A COMPARATIVE STUDY ON MICRO MACHINING OF SUPER FINE GRAIN TUNGSTEN CARBIDE BY VARIOUS MICRO PCD BALL END-MILLING TOOLS

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ABSTRACT
BL-PCD is expected to be an excellent material for a micro cutting tool because it is the hardest material in the world. Micro tools are used for the direct machining of high precision die and mold, and conventional PCD tools are often used for such precise machining in general. However, conventional PCD tools are insufficient when it comes to wear and chipping resistance. To study the unique die and mold machining application using a micro end mill made of BL-PCD, systematic experiments involving the machining of ultrafine grain tungsten carbide alloy have been conducted. In the study, tool wear and machined surface quality of tungsten alloy material have been evaluated in relation to the machining conditions and machining process parameters. The results have justified the superior performance of BL-PCD micro end mill, as compared to results obtained in the machining experiment based on a regular PCD micro end mill, which has the same tool geometry.

INTRODUCTION
To facilitate the miniaturization of mechanical parts, high precision micro molds with fine structures are required. For such high precision molds, fine structures, high edge sharpness, and very low surface roughness are required. To productively manufacture such molds, high accuracy micro-milling tools with features of sub-millimeter dimensions are necessary (hereinafter referred to as micro tools). To efficiently produce high precision molds using difficult to machine materials, the micro tool must have high hardness, excellent wear resistance, and a long tool life. Synthetic diamond can be cited as such a tool material; however, since single crystal diamond (SCD) has anisotropic mechanical strength dependent on the crystal orientation, it is not a suitable material for rotary tools. Polycrystalline diamond (PCD) sintered with a binder material, such as cobalt, does not have sufficient tool life owing to the releasing and chipping of abrasives during abrasion, similar to that in grinding wheels. Binder-less nano polycrystalline diamond (BL-PCD) developed in 2003 [1], is synthesized from high-purity graphite at ultra-high temperature and pressure without using any binder materials. The polycrystalline structure of BL-PCD means that it is isotropic and does not exhibit cleavage fracture such as the case in SCD. Also, BL-PCD has a higher hardness than SCD. The high hardness and isotropic strength of BL-PCD makes it an ideal material for micro tools, and it is expected to become the next-generation micro tool material of choice [2]. Although there are some reports showing that the tool wear of BL-PCD tool is less than that of PCD [3], the result of detailed measurement of wear progression, change of cutting force due to the tool wear, and other factors have not been discussed yet. Therefore, in this paper, we will verify in detail the difference between a PCD and a BL-PCD tool by observing and comparing the tool wear characteristics and cutting force during the machining of tungsten carbide.

EXPERIMENTAL PROCEDURE
For this experiment, three types of tools were prepared to aid the comparison of the different wear mechanisms. The first type is a polished BL-PCD tool whose flank and rake face were polished to a surface roughness of 10 nmRa after pre-forming using a nano-second laser machining system. The second type is an unpolished BL-PCD tool whose flank and rake face were finished using only a nano-second laser machining system, and its surface roughness was ~50 nmRa. The third type is a conventional PCD tool, and the surface roughness of its flank and rake face was 130 nmRa. Scanning electron microscopy (SEM) images of each of the three types of tools before using micro-milling experiments are shown in Fig. 1. All of the tools were prepared in the same geometry of R0.5 mm single flute ball end mill, as shown in Fig. 2.
Ultrafine grain tungsten carbide (AF1) was used as the workpiece material to be machined. AF1 has an average particle size of 0.5 μm, Co content of 12.0 wt%, and a Vickers hardness of 1765 Hv. The above prepared tools were mounted on a three-axis vertical high precision machining center (AZ150L), as shown in Fig. 3. This machining center has an air turbine spindle with the rotational speed of 120,000 min⁻¹. A minimum feeding resolution of each liner axes is 10 nm. Machining tests were performed on the tungsten carbide that was tilted by 45° with respect to the table of the machining center such that the peripheral speed at the processing point of the ball end mill did not become zero. The machining conditions were determined with reference to the preceding study [3, 4] and are as shown in Table 1.

The surface roughness of the machined workpiece surface and tool surface was measured by a scanning white light interference microscopy (SWLIM, NewView7300) and an autofocus contour measuring instrument (MLP-3SP). Also, tool shapes and the machined surfaces observations were performed SEM (ERA 8900 FE). In addition, the cutting force during machining was measured by a dynamometer.

Table 1: Machining conditions

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Tungsten carbide(AF1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rev. speed</td>
<td>120,000 rpm</td>
</tr>
<tr>
<td>Workpiece size</td>
<td>0.5 × 10 × 0.05 mm³</td>
</tr>
<tr>
<td>Radial depth of cut</td>
<td>0.5 μm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>100–800 mm/min</td>
</tr>
<tr>
<td>Feed/revolution</td>
<td>0.83–6.7 μm</td>
</tr>
<tr>
<td>Cross feed</td>
<td>5 μm</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>45°</td>
</tr>
</tbody>
</table>

RESULT AND DISCUSSION

Analysis of the machined surface
The relationship between the average surface roughness (Ra) of the different samples of tungsten carbide machined by each of the three types of tools and the feed rate is shown in Fig. 4, and the images of machined surface profiles measured by SWLIM are shown in Fig. 5. As can be seen from the figure, for all different feed rate conditions, the surface roughness of the sample machined using the polished BL-PCD tool is lower than those of the sample machined by the unpolished BL-PCD and conventional PCD tools. With the unpolished BL-PCD tool, at the initial feed rate of 100 mm/min, the surface roughness was almost same with that of the machined surface using the polished BL-PCD tool. However, with increasing feed rate, the surface quality became worse and the surface roughness reached 180 nm Ra.

In the PCD tool, a comparatively superior surface roughness was obtained with a low feed rate, whereas a large deterioration in surface roughness was realized with increasing feed rate. During the PCD milling process, fine diamond abrasives appear on the tool surface whereby the surface roughness shows lower level [5]. With increasing feed rate, large chipping at the cutting edge occurred because of the higher cutting force.

As shown in Fig. 5, in all types of tools, a vertical pattern due to the influence of the cross feed was observed in parallel with the feeding direction. In the case of the PCD tool, rough portions are irregularly present due to the influence of chipping.

Investigation on flank wear of tools
Tool wear characteristics were investigated by focusing on the flank wear width of the tool which is defined as shown in Fig. 6. Figure 7 shows the relationship of the flank wear progression during each machining period. In two types of BL-PCD tools, although the flank wear width at the initial stage of machining distance was almost the same as that of the PCD tool, the progress of wear was gentle after the total machining distance of 200 m. However, in the PCD tool, the flank wear width tended to linearly increase up to 120 μm. In addition, since BL-PCD tools show a small amount of wear, excepting the initial wear, it is possible to use it for a drawn out progresses in proportion to
machining distance; therefore, it is considered difficult to maintain suitable shape accuracy with long distance machining. Figure 8 shows the relationship between the surface roughness of the flank wear of the tool and the machining distance. In the polished BL-PCD tool, the initial surface roughness started from around 10 nm; however, even though this value gradually increased as the machining distance increased, it remained stable at about 40 nm. On the other hand, with the unpolished BL-PCD tool, the initial surface roughness started from 50 nm; then the flank wear progressed with relatively large fluctuation, and finally the roughness was about 80 nm.

Figure 8: Surface roughness of worn flank face as function of the machining distance.

It is considered that the difference in the surface roughness of these flank wear of the tools is correlated with the surface roughness of the workpiece, as shown in Fig 4. In the PCD tool, the surface roughness of the flank wear was unstable throughout the machining distance.

Figure 9 shows the SEM images obtained by focusing on the flank face achieved using each type of tool. In the PCD tool, large chipping was observed at a machining length of 500 m. In addition, there was a large amount of adhesive materials on the tool surface. It is known that adhesive materials on the tool surface increase the frictional resistance during machining, leading to degradation of machining performance. This is one of the reason why the PCD tool shows degradation of surface roughness and tool life in long distance machining.

The wear mechanism in the BL-PCD tools is considered to be the micro-chipping that occurs at the finished chamfer portion at the initial stage of machining, and as the machining distance increases, the wear zone arising from micro-chipping progresses. In this study, we have not yet clarified the correlation between abrasion status and processed surface roughness between polished and unpolished BL-PCD tools. Further investigation on the relation between grain size and brittle fracture load from the viewpoint of nano-scopic material structure is needed.
Figure 10 shows the result of measuring the change of cutting force during machining with different feed rates. In the polished BL-PCD tool, the cutting force is relatively high in the range of F100 to F400 mm/min, and decreases with exceeding F600 mm/min. In the case of the unpolished BL-PCD tool, although the cutting force shows maximum value at F200 mm/min, its basic behavior is similar to that of the polished BL-PCD tool. Generally, when the surface roughness (especially at flank face) of the tool is low, it is known that a higher cutting force is observed because the contact area with the workpiece and tool surface increases at the micro level. In this experiment as well, it is considered that the polished BL-PCD exhibited a relatively high cutting force for the same reason. In the PCD tool, the cutting force increased with the increasing feed rate, and the tool broke at F800 mm/min. Since the BL-PCD tool did not break even at a higher feed rate, it was confirmed that the BL-PCD tool has better impact resistance during milling operation than the PCD tool does.

CONCLUSIONS

In this study, in order to investigate the unique die and mold machining application using a micro end mill made of PCD/BL-PCD, systematic experiments involving the machining of ultrafine grain tungsten carbide alloy (AF1) have been conducted. The results have revealed the superior performance of BL-PCD micro end mill, as compared to results obtained in the machining experiment based on a regular PCD micro end mill. The surface roughness of the sample machined using the polished BL-PCD tool is lower than those of the sample machined by the unpolished BL-PCD and conventional PCD tools. In particular, the correlation between the flank wear of each tool and the obtained surface quality of the samples was clarified.

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