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Energy Distribution in Electrical Discharge Machining with Graphite Electrode

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In EDM, the machining characteristics greatly depend on the energy distribution. Therefore, it is very important to clarify the energy distribution for understanding various phenomena in EDM. In this paper, the energy distribution in EDM with graphite electrode is investigated by measuring the temperatures of electrode and workpiece. Experimental analysis shows that the material removal rate depends on energy density while the electrode wear greatly depends on the adhesion of heat resolved carbon from machining fluid, and the energies distributed into electrode and workpiece are almost constant regardless of pulse duration.

1. INTRODUCTION

In electrical discharge machining (EDM) process, not only electrical conditions but also distribution of electrical energy into electrode and workpiece has a great influence on the machining characteristics such as material removal rate, electrode wear and so on. Therefore, it is very important to make the energy distribution clear, in order to understand various phenomena in EDM process. As an electrode, copper, graphite and tungsten have been widely used, since their large thermal conductivity and high resistance to discharge impact are effective for low electrode wear EDM, which leads to high accuracy machining. In particular, graphite has often been used for high speed EDM because larger current can be applied. Moreover, it has many advantages such as light weight, easy forming, low cost and so on. However, the energy distribution using graphite electrode has not yet been investigated sufficiently.

In this paper, by measuring the temperatures of electrode and workpiece during process, the energy distributions in EDM with graphite electrode using kerosine and deionized water as a dielectric fluid are calculated. Furthermore, the effects of energy distribution on the machining characteristics are investigated.

2. ENERGY DISTRIBUTION

The total discharge energy Et supplied into the gap between electrode and workpiece is distributed among four parts as shown in Fig.1, that is, the energy into electrode Ee, workpiece Ew,

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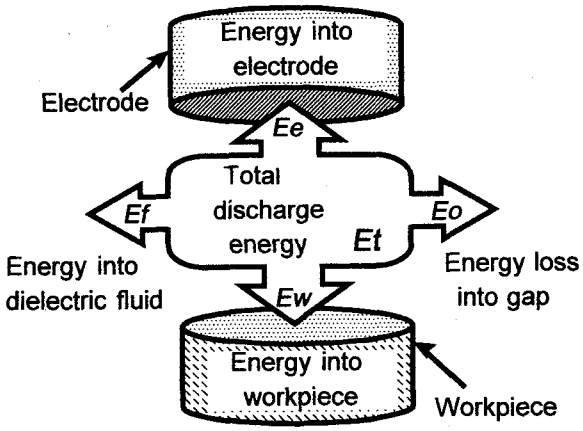


Fig.1 Energy distribution

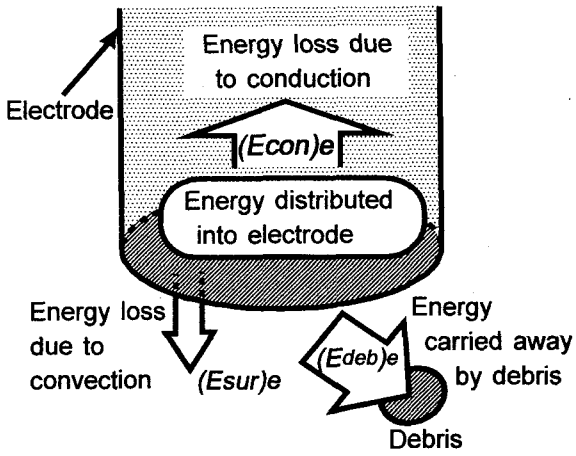


Fig.2 Energy distributed into electrode

dielectric fluid *Ef* and the energy loss *Eo* used for sound and flash during arc generation, polymerization of dielectric fluid and others.

$$Et = Ee + Ew + Ef + Eo \tag{1}$$

Furthermore, the energy distributed into electrode *Ee* is divided by the energy loss due to heat conduction in electrode *(Econ)e*, the energy loss due to convection and radiation from the surface *(Esur)e* and the energy carried away by worn debris *(Edeb)e* as shown Fig.2. The energy distributed into workpiece *Ew* is also divided in the same manner.

$$Ee = (Econ)e + (Esur)e + (Edeb)e \tag{2a}$$

$$Ew = (Econ)w + (Esur)w + (Edeb)w \tag{2b}$$

If the energy flow is limited in one dimension, the energy loss due to conduction in electrode *(Econ)e* is given by

$$(Econ)e = \lambda e \frac{\Delta \theta e}{\Delta \chi e} Ae \tag{3a}$$

where λe is thermal conductivity of electrode, $\Delta \theta e$ is temperature difference at measuring points, $\Delta \chi e$ is distance between two measuring points, and *Ae* is cross sectional area of electrode[1]. Similarly, the energy loss due to conduction in workpiece *(Econ)*w is given by the following equation.

$$(Econ)w = \lambda w \frac{\Delta \theta w}{\Delta \chi e} Aw \tag{3b}$$

The energy carried away by debris from electrode *(Edeb)e* can be expressed as follows,

$$(Edeb)e = [\, Ce\{(\theta v)e - (\theta s)e\} + (Lv)e \,]\, We \tag{4a}$$

where *Ce*, $(\theta v)e$, $(\theta s)e$, *(Lv)e* and *We* are specific heat, boiling point, surface temperature, heat of vaporization and removal amount per unit time in the case of electrode respectively. Similarly, as for workpiece,

$$(Edeb)w = [\ Cw\{(\theta v)w - (\theta s)w\} + (Lv)w + (Lm)w\ ]\ Ww \tag{4b}$$

where, $(Lm)w$ is heat of fusion.

The measuring of energy loss due to convection $(Esur)e$ or $(Esur)w$ seems to be quite difficult. It is, however, negligible[2], since most of gap space is occupied with bubbles generated by evaporations of dielectric fluid[3], electrode and workpiece material, and the temperature of gap during EDM process is very high. Consequently, Ee and Ew are given by the following equations.

$$Ee \fallingdotseq (Econ)e + (Edeb)e \tag{5a}$$

$$Ew \fallingdotseq (Econ)w + (Edeb)w \tag{5b}$$

3. EXPERIMENTAL PROCEDURES

Fig.3 shows the schematic diagram of experimental apparatus. Experiments are performed using a transistor switching circuit as a power supply. Kerosine and deionized water are used as a dielectric fluid, and electrode is graphite rod. Workpiece is alloy tool steel SKD11 in JIS specifications, whose shape is the same as the electrode. The temperatures of electrode and workpiece during process are measured by using thermocouple buried in the points at a distance of 10, 20 and 50mm from the machining surface. And the side surface of electrode is insulated by glass wool in order to reduce the conduction from side surface. Table 1 shows the properties of the materials, and Table 2 shows the machining conditions.

4. RESULTS AND DISCUSSIONS

4.1 Variation of Temperature

Fig.4 shows the variations of temperature at the measuring points on the electrode during EDM in kerosine. As shown in the figure, the temperature gradually rises with time, and then it becomes almost constant after 100sec. And, of course, the temperature is higher as the measuring point is close

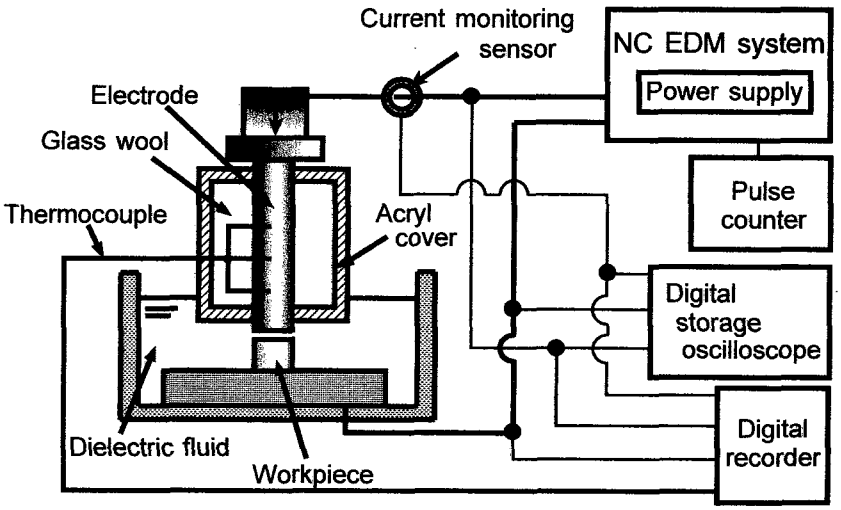


Fig.3 Experimental apparatus

Table 1 Physical properties of materials

Material		SKD11	Graphite
Density	ρ [g/cm]	7.9	1.8
Melting point	θm [K]	1803	-
Boiling point	θv [K]	3027	3973
Thermal conductivity	λ [W/(m · K)]	29.23	75.4
Heat of vaporization	Lm [J/kg]	2.1×10^{5}	-
Heat of fusion	Lv [J/kg]	6.3×10^{6}	4.6×10^{7}
Specific heat	C[J/(kg · K)]	502.8	837

Table 2 Machining conditions

Machining fluid	Kerosine
	Deionized water
Open circuit voltage	ui=120(V)
Discharge current	ie=8, 12, 20, 24(A)
Discharge duration	te=12, 20, 50, 100, 200(μ s)
Duty factor	τ =50(%)
Machining time	T=540 , 360(s)

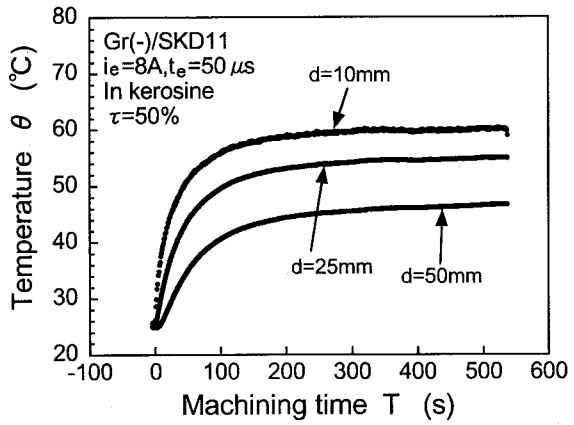


Fig.4 Variations of electrode temperature during EDM in kerosine

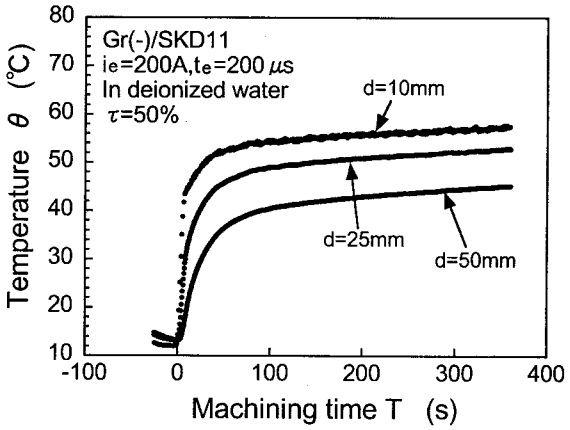


Fig.5 Variations of electrode temperature during EDM in deionized water

to the machining surface at any time. Also in the cases under other conditions and those on the workpiece, similar tendency was observed. Therefore, the average of temperatures from 420 to 480sec is defined as a temperature in a steady state.

The variations of temperature on the electrode during EDM in deionized water are shown in Fig.5. In this case, the time required to reach the steady state is about 50 sec, which is shorter than that of kerosine shown in the previous figure. Then, the average of temperature from 300 to 360sec is defined as a temperature in the steady state in the case of deionized water.

4.2 Distributed Energy

Fig.6 shows the relationships between energy loss due to conduction and discharge duration in EDM using kerosine as a dielectric fluid. The energy loss due to conduction into electrode is larger than that into workpiece in both polarity conditions, regardless of the discharge duration. And, as the discharge duration is shorter, the energy loss due to conduction into electrode and workpiece becomes larger, especially under normal polarity condition.

Fig.7 shows the relationships between energy carried away by debris and discharge duration. In the case of electrode, the energy carried away by debris under reversed polarity condition is less than 0.5W, which is very small in comparison with that due to conduction shown in Fig.6. On the other hand, under normal polarity condition, it is as large as about 1W, because of large electrode wear rate. Next, comparing the energies carried away by debris from electrode and workpiece, the energy in the case of workpiece under normal polarity condition is about 5W, which is much larger than that in the

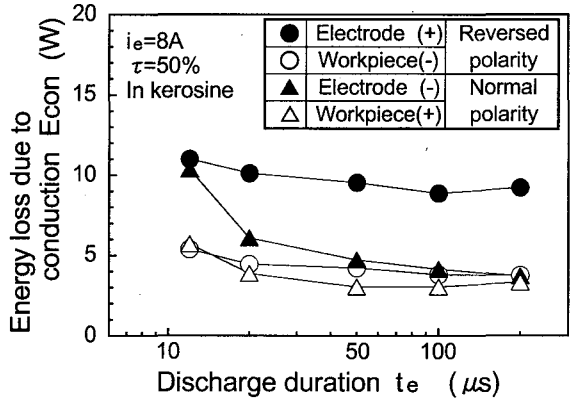


Fig.6 Relationships between energy loss due to conduction and discharge duration

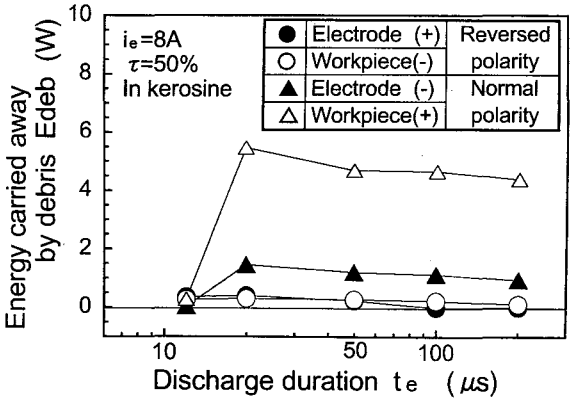
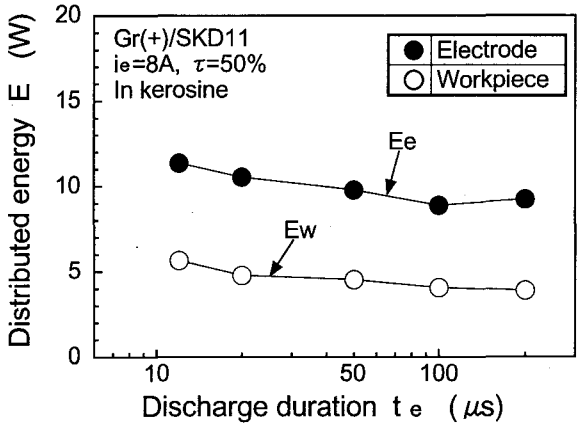
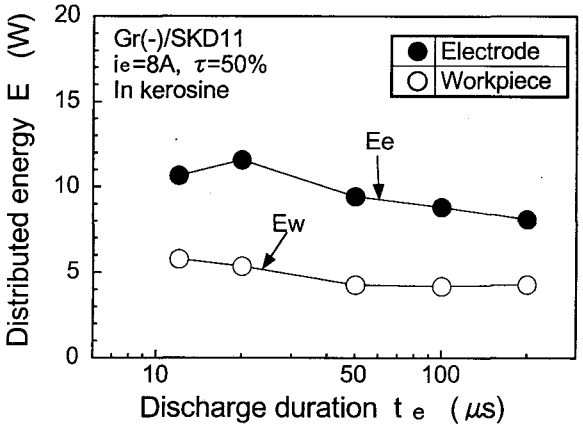


Fig.7 Relationships between energy carried away by debris and discharge duration



(a) Reversed polarity



(b) Normal polarity

Fig.8 Energies distributed into electrode and workpiece

case of electrode, because of large material removal rate. Moreover, under reversed polarity condition, it is almost the same as that from electrode.

The sum of the energy loss due to heat conduction and the energy carried away by debris is shown in Fig.8. These values represent the energies distributed into electrode and workpiece as shown in equations (5a) and (5b). As can be seen from the figure, the energies distributed into electrode and workpiece become smaller with discharge duration, and the energy distributed into electrode is always larger than that into workpiece under both polarity conditions.

4.3 Influence of Distributed Energy on Machining Characteristics

Fig.9 shows the variations of energy distributed into electrode and electrode wear rate with discharge duration. As shown in the figure, the electrode wear rate becomes larger when the energy is larger. However, under the shortest discharge duration 12 μs, the electrode wear is small in spite of large energy in comparison with that under other conditions, because the discharge concentration tends to occur under this condition and the number of effective electrical discharge decreases. Moreover, the electrode wear rate on anode side is smaller than that on cathode side under any discharge durations, in spite of no difference in the energy distributed into electrode under both polarities. It is well known

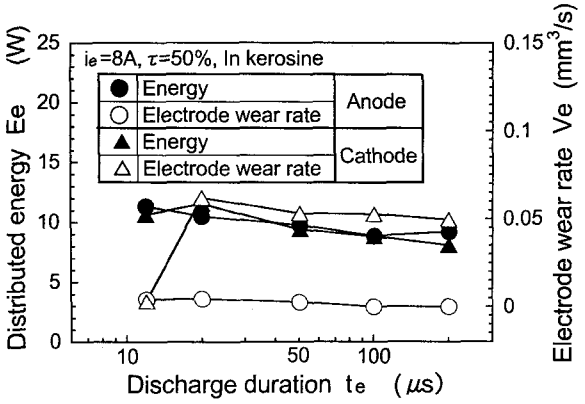


Fig.9 Variations of energy distributed into electrode and electrode wear rate

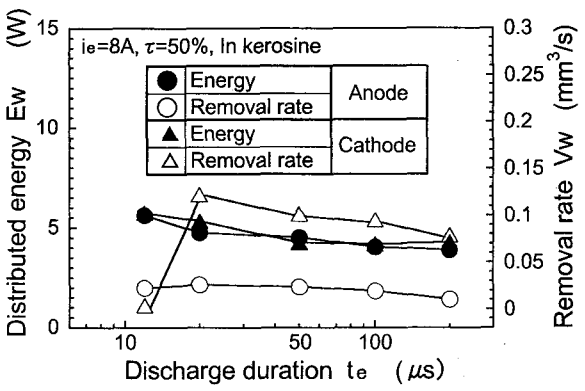


Fig.10 Variations of energy distributed into workpiece and removal rate

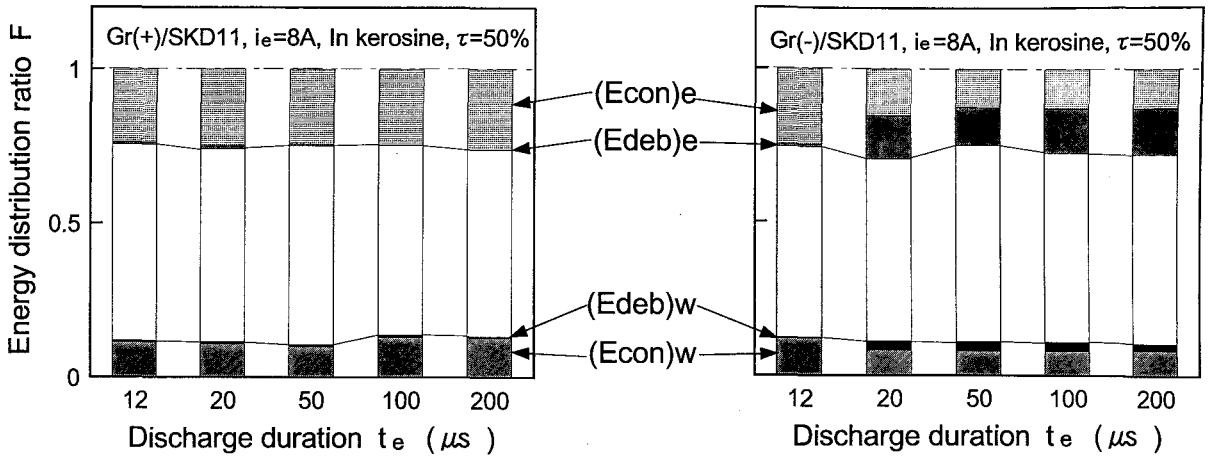
that the heat resolved carbon from kerosine adheres on anode surface and protects anode material from the heat and the impact due to arc generation[4-6]. As a result, it is considered that the electrode wear rate on anode side becomes smaller. That is, the electrode wear rate in EDM process using kerosine as a dielectric fluid greatly depends on the adhesion phenomenon of heat resolved carbon to the electrode surface.

Fig.10 shows the variations of energy distributed into workpiece and material removal rate with discharge duration. These variations are almost the same as those in the case of electrode wear rate shown in the previous figure. And, the removal rate under normal polarity condition is larger than that under reversed polarity one, in spite of no change in the energy distributed into workpiece under both polarities. It was reported that the area of crater on anode side is smaller than that on cathode in EDM process[7]. Therefore, it is considered that the cross sectional area of arc column on cathode side is smaller and the energy density is higher, compared with anode one. Consequently, the removal rate on cathode side becomes larger. Also, the adhesion phenomenon of heat resolved carbon mentioned before, seems to influence small removal rate in the case of anode.

4.4 Energy Distribution Ratio

The energy distribution ratios under each discharge duration in EDM using kerosine are shown in Fig.11. The energy distribution ratio presents the ratio of energy distributed into electrode or workpiece to the total discharge energy which is calculated by the discharge voltage, the discharge current, the pulse duration and the duty factor. The energy distribution ratios into electrode are from 24 to 29%, while those into workpiece are from 10 to 13% under any discharge durations. Therefore, it is confirmed that the energy distribution ratios are almost constant regardless of pulse duration. And, the energy loss due to conduction is large when the energy carried away by debris is smaller. In other words, the heat conducted into electrode or workpiece increases as the heat carried away by debris decreases.

Fig.12 shows the variations of energy distribution ratios with discharge current. As discharge current is larger, the energy ratio distributed into electrode decreases and that into workpiece increases as shown in the figure. This phenomenon has not yet been discussed sufficiently. However, it is known that electrode wear rate becomes smaller when discharge current is large in EDM with graphite electrode[8], which well corresponds to these variations. Therefore, the machining characteristics with



(a) Reversed polarity (b) Normal polarity

Fig.11 Relationships between energy distribution ratio and discharge duration

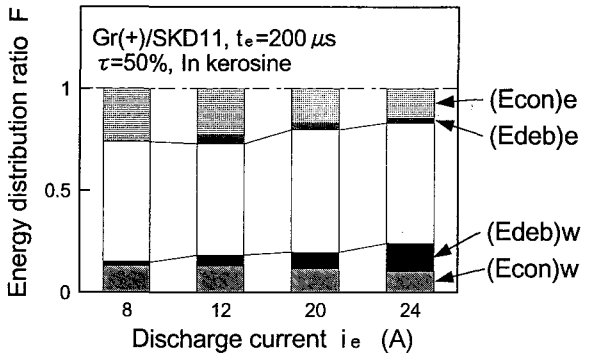


Fig.12 Variations of energy distribution ratios with discharge current

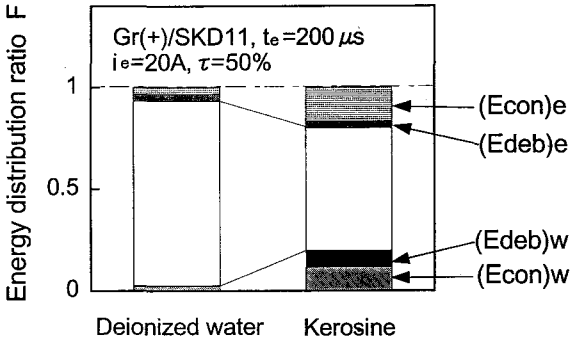


Fig.13 Energy distribution ratios in EDM with kerosine and deionized water

discharge current greatly depend on the energy distribution ratio.

Fig.13 shows the energy distribution ratios in EDM process using kerosine and deionized water as a dielectric fluid under discharge duration 200 μ s. Both ratios of energy distributed into electrode and workpiece in deionized water are much smaller than those in kerosine type fluid as shown in the figure. It is considered that the energy loss due to convection from electrode or workpiece to dielectric fluid are very large in the case of deionized water because of its high cooling effect.

5. CONCLUSIONS

In this paper, energy distribution in the EDM process with the graphite electrode is investigated by measuring the temperatures of electrode and workpiece. Main conclusions obtained in this study are as follows:

(1) The removal rate depends on energy density, while electrode wear mainly depends on the adhesion

of heat resolved carbon from machining fluid.

(2) The ratios of energy distributed into electrode and workpiece are almost constant regardless of discharge duration.

(3) The ratio of energy distributed into workpiece becomes larger with an increase of discharge current.

(4) The ratios of energy distributed into electrode and workpiece in the EDM process with deionized water are much smaller than those with kerosine type fluid because of high cooling effect of deionized water.

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