Workpiece vibration in feed direction assisted electrochemical cutting using tube electrode with inclined holes

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Abstract
Electrochemical cutting using tube electrode with inclined holes is a machining method that directly and obliquely injects electrolyte into the machining gap through inclined jet-flow holes on the sidewall of a tube electrode, allowing the electrochemical cutting of a workpiece. To improve the machining efficiency and accuracy of this cutting technique, a method of workpiece vibration in feed direction—assisted electrochemical cutting is proposed in which workpiece vibration rapidly and periodically changes the machining gap. The near-instantaneous increases in the machining gap promote the renewal of electrolyte and the removal of electrolytic products. At the same time, the electrochemical reaction time under the nonuniform flow field caused by the inclined downward injection of electrolyte is reduced. The flow field simulation of electrolyte in machining gap indicates that the near-instantaneous increases in the machining gap can improve the flow velocity of electrolyte. The effect of the vibrational amplitude and frequency on the machining result is investigated by cutting slit experiments. Compared with that of electrochemical cutting without workpiece vibration in feed direction, the average feed rate of electrochemical cutting assisted by workpiece vibration with amplitude of 0.1 mm and frequency of 1.5 Hz can be increased by 50%, and the width difference between the upper and lower end of the slit is reduced from 115.56 to 49.6 μm. The machining efficiency and machining accuracy of electrochemical cutting using tube electrode with inclined holes are improved. Finally, an array slice structure is fabricated on a stainless steel block with a cross-section of 10 mm × 10 mm at average feed rate of 6 μm/s using a vibrational amplitude and frequency of 0.1 mm and 1.5 Hz, respectively.

Keywords Electrochemical cutting · Tube electrode · Inclined jet-flow holes · Workpiece vibration

1 Introduction

Wire electrochemical machining (WECM) is based on conventional ECM and uses a metal wire to cut the workpiece in a 2D plane [1]. This method not only inherits the advantages of conventional ECM, but also has its own unique benefits. A linear cathode with a simple structure is used, thus avoiding the complex shaped cathode designs employed in conventional ECM, and thereby improving machining flexibility. WECM is suitable for the processing of high-precision 2.5-dimensional parts [2].

The limitation of mass transfer in narrow slits is a decisive factor that restricts the improvement of machining efficiency and accuracy [3, 4]. This is because the electrolytic products that remain in the machining gap change the electrolyte conductivity and negatively affect the distribution of the electric field in the machining gap, thus degrading the efficiency and accuracy of WECM. This problem becomes worse as the depth of the cutting slit increases, i.e., with increasing workpiece thickness. In recent years, a large number of studies have attempted to accelerate the removal of electrolytic products and refresh the electrolyte in the machining gap, thereby improving the machining efficiency and accuracy. For wire electrochemical micromachining, the axial reciprocating vibration of a wire electrode has been proposed [5]. This uses the reciprocating vibration of the wire electrode to drag the electrolyte, promoting the removal of electrolytic products and the renewal of the electrolyte. A microscale square column tool array
with a surface roughness of 0.058 μm was fabricated on an 80-μm-thick cobalt-based superalloy at a feed rate of 0.5 μm/s. Upward and downward reciprocating movement of the workpiece was found to induce a fluid flow in the electrolyte that aids the removal of electrolytic products. With this technique, a microgear structure was fabricated on an amorphous material, namely nickel-based metallic glass, at a feed rate of 0.5 μm/s [6]. The intermittent vibration of the electrode in the feed direction was observed to induce electrolyte flow in the machining gap, accelerating the removal of electrolytic products. This method has been proved to be effective in both simulations and experiments [7].

For the electrochemical cutting of thick workpieces, Volgin et al. [8] performed simulations that examined whether rotation or reciprocating movement of the cathode assisted electrochemical cutting and improved machining efficiency, especially if an electrode with a noncircular (e.g., square or triangular) cross-section was adopted. The auxiliary measures have improved the machining efficiency and machining ability of thick workpieces [9, 10], but there is still room for improvement. Thus, WECM methods assisted by electrolyte flushing have been proposed. The high-velocity flow of electrolyte into the machining gap can flush electrolytic products rapidly from the gap and refresh the electrolyte [11]. Using two twisted metal wires as cathodes, machining tests were carried out on 40-mm-thick direct-aged (DA) Inconel 718 with axial electrolyte flushing and a rotating cathode [12]. However, the top and bottom sides of the slit have quite different widths. In another approach, a linear metal tube with array holes replaces the conventional metal wire as the tool cathode, with electrolyte being injected directly into the machining gap through these holes to wash out electrolytic products [13]. By using this technique, the electrochemical cutting of difficult to cut materials with large thickness such as nickel superalloy (Inconel 718) [14] and titanium alloy (Ti-6Al-4V) [15] is realized. Yang et al. studied the effect of the holes spacing and inclination angle on the machining results. Through simulations and experiments, they found that when the tube electrode with inclined holes is used, the electrolyte in the machining gap has a downward flow velocity, which promotes the refreshment of electrolyte and the removal of electrolytic products in the area between the two jet-flow holes, and improves the machining efficiency of inner-jet electrochemical cutting.

However, a large amount of electrolyte flows down along the tube electrode. The electrolyte in the upper part of the slit has a lower flow velocity and a smaller flow rate, while the electrolyte in the lower part of the slit has a higher flow velocity and a larger flow rate. This makes the upper end of the slit narrower (the average width of 518.6 μm) and the lower end of the slit wider (the average width of 594.4 μm). There is a width difference of 75.8 μm between the upper and lower end of the slit [16].

To improve the machining efficiency and reduce the width difference between the upper and lower end slit, a method of workpiece vibration in feed direction assisted electrochemical cutting using tube electrode with inclined jet-flow holes is proposed. Workpiece vibration in the feed direction rapidly and periodically changes the machining gap. The near-instantaneous increases in the machining gap promote the renewal of electrolyte and the removal of electrolytic products. At the same time, the electrolytic reaction time under the nonuniform flow field caused by the inclined downward injection of electrolyte is reduced. The flow field simulation of electrolyte in machining gap indicates that the near-instantaneous increases in the machining gap can improve the flow velocity of electrolyte. The effect of the vibrational amplitude and frequency on the machining result is investigated by cutting slit experiments. Compared with that of electrochemical cutting without workpiece vibration, the average feed rate of electrochemical cutting assisted by workpiece vibration (amplitude of 0.1 mm and frequency of 1.5 Hz) in feed direction can be increased by 50%, and the width difference between the upper and lower end of the slit is reduced from 115.56 to 49.6 μm. The machining efficiency and machining accuracy of electrochemical cutting using tube electrode with inclined holes are improved. Finally, an array slice structure is fabricated on a stainless steel block with a cross-section of 10 mm × 10 mm at average feed rate of 6 μm/s.

2 Machining principle and simulation analysis

Figure 1 shows the machining principle of workpiece vibration in feed direction assisted electrochemical cutting using...
tube electrode with inclined holes. A linear metal tube with a closed bottom end and an array of inclined jet-flow holes on the tube wall acts as the tool cathode. The electrolyte passes through the inner cavity and the inclined jet-flow holes, and sprays directly onto the machining area to cause the electrochemical reaction and flush away electrolytic products. With the continuous feeding of the workpiece, a slit structure is produced on the workpiece.

In the electrochemical cutting process, workpiece vibration in the feed direction rapidly and periodically changes the machining gap. When the machining gap increases, the flow resistance of the electrolyte in the machining gap decreases, and the electrolyte injected downward at an inclined angle quickly flows out of the machining gap. When the machining gap reduces suddenly, the electrolyte ejected from the jet-flow holes is squeezed into the long and narrow machining gap instantly. A large amount of electrolyte flows from the gap between the tube electrode and the workpiece to the machined slit, and then flows out of the slit along the back of the tube electrode. A small amount of electrolyte spills from the upper and lower ends of the machining gap. This constantly changes the spraying state of the electrolyte, which promotes the rapid removal of electrolytic products and the renewal of the electrolyte. At the same time, with the vibration of the workpiece, the spraying position of the high-flow-velocity electrolyte from the inclined jet-flow holes onto the machined surface changes continuously, which improves the uniformity of the flow field distribution in the machining gap (see Fig. 1c). In addition, the electrolytic reaction time under the nonuniform flow field caused by the inclined downward injection of electrolyte is reduced. This is beneficial to improving the machining accuracy.

Figure 2 shows the variations of the machining gap Δb with time t during workpiece vibratory. It is assumed that there is no contact between the workpiece and the tube electrode during the vibration. Backward vibration occurs when Δb increases from small to large values, and the end position of workpiece vibration is defined as the position at which Δb reaches its maximum value Δb2. Forward vibration occurs when Δb decreases from large to small values, and the starting position of workpiece vibration is defined as the position at which Δb reaches its minimum value Δb1. The vibrational amplitude of the workpiece is thus given by the distance between the starting position and the end position: x' = Δb2 − Δb1.

To investigate the effect of workpiece vibration in the feed direction on electrolyte flow state in the machining gap, the flow field is simulated when the workpiece is in the end position under different vibrational amplitudes. In the process of the electrochemical cutting using tube electrode, the balance-machining gap between the tube electrode and the workpiece surface is usually 0.05–0.15 mm. The outer diameter of the tube electrode in this study is 0.3 mm. When the tube electrode cuts completely into the workpiece, the machined length is greater than 0.45 mm. At this time, the electrochemical cutting tends to be stable. As the electrochemical cutting continues, the flow state of electrolyte in the machining gap remains unchanged. In the simulation and calculation, the change of machined length will not affect the flow state of electrolyte in the machining gap. Therefore, it is assumed that the machined length is 1.5 mm. A flow field model is established, as shown in Fig. 3. The vertical section A of the plane Y = 0 mm and the line L of 50 μm away from the workpiece machining surface are chosen to illustrate the different velocity distributions in electrochemical cutting. The calculation is performed by ANSY Fluent 17.0 based on the parameters listed in Table 1.

Figure 4 shows the electrolyte flow velocity contours at different vibrational amplitudes. The results show that electrolyte always exists in the machining gap, which ensures normal electrochemical reaction, and that the electrolyte flows rapidly through the machining gap, facilitating rapid washing out of the electrolytic products.

Figure 5 is obtained by extracting and fitting the flow velocity on the line L at different vibrational amplitudes. On taking these results together with those in Fig. 4, it can be seen that the near-instantaneous increase in the machining gap leads to rapid flow of the electrolyte. This is because the electrolyte sprays onto the machining surface and bounces back.
into the machining gap. Finally, the electrolyte flows out from the upper and lower ends of the slit, and the side gap between the tube electrode and the workpiece. In the normal machining process, the flow resistance of electrolyte is great and the flow velocity is slow, since the machining gap between the tube electrode and the workpiece is very small. However, when the workpiece vibrates, and the machining gap becomes larger, the flow resistance decreases, and the electrolyte flows rapidly out of the machining gap along the lower end of the machined slit under the action of electrolyte internal pressure and gravity, as shown in Fig. 1c.

3 Experimental details

Figure 6 shows a schematic diagram of the workpiece vibration in feed direction assisted electrochemical cutting setup. To allow relative independence of the vibrational movement along the feed direction and the normal feed movement of the workpiece, as well as to ensure the machining efficiency of electrochemical cutting, this mode of coupling two kinds of movement is adopted.

| Parameter                        | Value  |
|----------------------------------|--------|
| Diameter of tube cavity (mm)     | 0.15   |
| Thickness of tube wall (mm)      | 0.075  |
| Number of holes                  | 10     |
| Diameter of array holes (mm)     | 0.1    |
| Spacing of holes (mm)            | 1      |
| Machined length (mm)             | 1.5    |
| Slit width (mm)                  | 0.5    |
| Vibrational amplitude (mm)       | 0, 0.1, 0.2, 0.3, 0.4 |
| Workpiece thickness (mm)         | 10     |
| Inlet pressure (MPa)             | 2.0    |

A high-precision motion stage (X’-axis) is added to the original three-axis (X/Y/Z-axis) machine tool. The workpiece is mounted on an anode clamp fixed to the motion stage of the machine tool, and the tube electrode is installed in a cathode clamp fixed to the pillar of the machine tool. The relative feed movement between workpiece and cathode is driven by the X/Y-axis, the relative height between the workpiece and the jet-flow holes of the cathode is adjusted by the Z-axis, and the

Fig. 3 Simulation model of flow field in machining gap

Fig. 4 Electrolyte flow velocity contours for the different vibrational amplitudes: a 0 mm; b 0.2 mm; c 0.4 mm

Fig. 5 Electrolyte flow velocity on the line L at different vibrational amplitudes
vibrational movement between workpiece and tube electrode is driven by the X’-axis.

The tool cathode is a commercial 304 stainless steel tube. Its closed end is machined by microlaser welding, and the array jet-flow holes are machined by microlaser drilling. The outer and inner diameters of the tube cathode are 0.3 mm and 0.15 mm, respectively. There are 10 holes in the array, each with a diameter of 0.1 mm and which are spaced 1 mm apart. The array holes are inclined downward at an angle of 45°. The machining workpieces are ultrasonically cleaned 304 stainless steel pieces of size 60 mm (length) × 30 mm (width) × 10 mm (height). Table 2 summarizes the machining parameters applied in the experiment.

For electrochemical cutting, the machining efficiency refers to the machined surface area of electrochemical cutting per unit time. The feed rate can be used to characterize the machining efficiency, because the thickness of the workpiece used in this study is constant. In the normal workpiece feed process, the variation in workpiece displacement is as shown in Fig. 7a. In the process of workpiece vibration along the feed direction, the variation in workpiece displacement is as shown in Fig. 7b. In the process of workpiece feeding and vibration, the variation in workpiece displacement is as shown in Fig. 7c. In this study, the vibrational movement and feed movement of the workpiece is driven by the X’-axis and the X-axis, respectively. The movement of the X-axis determines the overall feed movement of the workpiece. The average feed rate of the workpiece is equal to the movement speed of the X-axis, although the actual feed rate of the workpiece varies periodically. During the experiment, the X-axis moves at the speed of 5 μm/s, to cut out 10-mm-long slit for the processing task. If there is no short circuit in the whole process, increase the speed of X-axis (the increment is 0.5 μm/s) for the next cutting task. If there is a short circuit in the whole process, reduce the speed of X-axis (the decrement is 0.5 μm/s) for the next cutting task. Through many experiments, the maximum movement speed of X-axis under different machining conditions is obtained.

The machined slit structure is cleaned by ultrasonic. A digital microscope (DVM5000, Leica, Germany) and an optical microscope (SMT7-SFA, Olympus, Japan) are used to capture the shapes of the machined slit and measure the widths. The upper and lower surfaces of each slit are measured 10 times. The average width and the width difference between the upper and lower end of the slit are calculated. In this study, the slit width and the width difference are used to characterize the machining accuracy.

Table 2  Experimental parameters

| Parameter                  | Value                        |
|----------------------------|------------------------------|
| Electrolyte                | NaNO₃                        |
| Concentration (g/L)        | 100                          |
| Inlet pressure (MPa)       | 2.0                          |
| Initial electrode gap (mm) | 0.3                          |
| Vibrational amplitude (mm) | 0, 0.1, 0.2, 0.3, 0.4        |
| Vibrational frequency (Hz) | 0.5, 1, 1.5, 2, 2.5          |
| Electrical parameters      | 16 V-35%-50 kHz              |
4 Results and discussion

4.1 Effect of vibrational amplitude

To examine the effect of workpiece vibrational amplitude on electrochemical cutting, the vibrational frequency is fixed at 1 Hz. Figure 8 shows the variations in the maximum movement speed of X-axis and the slit width with respect to vibrational amplitude.

In the process of electrochemical cutting without workpiece vibration (the vibrational amplitude is 0 mm), the maximum movement speed of X-axis is 4 μm/s. In the process of electrochemical cutting assisted by workpiece vibration in feed direction (the vibrational amplitude is 0.1 mm), the maximum movement speed of X-axis is 5.5 μm/s, and the machining efficiency is higher compared with that of electrochemical cutting without workpiece vibration. This is because the vibration of the workpiece in the feeding process changes rapidly and periodically the machining gap between the workpiece and tube electrode. When the machining gap increases, the flow resistance of the electrolyte decreases and the flow velocity becomes faster. When the machining gap decreases, the electrolytic reaction between the workpiece and tube electrode occurs rapidly in the fresh electrolyte, and the workpiece material is quickly corroded and removed. Figure 9 shows the flow state of the electrolyte during workpiece vibration. When the machining gap increases, more electrolyte flows downward along the front side of the tube electrode, as shown in Fig. 9a. When the machining gap decreases, more electrolyte flows out of the gap between the tube electrode and the slit sidewall, and then flows downward along the backside of the tube electrode, as shown in Fig. 9b. In addition, the vibration of the workpiece periodically changes the spraying position of the high-flow-velocity electrolyte ejected from the jet-flow holes on the machining surface, which allows the electrolytic products of the machining surface to be quickly removed.

When the vibrational amplitude is greater than 0.1 mm, the maximum movement speed of X-axis gradually decreases as the amplitude increases. This is because, in the process of workpiece vibration, the vibrational frequency remains unchanged, that is, the time taken for the workpiece to move a stroke is the same. As the vibrational amplitude increases, the travel distance of the workpiece increases, and the reaction time between the workpiece and the tube electrode decreases under the conditions of a high current density and small machining gap. Therefore, less material is removed, and the maximum movement speed of X-axis decreases. In addition, as the distance between the workpiece and the tube electrode increases, the position of the high-flow-velocity electrolyte ejected from the jet-flow holes to the machining surface becomes lower. A lower flow rate and lower flow velocity of electrolyte at the upper part of the machining gap result in a lower material removal rate at the upper part of the cutting slit. This limits the overall movement speed and reduces the machining efficiency. When the vibrational amplitude is too large (0.4 mm), the flow rate of electrolyte at the upper part...
of the machining gap is too low to ensure the electrochemical reaction between the tube electrode and the workpiece, and the machining fails.

Figure 10 shows the cut slits at the maximum movement speed of X-axis when the vibrational amplitude of the workpiece is 0 mm and 0.1 mm, respectively. Combined with Fig. 8, it can be seen that the slit cut by electrochemical cutting without workpiece vibration (the vibrational amplitude is 0 mm) gives a wide variation of 115.56 μm. This is because the electrolyte is ejected downward from the jet-flow holes at an inclined angle, and so the upper part of the machining gap has a low flow rate while the lower part has a high flow rate. This flow field distribution results in less material being removed at the upper part of the slit and more material being removed at the lower part. Thus, the cut slit is narrow at the upper end and wide at the lower end. In the process of electrochemical cutting assisted by workpiece vibration in feed direction (the vibrational amplitude is 0.1 mm), the vibration of the workpiece not only speeds up the renewal of the electrolyte, but also makes the flow field in the machining gap more uniform. In addition, the continuous vibration of the workpiece shortens the electrochemical reaction time and reduces the influence of the uneven distribution of the electrolyte flow field on the consistency of slit width. As a result, the slit cut by electrochemical cutting assisted by workpiece vibration in feed direction has the smaller width difference between the upper and lower end.

When the vibrational amplitude is more than 0.1 mm, with an increase in vibrational amplitude, the width difference between the upper and lower end of the slit gradually increases. As the machining gap increases, a larger vibrational amplitude of the workpiece causes the machining surface to be farther away from the tube electrode, leading to a decrease in the electrochemical reaction efficiency. Therefore, the slit cut by electrochemical cutting with workpiece vibration is wider than that without workpiece vibration.
from the tube electrode and lowers the spraying position of the high-flow-velocity electrolyte ejected from the jet-flow holes to the machining surface. A lower flow rate and lower flow velocity of the electrolyte in the upper part of the machining gap are associated with a greater flow rate and faster flow velocity of the electrolyte in the lower part. In the process of narrowing the machining gap, the electrolyte that is instantaneously squeezed into the machining gap has lower velocity on the top and higher velocity on the bottom. This distribution of the flow field causes the width difference between the upper and lower end of the slit to increase.

4.2 Effect of vibrational frequency

To examine the effect of workpiece vibrational frequency on electrochemical cutting, the vibrational amplitude is fixed at 0.1 mm. The variations in the maximum movement speed of X-axis and the slit width with respect to vibrational frequency are shown in Fig. 11.

It can be seen from Fig. 11 that the vibrational frequency has little effect on the machining results. When the vibrational amplitude is constant, changes in the vibrational frequency only affect the vibrational number of the workpiece, and have little effect on the overall flow field and electric field. However, when the vibrational frequency increases from 1 to 1.5 Hz, the maximum movement speed of X-axis increases from 5.5 to 6 μm/s. This is because, as the vibrational frequency increases, the spraying number of the electrolyte hitting a given position on the machining surface increases, promoting the removal of electrolytic products and refreshing the electrolyte. The rapid removal of electrolytic products increases the conductivity of electrolyte in the machining gap, and so the current density increases and the material is removed at a faster rate. Similarly, for a given feed rate, an increase in frequency causes the slit width and the difference between the upper and lower slit widths to increase.

Compared with that of electrochemical cutting without workpiece vibration in feed direction, the average feed rate of electrochemical cutting assisted by workpiece vibration with amplitude of 0.1 mm and frequency of 1.5 Hz can be increased by 50%, and the width difference between the upper and lower end of the slit is reduced from 115.56 to 49.6 μm. The machining efficiency and machining accuracy of electrochemical cutting using tube electrode with inclined holes are improved.

4.3 Fabrication of array slice structure

Array slice structure is usually composed of slices with a thickness of several microns to millimeters arranged
according to certain rules. It is often involved in many products, such as comb structure in inertial navigation system, stamping die of array structure, and imaging grating. Therefore, electrochemical cutting of array structures with 7 slices was carried out in this study.

Using the optimized machining parameters, namely, a workplace vibrational amplitude and frequency of 0.1 mm and 1.5 Hz in the feed direction, an array slice structure was fabricated on a 304 stainless steel block with a cross-section of 10 mm × 10 mm at average feed rate of 6 μm/s. The result is shown in Fig. 12. The thickness of every slice is measured, and the average thickness and standard deviation are calculated, as shown in Fig. 13. The average thickness of the all slices is 915.8 μm, and the standard deviation of thickness is 29.5 μm. The radius of edge between the slit wall surface and the workpiece upper surface is 135.11 μm, as shown in Fig. 14. The roughness of machined surface is 1.203 μm, as shown in Fig. 15.

5 Conclusions

To improve the machining efficiency and accuracy of electrochemical cutting using tube electrode with inclined jet-flow holes, this paper has described a method of workpiece vibration in feed direction assisted machining. A series of simulations and experimental tests lead to the following conclusions regarding the proposed method:

1. In the process of electrochemical cutting assisted by workpiece vibration in the feed direction, this vibration rapidly and periodically changes the gap between the tube electrode and the workpiece, the spraying state of electrolyte on the machining surface, and the spraying position along the workpiece thickness. This can speed up the renewal of electrolyte and promote the removal of electrolytic products.

2. The vibrational amplitude determines the changes in the machining gap and has a great influence on the machining result. The vibrational frequency determines the number of changes in the machining gap, but has only a weak influence on the machining result.

3. Compared with that of electrochemical cutting without workpiece vibration in feed direction, the average feed rate of electrochemical cutting assisted by workpiece vibration with amplitude of 0.1 mm and frequency of 1.5 Hz can be increased by 50%, and the width difference between the upper and lower end of the slit is reduced from 115.56 to 49.6 μm. The machining efficiency and machining accuracy of electrochemical cutting using tube electrode with inclined holes are improved.

4. Using the optimized machining parameters, an array slice structure has been fabricated on a 304 stainless steel block with a cross-section of 10 mm × 10 mm at average feed rate of 6 μm/s.

Availability of data and materials All data generated or analyzed during this study are included in this article.

Author contribution Tao Yang conceived of the study, designed the study, and collected the data. All authors analyzed the data and were involved in writing the manuscript.

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Declarations

Ethics approval The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interest The authors declare no competing interest.
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