POLISHING OF SINGLE POINT DIAMOND TOOL BASED ON THERMO-CHEMICAL REACTION WITH COPPER

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Abstract:
This paper describes a new polishing method for diamond cutting tools. It is based on the principle of oxidization of copper and deoxidization of copper oxide by diamond. Practically speaking, a diamond tool is brought into contact with copper plates heated to a temperature range from 323 K to 523 K in air. The wear amount of the diamond increased almost exponentially with contact time and reached about 30 nm after 6 hours. In this erosion process, pre-existing microcracks on the diamond surface were eliminated. Accordingly, the thermo-chemically polished tool is highly resistant to chipping and yields a remarkable rise in tool life compared to the mechanically polished one.

1. Introduction
The cutting edges of a single point diamond tool are usually carefully formed by fine polishing with a scythe. However, mechanical polishing produces microcracks on the diamond surface because of the high polishing pressures and elevated temperatures. The microcracks lengthen as a result of the thermo-chemical erosion of oxygen at their tips, and thereby reduce the microstrength of the diamond [1]. This is thought to be the source of chipping that occurs on cutting edges during the tuning process. Hence, the elimination of microcracks is very important because the workpiece quality and/or tool life are reduced due to the occurrence of chipping.

To solve this problem, novel polishing methods have been proposed using various techniques, including the diffusion of carbon atoms into a certain sort of metals [2], the sputtering-off of carbon atoms by bombardment of energized ions [3], and tribochemical polishing combining mechanical abrasion and chemical dissolution of surface atoms [4]. These methods, however, possess drawbacks in terms of difficulty of use and high cost. Thus, a simpler polishing method, based on thermo-chemical reaction with copper, is proposed and discussed in this paper.

2. Principle of thermo-chemical polishing
Figure 1 shows the Ellingham diagram in which the change in Gibbs’s free energy, $\Delta G^0_T$, for oxide formation of copper and carbon for 1 mol oxygen is shown as a function of atmospheric temperature [5]. As seen from the diagram, the values of $\Delta G^0_T$ are negative. Hence, chemical reactions can occur between C and O$_2$, according to the equations: C+O$_2$ $\rightarrow$ CO$_2$ and 2C+O$_2$ $\rightarrow$ 2CO. In addition, a reaction can occur between Cu and O$_2$, according to the equations: 2Cu+O$_2$ $\rightarrow$ 2CuO and 4Cu+O$_2$ $\rightarrow$ 2Cu$_2$O. The diagram also shows that the values of $\Delta G^0_T$ for

FIGURE 1. Change in Gibbs’s free energy during oxide formation of copper and diamond for 1 mol oxygen.
the formation of CO$_2$ or CO are lower than those for the formation of CuO or Cu$_2$O. This suggests that when carbon atoms are close to copper oxide, they deoxidize it and are themselves oxidized. Therefore, by bringing diamond into contact with copper oxides at temperatures higher than room temperature in air, there is a very fair possibility of taking carbon atoms on its surface away.

3. Properties of thermo-chemical polishing

In order to ensure that the oxidation-deoxidization reaction mentioned above is applicable to the polishing of diamond tools in practice, erosion tests were carried out. A diamond specimen was brought into contact with copper plates heated to a range of temperatures from 323 K to 523 K in air. The specimen was natural monocrystalline diamond finished mechanically as smooth as the rake face of diamond tools. On its surface, a tiny ring crack was produced to measure its wear amount.

The erosion tests showed that the wear amount increased almost exponentially with contact time and reached about 30 nm after 6 hours, as shown in Fig. 2. Figure 3 shows the Arrhenius plot of the wear rate versus the heating temperature. The decrease in wear rate is very nearly linear with decreasing temperature, and the apparent activation energy for the erosion of diamond in contact with copper is calculated to be 218 kJ/mol. According to Fig.1, a change in free energy $\Delta G^0_{523K}$ of more than 133 kJ/mol is required for the deoxidization of copper oxide by carbon at 523 K. Since the activation energy obtained exceeds $\Delta G^0_{523K}$, it was confirmed that the carbon atoms on the diamond surface could be removed through oxidization accompanied by deoxidization of copper oxide.

Next, Hertzian fracture tests were carried out in order to indirectly investigate whether surface microcracks can be eliminated by thermo-chemical polishing. The test involves pressing a spherical diamond indenter with a 50 $\mu$m tip radius on the flat specimen surface. If microcracks exist at the maximum tensile stress circle of the contact area, a ring crack fracture occurs. The average contact pressure at the moment yields the fracture strength of the specimen.

Figure 4 shows the change in fracture strength of the diamond specimens in contact with a copper plate or copper powder heated to 523 K. The strength of the diamond put in the copper power clearly decreases as the contact time
increases. This phenomenon is explained as follows [1]. On the solid surface, thermally activated atoms frequently jump in and out of the surface. The carbon atoms which jump out of the crack tip are oxidized by thermally activated oxygen and eliminated as CO or CO₂. Simultaneously, vacancies diffuse into the bulk from the crack tip on the diamond surface, and the microcracks thereby lengthen and reduce the strength. In this case, the copper powder functions as a catalyst and accelerates the extension of the crack. On the other hand, the strength of the diamond placed on the heated copper plate decreases and then increases as the contact time increases. This increase in strength is probably due to the elimination of microcracks existing on the diamond surface. This is because when a diamond surface of few tens of nanometers is eroded by the oxidization-deoxidization reaction, the microcracks are also removed. This thermo-chemical polishing is thus very promising as a finishing technology of diamond tools.

4. Durability of thermo-chemically polished diamond cutting tool

In order to demonstrate the effects of thermo-chemical polishing on the wear resistance and life of a cutting tool, diamond turning of electrolytic deoxidized copper was carried out using the thermo-chemically polished diamond tool and a mechanically polished one. Table 1 shows the detailed tool geometries and cutting conditions that were used.

<table>
<thead>
<tr>
<th>Cutting tool</th>
<th>Material</th>
<th>Monocrystalline diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystallographic orientation</td>
<td>(100) rake plane</td>
<td></td>
</tr>
<tr>
<td>Included angle [deg]</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Rake angle [deg]</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Clearance angle [deg]</td>
<td>7</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Material</th>
<th>OFHC (ASTM F6 Class 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting conditions</td>
<td>Cutting speed [m/s]</td>
<td>15.7</td>
</tr>
<tr>
<td>Feed rate [µm/rev]</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Depth of cut [µm]</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Blowed gas</td>
<td>Air</td>
<td></td>
</tr>
</tbody>
</table>

When turning copper, crater wear and notch wear occur on the rake face where the chip flows. Moreover, chipping occurs on the cutting edge, as shown in Fig. 5. These different types of tool failures can be measured by the following method [6].

The level of wear can be distinguished by the qualitative difference in the dynamic component of the cutting force. When the tool wear is high, the cutting force fluctuates self-similarly, namely, $1/f^\beta$ noise with a spectral exponent of $\beta>1$ appears in the cutting force. On the other hand, when chipping occurs, acoustic emission (AE) due to fracture is released. This type of AE can be detected by the AE amplitude distribution spectrum follows the power law $N \sim a^{-m}$ with a scaling exponent of $m<2$, where $N$ is the AE event rate and $a$ is the AE amplitude. In addition, at the end of the life of diamond tools, the tool wears out and chipping of the cutting edge occurs simultaneously. Therefore, knowing that the spectral exponent is always greater than 1 for the cutting force and that the scaling exponent is always less than 2 for the AE, the end of the life of a tool can be effectively detected.

Judging from the criteria mentioned above, there is considerable difference in the wear resistance between the two tools. As seen from Fig. 6, comparing each cutting distance at which the $1/f^\beta$ noise appears in the cutting force, except for the period of the running-in cutting of the fresh tool, the distance for the thermo-chemically polished tool extends to about 1.4 times that of the mechanically polished one. Therefore, the thermo-chemically polished tool is clearly more resistant to wear. In addition, the thermo-chemical polishing manifests its beneficial effects in the form of suppression of chipping, as shown in Fig. 7. In turning with the thermo-

TABLE 1. Tool geometries and cutting conditions.
chemically polished tool, the scaling exponent is seldom less than 2, whereas this occurs often in turning with the mechanically polished tool. Accordingly, it is clear that the thermo-chemically polished tool is also resistant to chipping.

Thus, the improvement in wear resistance extends the durability of a tool. As seen from Figs. 6 and 7, when the cutting distance exceeded 345 km in the case of the mechanically polished tool, the spectral exponent became greater than 1 and the scaling exponent became less than 2. These changes in the signal indicate that the tool comes to the end of its life at a cutting distance of 345 km. On the other hand, the end of the life of the thermo-chemically polished tool was evaluated to occur at a cutting distance of 484 km. Thus, the thermo-chemically polished tool enjoys an unusually long life compared to the mechanically polished one. Our simple polishing method is thus very useful and effective to prolong the tool life.

5. Conclusions
In this paper, a new polishing method for diamond cutting tools has been discussed using thermo-chemical reaction with copper. It is a very simple and practical way of bringing a diamond tool into contact with a copper plate heated in air. Hertzian fracture tests showed that the microstrength of thermo-chemically polished diamond surface becomes higher because of the elimination of microcracks. In addition, the cutting experiments abundantly demonstrated that the thermo-chemically polished tool is superior in terms of the wear resistance and the tool life to the mechanically polished one. Accordingly, thermo-chemical polishing is recommended as a finishing technique for the diamond tool because of its efficiency.

6. Acknowledgments
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References