EDM at Low Open-Circuit Voltage

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Abstract

The possibilities for electrical discharge machining (EDM) at open-circuit voltages lower than 30V are examined using an RC circuit. Low voltages are preferable in terms of machining accuracy. However, machining at such voltages has not been attempted before. Drilling in copper is carried out using tungsten electrodes with 15μm and 7μm diameters to investigate the material removal rate. At open-circuit voltages of 5V or higher, the average electrode feed speed, defined as the feed length per machining time, is higher than 5μm/min under certain electrical conditions. Although the material removal rate is very low, machining is possible even at an open-circuit voltage of 2V. These voltages are much lower than for conventional EDM. A tungsten pin 1μm in diameter could be fabricated at an open-circuit voltage of 20V by wire electrodischarge grinding (WEDG), suggesting possible future applications of EDM to submicron machining and nanomachining.

Key words: EDM, low open-circuit voltage, RC circuit, WEDG

1. INTRODUCTION

Electrical discharge machining (EDM) with an RC circuit in which the discharge pulse duration can be very short is employed for micromachining and finish machining. To obtain high machining accuracy, the unit removal per discharge pulse must be small. This is realized with short pulse duration and small discharge energy, the latter for which a low open-circuit voltage must be applied and electrical capacitance must be minimized. Lowering the open-circuit voltage also improves accuracy when replicating electrode shapes into workpieces because the discharge gap becomes narrow. Normally, EDM is carried out at open-circuit voltages of 60V or greater. It has been said that machining cannot proceed at open-circuit voltages lower than approximately 30V [1]. To the best of our knowledge, the lowest reported voltage at which EDM has been carried out is 30V, for drilling microholes in stainless steel [2].

Voltages across the discharge gap have been measured at 10 to 40V [1), 3)]. For EDM with a switching circuit, such voltages are necessary for the continuous arc discharge. Open-circuit voltages greater than 10 to 40V must be therefore applied over the gap. For EDM using an RC circuit, however, material is removed by a discharge of short pulse duration generated immediately after dielectric breakdown at the gap. This discharge does not have to be maintained for a particular duration, making the high voltage unnecessary and enabling EDM at low open-circuit voltages. Even if the open-circuit voltage is less than usual, discharge occurs over a narrower gap because the dielectric breakdown begins with an electrical field of approximately 100V/μm (and can be much lower under certain conditions) [4]. What has not been clear is whether materials can be melted and then removed with small discharge energy at low open-circuit voltages. Another possible problem is that machining does not proceed because of repeated short-circuiting due to the narrow discharge gap. In the present work, therefore, EDM experiments at open-circuit voltages of 30V or less are carried out to clarify the possibilities for machining at low voltages.

2. EXPERIMENTAL

The feasibility of EDM at low open-circuit voltages is investigated by drilling microholes. The experiments are carried out on a microultrasonic machine (ASWU-1, Creative Technology) having three NC axes with a minimum increment of 0.05μm. The machine is equipped with an RC circuit for fabricating ultrasonic machining tools by EDM [5] and is used in the present experiments. The feeding motion of the electrode is controlled by measuring the average charging current (obtained from the voltage over the charging resistor). The electrode is fed or retracted as the average charging current is made less than or greater than the preset value, respectively. The drilling conditions are shown in Table 1. Tungsten electrodes of 15μm and 7μm diameters are employed. The workpiece material is copper. Drilling is performed until the feed length reaches 30μm (15μm with the 7μm-diameter electrode) or until the drilling time reaches 5 min. The average electrode feed speed is calculated as the feed length divided by the drilling time.

The electrodes are fabricated on a micro EDM machine (MG-ED72, Matsushita Electric Industrial)

Table 1 Drilling conditions

Electrodischarge circuit	RC circuit
Polarity	Electrode (–), Workpiece (+)
Charging resistance	1.1kΩ, 100Ω, 10Ω
Average charging current	1mA when the electrode diameter is 15μm and the charging resistance is not 10Ω; 0.5mA under the other conditions
Electrode diameter	15μm, 7μm
Electrode rotation speed	3000rpm
Working fluid	Kerosene type fluid
Electrode material	Tungsten
Workpiece material	Copper (99.9%)

by wire electrodischarge grinding (WEDG) [6]. The workpieces are observed with a scanning electron microscope (SEM, S-22150, Hitachi). Waveforms of the discharge gap voltage are recorded with a digital oscilloscope (DL-4100, Yokogawa Electric).

3. RESULTS

3.1 Penetration rate

In this paper, E, C and R indicate open-circuit voltage, capacitance and charging resistance, respectively. Figure 1 shows the results of drilling with the 15μm-diameter electrodes. Longitudinal electrode wear is shorter than 1μm even when the feed length reaches 30μm. Because the diameters of the drilled holes are almost the same, the average electrode feed speed is nearly equal to the penetration rate and proportional to the material removal rate.

Figure 1 (a) shows the average electrode feed speed with an R of 1.1kΩ. At the beginning of the experiment, C and E are set to the stray capacitance and 30V, respectively. E is gradually lowered until the average electrode feed speed decreases to around 0. With the feed speed at about 0, C is increased and E is lowered again. This process is repeated until E decreases to 3V. It is not desirable to increase C in order to minimize the discharge energy, however, the purpose of the experiment is to find the lowest E at which drilling proceeds.

The average electrode feed speed is higher than 5μm/min with C at stray capacitance and E at 30V, C at 0.001μF and E at 25V, C at 0.01μF and E at 20V, C at 0.1μF and E at 10V, and C at 1μF and E at 7.5V or 5V. Although the penetration rate decreases with a decrease in E due to the small discharge gap and energy, by increasing C, drilling is possible even at a low E of 5V.

Although drilling proceeds with C at 1μF and E at 5V, it proceeds only minimally for C at 10μF and E at 5V where the discharge energy is higher. This is because of a longer capacitor charging time due to the large CR. Drilling is then carried out with an R of 100Ω. As shown in Fig.1 (b), this drilling proceeds with C at 10μF and E at 5V with an average electrode feed speed higher than that of C at

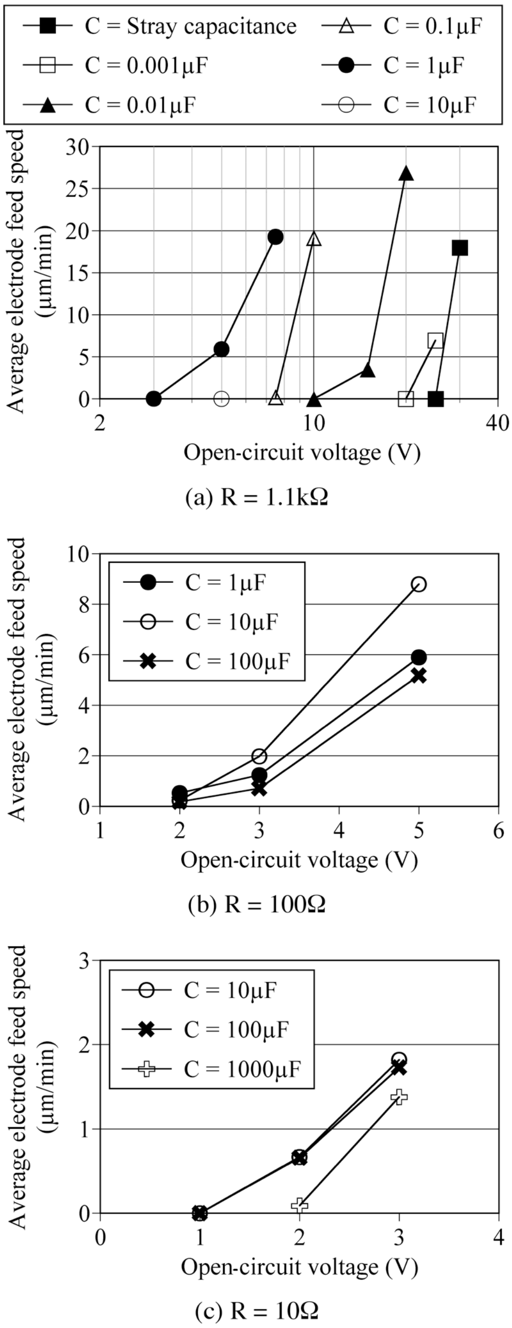


Fig.1 Average electrode feed speed (feed / machining time, electrode diameter = 15μm)

1μF and E at 5V. It decreases again when C is increased to 100μF. At an R of 10Ω, it rises with C at 100μF and is almost the same as, but not higher than, that with C at 10μF, as shown in Fig.1 (c). With a C of 1000μF, it decreases again. Drilling therefore proceeds with an E of 2V under some electrical conditions, although the average electrode feed speed is very low. With an E of 1V, drilling does not proceed at all.

In some cases in Fig.1 where the average electrode feed speed is around 0, discharge craters can be found on the workpiece surfaces. The reason drilling does not proceed in such cases seems attributable to constant short-circuiting at the gap. Using an electrode with a diameter smaller than 15μm, short-circuiting may decrease because it is easier to remove debris from the central region under the electrode. Figure 2 shows the average electrode feed speed for drilling with an R of 1.1kΩ using 7μm-diameter electrodes as well as that for the 15μm-diameter electrodes for comparison. The condition sets for C and E are chosen for feed speeds around 0 using the 15μm-diameter electrodes. There is hardly any longitudinal electrode wear. Although drilling does not proceed for either C at 0.01μF and E at 10V, or C at 1μF and E at 3V, the average feed speed under the other condition sets is greater than 20 times that for the 15μm-diameter electrodes, and the material removal rate is also higher. This result indicates that, even for electrical conditions under which drilling is not possible, the use of a smaller-diameter electrode allows drilling to proceed, enabling a lower E.

3.2 Observation of drilled holes

Figure 3 shows SEM micrographs of holes drilled with the 15μm-diameter electrodes. The tool feed length is 30μm. The hole in Fig.3 (a) was drilled with E at 30V, C at stray capacitance and an R of 1.1kΩ, showing good surface quality. Figure 3 (b) shows a hole drilled with E at 25V, C at 0.001μF and an R of 1.1kΩ. Its surface is rough because of the high discharge energy. The hole in Fig.3 (c), which was drilled under an even higher discharge energy condition with E at 5V, C at 10μF and an R of 100Ω, has swelling around its entrance as well as a rough surface. There is no remarkable difference in the diameter, around 20μm, of the three holes.

Holes drilled using the 7μm-diameter electrodes with an R of 1.1kΩ are shown in Fig.4. The tool feed length is 15μm. The hole in Fig.4 (a) was drilled with E at 25V and C at stray capacitance, and that in Fig.4 (b) with E at 5V and C at 1μF. Both holes are about 8.5μm in diameter. The differences in appearance among these holes are similar to those of Fig.3.

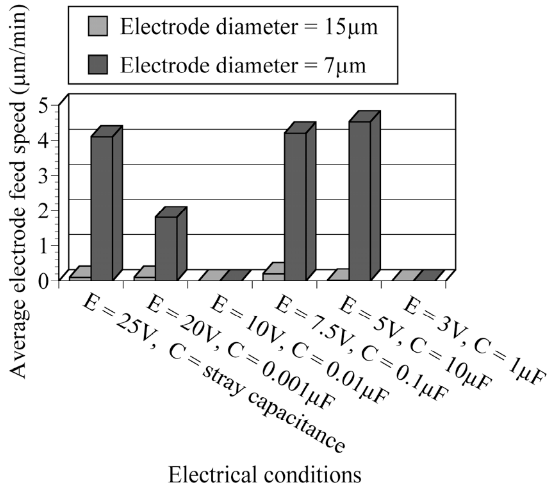
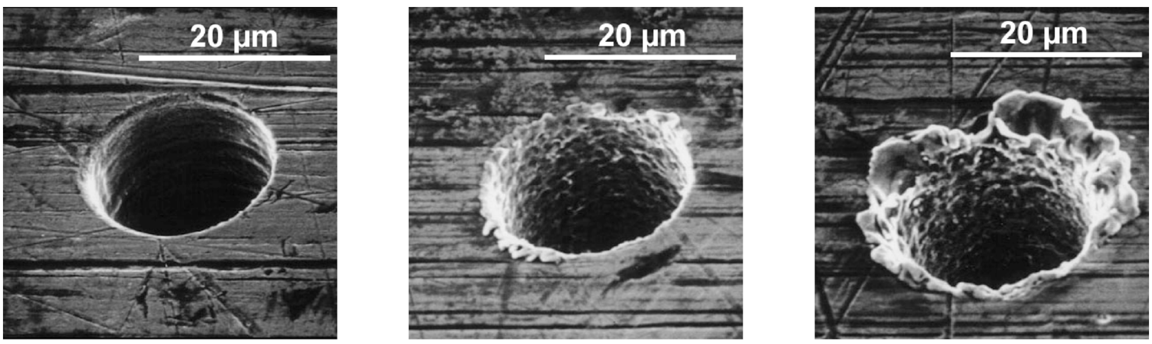


Fig.2 Comparison of average electrode feed speed (R = 1.1kΩ)

Figure 5 shows a hole drilled with the 15μm-diameter tool for E at 2V, C at 10μF and an R of 10Ω. With the very low average tool feed speed, the depth is very shallow. However, it is obvious that the material has been removed by the discharge. In the case of drilling with E at 1V, on the workpiece surface where the electrode has been fed, discharge craters are not clearly observed but scratches from the electrode can be found.

3.3 Discharge gap voltage

Waveforms of the discharge gap voltage are shown in Fig.6 for drilling using a 15μm-diameter electrode with E at 3V, C at 1μF and an R of 1.1kΩ. Figure 6 (a) indicates a stable machining state in which insulation at the gap recovers immediately after discharge. In contrast, insulation does not recover as quickly in Fig.6 (b). The gap voltage of slightly less than 1V continues for 7 to 8ms approximately every 20ms. The waveform is similar to that of the gap voltage when arc discharge

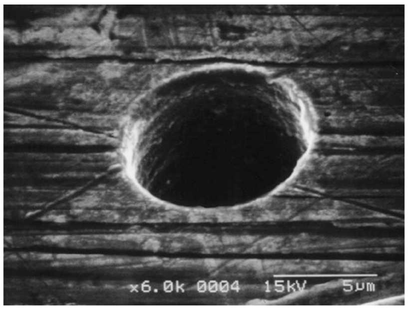


(a) E = 30V, C = stray capacitance, R = 1.1kΩ

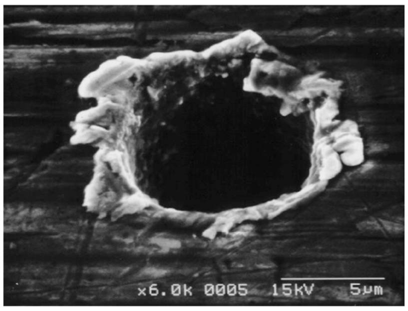
(b) E = 25V, C = 0.001μF, R = 1.1kΩ

(c) E = 5V, C = 10μF, R = 100Ω

Fig.3 Drilled holes (electrode diameter = 15μm, feed = 30μm)



(a) E = 25V, C = stray capacitance



(b) E = 5V, C = 1 μF

Fig.4 Drilled holes (R = 1.1kΩ, electrode diameter = 7μm, feed = 15μm)

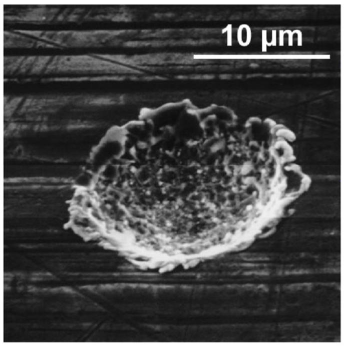
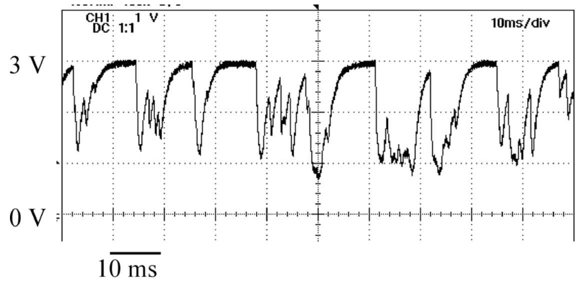


Fig.5 Drilled hole (E = 2V, C = 10μF, R = 10Ω, electrode diameter = 15μm)

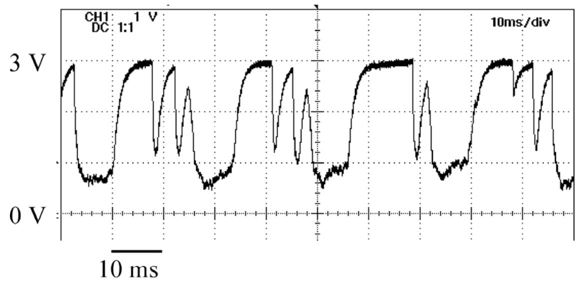
continues. However, maintaining arc discharge is difficult under this electrical condition. This phenomenon is considered to be short-circuiting due to sludge sticking at the gap. The period of 20ms is attributable to electrode rotation of 3000rpm.

3.4 Fabrication of the micropin

The above results show that drilling is possible with an open-circuit voltage lower than usual and suggest that it might be employed for EDM methods other than drilling. The fabrication of a micropin was therefore attempted by WEDG. It has been reported that WEDG is capable of fabricating pins with a diameter of several micrometers [3], but further improvement is necessary for making thinner pins. One possible method for improvement is to minimize discharge energy by lowering the open-circuit voltage.



(a) Insulation recovered immediately after discharge



(b) Insulation not recovered immediately

Fig.6 Waveforms of discharge gap voltage (E = 3V, C = 1μF, R = 1.1kΩ)

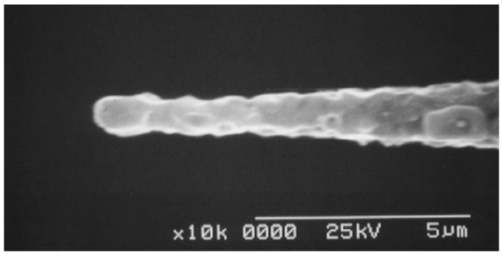


Fig.7 Tungsten pin 1μm in diameter fabricated by WEDG (Electrode material = brass, E = 20V, C = stray capacitance, R = 1.1kΩ)

Figure 7 shows a pin fabricated by WEDG using an RC circuit. It was processed from a 4μm-diameter tungsten pin with E at 20V, C at stray capacitance and an R of 1.1kΩ. The wire material is brass. Although the pin is not entirely straight, its diameter is less than 1μm from its tip to about 5μm in the longitudinal direction. This result suggests that, with a much lower E, submicron- or nano-diameter pins can be fabricated.

4. DISCUSSION

The results of this study show that EDM is possible with an open-circuit voltage as low as 2V (although the penetration rate is very low) and drilling proceeds at an average feed speed of more than 5μm/min with voltages higher than 5V under certain conditions. Drilling does not proceed at a voltage of 1V (distinct discharge craters having not been found), however, drilling may proceed if thinner electrodes and a feed control with smaller

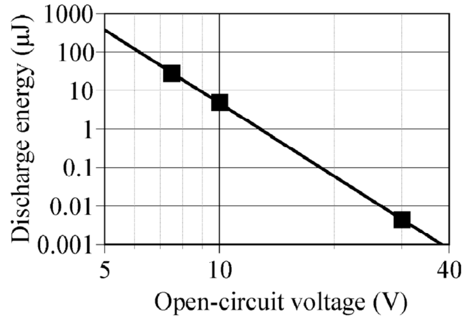


Fig.8 Relationship between open-circuit voltage and discharge energy (R = 1.1kΩ, electrode diameter = 15μm, average electrode feed speed range is 18 to 19.5μm/min)

minimum increment are employed in comparison to the electrodes and feed control used in the experiments.

In an RC circuit, the energy released in the gap by one pulse of discharge is approximately $(1/2)CE^2$ [7]. Figure 8 shows the relationship between the open-circuit voltage and discharge energy at which the average feed speed is almost the same and falls in the range of 18 to 19.5μm/min under the conditions shown in Fig.1 (a). Stray capacitance is assumed to be 10pF here. The discharge energy is inversely proportional to the open-circuit voltage to the power of approximately 6.3. The discharge energy must be greatly increased by the increasing capacitance so as not to decrease the penetration rate with a lower voltage. A possible reason is that, since the gap is narrow and short-circuiting is frequent at low voltage, the gap must be widened to raise the penetration rate by a large increase in discharge energy. This is confirmed also by the fact that the diameters of the drilled holes are almost the same, even at different voltages, as shown in Fig.3 and Fig.4. Therefore, surface quality deteriorates with low voltage when electrical conditions are chosen such that the penetration rate does not decrease. In the case of lowering the open-circuit voltage for high-precision machining, it is recommended that the voltage be set to a value at which machining proceeds without increasing the capacitance.

In an electric circuit, switching the electrical contact may induce a voltage across the circuit that is higher than the open-circuit voltage, generating a continuous arc discharge at the contact. Under some conditions, erosion caused by this discharge can be observed on the contact surface even at the low open-circuit voltages used in the experiments [8]. In EDM the electrode and workpiece form an electrical contact, before and after short-circuiting occurs between them, that acts as a switching contact. It may therefore appear in the present experiments that the material is removed by an induced high voltage. However, erosion of a contact is caused mainly by a continuous arc discharge that occurs when the contact opens or when it bounces after closing. Discharge immediately after dielectric breakdown at the contact is much shorter in duration and smaller in power than a continuous arc discharge. Furthermore, arc discharge continues only minimally with capacitance connected in parallel [8]. Considering these factors, for EDM using an RC circuit where continuous arc discharge does not occur and capacitance is connected in parallel (and is empty of charge after dielectric breakdown or short-circuiting), the type of discharge primarily responsible for material removal is unlike the type of discharge that erodes electrical contacts. There is therefore little influence on material removal from induced high voltage.

5. CONCLUSION

EDM using an RC circuit with open-circuit voltages lower than 30V was carried out. The following results were obtained:

(1) Copper was drilled using tungsten electrodes with diameters 15μm and 7μm at an average electrode feed speed higher than 5μm/min under open-circuit voltages of 5V or more.

(2) Although the penetration rate is very low, drilling proceeded at an open-circuit voltage of 2V, much lower than that at which EDM is normally carried out.

(3) A micropin 1μm in diameter was fabricated at an open-circuit voltage of 20V, suggesting the possible use of EDM for submicron machining and nanomachining.

(4) To avoid a decrease in the penetration rate, it was found that electrical capacitance must be greatly increased, leading to poor quality in processed surfaces.

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