

## Investigation into the low wear of EC-CVD diamond electrode with respect to the thermal diffusivity

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In electrical discharge machining (EDM) the property of an electrode is one of the most important factors for improving the EDM performances, such as material removal efficiency, machining accuracy, and quality of workpiece surface. This paper deals with an investigation into the effect of the thermal diffusivity on the low wear of the electrically conductive CVD diamond (EC-CVD diamond) electrode. The EDM experiments show that the EC-CVD diamond electrode shows a lower wear even in water as the dielectric medium compared to copper and graphite electrodes. Thermal FEM analysis of the electrode materials indicates that there is a significant decrease in the electrode temperature for the EC-CVD diamond compared to copper and graphite due to its high thermal diffusivity.

### 1. Introduction

In general electrode materials show a low wear when used as anode and in oil as the working fluid at long pulse durations more than 20 $\mu$ s due to the adhesion of heat resolved carbon from the working fluid onto the electrode surface, which protects the electrode from thermal wear<sup>1)</sup>. However, at short pulse durations less than 20 $\mu$ s the electrode wear starts to increase. The authors demonstrated that by using the electrically conductive CVD diamond (hereafter EC-CVD diamond) electrode, EDM could be performed with almost no wear of the electrode at short pulse durations in oil<sup>2)</sup> and also in water<sup>3, 4)</sup>. It is therefore thought that the EC-CVD diamond has a possibility to become a superior electrode material. This research investigates the low wear of the EC-CVD diamond electrode with respect to thermal diffusivity. Thermal FEM analysis of three electrode materials, EC-CVD diamond, copper and graphite are performed and the results are compared with the experimental electrode wear ratios of the respective materials. The results show a close relation between the thermal diffusivity and electrode wear ratio, that is the electrode wear ratio increases as the thermal diffusivity decreases.

### 2. Experimental setup and conditions

The electrode and workpiece used in this study were of the same thickness (0.5mm) and similar size. Three electrode (anode) materials, EC-CVD diamond, copper and graphite were used. The workpiece (cathode) materials were EC-CVD diamond, copper and steel (SKD11). Kerosene and de-ionized water were used as the dielectric working fluids. EDM was performed on a die-sinking EDM machine. The electrode and workpiece were set perpendicular to each other as shown in Fig.1 in order to ease the removal of the debris and stabilize the EDM process. EDM conditions  $V=90V$ ,  $i_c=6A$ ,  $t_o=50\mu s$ ,  $t_c=3, 6, 15, 25, 50\mu s$ , EDM time=1min and EDM area=0.5 $\times$ 0.5mm were used for the experiments. The experimental conditions are listed in Table 2.

### 3. Experimental results

#### 3.1 EDM of SKD11

Figure 2 shows the results of the experiment when EDM was performed on SKD11 as the workpiece (cathode) using three electrode materials, EC-CVD diamond, copper and graphite as the electrode (anode), in oil and water as the dielectric medium.

Table.1 Properties of EC-CVD diamond\* thick film

Material	EC-CVD diamond	Copper	Graphite
Specific resistance ( $\Omega\cdot m$ )	$0.4 \sim 1 \times 10^{-3}$	$17 \times 10^{-9}$	$14 \times 10^{-6}$
Specific gravity	3.5	9.0	1.8
Young's modulus ( $N/m^2$ )	$1000 \sim 1100 \times 10^9$	$130 \times 10^9$	-
Thermal conductivity ( $W/m\cdot K$ )	$500 \sim 600$	400	75
Coefficient of thermal expansion	$1 \times 10^{-6}$	$17 \times 10^{-6}$	-
Thermal diffusivity ( $m^2/s$ )	$0.27 \sim 0.33 \times 10^{-3}$	$0.12 \times 10^{-3}$	$\approx 0.05 \times 10^{-3}$

\* CVDITE-CDE from Element Six Co., Ltd

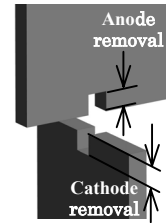


Fig.1 Experimental setup

Table.2 Experimental conditions

EDM machine	Die sinking EDM machine (AQ35L, Sodick)
Working fluid	1. Oil (Vitol 2, Sodick) 2. De-ionized water (200~400 k $\Omega\cdot cm$ )
Electrode & workpiece	1. Electrically conductive CVD diamond film (CVDITE-CDE, 5 $\times$ 6 $\times$ 0.5mm, Element Six) 2. Copper (10 $\times$ 10 $\times$ 0.5mm) 3. Steel (SKD11, HRC 61, 10 $\times$ 10 $\times$ 0.5mm) 4. Graphite (ED 3, 10 $\times$ 6 $\times$ 0.5mm)
EDM conditions	$u_i=90V$ , $i_c=6A$ , $t_c=3\sim 50\mu s$ , $t_o=50\mu s$ , EDM time=1 min, EDM area=0.5 $\times$ 0.5mm

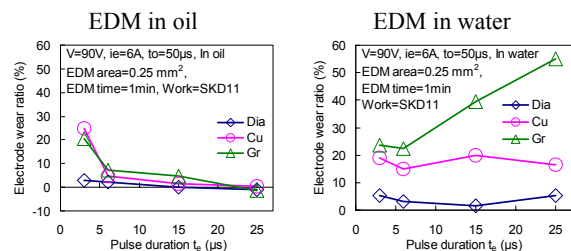


Fig.2 Electrode wear ratio for EDM of SKD11 in oil and water ( $V=90V$ ,  $i_c=6A$ ,  $t_c=50\mu s$ , EDM area=0.25mm<sup>2</sup>, EDM time=1min)

For all the cases the electrode wear ratio of the EC-CVD diamond electrode is the lowest compared to copper and graphite. Especially in the case when EDM is performed in water, the distinction in the electrode wear ratio among EC-CVD diamond, copper and graphite can be clearly observed.

#### 3.2 EDM of EC-CVD diamond and copper

EDM was performed using EC-CVD diamond and copper as the electrode (anode) on the same materials as the workpiece (cathode) in oil and water and the electrode wear rate was

investigated. Figure 3 shows the electrode wear rate of EC-CVD diamond and copper with respect to the pulse duration. The electrode wear rate of the EC-CVD diamond electrode is lower than that of copper for EDM in both oil and water. The electrode wear rate of EC-CVD diamond when EDM is performed in water is especially lower than the copper electrode.

**4. Thermal FEM analysis for a single discharge pulse**

It is well known that during EDM in oil, at long pulse durations of more than 20μs, the heat resolved graphitic carbon from the EDM oil adheres onto the anode surface and protects it from thermal wear and therefore the anode removal rates of copper as well as diamond are low for EDM in oil. However, even when EDM is performed in water (absence of carbon), the anode removal rate of the EC-CVD diamond is significantly lower than copper and graphite. One reason for this is thought to be the high thermal diffusivity of EC-CVD diamond compared to copper and graphite as can be seen in Table 1.

Thermal FEM analysis of three electrode materials, EC-CVD diamond, copper and graphite is performed to investigate the effect of the high thermal diffusivity by comparing the rise in temperature of the electrodes due to a single discharge pulse. The equations <sup>5,6)</sup> used to calculate the heat flux and the discharge plasma diameter along with physical properties of the electrode materials and the calculated values are shown in Table 3. Analysis was performed for pulse durations of 2 and 100μs. The actual value of the heat flux input into the analysis model is 30% of the calculated <sup>6)</sup>. The analysis model is shown in Fig.4 (a) and the maximum temperature rise in the electrode material at the end of the discharge pulse is shown in Fig.4 (b). A significant difference in the maximum temperature of the electrodes between EC-CVD diamond and copper of about 250°C and 1100°C for the pulse durations of 2 and 100μs respectively is obtained. A very large difference in the maximum temperature of the electrodes between copper and graphite of 5100°C and 19000°C for the pulse durations of 100 and 2μs respectively is obtained.

From the results of the analysis it can be said that there is a significant decrease in the temperature rise of EC-CVD diamond electrode due to its high thermal diffusivity and this may be one of the reasons for the low wear of the EC-CVD diamond electrode.

**5. Conclusion**

EDM experiments and thermal FEM analysis to investigate the effect of thermal diffusivity on the low wear of the EC-CVD diamond electrode were performed. The experimental results show low wear of the EC-CVD diamond electrode in oil as well as water as the dielectric medium. Thermal FEM analysis indicates that due to the high thermal diffusivity of the EC-CVD diamond electrode, the temperature rise in the electrode during EDM is significantly low. It can therefore be said that the high thermal diffusivity of the EC-CVD diamond electrode plays an important part in the low wear of the EC-CVD diamond electrode.

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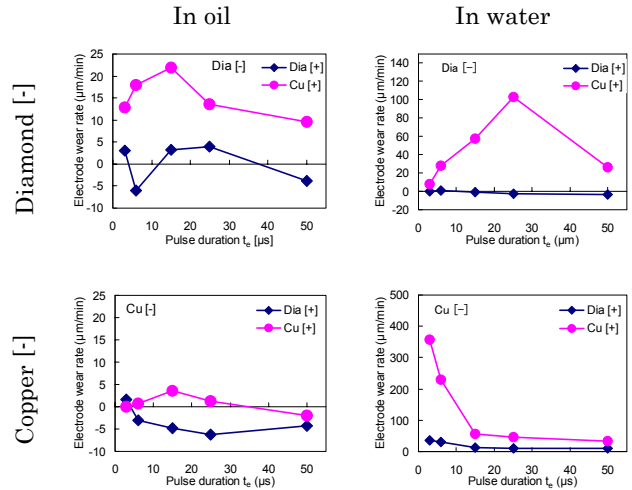
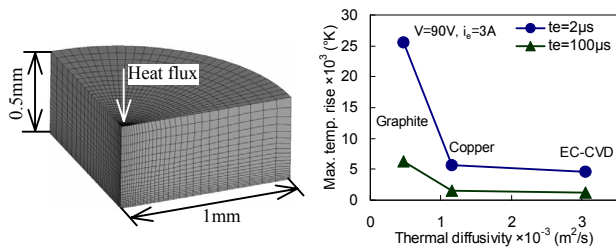


Fig.3 Electrode wear rate during EDM of EC-CVD diamond and copper (V=90V,  $i_c=6A$ ,  $t_p=50\mu s$ , EDM time=1min, EDM area=0.25mm<sup>2</sup>)

Table 3 FEM analysis conditions

Analysis software	ANSYS 8.1			
Equations used for calculation of heat flux	Diameter ( $d$ ) of the arc column: $d=0.0024 \times i_c^{0.4} \times t^{0.4}$ (m) (1) where, $i_c$ is the discharge current in amperes, and $t$ is the time after breakdown in seconds			
	The heat flux ( $q$ ) into the electrode is: $q=[i_c \times V] / \pi \times (d/2)^2$ (W/m <sup>2</sup> ) (2) where, $V$ is the discharge voltage in volts			
Thermophysical properties		Density (kg/m <sup>3</sup> )	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
	EC-CVD diamond	3520	510	550
	Copper	9000	385	400
	Graphite	2260	700	75
Calculated arc diameter [ $d$ ] and heat flux		Pulse on time (μs)		
		2	100	
	[ $d$ ] (m)	$1.9 \times 10^{-5}$	$9.3 \times 10^{-5}$	
	[ $q$ ] (W/m <sup>2</sup> )	$8.9 \times 10^{11}$	$3.93 \times 10^{10}$	



(a) Analysis model (b) Analysis results

Fig. 4 Maximum temperature rise in the electrode for a single discharge pulse.

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