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Experimental Study of Material Removal Efficiency in EDM Using Various Types of Dielectric Oil

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Abstract:- The machining process in electrical discharge machining (EDM) consists of a melting process and a removal process. A region of the workpiece surface heated by the discharge plasma is melted and a portion of the melted region is removed from the workpiece body. The rest of the melted region remains on the workpiece surface and re-solidified as a white layer. In previous research, to evaluate the removal ability, a ratio of the removal volume to the melted volume is defined as the material removal efficiency.

In this study, the material removal efficiency was investigated to develop an understanding of the machining mechanism in EDM. As a result of experiments, it is found that the material removal efficiencies show almost the same value, whereas the removal volume varies with the type of dielectric oil or the discharge duration. To advance the study about the machining mechanism in EDM, the simulation for the workpiece temperature distribution, considering the effect of the type of dielectric oil or the discharge duration, should be conducted further.

Keywords:- EDM, Dielectric oil, Material removal rate, White layer, Material removal efficiency

I. INTRODUCTION

Electrical discharge machining (EDM) is a non-contact and thermal process which can machine the hard-to-cut material and widely used especially in mold manufacturing field. The thermal energy used in EDM process is created by repeating pulse discharges which are generated between the tool electrode and the workpiece. Each discharge produces a thermal plasma which exceeds 5000K [1]. The tool electrode and the workpiece are submerged in a dielectric fluid. Usually, hydrocarbon oil is used as the dielectric fluid in EDM and there are many varieties of dielectric oil for EDM in the market. The machining process in EDM consists of two main processes. One is a melting process and the other is a removal process. In the melting process, the temperature of the workpiece goes up during the discharge duration due to the energy from the thermal plasma and a region of the workpiece surface which exceeds a melting point of the material is melted. On the other hand, in the removal process, a portion of the melted region of the workpiece is removed by the effects such as strong electric field at the cathode [2], impingement of the dielectric fluid against melted region of the workpiece [3] and boiling of the superheated molten material [4]. Eubank et al. [5] presented that superheating is the dominant mechanism for the material removal in EDM. By the repetition of the melting process and removal process, the workpiece is machined in desired form. After EDM process is finished, non-removal portion of melted material is re-solidified and remains on the workpiece surface as a white layer [6]. Many studies about such melting and removal process in EDM were carried out so far, but the machining mechanism has not been fully understood.

In previous researches, to evaluate the removal ability, a ratio of the removal volume of the workpiece to the melted volume of the worpiece is defined. Marafona et al. [7] and Shabgard et al. [8] have reported about the ratio and Marafona et al. [7] called the ratio 'material removal efficiency', whereas Shabgard et al. [8] called the ratio 'plasma flushing efficiency'. In this paper, the ratio is called material removal efficiency. In these two previous literatures, the removal volume was measured experimentally using continuous-pulse-discharge while the melted volume was determined by numerical simulation using single –pulse-discharge model. Shabgard et al. [8] studied about the material removal efficiency with various machining conditions and found out that the material removal efficiency is affected by discharge current. It was also reported by Shabgard et al. [8] that the material removal efficiency is affected by discharge duration which is within a range of 12.8-25μs, while in the case of the discharge duration is within a range of 50-100μs, the material removal efficiency is almost constant. However, Ikai et al. [9] have stated that there is a difference of the material removal volume per pulse between single-pulse-discharge and continuous-pulse-discharge. Therefore, the evaluating method of the material removal efficiency conducted by Marafona et al. [7] and Shabgard et al. [8] seems to be inexact. On the other hand, to examine both of the melting ability and the removal ability together, the material removal rate (MRR, the removal mass per unit time) is also defined in previous researches. It is well-known-fact [10], [11] that MRR is affected by the machining conditions including discharge current and discharge duration. Moreover, it is also empirically known that MRR varies with the type of dielectric oil even if the machining conditions are the same.

The same machining conditions mean the same input energy into the thermal plasma. It is very interesting phenomenon that MRR can be changed by changing the type of dielectric oil without changing the input energy.

The present study was conducted in order to develop an understanding of the machining mechanism in EDM. For this purpose, the material removal efficiency was investigated by two methods. One method was a machining experiment using nine commercial oils under the same machining conditions. The other method was a machining experiment using shorter duration of the discharge pulse. The purpose of former experiment was to change the removal volume without changing input energy, and the purpose of the latter experiment was to make the removal volume smaller by means of the shorter discharge duration. As described in II-C, to calculate the material removal efficiency, the average removed depth was used for the removal volume and the average melted depth was used for the melted volume in this study. Both of the average removed depth of the workpiece and the average melted depth of the workpiece were determined experimentally using continuous-pulse-discharge. For the determination of the average melted depth, white layer thickness was measured. As far as authors know, there have been few papers which investigate the material removal efficiency only by the experimental method without performing any numerical simulation.

II. EXPERIMENTAL METHOD

A. Machining Conditions and Properties of Dielectric Oils

Experiments of this study were conducted on a Sodick EDM machine AQ35L equipped with linear motor. The material of tool electrode was copper and the material of workpiece was steel (JIS-G4051 S45C, density: 7.84mg/mm^3). The area of machining surface of the workpiece was 5mm×9mm (45mm^2). The setup of the experiments, machining conditions and typical properties of dielectric oils used in this study are shown in Fig.1, Table I and Table II respectively. To change the removal volume, nine commercial oils and three discharge durations were used in this study. As shown in Fig.1, small tank was set on the machine table of AQ35L and the each dielectric oil had been poured into small tank before the machining experiment got started.

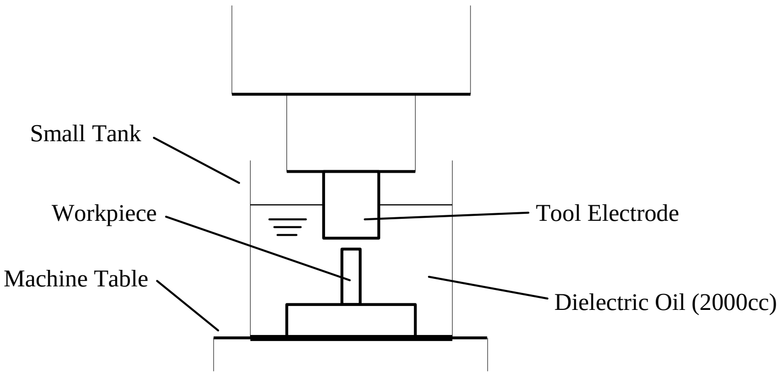


Fig.1: Setup of Experiments

Table I: Machining Conditions

Tool Electrode Material	Copper	
Workpiece Material	Steel (JIS-G4051 S45C)	
Open Circuit Voltage	90 V	
Discharge Current	10 A	
Machining Time	4 min.	
Dielectric Fluid	9 commercial oils	
Discharge Duration	50 µs	oil A, G, I
	100 µs	oil A, G, I
	250 µs	9 oils
Pulse Interval	250 µs	
Workpiece Polarity	Cathode	

Table II: Typical Properties of Dielectric Oils

OIL	A	B	C	D	E	F	G	H	I
Viscosity at 313K, mPa·s	1.327	2.051	1.390	1.378	1.809	1.184	1.958	1.993	5.239
Density at 313K, g/cm^3	0.776	0.770	0.741	0.747	0.824	0.743	0.797	0.758	0.826

B. Measurement of Material Removal Rate

The mass of workpiece was measured before and after machining. The sum of actual individual discharge pulse duration during the machining was also measured by the pulse counter. Material removal rate (MRR) was calculated by:

$$MRR = \frac{W_0 - W_m}{t_m} \tag{1}$$

where W_0 is a workpiece mass before machining, W_m is a workpiece mass after machining and t_m is a sum of individual discharge pulse duration.

C. Determination of Material Removal Efficiency

In this study, EDM experiments were carried out using continuous-pulse-discharge because the volume removed by single-pulse-discharge is different from the volume removed by one pulse from continuous-pulse-discharge [9]. Therefore continuous-pulse-discharge which is applied in usual EDM process was used in this study. To determine the material removal efficiency, average removed depth (D_{remv}) and average melted depth (D_{melt}) were calculated as follows. A mass of workpiece was measured before and after machining and D_{remv} was calculated by:

$$D_{remv} = \frac{W_0 - W_m}{\rho \cdot S} \tag{2}$$

where ρ is the density of the workpiece material and S is a area of machined surface of the workpiece.

The cross section image of the workpiece EDMed by continuous-pulse-discharge is shown in Fig.2. After the machining was finished, the workpiece was cut and polished. Then the section view of the machined surface was obtained by a laser microscope after etched with nital. After that, white layer thickness (WLT) was measured by the laser microscope and accounting for their average. D_{melt} was calculated by Eq. (3) and the material removal efficiency (MRE) was figured out by Eq. (4).

$$D_{melt} = D_{remv} + WLT \tag{3}$$

$$MRE = \frac{D_{remv}}{D_{melt}} \tag{4}$$

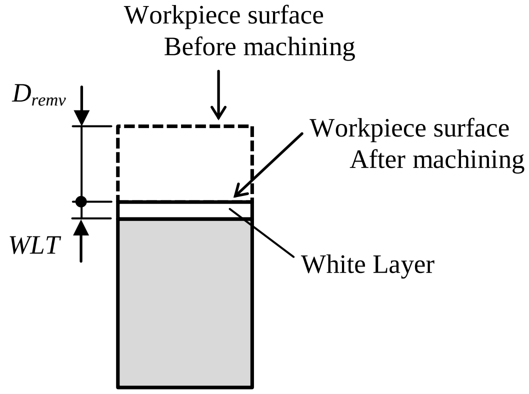


Fig.2: Cross Section Image of EDMed Workpiece

III. RESULTS AND DISCUSSIONS

A. Material Removal Rate

The material removal rate (MRR) shows a overall result of the melting process and the removal process in EDM. MRR of each of nine oils using 250μs discharge duration is presented in Fig.3. As shown in Fig.3, the minimum value of MRR is 2.32mg/s for oil A and the maximum value of MRR is 3.44mg/s for oil I. Clearly, there are MRR differences between nine oils. Fig.3 shows that the ratio of the maximum MRR (oil I) to the minimum MRR (oil A) reaches about 1.5.

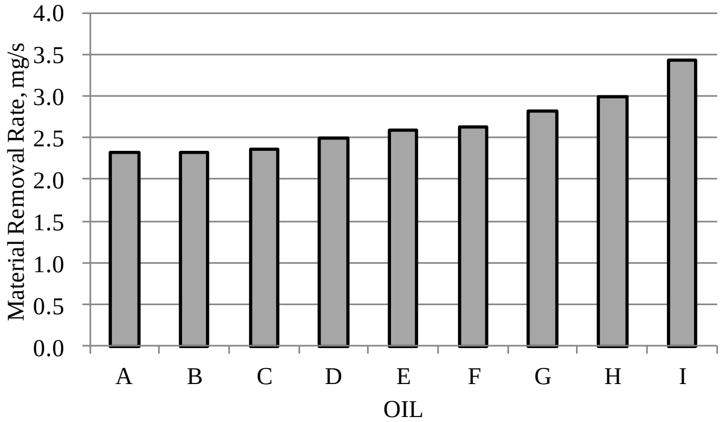


Fig.3: Material Removal Rate (Discharge duration: 250 μs)

B. White Layer Thickness

Fig.4 shows the cutting line of machined workpiece to observe the white layer. After the workpiece was cut, the cross section of the workpiece was well polished and etched with nital for clear observation of the white layer. Fig.5 is the photograph of the white layer machined using oil A. Fig.4 and Fig.5 were taken by the laser microscope. The average white layer thickness (WLT) on the cutting line is determined by:

$$WLT = \frac{1}{n \cdot L} \sum_{i=1}^{5} S_i \tag{5}$$

where S_i is a white layer area from area-1 through area-5 shown in Fig.5(a), n is a number of area (in this study, n=5) and L is a length of x direction for each area (in this study, L=282μm). Fig.6 shows average thickness of the white layer for nine oils in the case of discharge duration is 250μs. As shown in Fig.6, the average white layer thickness is within a range of 9.2-12.6μm, and the average value is 10.1μm.

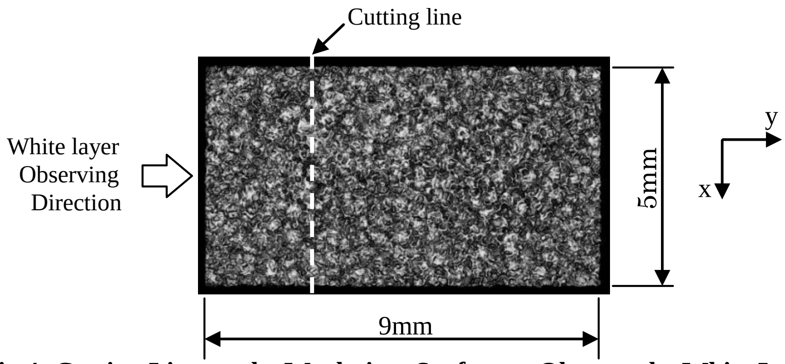
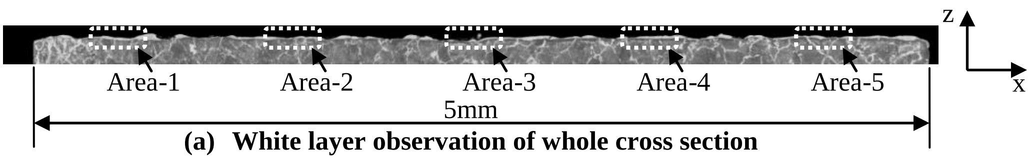
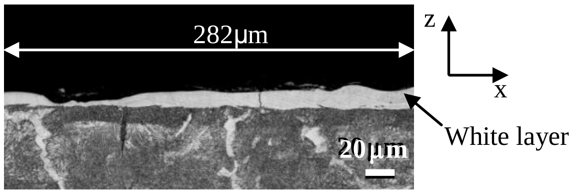


Fig.4: Cutting Line on the Workpiece Surface to Observe the White Layer



(a) White layer observation of whole cross section



(b) Enlargement of area-4

Fig.5: Example of White Layer Observation (Oil A)

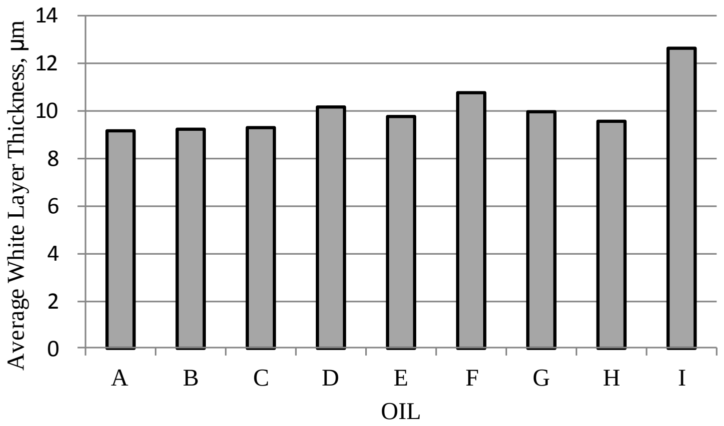


Fig.6: Average White Layer Thickness (Discharge duration: 250 μs)

C. Material Removal Efficiency and Discussions

The material removal efficiency is calculated by Eq. (4) and the calculated results are shown in Fig.7. As shown in Fig.7, the material removal efficiencies for each of nine oils are almost the same, though the material removal rates are different from each other as shown in Fig.3. The material removal efficiencies in Fig.7 vary from 97.6 to 98.1% and the range of them is only 0.5 percentage points. Here substituting Eq. (3) into D_{melt} in Eq. (4), then Eq. (6) is derived. In Eq. (6), it is found that the material removal efficiency is dependent on the ratio of WLT to D_{remv}.

$$MRE = \frac{D_{remv}}{D_{melt}} = \frac{D_{remv}}{D_{remv} + WLT} = \frac{1}{1 + \frac{WLT}{D_{remv}}} \tag{6}$$

The average removed depth (D_{remv}) calculated from MRR value in Fig.3 is shown in Fig.8. As shown in Fig.8, the values of the average removed depth vary from 381 to 557μm and the ratio of the maximum value to the minimum value is about 1.5. Comparing WLT in Fig.6 and the average removed depth in Fig.8, it is found that the ratio of WLT to D_{remv} is much smaller than 1. In the case of oil A for example, WLT is 9.2μm and D_{remv} is 381μm, so the ratio is 0.024. There is a possibility that almost the same MRE in Fig.7 is the result of the small ratio of WLT to D_{remv}, therefore, another experiments were carried out in the next place. The next experiments used shorter discharge duration than that of Fig.7 to make the average removed depth smaller than that of Fig.8. Two discharge durations (50 and 100μs) for three oils (oil A, oil G and oil I) were used in the next experiments. Fig.9 and Fig.10 show the results of the experiments. The average removed depths for three discharge durations (50, 100 and 250μs) are shown in Fig.9. It is clear in Fig.9 that the average removed depth decreases with decreasing of discharge duration. Meanwhile, the material removal efficiencies (MRE) for three discharge durations are shown in Fig.10 and it is found that all material removal efficiencies in Fig.7 and Fig.10 vary from 97.0 to 98.1% and the average is 97.7%.

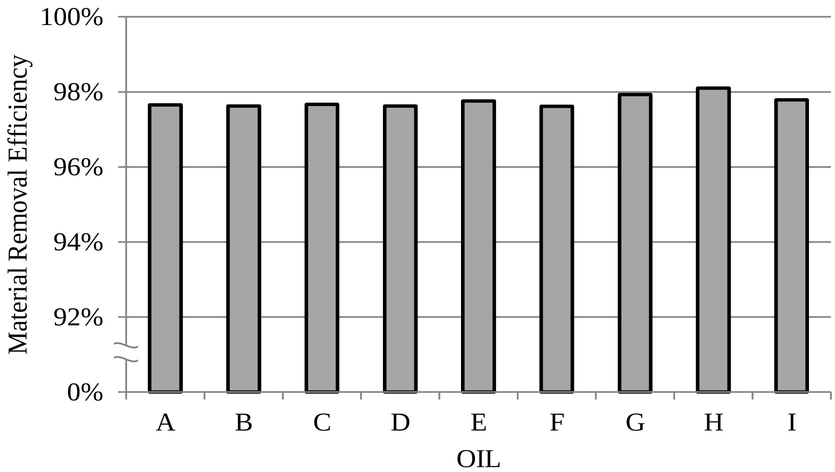


Fig.7: Material Removal Efficiency (Discharge duration: 250 μs)

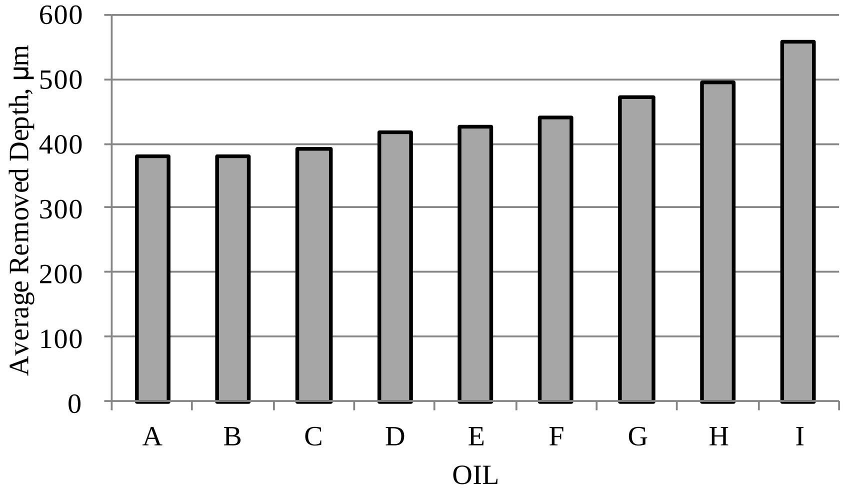


Fig.8: Average Removed Depth (Discharge duration: 250 µs)

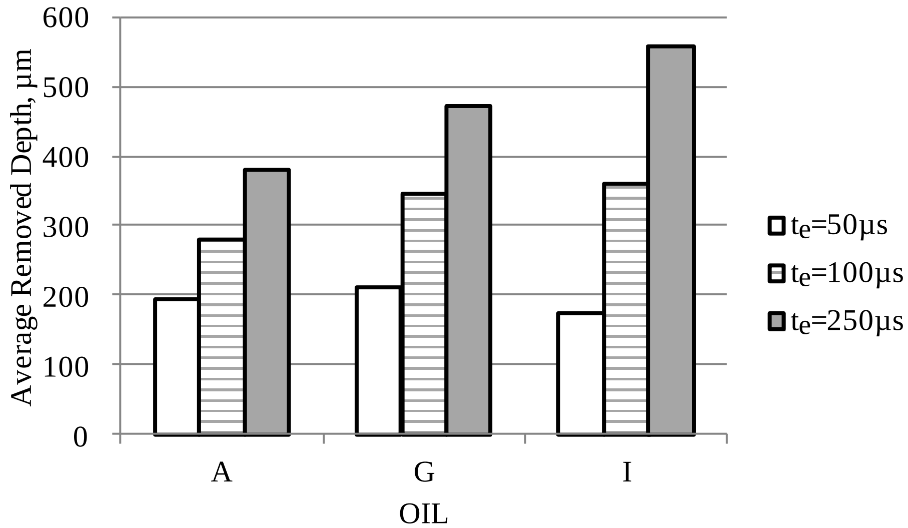


Fig.9: Average Removed Depth for Various Discharge Durations

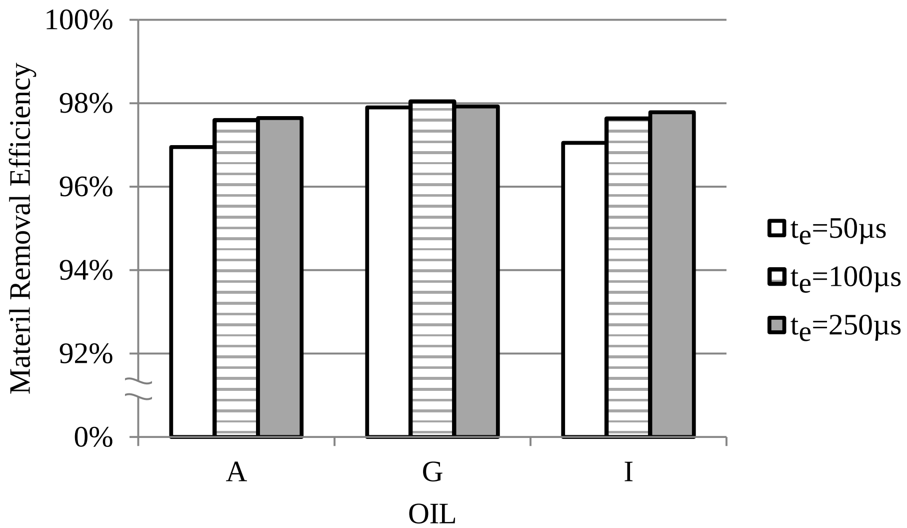


Fig.10: Average Removal Efficiency for Various Discharge Durations

As described above, this study investigated about the material removal efficiency only by the experimental methods using continuous-pulse-discharge without conducting any numerical simulation, whereas the previous studies [7], [8] have determined the material removal efficiency by both results of continuous-pulse-discharge experiment and the simulation with single-pulse-discharge model. The method to determine the material removal efficiency adopted in the previous studies [7], [8] seems to be inexact because of the difference of the material removal volume per pulse between single-pulse-discharge and continuous-pulse-discharge [9]. Thus, in this study, only continuous-pulse-discharge methods were used to undertake the experiments in a state further close to an actual EDM operation, and to make the value of material removal efficiency more practical. As a result, this study reveals that the material removal efficiencies for all experiment cases show almost the same value from 97.0 to 98.1% and the mean value is 97.7%, whereas the average removed depth varies with the type of dielectric oil or the discharge duration. In the results of the previous study [8], the value of material removal efficiencies are 15.7% and 32.0% for the discharge current of 8A and 16A respectively. One of the main reasons why these values are much smaller than that of this study is the method to determine the material removal efficiency as mentioned above in this paragraph. For example the reported ratio of the removal volume per pulse using continuous-pulse-discharge to the removal volume per pulse using single-pulse-discharge is around 0.38 [9]. On the other hand, according to Eubank et al. [5], the super heating is the dominant mechanism for the material removal in EDM. Therefore, one of the probable causes why the material removal efficiencies indicate almost the same value is the temperature distribution in the melted region of the workpiece. If the temperature distributions in the melted region for each of experiment cases are in the similar pattern, the material removal efficiencies would be the same because the ratios of the melted volume which exceeds certain temperature to the whole melted volume become the same value for each other. The essential finding drawn from the discussion above is that the temperature distribution of the workpiece material plays an important role for the machining mechanism in EDM.

To advance the study about the machining mechanism in EDM, the numerical simulation for the workpiece temperature distribution, considering the effect of the type of dielectric oil or the discharge duration, should be conducted further.

IV. CONCLUSIONS

In this paper, the material removal efficiency was studied experimentally to make advances in understanding of the machining mechanism in EDM. In conclusion, it is found that the material removal efficiencies for all experiment cases show almost the same value whereas the average removed depth varies substantially with the type of dielectric oil or the discharge duration. This means a certain ratio of whole melted volume is removed from the workpiece body and the cause of this phenomenon would be the temperature distribution in the melted region of the workpiece. Hence, heat transfer analysis of the workpiece material, considering the effect of the type of dielectric oil or the discharge duration, should be performed for the next step.

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