*Materials Transactions*, Vol. 45, No. 4 (2004) pp. 1027 to 1032
Special Issue on Frontiers of Smart Biomaterials


# Experimental Relationships between Surface Roughness, Glossiness and Color of Chromatic Colored Metals

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This paper describes the establishment of an evaluation method for metal surface texture. The evaluation parameters used for surface texture were roughness, glossiness and color. Seven sample materials were studied: aluminum alloys (A2017, A5052), stainless steel (SUS304) and copper alloys (tough pitch copper C1100, brass C2801, phosphor bronze C5191 and nickel silver C7541). The surfaces of all specimens were polished using waterproof abrasive papers. The correlation of the surface texture parameters for all specimens was investigated experimentally. The surface roughness of specimens was evaluated using the arithmetical mean roughness "*Ra*". The method for evaluating surface color was assessed by using CIELAB color space. The CIELAB color space is one of a uniform color space defined by CIE (Commission Internationale de l'Eclairage) in 1976. The results indicated that as surface roughness value "*Ra*" decreased, as the glossiness value "*Gs*(60°)" increased exponentially. The lightness value "$L^*$" of the CIELAB color space decreased, as surface roughness value "*Ra*" decreased. Thus, the relationship between the lightness value "$L^*$" and surface roughness value "*Ra*" showed an inverse correlation with the glossiness value "*Gs*(60°)" and surface roughness value "*Ra*". Moreover, the surface color showed that the blue hue increased, as the surface roughness value "*Ra*" decreased for all seven types of materials.

(Received December 11, 2003; Accepted March 12, 2004)

***Keywords:*** *surface texture, roughness, glossiness, color*

## 1. Introduction

The sensory parameters that characterize the surface textures of object surfaces can be described as "roughness," "glossiness," "sense of depth," etc. In recent years, surface texture has been attracting attention as a very important factor in characterizing the image of a product.[1)] However, the indication of surface textures in the manufacturing of industrial products merely illustrates the surface roughness and the process method symbols. The evaluation of surface texture during the manufacturing process depends on visual inspections in most cases. In order to improve the reproducibility of surface quality, it is necessary to establish a quantitative evaluation system for surface texture.

Conventional studies related to surface texture are almost all based on the evaluation of sensory intensity.[2,3)] Most quantitative studies evaluate roughness physically.[4–7)] The authors have indicated in a previous report that a combination of the surface roughness and glossiness are effective surface texture parameters for aluminum alloy A5052.[8)]

In the present study, an experimental investigation is made of an overall method for evaluating surface texture from the relationship among surface roughness, glossiness, and surface color. Seven conventional metallic materials are examined for checking the surfaces for these factors.

## 2. Experiment Method

### 2.1 Test Specimen Materials and Surface Roughness

The materials used in this study are aluminum alloys (A2017 and A5052), a copper alloy (nickel silver C7541) and a stainless steel (SUS304) for achromatic colored metals, and a tough pitch copper C1100, a brass C2801 and a phosphor bronze C5191 for chromatic colored metals. The chemical compositions of these materials are shown in Table 1. The heat-treatment condition for SUS304 according to JIS G 4303 is shown in Table 2. The major test material of aluminum alloys used in this study is A5052. Al-Cu type aluminum alloy A2017 is used for a comparison. Phosphor bronze C5191 is a copper alloy having the same type of surface color as the tough pitch copper C1100.

Test specimens were square 70 mm × 70 mm. The surface of the specimens were polished using waterproof abrasive paper so that the arithmetical mean roughness, *Ra*, was in the range of $0.03\,\mu m < Ra < 1.00\,\mu m$. During the polishing process, two types of polishing directions were used: unidirectional and multidirectional. The surface roughness of the test specimen was measured with a stylus profilometry-type instrument (SV624, Mitutoyo Corporation). The measuring condition was set so that the cut-off value was 0.8 mm with a measuring length of 4 mm.

The central portion of the test sample was measured in the direction orthogonal to the polishing direction at three places with an interval of about 5 mm for the test specimens polished in the unidirectional direction. The central portion of the multidirectionally polished test specimens was measured in four directions: 0°, 45°, 90°, and 135°. The average was then taken to be the surface roughness for each test sample.

### 2.2 Glossiness and Surface Color Measurement Methods

Glossiness was measured using a mirror-TRI-gloss meter (BYK-Gardner). The gloss meter light source used was a

Table 1 Chemical compositions.

| Materials | Concentrations (mass%) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Al | Si | Cu | Pb | Fe | Sn | Zn | Mn | Cr | Mg | P | Ti | C | S | Ni |
| A2017[*1] | Residual | 0.20 to 0.8 | 3.5 to 4.5 | — | 0.7 max. | — | 0.25 max. | 0.40 to 1.0 | 0.10 max. | 0.40 to 0.8 | — | 0.15 max. | Zr+Ti 0.20 max. | | |
| A5052[*1] | Residual | 0.25 max. | 0.10 max. | — | 0.40 max. | — | 0.10 max. | 0.10 max. | 0.15 to 0.35 | 2.2 to 2.8 | — | — | — | — | — |
| C1100[*2] | — | — | 99.90 min. | — | — | — | — | — | — | — | — | — | — | — | — |
| C2801[*2] | — | — | 59.0 to 62.0 | 0.10 max. | 0.07 max. | — | Residual | — | — | — | — | — | — | — | — |
| C5191[*3] | — | — | — | 0.05 max. | 0.10 max. | 5.5 to 7.0 | 0.20 max. | — | — | — | 0.03 to 0.35 | Cu+Sn+P 99.5 min. | | | |
| C7541[*3] | — | — | 60.0 to 64.0 | 0.10 max. | 0.25 max. | — | Residual | 0 to 0.50 | — | — | — | — | — | — | 12.5 to 15.5 |
| SUS304 | — | 1.00 max. | — | — | — | — | — | 2.00 max. | 18.00 to 20.00 | — | 0.045 max. | — | 0.08 max. | 0.030 max. | 8.00 to 10.50 |

[*1]JIS H 4000, [*2]JIS H 3100, [*3]JIS H 3110

Table 2 The condition for heat-treatment for SUS304[*1].

| Symbol of grade | Solution treatment °C |
|---|---|
| SUS304 | 1010 to 1150 rapid cooling |

[*1]JIS H 4303

white light source with the spectral characteristics of a CIE standard light source C. In the present experiment, glossiness was measured with a light-source incident angle of 60°. The measurement position, the direction, and the number of measurements for test specimens polished in both unidirectional and multidirectional directions were similar to those used for the surface roughness measurements. The average value for the glossiness for each test specimen was employed. The opening angle of the receptor was $\alpha_2 = 4.4^\circ \pm 0.1^\circ$ in the incident plane and $\beta_2 = 11.7 \pm 0.2^\circ$ in the orthogonal plane.

The spectral colorimeter method was used for the surface color, and the measurement was made with the spectral colorimeter CM2600d (Minolta, Co. Ltd.). The colorimeter light source was similar to the above. The measurement surface consisted of a circle having a diameter of 3 mm. The measurements were done at totally 5 positions: the central portion and two orthogonal directions about 5 mm away from the center. The surface color was then averaged.

The method for evaluating surface color was assessed by using CIELAB color space (JIS Z 8729:1994). The CIELAB color space is one of a uniform color space defined by CIE (Commission Internationale de l'Eclairage) in 1976. This is a color space in which the apparent sensory color difference and the difference in geometrical distance between colorimetric values on the coordinates of chromaticity are equal. The CIELAB color space is based on three stimulating values $X$ (Red), $Y$ (Green), and $Z$ (Blue) of the $XYZ$ color system (JIS Z 8701:1999).

## 3. Results and Discussion

### 3.1 Relationship between Surface Roughness and Glossiness

The relationship between arithmetical mean roughness $Ra$ and glossiness $Gs(60^\circ)$ for achromatic and chromatic colored metals is shown in Fig. 1(a) and Fig. 1(b). Figure 1 shows that there is a tendency for the glossiness to become higher as the $Ra$ becomes smaller regardless of the type of test material or the direction of the roughness. In particular, when $Ra$ becomes smaller than about 0.2 µm, the glossiness increases rapidly. When the roughness interval is small compared to the wavelength of the light, the diffused reflection is considered to affect the incident light at the roughness plane. In other words, since the wavelength range of the light source used to measure the glossiness is in the visible region of 0.38 to 0.78 µm, in a region where $Ra$ is less than about 0.2 µm, the specular reflection occurs irregardless of the roughness.

### 3.2 Relationship between Surface Roughness and Surface Color

For an incident angle of 60°, the specular reflectance 10 (%) of the reference plane (glass surface of refractivity 1.567) in the gloss meter was $Gs(60^\circ) = 100$ (%). Thus, by multiplying the glossiness value, $Gs(60^\circ)$ by $10^{-1}$ the specular reflectance with an incident angle of 60° could be calculated. The effect of arithmetical mean roughness $Ra$ on lightness $L^*$ (shown by the lightness of a color in the CIELAB color space) is shown in Fig. 2(a) and that on specular reflectance $Gs(60^\circ)/10$ is shown in Fig. 2(b) for the achromatic colored metals. Similar figures are shown in Fig. 3 for the chromatic colored metals. It is seen from Fig. 2(a) and Fig. 3(a) that the lightness $L^*$ also becomes higher when $Ra$ becomes larger regardless of the difference in materials. Furthermore, the lightness $L^*$ value of A2017 was the highest among A2017, A5052, C7541 and SUS304. Its color looks light color in comparison with A5052, C7541 and SUS304. All materials showed a similar trend regardless of the

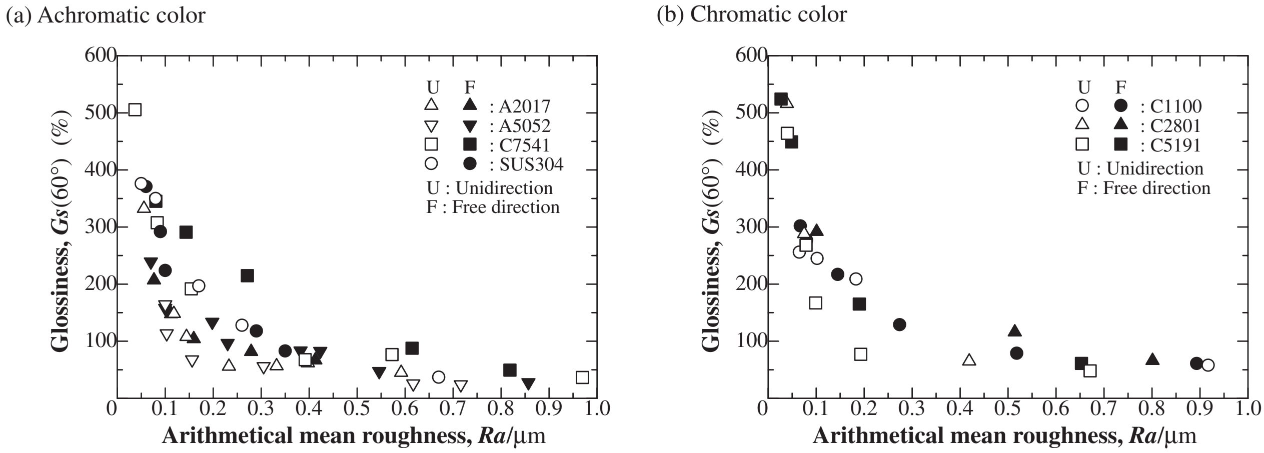


Fig. 1 Relationship between arithmetical mean roughness $Ra$ and glossiness $Gs(60°)$: (a) achromatic color and (b) chromatic color.

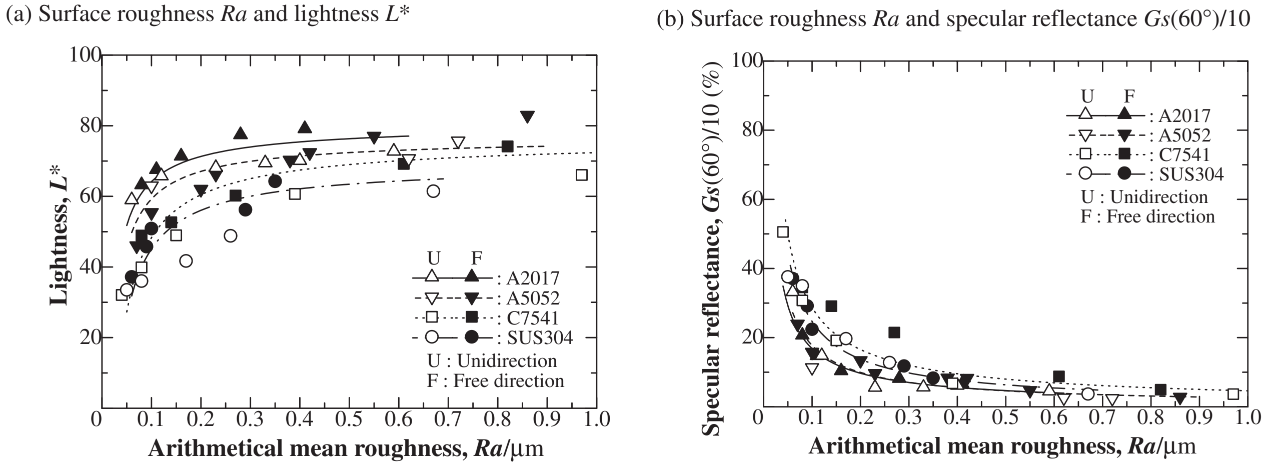


Fig. 2 Effect of arithmetical mean roughness $Ra$ on lightness $L^*$ and specular reflectance $Gs(60°)/10$ for achromatic colored metals: (a) surface roughness $Ra$ and lightness $L^*$ and (b) surface roughness $Ra$ and specular reflectance $Gs(60°)/10$.

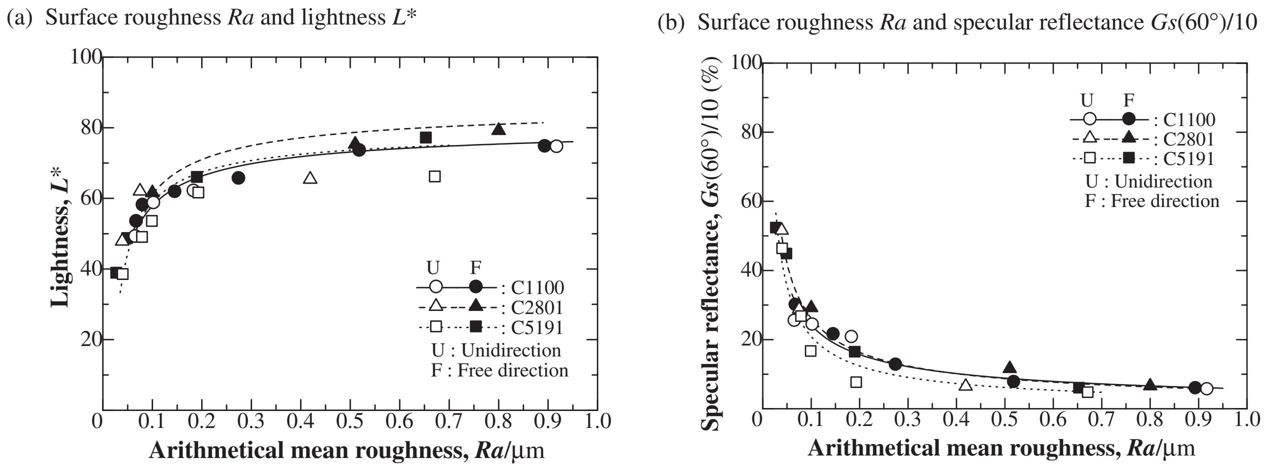


Fig. 3 Effect of arithmetical mean roughness $Ra$ on lightness $L^*$ and specular reflectance $Gs(60°)/10$ for chromatic colored metals: (a) surface roughness $Ra$ and lightness $L^*$ and (b) surface roughness $Ra$ and specular reflectance $Gs(60°)/10$.

roughness direction. And also, the lightness $L^*$ indicated an inverse correlation between specular reflectance $Gs(60°)/10$ and $Ra$ at a reflectance of 40% as the boundary. That is because the glossiness consists of specular reflection light components, whereas the lightness $L^*$ that indicates the lightness of the surface color is calculated from the diffused reflection light components. Thus, the correlation of $Ra$ versus $L^*$ or $Gs(60°)/10$ was calculated and displayed as the regression curves by the least-square method. In Eq. 1 and Eq. 2, the regression curves for the correlation of $Ra$ versus

$Gs(60°)/10$ are expressed as.
Achromatic color:

$$\begin{aligned} &\text{A2017: } y = 2.689 \times x^{-0.797} \\ &\text{A5052: } y = 2.576 \times x^{-0.838} \\ &\text{C7541: } y = 4.614 \times x^{-0.794} \\ &\text{SUS304: } y = 3.537 \times x^{-0.844} \end{aligned} \quad (1)$$

Chromatic color:

$$\begin{aligned} &\text{C1100: } y = 5.758 \times x^{-0.622} \\ &\text{C2801: } y = 5.428 \times x^{-0.683} \\ &\text{C5191: } y = 3.636 \times x^{-0.760} \end{aligned} \quad (2)$$

Equation 3 and 4 are the regression-curves of $Ra$ versus $L^*$ for achromatic and chromatic color, respectively.
Achromatic color:

$$\begin{aligned} &\text{A2017: } y = -2.689 \times x^{-0.797} + 81 \\ &\text{A5052: } y = -2.576 \times x^{-0.838} + 77 \\ &\text{C7541: } y = -4.614 \times x^{-0.794} + 77 \\ &\text{SUS304: } y = -3.537 \times x^{-0.844} + 69.8 \end{aligned} \quad (3)$$

Chromatic color:

$$\begin{aligned} &\text{C1100: } y = -5.758 \times x^{-0.622} + 82 \\ &\text{C2801: } y = -5.428 \times x^{-0.683} + 87.3 \\ &\text{C5191: } y = -3.636 \times x^{-0.760} + 79.8 \end{aligned} \quad (4)$$

The value $x$ in Eq. 1 to 4 expresses the arithmetical mean roughness $Ra$. The value $y$ expresses $Gs(60°)/10$ in Eqs. 1 and 2 but expresses lightness $L^*$ in Eqs. 3 and 4. Equations 3 and 4 are respective symmetric functions of Eqs. 1 and 2 for y-axis direction, and the arbitrary constants are added in these functions. From Eq. 3 and Eq. 4, the correlation coefficients of $Ra$ and $L^*$ are 0.731 for A2017, 0.890 for A5052, 0.806 for C7541, 0.717 for SUS304, 0.965 for C1100, 0.716 for C2801 and 0.820 for C5191. A high value was indicated for each material. Thus, when either the gloss or lightness is measured for the test specimen surface, the other can be estimated by these correlations.

Figure 4 shows the $a^*b^*$ chromaticity diagram of the CIELAB color space. The positive direction of the horizontal axis indicates a red hue ($+a^*$) and the negative direction indicates a green hue ($-a^*$). The positive direction of the vertical axis indicates a yellow hue ($+b^*$) and the negative direction indicates a blue hue ($-b^*$): The color spectrum on the circumference having a center at the origin of coordinates is also shown. The absolute value of the distance from the origin of coordinates to the colorimetric value indicates the chromaticity that expresses the intensity of the color, and the greater the distance, the higher the chromaticity.

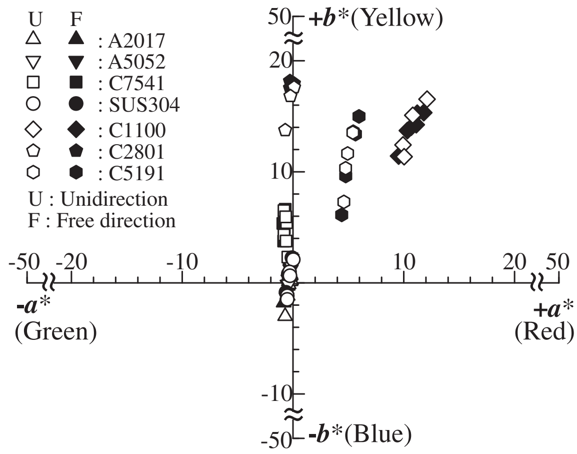


Fig. 4 $a^*$, $b^*$ chromaticity diagram.

It could be said from Fig. 4 that A2017, A5052, 7541 and SUS304 are located near the origin of the coordinates. In other words, chromaticity is low for A5052, C7541 and SUS304. The values of $a$, $b$ chroma $C^*_{ab}$ and hue-angle $h_{ab}$ are shown in Table 3. A2017 achromatic colored metal values are low. And C7541 is located on the $+b^*$ direction axis. Thus, the surface color of C7541 is yellow with a low chromaticity. In other hand, the value of $a$, $b$ chroma $C^*_{ab}$ for C1100, C2801 and C5191 are high. Furthermore, the color coordinates for C1100 and C5191 are located in an intermediate axial position in the $+a^*$ and $+b^*$ directions. As a result, its surface color is yellowish red (orange) with a relatively high chromaticity.

For all test specimens shown in Fig. 4, as the value of $Ra$ became smaller, the color coordinates were positioned farther in the $-b^*$ direction. Figures 5(a) and (b) show the relationships between $Ra$ and the color coordinates $b^*$ for achromatic and chromatic colored metals, respectively.

As Fig. 5 shows the results for all specimens, when $Ra$ became smaller, the value of the color coordinate $b^*$ moves towards the negative direction, same meaning of the blue direction. In particular, if $Ra$ becomes smaller than 0.2 µm, the movement towards the $b^*$ direction becomes lager, and the bluish tint of the surface color is believed to increase.

Figures 6(a) to (d) show the spectral distribution curves for the test specimens polished in the free direction for achromatic colored metals. In all specimens, as the $Ra$ became smaller, a tendency was seen that the reflectance in the measured wavelength region became lower. In particular, the drop in reflectance in the long wavelength side was significant in comparison with that of the short wavelength side. In the A2017 spectral distribution curve shown in Fig. 6(a), the reflectance of the short wavelength side showed a tendency to be larger than that of the long wavelength side

Table 3 Values of $a$, $b$ chroma $C^*_{ab}$ and hue-angle $h_{ab}$ in the CIELAB color space.

| Achromatic Color | $C^*_{ab}$ | $h_{ab}$ | Chromatic Color | $C^*_{ab}$ | $h_{ab}$ |
|---|---|---|---|---|---|
| Aluminum Alloy A2017 | 0.94 | 168 | Tough Pitch Copper C1100 | 17.61 | 52 |
| Aluminum Alloy A5052 | 1.31 | 120 | Brass C2801 | 16.68 | 91 |
| Nickel Silver C7541 | 5.02 | 99 | Phosphor bronze C5191 | 12.31 | 64 |
| Stainless Steel SUS304 | 1.47 | 159 | — | — | — |

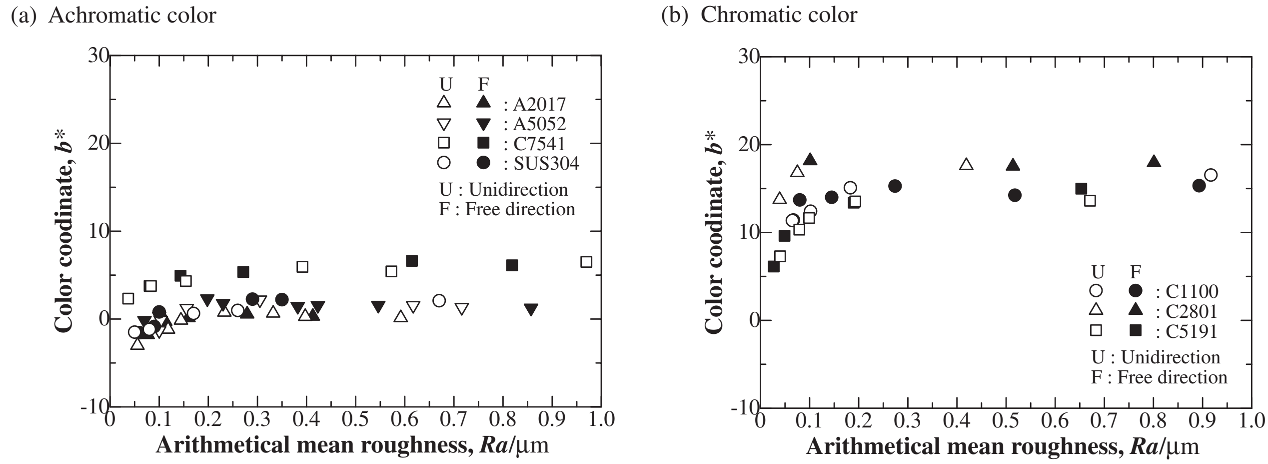


Fig. 5 Relationship between arithmetical mean roughness *Ra* and chromaticity $b^*$: (a) achromatic color and (b) chromatic color.

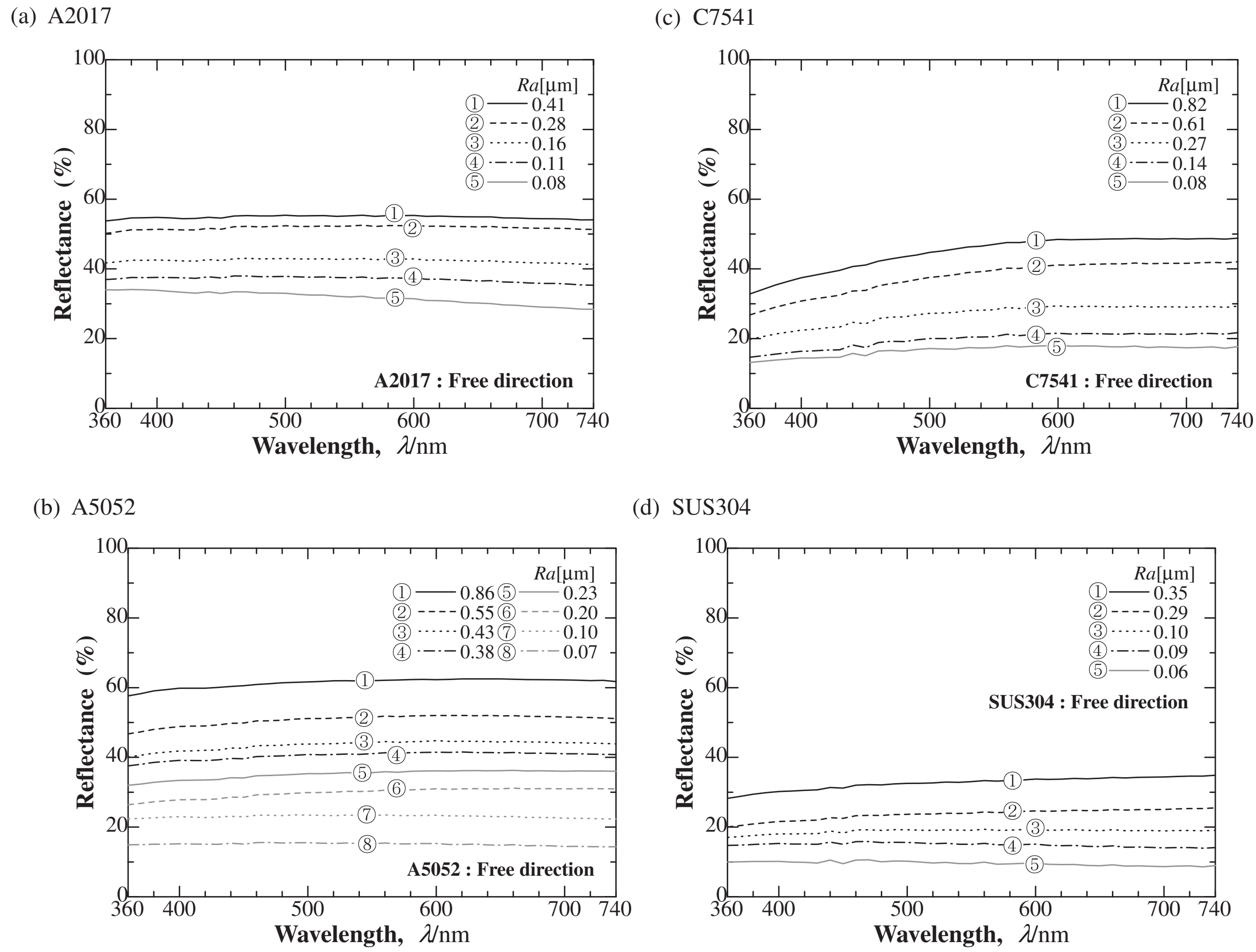


Fig. 6 Spectral distribution curve for achromatic colored metals: (a) A2017, (b) A5052, (c) C7541 and (d) SUS304.

only for the test specimens having an $Ra = 0.08\,\mu m$ (gray solid line). For C7541 shown in Fig. 6(c), the reflectance of $Ra = 0.08\,\mu m$ (gray solid line) became a constant value in the measured visible wavelength region.

Furthermore, similar trends were seen for the spectral distribution curves C1100, C2801 and C5191 shown in Fig. 7(a) to (c) that had free directional roughness. As the relationship between *Ra* and glossiness in Fig. 1, when the roughness is sufficiently small compared to the wavelength of the incident light, diffused reflection based on roughness will not occur. In other ways, for the case where the roughness plane is the same, in comparison with the short wavelength side, the light of the long wavelength side causes specular reflection more easily. Thus, from Fig. 6 and Fig. 7, as the *Ra* became smaller the diffused reflection shown by the spectral distribution curve will decrease since the light of the long

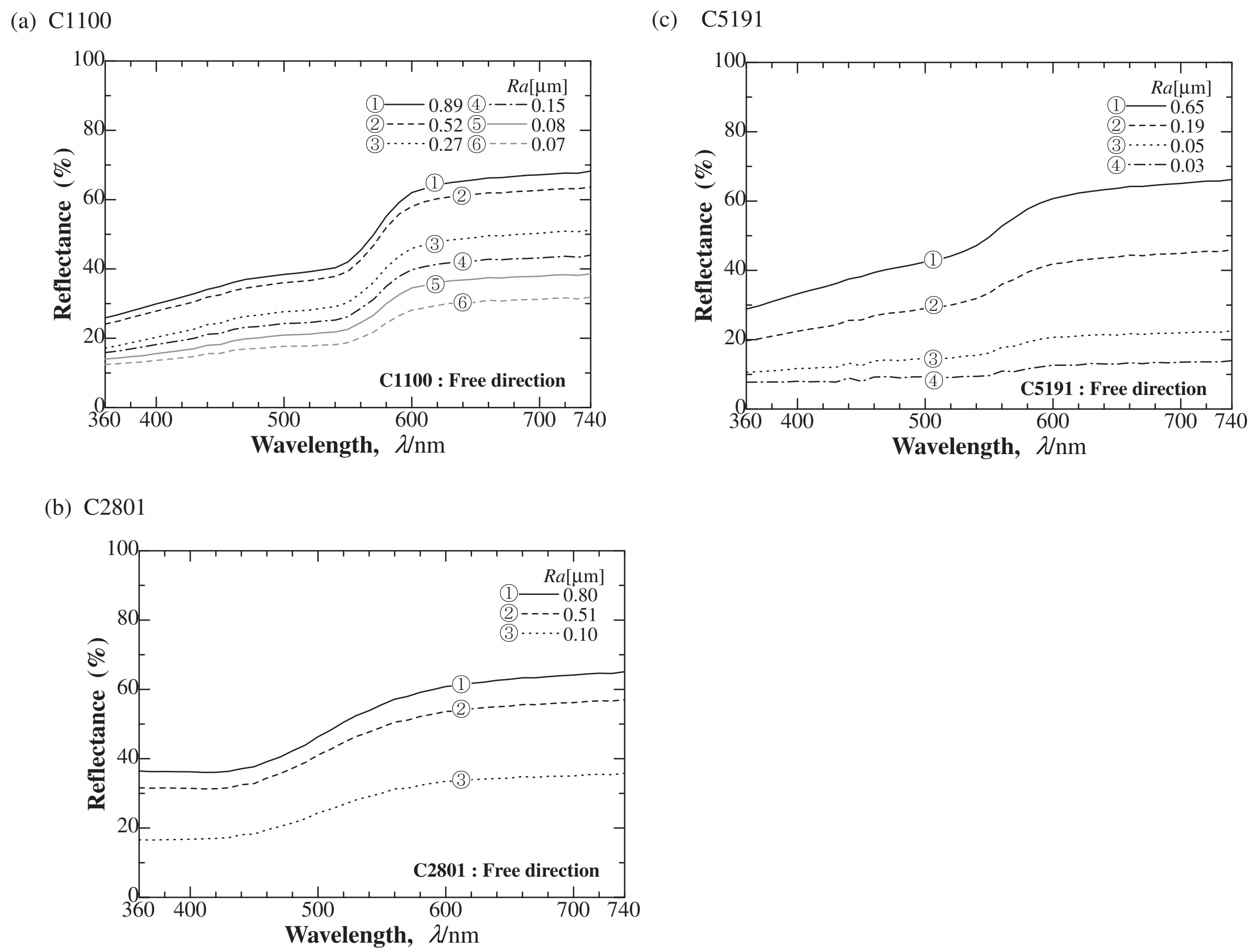


Fig. 7 Spectral distribution curve for chromatic colored metals: (a) C1100, (b) C2801 and (c) C5191.

wavelength side causes specular reflection easily. On the other hand, the light of the short wavelength side will be easily diffused as the *Ra* becomes smaller. The Fig. 5, Fig. 6 and Fig. 7 indicate that as *Ra* value becomes smaller, the reflectance of the long wavelength side is much decrease than that of the short wavelength side. And the surface color will be getting a bluish tint.

Sensory intensity evaluation studies of surface texture that are being conducted by researchers in various fields have found, for instance, that a coated surface having a stronger bluish tint increases the sense of depth.[3)] The experimental results reported, in which the short wavelength components of the surface color of materials increased as the *Ra* became smaller, establishes a guiding principle for manufacturing industrial products having surface textures that convey a sense of depth.

## 4. Conclusion

(1) The glossiness of all specimens increased exponentially as the arithmetical mean roughness *Ra* value became smaller.

(2) The Lightness $L^*$ value of all the specimens showed an inverse correlation between the arithmetical mean roughness *Ra* value, and specular reflectance that indicates the glossiness $Gs(60°)$ value. Thus, when either the glossiness of the specimen surface or the lightness $L^*$ value, is measured, the other can be estimated by the correlations obtained in this study.

(3) As the arithmetical mean roughness *Ra* value of all the specimens became smaller, the reflectance of the long wavelength side was much decrease than that of the short wavelength side. And the surface color will be getting a bluish tint.

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