MANUFACTURING OF MICRO V-GROOVE WITH AN ELECTRICALLY CONDUCTIVE DIAMOND ELECTRODE IN EDM

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INTRODUCTION
In order to realize successful fine and precise EDM, it is important to minimize the wear of the electrode under the condition of very small pulse duration. To cope with this issue, the authors focused attention on the electrically conductive CVD diamond (EC-CVD diamond here after) having very high thermal conductivity, and have already shown that an extremely low wear machining could be realized by using the EC-CVD diamond as an electrode [1, 2]. Subsequently, the authors proposed the use of PCD (polycrystalline diamond) material having adequately high thermal conductivity instead of expensive EC-CVD diamond, and have shown that the PCD also has superior wear resistance in EDM on die steel (SKD11 in JIS) similar to the EC-CVD diamond electrode [3].

In this study, fine EDM experiments were conducted using a PCD electrode having a knife edged shape with an included angle of 45°, for the purpose of realizing a practical use of PCD material as an electrode for fine and precise ED machining on tungsten carbide workpiece.

PCD MATERIAL USED
Table 1 shows the physical properties of typical PCD materials (Syndite, CTB-010 & CTH-025) as well as presently used electrode materials [4]. Each of the PCD materials has a thermal conductivity value falling between those of copper and EC-CVD diamond, and the thermal diffusivity calculated from the specific heat is also close to that of the EC-CVD diamond material. Therefore, PCD is expected to serve as a superior electrode material for precise micro-EDM on tungsten carbide materials. Such a superior thermal property is derived from the composition and structure of the PCD materials. Concretely, PCD is composed of micron-size diamond particles that are firmly bonded (intergrowth) with each other during the synthesis process under ultra-high pressure and high temperature with the help of metallic catalyst (cobalt in this case).

EDM PROPERTIES OF PCD ELECTRODES WITH FLAT SURFACE
EDM experiments on tungsten carbide (G5) were conducted using a flat surface of a PCD material with the setup shown in Fig.1 to investigate the properties of PCD as an electrode, and the results were compared with those of other electrode materials. The EDM conditions used were no-load voltage of $u_i=90\text{V}$, set peak current of $i_P=3\text{A}$, pulse duration of $t_e=1$ and $30\mu\text{s}$ for the PCD electrode. And for the Cu-W electrode the recommended condition, by an EDM machine maker, of $u_i=120\text{V}$, $i_P=1.6\text{A}$, $t_e=0.5\mu\text{s}$ and the electrode polarity fluctuating between positive and negative were used because the electrode wear of the Cu-W is stated to be the lowest under these condition. The results of the experiments are shown in Fig.2.

Figure 2(a) shows a comparison of the electrode wear ratio ($=\text{electrode wear depth / workpiece removal } \times 100\%$) for the various electrode materials at a short pulse ($t_e=1\mu\text{s}$) as well as a long pulse ($t_e=30\mu\text{s}$) duration. A positive value shows electrode wear and a negative value shows an increase in the length of the electrode.

<table>
<thead>
<tr>
<th>Material</th>
<th>PCD (Syndite*)</th>
<th>EC CVD diamond (CVDITE-CDE*)</th>
<th>Existing electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder:</td>
<td>Cobalt Cobalt</td>
<td>Cobalt Cobalt</td>
<td>Cobalt Cobalt</td>
</tr>
<tr>
<td>Binder: wt%/vol%</td>
<td>22.6/10.3</td>
<td>17.9/7.9</td>
<td>0</td>
</tr>
<tr>
<td>Diamond size: μm</td>
<td>10</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Density: g/cm³</td>
<td>4.08</td>
<td>3.95</td>
<td>3.5</td>
</tr>
<tr>
<td>Specific resistivity: Ω·m</td>
<td>1.4×10⁻⁴</td>
<td>-</td>
<td>0.4~1×10⁻³</td>
</tr>
<tr>
<td>Thermal conductivity: W/m·K</td>
<td>459</td>
<td>501</td>
<td>500~600</td>
</tr>
<tr>
<td>Thermal diffusivity: m²/s</td>
<td>0.24×10⁻⁴</td>
<td>0.27×10⁻⁴</td>
<td>0.27~0.33×10⁻⁴</td>
</tr>
</tbody>
</table>

*1 Calculated value, *2 Element Six Ltd. [4], *3 D.S. McLachlin [5], *4 Calculated value from specific heat measured by Univ. of Limerick
Here, the negative value means the adhesion of the graphitic carbon, which generated from the decomposition of the dielectric oil due to discharge, on the electrode surface. The wear on Cu-W electrode, generally used in conventional EDM on tungsten carbide workpiece, was very high about 10% even under the recommended condition. In addition to this, the electrode wear ratio was very low such as only 1.5% with CTB-010 (particle size 10µm) and 0.6% with CTH-025 (particle size 25µm) even at very short pulse duration of $t_e=1µs$. On the other hand, the electrode wear ratio showed negative value (adhesion of carbon) at $t_e/t_o=30/30µs$.

Figure 2(b) shows a comparison of the rate of material removal for the various electrodes. The rate of material removal of Cu-W electrodes is about 2.5~3 times higher than those of the PCD and EC-CVD diamond electrodes. But, it is believed to be meaningless to talk about material removal rate without considering electrode wear ratio.

**EDM PROPERTIES OF PCD ELECTRODE WITH V SHAPE**

1. **Shape of the PCD electrode:** Two kinds of PCD materials with different grain sizes, namely, 10 and 25μm (Table 1), were formed to have a 45° V shape (knife edge shape) by wire EDM. Figure 3 shows an appearance of the knife-edge shape and the oblique plane. Nose radius of the edge is under 10µm for each case from the results of SEM observation.

2. **Fine groove machining condition:** An attempt was made to create a fine groove on a tungsten carbide workpiece by performing an EDM operation up to a depth of 0.2mm in oil using the knife edge shaped electrode (Fig.4). In this experiment, the performance assessment of electrode in EDM was specially focused on the amount of wear of the electrode. Specifications of the experimental apparatus and conditions are shown in Table 2. Effect of various parameters of EDM condition (ED voltage, ED current and ED duration) on the electrode wear was investigated.

**EDM Characteristics With Cu-W Electrode**

First, for comparison, a 2mm wide fine V-groove was machined on a WC workpiece using a Cu-
W electrode under the EDM conditions recommended by the machine manufacturer. Results are shown in Fig. 5. Wear on the Cu-W electrode was relatively large, showing a depth of wear of 50µm on the edge after machining. The nose radius of the V-groove also became large.

**EDM Characteristics Using PCD Electrode**

The same EDM tests were carried out using other two kinds of PCD (CTB-010 and CTH025) electrodes. The relation between the EDM conditions and wear depths is shown in Fig. 6. And, Figure 7 shows the results of the electrode wear and machined groove observed by SEM.

**Effect of no-load voltage** (Fig. 6(a), Fig. 7(a))

Varying the no-load voltage in the range of $u_i=60$~$120$V, an attempt was made to find out the condition where no wear machining was possible. For other conditions, set peak current of $i_p=2$A and rather long pulse duration of $t_e=15$µs ($t_o=15$µs) were used. Although the time required and machining efficiency are not discussed here, it is observed that the higher the voltage and current, the shorter the machining time was, e.g. the machining was completed in 5 minutes when $i_p≥2$A.

When no-load voltage was $u_i=120$V, the wear on both CTH025 and CTB010 was large as 15~20µm. But, by setting the voltage at 60V, electrode wear was largely reduced. Especially, almost no wear was observed with CTH025. By comparing the two different PCD electrodes, it has become clear that there is a tendency that a coarser grade PCD (CTH025) shows low wear than a finer grade PCD (CTB010).

**Effect of set ED current** (Fig. 6(b), Fig. 7(b))

In order to investigate the ED condition for low electrode wear, experimental test was carried out by varying the set ED current in the range of $i_p=0.5$~$4$A, and keeping the no-load ED voltage at $u_i=60$V. ED pulse was set at $t_e/t_o=15/15$µs. When the set current was as small as 0.5A, the electrode wear was large on the both PCD electrodes. However, it was revealed that low-wear machining was possible at the set current larger than 1A. In this experiment, the CTH025 electrode also proved to show lower wear than the CTB010 electrode.

**Effect of ED duration** (Fig. 6(c), Fig. 7(c))

Effect of ED duration (pulse-on time) was investigated by setting the conditions of ED voltage $u_i=60$V, ED current $i_p=2$A and off time $t_o=15$µm. At the short-pulse duration of $t_e=2$µs which is generally used to obtain a good surface, wear on the both PCD electrodes was between 20-30µm. On the other hand, it was revealed that, when $t_e$ is larger than 15µs, CTH025 showed almost no wear. Moreover, in this case, wear on CTB010 electrode was also nearly zero.

From the above results, it has become clear that the problem of high electrode wear in fine EDM on tungsten carbide can be solved by using the proposed PCD electrode achieving almost zero wear. Cu-W electrode has never been able to achieve this. From now on, the authors plan to make a further study to investigate the machining efficiency and the dimensional accuracy of the groove.

**CONCLUSION**

Two types of PCD electrodes of different kind were applied to fine groove machining as well as flat surface machining on tungsten carbide and their machining characteristics were investigated. From the results, the following points have become clear.

1. PCD electrodes with flat surface show an almost zero wear at the long pulse duration and a significantly low wear of 0.6~1.5% at the short pulse duration compared to 10% wear of the Cu-W electrode at suggested
condition for EDM on tungsten carbide (G5).

2. The electrode wear is extremely less with PCD electrode compared to a Cu-W electrode and a zero wear machining is achieved by optimizing the ED conditions ($u_i=60V$, $i_p=2A$, $t_e>15\mu s$).

3. Thermal conductivity of PCD is different according to the diamond grain size of the PCD. In this study, it was expected that the electrode with higher thermal conductivity would show less wear. In fact, the result is just as expected, i.e. CTH025 exhibits less wear than CTB010.

4. As the diamond is an insulator, it was expected that the grain size of the diamond would affect ED performance. In order to investigate, how this would affect the electrode wear, various tests were carried out by varying the parameters under the ED condition. However, the result revealed that wear on CTH025 is less than CTB010 although CTH025 is thought to have more contributing factor to cause unstable ED performance.

ACKNOWLEDGMENTS
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REFERENCES


4. Element Six Ltd., Catalogue.


FIGURE 7. Effect of EDM conditions on electrode wear and EDMed V groove.