TOOL WEAR IN DIAMOND TURNING OF STEELS

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INTRODUCTION
Excessive tool wear occurs when commercial steel alloys are single-point diamond turned. Therefore, development of diamond-turnable steels are awaited in the manufacture of molds for high-precision, complex optical components.

In this paper, wear suppression factors of diamond tool in turning of steels are discussed based on the results of thermodynamic analysis, cutting tests, and metallographic analyses.

WEAR MECHANISM OF DIAMOND TOOL

Fig. 1 shows a scanning electron micrograph of tool wear at the nose point in turning of steel. Tanaka et al. stated that some thermo-chemical reactions between a diamond tool and a workmaterial cause tool wear [1]. The mechanisms of tool wear are classified into four types, i.e., oxidization-deoxidization reaction, carbonization, carbon diffusion into work material, and graphitization.

It is necessary to know the cutting temperature to judge whether the chemical reactions happen. Sato et al. [2] investigated the temperatures on the rake faces in cutting of 0.45%carbon steel and SUS304 with diamond tools by the depth of 10 microns. The temperatures on the rake faces were about 623 K in case of 0.45%carbon steel and 873 K in case of SUS304, respectively.

We used thermodynamics analysis to investigate the interactions. The energy change can be calculated using the following equation and thermo-chemical data:

\[
\Delta G_r = \Delta H_r - T \Delta S_r
\]

\[
= \Delta H_{298K} + \int_{298K}^{T} \Delta C_p dT - T \Delta S_{298K} - T \int_{298K}^{T} \frac{\Delta C_p}{T} dT
\]  

(1)

where \(\Delta H^o\) is the standard enthalpy change, \(\Delta S^o\) is the standard entropy change, \(\Delta C_p\) is the difference between the heat capacities of the reactants and products at constant pressure, and \(T\) is the temperature.

Then, the mechanism of the diamond tool is presumed referring to above-mentioned temperatures and the change in Gibbs free energy.

First, diamond can deoxidize \(\text{Fe}_3\text{O}_4\) at the temperature higher than 773K [3]. Therefore, the deoxidization does not happen in cutting of carbon steel.

Second, there is little possibility of iron carbide formation by diamond at the temperature lower than 873K because the energy change \(\Delta G^o_r = 33.43 - 18.89 \times 10^{-3} \cdot T \text{ln} T + 61.45 \times 10^{-3} \cdot T > 0\) [kJ/mol] \((298K < T < 873K)\) for \(3\text{Fe} + \text{C}_0 = \text{Fe}_3\text{C}\). Third, the diamond graphitizes at temperature above 1100 K in the presence of iron [4]. Therefore, diamond is presumed not to be worn by graphitization because these cutting temperatures are lower than this temperature. Consequently, the mechanism of tool wear in diamond turning of steel is the diffusion of the carbon atoms in diamond into iron.

Based on the thermodynamics analysis, vacuum contact heating tests simulating wear process of diamond tool in cutting were carried out.

Fig. 1. SEM micrograph of flank of diamond tool after turning SK3 steel.
VACUUM CONTACT HEATING TEST SIMULATING WEAR PROCESS

For a simplified experiment simulating the essential wear process, a vacuum contact heating test is proposed. Figure 2 shows the schematic illustration of the test. A diamond specimen in contact with Fe wire was heated at different temperatures from 673 K to 973 K, in a vacuum of 4.2×10⁻³ Pa for 3 hours. In the tests, erosion pits were generated on the specimen surface due to thermo-chemical reaction with the wire. The cross section of the pit is shown in Figure 3 (a). After the tests, the distribution of carbon concentration on a cross section of each wire was examined by energy dispersive X-ray spectroscopy (EDX).

Figure 3 (b) shows the concentration profile of carbon diffused into Fe wire at 973 K in 4.2×10⁻³ Pa for 3 hours. The carbon concentration shows the maximum value on the wire surface and decreases as the depth increases. The depth where the carbon concentration decreases to the background level is defined as the diffusion depth. These results imply that the carbon atoms of diamond surface directly diffused into Fe, or dissociated carbon atoms from the diamond surface diffused into Fe.

In general, the chemical reaction rate tends to increase with a temperature rise, and this temperature dependence is described by an Arrhenius equation of the following form:

\[
\kappa = A \exp\left(\frac{-E}{RT}\right) \tag{2}
\]

where \(\kappa\) is the reaction rate, \(A\) is the frequency factor, \(E\) is the activation energy, \(T\) is the absolute temperature, and \(R\) is the gas constant.

If the carbon diffusion into the wire is thermal activation process as chemical reaction, the diffusion coefficient will obey the equation.

Figure 4 shows the Arrhenius plots of the carbon diffusion coefficient into Fe wire. The diffusion coefficient \(D\) is calculated from the Einstein equation as follows:

\[
D = \frac{x^2}{2t} \tag{3}
\]

where \(x\) is the average diffusion depth and \(t\) is heating time. The diffusion coefficient increases as the temperature rises. The activation energy was 44 kJ/mol, at the same order of the literature [5]. The carbon diffusion coefficient and the activation energy were small; that is, the diffusion rate was not high, whereas the energy barrier of the diffusion was not high.

This result suggests that the difference of the diffusibility influences the wear in turning of steel.
MACHINABILITY OF STEEL
EXPERIMENTAL METHOD
As a preliminary investigation, various quenched and tempered steels were turned using single-crystal diamond tools, and tool wears were measured using a scanning electron microscope. Table 1 shows the detailed tool geometries and cutting conditions.

RESULTS AND DISCUSSIONS
Maximum wear was observed at the tool nose, and its extent varied for different steels. Fig. 5 shows the relationship between hardness of steel and the corner wear. The wear is not influenced by the hardness because the correlation coefficient is very low. To clarify the reasons, metallographic analysis of the steels used in the turning experiments was performed by X-ray diffraction. This analysis revealed that the steels had considerably different microstructures that could be classified into four broad groups: $\alpha$-ferrite, $\alpha$-ferrite + $\gamma$-austenite, $\gamma$-austenite, and $\alpha$-ferrite + carbide compounds (e.g., Fe$_3$C, Cr$_2$C$_6$, and WC).

On the basis of this result, we analyzed whether a causal relationship exist between the microstructure of the steel and the nose wear of the diamond tool. To ensure unbiased analysis, an inductive inference technique known as C4.5 was applied to the tool wear measurement and phase analysis results. C4.5 generated valuable classification rules in the form of a decision tree that had branches associated with the matrix phases of the steels and leaves associated with the extent of nose wear. Fig. 6 shows the decision tree. The tree described the following two rules: steels whose microstructures consist of $\alpha$-ferrite and carbide phases (e.g., JIS SK5, JIS SKS3, and JIS SUS420J2) wore the tool nose slightly, whereas steels whose microstructures consist of $\alpha$-ferrite, $\alpha$-ferrite + $\gamma$-austenite, or $\gamma$-austenite wore the tool nose severely. Hence, the presence of carbon compounds in the $\alpha$-ferrite matrix appears to be very effective in reducing the nose wear of diamond tools.

To confirm this hypothesis, diamond turnabilities of steels in which carbon atoms remain as a solid solution in the martensite phase instead of forming carbon compounds were investigated.

Table 1. Machining parameters used to assess the flank wear on diamond tools.

<table>
<thead>
<tr>
<th>Cutting tool</th>
<th>Material</th>
<th>Monocrystalline diamond la</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystallographic</td>
<td>orientation</td>
<td>(100) rake plane /</td>
</tr>
<tr>
<td>included angle</td>
<td></td>
<td>(110) front plane</td>
</tr>
<tr>
<td>Rake angle</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>Clearance angle</td>
<td>7°</td>
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<table>
<thead>
<tr>
<th>Cutting conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
</tr>
<tr>
<td>Feed rate</td>
</tr>
<tr>
<td>Depth of cut</td>
</tr>
<tr>
<td>Cutting length</td>
</tr>
<tr>
<td>Coolant</td>
</tr>
</tbody>
</table>

![Fig. 5. Corner wear of diamond tool versus hardness of steel.](image)

![Fig. 6. Decision tree classifying the tool wear into three categories by the matrix phase and carbide.](image)
Fig. 7 shows the X-ray diffraction patterns of tempered steel and a quenched one. Fig. 8 shows the scanning electron micrographs of tempered steel and quenched one. Fig. 9 shows the corner wear of diamond tools in turning of tempered steels and quenched ones.

Turning experiments revealed that steels supersaturated with carbon atoms (i.e., quenched JIS SK5 and JIS SUS420J2) severely wore the tool nose. Therefore, it can be concluded that the formation of small carbon compound particles that are uniformly dispersed within a continuous α-ferrite matrix suppresses nose wear of diamond tools.

CONCLUSIONS

In this paper, wear mechanism and wear suppression factors of diamond tool were discussed based on thermodynamics analysis and erosion test, and the wear of diamond tools in turning of several steels.

The thermodynamics analysis and the erosion test suggest that carbon atoms in diamond diffuse into iron.

The wear of diamond tools in turning of several steels suggests that metallographic structures of steels influence the diffusibilities of carbon atoms, and thus influence the wear rate.

The machinability test shows the wear suppression factors of diamond tool in turning of steels are as follows:

1. Carbides precipitation, e.g., Fe3C, Cr23C6, and WC, in α-Fe prevents diamond tools from severe wears.
2. Oversaturated carbon solution in steel matrix does not prevent diamond tools from severe wears.

REFERENCES


