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Characteristics of MEDM for micro-holes with respect to circuit elements

Pil Joo Cho[1], Bo Hyun Kim[2], Deok Ki Choi[3,*] and Chong Nam Chu[4]

[1]*Mechatronics and Manufacturing Technology Center, Samsung Electronics Co., LTD, Suwon, South Korea, 443-742*
[2]*School of Mechanical Engineering, Andong National University, Andong, South Korea, 760-749*
[3]*Department of Precision Mechanical Engineering, Kangnung National University, Gangneung, South Korea, 210-702*
[4]*School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea, 151-742*

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Abstract

Micro electrical discharge machining (MEDM) is a promising technology for fabricating micro-parts on a variety of materials. An RC circuit is suitable for MEDM because it produces low pulse width and relatively high peak current. However, it is not well understood how circuit elements affect machining characteristics of MEDM. In this paper, the effects of circuit elements on MEDM of micro-holes and the relation between characteristic variables of process and machining characteristics was investigated. Since the discharge inductance causes an increase in electrode wear and machining time, it should be minimized in MEDM. From this study, it should be less than a few μH. The machining time also increases with increasing the charging resistance. If the charging resistance is less than a few hundreds Ω, however, continuous arc discharge occurs and the machining speed is markedly reduced.

Keywords: Micro electrical discharge machining; RC circuit; Micro-holes; Discharge inductance; Charging resistance; Low electrode wear condition; High-speed machining

1. Introduction

MEDM is one of the most important technologies for fabricating micro 3D shapes such as micro-holes, micro-shafts, and complex cavities [1]. It can be used on a variety of workpiece materials and burr-free surface finishes and has relatively high aspect ratio. But MEDM is not suitable for mass-production because it produces large electrode wear and has relatively low machining speed. There are two types of discharge circuits in MEDM: the RC circuit and the TR circuit. In MEDM, the RC circuit is generally used because it can carry a low width pulse and relatively high peak current. But the RC circuit can work in limited machining conditions because the charge condition depends on the gap state in MEDM. In other words, the RC circuit has very low controllability for machining conditions such as pulse width or peak current. So far, how circuit elements of the RC circuit affect machining characteristics and the difference in MEDM compared to EDM are not exactly known.

In this paper, machining characteristics of MEDM for micro-holes according to circuit elements of the RC circuit such as capacitance, open voltage, charging resistance were studied. Considering the relation between circuit elements and MEDM characteristic variables such as unit discharge energy, pulse width, peak current etc., we investigated the machining characteristics with respect to these characteristic variables and compared these characteristics with those of EDM.

*Corresponding author. Tel.: +82 33 640 2394, Fax.: +82 33 640 2330
E-mail address: choidk@kangnung.ac.kr
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2. Experimental procedure

The experimental procedure is mainly divided into three parts: I) electrode fabrication, II) micro-hole fabrication and III) electrode cutting. An electrode is set up in the precision spindle and machined by wire electric discharge grinding (WEDG) [2]. The fabricated electrode is directly used in micro-hole fabrication without electrode reset. The micro-hole can be fabricated precisely because WEDG eliminates the rotational error of the electrode. Using the difference between contact positions of the reference point before and after micro-hole fabrication, the electrode wear is calculated. After a micro-hole is machined, the electrode is worn and the electrode end becomes a half sphere. Therefore, to maintain the same experimental condition, the electrode should be cut to make the end of the electrode flat after experiments.

3. Experimental results and discussion

Machining characteristics of MEDM for micro-holes with respect to RC circuit elements such as capacitance and open voltage are investigated. The electrode material is W (Tungsten) with ϕ 50 μm in diameter and a workpiece is stainless steel (304SS) with 100 μm in thickness. Kerosene is used as a dielectric fluid. Positive voltage is applied to the workpiece and negative voltage is applied to the electrode. A schematic diagram of the RC circuit is shown in Fig. 1.

3.1 Effects of capacitance, C

Capacitance (C) is a very important circuit element in MEDM using an RC circuit. It affects all characteristic variables, such as the unit discharge energy (E_{unit}), peak current (I_P), and pulse width (τ_d). E_{unit} can be expressed as Eq. (1).

$$E_{unit} = \int_0^{\tau_d} i_2(t) V_{gap}(t) dt = \frac{1}{2} C V_d^2 \quad (1)$$

where $i_2(t)$ is the discharge current, $V_{gap}(t)$ is the gap voltage during discharge, and V_d is the break down voltage. Therefore, E_{unit} can be controlled by capacitance, C.

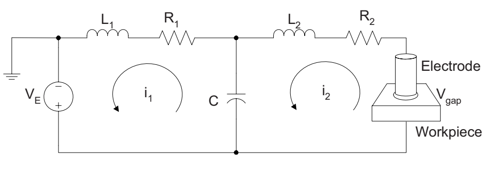


Fig. 1. Schematic diagram of RC circuit.

Fig. 2 shows the experimental results obtained by varying C from 10 pF to 3000 pF. As shown in Fig. 2, machining time decreases and the electrode wear increases as C increases from 200-3000 pF. Because high E_{unit} increases the machined volume per unit discharge, the machining time reduces and the electrode wear increases when C is high. But if E_{unit} is very low, the discharge explosion pressure is not sufficient for flushing debris out of the micro-hole as machining depth increases. This yields an unstable

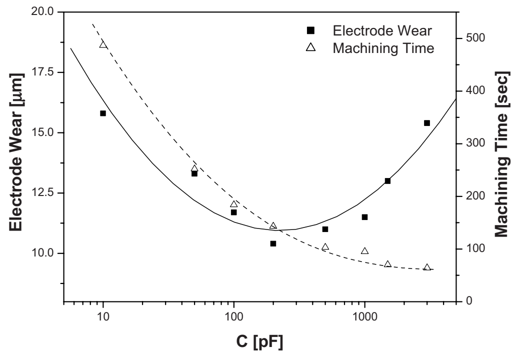
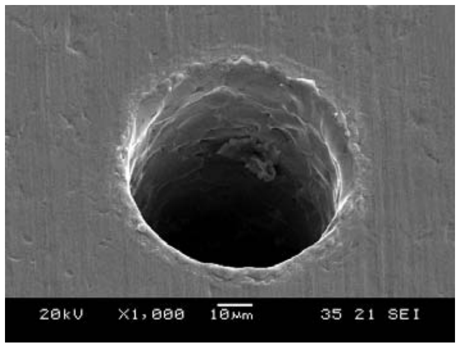
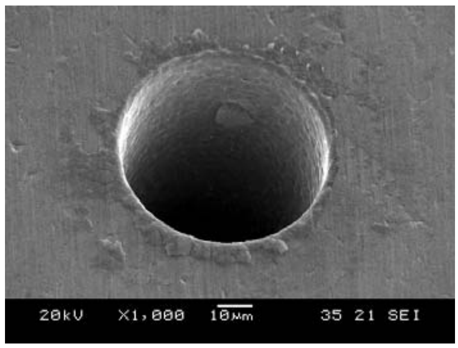


Fig. 2. Electrode wear and machining time w.r.t. C (100 V, 1032.3 Ω, cable inductance).



(a) 3000 pF



(b) 10 pF

Fig. 3. Machined micro-hole w. r. t. C.

discharge and increases the electrode wear. Fig. 3 shows SEM images of the machined micro-holes at 10 pF and 3000 pF. As expected, when E_{unit} is very high, the machined micro-hole has a severe thermal damage and very poor surface roughness.

3.2 Effects of open voltage, V_E

In EDM, the V_E does not have a wide available range. Generally, the lowest voltage level in EDM, arc voltage (V_{arc}), generates a stable discharge. V_{arc} can be changed according to the dielectric fluid and the materials of the electrode and work piece [3]. In this experimental condition, V_{arc} is measured to approximately 26.5 V. If V_E is set very high, charging resistance (R_1) with a high power and large size is needed. But it is not generally available in the market. In this study, V_E was set in the range of 40~120 V and 100 pF, 1000 pF were used as capacitance. Fig. 4 shows that machining time decreases as V_E increases. Since machining time depends on E_{unit} which consists of V_E and C, this result is evident. When small capacitance (100 pF) and voltage (40 V) were used, the through hole machining failed. It resulted from too small E_{unit}. However, there is no clear relation between V_E and the electrode wear. Although the two machining conditions (1000 pF, 40 V and 100 pF, 120 V) have approximately the same E_{unit} (0.80 μJ and 0.72 μJ), they produced a large difference in the electrode wear. This shows that the electrode wear is not determined only by E_{unit}. In the components of E_{unit}, τ_d and $V_{gap}(t)$ can be considered as a constant value during discharge at a given discharge inductance L_2 and only I_P is varied. So, in these experiments, effects of I_P on MEDM were investigated. Fig. 5 shows the relation between I_P and the electrode wear. Although V_E of the two machining conditions (1000 pF, 40 V and 100 pF, 120 V) are almost same in E_{unit}, they have different I_P. The former with 0.39 A has very low I_P but higher electrode wear than the latter with 0.90 A.

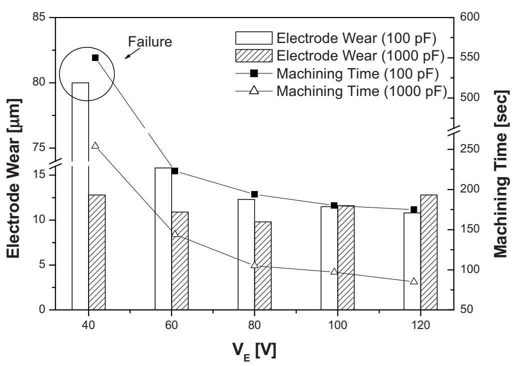


Fig. 4 Electrode wear and machining time w. r. t. V_E (1032.3 Ω, cable inductance).

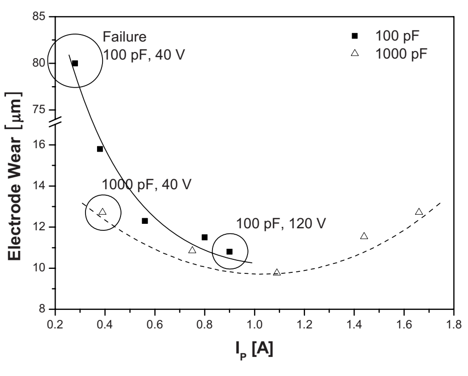


Fig. 5 Electrode wear w. r. t. I_P (Varying V_E)

3.3 Effects of discharge inductance, L_2

Fig. 6 shows the effect of L_2 on the machining time and the electrode wear. As shown in Fig. 6, machining time increases as L_2 increases. When the unit discharge energy was low (100 pF) and L_2 was larger than 4 μH, the hole machining failed. This is because L_2 affects the current density. When L_2 is large, the unit discharge energy is consumed over a long time. Therefore, the peak current, I_P is low and the pulse width, τ_d is long. This relation is shown in Fig. 7. However, L_2 does not affect the value of E_{unit}. E_{unit} is calculated by numerical integration. In the figure, E_{unit} is from 4.10μJ to 4.25 μJ. The electrode wear also depends on the current density, J.

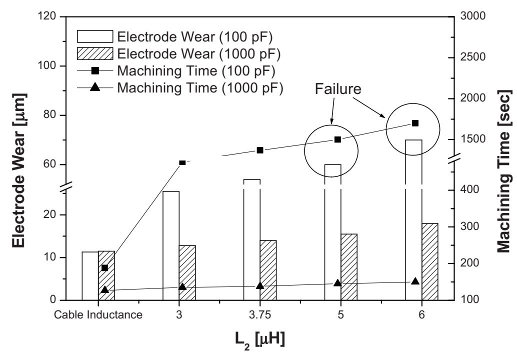


Fig. 6. Electrode wear and machining time w. r. t. L_2 (100 V, 1032.3 Ω, L_1 = cable inductance).

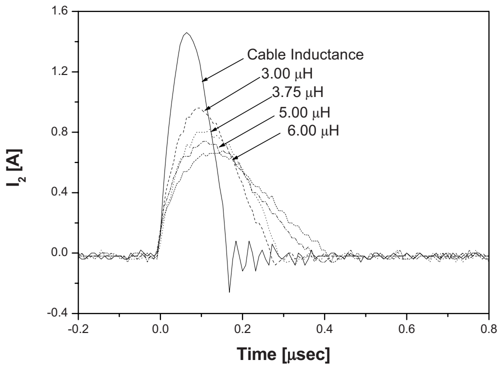


Fig. 7. Sampled discharge currents w. r. t. L_2 (1000 pF).

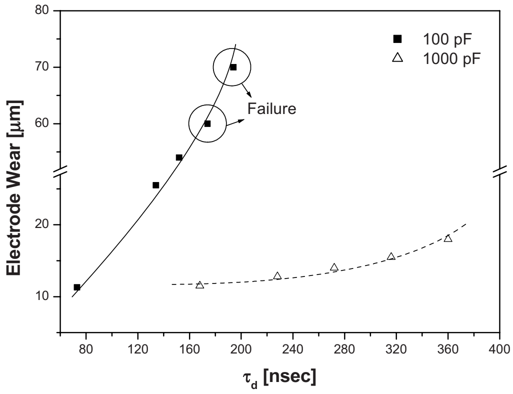


Fig. 8. Electrode wear w. r. t. τ_d (Varying L_2).

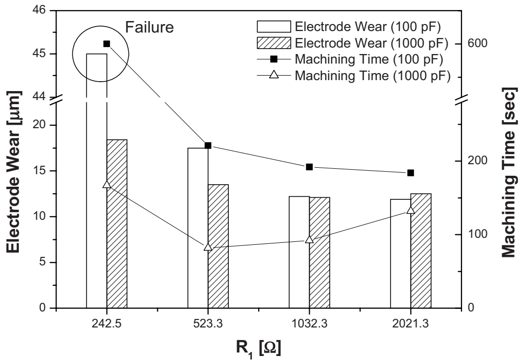


Fig. 9. Electrode wear and machining time w. r. t. R_1 (100 V, Cable inductance).

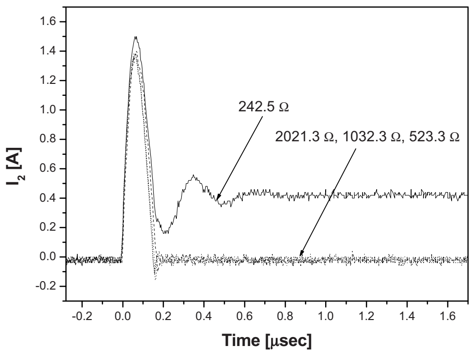


Fig. 10 Sampled discharge currents w. r. t. R_1 (1000 pF)

Fig. 8 shows the relation between τ_d and the electrode wear. The electrode wear is proportional to τ_d regardless of C. If the current density is not high, the discharge explosion pressure will not be enough to remove the melt materials from holes, which would increase the machining time and the electrode wear. Therefore, in MEDM, the cable inductance (L_2) should be minimized and since cables have 0.2-0.5 μH inductance, it is important to make the cable length as short as possible.

3.4 Effects of charging resistance, R_1

The charging resistance has influence on the charging time and the discharge frequency (S), but it does not change E_{unit}, as shown in Eq. (1). Fig. 9 shows the change of the electrode wear and the machining time according to R_1. As R_1 increases, the electrode wear decreases regardless of C. But machining time at 100 pF is inversely proportional to R_1 and machining time at 1000 pF is proportional to R_1 except at 242.5 Ω. The decrease of machining time at 1000 pF, 523.3-2021.3 Ω is due to the increased S. But the increase of the machining time at 242.5 Ω is due to the continuous arc discharge.

Fig. 10 shows the measured $i_2(t)$ at 1000 pF. In the region of 523.3-2021.3 Ω, shapes of $i_2(t)$ are approximately the same, but the shape of I_P at 242.5 Ω is different from the others. This type of discharge is called continuous arc discharge. When the charging time is too short or discharging pressure is not high enough, the resistance of the dielectric cannot recover. This phenomenon keeps discharge current flowing and makes the next discharge impossible. Continuous arc discharge is very harmful to MEDM because it makes pits on both the electrode and workpiece, which increases the electrode wear and machining time. As shown in Fig. 9, when unit discharging energy is small (100 pF), small R_1 (242.5 Ω) causes machining failure. During machining of micro holes, two kinds of a continuous arc discharge were observed. Fig. 11 shows the two kinds of a continuous arc discharge with the resistance, 242.5 Ω. One type is characterized by the continuous

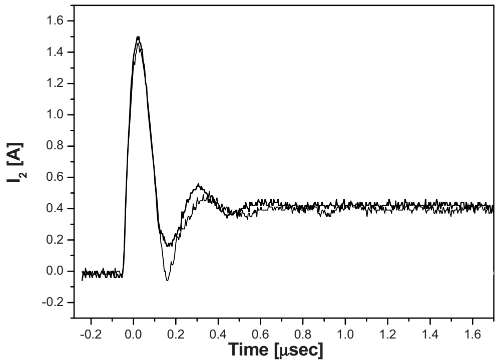


Fig. 11. Sampled continuous discharge currents (242.5Ω, 1000 pF).

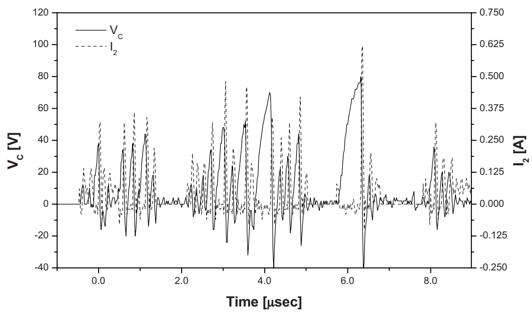


Fig. 12. Normal arc discharge (100pF, 1032.3Ω).

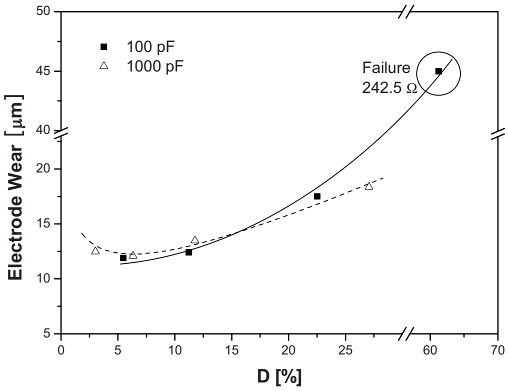


Fig. 13. Electrode wear w. r. t. D (Varying R_1).

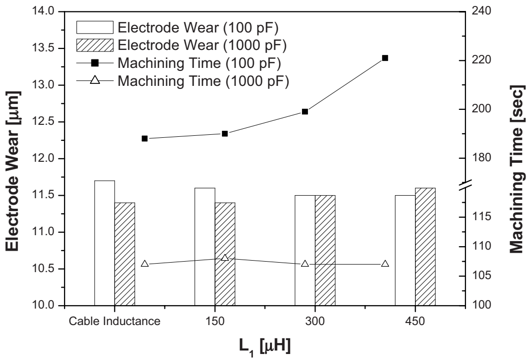


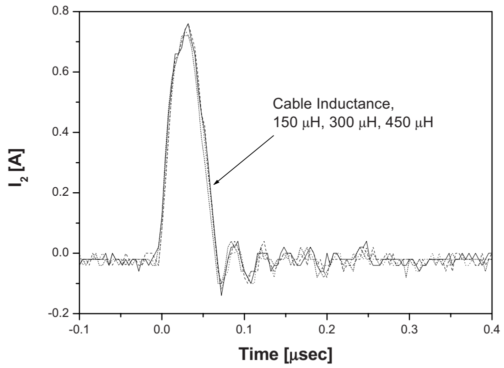
Fig. 14 Electrode wear and machining time w. r. t. L_1 (100 V, 1032.3 Ω, L_2 = cable inductance).

flow of I_P for extended time without reversing the current polarity, and the other type is characterized by the transformation of I_P to a continuous arc discharge during charging after the reversing of the current polarity. From Fig. 11, the deterioration of the machining characteristics at 1000 pF, 242.5 Ω and 100 pF, 242.5-523.3 Ω, is due to the continuous arc discharge.

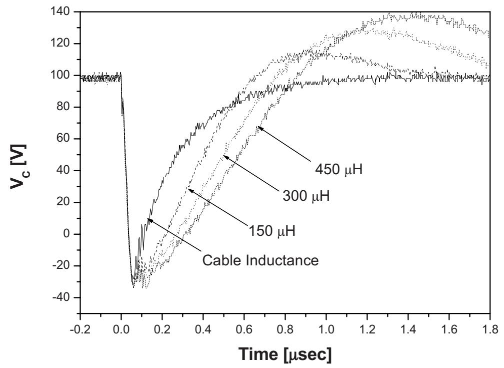
On the other hand, machining time increases as R_1 decreases though continuous arc discharge is not observed at 100 pF, 1032.3-2021.3 Ω. This is due to the very short charging time at 100 pF. If the charge time is very short, the discharge tends to occur near V_{arc} regardless of V_E. This is due to the large number of ions in the gap generated by the former discharge. This type of discharge is defined as a normal arc discharge. Fig. 12 shows the measured $i_2(t)$ and capacitance voltage, $V_C(t)$ at 100 pF, 1032.3 Ω. The discharge occurs regardless of V_E with 100 V. This normal arc discharge obstructs the following normal spark discharge and dispersion of the normal spark discharge over the machining area. Therefore, the normal arc discharge increases the electrode wear and machining time. As shown in Fig. 10, since R_1 does not change the shape of the discharge current except for very low R_1, R_1 almost does not change E_{unit} but only the S. Therefore, in this work, the effects of the duty factor (D) on machining characteristics can be investigated because D is defined as the ratio of τ_d to the discharge period. The relation between D and the electrode wear is shown at Fig. 13. From it, we can see that the electrode wear increases according to D except at a very low D.

3.5 Effects of charge inductance, L_1

Fig. 14 shows the experimental results. From Fig. 14, machining time at 100 pF increases and the electrode wear at 100 pF decreases slightly as L_1 increases. But there is no distinct trend at 1000 pF. L_1 affects the charging time only. In EDM, L_1 inserted to the RC circuit can reduce machining time [2]. However, it can be seen that an increase in L_1 cannot guarantee a decrease in charging time, as shown



(a) i_2



(b) V_C

Fig. 15. Sampled i_2 and V_C w. r. t. L_1.

in Fig. 15. And we cannot prove from Fig. 14 that L_1 has any effect on the reduction of the machining time. Therefore, charge inductance is not beneficial to MEDM.

3.6 *Low electrode wear and high-speed machining condition in MEDM*

From the above experimental results, we can conclude that circuit elements as well as characteristic variables affect MEDM. In this work, the low electrode wear and high-speed machining condition was extracted and arranged with respect to characteristic variables. Then, this condition was compared to the condition of EDM. Table 1 shows the comparison of the machining characteristics between EDM and MEDM:

In table 1, ↑ means a direct proportion and ↓ means an inverse proportion.

The machining characteristics of MEDM when C is not too low are shown in Table 1. If a very low C is used, not only the relations between E_{unit}, I_P and

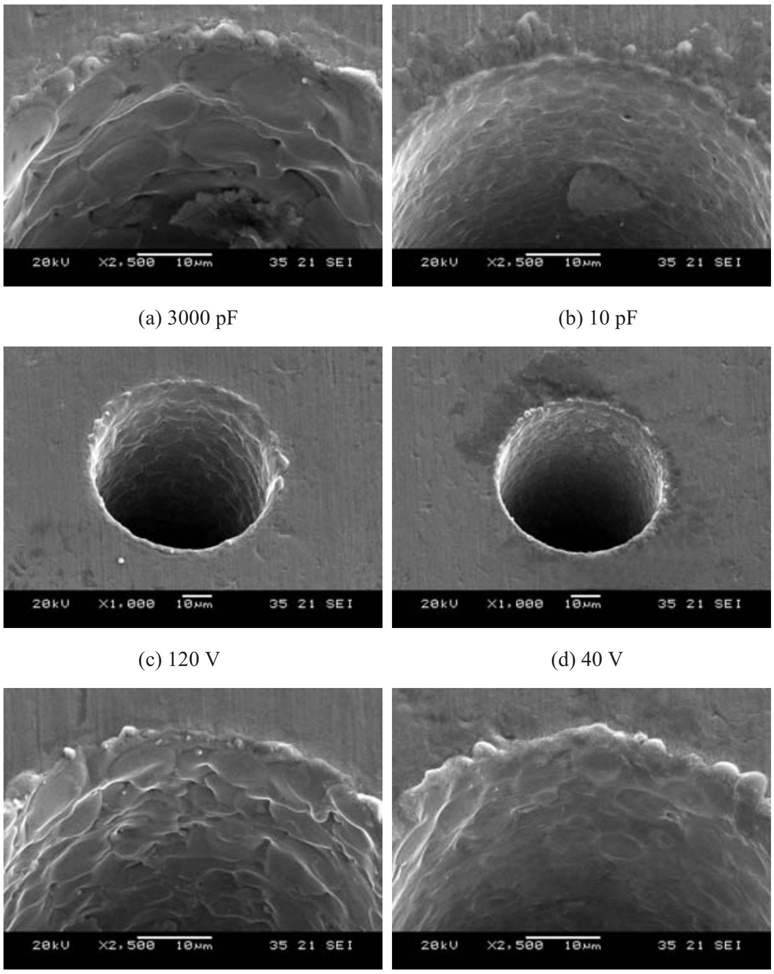
Table 1. Comparison of machining characteristics between EDM and MEDM.

Characteristic Variable	Proportion Variable	Electrode wear		Machining time	
		EDM	MEDM	EDM	MEDM
E_{unit}	$C V_E^2$	↑	↑	↓	↓
I_P	V_E	↑	↑	↓	↓
τ_d	$\sqrt{L_2}$	↓	↑	↓	↑
J	$V_E / \sqrt{L_2}$	↑	↓	↑	↓
D	$1/R_1$	↓	↑	↓	↓

the electrode wear but also the relation between duty factor (D) and machining time is reversed. Even if D is increased, machining time increases at a very low C. It is due to a continuous arc discharge and a normal arc discharge results from a very low R_1. Also, a large electrode wear at high D in MEDM is due to the same reason. In Table 1, τ_d and J are the major characteristic variables that show the different trends in both electrode wear and machining time. According to the above results, the low electrode wear and high-speed machining condition in MEDM can be summarized as follows.

To realize a low electrode wear in MEDM, E_{unit} must be reduced same as in EDM. Since all conductive components such as tool collets and jigs between an electrode and a workpiece form a capacitance, called stray capacitance, this capacitance must be reduced when designing an MEDM system. All conductive components should be downsized and insulated from the machining zone. However, the electrode wear increases when E_{unit} is very low because of low discharge explosion pressure. Therefore, V_E should be reduced, but not to a value less than V_{arc} which generates a stable discharge. L_2 increases τ_d and the electrode wear. To reduce L_2, the cable length of the discharge part in the RC circuit should be as short as possible and not make a loop, which can cause additional inductance, when an MEDM system is constructed. Since L_1 hardly affects the electrode wear, the cable length of the charge part in the RC circuit can be lengthened, if necessary. If R_1 is very low, continuous (or normal) arc discharge is generated and the electrode wear increases. This low limit of R_1 is varied with respect to C; therefore, R_1 should not be reduced under this limit at each C.

High-speed machining can be achieved in MEDM by two methods. The first one is to increase E_{unit} under the low electrode wear condition. The former condition can be achieved by increasing C or V_{Et}. However, this is not a suitable method in MEDM.



(a) 3000 pF (b) 10 pF

(c) 120 V (d) 40 V

(e) Cable inductance (f) 6.0 μH

Fig. 16. Surface image of machined micro hole (default machining condition: 100 V, 1000 pF, 1032.3 Ω, cable inductance).

When E_{unit} is too high, the workpiece becomes severely damaged thermally so that the surface roughness of the workpiece increases and the electrode wear becomes severe. The second one is to increase S. Since machining speed is proportional to J, L_2 should be minimized. When L_2 was larger than 3 μH, electrode wear was over 60 μm in the machining of 100 μm deep hole. L_1 has a negligible effect on machining speed but it is inversely proportional to machining speed at a very low C. Therefore, it also would be better to set L_1 to the lowest value. Then, R_1 is the only controllable variable which can control the machining speed without affecting E_{unit}. It means that the machining speed can be increased by reducing R_1. But, if R_1 is too low, continuous (or normal) arc discharge is generated and the machining speed is markedly reduced. Therefore, as under the low electrode wear condition, R_1 should not be reduced below this low limit at each C.

3.7 Hole quality in MEDM

In hole machining by EDM, the hole quality is determined by the size of craters which are generated by each electrical discharging. With increasing the unit discharging energy increases, the crater size becomes larger and poor hole quality is obtained. Therefore, small capacitance and voltage produce a hole with good surface quality. Even with long cable inductance, which causes an increase in the machining time and electrode wear, since the current density or discharging density is low, better hole quality can be obtained.

Fig. 16 shows the effects of the circuit elements on the hole quality.

4. Conclusions

In this paper, machining characteristics of MEDM for micro-holes with respect to circuit elements were investigated. From experiments, the following results were derived.

(1) C is the most important variable in an RC circuit. It affects every characteristic variable, especially E_{unit}. Electrode wear is proportional to E_{unit} and machining time is inversely proportional except at very low E_{unit}. Since E_{unit} is proportional to C, stray capacitance must be minimized when an MEDM system is designed.

(2) V_E is a variable that can show how I_P affects the machining characteristics. Electrode wear is proportional to I_P and machining time is inversely proportional except for very low I_P. V_E should be larger than V_{arc}.

(3) By controlling L_2, J can be changed. As L_2 increases, τ_d increases and J decreases. Electrode wear and machining time are proportional to L_2. Therefore, L_2 should be set to the cable inductance resulting from the shortest cable length.

(4) R_1 can change D and S without changing E_{unit}. Machining time decreases when R_1 is low. But if R_1 is too low, a continuous arc discharge occurs. When C is too low, a normal arc discharge occurs even if R_1 is high. These kinds of arc discharge increase machining time. Electrode wear is proportional to D and machining time is inversely proportional except very low C.

(5) L_1 hardly affects the machining characteristics of MEDM. Therefore, it is not necessary to insert L_1 into the RC circuit. L_1 can be high, if necessary, when an MEDM system is designed. However, L_2 should be decreased as much as possible.

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