

Evaluation of Surface Topography and Microstructure of Electroplated Copper Ultraprecision-machined with a Single-crystal Diamond Tool

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Abstract –We investigated in detail the surface characteristics of ultraprecision-machined electroplated copper (Cu). Electroplated Cu, as well as electroless-plated nickel phosphorus (NiP) and oxygen-free copper (OFC) for comparison, was machined using an ultraprecision turning machine with a single-crystal diamond tool. The resulting surfaces were measured over an area of $140\ \mu\text{m} \times 105\ \mu\text{m}$ by white-light interferometry, revealing that the electroplated Cu surface exhibited the lowest surface roughness of **0.83** nm root-mean-square (RMS) among the three materials. For a smaller area of $1\ \mu\text{m} \times 1\ \mu\text{m}$ measured by atomic force microscopy, the electroplated Cu surface exhibited a sand-like texture with a surface roughness of **1.74** nm RMS. Power spectral density (PSD) analysis revealed that the electroplated Cu surface had a lower PSD than the OFC surface below a spatial frequency of $2 \times 10^4\ \text{mm}^{-1}$ and was comparable to the electroless-plated NiP surface below a spatial frequency of $1 \times 10^3\ \text{mm}^{-1}$. Electron backscatter diffraction (EBSD) and X-ray diffraction (XRD) analyses indicated that the electroplated Cu was composed of fine crystalline microstructures, which was probably the reason for the sand-like texture. Overall, the electroplated Cu surface exhibited excellent smoothness and machinability, superior to the OFC surface and close to electroless-plated NiP surface, demonstrating its suitability for ultraprecision optical components.

Keywords: Surface, Machining, Diamond turning, Electroplated Cu, Electroless-plated NiP, Oxygen-free copper

1. Introduction

In optical fabrication, an ultraprecision machine tool with a single-crystal diamond tool is effectively used to obtain smooth and highly accurate metal surfaces [for optical components](#), such as those of mirrors and injection molds [1, 2]. Electroless-plated nickel phosphorus (NiP) is [a widely used material](#) for single-crystal diamond machining to achieve a smooth surface [3-14]. However, the major issues in machining electroless-plated NiP are tool wear and chipping [4, 5, 7, 8-10, 13, 14].

[\[C-1\] To overcome this problem, alternative materials that can achieve smooth optical surfaces with lower tool wear are desirable. Because copper is softer than electroless-plated NiP, machining copper may help reduce the wear and chipping of the diamond tool.](#) Oxygen-free copper (OFC) is [one candidate material because it can be machined with](#) a single-crystal diamond tool [15-22]. However, the machined surface of OFC often exhibits irregularities owing to crystal grains, resulting in an increase in surface roughness [15, 16, 18, 19, 21]. [\[B-1, C-2\] Although OFC has high thermal conductivity and is suitable for optical components subjected to high thermal loads when adequate cooling is applied, these surface irregularities can affect the surface quality when extremely smooth optical surfaces are required. Therefore, it is important to investigate alternative copper-based materials that can maintain the advantages of OFC while enabling the formation of smoother optical surfaces by ultraprecision diamond machining.](#)

[\[C-3\] Electroplated copper \(Cu\) is therefore expected to be a promising alternative material for optical components. Because electroplated Cu generally has finer grains than OFC, it may enable the formation of smoother optical surfaces. In addition, electroplated Cu is also softer than electroless-plated NiP and is therefore expected to reduce tool wear and chipping during](#)

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diamond machining. [B-2] Furthermore, when a copper electroplating layer is applied to the surface of OFC, it may enable the fabrication of optical components that combine extremely smooth optical surfaces with high thermal conductivity.

In our previous studies [23, 24], we demonstrated the successful fabricating of mirror arrays with high shape accuracy using an ultraprecision milling machine with a single-crystal diamond tool. [B-3] In the machining, a mirror surface was formed on a 1-mm-thick electroplated Cu layer on a block, allowing the mirror array to be machined into the thick copper layer. The reason for the use of electroplated Cu was that it is considered to cause less tool wear and chipping than electroless-plated NiP. Moreover, we expected that the grain size of electroplated Cu would likely be smaller than that of OFC, providing smooth surfaces without irregularities. In our previous studies, we focused on the shape accuracy of the electroplated Cu surface in ultraprecision milling, and we have not studied the roughness of the machined surface in detail.

[A-1] For optical components, the surface roughness after machining is a critical factor because it directly affects optical performance. To the best of our knowledge, the surface characteristics of electroplated Cu after ultraprecision diamond machining have not yet been fully clarified [23-31]. Understanding these surface characteristics is important for the design and fabrication of high-performance optical components. Therefore, the objective of this study is to clarify the surface roughness characteristics of electroplated Cu after ultraprecision machining and to compare them with those of OFC and electroless-plated NiP.

[A-2] To achieve this objective, the surfaces of electroplated Cu, OFC, and electroless-plated NiP were machined by ultraprecision turning with a single-crystal diamond tool, and the resulting surface roughnesses in areas of $140\ \mu\text{m} \times 105\ \mu\text{m}$ and $1\ \mu\text{m} \times 1\ \mu\text{m}$ were evaluated. Moreover, the microstructure of the machined surfaces was analyzed by electron backscatter diffraction (EBSD) and X-ray diffraction (XRD) to investigate the relationship between the microstructure and the surface topography. [A-3] This study provides insight into the feasibility of electroplated Cu as an alternative material for ultraprecision optical fabrication.

2. Experimental Methods

The electroplated Cu specimens and the OFC specimens were cylinders with a diameter of 20 mm and a height of 10 mm. The NiP-electroless-plated specimens were cylinders with a diameter of 20 mm and a height of 7 mm. Cu plating and NiP plating were carried out by Kyowa Sangyo Corporation, Japan. The thicknesses of the electroplated Cu and electroless-plated NiP were approximately 0.2 mm and 0.1 mm, respectively. The substrates for the electroplated Cu and the electroless-plated NiP were OFC and stainless-steel cylinders, respectively. Cu electroplating was carried out using a plating solution in which Cu sulfate served as the main constituent. Electroless-plated NiP used in this study had a phosphorus concentration of approximately 11%.

The face of the specimens was turned with an ultraprecision turning machine with a single-crystal diamond tool having a nose radius of 0.5 mm. First, all specimens were roughly turned. [H] After replacing the rough-turning tool with a new one, finish turning was performed using the same tool for all materials. The finishing process was performed sequentially on the OFC, electroplated Cu, and electroless-plated NiP [H] so that electroless-plated NiP, which was considered most likely to cause tool damage, was machined last. The depth of cut was set to 5 μm and 2 μm in the rough and finishing processes, respectively. The tool feed rate was 2 mm/min, and the spindle speed was 1000 rpm for each process. At these tool feed rate and spindle speed, the distance between tool marks is calculated to be 2 μm .

After turning, the surface topographies of the machined surfaces were measured using a white-light interferometer (WLI) (Zygo, NewView 7300) and an atomic force microscope (AFM) (Shimadzu, SPM-9700HT). In the measurement using the WLI, an area of $140\ \mu\text{m} \times 105\ \mu\text{m}$ was measured with a horizontal resolution of 220 nm. In the measurement using the AFM, an area of $1\ \mu\text{m} \times 1\ \mu\text{m}$ was measured with a horizontal resolution of 4 nm. Both measurements were performed at approximately the midpoint in the radial direction of the workpiece, 5 mm from the center. Moreover, the microstructure of the machined surfaces was analyzed by XRD (Rigaku, SmartLab) and EBSD (Oxford Instruments, Symmetry). XRD analysis was performed using the in-plane method. This method enables the investigation of the surface structure by limiting X-ray penetration through grazing incidence.

3. Results and Discussion

3.1. Machined surface topography

Figure 1 shows the topographies of the machined surfaces measured using the WLI. Figures 1(a), 1(b), and 1(c) correspond to the topographies of the OFC, electroplated Cu, and electroless-plated NiP surfaces, respectively. As shown in Fig. 1(a), the OFC surface shows steps, which probably result from crystal grains. In Fig. 1(a), the height of the step through the center of the

94 measured area is approximately 5 nm, and measurements performed at several other locations also revealed **[G]** step structures
 95 showing comparable overall morphology with minor variations in contour and height. The root-mean-square (RMS) roughness
 96 of the OFC surface was 1.78 nm. As shown in Fig. 1(b), the electroplated Cu surface shows no steps. The RMS roughness of the
 97 electroplated Cu surface was 0.87 nm, showing a smoother surface than the OFC surface. As shown in Fig. 1(c), the electroless-
 98 plated NiP surface also shows no step structures, but two hills can be observed with an amplitude of approximately 3 nm and an
 99 interval of approximately 90 μm . The RMS roughness of the electroless-plated NiP surface was 1.21 nm. Since similar hills were
 100 observed in measurements at several locations, it is considered that concentric waves with a pitch of approximately 90 μm were
 101 generated on the surface. Referring again to the electroplated Cu surface shown in Fig. 1(b), high regions can be observed at
 102 approximately 90 μm intervals, although they are less distinct than those on the electroless-plated NiP surface. This reduced
 103 clarity may be attributed to the softness of the electroplated Cu, which could have caused deformation during machining. For the
 104 OFC surface shown in Fig. 1(a), it is likely that the large step structures make it difficult to observe the hills. Although not shown
 105 here, the hills can be observed on the OFC surface when the step height is small. From these results, it is inferred that these hills,
 106 i.e., the waviness, were not caused by the material properties but by the motion error of the ultraprecision turning machine.

107 **[E-1]** In addition, measurements were performed at three different locations near the radial midpoint of each workpiece, and
 108 the average, maximum, and minimum RMS roughness were obtained. The average, maximum, and minimum RMS roughness
 109 were 1.65, 1.78, and 1.52 nm for OFC; 0.83, 0.87, and 0.77 nm for electroplated Cu; and 1.26, 1.30, and 1.21 nm for electroless-
 110 plated NiP, respectively. The relatively large range between the maximum and minimum values for OFC is attributed to
 111 variations in the contour and height of the crystal grain boundary steps. Thus, the relative magnitudes of the average RMS
 112 roughness values obtained from multiple measurements were consistent with those shown in Fig. 1.

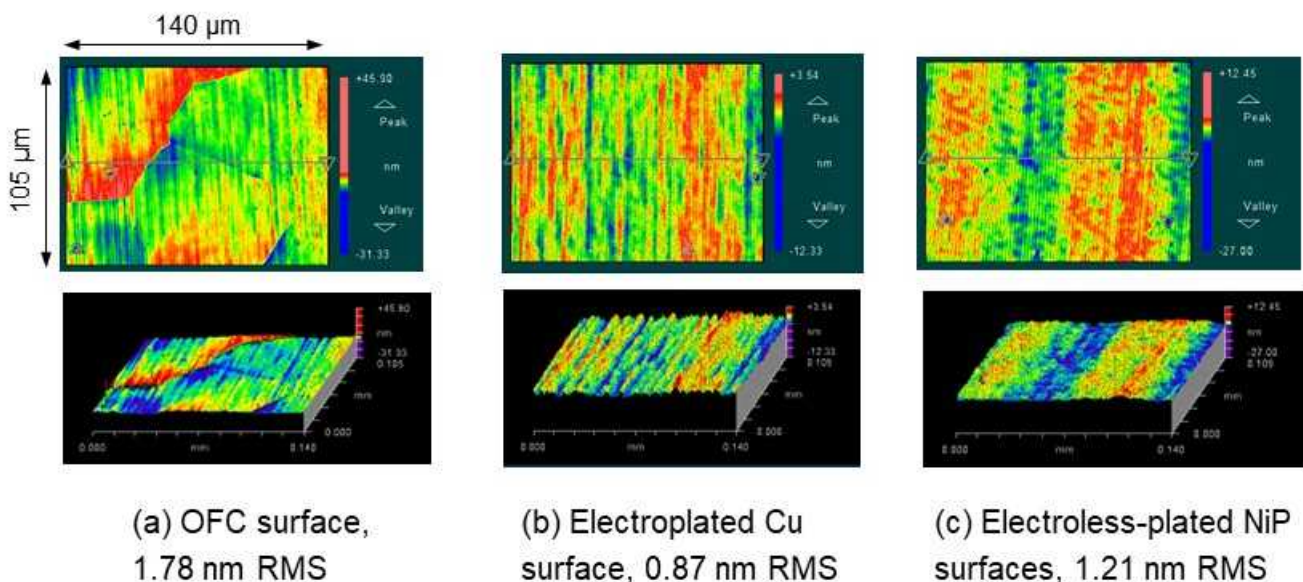


Fig. 1. Surface topographies measured with a WLI.

Next, the surface topographies within an area of $1\ \mu\text{m} \times 1\ \mu\text{m}$ were measured with the AFM. Figure 2 shows the measurement results, including the surface topographies together with cross-sectional profiles approximately through their centers. The OFC surface had tiny holes, as shown in Fig. 2(a), whereas the electroplated Cu surface had a sand-textured finish, as shown in Fig. 2(b). The RMS roughness of the electroplated Cu surface was smaller than that of the OFC surface, that is, 1.72 nm and 2.32 nm, respectively. Compared with these surfaces, the electroless-plated NiP surface was smoother, as shown in Fig. 2(c). For the electroless-plated NiP surface, the RMS roughness was 1.50 nm. **[D]** In Fig. 2(c), small elevations (white dots) are observed scattered on the surface. These are considered to be fine chips generated during turning adhered to the surface. After turning, the surface was only rinsed with an organic solvent using a wash bottle without wiping, in order to preserve the surface morphology as much as possible. As a result, some fine chips likely remained on the machined surface. Thus, although each machined surface exhibited a different surface appearance, the electroplated Cu surface was not as smooth as the electroless-plated NiP surface but was smoother than the OFC surface when uniformly compared in terms of RMS roughness.

[J] Figure 3 shows the AFM measurement result for a $10\ \mu\text{m} \times 10\ \mu\text{m}$ area of the electroless-plated NiP surface machined last. Regular tool marks are observed, and each tool mark exhibits a profile corresponding to the arc of the tool tip. These observations indicate that the original geometry of the cutting edge was almost maintained during the finishing process, suggesting that no significant tool wear or chipping occurred.

[E-2] In addition, measurements were performed at three different locations near the radial midpoint for each material. The average, maximum, and minimum RMS roughness were 2.29, 2.32, and 2.27 nm for OFC; 1.74, 1.77, and 1.72 nm for electroplated Cu; and 1.44, 1.50, and 1.36 nm for electroless-plated NiP, respectively. Thus, the relative magnitudes of the average RMS roughness values obtained from multiple measurements were consistent with those shown in Fig. 2.

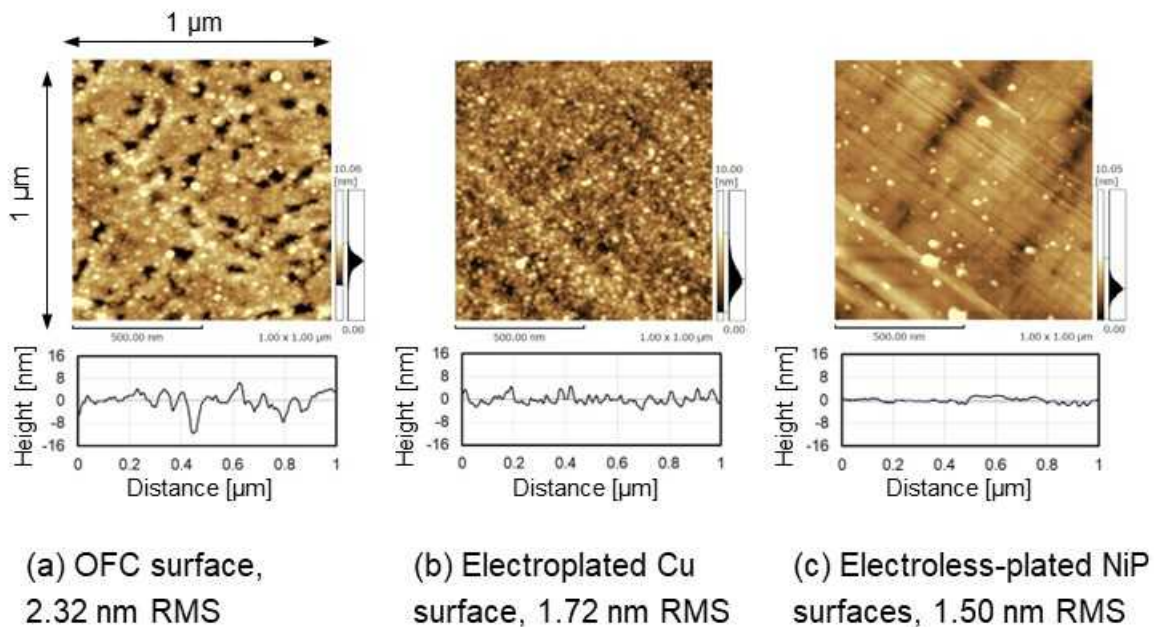


Fig. 2. Surface topographies measured with an AFM.

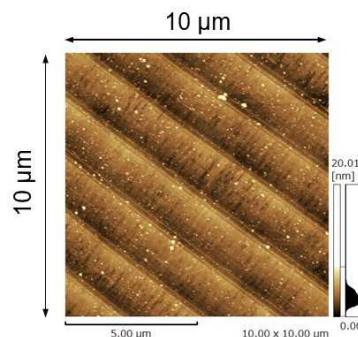


Fig. 3. Surface topography measured with an AFM: measurement result for a $10\ \mu\text{m} \times 10\ \mu\text{m}$ area of the electroless-plated NiP cut surface.

133 **3.2. Power spectral density (PSD) analysis**

134 We performed the PSD analysis of the obtained surface profiles. Figure 4 shows the PSD curves calculated from the surface
 135 profiles measured with the WLI. **[K-1] Specifically, the one-dimensional (1D) PSD curve obtained by WLI was calculated**
 136 **using the software built into the measurement system. The PSD was calculated from a line profile extracted from the center of**
 137 **the measured surface, and the analysis was performed over the full evaluation length of the profile. The PSD curve shown**
 138 **represents the average of three measurements for each material.**

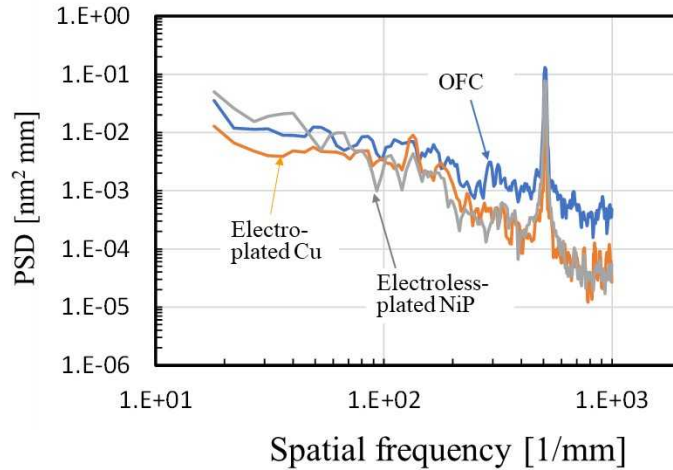


Fig. 4. PSD curves calculated from topographies of various machined surfaces measured with a WLI.

139 As shown in Fig. 3, the PSD of the OFC surface tends to be the highest among the three materials, whereas those of the
 140 electroplated Cu and electroless-plated NiP surfaces are similarly low. Thus, the electroplated Cu and electroless-plated NiP
 141 surfaces exhibited comparable smoothness and were smoother than the OFC surface. Furthermore, the electroplated Cu and
 142 electroless-plated NiP surfaces exhibited similar spatial frequency characteristics over the entire frequency range.

143 In the previous section, we described that the electroplated Cu and electroless-plated NiP surfaces exhibited hills at intervals
 144 of approximately 90 μm . Although the peaks corresponding to these hills exist, the peaks do not appear in the PSD curves because
 145 they must be located in the low-frequency region outside the plotted range. However, it is possible that the increase at the left
 146 end of the PSD curve of the electroless-plated NiP surface is related to the presence of these hills. Moreover, Fig. 4 shows that

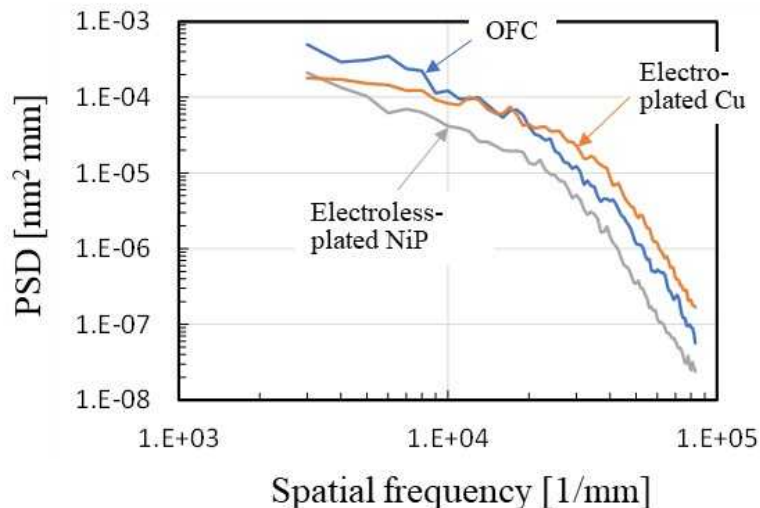


Fig. 5. PSD curves calculated from topographies of various machined surfaces measured with an AFM.

each PSD curve exhibits a similar sharp peak at a spatial frequency of approximately $5.0 \times 10^3 \text{ mm}^{-1}$. This corresponds to a tool-mark interval of about $2 \mu\text{m}$ attributed to turning.

Figure 5 shows the PSD curves calculated from the surface profiles measured with the AFM. Similarly, the one-dimensional (1D) PSD curves obtained from the AFM measurements were calculated using in-house software. The software calculates the PSD for all cross-sectional profiles across the measured surface, and the analysis was performed over the full evaluation length of each profile. The PSD curves shown in the figure represent the average of these profiles and correspond to the surface data of the measured area shown in Fig. 2. The PSD of the OFC surface was the highest among all materials at spatial frequencies below $1 \times 10^4 \text{ mm}^{-1}$, likely attributable to the presence of the tiny holes on the surface. For the OFC surface, the high PSD in the low-frequency region below $1 \times 10^4 \text{ mm}^{-1}$ is considered to result in the largest RMS value among the three materials. On the other hand, the PSD of the electroplated Cu surface was the highest among all materials at spatial frequencies above $2 \times 10^4 \text{ mm}^{-1}$, which is considered to result from the sand-like texture appearing on the surface.

Overall, from the PSD analysis results shown in Figs. 4 and 5, it can be concluded that the PSD of the electroplated Cu surface is lower than that of the OFC surface at spatial frequencies below $2 \times 10^4 \text{ mm}^{-1}$. Furthermore, at spatial frequencies below $1 \times 10^3 \text{ mm}^{-1}$, the PSD of the electroplated Cu surface is as low as that of the electroless-plated NiP surface, indicating comparable surface quality.

3.3. Material microstructural analysis

The microstructure of the machined electroplated Cu was analyzed by EBSD. This analysis was carried out on the machined surfaces without post-treatments such as polishing and etching, because the machined electroplated Cu was smooth enough for analysis. Figure 6 shows the results of the EBSD analysis, in which (a) the grain map over an area of $6 \mu\text{m} \times 6 \mu\text{m}$ and (b) its grain size distribution histogram are shown. EBSD data were analyzed by defining misorientations exceeding 5° as grain boundaries. The measurements were conducted by scanning an electron beam at a pitch of 20 nm , and the lower detection limit of the EBSD instrument was 40 nm . Thus, fine grains with sizes ranging from 40 to 280 nm were detected on the electroplated Cu. The black areas in Fig. 6(a) are considered to correspond to either micro-grains smaller than 40 nm or amorphous regions.

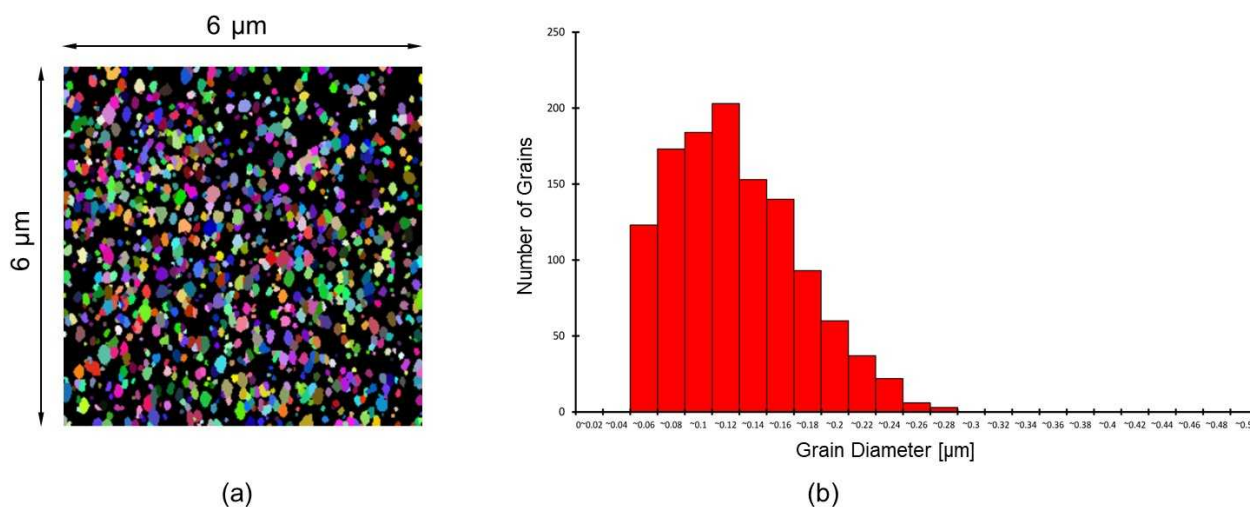


Fig. 6. Results of EBSD analysis of the machined electroplated Cu surface. (a) Grain map and (b) grain size distribution histogram.

Next, the microstructure of the machined electroplated Cu surface was analyzed by XRD. The electroless-plated NiP surface was also analyzed as a reference for comparison; in general, the electroless-plated NiP with a phosphorus concentration of 11 % is amorphous [32, 33]. The XRD analysis was also carried out for the machined surfaces without post-treatments. Figures 7(a) and 7(b) show the XRD profiles of the electroless-plated NiP and electroplated Cu surfaces, respectively. In Fig. 7(a), the XRD profile of the electroless-plated NiP surface is broad, which indicates that the electroless-plated NiP is amorphous, as generally known. In contrast, the XRD profile of the electroplated Cu surface in Fig. 7(b) is not broad. Instead, multiple peaks attributed to Cu were detected. This indicates that there was no amorphous region on the electroplated Cu surface, and the electroplated Cu is crystallized and exists in a polycrystalline state. Table 1 shows the peak fitting results for the major Cu-related reflections

178 shown in Fig. 7(b). Table 1 lists the relative intensities of other reflections normalized to the (111) reflection and the average
 179 crystallite sizes calculated from the full width at half maximum (FWHM) of each peak. The average crystallite size for each
 180 reflection ranged from 20 to 47 nm. Thus, the absence of an amorphous phase on the electroplated Cu indicates that the black
 181 regions in the EBSD grain map in Fig. 6 are not amorphous, but they are micrograins smaller than 40 nm, which is below the
 182 measurement limit.

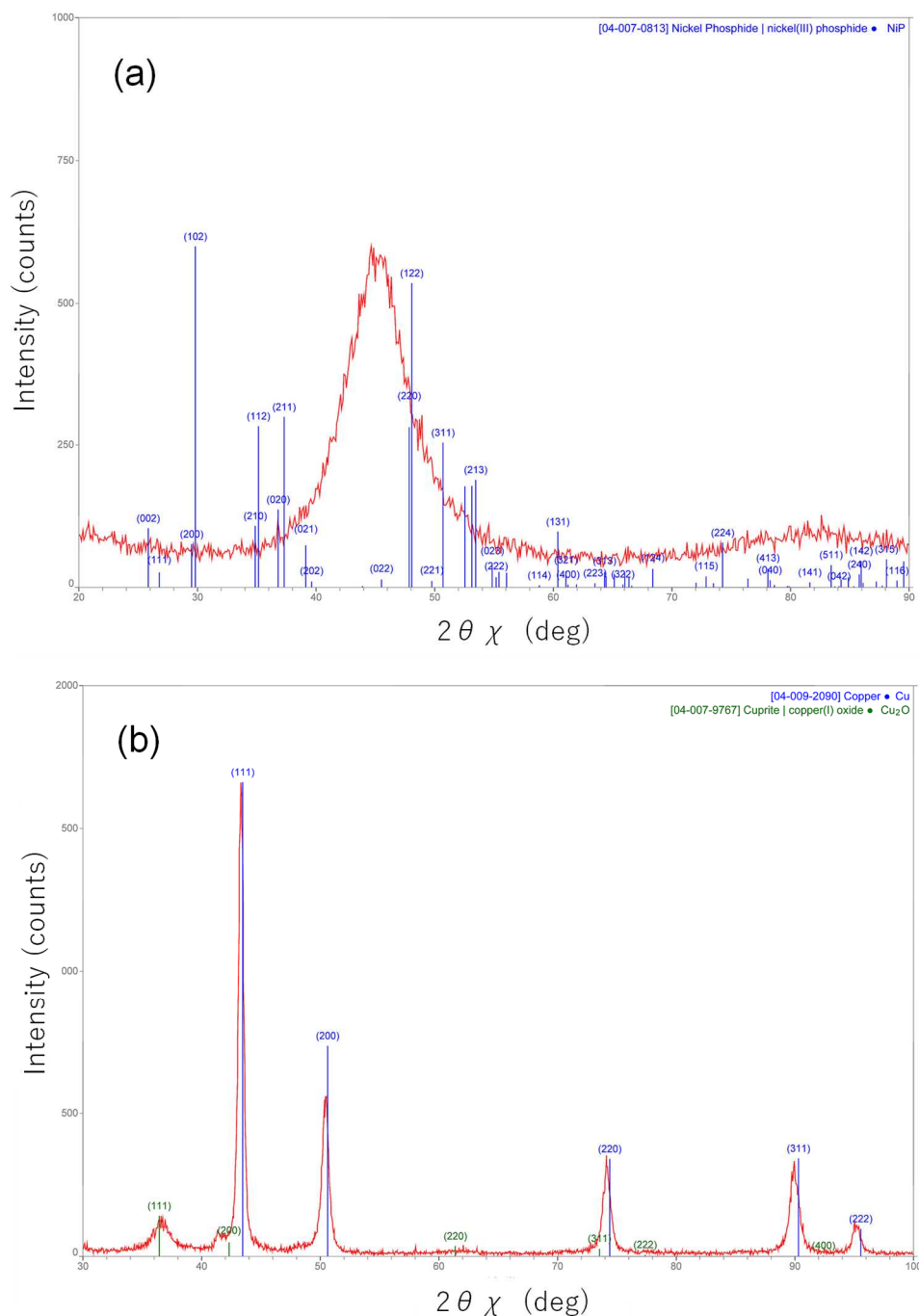


Fig. 7. XRD profiles of the machined (a) electroless-plated NiP and (b) electroplated Cu surfaces.

184 The difference between the EBSD and XRD results arises from both their measurement principles and the nature of what
 185 they detect. EBSD identifies grains on the basis of orientation differences and merges slightly misoriented crystallites into a
 186 single grain if the misorientation is below the threshold angle. In contrast, XRD estimates the size of crystallites, i.e., coherently
 187 diffracting domains within a grain that correspond to subdomains of a crystal. Consequently, the crystallite sizes obtained by
 188 XRD analysis tend to be smaller, whereas the grain sizes measured by EBSD analysis appear larger. In any case, the electroplated
 189 Cu surface exhibits fine crystalline microstructures; thus, the sand-like texture observed on the machined electroplated Cu surface,
 190 as shown in Fig. 2(b), is considered to result from these fine microstructures. Moreover, a possible reason for the absence of the
 191 step structures on the machined electroplated Cu surface, as shown in Fig. 1(b), is that its crystal grains are too small to
 192 significantly affect the machining process.

Table 1. Peak fitting results of the obtained XRD profile of electroplated Cu surface.

(hkl)	2θ	χ (°)	d (Å)	Height	Area	Area (%)	FWHM (°)	Crystallite size (nm)
(111)	43.279		2.0888	1156	15563	100.0	0.468	47
(200)	50.381		1.8098	370	6875	44.2	0.646	23
(220)	74.076		1.2788	210	4250	27.3	0.695	23
(311)	89.877		1.0905	207	4771	30.7	0.822	20
(222)	95.099		1.0440	71	1208	7.8	0.703	26

193 4. Conclusions

194 We investigated the roughness and microstructures of the electroplated Cu machined by ultraprecision diamond turning, as
 195 well as those of the OFC and electroless-plated NiP for comparison.

196 **[F-1]** The average RMS surface roughnesses measured over a large area of $140 \mu\text{m} \times 105 \mu\text{m}$ using a WLI in ascending order
 197 were **0.83 nm for electroplated Cu, 1.26 nm for electroless-plated NiP, and 1.65 nm for OFC.** Step structures were observed on
 198 the OFC surface, probably caused by crystal grains, leading to larger RMS roughnesses. Concentric waves were observed on the
 199 NiP plating; however, they are considered to be caused not by the material itself but by the motion error of the ultraprecision
 200 turning machine. The electroplated Cu surface appeared the smoothest with no step structures.

201 For a smaller area of $1 \mu\text{m} \times 1 \mu\text{m}$ measured using an AFM, **[F-2]** the average RMS surface roughnesses in ascending order
 202 were **1.44 nm for electroless-plated NiP, 1.74 nm for electroplated Cu, and 2.29 nm for OFC.** The OFC surface showed tiny
 203 holes, whereas the electroplated Cu surface showed a sand-textured finish. In comparison, the electroless-plated NiP surface was
 204 smoother than the other two.

205 Focusing on the electroplated Cu, the results of PSD analysis can be summarized as follows. At spatial frequencies below 2
 206 $\times 10^4 \text{mm}^{-1}$, the PSD of the electroplated Cu surface is lower than that of the OFC surface. When the range is narrowed to spatial
 207 frequencies below $1 \times 10^3 \text{mm}^{-1}$, the PSD of the electroplated Cu surface becomes comparable to that of the electroless-plated
 208 NiP surface and remains lower than that of the OFC surface.

209 Microstructural analysis by EBSD revealed fine crystal grains on the electroplated Cu surface ranging from 40 to 280 nm,
 210 whereas XRD indicated smaller crystallite sizes of 20–47 nm, confirming that the electroplated Cu is fully crystallized and
 211 polycrystalline. The discrepancy between the EBSD and XRD results arises from differences in their measurement principles.
 212 In any case, the electroplated Cu was found to be composed of microcrystalline grains, as confirmed by both EBSD and XRD
 213 analyses. Therefore, the sand-like texture observed on the machined electroplated Cu surface is likely due to the presence of
 214 these microcrystalline grains. Moreover, a possible reason for the absence of the step structures on the machined electroplated
 215 Cu surface is that its crystal grains are too small to significantly affect the machining process.

216 Overall, the findings demonstrate that electroplated Cu provides superior surface smoothness and machinability compared
 217 with OFC, although it is slightly inferior to electroless-plated NiP at high spatial frequencies, highlighting its suitability for the
 218 ultraprecision machining of optical components, where both high shape accuracy and small surface roughness are essential.

219 **Acknowledgments**

220 We thank Hideyuki Aizawa of Sendai Nikon Corporation for turning the specimens. We also thank Hideki Munakata of
221 Chiba Institute of Technology for measuring the surface topographies.

222 **Funding**

223 This research received no external funding.

224 **Conflicts of interest**

225 The authors declare that they have no conflicts of interest.

226 **Data availability statement**

227 The data that support the findings of this study, including those not shown in this article, are available from the corresponding
228 author upon reasonable request.
229

230 **Author contribution statement**

231 HT conceptualized and supervised the study, participated in all experiments, interpreted all the data, and wrote the manuscript.
232 HA supervised and managed the machining experiments, and provided expert advice. MK supervised and managed the
233 measurements, interpreted the data, and provided expert advice. All authors have read and approved the final manuscript.

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