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ORIGINAL ARTICLE

Study on the micro through holes machining using the electrochemical machining (ECM) method with a graphite electrode

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Abstract
Electrochemical machining is widely used in biomedical, aerospace, automotive, and other fields. The development of electrochemical machining (ECM) is restricted by many factors such as the difficulty of preparing micro-electrode, large machined gap and serious stray corrosion. In this paper, we present a method to fabricate micro-holes by combining micro-graphite electrode with hollow structure. Firstly, a sealed graphite electrode was proposed to guarantee that the sediment can be fully removed by the flowing electrolyte. Then, the effect of machined parameters such as the pulse frequency, machined voltage, electrode feeding speed, and electrolyte concentration on machining quality was studied. By optimizing the machined parameters, the minimum value of micro-hole taper with 0.07 could be obtained. To improve the shape precision of workpiece, this paper designed the hollow structure inside the electrode. With the increasing of the pulse frequency, the machining accuracy of micro-holes increased. The results suggested that the pulse frequency of 100 kHz, the machined voltage of 18 V, the feeding speed of 1 μm/s, and electrolyte concentration of 5% were more suitable for micro-holes machining with ECM.

Keywords The micro-hole · Electrochemical machining · Micro-machining · Graphite electrode

1 Introduction

Electrochemical machining is a kind of processing method in which the workpiece and electrode do not need to contact, and the material is removed through the electrochemical reaction between the poles to achieve the processing purpose [1]. For a wide range of materials, electrochemical machining (ECM) does not need to consider the hardness and strength, and its advantages include the processed surface without burr, recast layer, and mechanical stress and tool electrode with no loss [2]. Now, ECM is widely used in electronic, aerospace, automotive, biomedical, microfluidic system fields [3]. Especially, the demand of micro-hole structures is becoming more and more urgent in those fields. For example, a lot of micro through holes are needed in turbine blades of aero-engines to solve the heat dissipation problem [4–6]. Electro discharge machining (EDM) is a general method to fabricate micro-holes. Unfortunately, the low material removal rate of EDM limited its application [7, 8]. In recent years, micro electrochemical machining (MECM) was started to be applied into the micro-holes machining process [9].

For the micro-holes machining, there are still some problems to be solved in micro-hole fabrication process with MECM. For example, the electrolyte updating will become difficult due to the small machining gap, which probably leads to removal difficulty for chemical products and even causes short circuit [3]. Moreover, the metal electrode will be more and more difficult to be manufactured with its size decreasing [9]. Considering graphite material is easy to machine and has very stable chemical properties [10], the graphite material was firstly used as tool electrode for the MECM in this study.

On the other hand, the narrow gap between the tool electrode and workpiece could cause the short circuit phenomenon easily. To solve this problem, many efforts were done to increase the fluidity of the electrolyte. Yue Xiaoming et al. proposed a kind of spiral electrode with external spray electrolyte [11]. Wang Minghuan et al. designed an inverted

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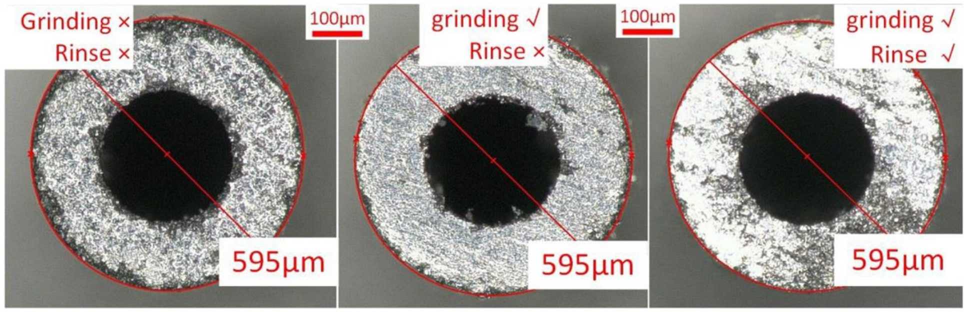

Fig. 1 Comparison chart of graphite

T-shaped structure electrode and applied the ultrasonic effect on ECM [12]. Jin Wang et al. coated the electrode side wall with a double insulating layer composed of ceramic and thin film to increase the forming accuracy of micro-holes using MECM [13]. For this aspect, the manuscript will design a graphite micro electrode with hollow structure to improve the machining accuracy of micro-holes and reduce the corrosion of round holes by optimizing the process parameters.

2 Method

If metal conductive materials are used as tool electrodes in electrochemical experiments, thick oxide film and a large number of bubbles will accumulate on the surface of the workpiece. These oxide film and bubbles will lead to defects on the workpiece surface and even affect the machining accuracy and quality of the workpiece [14–16]. Considering graphite material has good processing characteristics and thermal properties, it could be beneficial to use graphite material as tool electrodes to improve the stability of the processing process [17]. Therefore, in this study, graphite material instead of metal material was used as tool electrode.

2.1 Cleaning

Firstly, a shaped graphite electrode is prepared, and then the tip of the graphite electrode cylinder is slightly grounded on A4 paper. Then put it into the ultrasonic cleaning machine for 5 min to clean. Grinding is to reduce roughness on the graphite electrode cylinder, while cleaning is to remove residue attached to the graphite (Fig. 1).

2.2 Measurement

The size of the electrode is designed to 600 μm. Due to the inconsistency of the size of the processed graphite electrode, it is necessary to measure the diameter of the electrode with a depth of field microscope every time before using the electrode (Fig. 2). We fixed the electrodes and placed them under a super depth of field microscope. The diameter of electrode can be obtained by measuring the size of the circle at the top of the electrode. Electron microscope (Quanta 450 FEG, FEI, America) was used to characterize the size of micro-holes.

2.3 Sealing

In electrochemical experiments, the machining gap between electrode and workpiece is relatively small. To prevent the electrolyte from flowing back through the pinhole of the electrode, it is necessary to seal the pinhole on the electrode. The sealing treatment mainly includes sticking a layer of transparent silica gel strip at the pinhole end of graphite electrode (Fig. 3).

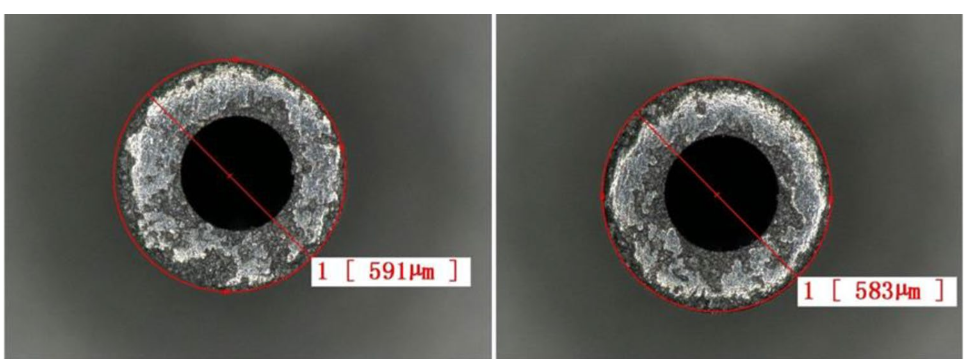

Fig. 2 The size of each electrode before processing is inconsistent

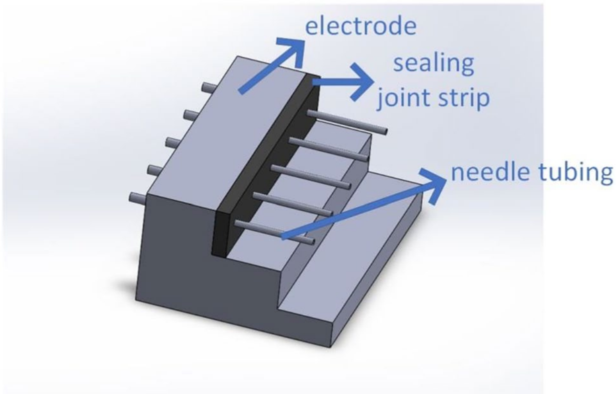

Fig. 3 Sealed graphite electrode

3 Experimental equipment and procedures

In this experiment, graphite electrode and hollow structure are combined to process the micro-hole. Graphite electrodes can be easily fabricated. The hollow structure is beneficial to the rapid renewal of electrolyte. The experimental scheme of electrochemical machining is shown in Fig. 4.

As shown in Fig. 5, this electrochemical experiment was mainly completed on the PI platform made in Germany. The PI platform model is M511.DD. The platform can also move in any of the three axes of *XYZ*, and the motion of the three axes can reach ± 0.2 μm. In addition, other experimental equipment includes oscilloscope (TDS1012, Tektronix, USA), micro pump and ultra-depth of field microscope (VHX-2000C, Keyence, Japan). Before the experiment, the graphite electrodes need to be mounted on the *X*-axis of the PI platform and then clamped together by a splint clamp. When the electrode and workpiece are installed, the distance between electrode and workpiece is adjusted by moving the PI platform. The parameters for controlling platform movement are set as voltage 2 V and speed 1 μm/s firstly. When the electrode comes into contact with the workpiece, the pulse signal changes and then the electrode stops moving. Then, the electrode returned about 20 μm to maintain a certain initial machining gap between the electrode and the workpiece. The experimental conditions of electrochemical machining are shown in Table 1.

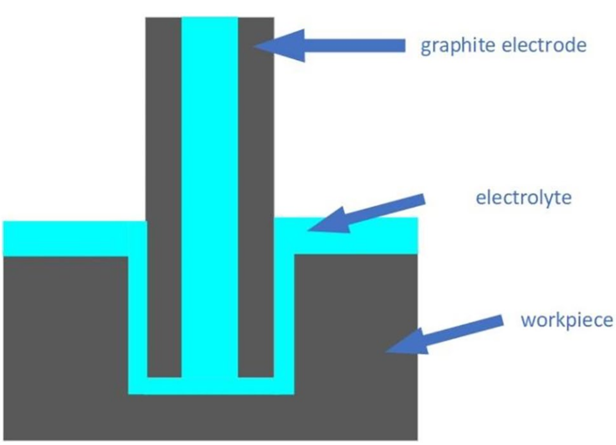

Fig. 4 Schematic diagram of the graphite electrode machining

In this experiment, the workpiece is composed of a 300-μm-thick piece and a 30-μm 304 stainless steel. In order to ensure the integrity of the micro-hole, a 30-μm-thick 304 stainless steel sheet needs to be superimposed on the back of the 300-μm workpiece (Fig. 6). The electrode stops moving when an electrochemical reaction is observed between the 30-μm-thick sheet of steel and the electrode.

4 Optimize the technological parameters of the experiment

In this study, the effects of pulse frequency, machined voltage, electrode feeding speed, and electrolyte concentration on micro-holes manufacturing were analyzed separately. When each experiment was finished, the inlet and exit diameters of micro-holes were measured by the Ultra-deep 3d microsystem. Taper as an important index to measure the machined accuracy of micro-hole is also not negligible. The machined depth of micro-holes is determined by the feeding depth of PI platform. The phenomenon of stray etching could be analyzed from the two-dimensional image of micro-hole.

4.1 Influence of pulse frequency

For analyzing the pulse frequency effect on the micro-hole machining in MECM, those experiments were conducted at different pulse frequency (25, 33.3, 50, 100 kHz); when the machined voltage was 18 V, the feeding speed was 1 μm/s and the electrolyte concentration was 5% NaNO3.

The effect of pulse frequency on the inlet, outlet size, and taper of micro holes is shown in Fig. 7. As the pulse frequency increased, the size of the micro hole decreased. The results showed that it is common that the outlet size of the micro-hole was smaller than its inlet size, which directly caused that the micro-hole taper generated. Generally, the value of micro-hole taper decreased as the pulse frequency increased. The reason probably is that increasing pulse frequency will decrease the energy of single discharge, which could reduce the amount of material removal and the micro-hole size could be closer to the electrode size. However, the machining of micro-hole failed when the pulse frequency increased to 167 kHz. The smallest value of micro-hole

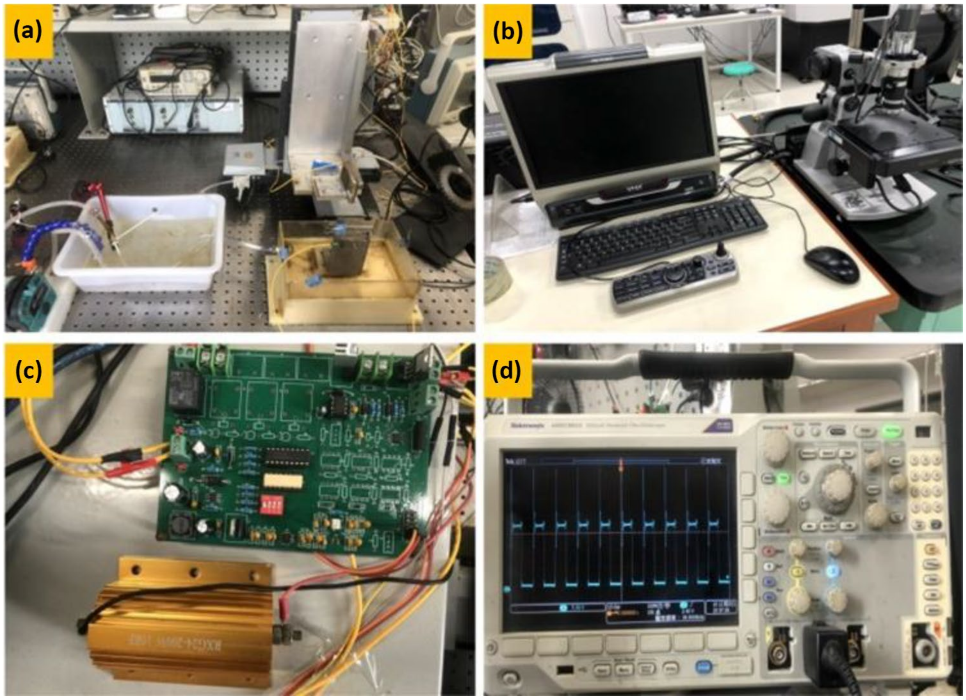

Fig. 5 Experimental equipment: **a** micro-machining system, **b** super-depth three-dimensional microscopy system, **c** discharge board, **d** oscilloscope

could achieve about 0.07 at the pulse frequency of 100 kHz. The average gap and processing time of micro-holes in the MECM are shown in Table 2. The processing time of micro-holes increased with the increasing of pulse frequency. The reason might be that higher pulse frequency decreased the single pulse energy. However, when the pulse frequency was higher than 167 kHz, the machining process failed due to the short circuit occurring frequently. The VHX images of inlet and outlet of micro-holes at different pulse frequency are shown in Fig. 8. It can be seen that the stray corrosion phenomenon at the inlet of micro-holes was improved obviously as the pulse frequency increased at the range from 25 to 100 kHz.

4.2 Influence of machined voltage

For analyzing the machined voltage effect on the micro-hole machining in MECM, experiments were conducted at different machined voltage (16, 18, 20, 22, 24 V) with pulse frequency of 100 kHz, feeding speed of 1 μm/s and electrolyte concentration of 5%, as shown in Fig. 9.

Table 1 Experimental conditions of electrochemical machining

Experimental parameters	Parameter value
The electrode diameter	600 μm
The workpiece material	304 stainless steel
Pulse frequency	25, 33.3, 50, 100 kHz
Machined voltage	16, 18, 20, 22, 24 V
Feeding speed	0.5, 0.8, 1, 1.2, 1.5 μm/s
Electrolyte concentration	2, 5, 8, 11%

The results showed that the machining of micro-hole was failed at the voltage of 16 V, which probably indicated that the discharge energy was not enough to remove whole materials in this low-voltage case. However, as the machined voltage increased from 18 V, the inlet size of micro-hole increased gradually. For the outlet size of micro-hole, it decreased when the machined voltage increased from 18 to 20 V but started to increase as the machined voltage increased from 20 to 24 V. The micro-hole taper increased when the machined voltage from 18 to 22 V. Oppositely,

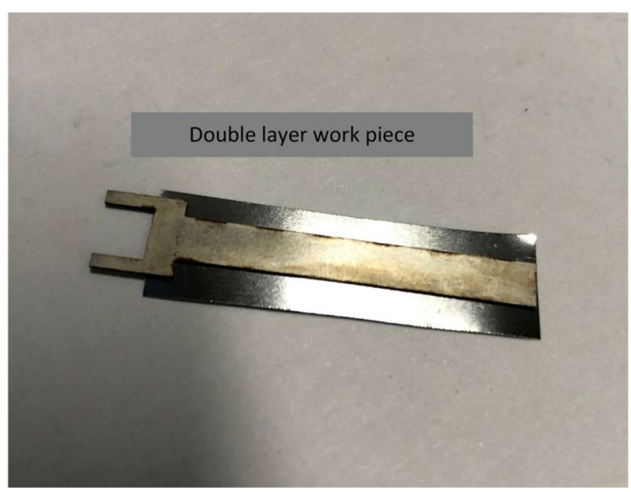

Fig. 6 Workpiece with a steel sheet

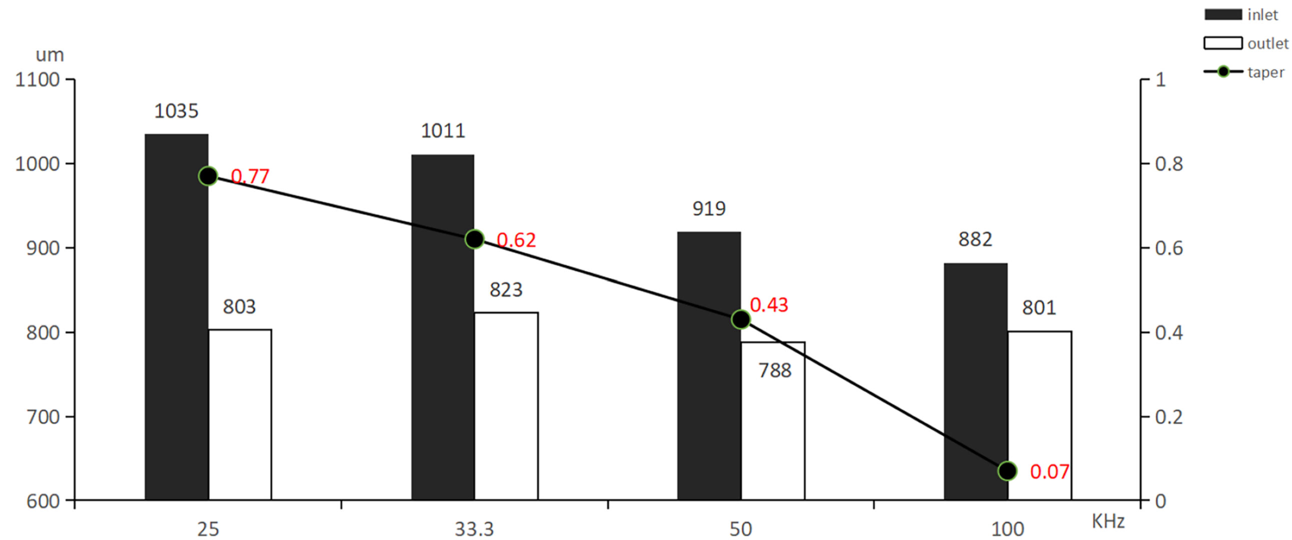

Fig. 7 Influence of pulse frequency on inlet and outlet dimensions and taper

Table 2 Processing time of micro-hole at different pulse frequencies

Pulse frequency (KHz)	25	33.3	50	100	166.67
The average gap[a] (μm)	162.5	160.5	129.75	137.75	-
The processing time (s)	373	381	422	518	-

[a]The calculation formula of average age ((inlet gap + outlet gap)/2)

the taper of the micro-hole decreased when the machined voltage from 22 to 24 V.

The average gap and machined time of micro-holes in the MECM are shown in Table 3. The machined gap decreased when the machined voltage increased from 18 to 20 V but then increased as the machined voltage increased at the range of 20 to 24 V. On the other hand, the processing time decreased firstly and then increased when the machined voltage increased. The reason might be that a higher machined voltage could provide more energy for the machining process which could be helpful to decrease the average gap and the processing time. However, as the machined voltage was too high, the amount of debris increased which might be challenge for the debris removing ability of this system and probably could increase the average gap and the processing time. The microscope images of inlet and outlet of micro-holes under different machined voltages are shown in Fig. 10. With the increasing of the machined voltage, the level of stray corrosion at micro-hole inlet became more and more serious. It could be observed that the inlet size is closet to outlet size at the machined voltage of 18 V which is more suitable to increase the size accuracy of the micro-holes.

4.3 Influence of electrode feeding speed on micro-hole

To analyze the feeding speed effect on the micro-hole machining by MECM, those experiments were conducted at different feeding speed (0.5, 0.8, 1, 1.2, 1.5 μm/s) with the pulse frequency of 100 kHz, the machined voltage of 18 V, and the electrolyte concentration of 5%.

Figure 11 shows the effect of different feeding speed on the inlet and outlet size and taper of micro-hole. The results showed that the taper of micro-hole decreased as

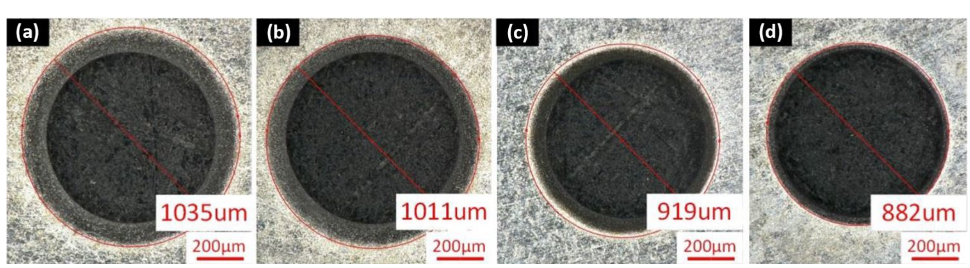

Fig. 8 Micro-hole images at different pulse frequencies: **a** 25 kHz, **b** 33.3 kHz, **c** 50 kHz, **d** 100 kHz

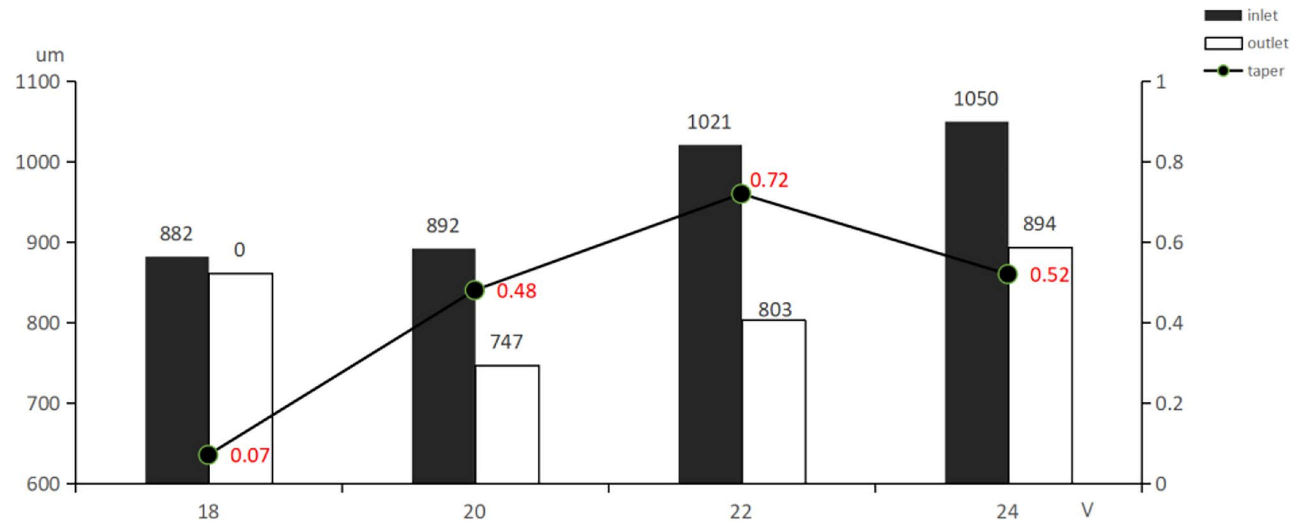

Fig. 9 Effect of machined voltage on inlet and outlet sizes and tapers

Table 3 Processing time of micro-hole under different machined voltages

Processing voltage (V)	16	18	20	22	24
The average gap[a] (μm)	-	137.75	111.25	156	191
The processing time (s)	-	518	392	471	395

[a]The calculation formula of average age ((inlet gap + outlet gap)/2)

the feeding speed increased. This could be explained by that a low feeding speed cannot compensate the space of the removal materials, which can lead to more serious stray corrosion and low machining efficiency. However, as the feeding speed increased over 1 μm/s, the short circuit occurred frequently and the machining process even failed at last. Moreover, the processing time could decreased by increasing feeding speed but over high feeding speed could also increase the risk of short circuits (Table 4).

The microscope images of inlet and outlet of micro-holes under different feeding speeds are shown in Fig. 12. The corrosion degree of micro-hole inlet was small when feeding speed varying, indicated that the feeding speed probably has limited influence on stray corrosion in the micro-hole machining process.

4.4 Influence of electrolyte concentration on micro-hole machining

In order to analyze the effect of electrolyte concentration on the accuracy of micro-holes, different electrolyte concentrations (2, 5, 8, 11%) were used in this experiment; as the pulse frequency was 100 kHz, the machined voltage was 18 V and the feeding speed was 1 μm/s.

Figure 13 showes the effect of different electrolyte concentration on the inlet and outlet size and taper of micro-hole. The results showed that the taper of micro-hole decreased as the electrolyte concentration increased from 2 to 5%. The reason might be that a higher electrolyte concentration could increase the electrochemical reaction rate and the machining efficiency could be enhanced. However, as the electrolyte concentration was over high, the degree of stray corrosion increased dramatically and the taper of micro-hole increased largely (Fig. 1 and Table 5).

The microscope images of inlet and outlet of micro-holes under different electrolyte concentration are shown in Fig. 14. When the electrolyte concentration was 11%, the micro-hole stray corrosion was the most serious. The

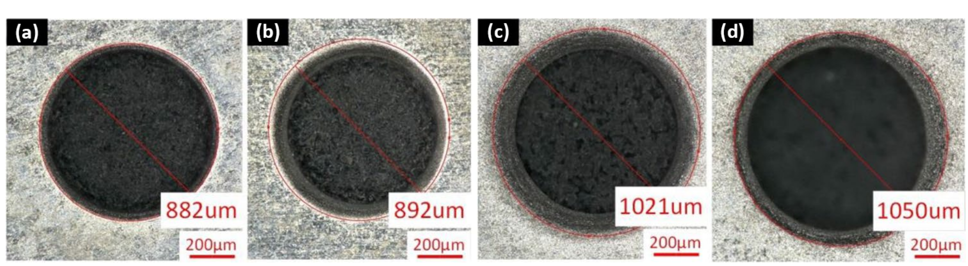

Fig. 10 Micro-hole images under different processing voltages: **a** 18 V, **b** 20 V, **c** 22 V, **d** 24 V

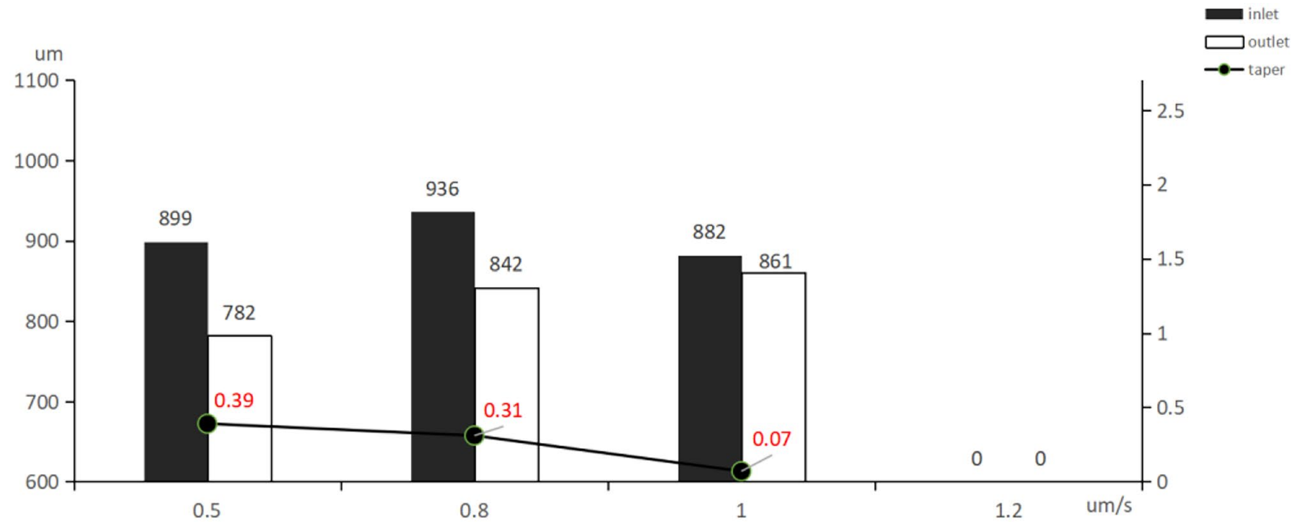

Fig. 11 Influence of feeding speed on inlet and outlet dimensions and taper

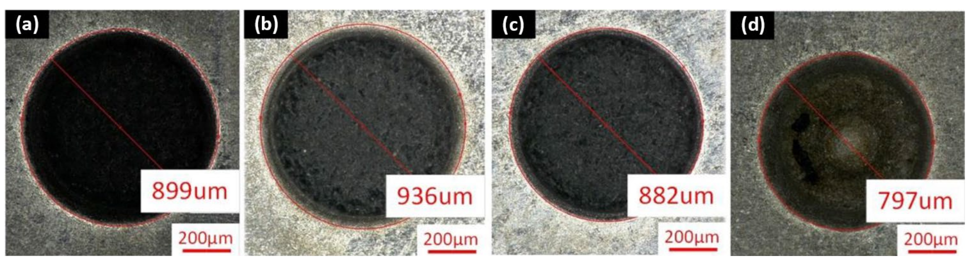

Fig. 12 Microporous images at different feeding speeds: **a** 0.5 µm/s, **b** 0.8 µm/s, **c** 1 µm/s, **d** 1.2 µm/s

Table 4 Processing time of micro-hole at different feeding speeds

Feed speed (µm/s)	0.5	0.8	1	1.2	1.5
The average gap[a] (µm)	124.5	148	137.75	-	-
The processing time (s)	972	592	518	-	-

[a]The calculation formula of average age ((inlet gap + outlet gap)/2)

inlet size was larger than its outlet size obviously due to the excessive corrosion. The phenomenon was partly caused by too fast electrochemical reaction, partly caused by that high electrolyte concentration generated much more removed material particles which could block the machining gap and then decreased the machining efficiency.

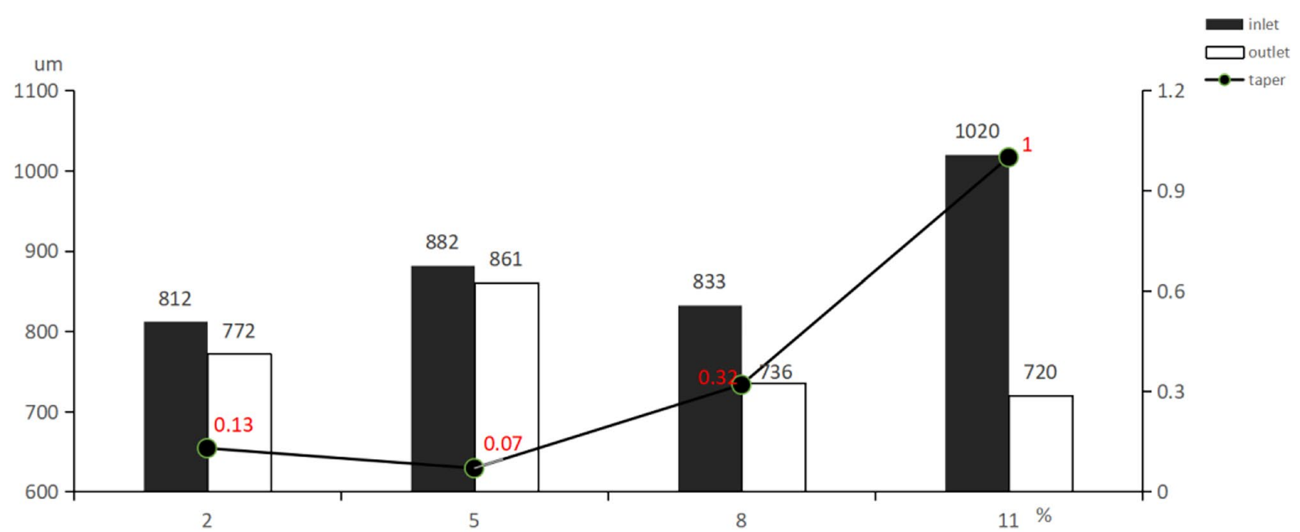

Fig. 13 Influence of electrolyte concentration on inlet and outlet dimensions and taper

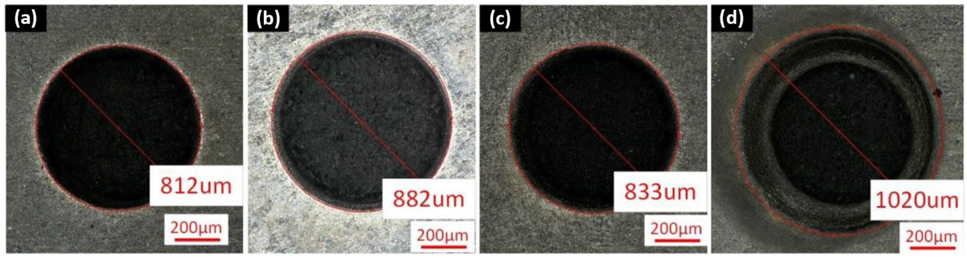

Fig. 14 Microporous images of different electrolyte concentrations: **a** 2%, **b** 5%, **c** 8%, **d** 11%

Table 5 Processing time of micro-hole under different electrolyte concentration

Electrolyte concentration (%)	2	5	8	11
The average gap[a] (μm)	99	137.75	96.75	139
The processing time (s)	475	518	527	454

[a]The calculation formula of average age ((inlet gap + outlet gap)/2)

5 Conclusion

In this paper, the electrochemical machining of micro-holes was carried out by using the micro-graphite electrode with the hollow structure. Firstly, the shape accuracy of the micro-holes was improved by using the laminated workpiece, and then the size accuracy and taper and stray corrosion of the micro-holes were improved by changing the machine parameters. The result are as follows:

1. Changing the voltage and pulse frequency has a greater effect on the stray corrosion at the inlet of micro-holes than changing the feeding speed and electrolyte concentration.
2. To obtain high machining accuracy, the electrolyte concentration of 5%, the pulse frequency of 100 kHz, the machined voltage of 18 V, and the feeding speed of 1 μm/s were proposed.
3. The taper of the micro hole could be decreased to 0.07, which testified that the micro-graphite electrode with a hollow structure was suitable for the micro-machining process with the method of MECM.

Author contribution Likuan Zhu made the overall plan and provided the fund support. Jinhui Hao conducted the experiments and wrote the original draft. Bin Xu analyzed the result data. Bei Wang revised the manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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