Measuring Metallic Appearance

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Abstract

Cost-effective techniques for the quantification of metallic appearance, sometimes called metallic brilliance, have been elusive. The present study presents preliminary and exploratory research using prototypes and a commercially available gloss meter with goniophotometric capabilities, with a goal of informing further exploration of this increasingly important topic.

Background

Metallic inks are used by brand owners of consumer products seeking to project a premium, luxurious image for their products. On the store shelf, metallics are distinctive compared to non-metallics and attract the attention of potential buyers, such that companies are willing to pay a premium for the metallic appearance.

The optical properties that make metallics distinctive introduce challenges for measuring them in production. The eye-catching "glint" caused by glancing light is highly sensitive to lighting geometry. Under diffuse illumination, metallic surfaces tend to lose this characteristic and appear flatter and less metallic, while directional lighting enhances the optical metallic effect.

Previous researchers have focused on methods that provide process control parameters for printers using metallic inks, including studies by Mannig and Verderber (2002), Breede and Sharma (2008), Habekost and Andino (2016), and Habekost and Ma (2017, 2018), which demonstrate that practitioners can use bi-directional 45:0 or 0:45 instruments, especially with polarization filters as defined by measurement condition M3 in ISO 13655 (2017) to quantify ink film thickness and achieve process consistency. Such methods minimize the contribution of specular gloss and thereby enable more stable process control. While such methods are shown to be effective for process consistency, they do not quantify the perceptual qualities of metallic brilliance.

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In a 2001 study, Rosenberg explored the use of gonio-spectrophotometry, which offers the ability to measure spectral reflectance at multiple angles. Using this approach, Rosenberg demonstrated that our standard geometry for measuring color (0:45) fails to capture the effect of metallic brilliance.

This suggests that the information associated with metallic brilliance is located at or near the gloss angle, otherwise known as the specular angle: a key principle for the quantification of metallic brilliance. As indicated by Rosenberg (2001), the direction of the lighting for quantifying metallic appearance must be measured at or near the gloss angle.

A second realization for measuring metallic brilliance is that the surface must have a high level of gloss to be associated with a high level of metallic brilliance. This can be illustrated with household aluminum foil: the polished, shiny side of the foil appears metallic, while the unpolished matte side appears less metallic. It is critical to recognize that not all materials with a high level of gloss appear metallic. For example, a ceramic tile will never look metallic, no matter how highly polished it is. Gloss by itself is insufficient for metallic brilliance.

That leads us to the third consideration; that the material should have a high degree of surface reflection to achieve metallic brilliance. Non-metallic materials, like ceramic tiles and printing ink, will reflect 5% to 10% of the incident light directly at the surface, causing the gloss effect. Metallic surfaces will reflect considerably more of the light at the surface. This condition aligns with the physical principles described by Fresnel's laws, which govern how light is reflected and transmitted at material boundaries. According to these laws, the proportion of reflected light increases with angle and depends on material properties and polarization, providing a theoretical foundation for the observed importance of specular reflection in metallic brilliance. The principal investigator of the present study posits that the surface should reflect more than 70% of the indent light if metallic appearance is desired.

The assumptions of this work can be summarized as follows: for an object to appear metallic, it must have a smooth surface and reflect a high proportion of the incident light at the surface.

Metallic Quantification Prototypes

A traditional goniospectrophotometer includes a light source and a spectral detector which can be mechanically adjusted so as to point at a position on the sample from a variety of angles. Ideally, the light source and detector can independently be positioned at arbitrary longitudes and latitudes. The goniospectrophotometer used in Rosenberg's paper was limited to moving the light source and detector along the same arc. These instruments could capture the

data needed for this study, but such instruments are generally large, expensive, and take time to move from one measurement position to the next.

A popular variant on this is the abridged goniospectrophotometer. This device has a limited number of light sources and detectors, each in a fixed angular position. These devices are compact, less expensive and since there are no moving parts, they are much faster at collecting a set of measurements. While these have proven useful for process control of automobile finishes, they lack the angular resolution for this project. We need a large number of measurements taken very near the gloss angle.

In 2012, the principal author conceived a simple design capable of instantaneously collecting measurements from hundreds of thousands of angles at a very high angular resolution, and which could be made very inexpensively. Figure 1 illustrates the general concept.

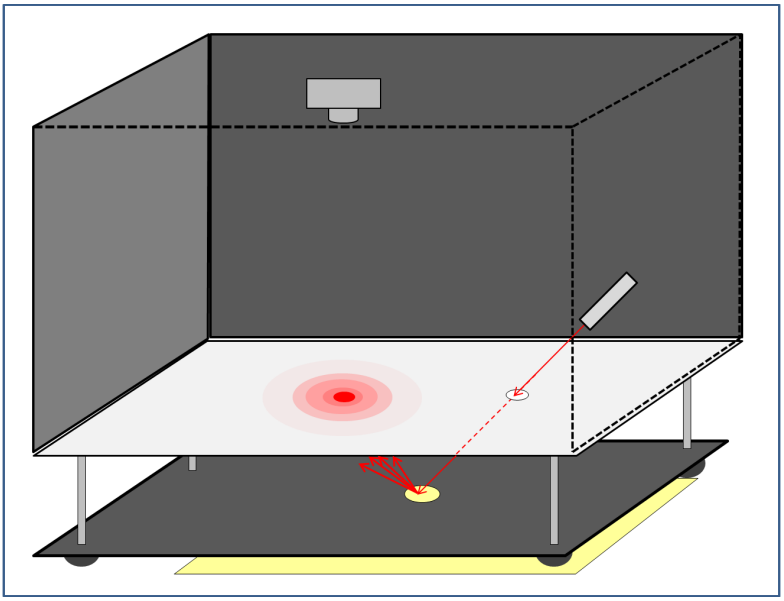


Figure 1: Conceptual drawing of the gonioscope

A laser is represented on the right side of the drawing in Figure 1, pointing at the sample (shown in yellow) through a sample port. The light reflected from the sample will reflect at a collection of angles and hit a translucent screen which is parallel to the sample surface. The location on the translucent screen is indicative of the angle of reflectance, so the angular distribution of reflection can be viewed from above.

When viewed by a human, this is a *gonioscope*. If the instrument is equipped with a camera (shown at top in the drawing), *goniograms* (images of the angular distribution) can be collected. With adequate software for processing goniograms, this is a *goniophotometer* which can report the reflectance at a large collection of angles. In the literature, this distribution is called the *indicatrix* or the *Bidirectional Reflectance Distribution Function* (BRDF).

The drawing shows a red laser pointer, so that the indicatrix is reported for a single wavelength. Since specular reflection is generally non-spectrally selective (the gloss reflection has the same spectral shape as the light source), a single wavelength may be adequate. A relatively simple adaptation of this design substitutes an RGB laser. This is a combination of a red, a green, and a blue or violet lasers with a set of dichroic filters to collimate the three lasers together. An RGB camera is then used to collect the goniograms.

A number of prototypes have been created. Figure 2 shows an instrument with an RGB laser (at the bottom). In this device, a rotatable mirror (at the top) can be used to change the angle of illumination. In this device, the translucent screen (not shown) was an arc in order to extend the device to increase the angular range. Figures 3 and 4 show other prototypes that have been developed.

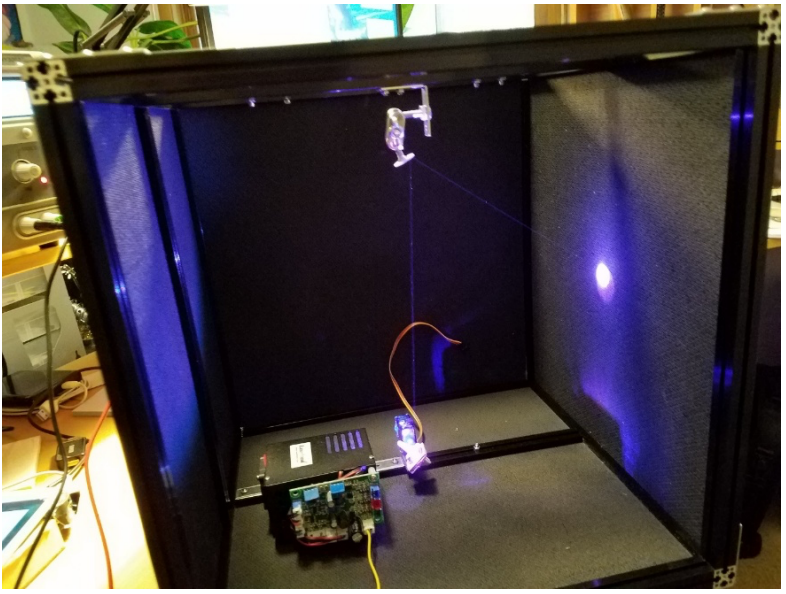


Figure 2: An RGB goniophotmeter with selectable illumination angle
(curved translucent sheet not shown)

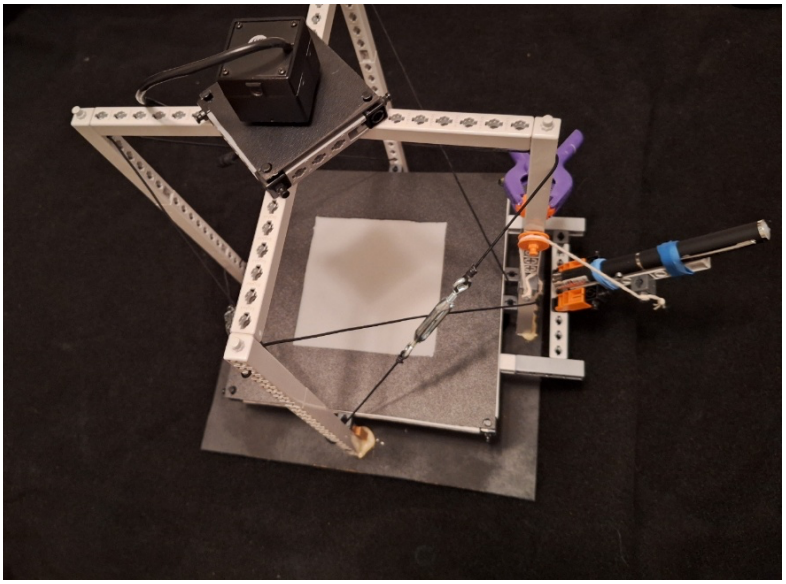


Figure 3: Goniophotometer used for initial work on this project
(The laser pointer was replaced with a laser module and an aperture.)



Figure 4: Goniophotoscope tailored for the specular angle with translucent screen at bottom of tube
(The scissors jack allows for eucentric adjustment of angles.)

The goal of these prototype systems is to capture high-resolution angular reflectance data, which can be analyzed using methods such as two-dimensional Gaussian fitting to describe the intensity distribution across viewing angles. Work on these prototypes and resultant images is ongoing, and the analysis code is being optimized.

Placing the translucent screen further from the sample allows for greater dispersion of light rays leaving at slightly different angles. This improves angular resolution. But increasing the size of the sample area will worsen the angular resolution, since one side of the sample area will have slightly different angles than the other. Thus, the angular resolution of the instrument depends on the relative area of illumination relative to the distance to the translucent screen.

As indicated in the caption of Figure 3, the laser module eventually used included a 2.0 mm aperture to limit the size of the laser beam on the sample. This allows for measurement of very small features on a sample, and the aperture also improves the angular resolution of the system. The prototype used for this paper also has a fairly large translucent screen. This provides a wide angular resolution. These two features (high angular resolution over a wide area) allow for a versatile instrument that can be used to determine ideal specifications for the particular application.

In parallel with custom instrumentation development, commercially available devices have been investigated. The Rhopoint IQ, which measures gloss at 20°, 60°, and 85° angles along with other metrics, may provide a more practical alternative. Notably, these instruments use a diode array which measures the distribution of reflected light from 12.75° to 27.25° evaluated around the 20° gloss angle. In this manner, they function as a goniophotometer by capturing reflectance data near the specular angle with high angular resolution.

The instrument offers a high degree of resolution, measuring 512 data points over the 14.5º range. This implies an angular resolution of ~0.03º. But this is misleading. The Rhopoint IQ is a fairly compact instrument, and it has a sample size of 6.0 X 6.4 mm, compared to the 2.0 mm sample area for the prototype instrument. Both of these limit the optical resolution (the effective resolution). Rhopoint does not provide a specification for the optical angular resolution of their instrument in goniophotometric mode.

Such devices offer a promising pathway for bridging the gap between laboratory research and industrial application.

Experimental results

Preliminary psychophysical and measurement analyses were conducted using eight printed samples of a silver metallic ink. For the measurement evaluation,

the Rhopoint IQ reported degree of gloss and degree of surface reflection. For these analyses, eight samples of silver metallic inks were produced by ECKART America Corporation on different substrates, including surface and reverse printed polyethylene terephthalate (PET), coated paper, and uncoated paper at two concentrations of ink film thicknesses, as illustrated in Table 1. Two samples were provided on each substrate: one printed at their normal metallic pigment load, and one at 25% of their normal pigment load.

	Standard Pigment Load Percent
Paper	
Uncoated	25
	100
Coated	25
	100
PET	
Surface Print	25
	100
Reverse Print	25
	100

Table 1: Printed Samples Analyzed

In a psychophysical evaluation of the printed samples, 20 subjects were asked to rank the eight samples in terms of metallic brilliance in an ISO-3664 compliant viewing booth. The printed samples were mounted to cardstock, and subjects were encouraged to handle the samples by the cardstock to minimize possible degradation of the printed samples. In this manner, subjects could adjust the angle of view to make their assessment.

Assessment of Relationship of Gloss to Metallic Brilliance

As shown in Table 2, 95% of the observers selected the reverse-printed PET samples as having the highest or second-highest level of metallic brilliance. Similarly, the surface-printed PET samples were ranked in the second group of metallic brilliance (ranking third or fourth) by over 95% of the observers. The prints on the uncoated paper stock were ranked in the lowest levels of (seventh or eighth), with over 95% indicating these prints had the least amount of metallic brilliance.

	Highest				Lowest			
Sample	1	2	3	4	5	6	7	8
25 Uncoated						5	15	80
100 Uncoated							85	15
25 Coated					30	65		5
100 Coated					70			
25 Surface PET	5		95					
100 Surface PET		5		95				
25 Reverse PET	65	30		5				
100 Reverse PET	30	65	5					

Note: "25" preceding substrate equals 25% standard pigment load, "100" preceding substrate equals standard pigment load.

Table 2: Percent Metallic Brilliance Ranking, n = 20

Gloss Unit Readings

Gloss Unit (GU) readings of the printed samples are illustrated in Tables 3 and 4. Using the measurement procedures indicated by Rhopoint and consistent with guidelines in ASTM D523, initial readings at 60° were made. The procedures suggest that when GU values are above 70 when measured at 60°, subsequent readings of the sample be taken using the 20° angle. Each sample was read with the instrument positioned at four different orientations: 90°, 180°, 270°, and 0°, with the mean and range of the four readings calculated.

	Paper				PET			
	Uncoated		Coated		Surface		Reverse	
Orientation	25	100	25	100	25	100	25	100
0°	22.1	38.0	237.8	176.7	414.8	300.9	543.8	505.8
90°	22.3	36.2	265.7	199.9	404.1	311.7	536.5	502.3
180°	21.0	41.8	235.5	173.4	411.8	295.1	543.1	506.3
270°	23.8	41.3	250.7	197.5	406.2	312.9	537.0	502.6
M	22.3	39.3	247.4	186.9	409.2	305.1	540.1	504.3
Range	2.8	5.6	30.2	26.5	10.8	17.8	7.3	4.0

Table 3: Gloss Units of Samples at 60°

As shown in Table 3, GU values for the uncoated paper samples were below 70. The coated paper and PET samples were above 70 GU, and remeasured at the 20° angle, as illustrated in Table 4.

	Paper		PET			
	Coated		Surface		Reverse	
Orientation	25	100	25	100	25	100
0°	82.9	63.0	367.3	218.5	918.0	831.2
90°	90.4	66.9	329.9	225.1	881.7	801.9
180°	82.8	62.8	349.1	212.1	931.0	816.3
270°	83.8	67.3	337.2	225.1	829.2	821.0
M	85.0	65.0	345.9	220.2	890.0	817.6
Range	7.6	4.4	37.4	13.0	101.8	29.4

Table 4: Gloss Units of Samples at 20°

The data suggests a correlation between gloss and metallic brilliance, with the reverse-printed PET showing the highest GU values and the uncoated paper exhibiting the lowest GU values. However, as previously indicated, although gloss is necessary, it is insufficient to result in metallic appearance alone. Rhopoint offers additional metrics that may be useful in quantifying related aspects of metallic brilliance: Distinctness of Image, Reflected Image Quality, and Peak Specular Reflectance, which are discussed below.

Distinctness of Image (DOI)

"Distinctness of Image" (DOI) is defined in two different ASTM standards: D5767 and E430. There are inconsistencies in the definition of DOI between the standards. ASTM offers no explanation of the differences, nor do the standards reference each other.

D5767 measures what amounts to the blur of a sequence of stripes reflected from the surface. E430 measures the gloss reflection in one small range of angles just off the specular angle. The two methods likely correlate with each other and also are correlated to the blur you would expect to see on a reflected image from a very glossy surface.

The Rhopoint IQ measures DOI in accordance with E430 and the resultant values from the printed samples are illustrated in Table 5. The measurements range from zero to 100, with a mirror-like surface resulting in a higher number. The need for DOI arises from the observation that two surfaces may exhibit similar gloss readings but the quality of one of the resultant coatings may be poor, resulting in defects such as "orange peel," pin holing, and texturing. These result in a distorted, unclear reflection of the metallic coating. By "…quantifying the way a reflected measurement beam is spread and distorted around the specular angle" (Rhopoint Instruments Ltd.,p. 36), the Rhopoint IQ produces a DOI number. Like the gloss readings, the PET samples have higher DOI numbers.

	Paper				PET			
	Uncoated		Coated		Surface		Reverse	
Orientation	25	100	25	100	25	100	25	100
0°	0.3	0.7	17.7	9.8	91.8	49.5	97.9	97.4
90°	0.0	0.5	18.1	9.4	67.1	70.3	96.8	97.6
180°	0.2	0.7	17.5	9.5	92.6	65.3	97.5	97.4
270°	0.5	1.1	17.4	9.4	92.3	71.5	92.4	97.4
M	0.2	0.7	17.7	9.5	85.9	64.2	96.2	97.4
Range	0.5	0.6	0.7	0.5	25.6	22.0	5.5	0.3

Table 5: Distinctness of Image of Samples at 20°

In evaluating the surface PET at 25% of the standard pigment load, and outliner is noted when the sample is read at the 90° orientation, and for the 0° orientation for the standard pigment load. As this was not noted in the GU readings, it may be attributable to coating inconsistencies which resulted in lower DOI readings at certain instrument/substrate orientations for the more sensitive metric.

Reflected Image Quality (RIQ)

RIQ is a proprietary method developed by Rhopoint. According to Rhopoint, it is similar to DOI but is more sensitive and offers a more proportionate response on a wider range of surface finishes. According to Weber (2024):

> *Even if this value is interesting for car manufacturers who deal with surfaces with very sharp reflectance, it is not a very good measure for printed samples because for those it predominantly reports low values that lack differentiation. Furthermore, pretests showed that the relative standard deviation of RIQvalues measured on metallized printed samples can be high.*

Like DOI, the resulting RIQ value is between 0 and 100, where undistorted images result in higher numbers. Once again, obtained values are consistent with the visual evaluations of the printed samples

	Paper				PET			
	Uncoated		Coated		Surface		Reverse	
Orientation	25	100	25	100	25	100	25	100
0°	0.4	0.6	0.4	0.6	83.3	28.6	94.8	92.4
90°	0.1	0.5	0.1	0.5	47.6	59.4	92.3	91.3
180°	0.2	0.6	0.2	0.6	86.8	49.9	93.9	93.7
270°	0.5	1.0	0.5	1.0	87.5	61.5	85.0	93.2
M	0.3	0.7	0.3	0.7	76.3	49.8	91.5	92.7
Range	0.4	0.5	0.4	0.5	39.9	32.9	9.8	2.4

Table 6: Reflected Image Quality Readings

Similar to the DOI readings, outliers are noted for RIQ values with the Surface PET at the 90° orientation for the 25% pigment load sample, and at 0° orientation for the full pigment load sample. Again, this may be attributable to process inconsistencies that were observed by the sensitive RIQ metric.

Peak Specular Reflectance (RSpec)

RSpec provides appearance information by representing the "…peak reflectance measured over a very narrow angle in the specular direction (+/-) 0.0991°" (Rhopoint Instruments Ltd., p. 38) based on 512 measurements above and below 20°. Any waviness on the surface acts as a reflector which deflects light around the gloss angle, which is sensed by RSpec due to its sensitivity to surface texture. Presented as a curve, when "…RSpec is equal to the gloss the surface is smooth, (and) RSpec drops as texture becomes apparent" (Rhopoint Instruments Ltd., p. 38). RSpec readings are presented in Table 7.

	Paper				PET			
	Uncoated		Coated		Surface		Reverse	
Orientation	25	100	25	100	25	100	25	100
0°	0.9	1.5	13.1	9.9	220.3	52.2	809.5	718.0
90°	0.9	1.4	14.3	10.4	107.2	70.7	708.8	684.0
180°	0.9	1.7	13.1	9.8	210.0	60.6	792.8	673.1
270°	0.9	1.8	13.2	10.5	200.8	71.4	530.9	701.3
M	0.9	1.6	13.4	10.1	184.6	63.7	710.5	694.1
Range	0.0	0.3	1.2	0.7	113.2	19.2	278.6	44.9

Table 7: RSpec Readings

Although the RSpec readings are generally consistent with the rankings of the observers, there are outliers in the data (25 PET/Surface/90º, and 25 PET/Reverse/270º). These are measurements of the same sample. Note that when the sample is flipped over, the 90º orientation would be 270º, so these are effectively the same orientation. One possible cause for these anomalies is

inconsistencies in the coating process or a scratch on the surface which are causing these results with the sensitive RSpec metric.

Goniophotometric Information

As previously stated, the Rhopoint IQ use a diode array which measures the distribution of reflected light at 12.75° to 27.25° at 512 data points. These readings are taken +/- 7.25° from with illumination from the 20% angle, and gloss values are provided within this range, which is represented graphically in Figure 5. The resulting data for the Coated Paper, Surface PET, and Coated PET. As the gloss values were very low at 20° for the Uncoated Paper, they are not included in the figure.

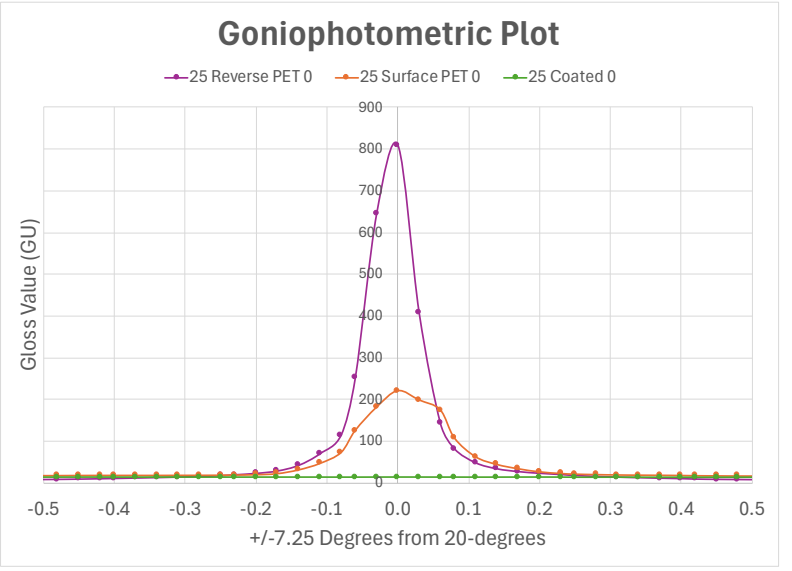


Figure 5: Goniophotometric Plot of Gloss Readings

The data represented by Figure 5 generally correlates to the psychophysical analyses of the samples, with the Reverse PET showing not only the highest amount of gloss, but more information is potentially available through the analysis of the area and spread of the representative curves.

Conclusions

These preliminary studies should be considered initial steps in best practices for quantifying metallic brilliance. Beginning with prototypes informing the nature

of metallic brilliance, the conditions necessary for a high degree of brilliance are outlined and the default information available from a commercially available gloss meter with goniophotometric capabilities were examined. It is suggested that the sensitivity of some of the metrics underscores the critical nature of controlling for ink film and substrate anomalies.

While the initial findings underscore the importance of gloss for metallic brilliance, quantifying the requisite impact of reflection at various angles of illumination around the gloss angle in a practical manner requires further exploration.

Future research can focus further analyses of the data provided by the goniophotometric data available, as well as on systematically evaluating a range of metallic materials. In addition, psychophysical testing can be conducted to establish correlations between instrumental measurements and human perception of metallic appearance. This combined approach will enable the development of standardized methods for quantifying metallic appearance, thereby supporting improved quality control and design optimization in printing and packaging applications.

Future research

There are two physical effects that determine the glossy appearance of a surface. The first is the smoothness/roughness of the surface. A smooth surface will provide little scattering of incident light and hence you will clearly see images when held at the correct angle. If the lighting is primarily from one direction, this will be perceived as a glint. A smooth surface will have a glossy appearance.

A rough surface will tend to scatter incident light in all directions so that there are no mirror-like images nor distinct glints. We will perceive rough surfaces as matte surfaces. When the surface is paint, these will ironically be called “flat”.

Figure 6 illustrates hypothetical goniophotometric plots near the specular angle for various degrees of surface roughness. The semi-gloss plot is half as high as the glossy plot and twice as wide. The matte plot is half as high as the semigloss, and again twice as wide. This illustrates an important rule: the total amount of surface-reflected light is unchanged when the surface roughness is changed.

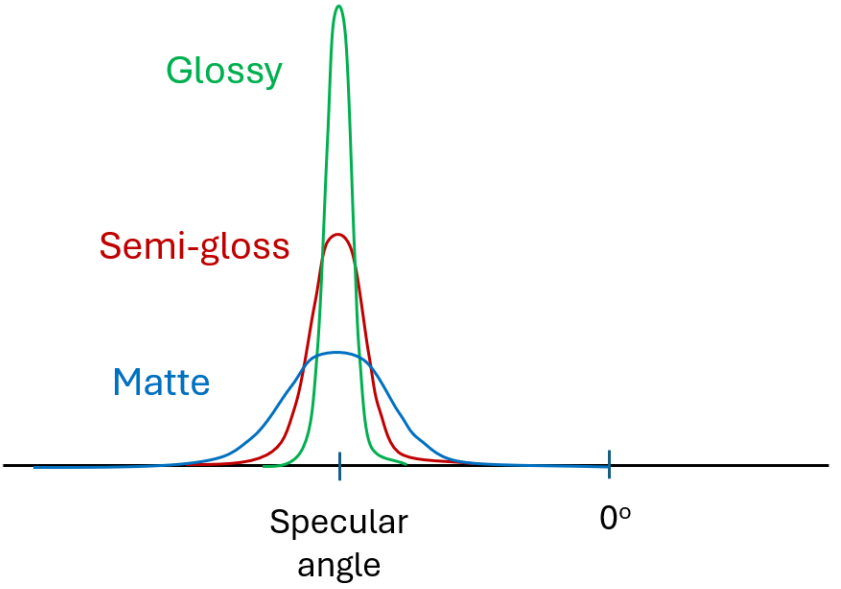


Figure 6: Comparison of a goniophotometric plot for the same surface with different degrees of polish

The second physical effect is caused by the "optical hardness" of the surface, which is called the *index of refraction*. Surfaces that have a low index (like water) will reflect less light at the surface than surfaces with a higher index, like printing ink or glass. The latter will reflect roughly 5% to 10% of the incident light at the surface. Metallic surfaces are considerably harder in the eyes of incident light and as a result may reflect 90% or more.

Figure 7 illustrates the goniophotometric curves for a metallic and a non-metallic surface with the same surface smoothness. The width of the two curves are the same, but there is a distinct difference in the height.

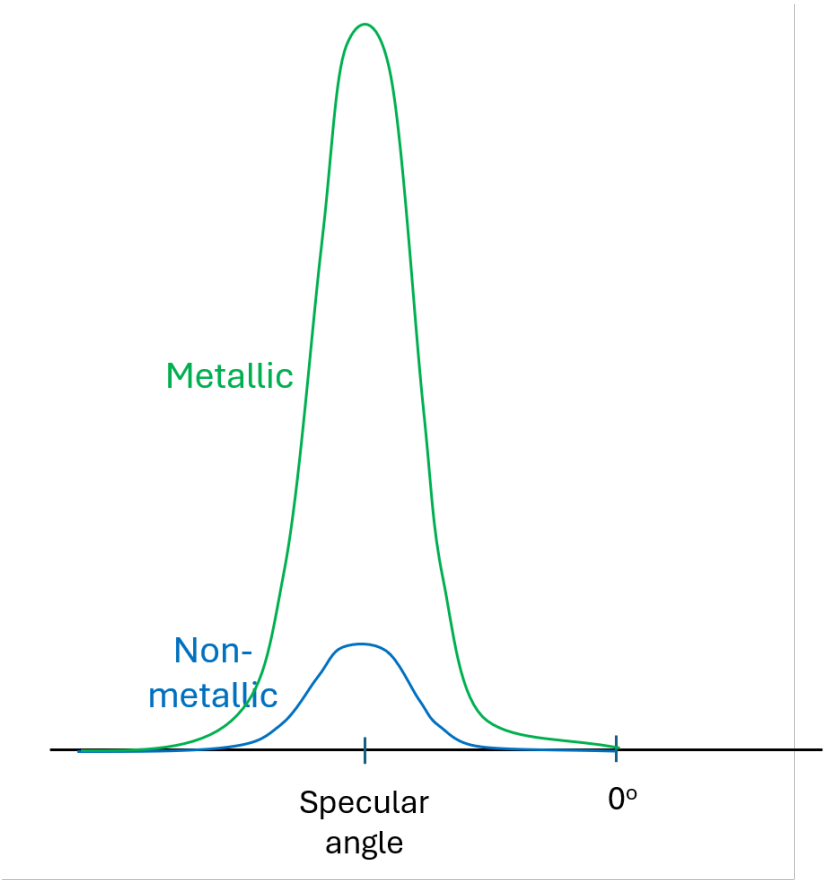


Figure 7: Comparison of goniophotometric plots for metallic and non-metallic surfaces

Thus, there are two distinct components to the goniophotometric curve: the width (the amount that collimated light is spread) and the area under the curve (the total amount of surface reflection). It is hypothesized that both of these aspects are taken into account when humans assess metallic appearance.

It has been noted that goniophotometric curves have a Gaussian shape, as illustrated in Figure 8.

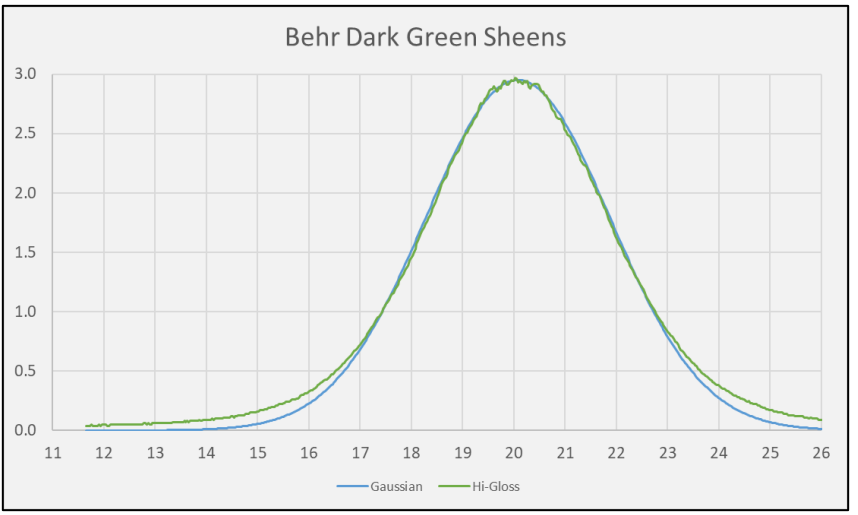


Figure 8: Gaussian shape of goniometric curves

If true, this hypothesis leads to the conclusion that the traditional methods for measuring glossy appearance, which rely on quantifying the light passed through narrow apertures of various sizes, may not be adequate for quantifying metallic appearance.

It is further hypothesized that fitting a Gaussian curve to goniophotometric data can provide the parameters (width and area) that correlate well with human perception of metallic appearance. This is part of future work.

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