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**Abstract.** Single-point diamond turning is a useful optical fabrication method for simultaneously obtaining a smooth surface and generating an accurate shape. Generally, a single-crystal diamond tool has been used in the single-point diamond turning method and a degree of the wear on the diamond tool is unavoidable. Tool wear causes the degradation of the surface quality, surface roughness, and shape accuracy of the workpiece. Inspection of tool wear is important in improving the surface quality. A single-crystal diamond tool used in electroless nickel turning was inspected by a laser scanning microscope and a scanning probe microscope. Regular grooves were observed on the flank face of the diamond tool, and the pitch interval was the same as the feed rate. The worn distance was obtained by measuring the clearance angle and the groove length on the flank face of the worn diamond tool. The worn distance of the diamond tool was  $1.7\ \mu\text{m}$  after machining electroless nickel for a 3.18 km cutting distance. The worn distance could also be obtained using the worn width on the flank face and the nose radius and was  $2.05\ \mu\text{m}$ , which was very close to  $1.7\ \mu\text{m}$ . Two methods based on the wear measurement of the flank face will be new methods to measure the worn distance of the single-crystal diamond tool. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.3.034102](https://doi.org/10.1117/1.OE.53.3.034102)]

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## 1 Introduction

Single-point diamond turning (SPDT) is an excellent optical fabrication technique. It is easy to generate aspheric shapes compared to conventional grinding and polishing processes. Single-crystal diamond tools are widely used in SPDT. The surface roughness and shape of a machined surface critically depend on the diamond turning machine and the diamond tool used in the fabrication process.

Generally, nonferrous materials and plastics can be machined with SPDT when a single-crystal diamond tool is used.<sup>1</sup> The commonly used metal materials are aluminum alloys, oxygen-free copper, and electroless nickel, which is an alloy of nickel and phosphorus.<sup>2</sup> The surface topography of a material after SPDT depends on the material properties, such as purity, grain size, and anisotropy.<sup>3,4</sup> Thus, the choice of material is notably important to obtain a supersmooth surface. Electroless nickel is an excellent material to use in SPDT because of its amorphous structure.<sup>5</sup> Electroless nickel is also widely used in industrial and optical applications<sup>6,7</sup> and is one of the best optical substrates for use in soft x-ray mirrors and synchrotron optics.<sup>8</sup>

Diamond is one of the hardest materials. However, the wear of the diamond tool is unavoidable during SPDT.<sup>9,10,11</sup> The mechanism of wear is related to thermochemical reactions between the diamond and the workpiece.<sup>10,12,13</sup> Because a worn diamond tool results in poorer machined surface quality, it is important to inspect the wear of the diamond tool. Usually the wear is measured with an optical microscope or a scanning electron microscope.<sup>14,15</sup> In this

paper, we inspect the wear of a diamond tool after SPDT of electroless nickel using a laser scanning microscope (LSM) and a scanning probe microscope (SPM).

## 2 Experimental Setup

The diamond turning machine (AHN-10, Toyoda Machine Works, Toyoda, Japan) used in this experiment had two perpendicular slide tables (Z and X axes), an air bearing spindle on the Z-axis slide table, and a rotary table (B axis) with a tool post. However, the rotary table was fixed in this experiment and showed at variation of  $\pm 0.0001\ \text{deg}$ . A laser interferometer system was used to determine positions accurately. The step resolution of the X and Z tables was 1 nm, respectively. The diamond turning machine was set up within a vibration isolator and supported by air mounts to prevent external vibration. The environment was maintained by a class 100 clean room and controlled within a temperature variation of 0.1 K. A workpiece was loaded on the vacuum chuck for machining, and kerosene mist with 0.2 MPa was sprayed on the cutting point to supply cutting oil and to remove chips from the diamond tool during machining.

Electroless nickel of  $110\ \mu\text{m}$  thickness was plated on an aluminum alloy (A5052) of 45 mm diameter and 10 mm thickness. The electroless nickel contained  $\sim 10\%$  phosphorus by weight. The crystal structure of electroless nickel is critically related to the percentage of the phosphorus in the electroless nickel, and the hardness and the surface roughness of electroless nickel after SPDT depends on the phosphorus content and heat treatment temperatures.<sup>16</sup>

A single-crystal diamond tool with a 5 mm nose radius and a rake face in the (110) crystallographic plane was

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used. The rake and clearance angles were 0 and 5 deg, respectively. The window angle was 60 deg. The shank of the diamond tool was made of steel. A new diamond tool was used to ensure that there would be no wears on its flank and rake faces. The cutting edge of the diamond tool was adjusted to locate at the center of the rotary table and the center of the workpiece, which gives no vertex on the center of the machined surface. The diamond tool was verified with a Nomarski microscope before machining electroless nickel.

After the diamond tool had machined the electroless nickel, the diamond tool was inspected with a confocal LSM that provided surface depth information. The wavelength of the semiconductor laser used in the LSM was  $408 \pm 5$  nm, and the height scan resolution was 50 nm. Magnifications of the LSM were 5 $\times$ , 20 $\times$ , and 100 $\times$ . The LSM system included several analysis tools that provided measurements of parameters, such as angle and length, by analyzing scan profiles. The length provided by the analyzing tool was verified with a scale. The LSM was coupled with an SPM, i.e., an atomic force microscope. The combination of the LSM and the SPM measuring systems within one instrument provided powerful inspection tools. The LSM could be applied to a relatively large surface area, whereas the SPM gave detailed surface information about a site without the need to change measurement tools and move the sample. The SPM provided surface information, such as peak-to-valley (PV) and root-mean-square (rms) surface roughness for a small area.

### 3 Machining of Electroless Nickel

Before the SPDT of electroless nickel was performed with the single-crystal diamond tool of 5 mm nose radius, a polycrystalline diamond tool with a 1 mm nose radius was used to make the workpiece flat. This ensured that the electroless nickel was fully cut when the first machining was carried out using the diamond tool. It also made it easy to calculate the machined distance after SPDT. Figure 1 shows the cutting configuration.

The machining conditions (1000 rpm spindle rotation,  $2 \mu\text{m}/\text{rev}$  feed rate, and  $1 \mu\text{m}$  cutting depth) were kept constant during the machining of the electroless nickel. The angle between the electroless nickel and the diamond tool was 90 deg. The machined distance per pass was 795.2 m. The electroless nickel was machined during four passes with a total cutting distance of 3.18 km. The machined surface was examined with the LSM and the

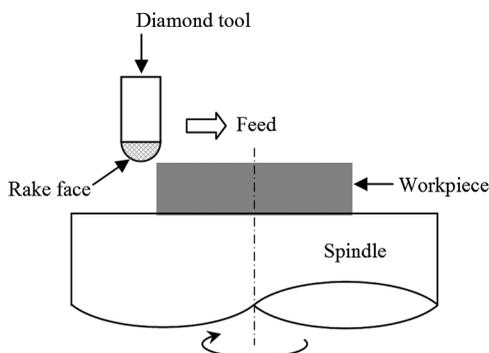
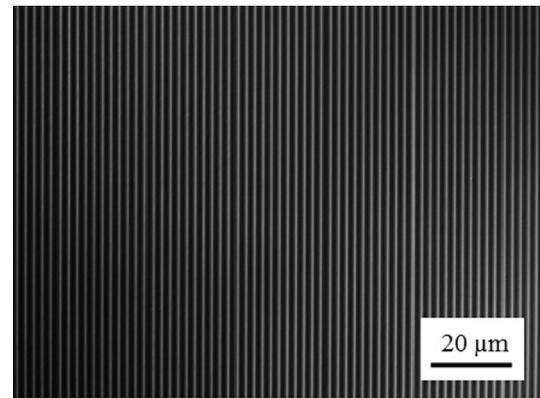
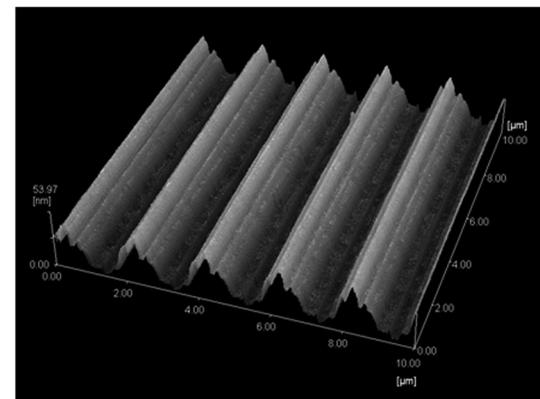


Fig. 1 Single-point diamond turning of electroless nickel.



(a)



(b)

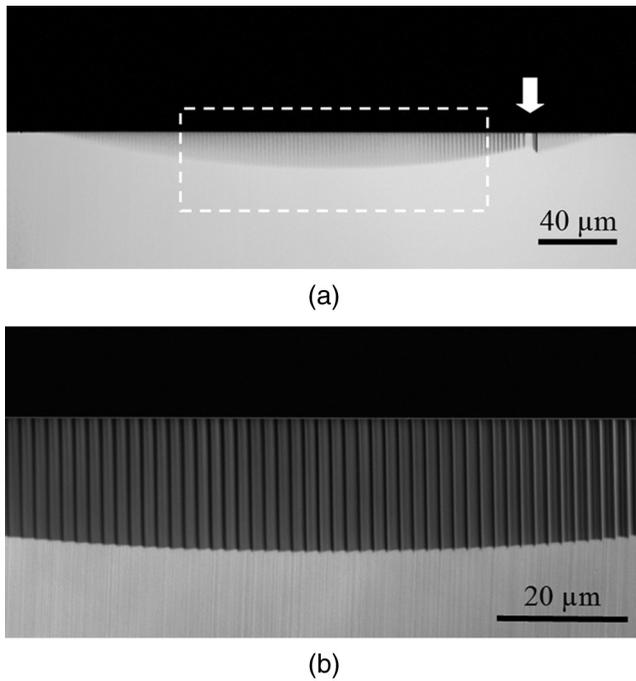
Fig. 2 Machined surface images of the electroless nickel from laser scanning microscope (LSM) (a) and scanning probe microscope (SPM) (b). The groove pitch was  $2 \mu\text{m}$ , which matched the feed rate.

SPM. Figure 2 shows images of the surface and topography measured with the LSM and the SPM, respectively, in which grooves can be seen clearly. The shapes of the grooves were highly similar and regular. The groove pitch was  $2 \mu\text{m}$ , which matched the feed rate exactly. Surface roughnesses in rms and PV were 12.9 and 53.97 nm, respectively. Usually to obtain smooth surface, for example,  $<3$  nm rms, a feed rate of  $1 \mu\text{m}/\text{rev}$  at a final pass was applied. However, a feed rate of  $2 \mu\text{m}/\text{rev}$  was chosen to examine the wear of the diamond tool. Premachining of the workpiece using a polycrystalline diamond tool and the fixed feed rate of  $2 \mu\text{m}/\text{rev}$  could make uniform wear on the diamond tool.

### 4 Tool Wear Inspection

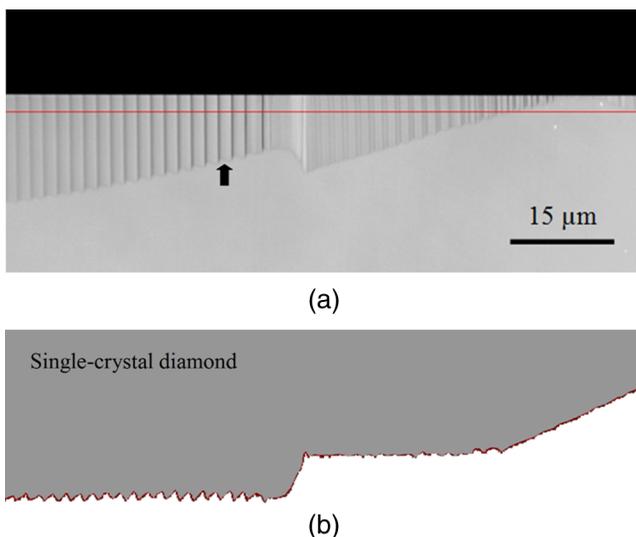
Conventionally, the three-point method for finding a best circle to measure the nose radius of the diamond tool is applied for an edge image on rake face. It is difficult to estimate the worn distance of the diamond tool using the three-point method, when the degree of wear is small.

Before using the diamond tool, the nose radius based on the three-point method was measured with the LSM. The measurement of  $4.948 \pm 0.001$  mm was notably close to the expected value of 5 mm. The manufacturer for the diamond tool gave measured values: nose radius of 4.945 mm, clearance angle of 4.983 deg, and waviness of 176 nm. The diamond tool was inspected again with the LSM after the four machining passes totaling 3.18 km distance. Before



**Fig. 3** Flank face of the worn diamond tool with a 5 mm nose radius after machining electroless nickel for a 3.18-km distance. Cutting direction is from left to right in (a).

the rake and flank faces were examined, the diamond tool was cleaned. Figure 3(a) shows an image of the worn diamond tool. A defect on the diamond tool, indicated by a white arrow in Fig. 3(a), was observed. The defect was made instantly when the diamond tool first touched the electroless nickel during the face cutting. The diamond tool fixed with the tool post would move back until force equilibrium was made between the diamond tool and the workpiece as shown in Fig. 4(b). The step height at the defect was  $0.39 \mu\text{m}$ , as measured by the LSM profile shown in Fig. 4. The relative step-back distance would be  $0.39 \mu\text{m}$ . The height of the groove shown by the black arrow in



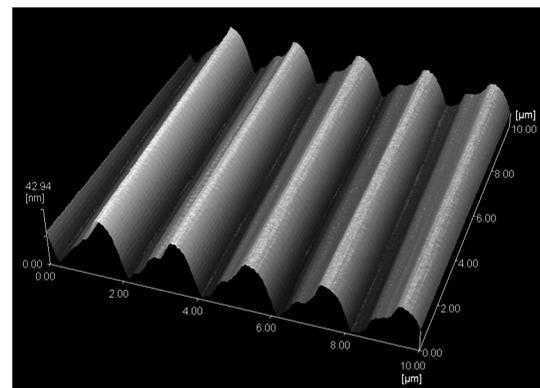
**Fig. 4** Measured line profile for the defect on the diamond tool after machining electroless nickel. The line profile (b) corresponds to the line in (a). Cutting direction is from left to right in (a) and (b).

Fig. 4(a), which was the magnified image around the white arrow in Fig. 3(a), was  $\sim 100 \text{ nm}$  (PV); at left end (20 grooves to the left of the black arrow) and beyond area of Fig. 4(a), the groove height was  $50 \text{ nm}$ . This finding shows that the impact disappears quickly and quasistable state between the diamond tool and the workpiece is continued from 1.272 s, a moving time from the sharp edge to the left end of Fig. 4(a), to the end of the cutting. As can be seen in Fig. 2, the defect on the diamond tool did not leave any marks on the machined surface of the electroless nickel.

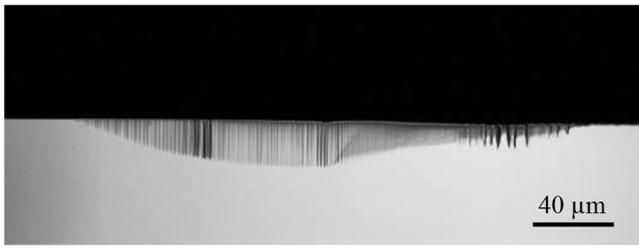
Fine grooves of  $2 \mu\text{m}$  width and  $19.5 \mu\text{m}$  maximum length were observed on the worn diamond tool, as shown in Fig. 3(b), corresponding to the region marked with a rectangle in Fig. 3(a). The groove interval was the same as the machining feed rate ( $2 \mu\text{m}/\text{rev}$ ). Because diamond turning is a displacement-controlled process, the nose radius of the diamond tool and the feed rate make grooves on the machined surface, and these grooves are also eventually mapped onto the flank face of the diamond tool. The groove depth was  $\sim 50 \text{ nm}$ . However, the groove depth was difficult to measure exactly with the LSM because its depth resolution was  $50 \text{ nm}$ . Thus, the flank face of the worn diamond tool was measured with the SPM and the depth was found to be  $42.94 \text{ nm}$  PV as shown in Fig. 5. If the grooves on the diamond tool were exactly copied onto the machined electroless nickel surface without plastic deformation of the surface, then the groove depth would be  $42.94 \text{ nm}$ . However, the machined surface of the electroless nickel showed a slightly higher value of  $53.97 \text{ nm}$  PV. This could be explained if the point at which the electroless nickel was cut by the diamond tool sprang back  $\sim 10 \text{ nm}$  after cutting.

Diamond is extremely hard compared to electroless nickel, the hardness of which depends on the heat treatment temperature as well as the phosphorus content. The hardness of the electroless nickel plated between  $200$  and  $300^\circ\text{C}$  is one of the reasons giving high groove depth ( $42.94 \text{ nm}$ ) on the flank face of the diamond tool.

When mixed feed rates, for example,  $1$  and  $2 \mu\text{m}/\text{rev}$ , were applied while machining the electroless nickel, the grooves on the flank face as shown in Fig. 6 were not as clear as a feed rate of  $2 \mu\text{m}/\text{rev}$  only. In addition, a few defects in the form of microchippings were found. Sub-grooves were found on the grooves on the machined electroless nickel surface. Thus, it might be difficult to



**Fig. 5** Flank face (measured with the SPM) of the worn diamond tool after electroless nickel turning.

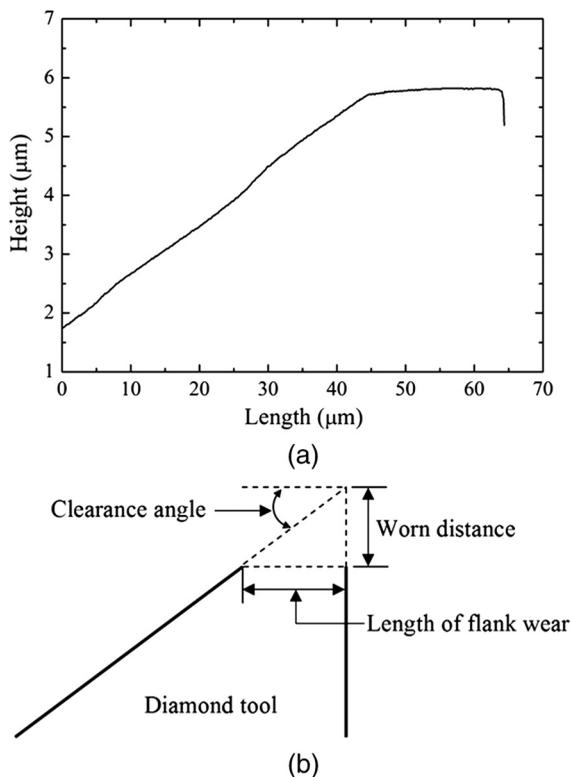


**Fig. 6** Wear for a single-crystal diamond tool with a 3 mm nose radius. The tool was used under mixed feed rates of 1 and 2  $\mu\text{m}/\text{rev}$  during machining the electroless nickel. The grooves on the flank face are not clear.

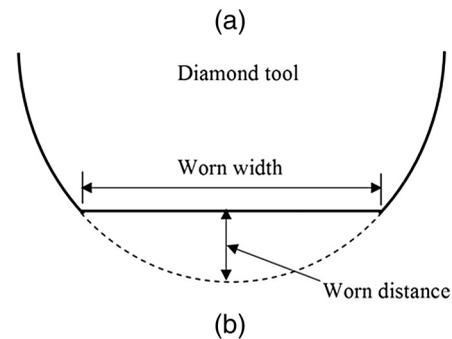
achieve better surface roughness with mixed feed rates than with a single rate when machining electroless nickel.

The clearance angle of the diamond tool could be determined with the LSM by measuring the vertical profile of the flank face, as shown in Fig. 7(a). The average value over five measurements was 4.96 deg, which was notably close to the value of 5 deg specified by the tool manufacturer. Using the measured clearance angle and the length of the flank wear (19.5  $\mu\text{m}$ ), the worn distance calculated from the simple geometry shown in Fig. 7(b) is 1.7  $\mu\text{m}$ . This method using the clearance angle and the worn length on the flank face will be a new method to determine the worn distance of the diamond tool.

There was no sign of damage (i.e., crater wear) on the rake face after machining the electroless nickel for a cutting distance of 3.18 km. Only the cutting edge of the diamond tool was worn. The measurement of the worn distance on the rake face was not easily performed because the quantity was small as shown in Fig. 8(a). There was a clear defect, the step



**Fig. 7** Measured profile of the flank face (a) and tool geometry (b).



**Fig. 8** Rake face image taken with the LSM (a) and tool geometry on the rake face (b) for the worn diamond tool after machining electroless nickel for a 3.18-km cutting distance.

height of 0.39  $\mu\text{m}$ , indicated by the black arrow in Fig. 8(a). The measurement could be calculated from the worn width measured on the flank face and the nose radius of the diamond tool as shown in Fig. 8(b). The worn width shown in Fig. 3(a) was 285  $\mu\text{m}$ . Using the measured nose radius of 4.948 mm, the worn distance could be calculated as 2.05  $\mu\text{m}$ , which was close to the value of 1.7  $\mu\text{m}$  obtained from the analysis of the flank face.

### 5 Conclusion

A measurement system combining the capabilities of the LSM and the SPM provides a powerful tool for inspecting a diamond tool. The wear of a diamond tool after machining electroless nickel for a distance of 3.18 km was measured using the LSM and the SPM. The fine grooves on the flank face of the diamond tool and on the machined electroless nickel surface were observed. The interval between these grooves was 2  $\mu\text{m}$ , which was the same value as the machining feed rate. The groove spacing seen on the workpiece surface was generated due to the cutting tool geometry and the chosen feed rate, but these grooves were also eventually mapped onto the flank face of the cutting tool. When the diamond tool struck the workpiece for machining, the impact gave rise to a tool defect, and the step difference of the defect was 0.39  $\mu\text{m}$ . The worn distance could be estimated from the flank angle and the length of flank wear, and the worn width and the nose radius; the estimates yielded similar values of 1.7 and 2.05  $\mu\text{m}$ , respectively. Both methods were based on the measurement of worn length and width on flank face of the diamond tool. These methods will provide new methods to measure the worn distance of the diamond tool. In addition, when the wear of diamond tool is small, these methods will be useful compared to the three-point method.

The wear of the diamond tool affects the machined surface. Thus, the understanding of tool wear can be used to improve surface-quality parameters, such as the surface roughness and shape, when, for example, fabricating an

x-ray microscope mirror requiring 3 nm rms in surface roughness and <100 nm in shape error.<sup>17</sup> The measurement system combining the LSM and the SPM together is useful to investigate the wear of diamond tool. For example, the worn distance on the rake face, measuring 1.7  $\mu\text{m}$  in this study, can indicate how to improve aspheric shape accuracy when a diamond tool is used in a long cutting distance.

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