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One-shot Multi-angle Measurement Device for Evaluating the Sparkle Impression

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Abstract. *The quantification of material appearance is important in product design. In particular, the sparkle impression of metallic paint used mainly for automobiles varies with the observation angle. Although several evaluation methods and multi-angle measurement devices have been proposed for the impression, it is necessary to add more light sources or cameras to the devices to increase the number of evaluation angles. The present study constructed a device that evaluates the multi-angle sparkle impression in one shot and developed a method for quantifying the impression. The device comprises a line spectral camera, light source, and motorized rotation stage. The quantification method is based on spatial frequency characteristics. It was confirmed that the evaluation value obtained from the image recorded by the constructed device correlates closely with a subjective score. Furthermore, the evaluation value is significantly correlated with that obtained using a commercially available evaluation device.* © *2019 Society for Imaging Science and Technology.*
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1. INTRODUCTION

There are many products whose design focuses on the material appearance. The material appearance conveys various impressions, such as luxury, and these impressions affect buyer motivation [1–3]. The evaluation of appearance has largely been based on descriptive language owing to the qualitative perception of appearance. However, measurement devices [4, 5] and evaluation methods have been developed to quantitatively evaluate appearance these days.

Among numerous types of appearance, the sparkle impression of metallic paint has received much attention because of the large volume of products, mainly automobiles and consumer electronics, using the paint [6–10]. The sparkle impression is perceived via the reflection of light from aluminum flakes and other particles that provide specular reflection present in the paint, and the perceived impression changes depending on the observation angle owing to the size and orientation angle of the flakes [11, 12]. Figure 1 shows an example of the sparkle impression varying with the observation angle. The left image in the figure is observed from a highlight angle, while the right image is observed from a shade angle. These angles indicate the angles under aspecular (not specular) angle conditions. The highlight angle is the angle near the specular condition, and the shade angle is the angle in the direction of diffuse reflection. We strongly perceive the sparkle impression in the left image, while we only perceive the impression locally in the right image. Methods for measuring painted surfaces using a multi-angle system and evaluating sparkle impressions have been reported. Watanabe and Sone proposed a model for evaluating sparkle impressions at different observation distances and confirmed the correlation with visual data [7]. Ferrero and Bayón identified features related to sparkles from measured images with a goniospectrophotometer. They reported the procedure to evaluate sparkle impression using the features [9]. Gómez et al. reported the correlation between the sparkle evaluation value and visual data of a commercial multi-angle measuring device [10]. The system illuminates painted surfaces from several angles and records an image of each angle condition with a camera. However, people observe an object from many different angles when perceiving the impression. In conventional methods, lighting and capture devices are arranged for each evaluation angle. Thus, there are problems in terms of the size and price of the measurement device when considering a great number of evaluation angles. Additionally, systems that make measurements at multiple angles, such as the goniophotometer, have been proposed [13–15]. However, the quantity of image data increases with the number of angles.

The present study constructed a multi-angle measurement device and proposed an evaluation method for the sparkle impression using the measurement image. To evaluate the impression, we prepared 26 samples that had different sizes of aluminum flakes. We next constructed a measurement device that can adjust the scan speed of the line scan camera and the rotation speed of the motorized rotation stage to which the lighting device was attached. The evaluation value of the impression was then calculated using the spatial frequency characteristics of the recorded images. The present article compared the evaluation results for several measurement angles with scores obtained in a subjective evaluation experiment. Moreover, the results are compared with those obtained using a commercially available measurement device.

The remainder of the article is structured as follows. Section 2 describes the samples prepared for measurement and evaluation. Section 3 describes the constructed one-shot multi-angle measurement device and procedure. Section 4

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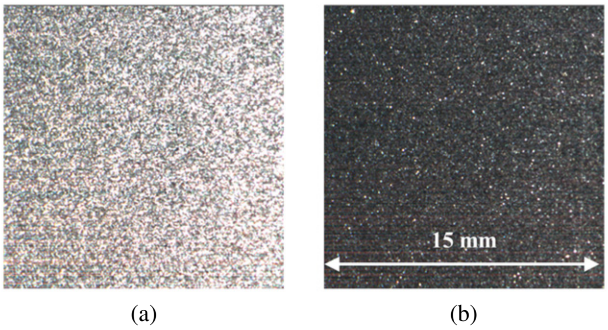

Figure 1. Example of the sparkle impression: (a) surface observed from the highlight angle (near the specular condition) and (b) surface observed from the shade angle (diffuse reflection direction).

explains the evaluation method of the sparkle impression. Section 5 compares the proposed evaluation values with scores obtained in subjective experiments and evaluation values obtained using a commercially available device. Section 6 presents conclusions and discusses future work.

2. SAMPLES

The sparkle impression is known to change in intensity depending on the size of metallic pigments [16]. The present study selected 26 silver metallic samples from a paint sample book (Isamu Paint Co., Ltd., Osaka, Japan). Figure 2 shows enlarged surface images of some samples captured at a standard light source booth (Spectra Light QC, X-Rite, Michigan, USA). Different samples contained aluminum flakes of different sizes. Sample 1 contained the largest flakes, while sample 26 contained the smallest flakes. The sample dimensions were approximately 30 mm × 25 mm. The size range of aluminum flakes contained in the samples was approximately 8–60 μm. We used these samples to measure and evaluate the sparkle impression.

3. MEASUREMENT DEVICE AND METHOD

3.1 *Measurement Device*

Figure 3 shows the measurement device constructed. The device comprised a lighting device, line spectral camera, and sample stage. The lighting device was attached to the motorized rotation stage, and the sample stage was attached to the linear stage.

The illumination device was a natural-light (high-color-rendering) light-emitting diode (LED) (CCS Inc., Kyoto, Japan) customized to a collimated light. The LED emitted all wavelengths of visible light and thus had characteristics similar to those of sunlight [17]. Figure 4 shows the spectral characteristics of the LED illumination. The spectral intensity on the vertical axis is normalized by the peak spectral intensity. It was confirmed that the frequency band of visible wavelength had a uniform distribution. The illuminance on the sample surface was approximately 14,000 lx.

The line spectral camera was a Pika L (Resonon Inc., Bozeman, Montana, USA), and an objective lens (Tamron Co., Ltd., Saitama, Japan) with a focal length of 50 mm was attached. The camera had 900 pixels and could record light in the wavelength range from 400 to 1000 nm with a 12-bit depth. We extracted the wavelength band of 400–700 nm from the raw spectral image obtained by the camera and converted the raw image into 31 band images (in 10 nm steps). Furthermore, the 900 pixels were trimmed to 850 pixels. The image resolution was approximately 1000 dpi (25 μm/pixel).

3.2 *Measurement Method*

The sparkle impression changes with the observation angle as mentioned in Section 1. Although people perceive the sparkle impression from many angles, conventional evaluation devices evaluate the impression at only a few angles to limit the device size and costs. The present article proposes a measurement method to evaluate the sample surface at multiple angles using the constructed device.

Figure 5 shows the proposed measurement setup. In the proposed method, while synchronizing the scan speed of the line scan camera and the movement speed of the linear stage, the lighting device attached to the motorized rotation stage is rotated to obtain a multi-angle measurement image. In this study, we adjusted the lighting device so

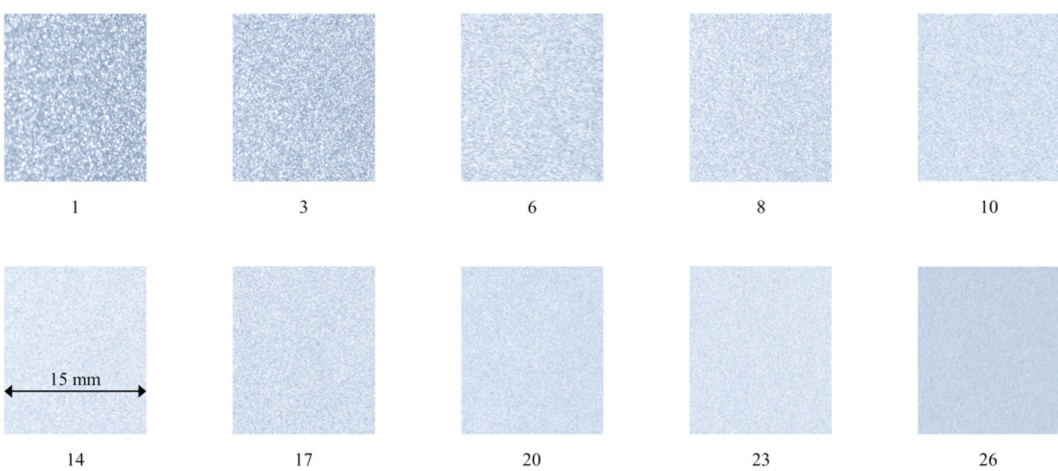

Figure 2. Sample surfaces.

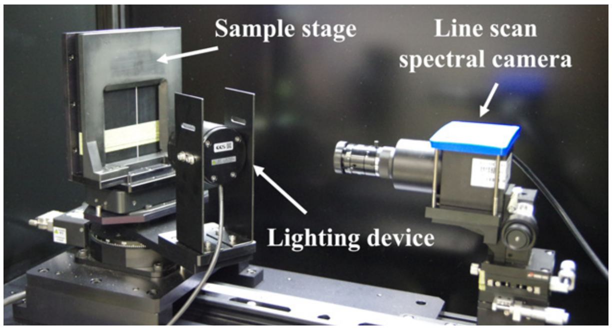

Figure 3. Measurement device.

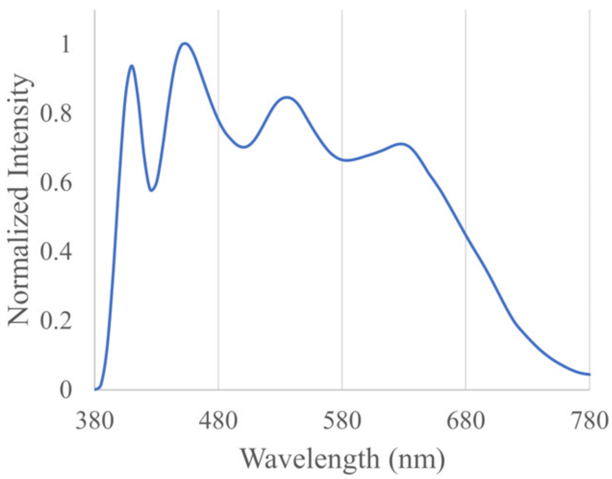

Figure 4. Spectral characteristics of the natural-light LED illumination.

that it rotates 1° while the line scan camera scans 10 pixels. The above condition was set in consideration of the spatial resolution limitations in this setup calculated based on the angle of view of the lens, the number of sensor pixels, and the rotational resolution of the rotary stage. The rotation range of the device was 19.5° –75.5° with respect to the sample's normal direction (geometry: 15° as −4.5° to 15° as −60.5°); i.e., the lighting device rotated through 56° while the line scan camera was recording. The dimensions of the measurement image were therefore 850 × 560 pixels. Here, "as" stands for "aspecular" and means the angle from the specular reflection. For example, 15° as −4.5° means that the measurement angle is 15° and the illumination angle is tilted −4.5° from the specular condition. By using the linear stage, since spatially continuous images can be acquired, the aluminum flakes with a size exceeding the image resolution (25 μm/pixel) of this setup can be measured. Line scan camera measures different positions of the sample in each vertical stripe (band). On the other hand, the multi-angle images also can be acquired without using the linear stage, but because the spatial position is fixed, the aluminum flakes with size more than 25 μm cannot be measured with this setup. The purpose of this study was to quantify the sparkle impression we perceive. Therefore, we inferred that it was appropriate to evaluate the sparkle impression on the two-dimensional surface using the linear stage as

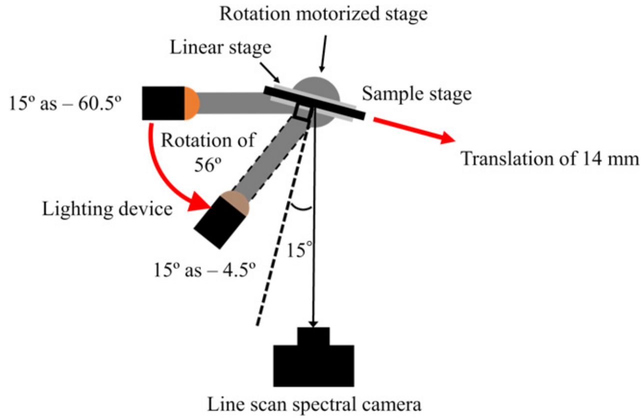

Figure 5. Measurement method.

we usually observed objects in two-dimension. Figure 6 shows an example of the captured images. Images have been converted to RGB images in the figure. The left image is of sample 1, the central image is of sample 13, and the right image is of sample 26. The sparkle impression was strongly perceived when the measurement condition was close to specular (geometry: 15° as 0°). A comparison of the images of the three samples confirms that there was a difference in intensity and size of the sparkle impression. In this study, since we used the line scan camera with a 12-bit dynamic range, no saturation occurred in the measured image. However, sparkle images have high contrast, and there is a possibility to cause saturation in other paint samples. In that case, a high dynamic range rendering is necessary to acquire and combine multiple images with different integration times.

4. METHOD OF EVALUATING THE SPARKLE IMPRESSION

Various methods for evaluating the sparkle impression have been proposed. The present study evaluated the impression using spatial frequency characteristics [7]. Evaluation values were calculated as follows.

4.1 *Conversion from Spectral Data to L**

The recorded spectral images $O(\lambda, i, j)$ were first divided by spectral images of a standard white target $W(\lambda, i, j)$ to obtain reflectance images $R(\lambda, i, j)$. Here, λ denotes the wavelength, while i and j denote the spatial coordinates. Also, i was associated with rotation angle information. The reflectance images were then converted into CIELAB images.

4.2 *Splitting of the L* Image by Every 1° and Obtaining Spatial Frequency Characteristics*

The obtained L^* image was split into stripe segments (bands) corresponding to 1° illumination angle. That is, the dimensions of each sub-image were 850 × 10 pixels. We defined the geometric condition of the sub-images using the central angle of the image. As an example, the sub-image from −60.5° to −59.5° is referred to as "15° as −60°". In other words, we obtained images for 56 geometric conditions

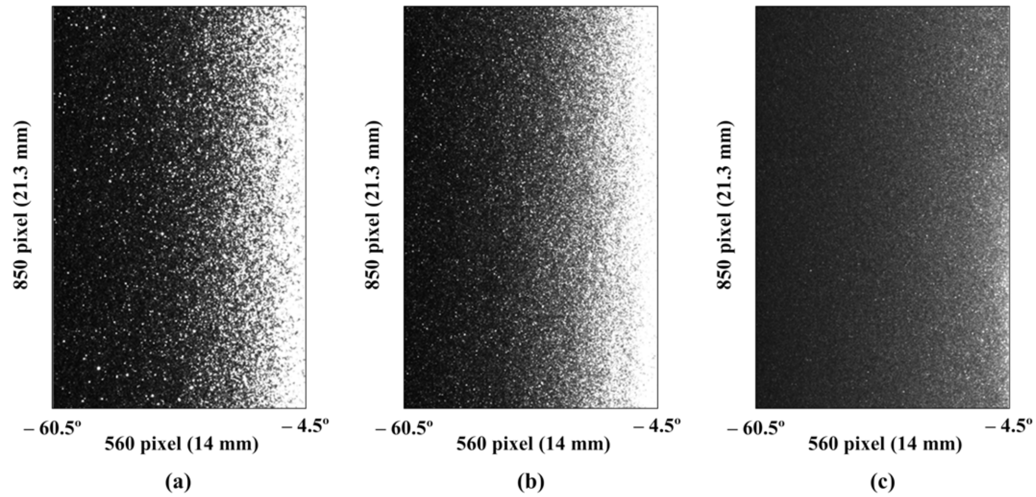

Figure 6. Examples of the captured images: (a) sample 1, (b) sample 13, and (c) sample 26. The left side of the image corresponds to 15° as −60.5°, while the right side corresponds to 15° as −4.5°.

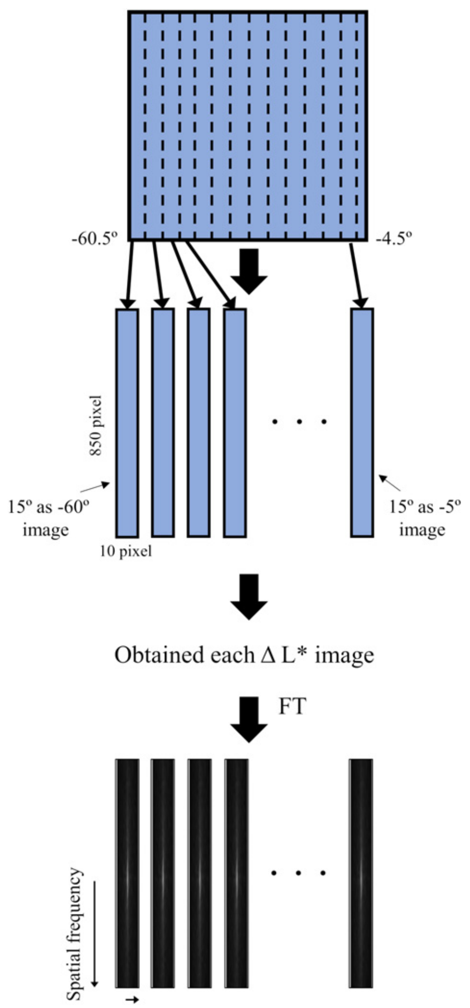

Figure 7. Procedure of calculating the spatial frequency characteristics every 1° from the L^* image.

(15° as −5° to 15° as −60°). Next, to extract the brightness contrast between the sparkle and the surrounding region in the sample, ΔL^* images were obtained by subtracting each average value from each sub-image. Since the average value of the ΔL^* image is 0, we can compare the sparkle impression using only the brightness contrast excluding the effect of the average value of the L^* image. A two-dimensional Fourier transform was then performed to calculate spatial frequency characteristics. Figure 7 illustrates these procedures.

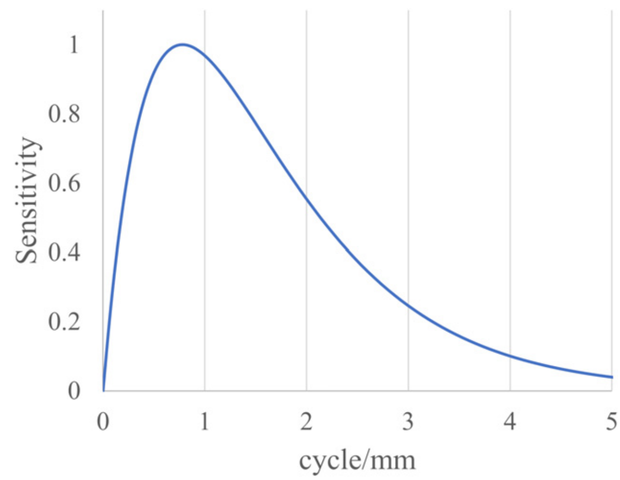

Figure 8. Human visual characteristics for an observation distance of 400 mm.

4.3 *Weighting of Human Visual Characteristics*

The obtained spatial frequency characteristics were weighted by the human contrast sensitivity characteristics, referred to as the contrast sensitivity function (CSF). The CSF is the characteristic frequency response of human vision [18]. We used the CSF model of Dooley et al. [19]. The CSF equation was mainly used for printed materials, and the sparkle was not assumed. However, according to previous studies that reported the reflected illuminance of aluminum flakes, the reflected illuminance of aluminum flakes illuminated with an artificial spotlight was very small [16]. From the above, the reflected illuminance perceived by the human eye was

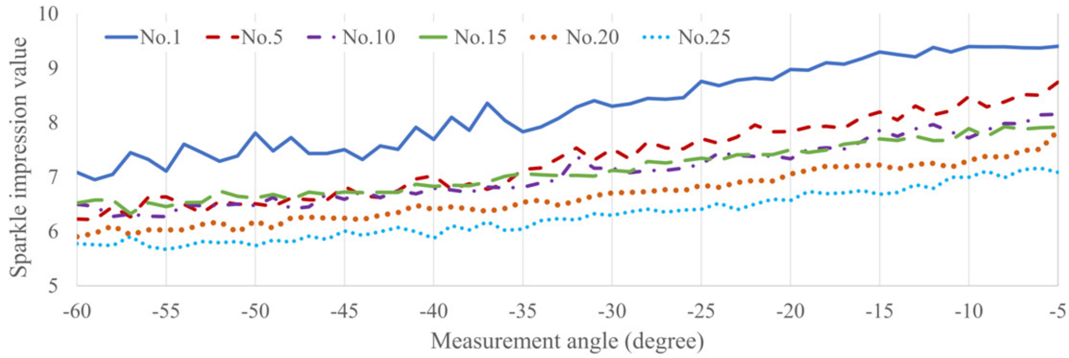

Figure 9. Sparkle impression values at every 1°.

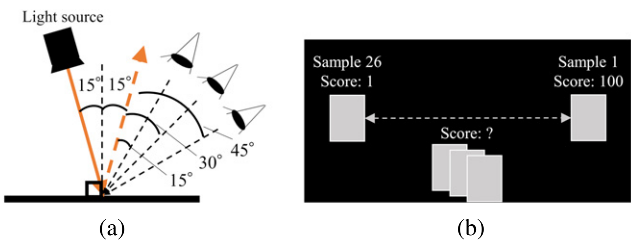

Figure 10. Subjective evaluation experiment: (a) experimental conditions and (b) experimental procedure.

so small that we assumed that the CSF could be applied to sparkles. The sparkle impression is strongly perceived when a surface is observed at short distance. In this study, the CSF for an observation distance of 400 mm was used (Figure 8). The CSF was converted from units of cycles per degree to units of cycles per millimeter. The sensitivity peaked at approximately 0.8 cycles per millimeter. The CSF model is a one-dimensional equation. To weight a two-dimensional spatial frequency with CSF, it was necessary to convert the CSF to two dimensions. Therefore, the CSF was converted to two dimensions by rotating around the origin of the coordinate axes. After weighting with the CSF, amplitudes of the two-dimensional spatial frequency characteristics were integrated.

4.4 *Calculating the Particularly Strong Reflection Value*

We hypothesized that "our visual perception is influenced by particularly prominent features in the visual image". Based on the above, we assumed that the sparkle impression was affected by pigments with particularly strong reflections (SR) and extracted pixels with particularly high L^* values in the image. The strong reflection value was therefore calculated by taking the average of high L^* values of pixels. These values corresponded to pigments that are strongly reflective. The present study used 10 pixels having the highest values of L^* because of the width of each sub-image, that is, the number of angles forming the sub-image. However, because the SR depends on the contrast of the pigments' reflection and its background, we assumed that corrections such as changing the number of extracted pixels depending on the sample color are necessary.

4.5 *Calculation of Sparkle Impression Values*

Based on the previous study that reported the correlation between sparkle impression evaluation equation and subjective evaluation data [7], the sparkle impression value (SV) used in evaluating the sparkle impression is expressed in the following equation:

$$\mathrm{SV} = \log\left(\int F(\upsilon) \cdot \mathrm{CSF}(\upsilon)\, d\upsilon \cdot \mathrm{SR} + 1\right). \qquad (1)$$

Here, υ is the spatial frequency (cycles/mm). This equation is a logarithm based on the Weber–Fechner law, which states that the magnitude of a subjective sensation increases proportionally to the logarithm of the stimulus intensity. If the integrated value or SR was 0, Eq. (1) diverged. Therefore, we added 1 in the equation to prevent divergence.

Figure 9 shows the proposed sparkle impression values calculated using Eq. (1) for part of a paint sample. Here, the horizontal axis represents the measurement angle and the vertical axis represents the sparkle impression value. The values are averages of three measurements for each sample. The figure confirms that a sample containing large pigments essentially had a high sparkle impression value. Furthermore, the figure confirms the change in the value depending on the measurement angle. The samples containing large pigments were particularly affected by the measurement angle, while the samples containing small pigments showed gradual changes. Samples 5, 10, and 15 had almost the same values under the shade conditions of 15° as −35° and so on. The above detailed variation in the sparkle impression of each sample depending on the measurement angle could be obtained because the proposed method measured and evaluated the sample surface every 1°.

5. RESULTS

We conducted a subjective evaluation experiment and visually confirmed correlation between the proposed sparkle impression value and the subjective evaluation value. We then confirmed correlation between the proposed sparkle impression values and results obtained using a commercially available evaluation device.

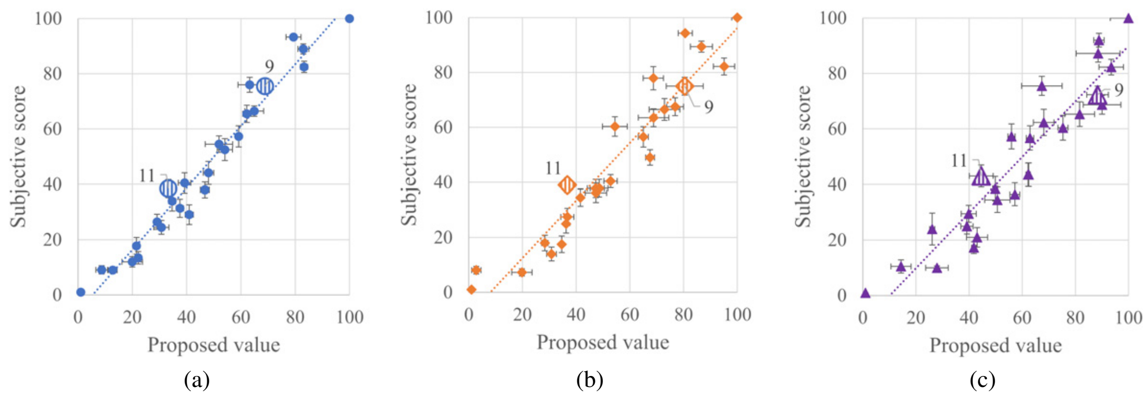

Figure 11. Correlation of the proposed sparkle impression values and subjective scores: (a) −15°, (b) −30°, and (c) −45° from the specular reflection angle.

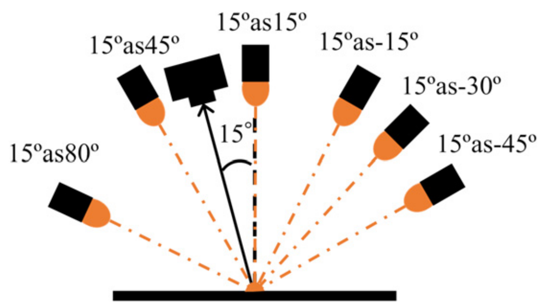

Figure 12. Measurement geometry of the MA-T12.

5.1 *Correlation with Subjective Scores*

To evaluate the validity of the proposed sparkle impression values, we confirmed the correlation between the proposed values and subjective scores. We therefore conducted a subjective evaluation experiment to obtain the subjective scores (Figure 10). Fig. 10(a) presents the experimental conditions. The experiment was conducted in a dark environment with low illumination (approximately 3 lx). The lighting device was an artificial solar lighting—XELIOS 500 W series lamp (SERIC Ltd., Tokyo, Japan)—and was illuminated on a sample. The illuminance of the sample surface was approximately 6000 lx. Ten participants observed the sample surface at a distance of 400 mm and evaluated the sparkle impression from three observation angles (−15°, −30°, and −45° from the specular reflection angle). Fig. 10(b) shows the experimental procedure. We first determined a sparkle score of 100 for sample 1 and a sparkle score of 1 for sample 26. The participants then evaluated the sparkle score in the range of 1–100 for the other samples. Black matte paper was used as the background. Each subjective score was obtained as the average score for the three participants.

Figure 11 shows the correlation between the proposed sparkle impression values and the subjective scores. The horizontal axis shows the proposed value, while the vertical axis shows the subjective score, and error bars represent the standard error. The proposed values have been converted to a score in the range of 1–100. We confirm that there is a strong positive correlation and obtain R-squared values of 0.96, 0.92, and 0.89 for the three observation angles. These results indicate that the proposed sparkle impression values have a good correlation with the subjective evaluation. As mentioned in Section 2, sample 1 contains the largest pigments, while sample 26 contains the smallest pigments. However, the figure shows that the ranks of pigment size and subjective scores deviated for samples 9 and 11 especially (striped plots in Fig. 11). Specifically, sample 9 had a subjective score larger than expected, while sample 11 had a subjective score smaller than expected.

5.2 *Correlation with Results Obtained Using a Commercially Available Evaluation Device*

Correlation between the sparkle impression value calculated from images at several angles and the evaluation value obtained using a commercially available evaluation device was confirmed. The commercial evaluation device was an MA-T12 (X-Rite, Grand Rapids, Michigan, USA). Figure 12 shows the measurement geometry of the device. There were six light sources attached to the measurement device and the sparkle impression could thus be measured and evaluated at six angles. The camera was attached at an angle of 15° from the normal direction of the sample. Lighting devices were attached at angles of 80°, 45°, 15°, −15°, −30°, and −45° from the specular reflection condition (geometry: 15° as 80°, 15° as 45°, 15° as 15°, 15° as −15°, 15° as −30°, and 15° as −45°). The present study thus confirmed correlations between the proposed sparkle impression values and the values of the commercially available device under three conditions (−15°, −30°, and −45° from the specular reflection angle). Figure 13 shows the comparison results. The horizontal axis shows the proposed values while the vertical axis shows the evaluation values of the MA-T12, and error bars represent standard errors. Here, the proposed values and the evaluation values of the commercially available device are converted to scores in the range of 1–100. R-squared values were 0.80, 0.93, and 0.92 for the three observation angles. These results indicate that the proposed sparkle impression values have high correlation with the

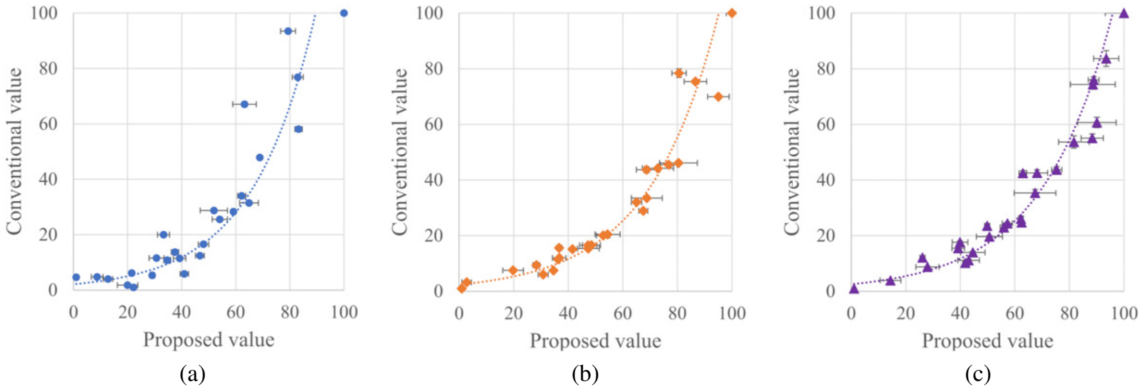

Figure 13. Correlation of the proposed sparkle impression values with the evaluation values of the commercially available device: (a) −15°, (b) −30°, and (c) −45° from the specular reflection angle.

evaluation values of the commercially available device. The proposed sparkle impression values were obtained using a logarithmic equation based on the Weber–Fechner law as described above, and the correlation was thus exponential. Although the correlation was exponential, the evaluation values obtained from the image recorded using the proposed measurement method have almost the same tendency as results obtained using the commercially available device.

6. DISCUSSION AND CONCLUSIONS

The present study focused on the sparkle impression of the appearance of a material surface. We proposed a measurement device and an evaluation method that solve problems when using conventional methods with a large number of evaluation angles. To this end, we first constructed a measurement device that obtains multi-angle images in one shot by adjusting the scan speed of the line scan spectral camera and the rotation speed of the lighting device. The proposed measurement device can measure the range of 15° as −5° to 15° as −60° with a resolution of 850 × 10 pixels per degree in one shot. Next, the measured image was split every 1°, and an evaluation value was then calculated using spatial frequency characteristics. The proposed measurement and evaluation methods were used to evaluate the sparkle impressions of 26 paint samples containing pigments of different sizes.

To investigate the validity of the proposed sparkle impression value, we compared values with scores obtained in a subjective evaluation experiment. A significant correlation with the subjective scores was confirmed. Moreover, it was found that the ranks of pigment size and subjective scores deviated for some samples. This suggests that the sparkle impression was affected not only by the pigment size but also by other factors, such as the orientation angle, distribution, and blending quantity of the pigments as described in prior studies [11, 12, 15, 16]. In the results of the present study, it is considered that the proposed values include the effects of such factors on the sparkle impression values because of the high correlation with the subjective scores (see Fig. 11). Similarly, it was confirmed that the proposed sparkle impression values are highly correlated with evaluation values obtained using a commercially available device. However, it was found that the standard error of the sparkle impression values obtained using the proposed method was larger than that of the evaluation values obtained using the commercially available device owing to the narrow image width per degree (see Fig. 13). In particular, the standard error for the 15° as −45° condition was large because there were few and sparse pigments that could be perceived sparkle at the shade angle. It was inferred that expanding the width of the sample image per degree decreases the number of evaluation angles but also reduces the variation of evaluation values. Also, by applying our proposed measurement method, we estimated that we can examine the change of standard error due to angle condition by fixing the spatial position of each sub-image at the same position without using a linear stage. It is necessary to adjust the resolution of the proposed measurement device to conduct the experiment. Although the present study evaluated the validity of the proposed evaluation value only for three angles, the proposed evaluation value was highly correlated with the subjective score. We therefore presume that the proposed sparkle impression values for other angle conditions not considered in this study also have high correlation with subjectivity. However, an additional subjective experiment needs to be conducted to confirm this hypothesis.

We plan to investigate the color effect on the sparkle impression using color metallic samples because we evaluated the sparkle impression with only metallic silver samples in the present study. In addition, some paints contain not only aluminum flakes but also pigments called mica pigments, having an interference color. Mica, therefore, provides a colored sparkle impression. We also plan to investigate the change in the colored sparkle impression with the observation angle.

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