Int. J. Electrochem. Sci., 15 **(2020)** 1691 – 1703, doi: 10.20964/2020.02.52

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

In-Situ Fabrication of Tube Electrodes with Array Slits using Multi-Wire Electrochemical Machining

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Received: 9 October 2019 / *Accepted:* 1 December 2019 / *Published:* 31 December 2019

Wire electrochemical machining using an inner-jet electrolyte is an efficient cutting method of thick workpieces. A tube electrode with array slits is used, the electrolyte is sprayed directly from the array slits onto the machining gap and the electrolysis products are flushed out rapidly. An efficient and high-precision in-situ fabrication method is proposed for fabrication of the array slits structure of tube electrodes. Using electrochemical machining, the array slit structure is machined on a metal tube wall using multiple metal wires as the tool cathode. The effects of voltage, duty cycle, pulse frequency and electrolyte concentration on array slit width and depth are investigated experimentally, and optimal machining parameters obtained. A tube electrode with an average slit width of 218.6 μm and depth of 270.7 μm is successfully fabricated on stainless steel tube with an external diameter of 0.7 mm and the wall thickness of 0.15 mm. The cutting experiment is completed on 20 mm thick stainless steel 304 using this fabricated tube electrode at a 5 μm/s feed rate. Three slits with an average width of 1.215 mm are successfully machined.

Keywords: tube electrode with array slits; situ fabrication; multi-wire ECM; WECM using a tube electrode

1. INTRODUCTION

High-precision ruled surface structural parts without micro cracks and recast layers are widely used in the aerospace, automobile, precision mould and other manufacturing fields, such as for turbine disc fir tree slots, blade tenons and precision transmission gears in aircraft engines [1]. Wire electrochemical machining (WECM) is a process of dissolving and removing local materials, using a metal wire as the tool cathode to cut the workpiece [2]. It has high machining accuracy and does not produce residual machining stress, recast layers and heat-affected layers, because the workpiece material is corroded and removed at the form of ions [3]. Owing to its technical characteristics, WECM technology is the preferred machining method for high-precision ruled surface structures.

WECM with an inner-jet electrolyte uses a metal tube with array slits on the sidewall as a tool cathode. During the cutting process, the electrolyte passes through the inside of the tube electrode and is sprayed rapidly from the array slits onto the side wall. It reaches the machining gap directly and participates in the electrolytic reaction. At the same time, the electrolytic products in the machining gap are washed out, which accelerates refreshment of the electrolyte and produces high-efficiency electrochemical cutting of thick workpieces [4]. Fabrication of the tube electrode with array slits is a key step in this machining technology. The diameter of the tube electrode is small (0.3 mm to 1.0 mm usually), which ensures a narrow slit and a high cutting accuracy, and the tube electrode is long (10 mm to 40 mm usually), which ensures the cutting thickness. These make fabrication of the tube electrode with array slits difficult.

Possible machining methods for the array slit structure of the tube electrode include micro-milling, wire saw cutting, wire electrical-discharge machining (WEDM), laser cutting and WECM. Micro-milling and wire saw cutting are methods for removing material from the metal tube wall using a tool with a cutting edge under mechanical force. However, there will be stress in the machining process[5,6], which can easily cause deformation of the long and thin metal tube. WEDM and laser cutting are machining methods that use a high temperature to melt and remove materials locally, with high machining efficiency. However, the melted material will enter the inner cavity of the metal tube and recast, which will affect the accuracy of the slits or block the slits[7,8]. In addition, for WEDM, the wire electrode will wear out [9]. WECM is a method for corroding and removing materials by electrochemical dissolution. It does not have the shortcomings of the other abovementioned machining technologies, and is suitable for precision micro machining. For example, a micro square columnar tool array with a small edge radius and good homogeneity of tool width has been fabricated using wire electrochemical micromachining [10], and a ribbed wire electrode has been fabricated using WECM on stainless steel rods with a diameter of 0.5 mm [11].

This paper proposes an efficient and high-precision in-situ fabrication method, where tube electrodes with array slits are fabricated on metal tubes using multi-wire ECM technology. The effects of voltage, duty cycle, pulse frequency and electrolyte concentration on array slit width and depth are experimentally investigated, and optimal machining parameters obtained. A tube electrode with an array slit of average slit width 218.6 μm and depth 270.7 μm are successfully fabricated on stainless steel tubes with an external diameter of 0.7 mm and the wall thickness of 0.15 mm. In addition, a cutting test is completed on 20 mm thick stainless steel 304 using this fabricated tube electrode at a 5 μm/s feed rate. Three slits with an average width of 1.215 mm are successfully machined.

2. EXPERIMENTAL

Figure 1 shows the process schematic diagram of in-situ fabrication and application of array tube electrodes with array slits. (1). The metal tube is immersed vertically in the electrolyte and connected to positive poles of the power supply. The multiple wire electrodes are placed horizontally and spaced equally in the vertical direction. The wire electrode are connected to the negative pole of the power supply and conducts a feeding movement to the metal tube in the horizontal plane. Meanwhile, the wire electrode conducts a transverse reciprocating movement to drag the electrolyte in the machining gap, promoting refreshment of electrolyte and accelerating the removal of electrolytic products [12]. (2). With electrolytic reaction occurring, the local material of the metal tube is gradually dissolved and removed, and the array slits are obtained. (3). The fabricated tube electrode with array slits is used as the tool cathode and connected to the negative pole of the power supply. The electrolyte is sprayed onto the workpiece machining surface through the inner cavity and array slits of the tube electrode. The workpiece is connected to the positive pole of the power supply and is cut as it is fed.

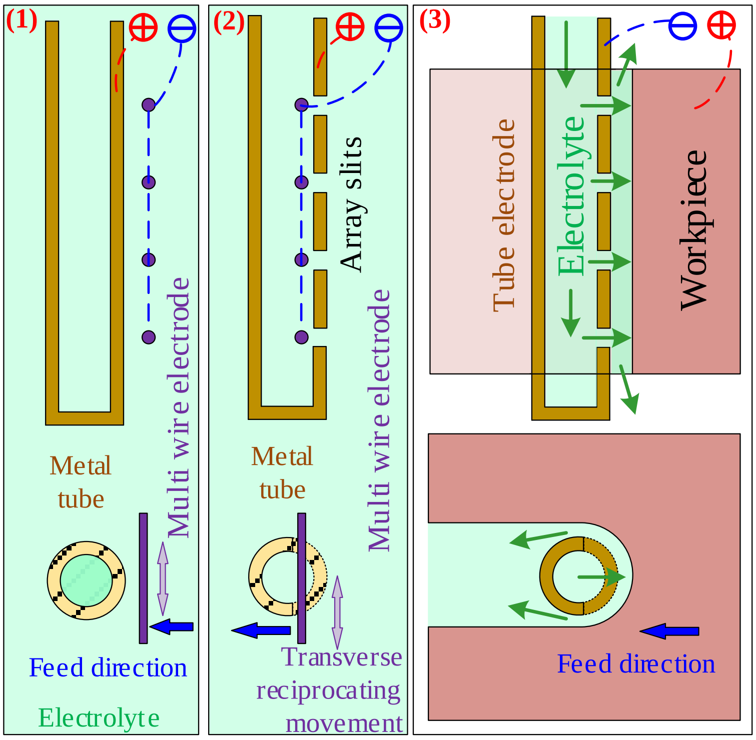


Figure 1. Process schematic diagram of in-situ fabrication and application of tube electrodes with array slits

Figure 2 shows a schematic diagram of the experimental system, which includes a three-axis machine tool, pulse power supply, a metal tube, a wire electrode, a special fixture and an electrolyte tank. The metal tube is installed on the pillar of the machine tool through the fixture, and the tensioned wire electrode is installed on the motion axis of the machine tool through the fixture. The relative movement between the wire electrode and the metal tube is controlled through movement of the X/Y axes. The pulse frequency of the high-frequency short-pulse power supply is 1–100 kHz, which ensures accuracy and efficiency of the electrochemical machining [13].

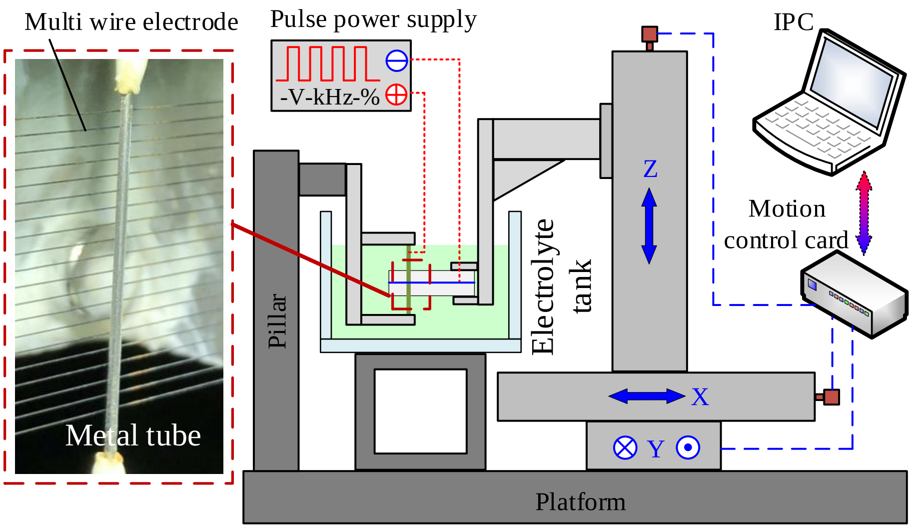


Figure 2. Schematic diagram of the experimental system

Stainless steel 304 tubes with an outer diameter of 0.7 mm and the wall thickness of 0.15 mm were used as the machining objects. 20 molybdenum wires with a spacing of 1 mm and a diameter of 0.1 mm were used as the wire electrodes. A neutral salt solution ($NaNO_3$) was used as the electrolyte. Table 1 lists the experimental parameters.

Table 1. Experimental parameters

Parameter	Value
Amplitude of transverse reciprocating movement (mm)	1
Frequency of transverse reciprocating movement (Hz)	1
Feed rate (μm/s)	0.5
Cutting depth (μm)	200
Pulse voltage (V)	16–20
Duty cycle (%)	25–45
Pulse frequency (kHz)	20–100
Electrolyte concentration (g/L)	15–35

For WECM with an inner-jet electrolyte, the size of the array slits determines the flow state (flow velocity and flow rate) of the electrolyte and the distribution of the current density between the two electrodes. Therefore, the dimensional accuracy of the tube electrode with array slits was evaluated using the machined array slit width and depth. The slit width and depth can also indicate the machining accuracy of WECM, because the width and depth reflect the corrosion range of the electrolytic reaction. Images of the machined slits were obtained using a SEM (S-3400N, Hitachi), and the slit width and depth were measured by Olympus microscope (SMT7-SFA, Olympus) (see Figure 3). Average values and standard deviations were obtained after taking many measurements.

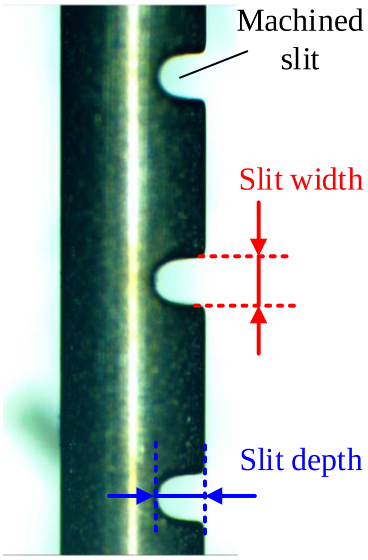


Figure 3. Measurement of the machined slit width and depth

3. RESULTS AND DISCUSSION

To fabricate a tube electrode with a high-precision array slit structure, the effect of key machining parameters such as voltage, duty cycle, pulse frequency and electrolyte concentration on slit width and depth was investigated using single-factor experiments.

3.1 Effect of voltage

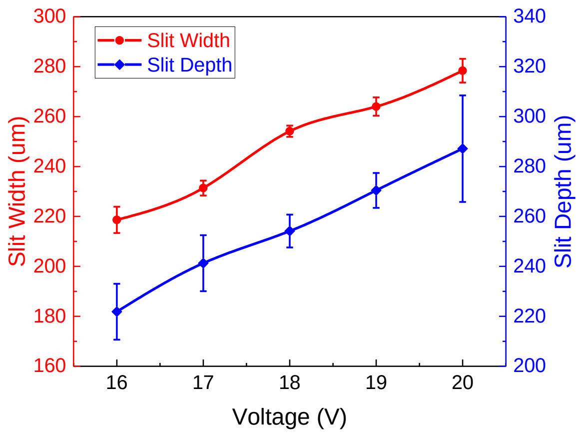
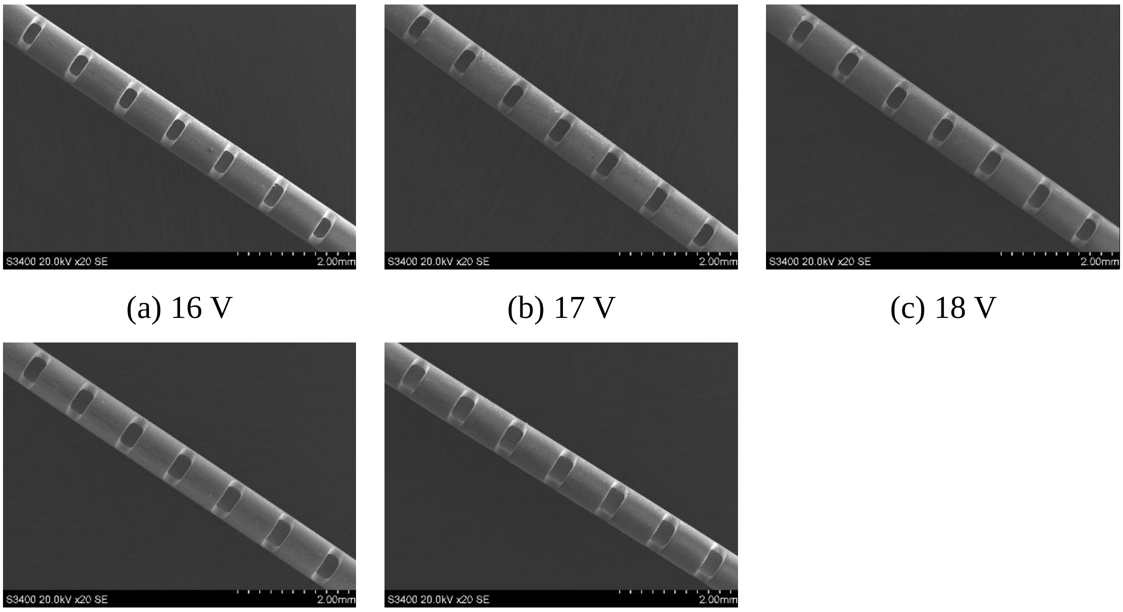


Figure 4. Variation of slit width and depth with voltage (duty cycle: 30%, pulse frequency: 100 kHz, and electrolyte concentration: 20 g/L)

Experimental parameters: duty cycle of 30%, pulse frequency of 100 kHz and electrolyte concentration of 20 g/L. Figure 4 shows the variation of slit width and depth with voltage. The slit width and depth increase with increasing voltage. This is because the increase of voltage increases the current density between the two electrodes and accelerates the MFR. The material removal amount per unit length increases and the slit width increases when the feed rate is constant. Qu et al. indicated that the application of a higher voltage will increase the side gap, resulting in a wider slit [14]. Sharma et al. also verified that the slit width increases with the increase of applied voltage [15]. At the same time, the machining balance gap increases, and the depth of the machined slit increases. Figure 5 shows the machined slits. Therefore, a small voltage value should be selected as far as possible in normal machining to improve the accuracy of the electrochemical cutting.



(a) 16 V (b) 17 V (c) 18 V

(d) 19 V (e) 20 V

Figure 5. Machined slits with different voltages (duty cycle: 30%, pulse frequency: 100 kHz, and electrolyte concentration: 20 g/L)

3.2 Effect of duty cycle

Experimental parameters: voltage of 16 V, pulse frequency of 100 kHz and electrolyte concentration of 20 g/L. Figure 6 describes the relationship between the change of duty cycle change and the change of slit width and depth. The slit width increases with increasing duty cycle. When the duty cycle is 25%, short circuiting occurs, and the machining fails. When the duty cycle is 45%, the slit width is 453.1 μm. The slit depth increases gradually, but the increase rate is slow compared to the increase rate of slit width. Therefore, the opening area of the machined slits increases, as shown in Figure 7. This is not conducive to subsequent application in electrolytic cutting. For WECM with inner-jet electrolyte, the larger the opening area of the slits, the smaller the conductive contact area between the two electrodes, the smaller the corrosion area of workpiece and the lower the cutting efficiency.

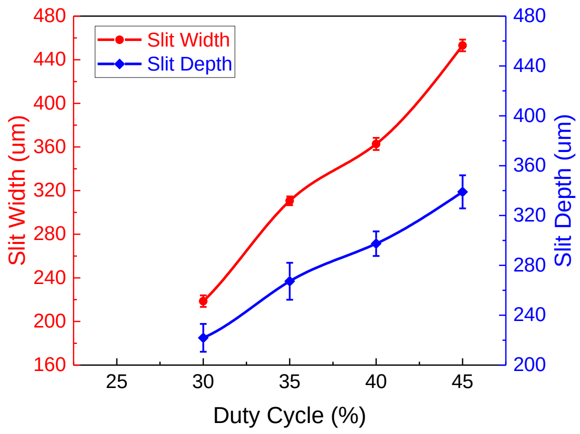
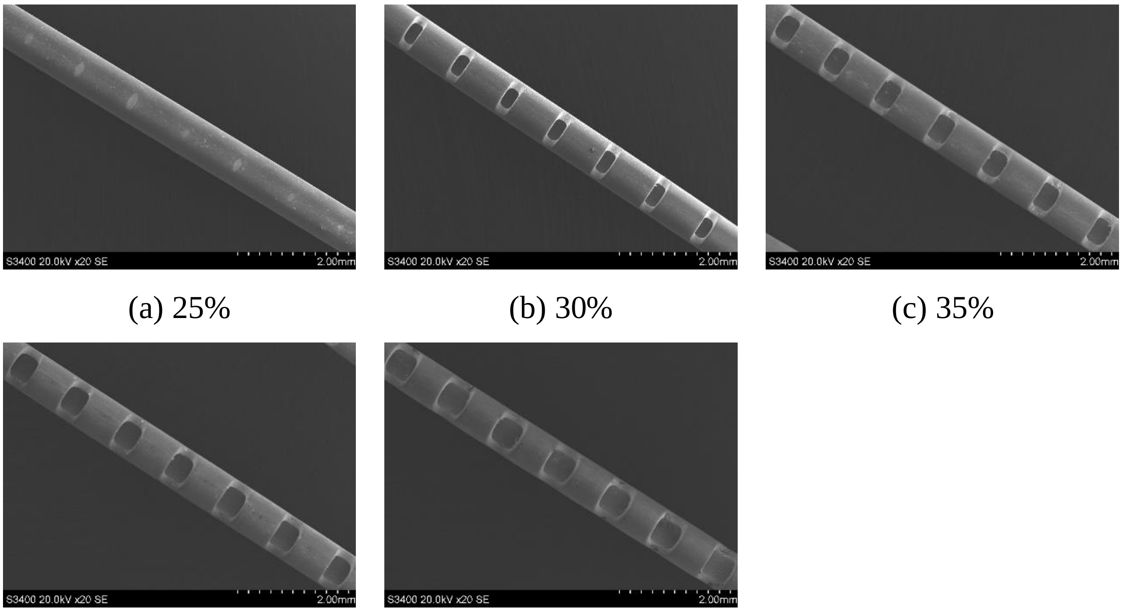


Figure 6. Effect of duty cycle change on slit width and depth (voltage:16 V, pulse frequency: 100 kHz, and electrolyte concentration: 20 g/L)



(a) 25% (b) 30% (c) 35%

(d) 40% (e) 45%

Figure 7. Machined slits with different duty cycles (voltage:16 V, pulse frequency: 100 kHz, and electrolyte concentration: 20 g/L)

In pulse electrochemical machining (PEM), the duty cycle determines the power-on duration in each cycle. When the duty cycle is small, the electrolytic reaction time between the two electrodes is short, and the material removal rate (MFR) is slow. When the feed rate of the wire electrode is greater than the MFR of the workpiece, short circuiting occurs and the machining fails, such as when the duty cycle is 25%. On the contrary, increasing the duty ratio can increase the electrolytic reaction time and material removal amount, so the slit width and depth also increase gradually. Shin et al. reported that the slit width increased with increasing pulse power-on time [16]. Yu et al. also obtained this conclusion through experiments [17]. Therefore, proper reduction of pulse duty cycle is conducive to reducing slit width and depth and improving machining accuracy.

3.3 Effect of pulse frequency

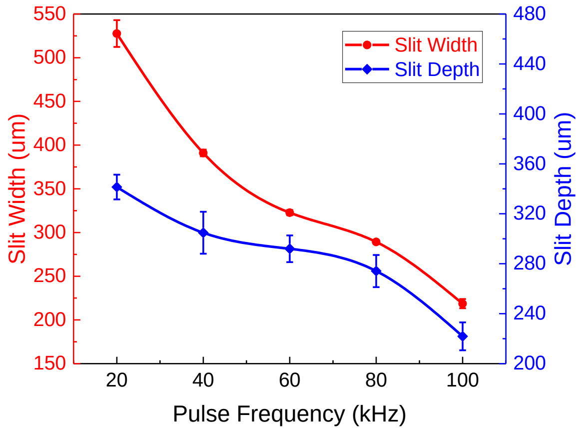


Figure 8. Effect of pulse frequency change on slit width and depth (voltage: 16 V, duty cycle: 30%, and electrolyte concentration: 20 g/L)

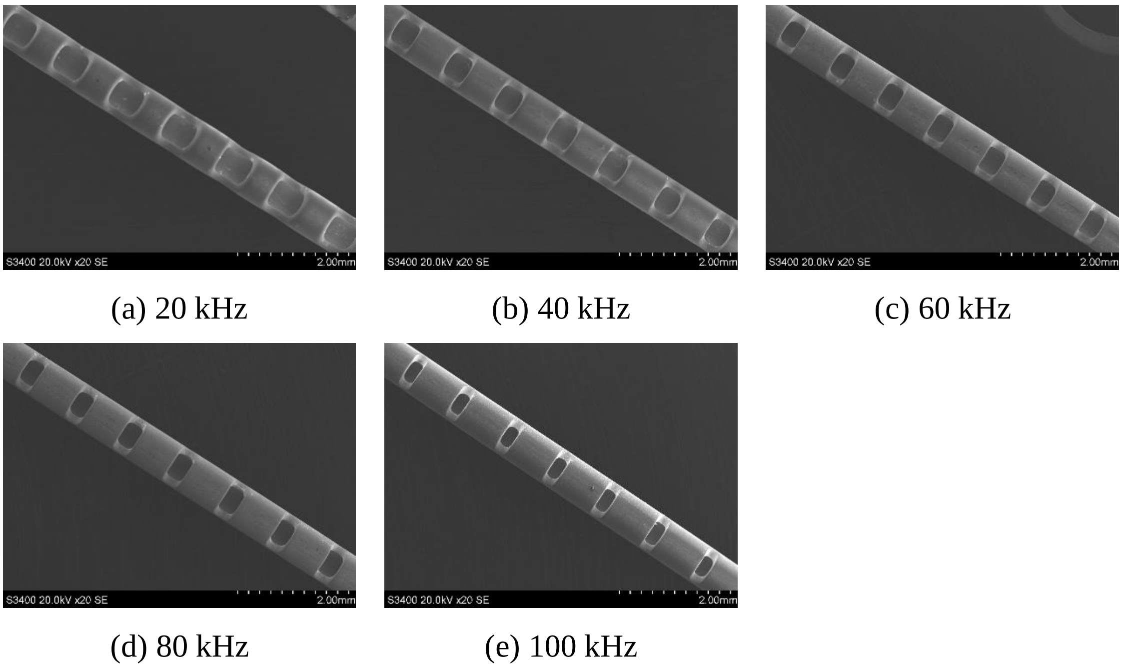


Figure 9. Machined slits with different pulse frequencies (voltage: 16 V, duty cycle: 30%, and electrolyte concentration: 20 g/L)

Experimental parameters: voltage of 16 V, duty cycle of 30% and electrolyte concentration of 20 g/L. Figure 8 shows the effect of pulse frequency changes on slit width and depth. Figure 9 shows the machined slits with different pulse frequencies. The figures show that the slit width and depth decrease with increasing pulse frequency, and so does the opening area of the slits. When the pulse frequency is 20 kHz, the slit width and depth are 527.6 μm and 341.4 μm, respectively, and when the pulse frequency increases to 100 kHz, the slit width and depth are 218.6 μm and 221.8 μm, respectively.

In electrochemical machining, a double electric layer is formed between the workpiece and electrolyte, and between the electrolyte and the tool cathode. For high-frequency pulse electrochemical machining, the charging process of the double electric layer cannot be ignored [18]. As the pulse frequency increases, the pulse period decreases, and the effective machining time in one cycle shortens, the material removal amount per unit time is small, so the width and depth of the slits are reduced. This is consistent with the effect of pulse frequency on slit width found by theoretical analysis and experimental verification [19,20]. Increasing the pulse frequency improves the cutting accuracy.

3.4 Effect of electrolyte concentration

Experimental parameters: voltage of 16 V, duty cycle of 30% and pulse frequency of 100 kHz. Figure 10 shows the variation of slit width and depth with electrolyte concentration, and Figure 11 shows the machined slits. When the electrolyte concentration increases from 15 g/L to 35 g/L, the slit width increases from 202.5 μm to 256.5 μm, and the slit depth increases from 209 μm to 266.7 μm. This is because with the increase of electrolyte concentration, its conductivity also increases, so the current density between the two electrodes increases, the material removal amount increases, and the slit widens and deepens. However, when the concentration of electrolyte is 15 g/L, the conductivity of the electrolyte is too low, the MFR of workpiece is slower than the feed rate of the tool cathode, and the workpiece contacts with wire electrode, resulting in short circuiting. This result agrees with the report of Wang et al. [21] and Meng et al. [22], which showed that the application of low-concentration electrolyte can improve the localization of electrochemical machining and reduce the gap width. Therefore, proper reduction of electrolyte concentration is conducive to reducing the slit width and depth and improving the accuracy of electrochemical machining under normal machining conditions.

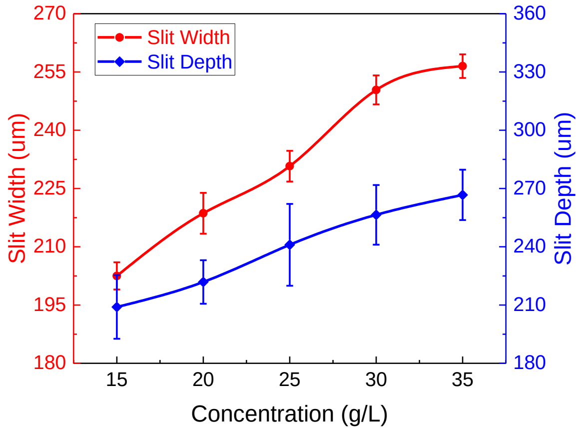
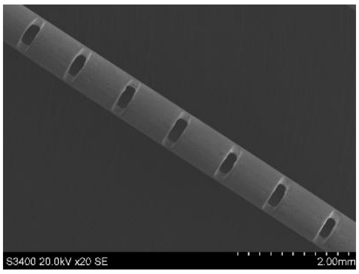
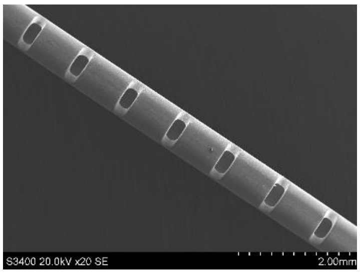


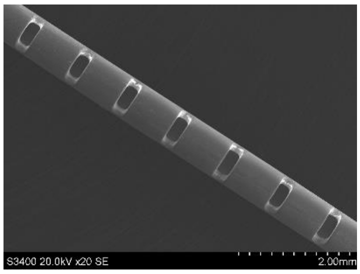
Figure 10. Variation of slit width and depth with electrolyte concentration (voltage: 16 V, duty cycle: 30%, and pulse frequency: 100 kHz)



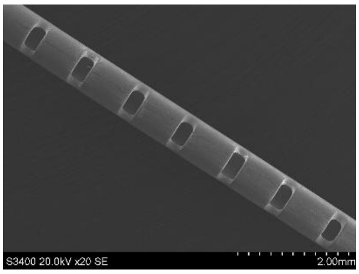
(a) 15 g/L



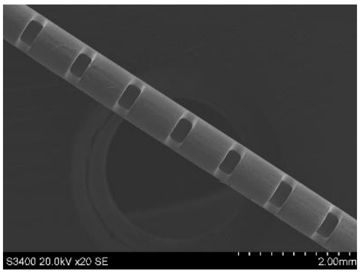
(b) 20 g/L



(c) 25 g/L



(d) 30 g/L

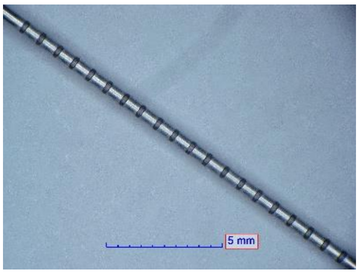


(e) 35 g/L

Figure 11. Machined slits with different electrolyte concentrations (voltage: 16 V, duty cycle: 30%, and pulse frequency: 100 kHz)

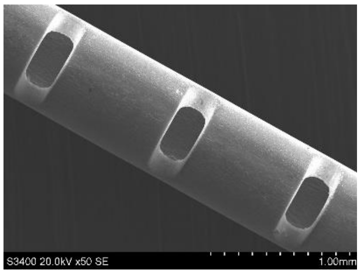
3.5 Fabrication of the tube electrode with array slits

The optimal machining parameters were obtained through the above experiments: voltage of 16 V, duty cycle of 30%, pulse frequency of 100 kHz and electrolyte concentration of 20 g/L. The other machining parameters are shown in Table 1. A tube electrode with array slits was successfully fabricated on stainless steel 304 tube with an outer diameter of 0.7 mm and the thickness of 0.15 mm, and it took 9 minutes. The number of array slits was 20, the average slit width was 218.6 μm (standard deviation of 5.3 μm) and the average slit depth was 270.7 μm (standard deviation of 16.4 μm), as shown in Figure 12.



(a) Overall view

(b) Local view



(c) Locally enlarged view

Figure 12. Fabricated tube electrode with array slits (voltage: 16 V, duty cycle: 30%, pulse frequency: 100 kHz, and electrolyte concentration of 20 g/L)

3.6 WECM using a tube electrode

Using the fabricated tube electrode with array slits as the tool cathode, a cutting experiment was carried out on the 20 mm thick stainless steel 304 workpiece. A schematic diagram of WECM using the tube electrode is shown in Figure 13. The electrolyte in the electrolyte tank was outflowed. The electrolyte circulation device was connected with the fabricated tube electrode and the electrolyte tank. The wire electrode was removed and the stainless steel 304 block was installed.

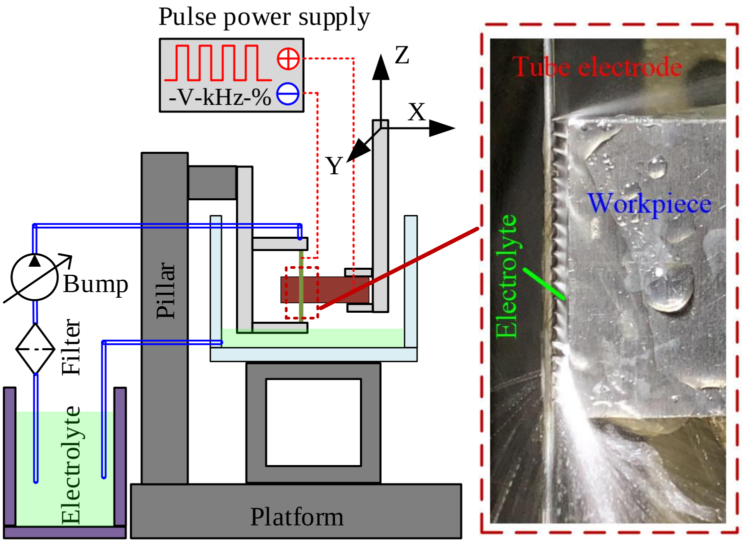


Figure 13. Schematic diagram of WECM using the fabricated tube electrode

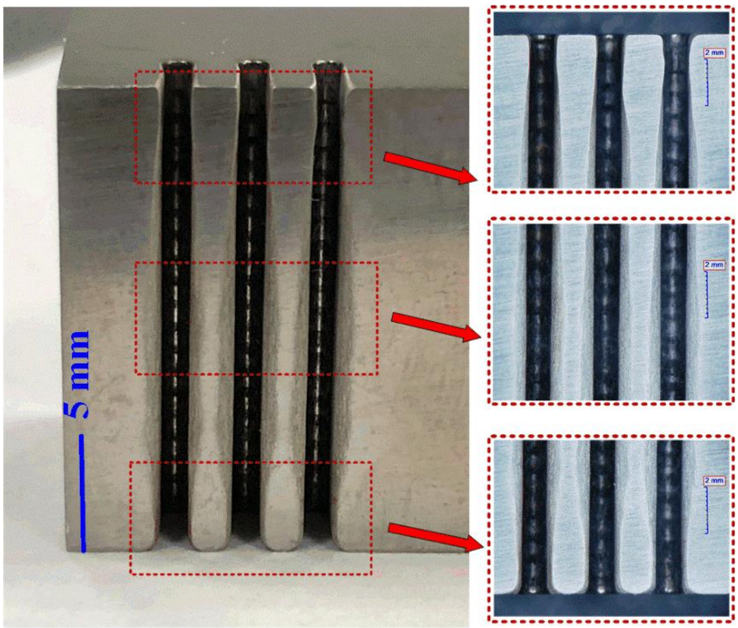


Figure 14. WECM machined slits using the fabricated tube electrode (applied electrical parameter: 20 V-40%-50 kHz, electrolyte concentration: 20%, inlet pressure: 2.0 MPa, feed rate: 5 μm/s, reciprocating amplitude: 1 mm, and reciprocating frequency: 1.5 Hz)

Experimental parameters: electrical parameter of 20 V-40%-50 kHz, sodium nitrate electrolyte concentration of 20% and inlet pressure of 2.0 MPa, and feed rate of 5 μm/s. To improve the uniformity and consistency of the electrolyte flow field in the machining gap, a reciprocating movement of the workpiece along the axial direction of tube electrode was added. The amplitude and frequency were 1 mm and 1.5 Hz, respectively. Three cutting slits were successfully machined, with an average width of 1.215 mm and a standard deviation of 33.4 μm, as shown in Figure 14.

4. CONCLUSIONS

An in-situ fabrication method of a tube electrode with array slits using multi-wire ECM technology and its application in WECM have been proposed. Based on the above experiments, the conclusions are as follows:

1. Appropriate reduction of voltage, duty cycle and electrolyte concentration and increase of pulse frequency are helpful to improve the dimensional accuracy of the array slits.
2. Using the optimum machining parameters, a tube electrode with array slits was successfully fabricated on stainless steel 304 tube with an outer diameter of 0.7 mm and the thickness of 0.15 mm, in 9 minutes. The number of array slits was 20, the average slit width was 218.6 μm (standard deviation of 5.3 μm) and the average slit depth was 270.7 μm (standard deviation of 16.4 μm).
3. The cutting experiment was completed on 20 mm thick stainless steel 304 using the fabricated tube electrode at a 5 μm/s feed rate, and three slits with an average width of 1.215 mm (standard deviation of 33.4 μm) were successfully machined.

ACKNOWLEDGEMENTS
This project was supported by the National Natural Science Foundation of China (51975291), the Natural Science Foundation of Jiangsu Province (BK20192007), the National Natural Science Foundation of China for Creative Research Groups (51921003), and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX19_0167).

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