Low-Wear Diamond Electrode for Micro-EDM of Die-Steel

A. Sharma¹, M. Iwai², K. Suzuki¹, T. Uematsu²
¹Nippon Institute of Technology, Miyashiro, Saitama 345-8501, Japan
²Toyama Prefectural University, Kosugi, Toyama 939-0398, Japan

Abstract
The reduction of electrode wear is very important for high finish and high accuracy machining in micro-EDM. Electrically conductive CVD diamond has shown almost zero electrode wear, even at short pulse duration of 3μs, which is extremely important for maintaining the desired shape. This research involves the investigation into the effect of various EDM parameters on the EDM of die steel using electrically conductive CVD diamond with respect to electrode wear, efficiency and EDMed surface property. The effect of joule heating due to the high electrical resistivity of electrically conductive CVD diamond was also studied and the results indicate that there is no deterioration of the workpiece surface due to joule heating when EDM is performed using the electrically conductive CVD diamond electrode. An investigation into the factors responsible for the low wear of the CVD diamond electrode leads us to deduce that an accelerated deposition of heat resolved carbon along with the high thermal stability of the diamond are mainly responsible.

Keywords: EDM, Electrically Conductive CVD Diamond, Low-wear electrode

1 INTRODUCTION
Electrical discharge machining (EDM) is being increasingly used in micro machining of various types of steels as well as other difficult to machine materials. In the case of micro machining using EDM it is extremely important not only to provide a good surface finish to the workpiece but also to reduce the electrode wear in order to increase the shape accuracy of the machined part. It is presently very difficult to achieve a good surface finish along with high shape accuracy due to the high wear rate of the presently used electrode materials under finish EDM conditions. Although EDM with very low electrode wear can be achieved due to the adhesion of heat resolved carbon from the dielectric fluid, which protects the electrode from thermal wear, it has been reported that this phenomenon takes place only at sufficiently long pulse durations [1,2]. A surface machined using EDM has a mat type texture resulting from the discharge craters. The size of these craters is directly proportional to the EDM current and pulse duration. To obtain a good EDMed surface finish it is necessary to reduce the size of these craters, which can be achieved by lowering the EDM current and making the pulse durations extremely short. However, presently at very short pulse durations, the wear rate of the electrode increases rapidly as a result of which the desired shape accuracy of the workpiece cannot be achieved.

Suzuki et al demonstrated the ability of an electrically conductive CVD diamond thick film (hereafter EC-CVD diamond) electrode to perform EDM even at short pulse durations of 3μs without any significant electrode wear [3]. The present research work deals with further investigation on the application of the EC-CVD diamond to EDM of die steels as well as the factors responsible for the low wear of the diamond electrode. The effect of various EDM conditions on the performance of the EC-CVD diamond electrode is investigated. EDM using the diamond electrode is also performed in dielectric water.

The results of the experiments indicate almost zero wear on the EC-CVD diamond electrode, when EDM is performed in oil even for very short pulse durations of 3μs. This is thought to be due to an accelerated adhesion of heat resolved carbon from the dielectric oil onto the electrode surface as well as the high thermal stability of the EC-CVD diamond.

2 THERMAL BEHAVIOUR OF EC-CVD DIAMOND
Table 1 lists the physical properties of EC-CVD diamond along with copper, graphite and CuW. EC-CVD diamond, which is made electrically conductive by doping with boron during CVD process, has sufficient electrical conductivity to perform EDM. It also has the highest thermal diffusivity compared to the presently used electrode materials, which may be helpful in a faster dissipation of the heat generated from the machining point.

The addition of boron as the doping agent has an additional effect of increasing the thermal stability of the EC-CVD diamond compared to non-conductive CVD diamond. Oxidation tests for EC-CVD diamond (CVDITE-CDE) and electrically non-conductive CVD diamond (CVDITE-CDM) were performed. The tests consisted of heating the CVD diamond thick films (5×6×0.5mm) at temperatures of 825, 850, 875 and 900°C in air for 30 minutes followed by visual inspection using an optical microscope as well as measuring the change in weight. The results are shown in Figure 1. There is no change in the appearance of the EC-CVD diamond surfaces after heating for 30 mins at 825 and 850°C, whereas, in the case of the electrically non-conductive CVD diamond thick film, the surfaces appear to be deteriorating along with a reduction in weight by 2-3% and 8-10% at 825 and 850°C respectively. However, in case of the EC-CVD diamond, oxidation is observed at 875°C, showing a 3-5% reduction in weight.
<table>
<thead>
<tr>
<th>Material</th>
<th>E-CVD diamond*</th>
<th>Copper</th>
<th>Graphite</th>
<th>CuW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific resistance (Ω-m)</td>
<td>0.4 x 10^{-3}</td>
<td>17 x 10^{9}</td>
<td>14 x 10^{9}</td>
<td>6.8 x 10^{9}</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>3.5</td>
<td>9.0</td>
<td>1.8</td>
<td>14</td>
</tr>
<tr>
<td>Young's modulus (N/m²)</td>
<td>1000 - 1100 x 10^{9}</td>
<td>130 x 10^{9}</td>
<td>-</td>
<td>255 x 10^{9}</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
<td>500 - 600</td>
<td>400</td>
<td>75</td>
<td>188-295</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>1 x 10^{-8}</td>
<td>17 x 10^{8}</td>
<td>-</td>
<td>6.5 x 10^{8}</td>
</tr>
<tr>
<td>Thermal diffusivity (m²/s)</td>
<td>0.27 x 0.33 x 10^{-3}</td>
<td>0.12 x 10^{-3}</td>
<td>0.15 x 10^{-3}</td>
<td>-</td>
</tr>
</tbody>
</table>

* CVDITE-CDE from Clement Six Co., Ltd.

Table 1: Properties of EC-CVD diamond thick film.

<table>
<thead>
<tr>
<th>CDE (electrically conductive)</th>
<th>825°C (30mins)</th>
<th>850°C (30mins)</th>
<th>875°C (30 mins)</th>
<th>900°C (30mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight reduction</td>
<td>0%</td>
<td>0%</td>
<td>3-5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CDM (electrically non-conductive)</th>
<th>825°C (30mins)</th>
<th>850°C (30mins)</th>
<th>875°C (30 mins)</th>
<th>900°C (30mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight reduction</td>
<td>2-3%</td>
<td>8-10%</td>
<td>15-25%</td>
<td>67%</td>
</tr>
</tbody>
</table>

Figure 1: Comparison of oxidation of EC-CVD diamond (CVDITE-CDE) with normal CVD diamond (CVDITE-CDM).

which increases to about 10% at 900°C. But in the case of electrically non-conductive CVD diamond thick film, there is a high reduction of 15-25% in weight at 875°C which increases drastically to 67% at 900°C.

3 EDM EXPERIMENTS USING EC-CVD DIAMOND IN OIL

3.1 Experimental setup and conditions

An electrode segment was mounted on the head of a die-sinking machine by clamping onto a copper jig as shown in Figure 2. The experimental conditions are listed in Table 2. An EC-CVD diamond segment (6.5x0.5mm) along with copper, graphite, and Cu-W segments of approximately the same size was used for the electrode. Die steel SKD11 (HRC 61) was used as the workpiece. Kerosene (vitol 2) was used as the working fluid.

3.2 Comparison of electrode wear and EDM efficiency

Experiments to compare the wear depth and EDM efficiency of the EC-CVD diamond electrode with copper, graphite and CuW electrodes were performed. EDM conditions such as pulse durations of 3, 7, 15, 30µs, an open circuit voltage of 90V, and a peak current of 6A were used for the experiments. The depth of EDM in each case was 0.5mm. A pulse interval of 50µs was employed to eliminate the possibility of arcing.

<table>
<thead>
<tr>
<th>EDM machine</th>
<th>Die sinking EDM machine (AQ35L, Sodick)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric working fluid</td>
<td>Oil (Vitol 2, Sodick) Deionized water (200000~400000Ω.cm)</td>
</tr>
<tr>
<td>Electrodes</td>
<td>1. Electrically conductive CVD diamond film (CVDITE-CDE, 5×6×0.5mm, Element Six) 2. Copper (10×5×0.5mm) 3. Graphite (5×6×0.5mm) 4. Cu-W (5×6×0.5mm)</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Die steel (SKD11, Hardness HRC61)</td>
</tr>
<tr>
<td>EDM conditions</td>
<td>u= 90V, l₁=3, 6A, l₂=3, 7, 15, 30, 50µs, l₃=10, 50µs, EDM depth=0.5, 1mm</td>
</tr>
</tbody>
</table>

Table 2: Experimental devices and conditions.
Results of the electrode wear depths and EDM efficiencies are shown in Figure 3. It is well known that the electrode wear is reduced at sufficiently long pulse durations when EDM is performed in oil at reversed polarity, and it was reported that this phenomenon is mainly due to the adhesion of carbon, resulting from dielectric breakdown, onto the electrode surface \cite{1,2}. However, this phenomenon is not observed at short pulse durations due to a reduction in the amount of carbon adhesion with a decrease in the pulse duration. The electrode wear depth in the case of the EC-CVD diamond electrode is almost zero even for the short pulse duration of 3\( \mu \)s, whereas, the electrode wear depths are about 255, 150 and 105\( \mu \)m for copper, graphite and CuW electrodes respectively. Therefore, no wear EDM condition may be achieved in the case of the EC-CVD diamond electrode under finish EDM conditions, which is impossible in the case of presently used electrode materials. This EDM characteristic of the EC-CVD diamond electrode is particularly important for the die sinking EDM of micro sized parts at finish EDM conditions without damaging the shape accuracy.

EDM efficiency of the EC-CVD diamond is significantly low compared to the copper electrode at pulse durations of more than 15\( \mu \)s. The efficiency of the diamond and graphite electrodes is found to be same for the various pulse durations. The efficiency of the CuW electrode is the lowest among the electrode materials.

3.3 Effect of polarity

The effect of polarity on the EC-CVD diamond electrode was investigated and compared with a copper electrode under the same EDM conditions. The experiment was performed under EDM conditions of \( u=90V \), \( I_p=3A \) and \( t_{p}/t_{o}=3/10, 50/50\mu s \). The results of this experiment are shown in Figure 4. There is no wear on the diamond electrode when it is used at reversed polarity even for the short pulse duration of 3\( \mu \)s, whereas, when used at straight polarity, a large amount of wear is observed and the wear depth increases with an increase in the pulse duration. In the case of the copper electrode, at the short pulse duration of 3\( \mu \)s, the wear depth at reversed polarity is greater than the wear depth at straight polarity, whereas, at the long pulse duration of 50\( \mu \)s, the wear depth when it is used at reversed polarity is zero compared to the wear depth of 220\( \mu \)m when it is used at straight polarity.

3.4 Discharge voltage and surface characteristics

The voltage and current waveforms during EDM using EC-CVD diamond, copper, graphite and CuW electrodes are shown in Figure 5. In the case of the EC-CVD diamond electrode a very large increase in the discharge voltage of about 9V is observed compared with the copper, graphite and CuW electrodes. This is attributed to the high electrical resistivity (@=0.4-1x10^{3} \Omega \cdot m) of the EC-CVD diamond.
Figure 5: Current and voltage waveforms during electric discharge. 
(V=90V, Ie=3A, EDM area=1.5mm², EDM depth=1mm, reversed polarity (electrode +), in oil)

Figure 6: SEM photographs of EDMed workpiece surface (tilt angle 45°). 
(u=90V, Ie=3A, EDM area=1.5mm², EDM depth=1mm, reversed polarity (electrode +), in oil)

Figure 7: Comparison of wear and efficiency among electrode materials. 
(u=90V, Ie=6A, to=50μs, Work=SKD11, EDM depth=0.5mm, reversed polarity (diamond +), in water)

(a) Comparison of wear depth
(b) EDM efficiency

It has been reported that in the EDM of electrically conductive Si3N4 ceramic (ρ=3×10³ Ω.m), there is an occurrence of joule heating due to the voltage drop in the material, resulting in an increase in the temperature of the material, in a region close to the discharge location [4]. This increase in workpiece temperature together with a low thermal diffusivity (κ=1.9×10⁻³ m²/s) of the electrically conductive Si3N4 ceramic causes arcing which results in a deteriorated EDMed surface quality.

Figure 8 shows the SEM photographs of the workpiece surfaces EDMed using EC-CVD diamond, copper, graphite and CuW electrodes at pulse conditions of to=10/10 and 50/50μs. In the case of the surface EDMed using the EC-CVD diamond, copper and CuW electrodes no evidence of arcing can be observed, whereas, in the case of the graphite electrode a deterioration of the surface due to arcing can be observed. Moreover, in the case when the pulse
condition is $t_d/t_s=50/50 \mu s$, the discharge craters on the surface of the workpiece EDMed using the EC-CVD diamond electrode appear larger in size compared to the craters on the workpiece surfaces EDMed using copper and CuW. This may be due to a high plasma temperature near the EC-CVD diamond electrode surface (because of joule heating), resulting in a higher rate of spread of the plasma. It can therefore be said that the high thermal diffusivity of the EC-CVD diamond helps in extinguishing the discharge plasma, which prevents the occurrence of arcing resulting in a good EDMed surface quality.

4 EDM EXPERIMENTS USING EC-CVD DIAMOND IN WATER

4.1 Electrode wear depth and EDM efficiency

EDM of SKD11 die steel using the EC-CVD diamond electrode was performed in de-ionized water as dielectric working fluid and compared with copper, graphite and CuW electrodes. Pulse durations of 3, 7, 15, 30 $\mu s$, peak current of 6A, open circuit voltage of 90V and pulse interval of 50$\mu s$ were used. Figure 7(a) shows the results for the wear depths of the EC-CVD diamond, copper, graphite and CuW electrodes. Although a maximum wear depth of about 30$\mu m$ is observed for the EC-CVD diamond electrode at the pulse duration of 3$\mu s$, it is significantly low compared to the wear depths of 174, 239 and 87$\mu m$ for the copper, graphite and CuW electrodes respectively. The wear of the EC-CVD diamond during EDM in water may be due to the oxidation of diamond by oxygen ions produced as a result of the ionization of water. On the other hand, the significantly low wear, compared to the other electrode materials, is thought to be due to the high thermal stability as well as the high thermal diffusivity of the EC-CVD diamond.

Figure 7(b) shows the EDM efficiencies of the EC-CVD diamond, copper, graphite and CuW electrodes. The EDM efficiency of the graphite electrode is the highest followed by the copper, diamond and CuW electrodes at the pulse duration of 7$\mu s$. For the pulse durations of 3, 15 and 30$\mu s$ much difference in the EDM efficiencies are not observed.

4.2 Surface characteristics of EC-CVD diamond electrode after EDM

In order to investigate the surface characteristics of the EC-CVD diamond electrode surface, Raman spectrum measurements of the surface of the diamond used for EDM were performed. Figure 8(a) shows the Raman spectrum of unused diamond surface. Figure 8(b) and (c) show the Raman spectra of the EC-CVD diamond electrode surface after EDM in oil and water respectively. The Raman spectrum of the EC-CVD diamond electrode surface after EDM in oil shows the presence of graphitic carbon. This is considered to be the heat resolved carbon from the dielectric oil. The Raman spectrum in Figure 8(c) shows that when EDM is performed in water, a damaged crystal structure of the EC-CVD diamond is observed. However, there is no presence of graphite or graphitic carbon on the surface, which indicates that the EC-CVD diamond may be oxidized by the oxygen ions during the discharge process.

5 MECHANISM OF LOW WEAR OF DIAMOND ELECTRODE

5.1 Accelerated adhesion of carbon

One of the most important reasons for the low wear of the EC-CVD diamond electrode, when oil is used as the dielectric medium, is an accelerated adhesion of carbon compared to other electrode materials. This is because of the fact that the EC-CVD diamond electrode does not show any wear even when EDM is performed at the short pulse duration of 3$\mu s$. However, when EDM is performed using water as the dielectric medium, the EC-CVD diamond electrode shows a wear depth of about 30$\mu m$ under the same conditions. Moreover, as shown previously in Figure 4, when EDM is performed in oil, the wear of the EC-CVD diamond electrode increases drastically at straight polarity (EC-CVD diamond electrode negative). In the case of EDM in oil, the wear of the positive electrode is less due to the formation of a carbon layer on the electrode surface, which protects the electrode from thermal wear.
5.2 Thermal stability
In the absence of oxygen, diamond is thermally stable up to 1000°C after which conversion to graphite starts. From the results of EDM using the diamond electrode in water in Figure 7(a), a very low wear of the diamond electrode compared to copper, graphite and Cu-W can be observed. This can be attributed to the high thermal stability of diamond in the absence of oxygen. This property of diamond may also be useful in the case of EDM using the EC-CVD diamond in oil.

6 CONCLUSION
In conclusion, the following observations may be pointed out.

1. The EDMing ability of the EC-CVD diamond electrode without any wear even at very short pulses gives it a great advantage to become an important electrode material for the machining of micro-parts.
2. There is a significant rise in the discharge voltage of about 9V in the case of the EC-CVD diamond resulting in an increase in the plasma temperature due to joule heating, however, detartration of the EDMed workplace surface due to arcing is not observed, which is thought to be due to the high thermal diffusivity of the EC-CVD diamond.
3. The EC-CVD diamond electrode shows an increased amount of wear depth when water is used as the dielectric fluid, however, this wear depth is significantly low compared to copper and CuW electrodes.
4. The wear depth of the EC-CVD diamond during EDM in water may be attributed to oxidation by oxygen ions produced as a result of the ionization of water.

5. The extremely low wear of the EC-CVD diamond electrode even for short pulse durations is thought to be due to an acceleration in the rate of carbon adhesion onto the EC-CVD diamond electrode surface as well as the high thermal stability of the EC-CVD diamond.

7 ACKNOWLEDGMENTS
The authors would like to thank Element Six Co., Ltd. for providing the EC-CVD diamond thick films. The authors would also like to acknowledge the support and advise from Mr. Sano and Mr. Karato of Sodick Co., Ltd. The authors would like to express their heartfelt thanks to Prof. M. Kunieda and Mr. Shoda for their valuable advice. The authors are very thankful for the support received from Osaka Scientific Studies Grants Foundation. The authors also appreciate the assistance of Mr. M. Suzuki of R&D center for Advanced Materials and Technology of N.I.T. for assistance in spectroscopy work.

8 REFERENCES