Angle-Resolved Light Scattering from Textured Injection-Molded Plastics

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ABSTRACT: With regard to surface appearance, the angle-resolved light scattering from textured polymeric surfaces was evaluated to link the reflectance properties to measured gloss as well as visually perceived gloss. Bidirectional reflectance distributions were determined by means of a scatterometer and the specimens involved were textured injection-molded plaques manufactured from three different polymers; an acrylonitrile-butadiene-styrene (ABS) copolymer, a polypropylene (PP), and a polycarbonate and ABS copolymer blend (PC/ABS). The influence of color, surface roughness, and angle of incidence on the scattering characteristics was evaluated. An off-specular reflectance peak was observed for the textured specimens the magnitude of which was clearly determined by the surface roughness and the angle of incidence. The color of the specimens mainly influenced the diffuse reflectance. The results provide a measure of perceived gloss and supported previously reported findings regarding the relevance of the concept of contrast gloss for the gloss characterization of textured polymeric surfaces.
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Key words: gloss; light scattering; plastics; surfaces

INTRODUCTION

The concept of perceived quality is becoming increasingly important in the manufacturing industry, especially in the production of high-quality and so-called premium products. In this context, the perceived quality is supposed to occur from the impression that the customer gains in the sensory interaction with the product. The surface appearance of products contributes greatly to the perceived quality impression and is determined by the interaction between color, gloss, and surface texture. Failure in realizing, for instance, a good color matching between adjacent surfaces in a component or achieving an even gloss level throughout the part will have immediate consequences for the overall quality impression. Deeper knowledge is consequently needed, for example, about the relations between color, gloss, and surface texture as well as the ability to characterize the attributes of appearance in a manner that agrees with the visual impression.

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In the particular case of the interior of an automobile, polymeric materials are commonly used, often in the form of injection-molded components. Typical polymers chosen are acrylonitrile-butadiene-styrene (ABS) copolymer, polypropylene (PP), and polycarbonate and ABS copolymer blends (PC/ABS). Plastic components having surfaces visually exposed in the interior are normally imposed with a texture to achieve a more sophisticated appearance as well as a desired gloss level. Traditionally, in the automotive industry, a low gloss is associated with the perception of higher quality.

There are several methods developed and equipments available for the characterization of surface appearance; however, many of them suffer from deficiencies especially when evaluating rough surfaces. A previous study addressed the shortcomings of the conventional specular gloss measurements for evaluating the gloss of textured polymeric surfaces.[1] These measurements correlated poorly with the visual perception of gloss, for instance, when comparing specimens manufactured from different polymers or specimens differing in color. As an alternative, the concept of contrast gloss was proposed, in which not only the reflected light in the specular angle is considered for the gloss characterization, but also the reflectance in other directions (nonspecular) is taken into account. To evaluate contrast gloss, a multiangle spectrophotometer was used and a contrast gloss factor (CGF) was introduced as a measure of gloss. The evaluation of the CGF resulted in a significant improvement of the correspondence between measured gloss and visual assessments of gloss. More detailed reflectance measurements were, however, desired to obtain a better understanding of angle-resolved scattering of light from textured polymeric surfaces. From such measurements, the characterization of contrast gloss would be less restricted by the fixed angles of detection and also the limited numbers of detection angles in a conventional multi-angle spectrophotometer.

The aim of the present study was to explore the angle-resolved light scattering from a textured polymeric surface and the influence of small-scale as well as large-scale differences in surface roughness on the scattering. Furthermore, the effect of the color of the specimens and the angle of light incidence on the surface reflection were studied. The overall goal was to gain a better understanding of the relation between the light scattering and the gloss, both in terms of measured specular and contrast gloss as well as the visual perception of gloss of polymeric surfaces typical of injection-molded components in the interior of an automobile.

BACKGROUND

Measuring gloss

Gloss is usually associated with the light that is reflected from a surface in the specular angle which, measured from the normal of the surface, is the opposite angle to the angle of the incident light.[2] The high gloss of an ideal, perfectly smooth surface results from that the reflected light from such a surface is confined only to the specular angle whereas in other directions the light reflection is zero. With increasing surface roughness, the reflected light from the surface is scattered in a more diffuse manner and consequently the gloss is reduced. Several other gloss concepts has however also been proposed such as a number contrast gloss, haze, sheen, distinctness of image, and surface nonuniformities such as orange peel.[2,3]

The visually perceived gloss is sometimes referred to as glossiness is determined by the reflectance properties of the surface but is also influenced by illumination conditions and by the direction of view. The perception of gloss is created in the mind of an observer and can as such not be measured. However gloss concepts, such as specular gloss and contrast gloss, can be evaluated from the angle-resolved reflectance characteristics of surfaces with the aim of subsequently linking them to the visual impression of gloss.

When evaluating specular gloss the light reflected in the specular angle is quantified at various angles of incidence and viewing. Typically, the gloss level is characterized by means of a glossmeter for which the most common angles of incidence and detection are $\theta_i = 20°$, $60°$, $75°$, and $85°$.[2] In the automotive industry the incident angle $\theta_i = 60°$ is most frequently employed and is the recommended angle for the measurement of specular gloss on textured and polymeric surfaces.[4,5] The conventional glossmeters determine the gloss g as the ratio between the specular reflectance of the surface of the test specimen ($R_{S\ \mathrm{specimen}}$) and that of a smooth standard surface ($R_{S\mathrm{standard}}$) at a specified angle;

$$g = 100 \cdot \left(\frac{R_{S\ \mathrm{specimen}}}{R_{S\ \mathrm{standard}}}\right) \tag{1}$$

A highly polished black glass tile with a refractive index of 1.567 is used as the standard surface. The standard surface assigned a specular gloss value of 100 gloss units (GU). The illuminant of the glossmeter is spectrally corrected to yield the Commission Internationale de l'Éclairage (CIE) luminous efficiency with CIE standard illuminant C.[5] Injection-molded components in the automobile interior typically have a gloss level in the order of 1–5 GU when measured with the 60° angle of illumination and detection. For such surfaces an experienced observer can usually discriminate gloss differences as small as 0.1 GU.

As mentioned in the "Introduction" section, the correspondence between the measured specular gloss and the visually perceived gloss is less satisfactory in the case of textured polymeric surfaces. The shortcomings of specular gloss characterization were addressed in a previous study[1] in which the evaluation of contrast gloss from measurements of angle-resolved reflectance was described. Contrast gloss, which is associated with the ratio between the amount of light reflected in the specular angle and that reflected in other directions, has been suggested to be more relevant as an indication of the visual perception of gloss, especially for low-gloss surfaces.[3,6,7] In Ref. 1, a CGF was determined from measurements of reflectance with a conventional multi-angle spectrophotometer. These measurements are described in more detail in the "Experimental" section below.

Perceived gloss through psychometric evaluation

For the characterization of surface appearance the subjective perception is certainly of great relevance. To numerically describe, for instance, the visual perception of a surface sensory testing may be applied, which is a psychometric evaluation technique.[8] The aim of the method is to quantify the relation between a physical stimulus such as gloss and the perceptual response of the observer.

TABLE I
An Overview of the Materials

Polymer	Trade name	Supplier	Density (ISO 1183)	Melt volume/mass-flow rate (ISO 1133)
Acrylonitrile-butadiene-styrene copolymer (ABS)	Terluran GP 22	BASF AG (Ludwigshafen, Germany)	1.04 g/cm^3	20 cm^3/10 min at 220°C and 10 kg
Polypropylene (PP)	Hostacom PPU X9067 HS	Basell (Bayreuth, Germany)	0.91 g/cm^3	15 g/10 min at 230°C and 2.16 kg
Polycarbonate/ acrylonitrile-butadiene-styrene copolymer blend (PC/ABS)	Cycoloy Resin C1100HF	GE Plastics (Cartagena, Spain)	1.12 g/cm^3	6 g/10 min at 260°C and 2.16 kg

In previous works,[1,9] the relation between glossmeter measurements of specular gloss, measurements of CGF, and the visual perception of gloss of textured polymeric specimens was studied by the means of a psychometric evaluation. Such an approach is also employed in the present study.

EXPERIMENTAL

Materials

The specimens were injection-molded plaques manufactured from three different polymers (specimens A–L, Table I) and of the same type as used in previous works.[1,9] Three additional specimens having textures which varied in surface roughness were also included (specimens M–O, Table I).

Specimen preparation

The surface texture of the specimens (A–L) was denoted Middle. The texture was fairly isotropic and is a typical kind of texture used for automotive interior panels. A photomicrograph of the surface texture is shown in Figure 1(a).

The specimen were injection-molded plaques manufactured by means of two different molds denoted Cavity I and Cavity II to obtain slight differences in surface texture between the specimens. The same texture was photo-etched in both cavities; however, Cavity II was subjected to a slight additional etching resulting in a somewhat more detailed texture. Both molds were rectangular cavities with the width 138 mm, the length 78 mm, and the thickness 2.7 mm. The molds were equipped with a film-edge gate with the width 123 mm, the length 2 mm, and a thickness of 1 mm. Evaluated by means optical laser profilometry, the RMS-roughness values, S_q, of the specimens (A–L) ranged from 17.9 μm to 22.4 μm, cf. to Ref. 9.

To study the influence of larger-scale differences in surface roughness on the angle-resolved light scattering, additionally three specimens were included in the study. Specimen M had a texture denoted Fine, see Figure 1(c), with the approximate RMS-roughness S_q = 5.5 μm and specimen N was denoted Fine II, see Figure 1(b), with the approximate RMS-roughness S_q = 11 μm. Alike the texture Middle, the textures Fine and Fine II were fairly isotropic textures typical for automotive interior applications. Furthermore, specimen O was included, having a smooth and glossy surface with a surface roughness value of approximately S_q = 0.03 μm.[10] The specimens M–O were injection-molded plaques manufactured in the ABS grade described in the "Materials" section and in molds similar to the mold also described in the same section. The surface roughness of the specimens is only described here in terms of the amplitude roughness parameter RMS-roughness, S_q. It is generally important to characterize surface roughness also in the lateral dimension and for this purpose the lateral

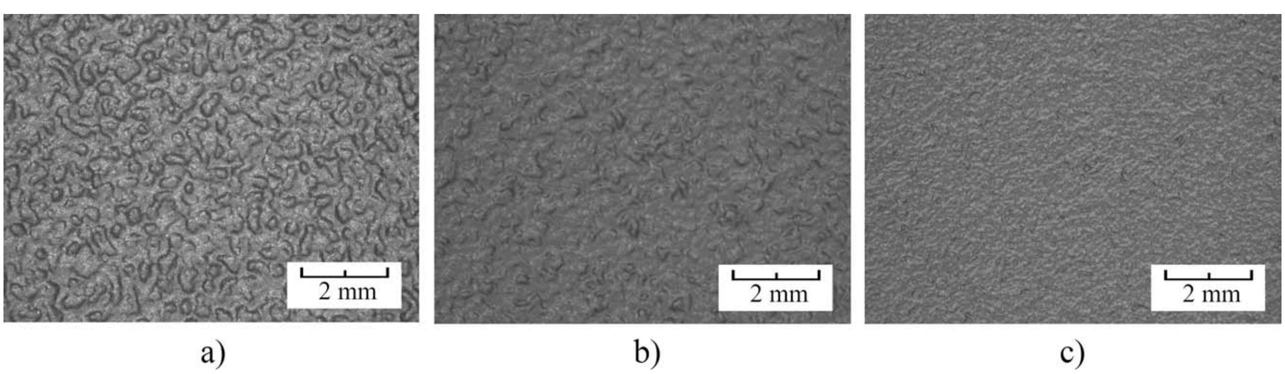

Figure 1 Photomicrographs of the surface textures of the specimens: (a) Middle, (b) Fine II, and (c) Fine.

TABLE II
An Overview of the Specimens

Specimen	Material	Color	Texture	Specular gloss (GU)	Contrast gloss, CGF_m
A	ABS	Dark grey	Middle	1.6	5.6
B	ABS	Dark grey	Middle	1.2	3.9
C	PP	Dark grey	Middle	1.6	4.4
D	PP	Dark grey	Middle	1.2	3.4
E	PP	Dark grey	Middle	1.2	3.0
F	PC/ABS	Dark grey	Middle	1.6	5.6
G	PC/ABS	Dark grey	Middle	1.2	4.0
H	PC/ABS	Dark grey	Middle	1.7	5.5
I	ABS	Brown	Middle	1.2	2.4
J	ABS	Grey	Middle	1.2	2.1
K	ABS	Dark beige	Middle	1.3	1.6
L	ABS	Light grey	Middle	1.6	1.3
M	ABS	Dark grey	Fine	4.0	14.3
N	ABS	Dark grey	Fine II	2.1	11.1
O	ABS	Dark grey	Smooth	97.4	N/A

correlation length has previously been used, cf. Ref. 9. However, for the specimens in the present study, a higher RMS-roughness value was always associated with a higher value of the lateral correlation length, cf. Ref. 11. Since the measures of lateral correlation length provided no additional information, they were not included here.

An overview of the specimens produced is given in Table II. The injection molding procedure and the processing conditions are described in detail in Ref. 9.

The color coordinates (D65/10°) of the specimens (B, I–L) employed in the study of the influence of the color on the angle-resolved light scattering are given in Table III. The color was measured by means of a 45°/0° spectrophotometer. The color of the specimens A–H and M–O was similar to the given value of lightness of specimen B. The color of the three polymers used to produce those specimens (A–H, M–O), was adjusted to minimize the color differences among the final specimens. The total color difference between the polymers was less than $\Delta E^* = 1.3$ (D65/10°) measured on a smooth, glossy injection-molded plaque with a spectrophotometer with a diffuse geometry in the specular-component-included (SCI) mode.

Specular gloss measurements

For gloss characterization, a portable glossmeter, BYK Gardner micro-trigloss (Germany) was used, which enables specular gloss measurements at three different angles of incidence 20°, 60°, and 85°. The instrument is in accordance with ISO 2813-1994 and ASTM D2457-03. The repeatability of the instrument is ± 0.1 GU in the range 0–10 GU.[12] The standard deviation of the measurements performed here was significantly smaller than 0.1 GU.

TABLE III
The Color Coordinates of Selected Specimens

Specimen	Color	CIELAB Lightness, L^*	CIELAB Chroma, C^*	CIELAB Hue, h (°)
B	Dark grey	14.4	0.1	289.7
I	Brown	25.0	4.4	59.6
J	Grey	27.1	2.8	287.6
K	Dark Beige	37.6	3.5	57.1
L	Light Grey	54.6	3.5	70.3

Measurements of contrast gloss

To evaluate the contrast gloss of the specimens, a MA68II multi-angle spectrophotometer from X-rite (Grand Rapids, MI) which conforms to ISO 7724 was used. This equipment employs a gas-filled tungsten lamp with an incident light angle of 45°. Its spectral range is 400–700 nm and the spectral interval is 10 nm. The reflectance properties at five different angles relative to the specular angle 15°, 25°, 45°, 75°, and 110° are simultaneously measured. The repeatability of the instrument is $\Delta E^* = 0.02$ given in CIELAB total color difference.

For the evaluation of contrast gloss, the reflectance data in two different angles were used. The reflectance data obtained at the 15° angle ($R_{15°}$) was used as a measure of specular reflectance being the closest to the specular angle. As a measure of diffuse reflectance, the reflectance data at 110° angle ($R_{110°}$) was used being the angle furthest away from the specular angle. In this case, the reflectance data refer to the integrated value of the measured reflectance between 400 nm to 700 nm, cf. to Ref. 1. A CGF was calculated as;

$$\text{Contrast Gloss Factor } [\text{CGF}_m] = R(\lambda)_{15°}/R(\lambda)_{110°} \quad (2)$$

where λ is the wavelength of the light.

The subscript m denotes the CGF obtained from the multi-angle spectrophotometer measurements to differentiate it from the measure of CGF obtained

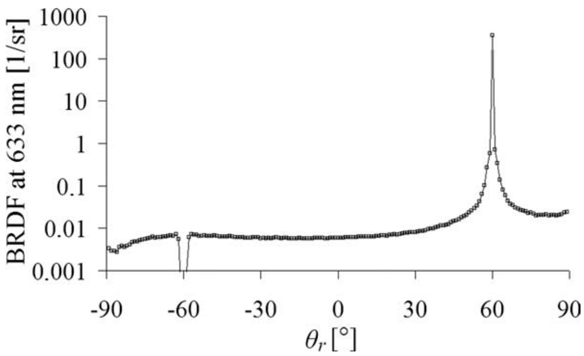

Figure 2 The BRDF for the smooth polymeric surface of specimen O.

from the bidirectional reflectance distribution function. For that measure, the subscript *s* is used, i.e., to denote scatterometer measurements. The characterization of contrast gloss using the multi-angle spectrophotometer is described in more detail in Ref. 1. The CGFs (CGF_m) for each of the specimens involved in the present study is shown in Table I. The standard deviation was typically about 0.2.

The psychometric evaluation

To assess how the attribute of gloss is visually perceived, a psychometric evaluation was performed in which two different sensory evaluation techniques were applied. For the evaluation of the visually perceived gloss on specimens varying slightly in surface texture and gloss (A–H) a paired-comparison test was applied in which the observers were asked to react to two new specimens at a time and state the difference between them. A ranking of all the involved specimens could be obtained when the results from all the paired-comparison evaluations was combined. To evaluate the influence of color on the perceived gloss, a more simple ranking technique was used for specimens B and I–L as only five specimens were involved. In this study, the observers were asked to rank the five specimens in the order of perceived gloss.

The observer test panel consisted of 10 individuals. Five of them were female and five male and their ages ranged from 28 to 63 years. All participants had extensive experience in assessing the surface appearance of injection-molded plastics and were professionals in the fields of design as well as engineering. To avoid interactions among the observers potentially influencing the assessments each evaluation was performed by one observer at a time.[13] All assessments were performed in a light cabinet which was in accordance with ASTM D 1729 with a CIE daylight illuminant D65 to simulate normal daylight viewing conditions. The consistency of the evaluation was also assessed and reported in a previous work.[9]

The psychometric evaluation, the result of which is used in the study presented here, is described in more detail in Ref. 9.

Angle-resolved light scattering

The angle-resolved scattering distribution of the specimens was determined by means of a TMA TASC scatterometer[14] (Bozeman, MT) which is in accordance with the ASTM standard for angle-resolved light scattering.[15] The scatterometer is equipped with a HeNe laser light source with a wavelength of 633 nm and a spot diameter (of the incident light) of approximately 1 mm. The measurements were performed with unpolarized light since mainly the relation to the visual impression was relevant in this case. The reflectance properties were measured with an incidence angle, θ_i, of 60° and the detection angle was varied from −89° to + 89° in the plane of incidence, which is the plane defined by the surface normal and the incident light. Measurements were performed on one specimen with the angles of incidence 45° and 75°.

The reflected power is reported in the form of a bidirectional reflectance distribution function (BRDF) which is defined as[16]

$$\text{BRDF} = (dP_r/d\Omega)/(P_i \cdot \cos(\theta_r)) \quad (3)$$

where dP_r is the portion of reflected power within the angle $d\Omega$ of the detector. P_i is the incident power and θ_r is the angle of reflectance. In the figures below (Figs. 2, 3, 5–7), θ_r is given in relation to the surface normal in the plane of incidence. BRDF is a differential function that depends on the direction and the wavelength of the incident flux, the scattering direction and the state of polarization of both the incident, and the scattered light. In practice it is calculated from the average radiance divided by the average irradiance.[15] The dimension of BRDF is sr^{-1}, with steradians [sr] being a unit of solid angle. In

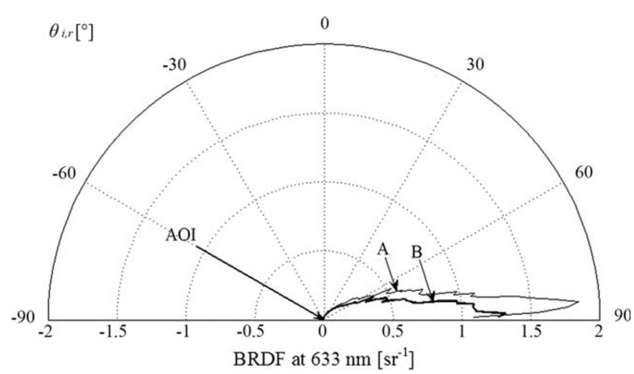

Figure 3 The effect of small-scale differences in surface roughness on the BRDF and the off-specular reflectance peak. AOI denotes the angle of incidence.

the scattering distribution a minimum will be evident when the detector physically passes behind the illumination source. The corresponding values were excluded in the analysis.

An indication of the measurement uncertainty, when measuring on the textured specimens, was obtained from three repeated measurements, including changing the measurement area, on specimen B. The repeatability of the BRDF-measurement was approximately 5% for reflectance angles smaller than 70°, relative to the surface normal, and approximately 20% for angles larger than 70°.

RESULTS AND DISCUSSION

Angle-resolved scattering from a smooth surface

The bidirectional reflectance distribution function for a smooth surface typically has a sharp reflectance peak in the specular angle. For an ideal and perfectly specular-reflecting surface, the peak would be exactly in the specular angle with its magnitude determined by the Fresnel equation. In other directions, the reflectance would be zero. Specimen O had a very smooth polymer surface and thus exhibited a reflectance distribution characteristic of a smooth surface as shown in Figure 2.

The reflectance peak was fairly narrow with its maximum value at the specular angle. The magnitude of the specular reflectance was approximately 60,000 times larger than the diffuse reflectance. The diffuse reflectance can be related both to diffuse reflectance from the surface but also to scattering from the bulk.[16]

Angle-resolved scattering from a textured surface and the effect of small-scale roughness differences

The specimens A–H were all imposed with a texture denoted Middle. However, very slight differences in texture and gloss on the specimens were obtained by means of altering polymer and varying the processing conditions. The RMS-roughness values, S_q, varied in the range 17.9–22.4 μm and the specular gloss values at 60° incident angle, were between 1.2 and 1.7 GU. The considerably higher surface roughness of these specimens, compared to the smooth specimen O, had a significant influence on the bidirectional reflectance distribution. All eight specimens exhibited similar distributions, however, here only the BRDFs for specimens A and B are shown in a polar coordinate system in Figure 3. Specimen A had a higher gloss value (1.6 GU) and lower RMS-roughness value ($S_q = 18.2$ μm) compared to specimens B with a gloss of 1.2 GU and a RMS-roughness value of $S_q = 22.2$ μm. The difference between the specimens were reflected in their bidirectional reflectance distributions functions as specimen A exhibited a higher reflectance in the specular region particularly at angles larger than the specular angle. The higher reflectance of specimen A corresponded to its higher gloss and its lower surface roughness.

The magnitude of the diffuse reflectance from the textured specimens was approximately 2–3 times larger than the corresponding reflectance from the smooth surface (specimen O). The amount of specularly reflected light was not only significantly lower than that from the smooth specimen but the peak was also considerably broader and shifted towards a larger angle than the specular angle. The maximum of the peak was approximately at $\theta_r = 85°$–$88°$ relative to the surface normal.

The phenomenon of off-specular peaks has been described by Torrance et al. in Refs. [17,18]. According to their theory regarding off-specular reflectance peaks, a maximum in the reflectance distribution occurs at larger angles than the specular angle in the case of rough surfaces. At a near-normal incident direction the light is reflected, from such surfaces, in a manner more similar to that of a perfect diffuser. However, as the angle of incidence increases the off-specular reflectance peak appears and its magnitude increases. The phenomenon takes place on surfaces having a root-mean-square roughness, S_q, comparable or larger than the wavelength of the incident light. The theory on the off-specular peak phenomenon is based on the assumption that reflection from a rough surface contains two components. The specular component originates from mirror-like facets and is subjected to shadowing and masking by adjacent facets. Shadowing and masking will either prevent the incident light from reaching the facet or from being reflected from it. The diffuse component originates from multiple reflections among the facets and from internal scattering. The alteration of the scattering caused by the mechanisms of shadowing and masking are assumed to account for the off-specular peak.

The small-scale differences in texture and gloss were reflected in differences in the bidirectional reflectance distribution for specimens (A–H) in a similar manner as is demonstrated for specimen A and B in Figure 3. A slightly lower RMS-roughness value and the consequently higher gloss resulted in increased magnitude of the off-specular reflectance peak compared to a specimen having higher roughness and lower gloss. There was no evident connection between the position of the off-specular reflectance peak and surface roughness or gloss, nor was an apparent maximum in the distribution observed for all specimens. For some specimens the reflectance appeared to continuously increase as the maximum measured angle, at $\theta_r = 89°$, was approached. The relation between the BRDF and the measured as well as the visually perceived gloss is further discussed below.

In the previous study,[1] the influence of the type of polymer on the measured and visually perceived gloss was discussed. In this study, no significant impact of the polymer type on the angle-resolved light scattering was observed.

The relation to measurements of specular gloss and contrast gloss

As mentioned before the determination of a CGF from multi-angle spectrophotometer measurement (CGF_m) was proposed in a previous study[1] showing very good correspondence to the visual perception of gloss for textured polymeric surfaces. A measure of contrast gloss, which signifies the relation between the specular reflectance and the diffuse reflectance from a specimen, may also be evaluated from the bidirectional reflectance distribution functions. For this measure, the subscript *s* is used to denote that the CGF was obtained from scatterometer measurements. The relation between the CGF (CGF_m) obtained from multi-angle spectrophotometer measurements and an equivalent CGF (CGF_s) obtained from scatterometer measurements was here investigated to some extent. As described above, the CGF (CGF_m) was obtained from reflectance data at two angles relative to the specular angle, $R(\lambda)_{15^\circ}$ and $R(\lambda)_{110^\circ}$. The angle of incidence, $\theta_i = 45^\circ$, in those measurements differed however from the incident angle in the scatterometer measurements which was $\theta_i = 60^\circ$. The values of the CGFs can thus not be compared in a straightforward manner. Nevertheless an approximate comparison was done using scatterometer measurements of reflectance in the equivalent angles to those used in the multi-angle spectrophotometer measurements relative to the specular angle; $\theta_r = 45^\circ$ and $\theta_r = -80^\circ$. Evaluated by means of Pearson correlation coefficient, a very good correlation ($\rho = 0.98$) was obtained when the measures of contrast gloss were compared for specimen A–N.

Unlike the data from the multi-angle spectrophotometer measurements, the reflectance data obtained from the scatterometer measurements were not restricted by the fixed and limited number of angles of detection. Therefore alternative methods for computing the CGF (CGF_s) may be employed. Formally, the expression for evaluating CGF_s is according to;

$$CGF_s = \frac{BRDF_{specular}}{BRDF_{diffuse}} \tag{4}$$

where $BRDF_{diffuse}$ in the present study refers to the average value from angles between $\theta_r = 15^\circ$ and -55°. Apart from being angles mainly related to diffuse reflectance, the particular range was chosen as, for these angles, the reflectance was generally fairly constant. The choice of one reflectance angle or a range of angles representing the "specular" reflectance was not apparent due to the broad and off-specular reflectance peak observed for the textured specimens. Several measures representing "specular" reflectance were evaluated from the scattering data. The reflectance at single reflectance angles between $\theta_r = 50^\circ$ and $\theta_r = 89^\circ$ was used, as well as average values calculated from various ranges in this span. Dividing the "specular" reflectance with the diffuse reflectance in this manner was regarded as measures of contrast gloss. The values obtained for specimens A–H were correlated to the CGF from the multi-angle spectrophotometer measurements[1] as well as the visual assessments of gloss,[9] cf., also next section. The best correspondence both to values of CGF (CGF_m) as well as to visual assessments were obtained when the reflectance at $\theta_r = 60^\circ$ was used as a measure of "specular" reflectance. Possibly the increasing measurement uncertainty observed for the reflectance measurements at larger (as mentioned in the Experimental section) angles contributed to the less satisfactory correspondence to values of CGF (CGF_m) and visual assessments when reflectance data at $\theta_r = 60^\circ$ was used.

The reflected light from a specimen in the opposite angle to the incident light is considered to determine its specular gloss. Using the same incident angle, $\theta_i = 60^\circ$, in both equipments, the reflectance at $\theta_r = 60^\circ$ from scatterometer measurements was compared to the measures of specular gloss obtained with a conventional glossmeter. The measures correlated very well ($\rho = 0.99$) for specimens A–N. In this context, it should however be mentioned that the relation between measured specular gloss and visual gloss assessments has occasionally been poor for textured polymeric specimens, for example when differing in color.[1]

Because of the observation of the off-specular reflectance peak, the relevance of measuring specular gloss with a glossmeter at a larger incident angle was investigated. The angle of incidence, $\theta_i = 85^\circ$ was used instead of $\theta_i = 60^\circ$, often recommended and preferred when measuring specular gloss on low-gloss polymeric surfaces. The choice of angle was based on the observation that the angle of incidence did not significantly alter the magnitude of the shift of the off-specular reflectance peak for large angles of incidence, which is further discussed below. The repeatability of the measurements was however unsatisfactory and their correspondence to visual assessments was even poorer than the measurements of specular gloss obtained at $\theta_i = 60^\circ$.

The relation to visual assessments

The CGFs (CGF_s) obtained from the bidirectional reflectance distributions were correlated also to the

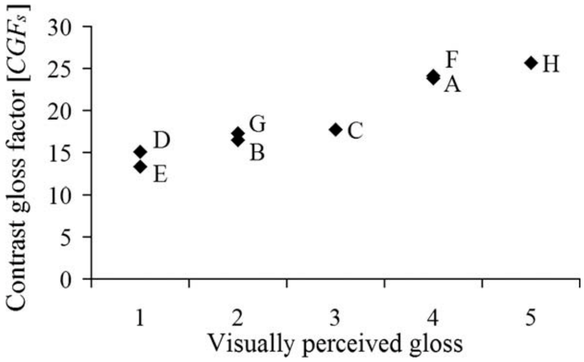

Figure 4 The relation between the visual assessments of gloss and values of contrast gloss obtained from the bidirectional reflectance distribution functions.

visual assessments of gloss. As mentioned earlier the best correlation, evaluated by means of Pearson correlation coefficient, with the visual assessments was generally obtained when the reflectance at $\theta_r = 60°$ (i.e., in the specular angle) was normalized with an average value of the diffuse reflectance despite that all specimens exhibited an off-specular reflectance peak. The relation between the visual assessments of gloss and the measure of contrast gloss (CGF_s) obtained in this manner for specimens A–H is shown in Figure 4. An ordinal scale was used for the gloss assessments where a high value indicates higher perceived gloss. The correlation between visual assessments of gloss and CGF_s for these specimens was very good ($\rho = 0.97$).

The effect of large-scale surface roughness differences

The bidirectional reflectance distributions for polymeric surfaces having large-scale surface roughness differences were studied by employing the three specimens having fairly different textures, denoted Fine, Fine II, and Middle. The specimens M, N, and B had approximate RMS-roughness values, S_q of 5.5 μm, 11 μm, and 18 μm, respectively. The BRDFs for the three textures are shown in Figure 5.

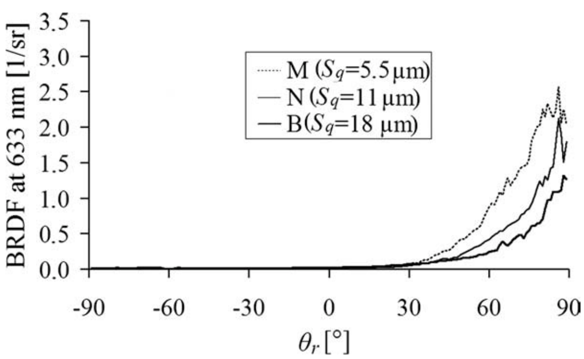

Figure 5 The effect of large-scale differences in surface roughness on the BRDF.

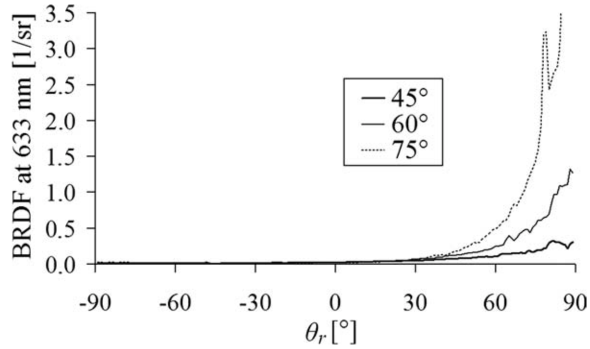

Figure 6 The effect of the angle of incidence on the BRDF in case of specimen B.

The magnitudes of the reflectance from the specimens at angles larger than $\theta_r = 30°$ were clearly in the order of their RMS-roughness and gloss. The highest values of reflectance were obtained for specimen M which had the lowest RMS-roughness as well as the highest measured gloss. The smallest values of reflectance were obtained for the specimen with the highest surface roughness (specimen B). All three specimens exhibited off-specular reflectance peaks at $\theta_r = 86–88°$ indicating that the magnitude of the shift from the specular angle was independent of the surface roughness, which is in accordance with the findings of Torrance et al.[17,18]

The effect of the angle of incidence

To study the effect of the incident angle on the light scattering, the bidirectional reflectance distribution functions for specimen B was determined at θ_i = 45°, 60°, and 75°. The off-specular reflectance phenomenon was observed for all three angles of incidence as shown in Figure 6. As the incident angle was increased the reflectance in this region was accentuated. For $\theta_i = 75°$ the off-specular reflectance was especially dominant and a prominent peak was detected approximately at $\theta_r = 79°$. The results were in accordance with the findings of Torrance et al.[17,18] in that the reflectance distributions from rough surfaces approaches that of a perfect diffuser when the angle of incidence comes close to the surface normal. As the angle of incidence is increased the off-specular reflectance becomes more dominant.

Although not apparent in Figure 6, the reflectance at angles between $\theta_r = 0°$ and $\theta_r = -50°$ was almost equal for the three specimens although the reflectance slightly decreased with increased angle of incidence. At angles smaller than $\theta_r = -50°$ the diffuse reflectance however increased with increasing angle of incidence.

The effect of color

In the previous study,[1] it was shown that the color, and in particular the lightness, L^*, of the specimens

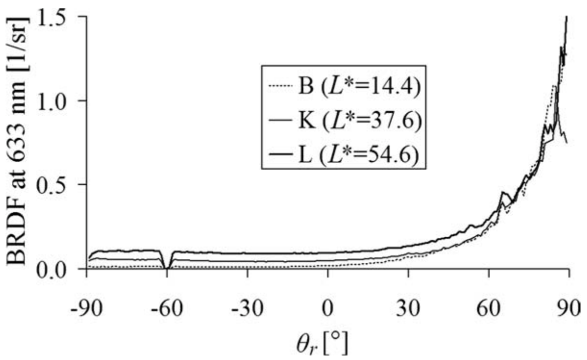

Figure 7 The effect of the lightness, L^* on the BRDF.

had a significant influence on both measured gloss and on the visual perception of gloss. To study the influence of color more in detail, the angular scattering distributions was determined for five specimens (B, I–L) varying in color (but mainly in lightness, L^*). The BRDFs for three of those specimens (B, K, and L) are shown in Figure 7. The diffuse reflectance clearly increased with increasing lightness of the specimens, L^*, due to the contribution of bulk scattering. No significant influence of the hue and chroma of the specimens was observed. Off-specular peaks were found also for these specimens though no significant difference in scattering between the specimens, in this region, could be discerned. Possibly, the nonsignificant influence of the color of the specimens on both the magnitude of the off-specular peak and the position of the peak was due to that the reflectance properties, at larger angles, were mainly determined by the texture of the specimens. As discussed in the previous study,[1] the five specimens can be expected to exhibit equal surface roughness as they were manufactured with identical processing conditions. The two remaining specimens (I and J) also conformed to the observed behavior concerning the off-specular peak and exhibited a magnitude of diffuse reflectance in between that of specimen B and K, which was in correspondence with their lightness, L^*. Specimens I and J were however excluded from Figure 7 to make the graph easier to read.

The CGF (CGF_s) of the five specimens was determined by means of eq. (4) using the reflectance at $\theta_r = 60°$ as a measure of specular reflectance. Those values of contrast gloss correlated well ($\rho = 0.95$) with the values of CGF obtained with a multi-angle spectrophotometer in the study described in Ref. 1 Also the correlation with the results from the ranking of the visually perceived gloss was satisfying ($\rho = 0.78$). As described in Ref. [1], a negative correlation was observed between the ranking of visually perceived gloss and measurements of specular gloss.

CONCLUSIONS

The determination of light scattering from a smooth and glossy polymeric surface resulted in a bidirectional reflectance distribution function typical for a surface of that kind. The distribution exhibited a sharp reflectance peak in the specular angle and a very slight amount of light was reflected diffusely. When measuring the reflectance from textured polymeric specimens, the amount of light reflected in the specular angle was not only significantly smaller compared to that of the smooth surface, but the peak was also broad and with a much less apparent maximum. However, most notable was the shift of the reflectance peak to an angle significantly larger than the specular angle.

The reflectance data obtained from the bidirectional reflectance distribution functions may be used to evaluate the contrast gloss. Several procedures for determining CGFs (CGFs) from the scatterometer measurements were assessed. Best correlation both with values of contrast gloss from multi-angle spectrophotometer measurements (CGF_m) and visual assessments of gloss was obtained when CGF_s were determined from dividing the reflectance in $\theta_r = 60°$, that is in the specular angle, with a mean value of the diffuse reflectance. The correspondence between the two methods for determining contrast gloss was in general very good.

Both the surface roughness and the color of the specimens had a significant influence on the bidirectional reflectance distribution function. Not surprisingly the amount of light reflected in the specular region decreased, as the surface roughness increased. The color, and the lightness, L^*, in particular, seemed to mainly influence the diffusely reflected light. The angle of incidence also had a major effect on the angle-resolved light scattering. As the incident angle was increased the amount of specularly reflected light also increased. At $\theta_i = 75°$ the reflectance peak was fairly sharp, however, as for all three evaluated incident angles, the maximum reflectance was shifted towards a much larger angle than the specular angle.

The deficiency of the conventional glossmeter to characterize gloss in a manner that relates to the visual perception of gloss on textured polymeric surfaces is supported by the findings presented here. Specular gloss is clearly a concept of less relevance for surfaces exhibiting off-specular peaks and for which the diffuse reflectance apparently also plays a major role for the visual impression of the gloss. Despite that considerably more advanced measurement equipment was used here, the results related very well to measurements of reflectance and measures of contrast gloss obtained from multi-angle spectrophotometer measurements.

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NOMENCLATURE

ABS	acrylonitrile-butadiene-styrene copolymer
AOI	angle of incidence
C	CIE standard illuminant, average daylight with a color temperature of 6770 K
CIE	Commission Internationale de l'Éclairage
CIELAB	CIE color coordinates
D65	CIE standard illuminant, average daylight with a color temperature of 6500 K
GU	gloss units
PC/ABS	polycarbonate/Acrylonitrile-butadiene-styrene copolymer
PP	polypropylene
BRDF	bidirectional reflectance distribution function [sr^{-1}]
CGF	contrast gloss factor
CGF_m	contrast gloss factor obtained from multi-angle spectrophotometer measurements
CGF_s	contrast gloss factor obtained from scatterometer measurements
dP_r	reflected power
$d\Omega$	angle of detection
g	gloss [GU]
L^*	CIELAB lightness
P_i	incident power
$R(\lambda)$	spectral reflectance of an object
R_s	specular reflectance captured by the detector of a glossmeter
ΔE^*	CIELAB total color difference
θ_i	Angle of incidence [°]
θ_r	Angle of reflectance [°]
ρ	Pearson correlation coefficient
λ	Wavelength of light [nm]

References

1. Ignell, S.; Kleist, U.; Rigdahl, M. Polym Eng Sci 2010, 50, 2114.
2. Hunter, R. S.; Harold, R. W. The Measurement of Appearance; Wiley: USA, 1987.
3. Hunter, R. S. US Bur Stand J Res 1937, 18, 19.
4. Judd, D. B.; Wyszecki, G. Color in Business, Science and Industry; Wiley: New York, USA, 1975.
5. ASTM D523. Standard Test Method for Specular Gloss, 1999.
6. Harrison, V. G. W. Definition and Measurement of Gloss; W. Heffer & Sons Ltd.: Cambridge, England, 1945.
7. Billmeyer, F. W., Jr.; O'Donnell, F. X. D. Color Res Appl 1987, 12, 315.
8. Meilgaard, M.; Civille, G. V.; Carr, B. T. Sensory Evaluation Techniques; CRC Press LLC: USA, 1999.
9. Ignell, S.; Kleist, U.; Rigdahl, M. Polym Eng Sci 2009, 49, 344.
10. Ariño I. Ph. D. thesis, Dept. of Materials and Manufacturing Technology, Chalmers University of Technology, Göteborg, Sweden, 2005.
11. Ignell, S.; Ariño, R.; Iannuzzi, G.; Kleist, U.; Rigdahl, M. Polym Eng Sci 2010, 50, 1527.
12. Byk-Gardner GmbH. Instrument Specification; Byk-Gardner GmbH: Germany, 2007.
13. Manual on Sensory Testing Methods, ASTM Special Technical Publication No. 434, Philadelphia, USA, 1968.
14. Schiff, T. D.; Stover, J. C.; Wilson, D. J.; Swimley, B. D.; Southwood, M.E.; Bjork, D. R. Proc SPIE 1993, 1753, 262.
15. ASTM E1392-90. Standard Practice for Angle Resolved Scatter Measurements on Specular or Diffuse Surfaces, 1991.
16. Stover, J. C. Optical Scattering Measurement and Analysis; McGraw-Hill Inc.: USA, 1990.
17. Torrance, K. E.; Sparrow, E. M.; Birkebak, R. C. J Opt Soc Am 1966, 56, 916.
18. Torrance, K. E.; Sparrow, E. M. J Opt Soc Am 1967, 57, 1105.