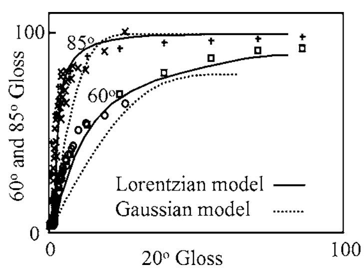

Figure 8. The BRDF model of gloss with constant n, and varying w_o, and shadowing factor, F, as a function of θ. Both Lorentzian and Gaussian functions were used to model the shape of the BRDF.

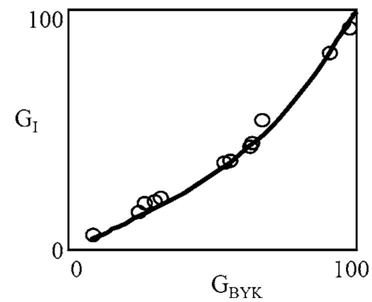

Figure 10. Comparison between gloss values measured with an Ihara gloss meter, G_I, and a BYK-Gardner gloss meter, G_{BYK}, at $\theta=75°$ for a variety of papers types, printed images, cloth samples, and plastic samples. The line is the model described in the text.

The is gloss model made the same assumptions as described previously. We again assumed $n=1.5$ and $\delta=2°$, and in addition we assumed $F=1$, 0.2, and 0.03 at $\theta=20°$, 60°, and 85°, respectively. Application of Eqs. (9) and (11) over a wide range of w_o values produced the model lines shown in Figure 8

$$\mathrm{BRDF}_1(\alpha) = \rho \cdot \frac{w_o \cdot F}{w_0^2 \cdot F^2 + \alpha^2}. \quad (11)$$

In spite of the simplifying approximations assumed in the model, Fig. 8 appears to rationalize the way in which gloss meter readings vary with changes in the angle of measurement. The Lorentzian curve shape appears to fit best, but it is reasonable to expect that curve shapes vary from sample to sample. Thus, the dotted and solid lines indicate a range of gloss behaviors one might expect as a result of differences in surface topography.

Another assumption of the model is that all materials have the same refractive index. This is clearly not the case, and in order to explore the effect of variations in n, the Lorentzian model was run with $n=1.33$ (water) and with $n=1.567$ (black glass). The results are shown in Fig. 9. The results indicate that the major reason for the differences between gloss values measured at different gloss angles, θ, is the difference in the width of the BRDF. Differences in refractive index, n, between materials, along with differences in BRDF shape, appear to make only secondary contribution to the overall gloss meter readings.

GLOSS AND ACCEPTANCE ANGLE δ

The BRDF models of gloss have assumed an acceptance angle of $\delta=2°$. This choice was made based on our reverse engineering of commercial gloss meters used in our laboratory. Choice of δ has an effect on the modeled value of G, and two of our meters appeared to have different δ values. Our BYK-Gardner meter appeared to have an acceptance angle of $\delta=2.9°$, and an Ihara meter seemed to have $\delta=2.0°$. Both meters measure at $\theta=75°$ and conform to TAPPI standard T480 for the measurement of paper gloss. Both instruments were found to be very repeatable. However, they produced different G numbers, as shown in Fig. 10.

The data in Fig. 10 were modeled with Eqs. (9) and (11) using $\theta=75°$, $n=1.43$, $F=0.05$, and by varying the roughness ($0.5° < w_o < 30°$). Although our efforts to reverse engineer these instruments may be flawed, we assumed acceptance angles of $\delta=2.9$ and $\delta=2.0$ to simulate the Ihara instrument and the BYK-Gardner, respectively. Using these limits in Eq. (9) produced the relationship shown by the solid line in Fig. 10. The agreement between the data and the model seems to indicate that an acceptance angle difference of only a few tenths of a degree can significantly alter the G values produced by an instrument.

CONCLUSIONS

This study clearly shows that gloss meters do not measure the reflectance factor, ρ, of a material but that their response is much more closely governed by material roughness, as manifested by the width of the BRDF. This conclusion is in agreement with previous reports.[3,7,8] In addition, higher order shape factors (Lorentzian versus Gaussian) can play some role in a gloss difference. However, such shape factors, along with differences in refractive index, appear to play only secondary roles in the readings of gloss meters for most common materials.

A significant factor that can cause nominally identical gloss meters to produce different G values appears to be the acceptance angle, δ, of the meter. Evidence suggests that a difference in δ of only a few tenths of a degree can significantly change G value. This suggests that acceptance angle may need greater scrutiny in the development of future gloss measurement standards.

Finally, this study may indicate that measurement of G values at multiple angles might be calibrated to produce more information about the underlying optical characteristics of a material. Multiple measurements might, for example, enable an estimate of the BRDF shape through application of this model or one developed from independent calibration data. The utility of such a multiangle measurement may be a fruitful area for further study.

Acknowledgments
The authors would like to express their appreciation to Per-Åke Johansson, Marie-Claude Béland, and the staff at STFI for getting them involved in the gloss problem. They also appreciate the encouragement and help received from Norm Burningham and financial support by Hewlett-Packard.

REFERENCES

[1] TAPPI T480; ISO-2813 (1994); ASTM-D523-89 (1999).
[2] J. R. Maxwell, J. Beard, S. Weiner, and D. Ladd, "Bidirectional reflectance model validation and utilization", Tech. Report AFAL-TR-73-303, Environmental Res. Inst. of Michigan, 1973.
[3] E. N. Dalal and K. M. Natale-Hoffman, "The effect of gloss oncolor", Color Res. Appl. **24**, 369 (1999).
[4] M. Mikula, M. Ceppan, and K. Vasko, "Gloss and goniocolorimetry of printed materials", Color Res. Appl. **28**, 335 (2003).
[5] M. E. Nadal and E. A. Thompson, "New primary standard for specular gloss measurements", J. Coat. Technol. **72**, 61 (2000).
[6] J. S. Arney, P. G. Anderson, G. Franz, and W. Pfeister, "Color properties of specular reflections", J. Imaging Sci. Technol. **49**, 228 (2005).
[7] M.-C. Béland and J. M. Bennett, "Effect of local microroughness on the gloss uniformity of printed paper surfaces", Appl. Opt., **30**, 2719 (2000); M.-C. Béland, S. Lindberg, and P.-Å. Johansson, "Optical measurement and perception of gloss quality of printed matte-coated paper", J. Pulp Pap. Sci. **26**, 120 (2000).
[8] R. Alexander-Datz and R. G. Barrera, "Surface correlation effects on gloss", J. Polym. Sci., Part B: Polym. Phys., **36**, 1321 (1998).
[9] M. E. Nadal and E. A. Thompson, "NIST reference goniophotometer for specular gloss measurements", J. Coat. Technol. **73**, 73 (2001).
[10] H. B. Westlund and G. W. Meyer, "Applying appearance standards to light reflection models", SIGGRAPH **28**, 501 (2001).
[11] R. Alexander-Datz and R. G. Barrera, "Surface correlation effects on gloss", J. Polym. Sci., Part B: Polym. Phys. **36**, 1321 (1998).
[12] M. Ashikhmin, S. Premoze, and P. Shirley, "A microfacet-based BRDF generator", SIGGRAPH **27**, 65 (2000).
[13] G. Obein, T. Leroux, F. Viénot, "BRDF and Gloss Scales", Proc. SPIE, **4299**, 279 (2001).
[14] W. C. Shemano, W. F. Lynn, D. Shemano, and T. A. Davis, "Modification of the Maxwell-Beard bidirectional reflectance distribution functio", SPIE Conference, Denver, Co, 1999, Vol. 3784, p.240.
[15] R. S. Hunter and R. W. Harold, *The Measurement of Appearance* (Wiley, New York, 1987).
[16] T. A. Germer, "Polarized light diffusely scattered under smooth and rough interfaces", Proc. SPIE **5158**, 193 (2003).
[17] M. Ashikhmin, S. Premoze, and P. Shirley, "A microfacet-based BRDF generator", SIGGRAPH **27**, 65 (2000).
[18] J. S. Arney, Hoon Heo, and P. G. Anderson, "A micro-goniophotometer and the measurement of print gloss", J. Imaging Sci. Technol. **48**, 458 (2004).