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ORIGINAL ARTICLE

Influence of pulse waveform on machining accuracy in electrochemical machining

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Abstract
Low machining accuracy has been a technical bottleneck for the application and promotion of electrochemical machining (ECM). Since the 1990s, it has been recognized by scholars that high-frequency pulsed power supply can improve the precision of ECM. But, in terms of the experimental results of our study, a new discovery was found that the increasing of the frequency has no effect on improving the machining accuracy of ECM. Comparing with the DC power supply, the experiment results show that the machining accuracy under pulsed power supply is decided by effective average voltage value, regardless of the frequency of the pulsed waveform, the duty cycle, and the pulse peak.

Keywords Electrochemical machining (ECM) · Machining accuracy · Pulsed power supply · Pulse waveform

1 Introduction

Electrochemical machining is an anodic electrochemical dissolution process in which a workpiece is molded through the electrochemical anodic dissolution of metal for removing excess material in an electrolyte. As a high efficient processing method, electrochemical machining (ECM) has received significant attention in the last decade due to its many advantages such as no tool wear, no remelted layer, stress free, and the ability to machine complex shape in materials regardless of their hardness. So it has great potential in the aerospace and microfabrication fields [1]. However, due to the difficult to control the electric field distribution between the positive and the negative electrode, the non-working surface will be corroded excessively. It caused a significant reduction in the machining accuracy, as taper error appeared in the punching process with ECM. The poor machining accuracy is a technical bottleneck for ECM applications. In order to solve this problem, tool electrodes with sidewall insulation and a high-frequency pulsed power supply are currently used [2]. For tool electrodes with sidewall insulation, an insulating layer is formed on the sidewall of a tool electrode to prevent ion exchange between the tool electrode and the machined surface of the sidewall, thereby avoiding stray corrosion at the sidewall. Although the sidewall insulation can improve the accuracy of ECM, the adhesion strength between the insulating film and the electrode is not high enough, and erosion of the electrolyte during the ECM process will result in the loss of the insulating film, which influences the accuracy of ECM [3–9]. When the shape of the tool electrode becomes more complex, it is much more difficult to form a uniform insulating film on the electrode sidewall. In practice, a pulsed power to take up the direct-current (DC) power and an increase in the pulse frequency are used to improve the shape accuracy and dimensional accuracy of ECM.

A great number of scholars have studied and discussed the mechanisms for why pulsed power supply improves the accuracy of ECM. Shin et al. [10] analyzed the influence of a high-frequency pulse on the side gap between the inner surface of the hole and the tool electrode sidewall in electrochemical micromachining line cutting and adjusted the applied voltage, pulse duration, and pulse period to obtain a small side machining gap. The side gap increases as the applied voltage and pulse duration increase and decreases as the pulse period increases. Liu et al. [11] used high-speed rotation microelectrodes to process deep eyelets and discovered that the side

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Table 1 Experimental conditions of different pulse frequencies with the same peak voltage

Parameters	Values
Workpiece	304 stainless steel, thickness = 1.2 mm
Electrolyte	NaCl concentration = 30 g/L
Frequency	20, 40, 60, and 80 kHz
Duty cycle	50%
Uniform feed rate	0.12 mm/min

gap increased with the pulse frequency. Researchers have processed the microstructure [12, 13] of stainless steel by ultrashort-pulse ECM and studied the relationship between the power parameters and the accuracy of ECM when the pulse duration decreases. It was also found that the slit width decreases by pulse ECM [14, 15]. Sebastian concludes that ultrashort voltage pulse electrochemical micromachining gave possibility to obtain an extremely high localization of anodic dissolution [16]. Das et al. [17] conducted a series of experiments on pulsed power ECM to study the effects of the pulsed

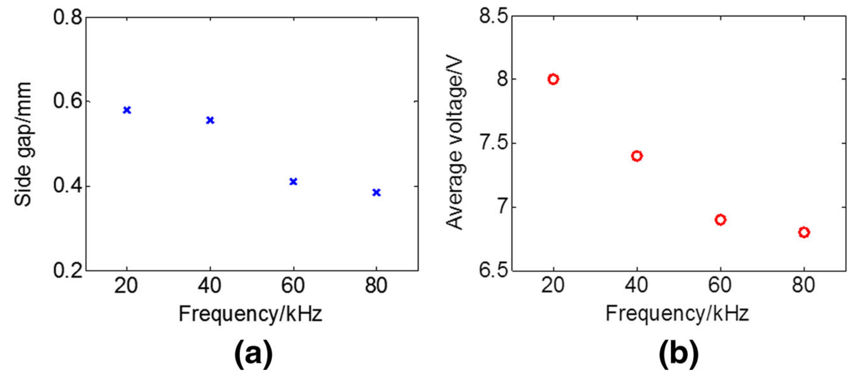

Fig. 1 Experimental results for various pulse frequencies with the same peak voltage. **a** Side gap. **b** Average voltage versus the frequency

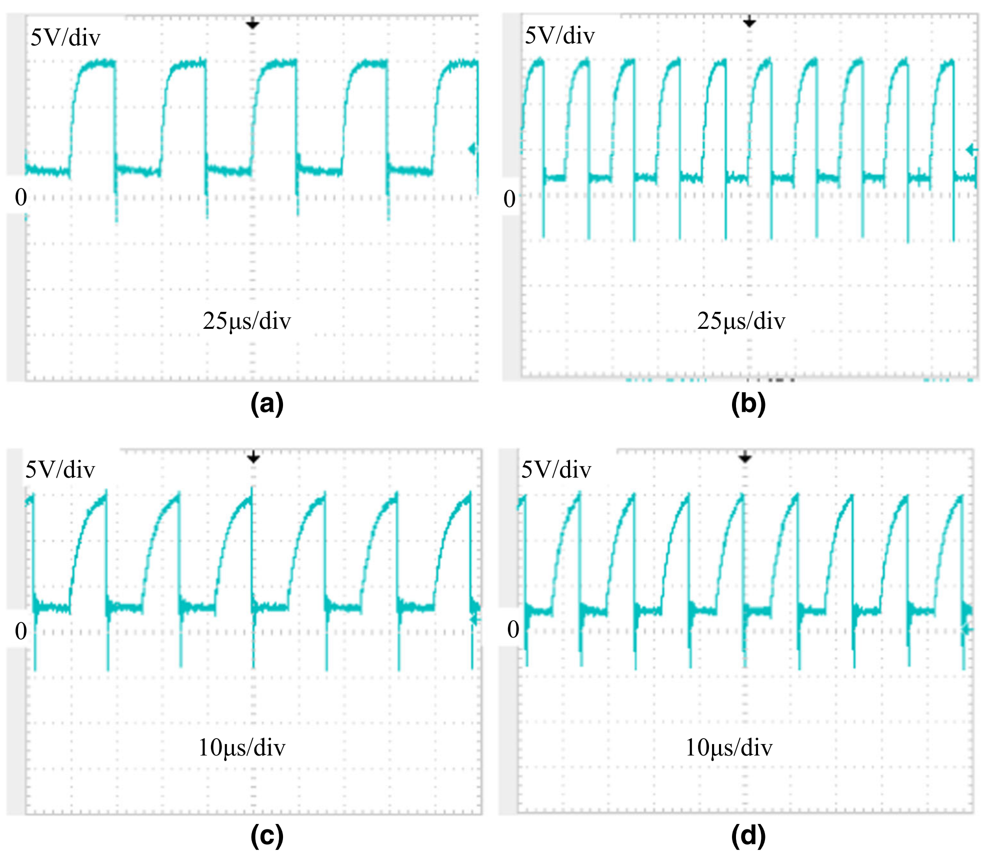

Fig. 2 High-frequency waveform distortion. **a** 20 kHz. **b** 40 kHz. **c** 60 kHz. **d** 80 kHz

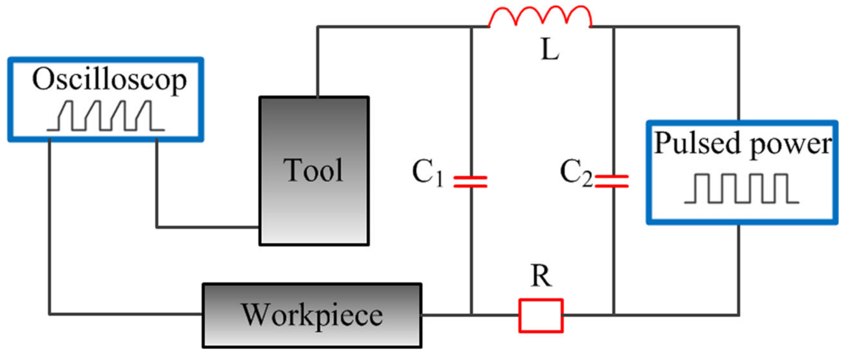

Fig. 3 Schematic of waveform distortion

power supply parameters on a microporous taper. Bhattacharyya et al. [18] studied the factors affecting the removal and processing precision of micro electrochemical machining. Research indicates that the side gap increases as the pulse duration increases. Schuster et al. [19] famously proposed a physical model based on RC charging and discharging made up of an electrical double layer and electrolyte resistor to explain the relationship between the pulsed power supply and the ECM accuracy. In the model, the workpiece, the end face of electrode and the electrolyte between them were equivalent to the RC circuit, and so were the workpiece, the side face of electrode, and the electrolyte between them. Because the resistance between the bottom of the electrode and the workpiece was smaller than that between the electrode side and the workpiece, the charging time for these two directions was not the same. Thus, the anodic dissolution time between the bottom surface of the electrode and the workpiece was longer than that between the side of the electrode and the workpiece during the pulse duration of each pulse period, which resulted in a larger material removal amount at the bottom than that at the side. Hence, the secondary processing of the machined surface on the electrode side will be reduced, and the electrolytic machining accuracy will be improved.

As mentioned previously, scholars in the field of ECM have always believed that the accuracy of ECM can be directly improved by replacing the DC power supply with a pulsed power supply and the better precision is obtained if higher-frequency pulsed power is used. However, in terms of the experimental results of our study, a new discovery was found that the frequency of pulsed power cannot improve the precision of ECM. Due to the power supply line from the workpiece to the tool electrode not be infinitely short, there are certainly capacitance and inductance effects in the circuit. Thus, the distortion of impulse waveform is rather obvious when the frequency of pulsed power supply is very high. It caused a significant reduction of the effective average voltage value in the ECM process. By their very nature, the machining accuracy is improved owning to the reduction of the effective average voltage value with ultra-high frequency. This fact will be demonstrated by the experimental results presented in this paper.

2 Experiments for various pulse frequencies and the same peak voltage

In order to verify that the accuracy of ECM was improved as the pulse frequency increases, the following experiments were conducted. The voltage frequency pulse was varied while maintaining the peak voltage of the pulsed power and the duty cycle at constant values. The peak voltage was 15 V. As shown in Table 1, our experiments

Table 2 Experimental conditions of different frequencies with the same average voltage in NaCl

Parameters	Values
Workpiece	304 stainless steel, thickness = 1.5 mm
Tool electrode	Copper pipe, diameter = 1.0 mm
Electrolyte	NaCl, concentration = 30 g/L
Frequency	20, 40, 60, 80, and 100 kHz
Duty cycle	50%
Average voltage	6 V
Uniform feed rate	0.16 mm/min

Table 3 Experimental conditions of different frequencies with the same average voltage in $NaNO_3$

Parameters	Values
Workpiece	304 stainless steel, thickness = 1.5 mm
Tool electrode	Copper pipe, diameter = 1.0 mm
Electrolyte	$NaNO_3$, concentration = 30 g/L
Frequency	20, 40, 60, 80, and 100 kHz
Duty cycle	50%
Average voltage	6 V
Uniform feed rate	0.15 mm/min

Table 4 Experimental conditions of different frequencies with the same average voltage in square hole machining

Parameters	Values
Workpiece	304 stainless steel, thickness = 1.5 mm
Tool electrode	Square copper pipe, length of side = 1.0 mm
Electrolyte	$NaNO_3$, concentration = 30 g/L
Frequency	40, 60, 80, and 100 kHz
Duty cycle	50%
Average voltage	12 V
Uniform feed rate	0.15 mm/min

used sodium chloride (NaCl) as the electrolyte and a uniform feed.

From the results shown in Fig. 1a, the machining accuracy improves as the frequency increases, which is indeed consistent with the experimental results obtained by previous researchers. However, we also find that the inter-electrode voltage pulse waveform is gradually distorted from a square waveform to an approximately triangular waveform as the frequency increases, as shown in Fig. 2. After the measurement of the average inter-electrode voltage, we find that the average voltage decreases as the frequency increases (Fig. 1b). The active current used for anodic dissolution during the ECM process is naturally reduced. Thus, the accuracy of ECM is improved. Accounting for the reduction in the average voltage during this process, it does not follow that an increase in the frequency directly promotes an improvement in the accuracy of ECM. Figure 3 shows schematic of waveform distortion, the pulse is transmitted from the power supply to the gap between the electrode and the workpiece. Due to the distributed capacitance and inductance on the power supply line and the working machines, the pulse voltage waveform is distorted.

3 Experiments for different pulse frequencies with the same average voltage

In the previous experiments, the average voltage and frequency are two variables, which change simultaneous-

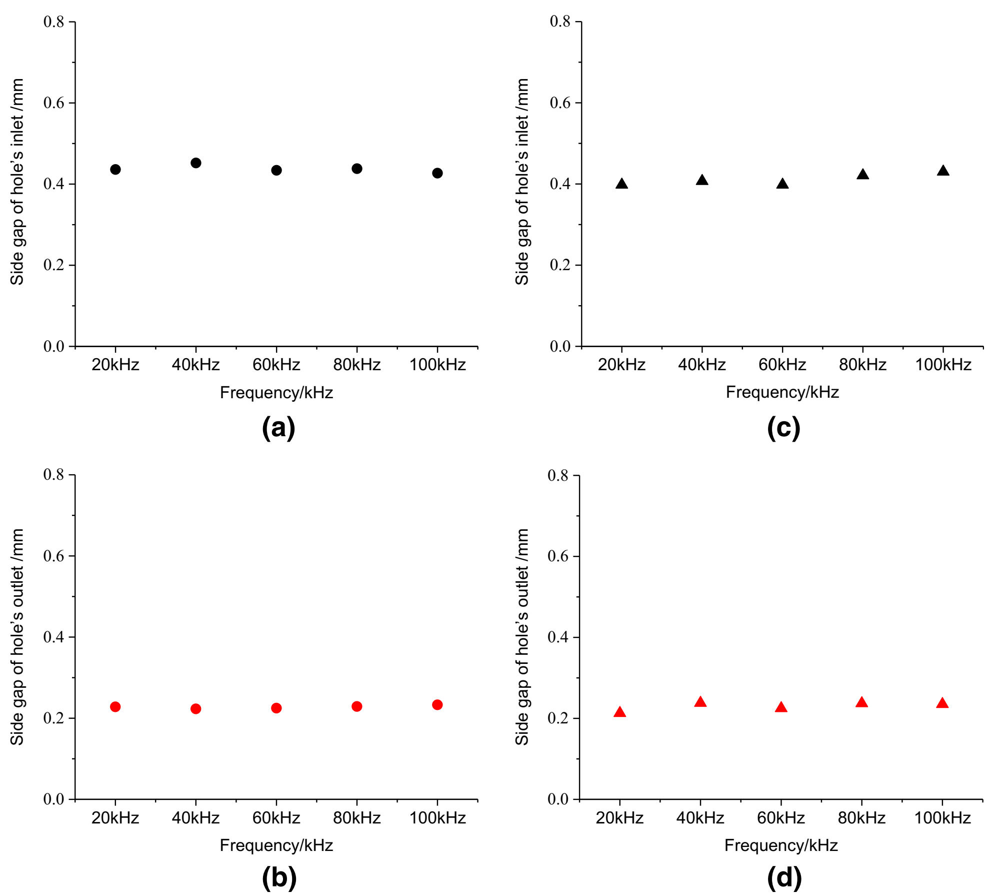

Fig. 4 Experiments for different pulse frequencies with the same average voltage in round hole machining. **a** Side gap of the round hole's inlet in NaCl. **b** Side gap of the round hole's outlet in NaCl. **c** Side gap of the round hole's inlet in $NaNO_3$. **d** Side gap of the round hole's outlet in $NaNO_3$

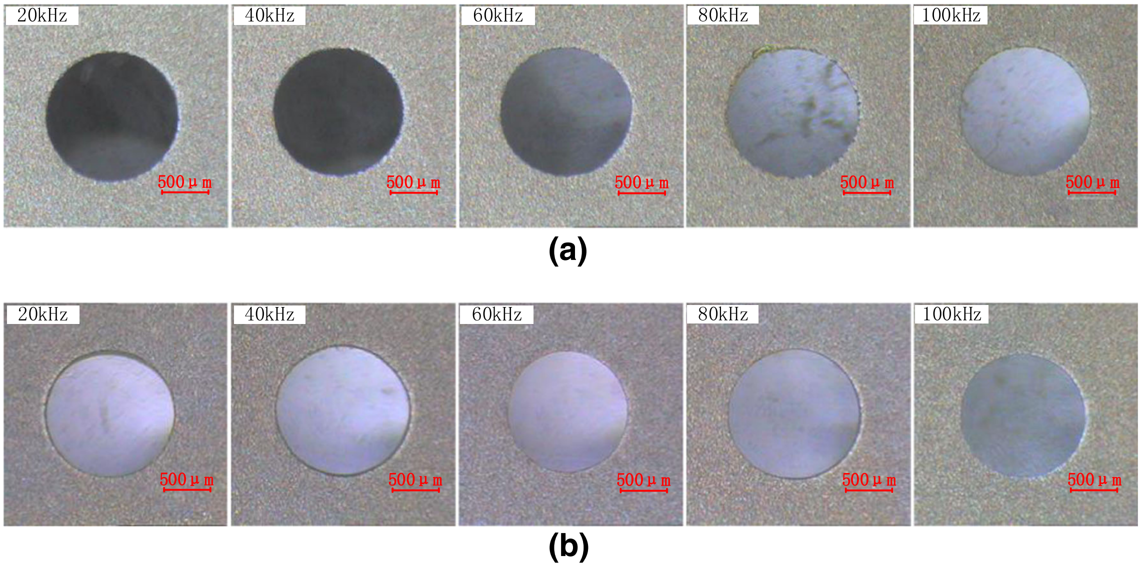

Fig. 5 Experimental results obtained for different pulse frequencies and the same average voltage in round hole machining. **a** Outlet of holes machined in NaCl. **b** Outlet of holes machined in $NaNO_3$

ly. Therefore, it is not possible to determine the factor that affects the machining accuracy. We demonstrate that the improvement in the accuracy of ECM is due to the reduction in the average voltage reducing rather than the increase in the frequency by designing the experiments that have the same average voltage and different frequencies.

3.1 Experiments of round hole machining

In the experiments, the average voltage at different frequencies was maintained at a constant value by adjusting automatically the duty cycle. The processing conditions were shown in Tables 2 and 3. Two different electrolytes, sodium chloride (NaCl) and sodium nitrate ($NaNO_3$), were used for these experiments, respectively. Because of the serious corrosion of the holes' surface, in order to measure the diameter of the hole more accurately, a thin layer of the upper and lower surface of the processing hole is removed by electric spark wire cutting.

3.2 Experiments of square hole machining

The experiments of square hole electrochemical machining were carried out under the same average voltage and different frequencies. The processing conditions were shown in Table 4. The tool electrode is a square copper pipe with a side length of 1.0 mm.

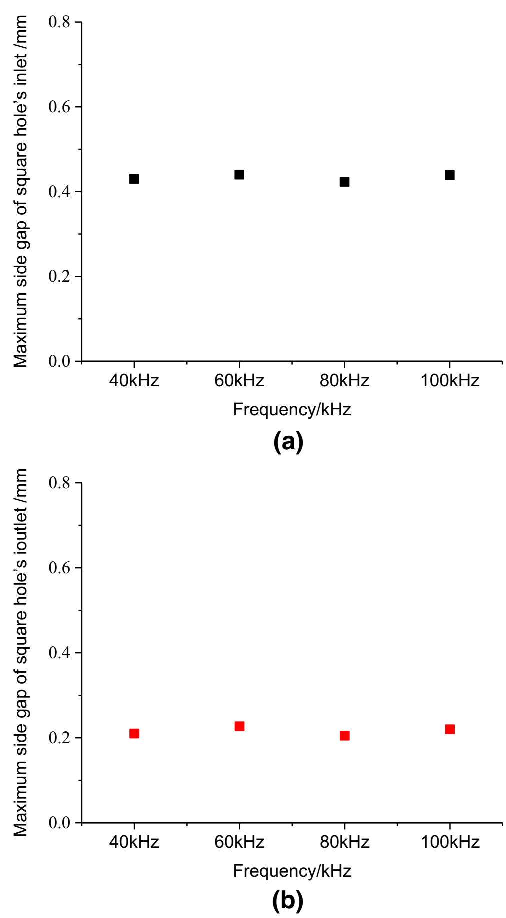

Fig. 6 Experiments for different pulse frequencies with the same average voltage in square hole machining. **a** Maximum side gap of the square hole's inlet. **b** Maximum side gap of the square hole's outlet

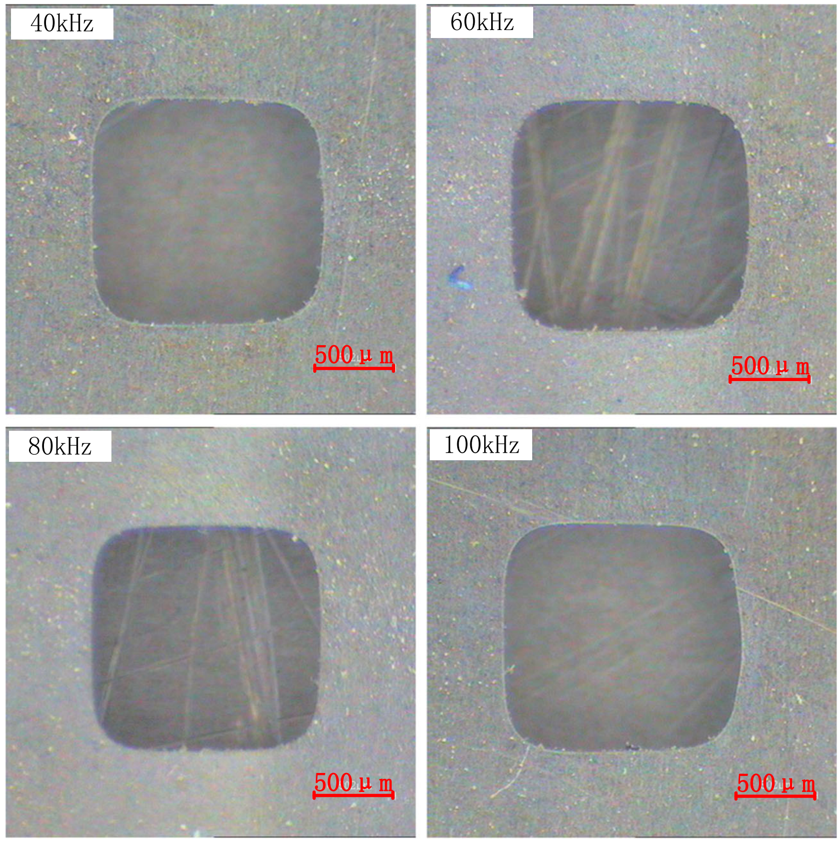

Fig. 7 Experimental results of the holes' outlet obtained for different pulse frequencies and the same average voltage in square hole machining

3.3 Discussion

Figures 4 and 5 show the results of round hole machining experiments in different types of electrolyte. Figures 6 and 7 show the results of square hole machining experiments in $NaNO_3$. It can be seen that there are very small changes in both side gaps of inlet and outlet as the frequency changes for the same average voltage. Moreover, same pattern is found in the experiments of round or square hole machining in different electrolytes. Due to effect of capacitance inductance in the circuit, the pulse voltage waveform is distorted transmitted from the power supply to the gap between the electrode and the workpiece, resulting in the decrease of the average voltage. The higher the frequency is, the more serious the waveform distortion is. The average voltage decreases as the frequency increases, leading to improving the machining accuracy. Therefore, when the average voltage is maintained at a constant value by adjusting automatically the duty cycle, an increase in the pulse frequency does not significantly improve the accuracy of ECM.

4 Comparative experiments using DC and pulsed power supply

To confirm that the improvement in the accuracy of ECM when the DC power supply was replaced with a pulsed power supply was attributed to the decrease in the average voltage rather than the charging and discharging caused by the pulse, comparative experiments were conducted with DC and pulsed power ECM, as shown in

Table 5 Comparative experiments of different average voltage

Number	Average voltage		Uniform feed rate
	DC power	Pulsed power	
A	12 V	12 V (20 kHz)	0.31 mm/min
B	10 V	10 V (20 kHz)	0.25 mm/min
C	8 V	8 V (20 kHz)	0.22 mm/min
D	6 V	6 V (20 kHz)	0.17 mm/min

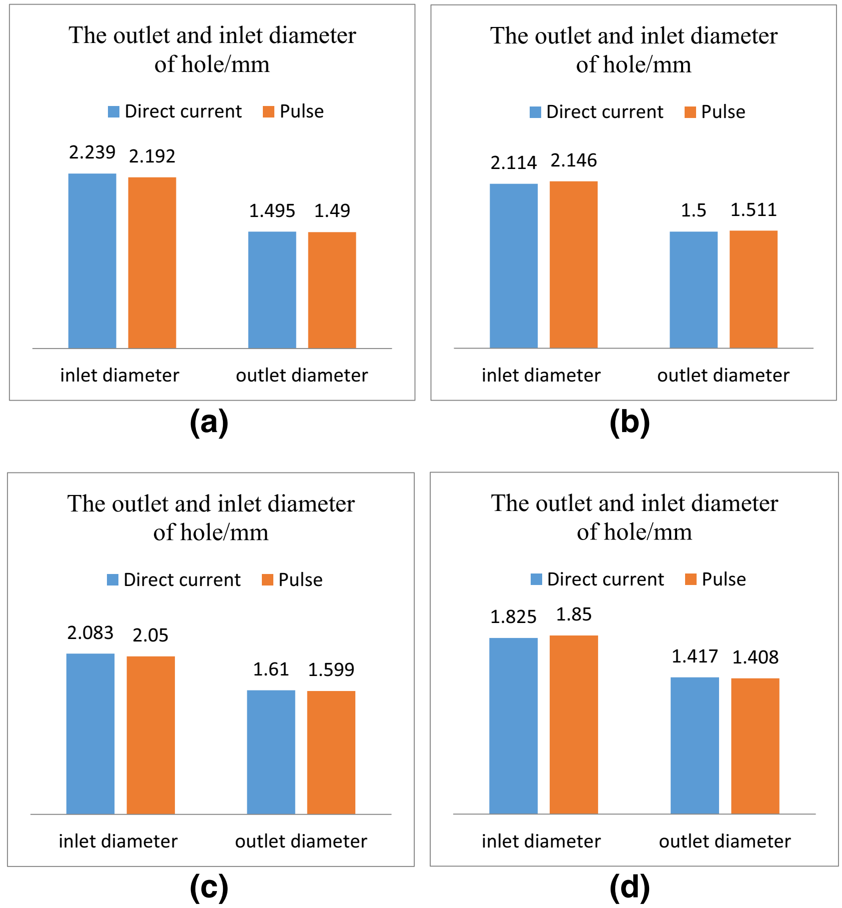

Fig. 8 Results of the comparative experiments using direct-current and pulsed power supply under different average voltage. **a** 12 V. **b** 10 V. **c** 8 V. **d** 6 V

Table 5. The experiments used NaCl as the electrolyte. In these experiments, the duty cycle of the power supply was adjusted, and the average pulse voltage of the power supply was maintained at the same value as the DC supply voltage. The results are shown in Fig. 8. The side gaps for pulsed ECM (PECM) and ECM with the DC power supply both increase as the average voltage increases. However, for the same average voltage, the side gaps for pulsed ECM are as the same as those for ECM by the DC power supply.

Table 6 Comparative experiments of different frequencies

Number	Average voltage		Uniform feed rate
	DC power	Pulsed power	
A	10 V	10 V (20 kHz)	0.25 mm/min
B	10 V	10 V (40 kHz)	0.25 mm/min
C	10 V	10 V (60 kHz)	0.25 mm/min
D	10 V	10 V (80 kHz)	0.25 mm/min

At the same time, comparative experiments were conducted with DC and pulsed power ECM under different frequencies, as shown in Table 6. The experiments used NaCl as the electrolyte. In these experiments, the average pulse voltage of the pulsed power supply was also maintained at the same value with the DC supply under different frequencies. The results are shown in Fig. 9. At the same average voltage, the side gaps for pulsed ECM are as the same as those for ECM with the DC power supply under different frequencies.

Therefore, the accuracy of ECM with pulsed power is not higher than that of the DC power supply, and the machining accuracy has no direct relationship with the pulsed power.

In order to verify this phenomenon in the field of ultrashort pulse, the pulse duration was reduced to 200 ns. The machining experiments uses copper tube electrode with a diameter of 1.0 mm. The diameters of pores by ultrashort pulse power and by DC power supply are 1.260 and 1.203 mm, respectively. It can be seen that even the ultrashort pulse power does not improve the accuracy of ECM in the same average voltage compared to the DC power.

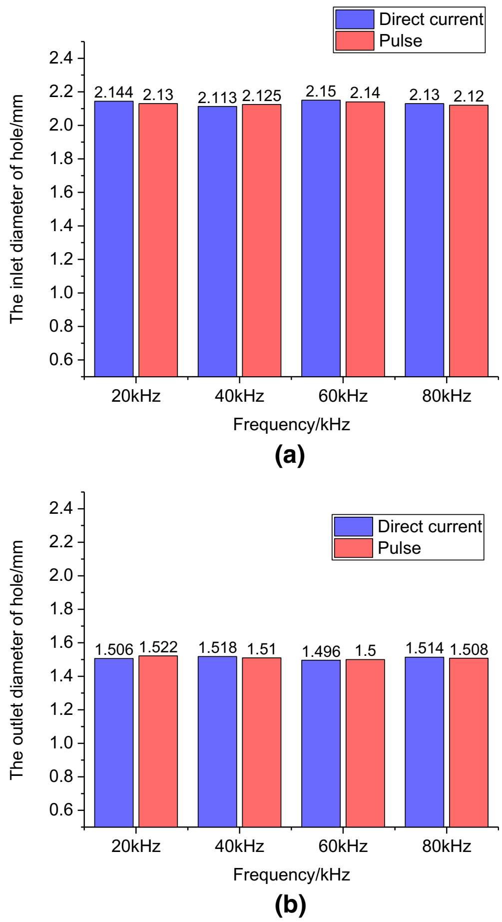

Fig. 9 Results of the comparative experiments using direct-current and pulsed power supply under different frequencies. **a** The inlet diameter of the hole. **b** The outlet diameter of the hole

5 Conclusions

From the results of the experiments presented previously, we can draw conclusions about the effects of the pulsed power on the accuracy of ECM:

1. High-frequency pulsed power can improve the accuracy of ECM owing to the distortion in the high-frequency pulse transmitted from the power supply to the gap between the electrode and the workpiece in the processing area. The pulsed power is affected by the inductance and capacitance distributed on the power supply line and the working machines, resulting in a high-frequency waveform distortion. Thus, the equivalent average DC voltage between the electrode and the workpiece decreases, leading to an enhancement in the machining accuracy. This method for improving the accuracy is not very different from reducing the DC supply voltage to improve the machining accuracy.
2. Whether using DC power or using pulsed power, the accuracy of ECM is the same when the average voltage is set the same.

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