https://doi.org/10.2352/issn.2169-2629.2021.29.294
©2021 Society for Imaging Science and Technology

Image-based goniometric appearance characterisation of bronze patinas

Yoko Arteaga[1 2] **, Clotilde Boust**[1] **, Angèle Dequier**[3] **, Jon Yngve Hardeberg**[2]
[1] **Centre of Research and Restoration of the Museums of France; Paris, France**
[2] **Norwegian University of Science and Technology; Gjøvik, Norway**
[3] **National Institute of Cultural Heritage; Paris, France**

Abstract

Patinas are a form of metal polychromy used to decorate metallic artworks. Due to the nature of the metallic surface, their colour and gloss is perceived differently when the illumination and viewing directions vary. Sparkle effect on surfaces is a physical phenomenom caused by micro-facets on the surface coating which are also perceived with changing viewing and illumination geometry.

In this paper, a method designed for the measurement of sparkle is applied for the goniometric characterisation of bronze patinas. Using a set of six different patinas, in three colours and two surface finishes, it is found that these surfaces exhibit different appearance when illuminated and viewed at different angles. Moreover, the roughness of the patinas is measured and as expected, as the roughness increases the specular reflection peak decreases. The experiment is repeated at two different institutions with different sets of equipment to test its repeatability and robustness.

The sparkle is presented as a function of the angle of tilting, and it is characterised by its maximum value and full-width half-maximum. It is found that the maximum and the roughness have a negative exponential relationship whereas the full-width half-maximum and the roughness have a linear relationship.

Introduction

Studying the visual appearance of cultural heritage objects is of great importance not only for aesthetic purposes but also because it provides information about the objects' provenance, manufacturing technique, storage conditions, and ageing processes amongst other attributes. Correctly measuring, characterising, and identifying these properties is extremely valuable for conservators but also the ease, availability, and practicality of the technologies used must be considered.

Patinas are a form of metal polychromy widely used to decorate metallic artworks. They allow craftsmen to obtain various coloured surfaces on copper-based alloys by applying chemical treatments which build a compound layer on the surface [1]. In this work, the patinas used were made by the Coubertin foundry, located in the outskirts of Paris. The patinas are present in three different colours, red, green, and black and they have been made with two surface finishes, smooth and rough. Examples of works fabricated using these techniques are the famous bronze sculptures by Rodin.

Sparkle is a visual effect in which, when viewed and illuminated from different angles, the surface exhibits points of high specular reflection [2]. This is caused by micro-facets added to the surface coating which are placed randomly at different orientations. Gloss, on the other hand, is an optical property which describes how an object reflects light in a specular direction. Gloss, similar to sparkle, is also perceived when viewed and illuminated from different directions however, the physical properties of the materials responsible of creating said effects are completely different. Despite being inherently different phenomena, the dynamics in which both effects are observed are similar and thus, it is interesting to evaluate the applicability of a method used to measure sparkle to measure gloss of bronze patinas.

Several commercial instruments are available to perform multi-angle planar measurements such as gloss-meters or the BYK-Mac specifically designed for sparkle measurements. However, these instruments are expensive and measure fixed illumination and reflection angles. Gonio-spectro-photometers used in research institutions provide a more accurate goniometric measurement, yet they are expensive and slow. Thus, there is an interest to develop an accurate but also fast and inexpensive method.

In this work, a method initially developed for the measurement of sparkle is tested and validated for the goniometric characterisation of bronze patinas used in cultural heritage statues. The benefit of using this method is the availability of the equipment necessary, which can be found in any cultural heritage research or documentation facility. Based on only a directional light source, a CCD camera and a tilting stage, these measurements can be done in museums, restoration workshops and laboratories. In order to test the robustness of the method, the experiment has been repeated in two different laboratories, the Centre for Research and Restoration of the Museums of France (C2RMF) and the National Institute of Cultural Heritage (INP), using the equipment available in each institution.

The patinas are also characterised in terms of their roughness, to evaluate the feasibility of applying this method to samples belonging to a range of different roughness. Since the bronze patinas do not strictly present sparkle by definition, whenever the author refers to *sparkle* in italic font, they mean the specular reflections from the patinas which have been calculated using the proposed method for sparkle measurements.

Related works

Sparkle

Sparkle is a sensation produced by different materials, where many luminous points are observed. These mini reflections are caused by the various orientations of many micro-facets on the surface which cause specular reflections. Some materials which can cause sparkle are inclusions of mica or sand in a paint. Given that each of these micro-facets has a different and random orientation, the sparkle effect is observed when either the illumination source or the viewing angle is modified. This is a non-permanent effect where the sparkle changes constantly as the observer or illumination changes.

To date there is still not a methodology defined by the CIE to measure sparkle, as this is a very current problem area. The CIE JTC 12 has as an objective to provide a standardised way to measure and evaluate sparkle [3].

Ferrero *et al.*, has defined sparkle as a non-uniform texture which is observed under a directional illumination, at a metre or less from the surface [2]. Sparkle, as previously defined, is given by a low density of highly reflective points over a darker background. In the case of a diffuse illumination, the perceived texture is no longer sparkly, and the effect becomes graininess. Thus, the illumination conditions are very important when studying sparkle or graininess. Under directional light the observed effect will be sparkle and under diffuse light, graininess.

A physical model is defined to simulate both sparkle and graininess [2]. Given the orientation of each micro-facet, the reflection flux can be simulated. In this model, sparkle and graininess are two extremes in the same reflection phenomenon. The contrast between the reflective points and the darker background will determine if the texture (sparkle or graininess) is observable or not. The density of lighter points defines the effect. For a high contrast and low density there is sparkle and for a low contrast and high density, graininess. Both characteristics, contrast and density are dependent on the source of illumination, the illumination and observation geometries, and the orientation of the micro-facets.

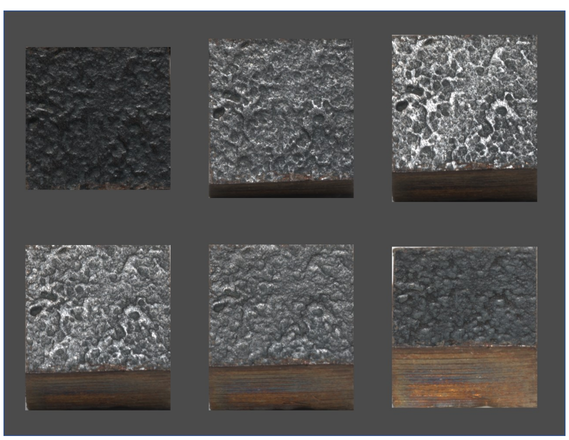

Figure 1: Demonstration of *black rough* patina mock-up and its colour change at different angles of tilting. From left to right: 0 ^{o}, 11 ^{o}, 22 ^{o}, 28 ^{o}, 34 ^{o} and 45 ^{o}. The angle of tilting is given from the horizontal axis.

Sparkle measurements

Ferrero *et al.* [4], proposes a protocol for the measurement of sparkle. The authors use the GEFE (Gonioespectrofotometro Español) for bidirectional measurements where the illumination and observation directions are modified. This device allows the absolute measurement of the bidirectional reflectance distribution function (BRDF). In the GEFE configuration, the sample is placed on a fixed platform relative to the illumination beam and the detector revolves around the sample [5].

The authors obtain grey level images, where the sparkle points are visible. From these images, three values are calculated relative to four parameters. Firstly, the contrast of a single sparkling point, C_S, given by the ratio of the flux of the point to the flux of the almost Lambertian background. It represents the ratio between the fluxes specularly reflected by the flake and diffusely reflected by the background. This ratio varies with the geometry of the surface coating because of the angular dependence of the Fresnel reflection and the non-perfect Lambertianity of the background.

To determine at which geometries the sparkle is visible, the whole contrast is necessary. The contrast of the set of sparkling points, C_{SP}, is defined as the mean of contrasts C_S higher than a threshold defined by Ferrero *et al.* as $C_{th} = 0.5$.

Finally, the density of the sparkle points, d_{SP}, is defined as the number of sparkle points per area with $C_S > C_{th}$. This is related to the number of flakes per area whose specularly reflected fluxes are partially or totally collected. It depends on the distribution of the inclination of the flakes, and in consequence, also on the illumination/viewing geometry. This distribution is usually peaked at inclinations where the flakes are parallel to the coating surface. Additionally, the wider the distribution, the more constant is the observed sparkle density at different geometries.

Due to the complexity of the sparkle effect, its measure cannot be reduced to a single number. Thus, four visual attributes related to sparkle are defined. The maximum sparkle visibility, defined as the capacity of the human visual system to discriminate sparkle events, correlated to C_S. The maximum density of sparkle points, correlated to d_{SP}. The visibility inconstancy, which is the variation of sparkle visibility as a function of illumination/viewing geometry, correlated to the total variation of C_S relative to its maximum. Finally, the anisotropy refers to the variation of the density of sparkle points with respect to the illumination/viewing geometry, which is correlated to the total variation of d_{SP} relative to its maximum.

Visual appearance in cultural heritage

Although bronze patinas are widely found in cultural heritage objects, they are normally characterised based on their chemical composition, using analytical methods such as X-ray diffraction, particle induced X-ray emission [1], Raman microscopy [6], scanning electron microscopy [7] and others [8]. To the authors knowledge, there have not been extensive works on the characterisation of the visual appearance of bronze patinas using imaging techniques.

Other cultural heritage materials that have been studied in terms of their visual appearance by performing goniometric measurements are polychrome wood [9] and paint and varnish [10]. Although surface characterisation is strategic for studies in conservation [8], this is not frequently done as most goniometric investigations of optical properties of surfaces are mostly performed considering industrial materials.

Materials and Methods

Sample patinas

The samples used for this work are bronze patinas from the Coubertin art foundry [11]. Six patinas are available, in three colours: red, green and black and two surface finishes: smooth and rough. Due to the polychrome alteration of the surface of the metal, a significant change in appearance dependent on viewing angle is produced, illustrated in Figure 1.

Goniometric sparkle measurements

Figure 2: Snapshot of sparkle set-up used at INP.

The sparkle measurements have been adapted from work done by Ferrero *et al.* [4] and Page [12]. This is illustrated in Figure 2 and Figure 3 shows a schematic of the set-up. The samples are placed on a tilting support, where the angle of inclination can be controlled with a micrometric turning stage. The camera is placed vertically above the samples and the illumination is set at a zenithal angle of 45^{o} degrees. The specular configuration corresponds to a 22.5^{o} rotation around the horizontal axis and the exposure is adjusted at this configuration. At every 1 degree, a capture is made. Table 1 shows the image acquisition parameters and experimental set-up used at each institution.

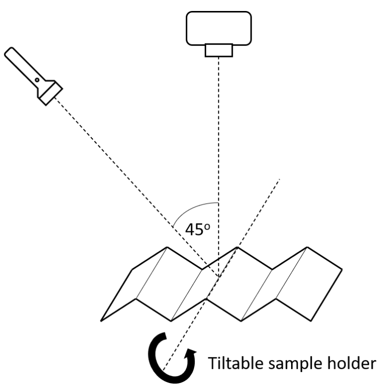

Figure 3: Set-up used for sparkle measurements.

The images are taken in raw format. To process the images and calculate the sparkle, an area of 200 x 200 pixels from the centre of each patina square is taken. This image is converted into the CIE 1976 L*a*b* colour space assuming the original images are in the sRGB colour space, using D65 illuminant as the white point, and only the L* channel is used. The images are calibrated by using a Lambertian white surface as a reference and setting its L* value to 95. The sparkle is defined as the percentage of pixels in the image over a threshold. Given that sparkle is defined by micro mirror-like facets, the threshold should be representative of specular reflections on the surface. In this case, the threshold is defined as L* = 96, since the Lambertian white has a value of 95. Finally, the percentage of pixels over the threshold is plotted for each patina, as a function of angle of rotation. This is illustrated

Table 1: Parameters used for sparkle measurements

	C2RMF	INP
Acquisition set-up parameters		
Camera	Hasselblad	Nikon D850
Lens	120 mm macro	105mm macro
Sensor size (pixels)	6708 x 8956	8256 × 5504
Light source	Flash 3000K	LED 5200K
Object distance (cm)	50	40
Illumination distance (cm)	70	80
Pixel size (mm^2)	2.89 $\times 10^4$	0.50 $\times 10^4$
Image capture parameters		
f-number	f/14	f/32
Exposure time (s)	1/125	1”30
ISO	50	64

in Figure 4.

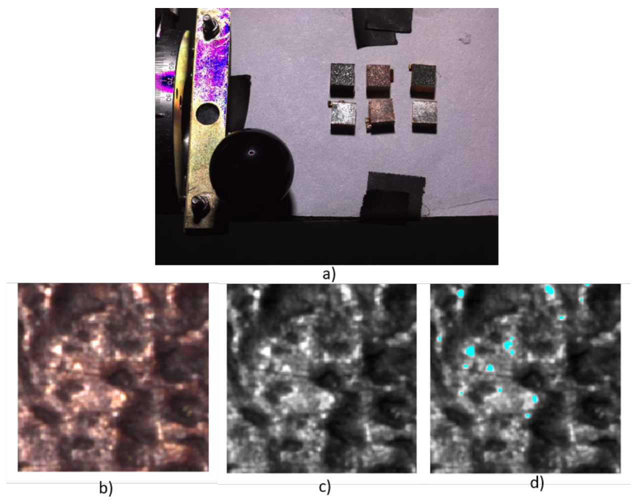

Figure 4: Processing steps to obtain sparkle. a): For each patina a patch is extracted from the centre, b): transformed to L*a*b* and a threshold is set in the L* channel. c): The value of sparkle is given by the percentage of pixels over the threshold, highlighted in cyan.

Roughness

The roughness of the patinas is measured under a white-light profilometer with chromatic coding (Altisurf 50 by Altimet^{TM}). A 8 mm probe is used with a 2 μm step in x and y directions; resolution in z is of 50 nm. The surface roughness is calculated using the arithmetical mean height (Sa), according to ISO25178, given by

$$Sa = \frac{1}{A}{}_{A}|Z(x,y)|, \qquad (1)$$

where A is the area of the surface and Z the height of each point from the arithmetical mean of the surface [13].

Results and discussion

Sparkle

Following the protocol introduced in the previous section, the *sparkle* is presented as a function of the difference between the angle of incidence and the angle of observation. Figure 5 shows the *sparkle* obtained using the equipment at C2RMF and Figure

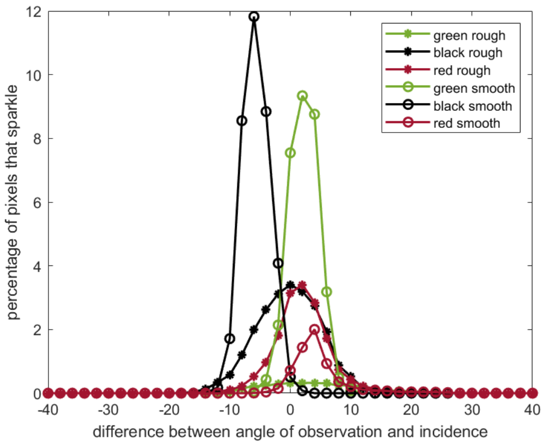

Figure 5: *Sparkle* as a function of the difference between the angle of incidence and reflection for images taken at C2RMF. Smooth samples are presented with a round marker, and rough samples are presented with a star marker.

6 shows the *sparkle* obtained at INP. The patinas can be grouped into two different types of curves: smooth samples have a narrow curve with a high peak and rough samples have a wider curve with a less pronounced peak.

It is expected that the peak in the *sparkle* curve occurs when the angle of incidence is the same as the angle of observation, at the specular configuration. This is not the case for all the patinas since they present a small difference in height. Thus, when the samples are placed at a rotation of 0^o on the horizontal, the angle of incidence is not 45^o for all of them.

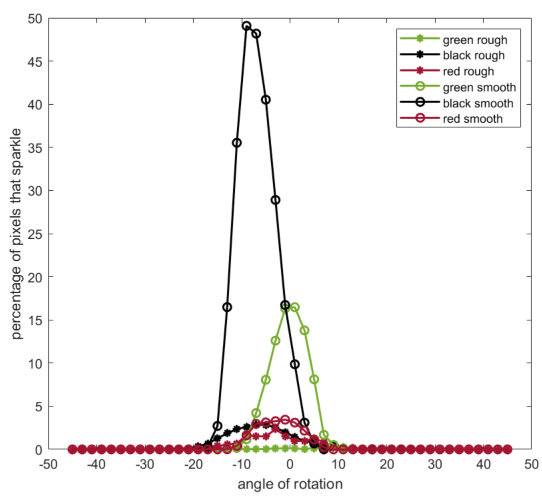

Figure 6: *Sparkle* as a function of the difference between the angle of incidence and reflection for images taken at INP. Smooth samples are presented with a round marker, and rough samples are presented with a star marker.

The *sparkle* curves can be described by their maximum point (percentage of pixels that sparkle) and spread, given by the full-width half-maximum (FWHM) in degrees. The values obtained from Figure 5 and Figure 6 are presented in Table 2. Except for the black and green smooth samples, there is a general agreement between the maximum values obtained. In terms of the FWHM, the relative difference between each patina is not so different with the exception of the red smooth sample.

Sparkle and roughness

The roughness of the patinas is calculated given Equation 1. The results are presented in Table 3. The roughest sample is the *green rough* patina and the smoothest is the *black smooth* patina. Although the patinas are grouped in two categories, smooth and rough, the variation in roughness of the smooth group is much lower than the variation in roughness of the rough group.

Figure 8 shows the FWHM taken from Figure 5 and Figure 6 as a function of surface roughness, Sa, given by Equation 1. A linear equation has been fit to both sets of data.

Table 2: Maximum and full-width half-maximum

Patina	**max** (%)		**FWHM** (^{o})	
	C2RMF	INP	C2RMF	INP
Green rough	0.3	0.3	20.57	16.04
Black rough	3.4	2.8	13.15	15.48
Red rough	3.4	2.4	8.32	10.32
Green smooth	9.3	16.5	6.53	9.88
Black smooth	11.8	49.1	6.00	9.87
Red smooth	2.0	3.4	5.07	12.73

The results show that there is a linear relationship between the roughness and the FWHM. As the roughness increases so does the FWHM and the spread of the *sparkle* curve gets wider. Considering a theoretical surface with a roughness equal to 0 would imply a perfect mirror-like surface. Said surface would present a very narrow distribution with a FWHM close to the y-intercept since most of the light would be reflected at the angle of specular reflection. On the other hand, a very rough surface where many facets are oriented at all possible orientations implies that at all angles of tilting a fraction of the light would be reflected at the same angle as the observation. Thus, the curve would be spread over a large range of angles.

Figure 7 shows the maximum taken from Figure 5 and Figure 6 as a function of surface roughness, Sa, calculated according to Equation 1. A two-term exponential model of the form $Ae^{Bx} + Ce^{Dx}$ has been fitted to both sets of data, where A, B, C and D are constants.

Table 3: Arithmetical mean height (μm) for each patina calculated according to ISO25178 standards. Scanning resolution of 2 μm, using an 8 mm probe.

Green rough	**Red rough**	**Black rough**
31.51	12.48	21.91
Green smooth	**Red smooth**	**Black smooth**
5.33	6.19	3.45

As the roughness increases, the *sparkle* decreases. Moreover, as the roughness approaches 0, the *sparkle* tends to infinity. Considering the same theoretical surfaces as above, it is expected that a surface with a roughness equal to 0 would have a maximum of *sparkle* tending to infinity as all the light incident on the surface would be reflected at the angle of specular reflection. On the other hand, surfaces with very high roughness would reflect only a partial amount of the radiant incident flux and thus the *sparkle* would be lower.

Although this method has been applied to goniometrically characterise the *sparkle* of bronze patinas, there are limitations on the range of samples that can be analysed with it. This method can only be applied to surfaces that are flat at a macro-scale. As commonly found in material appearance experiments, the surface topography and shape of the object play an important role in the light-matter interactions. Thus, at a macro-scale, when the interface between the light and the object is no longer a plane, computing the difference between the angle of observation and the angle of incidence is not sufficient.

However, at a micro-scale the surface topography poses another limitation. As seen on Figure 7, as the roughness increases, the maximum of the sparkle distribution tends towards 0. Thus, samples with a roughness higher than 35 μm cannot be characterised following this method.

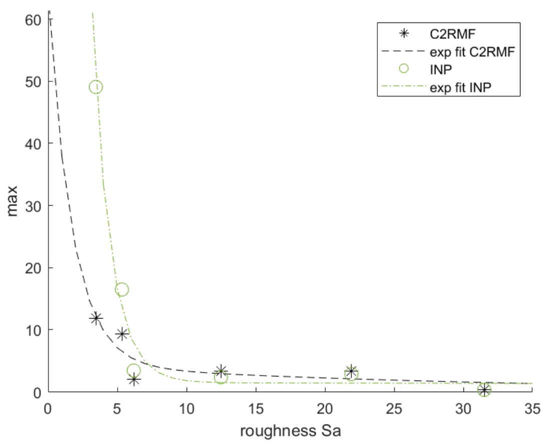

Figure 7: Maximum as a function of Sa (μm). Star markers are given for data taken at C2RMF and round markers for data taken at INP. The fit used is a two-term exponential model.

Robustness and repeatability

The robustness and repeatability of this experiment has been tested by repeating the experiment at two different institutions. The results obtained are presented in Figure 7 and Figure 8. There are slight differences in the distributions of maximum and FWHM as a function of roughness. Although both sets of results follow similar distributions, the constants used to fit the exponential model in the case of Figure 7 and the gradients on Figure 8 differ. However, it must be noted that the relative difference between each individual sample is relatively similar. The aim of this method is not to give an absolute result as a measure of *sparkle*, but to provide a simple protocol which compares the appearance of different surfaces. Since the results come from different equipment (camera and light source) it is evident that a calibration step is necessary to obtain more robust and comparable results.

However, there is potential for this method to be widely used in the cultural heritage field. This protocol is very accessible since the necessary materials can be found in any cultural heritage institution such as museums, laboratories and conservation workshops. The presented method is quick and inexpensive, and can be performed by non technical experts using only a CCD camera, a light source and a tilting stage.

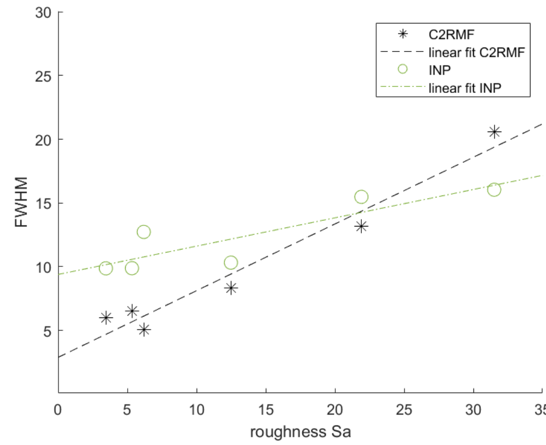

Figure 8: Full-width half-maximum as a function of Sa (μm). Star markers are given for data taken at C2RMF and round markers for data taken at INP. The fit used is a linear model.

Discussion

As mentioned previously, this method provides a relative characterisation of samples in terms of their roughness and appearance. However, in order to make these results more robust and accurate, a calibration step is needed. This could be done by calibrating the light source so the same amount of light is incident on the samples. Another possibility would be to make calibration targets with known roughness and gloss. This would allow a calibration step to be introduced in the processing pipeline to obtain repeatable results.

To produce such calibration targets, a possibility would be to analyse a set of samples ranging over a larger scale of roughness. In the case of the patinas used for this investigation, they have been labelled as smooth and rough. However, from the roughness measurements, it is clear that the samples cannot be just discriminated by smooth/rough. Moreover, they do not represent an equally distributed range of roughnesses either. Since the smooth samples do not vary very much in roughness, they can be considered almost as one set of similar samples. By having a wider range of roughnesses, the relationship between *sparkle* and roughness could be better understood. Moreover, the morphological characteristics of the surface such as the orientation and size of its micro-facets could be further related to the sparkle, as it is done by Ferrero *et al.* [2], where these parameters are fitted into a model to predict the sparkle.

Additionally, this method is limited by the scale of analysis. While this investigation has been done at a micro-scale, it is important to also evaluate if this method can be applied to the larger, macro-scale. Ferrero *et al.* defines sparkle as a texture observed at a distance of a meter or less. This limits the study of sparkle to smaller surfaces. From a cultural heritage point of view, it would be valuable to use this protocol as a means of monitoring samples before and after restoration processes such as cleaning and waxing in the case of patinas. Waxing is a common procedure which increases the saturation of the patinas and makes the surface glossier. This monitoring process could help conservators choose the most appropriate methods for conservation and restoration of cultural heritage objects.

Conclusion

In this work, a method initially proposed for sparkle measurements has been applied to goniometrically characterise the appearance of bronze patinas. Although there is an inherent difference between sparkly surfaces and the patinated bronze samples, it is possible to obtain information on the appearance of the bronze patinas.

A clear dependence between *sparkle* and angle of rotation has been found. As expected, the surfaces considered smooth have a narrow curve with a higher peak than the surfaces considered rough, which have a much wider curve and lower peak. Moreover, it has been found that there is linear relationship between the roughness of the samples and the FWHM of the *sparkle* distribution curve for each sample. Additionally, a negative exponential relationship has been found between the maximum of the *sparkle* curve and the roughness of the surfaces. Further, the experiment has been repeated at two institutions using the available equipment, giving similar results for the same set of samples.

Future work includes adding a calibration step in the processing of the data to make protocol more robust and repeatable. This could be done by exploring further the relationship between surface micro-topography and sparkle. By characterising the size and orientation of surface facets, a better understanding of the light-matter interactions at the surface can be achieved. Moreover, it is suggested to use the protocol as a monitoring tool for conservation methods.

Acknowledgements

This research was funded with the support of CHANGE Cultural Heritage Analysis for New Generations European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 813789.

The authors would like to thank Anne Maigret for her help with the image acquisition and Dominique Robcis for access to the bronze patinas used in this experiment.

References

[1] F. Mathis, S. Descamps, D. Robcis and M. Aucouturier, "Original surface treatment of copper alloy in ancient Roman Empire: chemical patination on a Roman strigil", Surface Engineering, 21, p. 346-351 (2005).

[2] A. Ferrero, J. Campos, A.M. Rabal and A. Pons, "A single analytical model for sparkle and graininess patterns in texture of effect coatings", Optics Express, 21, p. 26812-26819 (2013).

[3] JTC 12 (D2/D1/D8): The measurement of sparkle and graininess. url=http://cie.co.at/technicalcommittees/measurement-sparkle-and-graininess (Accessed 01/06/2021)

[4] A. Ferrero and S. Bayón, "The measurement of sparkle", Metrología, 52:2, p. 317-323 (2015).

[5] A. M. Rabal, A. Ferrero, J. Campos, J. L. Fontecha, A. Pons, A. M . Rubiño and A. Corróns, "Automatic gonio-spectrophotometer for the absolute measurement of the spectral BRDF at in- and out-of-plane and retroreflection geometries", Metrología, 49, p. 213-223 (2012).

[6] E. Joseph, A. Simon, S. Prati, M. Worle, D. Job and R. Mazzeo, "Development of an analytical procedure for evaluation of the protective behaviour of innovative fungal patinas on archaeological and artistic metal artefacts", Analytical and Bioanalitical Chemistry, 9 (2011).

[7] V. Hayez, T. Segato, A. Hubin and H. Terryn, "Study of copper nitrate-based patinas", Journal of Raman Spectroscopy, 37:10, p. 1211-1220 (2006).

[8] A. Giumlia-Mair, C. Albertson, G. Boschian, G. Giachi, P. Iacomussi, P. Pallecchi, G. Rossi, A. N. Shugar and S. Stock, "Surface characterisation techniques in the study and conservation of art and archaeological artefacts: a review", Materials Technology, 25:5, p. 245-261 (2010).

[9] O. Sidorov, J. Y. Hardeberg, S. George, J. S. Harvey and H. E. Smithson, "Changes in the Visual Appearance of Polychrome Wood Caused by (Accelerated) Aging", Proc. EI, Material Appearance Conference Proceedings, pp. 60-1-60-8(8) (2020).

[10] P. Iacomussi, M. Radis and G. Rossi, "Goniometric and colorimetric properties of paints and varnish", Proc. SPIE, Measuring, Modeling, and Reproducing Material Appearance, p.201 1 214 (2015).

[11] J. Edelson, "Elaboration d'une méthodologie d'analyse des patines artificielles sur les bronzes du patrimoine artistique", Master's thesis - École des Mines de Paris (2000).

[12] M. Page, "Création d'objets mats: optimisation d'un procédé d'impression en relief en termes d'apparence", PhD diss. Conservatoire national des arts et metiers - CNAM (2018).

[13] ISO25178-2:2012 Geometrical product specifications (GPS) - Surface texture: Areal - Part, 2: Terms, definitions and surface texture parameters.

Author Biography

Yoko Arteaga is a Marie Skłodowska-Curie early stage research fellow at the Centre of Research and Restoration of the Museums of France and part of the Colourlab at the Norwegian University of Science and Technology. She has a background in Physics and Colour Science. For her PhD she is working in the development of techniques to characterise surface topography and appearance for cultural heritage objects.

Clotilde Boust received her engineering degree in photography from the Ecole Nationale Supŕieure Louis Lumière, France in 1998. After working for two years as a colour consultant in the press industry and one year as researcher in the Vision laboratory of the National Museum of Natural History, she began a Ph.D. in image quality with Océ Print Logic Technologies and Paris VI University. She is now the head of the Imaging Group at the Centre for Research and Restoration of the Museums of France (C2RMF).

Angèle Dequier is a scientific documentalist for the French Ministry of Culture and a photographer-radiologist. She has worked at the Louvre Museum and at the National institute of Cultural Heritage (INP) on 3D projects and applications of imaging in conservation and restoration of cultural objects. She is currently head of imaging sector at the Arc'Antique underwater archaeology laboratory in Nantes, France.

Jon Y. Hardeberg is Professor of Colour Imaging at NTNU, Department of Computer Science, The Norwegian Colour and Visual Computing Laboratory, Gjøvik, Norway. His current research interests include spectral imaging, image quality, colour management, material appearance, cultural heritage imaging, and medical imaging, and he has co-authored more than 300 publications within the field. He has led several research projects funded by the Research Council of Norway, been NTNU's representative in two Erasmus Mundus Joint Master Degrees (CIMET and COSI), and the coordinator of three Marie Sklodowska Curie ITN projects (CP7.0, ApPEARS, CHANGE).