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Comparative study on discharge conditions in micro-hole electrical discharge machining of tungsten carbide (WC-Co) material

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Abstract: WC-Co is used widely in die and mold industries due to its unique combination of hardness, strength and wear-resistance. For machining difficult-to-cut materials, such as tungsten carbide, micro-electrical discharge machining(EDM) is one of the most effective methods for making holes because the hardness is not a dominant parameter in EDM. This paper describes the characteristics of the discharge conditions for micro-hole EDM of tungsten carbide with a WC grain size of 0.5 μm and Co content of 12%. The EDM process was conducted by varying the condenser and resistance values. A R—C discharge EDM device using arc erosion for micro-hole machining was suggested. Furthermore, the characteristics of the developed micro-EDM were analyzed in terms of the electro-optical observation using an oscilloscope and field emission scanning electron microscope.

Key words: micro-hole; electrical discharge machining; tungsten carbide; electro-optical observation

1 Introduction

Electrical discharge machining(EDM) is an effective method of machining since EDM can shape hard metals and process complex-shaped holes by arc erosion in all kinds of electro-conductive materials[1−3]. In addition, EDM does not make direct contact between the electrode and workpiece, which eliminates mechanical stresses, clatter and vibration problems during machining[4−5].

A discharge circuit is divided into transistor discharge circuit and R-C discharge circuit. The transistor discharge circuit cuts the discharge current to give the circuit a short insulation rehabilitation and high impact factor. Therefore, the transistor discharge increases the process speed. On the other hand, the R—C discharge circuit has a low impact factor but a short discharge time and a high discharge current peak value. Therefore, the R—C discharge circuit is suitable as a micro discharge circuit, which requires a low energy and high frequency discharge[6−8].

Tungsten carbide and its composites (WC-Co) are in great demand in the production of cutting tools, dies and other special tools and components on account of its high hardness, strength and wear resistance over a wide range of temperatures. Tungsten carbide, which is difficult-to-machine by conventional machining processes, was found to be machinable into different complex shapes using the micro-EDM process[9−11].

In this study, based on the R—C discharge circuit, a micro discharge machining system was designed and used to make holes in an electro-conducting high hardness material, such as WC-Co. During machining, the applied DC voltage was fixed at 300 V and the resistance (R) and capacitance(C) values were varied. The electrical characteristics were observed in all cases. The working liquid for discharge machining was secondary distilled water processed with an ion filter. It was used because distilled water has a high resistivity. The resulting micro hole was measured by field emission scanning electron microscope(FE-SEM). The optimal conditions for the micro hole of tungsten carbide by varying C and R were suggested.

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2 Experimental

The workpiece material used in this experiment was WC-Co with a WC grain size of 0.5 μm, a Co content of 12% and dimensions of 10 mm×20 mm×0.5 mm. The tool electrode was a tungsten (W) rod with 160 μm in diameter. The important properties of the workpiece and electrodes are shown in Tables 1 and 2, respectively. The positioning resolutions of the *Z* worktable and the *XY* worktable were approximately 1 μm and 10 μm. FE-SEM (Hitachi, S-4800) was used to measure the machined holes. Fig.1 shows the experimental set-up of the micro-EDM.

Table 1 Properties of workpiece material WC-Co

Material	Composition	Density/ $(g\cdot cm^{-3})$	Hardness
WC-Co carbide	0.5 μm WC, 12% Co	14.3	HRA 90.5
Melting point/℃	Ultimate tensile strength/MPa	Compressive yield strength/MPa	Elastic modulus/GPa
2 800	344	2 683	669

Table 2 Material properties of tungsten electrode

Material	Diameter/ μm	Density/ $(g\cdot cm^{-3})$	Melting point/ ℃
Tungsten	160	19.3	3 410
Boiling point/℃	Thermal conductivity/ $(W\cdot m^{-1}\cdot K^{-1})$	Electrical resistivity/ $(\mu\Omega\cdot cm)$	Hardness
5 530	163.3	5.5	HRA66

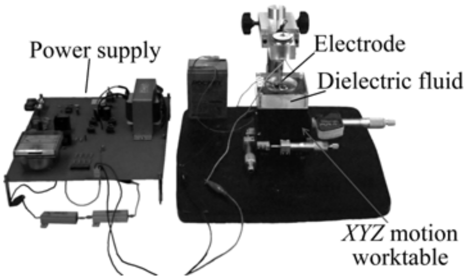

Fig.1 Apparatus of micro-EDM machine newly designed for micro-hole machining

Fig.2 shows the switching mode power supply (SMPS) and *R*—*C* circuit for micro EDM using arc erosion. The electrical part of the EDM was comprised of power supply, resistance, and capacitance. The SMPS of 30 W and the DC voltage of 500 V were applied. The power supply was connected to the resistance and the condenser, located in the series and parallel circuits, respectively. An oscilloscope (LeCroy, Wavesurfer 434), a current probe (Tektronix, P6041), and a voltage probe (LeCroy, PP006A) were used to evaluate the discharge characteristics according to the discharge conditions.

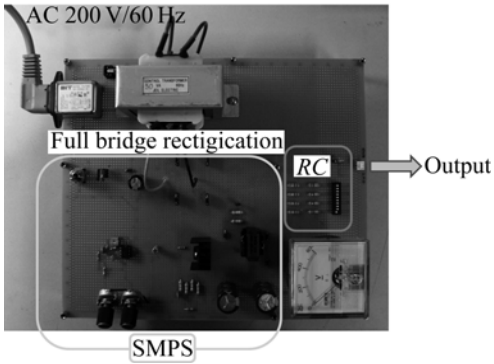

Fig.2 Photo of SMPS and *R*—*C* circuit for micro EDM

The constituent system was a hand-made SMPS, *R*—*C* circuit and mechanical system (Fig.2). The source of the 30 W class SMPS was 220 V/60 Hz AC, and the AC passes through a full bridge rectifier to become a DC of 20 V. The 20 V DC was boosted to 500 V DC using a buck-boost converter, and the applied voltage between the workpiece and electrode became 300 V. Since the inductor emitted an electromagnetic field, it affected the circuits as a source of electromagnetic interference (EMI). The EMI, or "noise," became a major problem of the EDM circuit because the devices were too far from each other to improve the EMC. The devices can be a noise source or receiver[12].

The discharge current and voltage were measured using an oscilloscope and the power consumption was calculated from the data. Based on these values, the dominant parameters for the micro-EDM can be found. The resistances were set to be 3.3, 4.3 and 6.6 kΩ. If the resistance was set to more than 10 kΩ, the voltage drop became so high that the electric field between the electrode and target became too low, and no discharge could occur. On the other hand, for a resistance less than 1 kΩ, the discharge current became very high, which damaged the circuit device. The energy supply from the condenser was calculated using $1/2CV^2$. Therefore, 50, 100 and 200 pF capacitors were chosen. These 9 cases were processed and the electrical characteristics were measured.

FE-SEM was used to measure the dimensions of the micro-holes. The taper angle was also measured to obtain the dimensions of the holes accurately. The taper angle is shown in Fig.3.

3 Results and discussion

3.1 Electrical characteristics

Fig.4 shows the discharge voltage and current graph

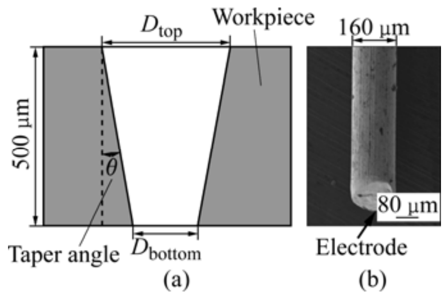

Fig.3 Measurement of taper angle(θ) (a) and picture of electrode using FE-SEM (b)

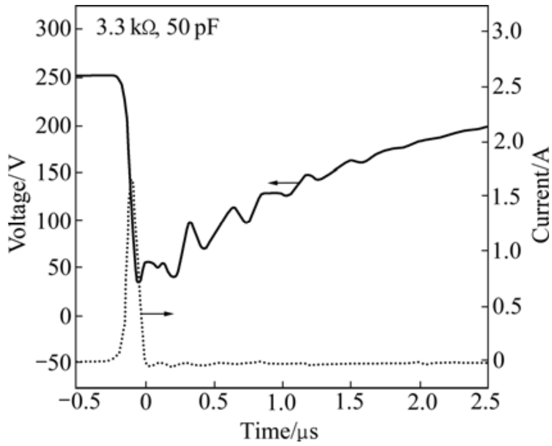

Fig.4 Waveforms of current and voltage

at 3.3 kΩ and 50 pF. The applied voltage was 300 V and discharge occurred when the gap between the electrode and workpiece was shorter than 10 μm. When discharge occurs, the condenser emits energy to the electrode. The energy from the condenser is stored as a DC voltage in the electrode. The energy makes an arc discharge and hole machining begins. The electrical energy is transformed into thermal energy at the target point and the workpiece melts and flies away. After the condenser exhausts the charged energy, the arc discharge is stopped and the condenser is recharged so the arc discharge repeats periodically. The discharge frequency on the micro-EDM is determined by the time constant τ (=RC). The input power is proportional to the peak value of the discharge current. The higher value of the current means stronger machining intensity. However, a large peak current damages the surface of the workpiece. Therefore the capacitance must be optimized.

In order to survey the effects of the condenser and resistor, the resistance was changed under a 50 pF capacity of the condenser, and the discharge current and voltage were measured. The measurement was also repeated with 100 and 200 pF. All cases are presented in Fig.5, and each graph shows the data under a fixed capacitance and changed resistance.

The capacity of the condenser was changed from 50

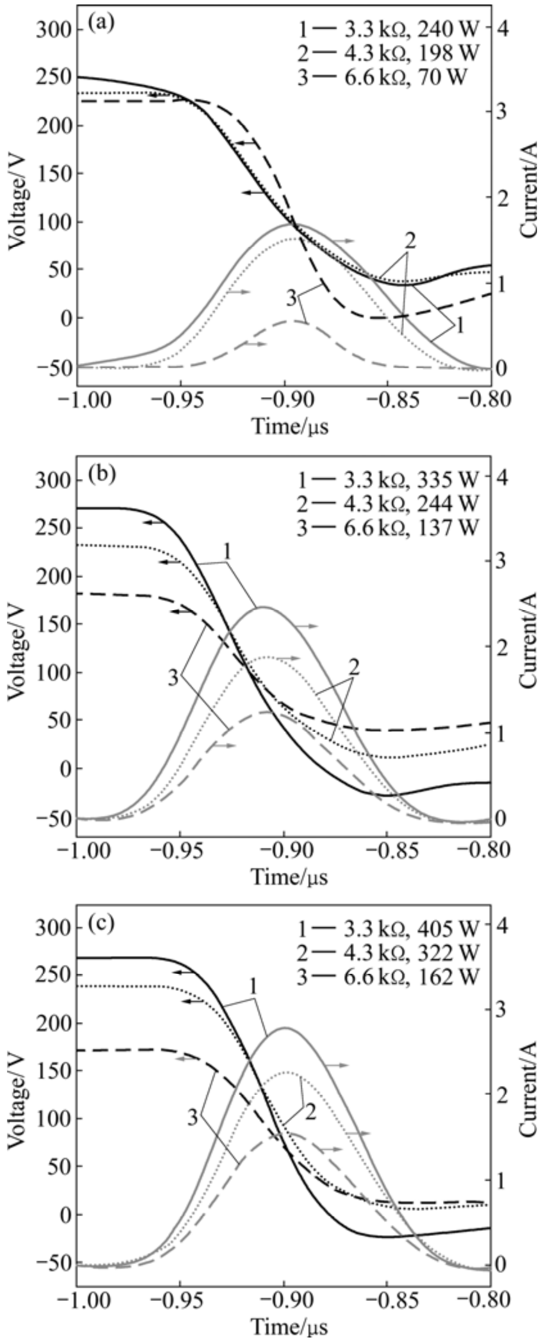

Fig.5 Waveforms of voltage and current under different R and C and instant power consumption: (a) 50 pF; (b) 100 pF; (c) 200 pF

pF to 200 pF. The discharge current is in proportion to the capacity because a higher capacity means higher electricity storage for the discharge energy. Consequently, the peak discharge current and power consumption, as shown in Fig.5, increased with increasing capacity. The power consumption was the instant power consumption because the discharge frequency was unstable.

The voltage drop on the resistance is increased with increasing resistance so that the voltage between the electrode and workpiece decreases. This decrease implies that it is difficult to machine the workpiece using a high resistance. In this study, the machining cannot be processed under a resistance over 10 kΩ. For this reason, the 6.6 kΩ case lowers the voltage between the electrode and the workpiece so that machining time takes longer. A long time machining involves a larger number of the discharges between the electrode and wall of the workpiece. Consequently, the hole becomes broader and damaged.

3.2 Optical characteristics

The FE-SEM photographs in Fig.6 shows three blind micro-holes machined using the EDM process. The hole in Fig.6(a) was machined with R=3.3 kΩ and C=50 pF, while the hole in Fig.6(b) was machined with R=3.3 kΩ and C=200 pF. The entrance and exit diameter of the hole shown in Fig.6(a) were 1.1 mm and 440 μm, respectively, and the diameter of the hole shown in Fig.6(b) were 1.28 mm and 550 μm, respectively.

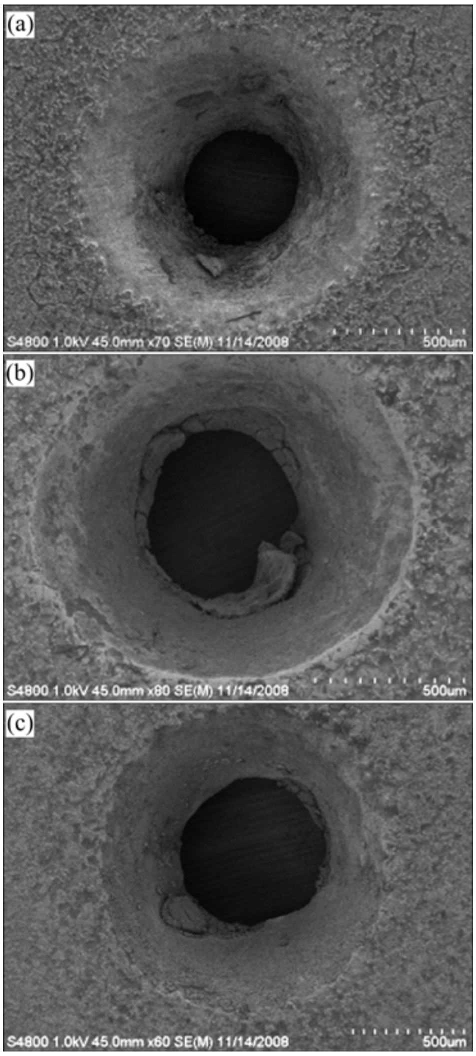

Fig.6 Machining shape of micro-holes using FE-SEM: (a) R=3.3 kΩ, C=50 pF; (b) R=3.3 kΩ, C=200 pF; (c) R=6.3 kΩ, C=200 pF

Although a same feed distance of the tool electrode was set up, the machined diameter of the hole in Fig.6(b) was larger than that of the hole in Fig.6(a). This indicates that a large discharge caused violent sparks, resulting in a larger diameter.

The entrance and exit diameters of the machined holes were not the same due to the corner wear of the electrode in addition to linear wear. Therefore, the taper angle was measured to evaluate the dimensional accuracy of the micro-holes. Fig.7 shows the taper angle of the micro-holes under different machining conditions of the micro-EDM. For dimensional accuracy, R=3.3 kΩ and C=50 pF yielded the best results.

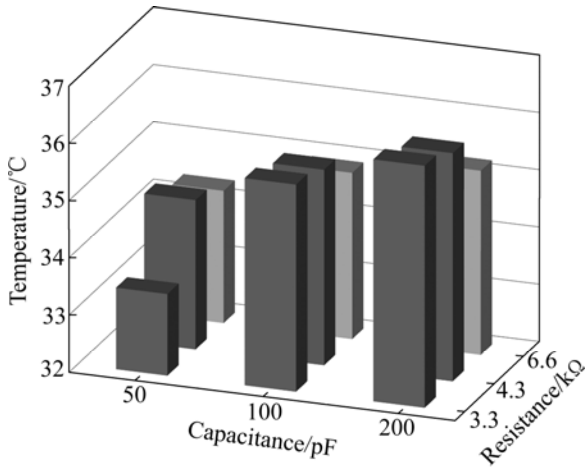

Fig.7 Comparison of taper angle from R—C value

On the other hand, Fig.6(b) shows a hole produced at R=3.3 kΩ and C=200 pF. In Fig.6(c), the hole diameters are 1.377 mm and 670 μm at R=6.6 kΩ and C=200 pF. At R=6.6 kΩ and C=200 pF, the surface quality is good in the micro-holes obtained with a rim free of burring and good circularity. However, the diameters of those holes are larger than those made at R=3.3 kΩ and C=200 pF. Overall, for micro-structure machining of WC-Co materials, the use of a higher resistance in the micro-EDM process can enhance the performance.

Furthermore, when the C and R values are compared, C has a more significant effect on this experiment, as shown in Fig.7. The taper angle measurements suggest that R=3.3 kΩ and C=200 pF are the optimal conditions for WC-Co.

4 Conclusions

Micro-EDM process for micro-hole of tungsten carbide (WC-Co) was newly designed. Electro-optical characteristics were evaluated on the discharge conditions with the R—C value. The voltage drop on the resistance increased with increasing resistance, which reduced the voltage between the electrode and workpiece. In the given discharge conditions, the optimal discharge conditions were found to be 50 pF and 3.3 kΩ. The resistance should be determined very carefully depending on the discharge current, and 1.5 A is suitable for machining. Future studies will examine the effect of attaching a servomotor-controlled *Z*-axis to minimize the taper angle.

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