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An experimental research on a kind of distributed-flushing ED milling†

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Abstract

In order to reduce the electrode wear and increase the material removal, this paper proposed a kind of distributed-flushing ED milling. A rotating electrode with some distributed holes was used during the machining process. The distributed flushing developed the machining environment and increased the adhesion of debris on the electrode, thus decreasing the electrode wear rate. Compared with the material removal rate of conventional ED milling, the relative electrode wear ratio decreased by 10.7 %. Furthermore, the material removal rate of the new method increased by 21.1 %. The effects of rotating speed, peak current, pulse duration, pulse interval, and tool electrode polarity on machining performance, including material removal rate, relative electrode wear ratio, and surface roughness were researched to determine the characteristics of the new process.

Keywords: Adhesion of debris; EDM; Flushing; Machining performance

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1. Introduction

Electrical discharge machining (EDM) is an unconventional manufacturing process, which transforms electrical energy into heat energy. Therefore, EDM can machine conductor materials regardless of the hardness, and has been devoted to machine difficult-to-cut materials [1-3]. However, the use of EDM is limited by its high Relative electrode wear ratio (REWR) and low Material removal rate (MRR) [4, 5]. During the EDM process, the dielectric fluid plays an important role in removing debris and cooling the electrode [6]. The machining efficiency can be improved by effective flushing [7, 8]. Several research works have been conducted to improve the machining efficiency and stability of EDM. Fluid flow simulation models have been built to study the EDM process and the flushing effects [9-11]. To avoid the accumulation of debris and improve the stability of EDM, an electrode with peripheral slots was developed. The results showed that the peripheral slots were conducive to MRR and debris evacuation [12, 13]. Gu et al. [14] developed a type of bunched electrode formed by a number of hollow cell electrodes; this electrode significantly increased the MRR of sinking EDM. Munz et al. [15] showed that excessive flushing resulted in a negative process behavior and found that a direct link existed between the removal mechanism and dielectric flow rate.

However, the published studies mainly focused on the evacuation of debris to improve machining stability. The study still has not been conducted to reduce the REWR with the help of dielectric fluid flushing. In this work, a kind of Electrical discharge (ED) milling with distributed flushing was used. A cylindrical electrode with some distributed holes was designed, and the rotating electrode followed a programmed path to obtain a desired shape with continuous discharge. During machining, the distributed flushing was used to develop the machining environment and increase the adhesion of debris on the electrodes. This process decreased the electrode wear rate. Compared with the conventional ED milling, the REWR decreases by 10.7 %. Furthermore, the MRR of the new method increases by 21.1 %. Many experiments have been conducted to study the machining performance and surface integrity.

2. Materials and methods

The illustration of traditional mono-hole flushing is shown in Fig. 1(a). During machining, the dielectric fluid flows to the gap through the mono-hole of the electrode. When the electrode moves to the workpiece, the materials left in the mono-hole decreases the flow area, and prevents the dielectric fluid from flowing to the gap effectively, thus destroying the machining environment. Moreover, the discharge location is around the mono-hole, as a result, the dielectric fluid flushes the debris to the outside, thus hindering the adhesion of debris on the electrode. During the distributed flushing, as shown in Fig. 1(b), the dielectric fluid flows to the gap through several holes, thus eliminating the blocking of the dielectric fluid. In

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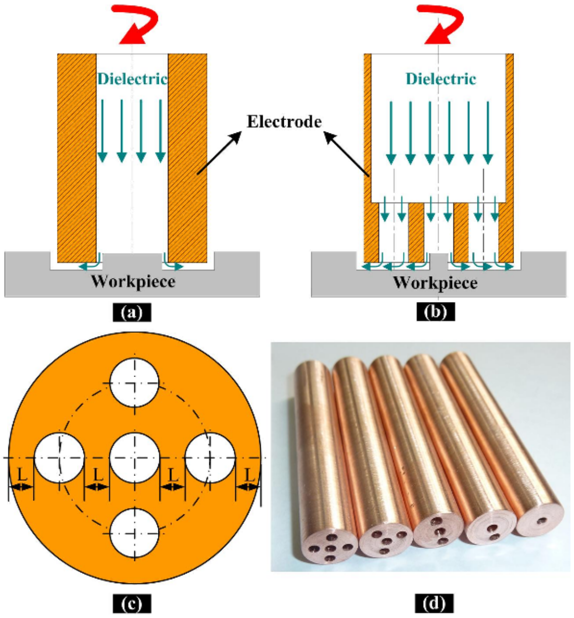


Fig. 1. The illustration of (a) mono-hole flushing; (b) distributed flushing; (c) arrangement of the distributed hole; (d) photograph of distributed flushing electrodes.

addition, the discharge location is throughout the end of the electrode. This situation is beneficial to the adhesion of debris, which can protect the electrode and reduce the electrode wear.

The arrangement of the distributed holes is illustrated in Fig. 1(c), and the material of the tool electrode was red copper. First, the electrode was machined by CNC lathes. Distributed holes were then drilled by a CNC machining center. A photograph of distributed-flushing electrodes with different number of holes is shown in Fig. 1(d). The diameter of the distributed hole was 2 mm, and the external diameter of the electrode was 10 mm.

Fig. 2 shows the photograph of the ED milling machine tool, the control system was developed based on the open architecture numerical control system. The electrode was fixed on the main spindle, which can supply dielectric fluid. The workpiece was fixed on XY-axis linear stages. The pressure of the dielectric fluid was adjusted by a pump, which is driven by a frequency converter. During ED milling, the electrode was connected to the negative pole of the power supply, and the workpiece was connected to the positive pole.

During the experiment, the material of the workpiece was AISI 1045. The dielectric fluid consisted of deionized water and emulsified oil (HY-C, Beijing Huaye Oil Factory) in the mass percent of 9:1. A high precision electronic balance (BS224S, Sartorus) was used to weigh the workpiece and tool electrode. Components were analyzed by an Energy dispersive spectrometer (EDS). A Scanning electron microscope (SEM, Hitachi S4800) was used to examine the characteristic of the surface after machining. The Surface roughness (SR) was tested by SR tester (TR220, Time Group Incorporation, China).

Table 1. Machining parameters used in experiments.

Machining parameter	Value
Peak voltage of pulse generator (V)	140
Pulse on time of pulse generator (μs)	100, 200, 300, 400
Pulse off time of pulse generator (μs)	100, 200, 300, 400
Peak current of pulse generator (A)	10, 25, 50, 75
External diameter of electrode (mm)	10
Number of holes	1, 2, 3, 4, 5
Rotating speed (r/min)	700, 1400, 2100, 2800
Electrode polarity	Positive, negative
Flow rate of flushing (m^3/h)	0.36

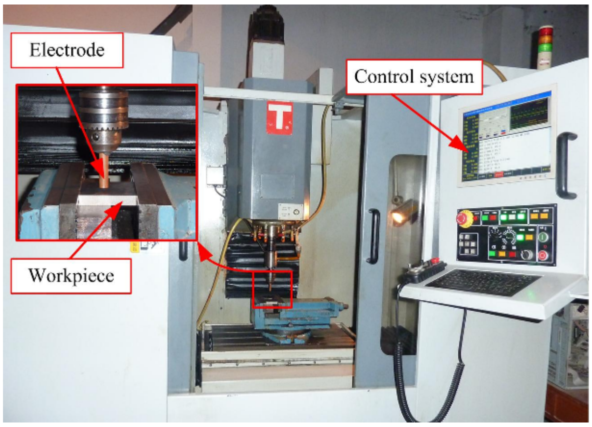


Fig. 2. Photograph of ED milling machine tool.

The other experimental parameters were listed in Table 1.

MRR and REWR can be simply calculated according to the following relations:

$$MRR = \frac{(m_{mb}-m_{ma})/\rho_m}{t} \times 100\ \% \tag{1}$$

$$REWR = \frac{(m_{eb}-m_{ea})/\rho_e}{(m_{mb}-m_{ma})/\rho_m} \times 100\ \% \tag{2}$$

where ρ_m, m_{ma} and m_{mb} represents the density of the workpiece, the weight of the workpiece after machining, and its weight before machining, respectively. t is the machining time. In addition, ρ_e and m_{eb}-m_{ea} represent the density of the electrode and the weight losses of the electrode, respectively.

3. Results and discussion

Comparative experiments were conducted with mono-hole flushing and distributed flushing. The result is shown in Fig. 3. The pulse interval, pulse duration, peak current, and rotating speed are 300 μs, 400 μs, 75 A and 2800 rpm, respectively. During the mono-hole flushing, the diameter of the mono-hole was 3.46 mm. Electrodes with three distributed holes were used during distributed flushing to ensure the same cross-

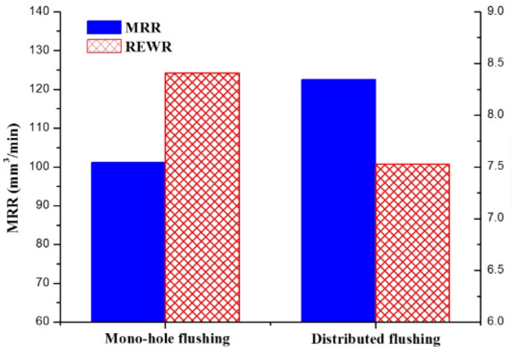


Fig. 3. Comparison of MRR and REWR of ED milling with mono-hole flushing and distributed flushing.

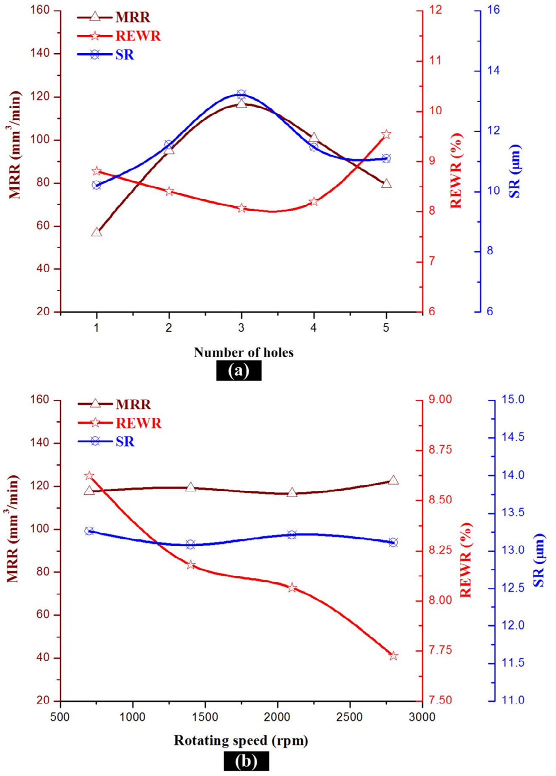


Fig. 4. Effects of (a) number of holes; (b) rotating speed on the machining performance.

sectional area. As shown in Fig. 3, the REWR of distributed flushing is 7.52 %, which is 10.7 % lower than that of mono-hole flushing. The MRR of distributed flushing was 122.47 mm^3/min, which is 21.1 % higher than that of mono-hole flushing. This result may be attributed to the flushing effect of distributed flushing. Owing to the distributed holes and electrode rotation, the discharge location is throughout the end of the electrode. This situation is beneficial to the adhesion of debris and the reduction of REWR. In addition, the distributed hole supplies enough dielectric fluid to the gap, thus improving the machining environment and discharging stability. As a result, the MRR is higher than that of mono-hole flushing.

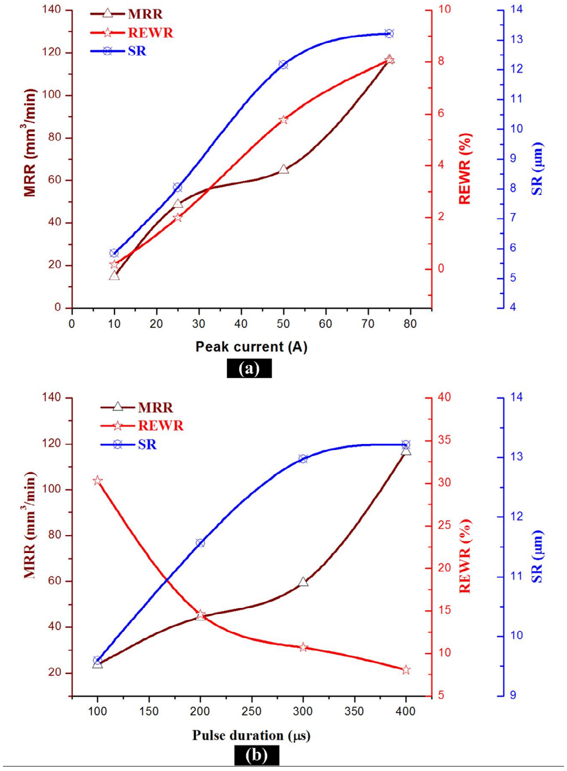


Fig. 5. Effects of (a) peak current; (b) pulse duration on the machining performance.

The effects of rotating speed on machining performance are shown in Fig. 4(b) with pulse interval of 300 μs, discharging peak current of 75 A, pulse duration of 400 μs, and three holes. Fig. 4(b) illustrates that the SR and MRR change slightly and that the REWR decreases with increasing rotating speed. This result may be attributed to the fact that the discharging energy changes slightly with increasing rotating speed. The removal rate of workpiece changes slightly; thus, the SR and MRR do not change obviously. However, the rotating speed affects the debris adhesion, and a high rotating speed increases the opportunities for debris to adhere to the electrode, thus decreasing electrode wear and REWR.

Fig. 5(a) shows the effects of peak current on machining performance with pulse interval of 300 μs, pulse duration of 400 μs, three holes, and rotating speed of 2100 rpm. Fig. 5(a) shows that the lowest REWR is 0.09 % with a current of 10 A and that all MRR, REWR and SR monotonically increase with increasing peak current regardless of machining condition. This result can be attributed to the enhancement of the single-pulse discharge energy, and higher discharge energy leads to more removed materials from both tool electrode and workpiece; this situation increases the MRR, REWR and SR.

Fig. 5(b) depicts the effects of pulse duration on the MRR, the REWR and SR, with pulse interval of 300 μs, three holes, discharging peak current of 75 A, and rotating speed of 2100 rpm. With increasing pulse duration, the MRR increases slightly, and the SR enhances, but the REWR decreases rap-

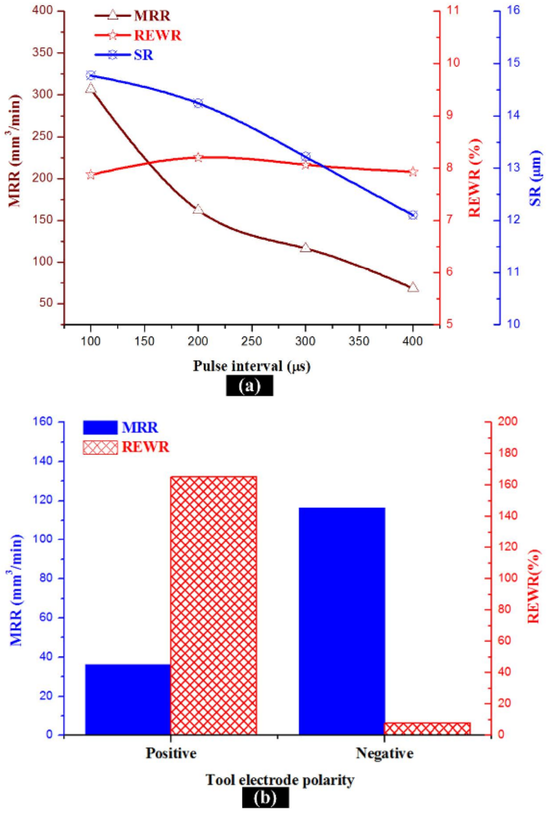


Fig. 6. Effects of (a) pulse interval; (b) tool electrode polarity on the machining performance.

idly. The reason for this result is that the energy of single pulse delivered into the machining zone enhances with increase of pulse duration. The melting and vaporization of materials are strengthened; therefore, the removed material and crater depth by single-pulse enhances with increase of pulse duration, as a result, the MRR and SR increases. Furthermore, with the increasing of energy, the amount of debris and explosive force during single-pulse discharging increase, thus allowing the released debris to easily adhere to the electrode, enhancing the compensate effect, and decreasing the wear of tool electrode. This situation reduces the REWR.

Fig. 6(a) illustrates the effects of the pulse interval on machining performance, with pulse duration of 400 μs, three holes, peak current of 75 A, and rotating speed of 2100 rpm. The MRR and SR decrease, whereas the REWR changes slightly. During discharging, the pulse duration and pulse interval affect the discharge energy. With the fixed pulse duration, the discharge energy in a period of time decreases with increasing pulse interval, then less material can be removed from both the electrode and workpiece, thus, the MRR decreases and REWR changes slightly. A lower pulse interval leads to higher frequency discharging, thus affecting the ejection of molten materials, i.e., more molten materials are left around the crater. As a result, the SR decreases with the increasing of pulse interval.

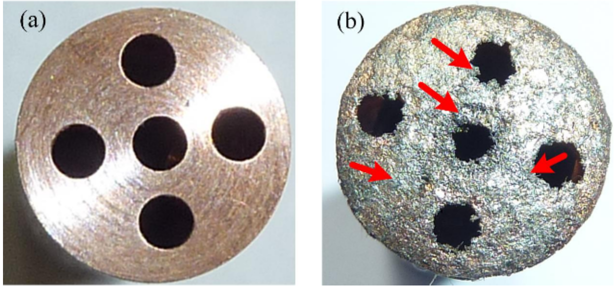


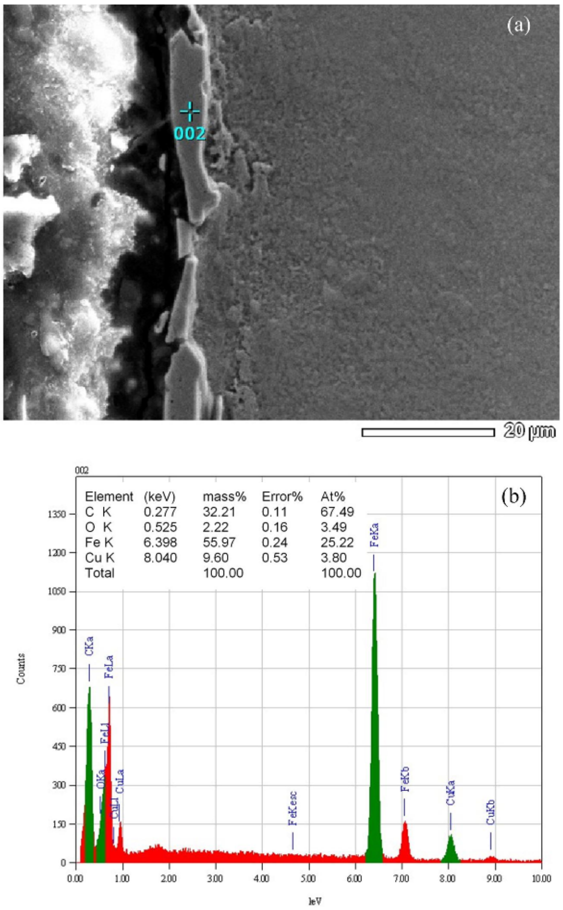
Fig. 7. Photographs of the electrode (a) before machining; (b) after machining.

Tool electrode polarity is one of the primary factors which affect ED milling performance. The effects of tool electrode polarity on the MRR, the REWR and SR are illustrated in Fig. 6(b), with pulse duration of 400 μs, pulse interval of 300 μs, three holes, peak current of 75 A, and rotating speed of 2100 rpm. As shown in Fig. 6(b), the MRR with negative polarity is 4.1 times larger than the MRR with positive polarity. The REWR with positive tool polarity is 20.6 times as large as that with negative tool polarity. This phenomenon can be explained as follows. During ED milling, the electrode and workpiece obtain different discharging energy, and the anode gets more energy than that of the cathode [16]; therefore, when the tool electrode is connected to the negative polarity, the workpiece gets more discharging energy than the tool electrode. This situation results in high MRR and low REWR.

The electrode morphology before machining is different from that after machining during the machining processing. Fig. 7(a) illustrates the photograph of the tool electrode before machining, and Fig. 7(b) shows the photographs of the electrode after machining. After machining, some silvery white materials are found on the electrode and the center hole gets blocked by silvery white materials. This phenomenon can be explained as follows. During distributed flushing, the discharge location is throughout the end of the electrode; this result is beneficial to adhesion of debris on the electrode. Moreover, when the number of holes is five, the center hole obtains less dielectric than other holes. Thus, the debris around the center hole easily adheres to the electrode, and the center hole gets blocked. Fig. 8(a) shows the SEM micrograph of silvery white materials on the electrode. EDS is used to identify the silvery white material, and the EDS results are shown in Fig. 8(b). These results indicate that a large amount of Fe(55.97 %) and Cu(9.6 %) are found. During discharging, the workpiece and tool electrode are both removed, and mixed together, then adhere to the electrode.

4. Conclusions

This paper proposes a type of distributed-flushing ED milling. A cylindrical electrode with some distributed holes was used, and a series of experiments have been carried out to research the machining performance of the new method. According to the experiment, the following conclusions can be drawn:



Element	(keV)	mass%	Error%	At%
C K	0.277	32.21	0.11	67.49
O K	0.525	2.22	0.16	3.49
Fe K	6.398	55.97	0.24	25.22
Cu K	8.040	9.60	0.53	3.80
Total		100.00		100.00

Fig. 8. SEM micrograph (a); EDS analysis (b) of the tool electrode.

(1) Compared with the conventional ED milling, the REWR of distributed-flushing ED milling decreases by 10.7 %. Furthermore, the MRR of the new method increases by 21.1 %.

(2) During the distributed-flushing ED milling, the discharge location is throughout the electrode. This situation is beneficial to adhesion of debris on the electrode. As a result, the REWR decreases with increasing adhesion of debris.

(3) The distributed-flushing ED milling improves the machining environment and discharging stability, thus obtaining higher MRR than traditional ED milling.

(4) Tool electrode polarity affects the distribution of energy, and negative polarity should be used during distributed-flushing ED milling.

(5) An optimum number of holes can be used to obtain the maximum MRR and lowest REWR. Excessive distributed holes will block the center hole, thus deceasing discharging stability.

(6) Higher MRR, REWR and SR can be obtained with higher peak current. The REWR decreases with increasing rotating speed and pulse duration. With increasing pulse duration, the SR and MRR enhance. Furthermore, the pulse interval affects the discharging energy; thus, the MRR and SR increase with the decreasing of pulse interval.

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