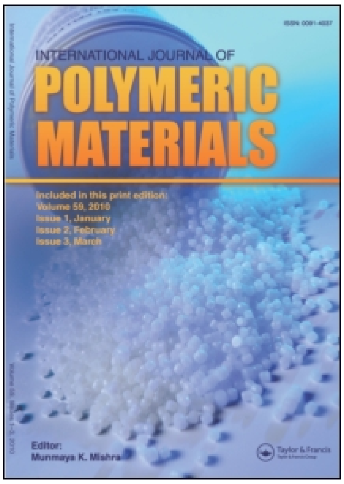

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The Influence of the Measuring/Viewing Angle on the Color of Injection-Molded Plastics

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A multi-angle spectrophotometer was used to measure the CIELab coordinates L^*, a^* and b^* in different angles relative to the incident light. The specimens used were acrylonitrile-butadiene-styrene injection-molded plaques in different colors and with different surface textures. Variations in the coordinates when changing the measuring angle depended on the color and the texture. In general, however, smooth (glossy) surfaces were measured to be darker and of higher chroma than textured surfaces and as the gloss of the surfaces decreased (due to texturing), the lightness of the surfaces increased and the absolute values of a^* and b^* decreased over the range of measuring angles (not too close to the specular reflection angle). A psychometric study involving a human test panel was used as a complement to the measurement. The agreement between the measurements and this study cannot be said to be satisfactory, unless the variation in the color coordinates was quite clear. Possible reasons are discussed.

Keywords color measurement, color perception, gloss, polymer, surface texture, viewing angle

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INTRODUCTION

For many products, the appearance or the visual impression is an important factor influencing the customer's choice. Taking the interior of a car as a typical example, it is obvious that it should convey a homogeneous and high-quality image. This may be a challenge for the design engineer in the case of adjacent components, differing in colorants of the materials, surface texture and shape, constituting the product. In addition, different light sources and changing the viewing conditions, e.g., viewing angle, may lead to perceived changes in color and gloss that could be different for different objects, due, e.g., to dissimilar surface textures.

Complexities of the above kind are not easily captured in a straightforward manner, partly because the gloss and color of an object often are assessed using standardized specimens, equipment, light sources and viewing conditions. Consequently, visual evaluation by trained personnel is a useful and often required complement to physical measurements. However, although such inspections are performed under rather strict conditions, some part of the perceived appearance can be disguised in such tests. This communication addresses only a limited part of the above complexity: the effect of the viewing angle on the measured color coordinates. Furthermore, polymeric surfaces are today often textured in order to give a more comfortable high-quality impression. To some extent, it is also investigated how a surface pattern will affect the viewing angle dependence of the color.

The color of the specimens is here described in terms of the CIELab color space concepts [1,2]. Conventionally, three rectangular coordinates are used; the lightness of the color L^*, an a^*-coordinate associated with the red-green axis and a b^*-coordinate associated with the yellow-blue axis [1,3–5]. The experimental (measured) results were compared with those from a corresponding psychometric study reflecting the human perception.

EXPERIMENTAL

Materials

The acrylonitrile-butadiene-styrene copolymer (ABS) used was an injection-molding grade from BASF AG (Ludwigshafen, Germany) denoted Terluran 967 K. It had a density of 1.05 g/cm^3 (ISO 1183) and a melt flow rate, MFR, (220°C/10 kg) of 14 g/10 min (ISO 1133).

Specimen Description

The study included primarily ten different ABS master plaques, manufactured by injection molding to the dimensions $138 \times 78 \times 2.7$ mm. These specimens were injection molded with a Krauss-Maffei machine with a clamping force of 250 tons and a screw diameter of 60 mm. The processing parameters followed the specifications provided by the material supplier and were kept constant for all compositions in order to avoid any possible influence on the appearance of the resulting moldings.

The surface ($138 \times 78\,mm^2$) of the plaques was in most cases divided into three areas, each of 46×78 mm, one for each specific surface texture. The textures considered here were denoted smooth or glossy (s), fine (f) middleI (mI), middleII (mII) and coarse (c). Each master plaque contained the smooth texture together with the textures fine and middleI, fine and coarse or middle II. In the last case the plaques only contained two textures, (see also Table 1). Optical micrographs of the textured surfaces (except the glossy surface) are shown in Figure 1.

Different colors of the plaques were used; a dark (two types), a half dark and a light color, described in more detail in Table 2. In order to compare these non-colorful plaques with a colorful one, a red master plaque was also included in the study.

Color and Gloss Measurements

The color and gloss measurements were initially carried out in four different directions, 0°, 90°, 180° and 270°, relative to the flow direction (parallel to the longest dimension of the plaques) when injection molding the specimens. Each experimental value is an average of five separate measurements. There was virtually no difference between the results from measurements carried out in the directions 0° and 180°. The same applied to the directions 90° and 270°. However, in some cases there were small but clear color differences between the 0° and the 90° directions, which perhaps can be associated with surface anisotropy. In the following, the results from the 90° directions are

Table 1: Description of the master plaques.

Notation of plaque	Color description	Texture
Bl1	Almost black	fine/middleI
Bl1 with metal flakes	Almost black	fine/coarse
Bl1 with metal flakes	Almost black	fine/middleI
Bl2	Almost black	middleII
GrA	Grey	fine/coarse
GrB	Grey	fine/middleI
GrC	Grey	middleII
BeA	Beige	fine/middleI
BeB	Beige	middleII
Re	Red	fine/middleI

Note: The plaques Bl1 and Bl2 do not have exactly the same color. Note that the plaques always contained an area with a smooth texture (not stated explicitly in the table).

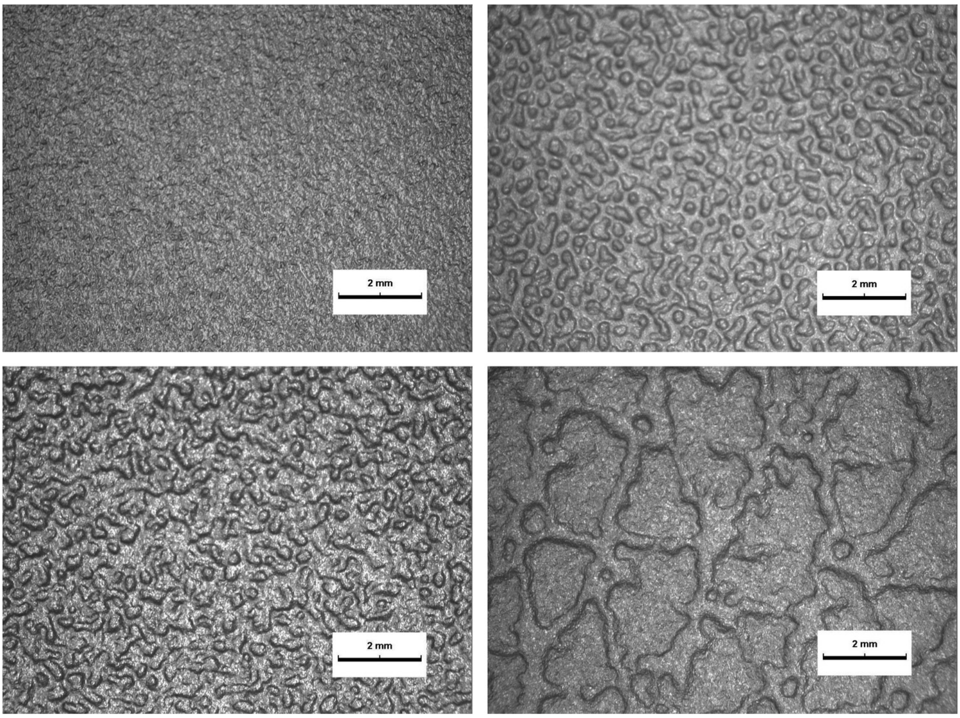

Figure 1: Optical micrographs of the used textures. Upper row: fine (left) and middleI (right). Lower row: middleII (left) and coarse (right).

used, since this direction corresponded to the angle used in the psychometric test.

The color in different viewing angles was measured with a MA68II multi-angle spectrophotometer from X-Rite, USA. This instrument contained a gas-filled tungsten lamp and the plaque was illuminated at an angle of 45° relative to the normal of the plaque (see Figure 2). With this instrument it was possible to measure the colour simultaneously at five different angles

Table 2: The color coordinates of the glossy surfaces of the plaques measured with a conventional spectrophotometer.

Notation of plaque	L^*	a^*	b^*
Bl1	12.2	−0.26	−1.23
Bl1 (with metal flakes)	12.7	−0.03	−0.80
Bl1 (with metal flakes)	13.7	−0.18	−0.95
GrA	38.5	1.83	2.09
GrB	38.6	1.79	1.99
GrC	38.7	1.84	2.04
BeA	64.5	0.88	12.56
BeB	64.7	0.90	12.53

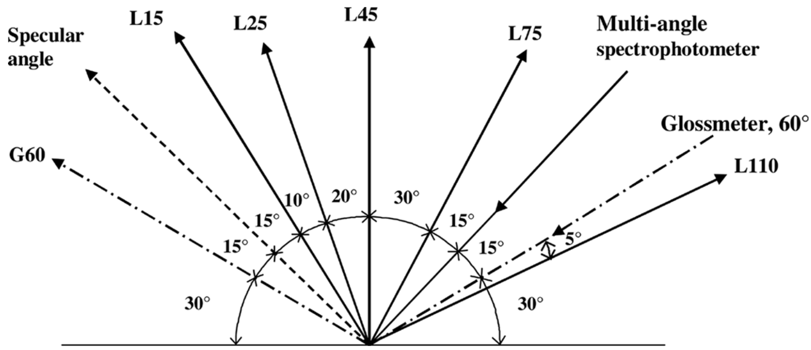

Figure 2: Schematic illustration of the incidence angles and the measuring angles for glossmeter (denoted G) and the multi-angle spectrophotometer (denoted L).

as indicated in Figure 2. The standard illuminant D65 was used and the results were given in terms of the CIELab rectangular coordinates. The measured area was 12 mm in diameter.

For the purpose of comparison and completeness, the color coordinates of the glossy regions of the plaques were also measured using a conventional spectrophotometer with a d/8° illumination/viewing geometry. The measurements were performed in the specular excluded mode with the standard illuminant D65 and the CIE 10° observer. The results are given in Table 2.

The gloss of the plaques was determined using a micro-TRI-gloss UR-1089 equipment from BYK-Gardner, Germany, according to ASTM D523. The instrument had an accuracy of 0.1 GU (gloss units) [6]. The angles of incidence and reflection (measuring) were both kept at 60° relative to the normal of the plaques. The reproducibility of the gloss measurements in the range 0 to 10 GU was ±0.2 GU and above 10 GU about ±0.5 GU [7].

The Psychometric Study

A psychometric study was carried out with the aim to relate the results from the physical measurements to human perception variations. The same type of master plaques as before were used and colors considered were Bl1, Bl2, GrA, GrB, GrC, BeA and BeB. The test was performed at Volvo Car Corporation and included twelve experienced persons, both men and women, working with color matching.

The experimental set-up for the experiment is schematically shown in Figure 3. Two master plaques to be compared were placed in a MacBeth Spectralight light booth, from GretagMacbeth, Germany, with the illuminant D65. The observers were put in the same position in front of the light box (see figure) and a screen was placed between the observer and the light

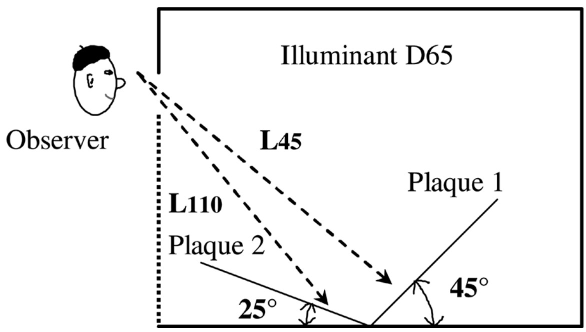

Figure 3: Sketch of the light booth and the viewing conditions during the visual investigation.

booth (dotted line in Figure 3) in order to keep the viewing angle relatively constant. The difference in appearance due to the viewing angle was evaluated as follows: Two master plaques, with the same color and texture, were placed next to each other. They were inclined in such a way that one had a viewing angle at 90°, corresponding to the measuring angle L45 in Figure 2 and the other with a viewing angle approximately corresponding to the measuring angle L110.

The observers were asked to make 15 different comparisons. They were told to compare the plaques in the light booth and answer if they could see if one of the master plaques was greener, redder, bluer, more yellow, lighter and/or glossier than the other one by answering 1 (corresponding to L45) or 2 (corresponding to L110). Figure 4 shows a part of the questionnaire. All comparisons were performed in approximately 30 minutes.

Comparison 1

________	greener than	________
________	redder than	________
No difference		
________	bluer than	________
________	yellower than	________
No difference		
________	lighter than	________
________	darker than	________
No difference		
________	glossier than	________
No difference		

Figure 4: Answering part of the questionnaire used in the psychometric test.

Table 3: Gloss values, measured at 60°, for the different textures of the grey master plaques.

Texture	Gloss, GU
Smooth	93.8
Fine	4.3
MiddleI	1.4
MiddleII	1.6
Coarse	2.0

RESULTS AND DISCUSSION

Gloss of the Master Plaques

The smooth surfaces of the master plaques exhibited as expected a very high gloss, measured at 60°, typically in the range 90–95 GU. The textured surfaces had more or less the same gloss, regardless of the color, for the same type of texture. The incorporation of metal flakes in the polymer matrix had no substantial effect on the measured gloss at 60°. Table 3 shows typical values of the gloss level for the different textures, in this case for the grey master plaques. Obviously, texturing of the surface led, as expected, to a large decrease in the gloss level, which mainly is to be associated with a decrease in the coherent (specular) component of the reflected light [8].

The Lightness Measured in Different Measuring Angles

Figure 5 shows the general change in the lightness L^* with increasing measuring angle for plaques of light (beige), half dark (grey) and dark (almost black) colors. The measurements were made on the fine-textured

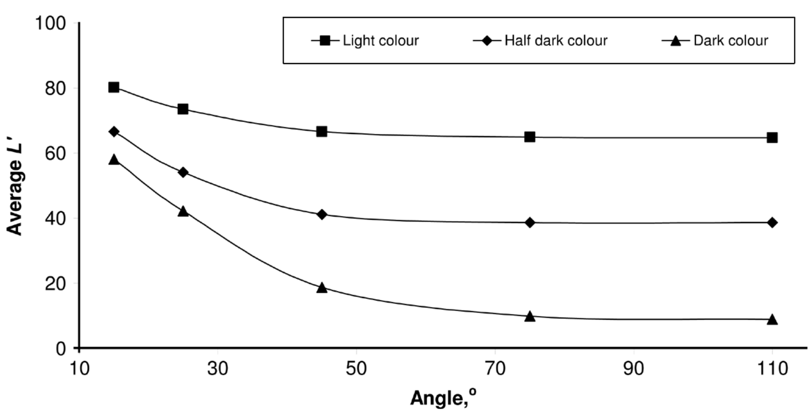

Figure 5: The lightness as a function of the measuring angle for plaques of light, half dark and dark colors. The measurements were made on the fine-textured area.

area. Note that the angle 0° corresponds to the angle of specular reflection. The general behavior was that at measuring angles near the specular reflection, the plaques exhibited a higher lightness, i.e., as the angle increased the lightness decreased [9] and, more or less, levelled out at measuring angles greater than 70°. The change in lightness was more pronounced for the dark specimens whereas the corresponding change for the other two colors was quite small in the region between 45° and 110°. Note that a well trained colorist can detect difference in lightness of the order of 0.2–0.3 (diffuse illumination) [10] which indicates that the changes shown in Figure 5 should be quite visible.

The texture also had an effect on the L^*-value and its dependence on the measuring angle as is shown in Figure 6 in the case of the grey plaques. The same trend as in Figure 5 is revealed and the smallest variation with the measuring angle was noted with the smooth region. At lower angles, the L^*-value increased sharply with decreasing angle in the case of the fine texture. It cannot be excluded that a similar increase can take place also for the smooth area (or the other textures) but then at angles closer to the specular angle. At angles greater than 75°, the lightness was virtually independent of measuring angle, but depended on the texture. The smooth area was the darkest and then L^* increased in approximately the same order as the gloss decreased (cf Table 2). Qualitatively, this is not unexpected, it is in agreement with the perceived impression and can be associated with an increased importance of the "dilution" effect of the diffuse reflection for matte (and rougher) surfaces [11,12]. A similar type dependence on the measuring angle as shown in Figure 6 was also noted for the plaques of the other colors.

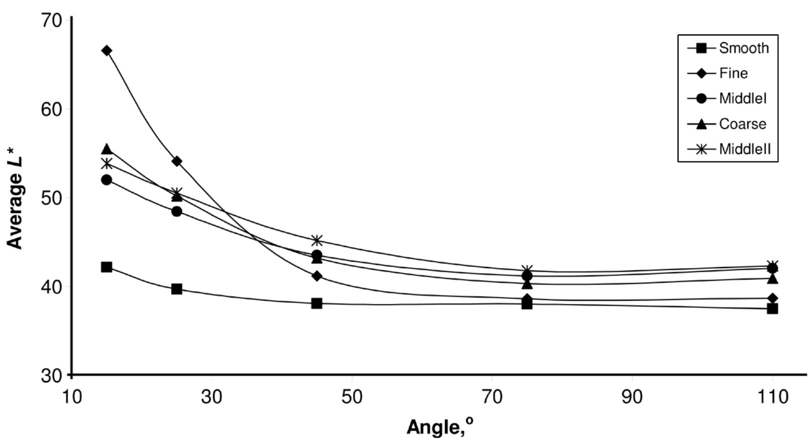

Figure 6: The lightness as a function of the measuring angle for the different textures on the grey plaques.

It may be noted that the L^*-value measured at higher measuring angles for the smooth surface was not too different from that determined using the conventional spectrophotometer (Table 2 and Figure 6).

The a^*- and b^*-coordinates at Different Measuring Angles

Both a^* and b^* depended on the measuring angle and the corresponding a^*- and b^*-curves could exhibit different shapes for different colors and textures. In general, b^* varied more with the measuring angle than a^* did. The change in b^* (nonchromatic plaques) over the range of measuring angles was typically 0.3 to 2, depending on the color and texture, whereas the corresponding change in a^* was 0.1 to 0.5. Both coordinates could exhibit significant variations over the measured range of angles, but in most cases the variations were more pronounced as the measuring angle approached specular reflection. Figure 7 shows the angle dependence of the a^*-coordinate for the different textures on the grey master plaques. It may be mentioned that, in diffuse illumination, practical experience indicates that color differences of the order of $\Delta a^* = \Delta b^* = 0.10–0.15$ are visible.

As shown in the graph, the a^*-value for the smooth surface was higher than for the textured surfaces, i.e., having a higher chroma. Also the b^*-coordinate appeared to follow this pattern; see Figure 8 in the case of the beige plaques. In a sense, all master plaques exhibited a similar behavior; the smooth surfaces appeared darker and of higher chroma compared to the textured surfaces [5]. The color coordinates corresponding to the fine texture were the ones closest to those for the smooth region (at measuring angles not too close to the specular reflection) and the coarser textures (lower gloss) were less chromatic over the range of measuring angles.

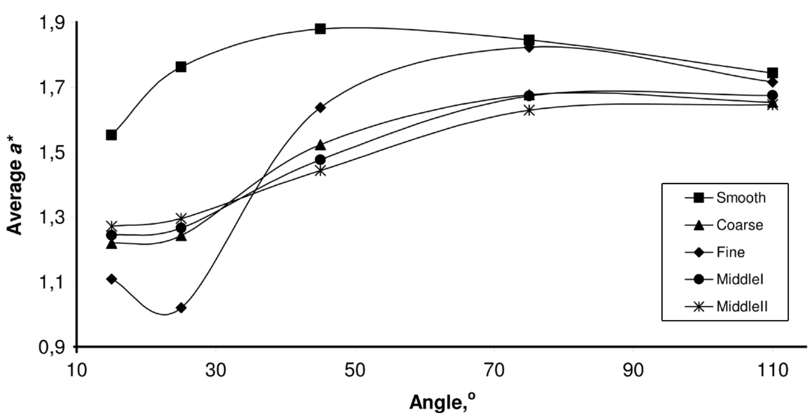

Figure 7: The a*-coordinate as a function of the measuring angle for the different textures on the grey plaques.

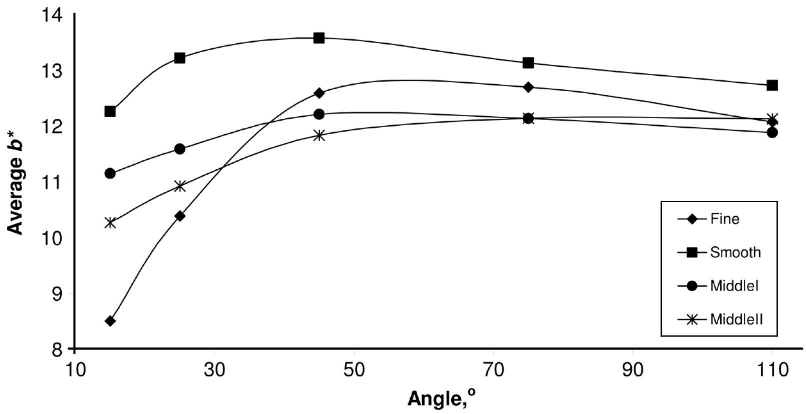

Figure 8: The b*-coordinate as a function of the measuring angle for the different textures on the beige plaques.

The majority of the colors considered here were nonchromatic. The included chromatic color (red) exhibited an even larger dependence of a^* and b^* on the measuring angle as shown in Figure 9.

It should once again be noted to that the detailed shape of the a^*- and b^*-curves shown above depends on the color, the texture and the structural composition of the material (as reflected by its scattering and absorption properties) and may thus be difficult to predict. The importance of the structure of the material can here be illustrated by comparing the b^*-values of the dark plaques containing metal flakes with the corresponding values for the unfilled specimens. For the fine textured region, the unfilled plaques appeared more yellow (according to the measurements), with increasing measuring angle, i.e., the b^*-value increased. The flake-containing plaques

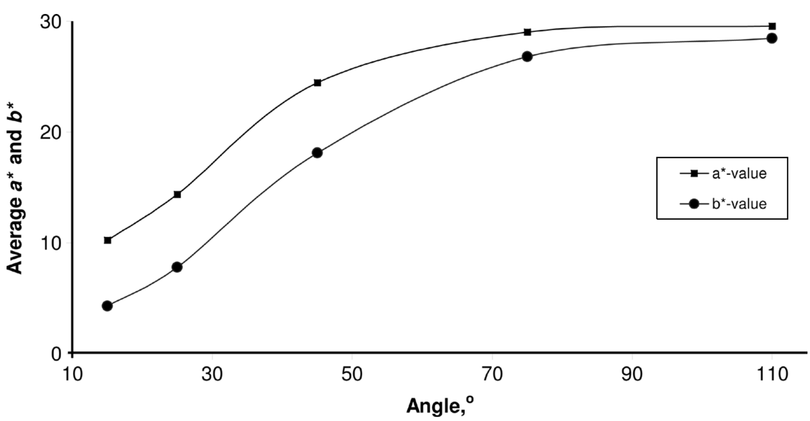

Figure 9: The a*- and b*-coordinates as functions of the measuring angle for the fine texture on the red plaques.

(same texture) exhibited the opposite behavior; b^* decreased with increasing angles and the plaques were measured to become more blue.

Comparison with the Psychometric Test

First it should be stressed that the results of the comparison should be viewed upon with some care; the number of participants in the test panel was limited (twelve persons) and the illumination conditions in the instrument and the light booth were not the same (the latter being more of the diffuse type). The observations reported are, of course, restricted to the specimens used here.

With regard to the lightness, the finely textured area will be considered separately and then the other textures. With the fine texture, the result from the psychometric test was in a sense straightforward, the 45°-surfaces were considered to be darker by the majority of the panel (Figure 10). This is opposite to the measured result, cf Figure 5. Admittedly, the change in lightness when increasing the measuring angle from 45° to 110° is quite modest (Figure 5) in the case of the grey and the beige colors, but this is not the case for the dark plaques. A contributing factor may be that the 45° surface appeared glossier than 110° surface and smooth (glossy) surfaces can appear darker than matte ones [9]. The psychometric study indicated that this was the case for the two dark colors, but for the grey and the beige plaques no great difference in gloss was, in most cases, observed between the two surfaces. This might be associated with the difficulty to perceive reflections from a light surface compared to a dark surface.

For the middleI, the middleII and the coarse textures, the dark plates were perceived to be lighter in the 45° viewing angle, which agreed with the measurements. For the plaques in the lighter colors, however, the opposite pattern of behavior was noted with these textures, i.e., a result similar to that encountered with the fine texture.

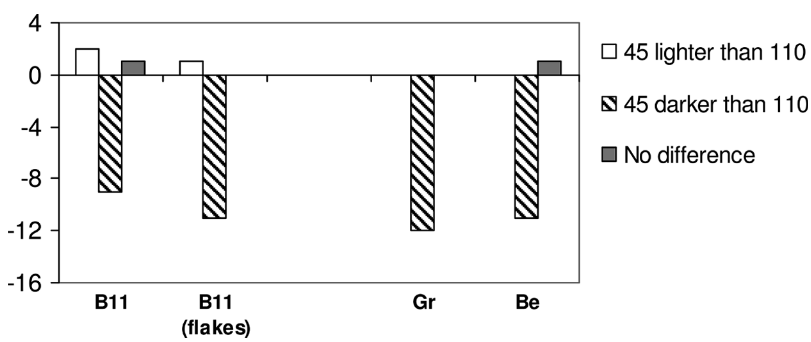

Figure 10: Results from the psychometric study showing that all master plaques with the fine texture were perceived darker in the 45° viewing angle.

The perceived difference in color between the viewing directions 45° and 110° for the textured regions (excluding the smooth area) will be discussed separately for the dark, the half dark and the light master plaques. The measured a^*-coordinate of the dark plates decreased, when the measuring angle increased from 45° to 110°, by an amount less than 0.2. The only exception was for the middleI texture in color Bl1 which exhibited a corresponding decrease of about 0.3. This corresponded quite well to the results from the psychometric test in which the majority of the observers answered "No difference" in redness/greenness between the two viewing directions. The b^*-coordinate for the dark plates could vary up to 1 CIELab unit over the range given by the angles, which should be visible. The observers however had, in general, difficulties in assessing clear differences along the blue/yellow axis. Only in one case, color Bl1 (with flakes) and with the fine texture, was there a good correlation between the perceived impression and the measurements (the area became more blue with increasing viewing angle). This was also the area that exhibited the greatest change in b^* when changing the viewing angle.

In case of the half dark (grey) surfaces, the measurements indicated a change in a^* of about 0.2 between the measuring angles 45° and 110° and a corresponding variation in b^* of less than 0.2. It may then not be surprising that the judgments from the observers were quite scattered or that no differences could be detected.

The a^*-coordinate decreased with 0.2 to 0.4 units over the measuring range (45° to 110°) for the plaques in the light (beige) color. Thus the plaques should have been perceived as more green at higher measurement angles. This was however not in agreement with the psychometric result, since many observers perceived the 45° surface as greener (about as many could not detect any difference at all). See Figure 11.

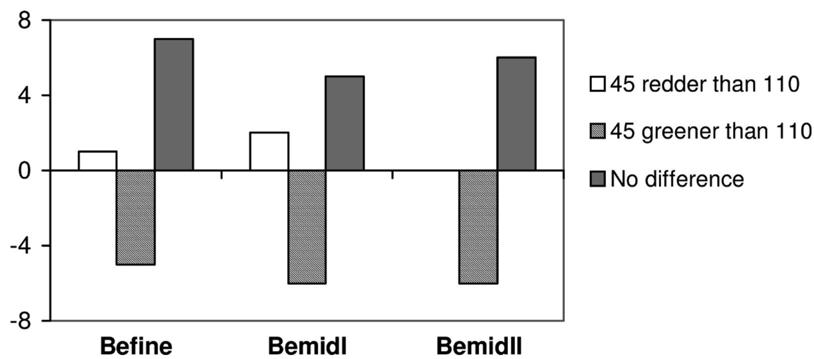

Figure 11: Results from the psychometric study showing the variation along the red/green axis for the beige master plaques when changing the viewing angle between 45° and 110°.

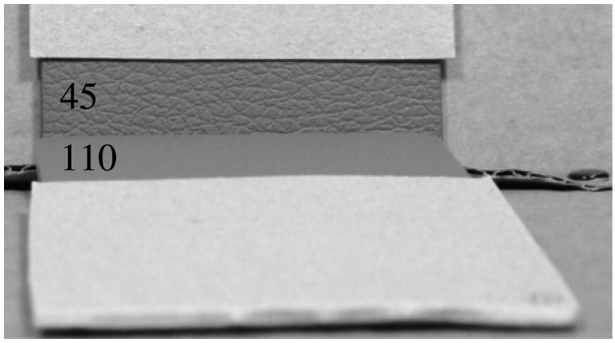

Figure 12: Appearance difference between two grey master plaques, both with the coarse texture, oriented in the two different viewing angles.

The b^*-coordinate for the beige plaques was shown in Figure 5. The maximum variation in the coordinate over the range corresponding to the viewing angles was of the order of 0.5 units. Most observers had, however, difficulties in detecting any difference with regard to changes in the blue/yellow proportions.

Summarizing to some extent, the physical measurements with the spectrophotometer pointed in most cases to changes in the CIELab coordinates as the measuring angle was altered. The corresponding variation in the perceived appearance were harder to assess and thus, in a sense, difficult to confirm. There could be several reasons (and room for improvements) for this. The changes in the coordinates were in some cases not very pronounced and the difference in illumination conditions and the limited number of observers have already been mentioned. Studying textured surfaces in the light booth may also present a problem. Figure 12 is a close-up of the arrangement in the light booth when examining the grey plaques (coarse texture). The texture itself appeared differently in the two viewing angles and it might be that this change "overwhelmed" or affected the perceived changes in color and lightness.

A Case Study

A car component in color Bl1 (with metal flakes and with the middle I texture) was examined in more detail during the course of a development project. The component appeared redder at larger viewing angles than a reference component did, but a conventional spectrophotometer measuring at only one angle (45°) could not detect any significant color difference between the two. The reference did not exhibit any appreciable change in appearance when changing the viewing angle. Both components were examined with the multi-angle spectrophotometer. Figure 13 shows the corresponding a^*-coordinates as function of the measuring angle.

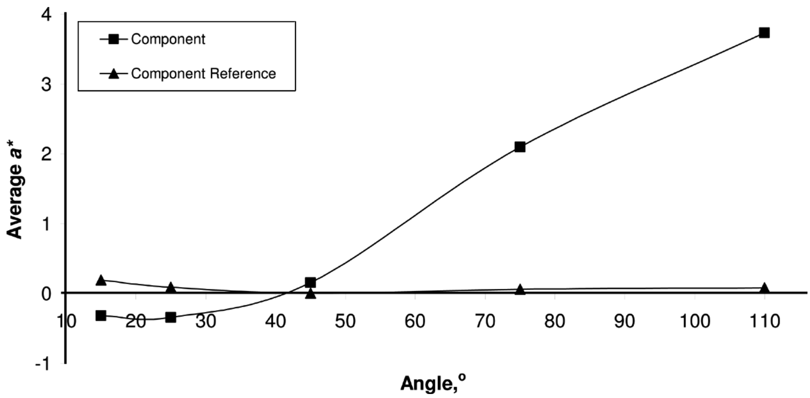

Figure 13: The a*-value as a function of the measuring angle for the component and the reference.

The a^*-values were nearly the same at 45° but the color coordinate for the component then increased strongly at larger measuring angles and at 110° the component measured to be almost 3.7 units redder than the reference. This change was substantially more pronounced than those encountered with the corresponding plaques described earlier and easily detected by the eye. The a^*-coordinate for the reference exhibited a quite small dependence on the measuring angle, Figure 13.

The component also displayed a rather large increase in the b^*-value as the measuring angle increased, but this change was smaller than that of the a^*-coordinate. In principle, this color change associated with measuring angle should have been seen by the observers and expressed in terms of "the component is more yellow than the reference", but it was not. One reason might be that the redness was so dominant in this case that the change in the blue/yellow balance could not be detected. The corresponding change in the b^*-value was significantly smaller for the reference. The lightness curves of the component and the references were quite similar when varying the measuring angle.

CONCLUSIONS

It is clear that the physical measurements showed that the CIELab coordinates varied with changes in the measuring directions and the variation in the coordinates were strongest in measuring directions closer to the specular reflection of the light. The detailed variation of the coordinates with the measuring angle depended on the color and the texture of the specimen. In general, however, smooth surfaces were measured to be darker and of higher chroma than the textured surfaces, and as the gloss of the surfaces decreased (due to the texturing), the lightness of the surfaces increased and the absolute values of a^* and b^* decreased over the range of measuring angles (not too close to the specular reflection angle). The latter statements should be regarded as tendencies only. For all colors and textures covered in this study, the a^*-coordinate was less sensitive to the measuring direction than the b^*-value.

The agreement between the measurements and the limited psychometric test cannot be said to be satisfactory, unless the variation in the color coordinates was quite clear. There may be several reasons for this. First, the variation in the color coordinates was not very large, in some cases it was even below what could be expected to be visually detected. Moreover, the illumination conditions in the spectrophotometer were not the same as in the light booth where the psychometric test was performed. The observers had difficulties in distinguishing lightness and gloss, which could have influenced their judgment. The textures did not appear in the same way in the two viewing angles which also might have affected the comparison. It can furthermore not be excluded that reflections from the two surfaces interact in some manner which could affect the visual comparison.

Thus, the measuring technique used here has certainly an interesting potential in further quantifying what we often call the "appearance" of a product, but more studies are required to establish the usefulness and limitations of the technique with regard to its ability to mimic human perception.

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