Micromachining of nickel phosphorus using textured diamond cutting tool

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Abstract. Texturing on a surface of cutting tools is an effective way to improve friction and resultant machining performances of the tool. This paper presents the machining performance of a textured diamond cutting tool at various machining parameters. The textures, which had width of 1.8 µm and 32 nm, were fabricated on the diamond tool surface utilizing the focused ion beam irradiation and subsequent heat treatment. Machining experiments of nickel phosphorus was conducted to evaluate the effect of the machining condition on the texture effect. The cutting force can be reduced by the texture. This effect was different due to the cutting speed, and significant effect was observed at low cutting speed. In addition, unevenness on the machined surface was improved by texturing, due to the reduced shear deformation at low cutting speed. These results indicate the effectiveness of the developed textured diamond tool, and the significant effect was obtained at low cutting speed.

1. Introduction

Ultra-precision machining is used for fabrication of high-precision parts and mold, such as lenses, molds, and biomedical system parts [1]. Single-crystal diamond tools are generally used for this method because of their high wear resistance, sharp cutting edge, high transcription ability, and other superior characteristics. Despite diamond being the hardest material in the world, diamond cutting tools still experience wear after extensive use or working with other hard materials. This degrades the machined surface quality and shape accuracy. Therefore, improving the performance and efficiency of diamond cutting tools is still an industrial concern.

The addition of textured features to a solid surface has been shown to improve the tribological characteristics between surfaces [2]. During cutting, friction at the tool–chip interface is a dominant factor that affects the machining performance of the tool. Therefore, reducing the friction on the tool surface is an effective way to satisfy this demand.

In the past experiments, we developed textured cutting tools, made of cemented carbide or high speed steel, to improve friction and resultant cutting performance [3]. The machining experiments indicated the effectiveness of the texture on the cutting tool. Based on this result, texture was applied
to the diamond cutting tools [4]. A combination of a focused ion beam (FIB) and heat treatment was applied to fabricate micro- to nanoscale textures on the diamond tool surface. Machining experiments of nickel phosphorus (NiP) and aluminum alloy indicated that texturing is also effective for diamond cutting tools to improve machining performance.

In the present work, machining experiments of NiP were conducted to investigate the difference in the texture effect, due to the machining condition. Based on these results, the effectiveness of the textured diamond cutting tool was presented.

2. Fabrication of textures on a diamond cutting tool

Figure 1 shows the method of fabricating a texture on a diamond tool surface using a combination of FIB irradiation and heat treatment proposed in this study [4]. Rake face of single crystal diamond tool was used for the texture fabrication. Graphitized carbon layer with a thickness of less than 10 nm was deposited on the diamond surface to avoid electrostatic charging. FIB is irradiated to the surface along the shape of the texture to form affected layers in the diamond phase. Affected layer was selectively removed by heat treatment, and the textured surface was formed.

This method is effective compared with the direct milling method because the direct milling is time consuming. In addition, non-diamond phases, which adversely affects the cutting performance of the diamond tool by causing high friction, adhesion and significant tool wear [5], is removed by the heat treatment. Therefore, this method can efficiently fabricate sub-micrometer- to micrometer-scale textures with low affected layers.

Figure 2 shows the developed textured diamond cutting tool, measured using a coherence scanning interferometer (NewView 7200, Zygo Corporation). The texture was successfully fabricated on the rake face of the diamond tool, as shown in Fig. 2 (b). The width, depth and pitch of the texture were 1.8 µm, 32 nm and 3.8 µm, respectively. The effect of machining conditions on the texture effect was investigated using these tools.

3. Experimental

Figure 3 shows the experimental machining setup. The machining experiment was carried out using an ultra-precision cutting machine (ROBONANO α-0i/B, FANUC Corporation) with 1-nm resolution along the translation axes. Two types of machining method was employed to investigate the effect of the cutting speed. The one is a high-speed shaping method using shuttle unit model B, as shown in Fig. 3. This method can machine a surface with the maximum reciprocating speed of 5.4 Hz, a stroke width of 200 mm, and a mean cutting speed of 130 m/min. The other is conventional shaping method using a movement of machine axes. The maximum cutting speed was 0.5 m/min. Hereafter, these methods will be called “high speed” and “low speed” cuttings, respectively. The work materials was a layer of electroless NiP with a thickness of 500 µm deposited on stainless steel. The work materials was mounted on a triaxial piezoelectric force sensor (9256C2, Kistler), and the
cutting force during the experiment could be measured. The machining was carried out at a depth of cut of 3 µm, and a feed per stroke of 10 µm, under wet conditions at 23 °C.

4. Results and discussion

The machining performance was evaluated by machining NiP. Figure 4 compares the cutting forces obtained while machining at high speed cutting. The cutting force decreased by texturing on a diamond tool surface. Larger-decreasing rate was observed for the thrust force, and the rate was about 18%. The friction coefficient also decreased for the textured tool, indicating that the texture effect was caused by the decreased friction between tool–chip interface.

Figure 5 compares the cutting forces obtained while machining at low speed cutting. Compared with the high speed cutting, larger texture effect was observed. Both the principal and thrust forces decreased significantly by texturing, and the decreasing rate of these forces were 44 %, and 70 %, respectively. Friction coefficient also decreased by 47 %.

![Fig. 4 Comparisons of the cutting forces while machining NiP using the nontextured and textured tool at high speed cutting.](image)

![Fig. 5 Comparisons of the cutting forces while machining NiP using the nontextured and textured tool at low speed cutting.](image)

Figure 6 shows an SEM image of the cutting chips generated while machining a NiP using the non-textured and textured tools at low speed cutting. For the non-textured tool, large magnitude of unevenness were observed on free surface side of the chip. This indicates that irregular large shear deformation occurred while machining. For the textured tool, large unevenness, indicated for the non-textured tool, was not observed, and the surface of the chip was uniform. This result indicate the machining was stable at the textured tool. Figure 7 shows surface topographies of the NiP after machining with a non-textured and a textured tools at low speed cutting. Cutting marks with the same pitch as the feed per stroke were observed on the machined area with both tools. The surface was uniform for the textured tool, indicating that the friction and resultant cutting force of the diamond tool, shown in Fig. 5, was improved by texturing while keeping the transcribability of the cutting edge. However, for the non-textured
tool, irregular unevenness occurred on the machined surface, as shown in the cross-sectional image in Fig. 7(a). The unevenness is caused by large shear deformation, indicated in Fig. 6. These result indicate that the machined surface was improved by the texturing at low cutting speed.

In contrast with the low speed cutting, a uniform surface was formed at both non-textured and textured tools at the high speed cutting, indicating that the texture effect to the machined surface quality was small in this condition. For the low speed cutting, the contact length of tool–chip interface is shorter than that at high speed cutting. Therefore, larger texture effect was obtained at low speed cutting, due to the relation between the contact length and the size of the texture.

These results indicate that the texturing on the diamond tool surface was effective to improve machining performance of the NiP in term of cutting force and machined surface quality. The texture effect was different due to the machining condition, they were improved significantly at the low cutting speed. Therefore, the textured tool is effective especially for low speed cutting of NiP.

5. Conclusions

In this research, we made a textured diamond cutting tool to improve machining performance. Our method combines a FIB and heat treatment to fabricate micro- to nanoscale textures on the diamond tool surface. Cutting experiments using the textured tool were carried out to investigate the effect of the machining parameters on the texture effect. The tool cutting performance was enhanced, as evidenced by the lower friction, cutting forces and superior machined surface. This effect was different due to the cutting speed, and superior texture effect was obtained at low cutting speed. The results demonstrate that texturing on diamond cutting tools can be an effective way of improving the machining performance, especially for the low speed cutting.

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References


