Experimental Study on Electrochemical Machining of Conical Micro-Holes

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Abstract: Micro holes with internal features are widely used as nozzle of engine nowadays, which are usually required to be with high aspect ratio and shape accuracy, as well as good surface quality. In order to solve the machining problem of the engine nozzle, a small taper hole was studied by electrochemical machining which has online machining tube cathode .By processing machining model and doing simulation of flow field and electric field, analyze the influencing factors in the experiment. Finally, the law of the feed speed, the voltage and electrolyte concentration and taper of hole are studied. A good conical micro-hole was worked out and taper error is 0.46 °.

1 INTRODUCTION

Mechanical components tend to be miniaturized and refined, and are widely used in engines, micro-electromechanical systems, precision instruments and other fields. Among them, the structure of the conical hole is complex and difficult to process. The conventional machining technology cannot achieve the general adoption of special processing technology. For example, the micro-tapered cavity is machined by electric spark or laser [1], and then the surface quality of the side wall is improved by abrasive flow polishing. However, in the EDM process of micro holes, the electrode loss is serious, the machining accuracy is difficult to ensure, and there are defects such as surface microcracks in laser processing [2]. The surface processed by the abrasive flow is improved compared with laser processing, but the residual stress is difficult to eliminate [3].Electrochemical machining has the advantages of no loss of cathode, good surface quality, and no residual stress. Prof. Li Yong of Tsinghua University processed micro-holes with smaller taper in the ECM test by changing the voltage between the electrodes, the duty ratio, and the feed rate, and achieved better results. Good effect, import deviation is 3μm and cone angle error <0.1° [4]. XuShiyu of Xi'an University of Technology successfully processed tapered holes by formulating a layered electrolytic milling process [5]. Nanjing University of Aeronautics and Astronautics adopts a compound feed electrolytic machining process to machine large taper holes with clear contours and stable machining [6].

The electrochemical product of micro-conical hole is difficult to discharge in the electrochemical machining. In order to eliminate manufacturing and secondary assembly errors, set up a micro-hole processing device, on-line machining conical tube electrodes. With the use of electrolyte injection technology and rotation of cathode, through the experimental study the influence of factors such as cathode feed rate, processing voltage and electrolyte concentration on the processing results.

2.INFLUENCE OF ELECTROLYTIC PROCESSING PRECISION OF TAPER HOLES

From the basic laws of electrolytic machining, namely Faraday's law and Ohm's law, it can be deduced that the dissolution rate of the anode during electrochemical processing in formula (1).

$$v_a=\eta\omega i=\frac{\eta\omega k U_R}{\Delta_b} \quad (1)$$

In the equation (1) where v_a is the anode phase dissolution rate; η is the electrolyte current efficiency; i is the current density; Δb is the end clearance; ω is the volume electrochemical equivalent; κ is the electrolyte conductivity; U_R is the ohmic pressure drop between poles . This formula reflects the parameters of the electrochemical machining and is the theoretical basis for analyzing the forming law of electrochemical machining.

In electrochemical machining, the size of the machining gap and its variation are the main sources of error in machining. The machining gap is affected by many factors such as electric field, flow field, temperature and electrochemical characteristics [7].

According to electrolytic processing end surface equilibrium gap formula(2).

$$\Delta b=\frac{\eta\omega k U_R}{v} \quad (2)$$

Fully differentiate it to get the gap dΔb:

$$d\Delta_b=\Delta_b\left[\frac{d\eta}{\eta}+\frac{dk}{k}+\frac{dU_R}{U_R}-\frac{dv}{v^2}\right] \quad (3)$$

Formula (3) shows that the use of small gaps can reduce the amount of change in the gap, thereby increasing the gap of electrochemical machining.

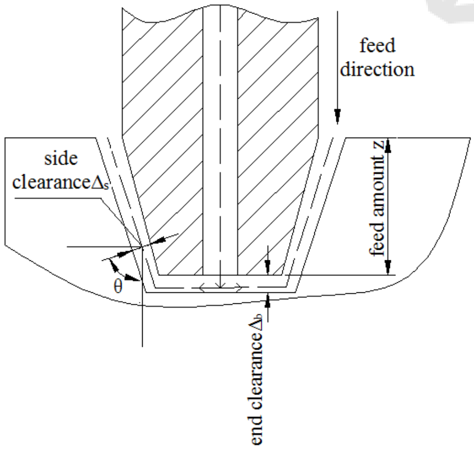

Figure 1 Schematic diagram of electrochemical machining of tapered tube electrode.

As shown in Figure 1, at any one of the cathode feeds z, it is again available:

$$\Delta_s=\frac{\Delta_b}{\cos\theta} \quad (4)$$

Formula (4) shows that when the conical cathode continuously feed, end clearance Δb affect the important factors of the precision of the tapered hole processing. From formula (3) ,the processing voltage, feed rate and electrolyte concentration affect the end of the tapered hole Gap, thus affecting the processing stability and machining accuracy of the tapered hole.

3.PREPARATION OF EXPERIMENT

3.1 Device of Experiment and Online Machining of Cathode

This experiment was based on a CNC engraving and milling machine. An L-shaped stainless steel plate was placed on the lower end of the spindle, and the processing device was connected to feed the taper hole up and down. As shown in Fig. 2, the high-pressure pipe joint leads to the electrolyte and flows from the liquid storage cavity into the cathode of the tapered pipe to form a liquid. As the diameter of the conical pipe is small, a 0.8 mm seal ring is inserted into the liquid storage cavity to avoid high pressure. The electrolyte overflows to ensure that the electrolyte flow is normal during processing. The drill chuck can hold 0.15mm-3mm diameter and it is not easily deformed. A carbon brush is placed in the conductive block, and the cathode and the power line are connected to form a path. The DC motor drives the cathode through the belt to rotate during processing and the spindle feed speed of CNC machine tool can reach 1μm/s, which can meet the requirements of the micro-hole machining.

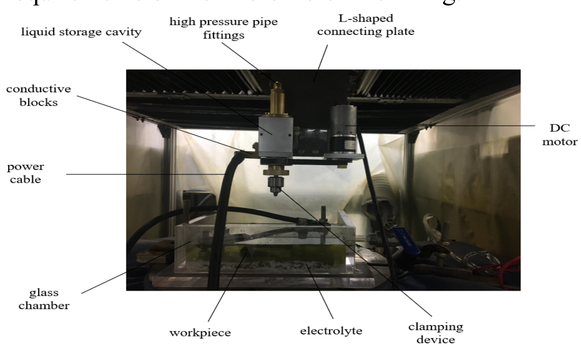

Figure 2 Device of ECM.

The manufacture of tool electrodes in the electro-processing of cone-shaped holes is very important. Turning and grinding of the tube electrodes can easily lead to bending of the front section of the cathode and leave marks on the surface, failing to meet the test requirements. The cone electrode can be obtained by electrochemical processing with a conical block. The processing device is as shown in FIG. 3. At this time, the tool electrode is connected to the anode of the power supply, the cone correction block is connected to cathode, and the motor drives the cathode to rotate at a relatively high speed. The current sensor is used to observe the processing current, and control the removal amount by changing the processing voltage and processing time. In the experiment, two types of materials that copper and stainless steel were used to make the cathode of the tapered tube. The surface of the resulting copper electrode was seriously pitted due to the use of nitric acid. Sodium electrolyte is not suitable for this type of material. Since the stainless steel is resistant to electrolyte corrosion and the hardness of the material is high, the stainless steel electrode obtained in FIG. 5 has a uniform taper and a good surface quality, and can be used as a forming cathode for the electrolysis of a tapered hole.

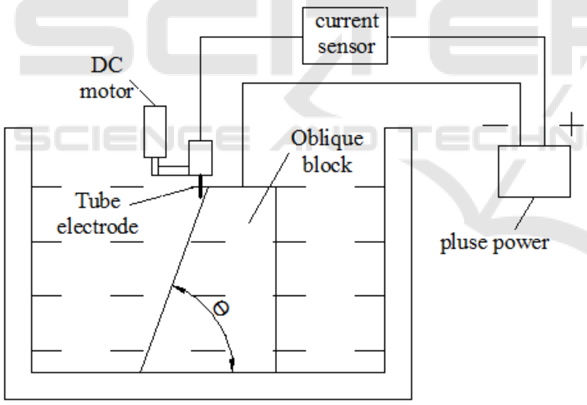

Figure 3 Device diagram for on-line cathode fabrication.

Figure 4 Copper conical tube electrode.

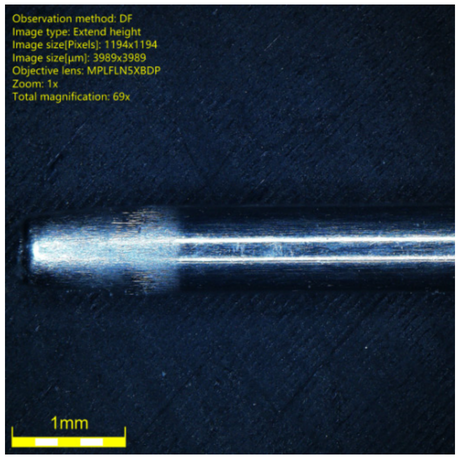

Figure 5 Stainless steel tapered tube electrode.

3.2. Analysis of Flow Field Simulation of Conical Tube Electrode

Assuming that the fluid is constant, incompressible, ideal, the loss of energy due to electrolyte temperature changes and temperature differences during processing is negligible, and the flow follows mass and momentum conservation equations.

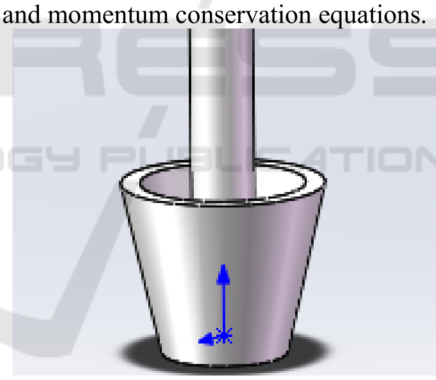

Figure 6 Three-dimensional model diagram of electrolyte flow channel.

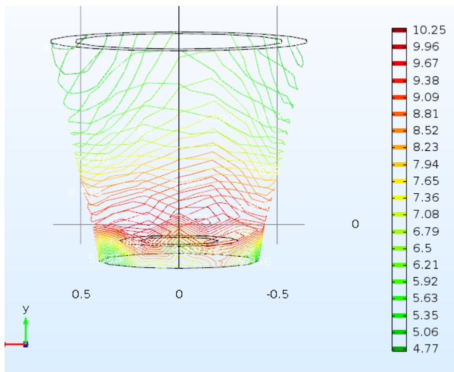

Figure 7 Velocity distribution of conical surface.

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In electrochemical machining, in order to satisfy the assumption of a steady distribution of the flow field, and to better remove the electrochemical products at the surfaces of cathode and anode to reduce the concentration polarization near the electrodes and to make the liquid flow uniform, the processing gap should be turbid. Flow state electrolyte, electrolyte flow rate v0 should meet [5].

$$v_0 > 2300\frac{v}{D_h} \qquad (5)$$

In the formula (5),v is the viscosity coefficient of water, which is used here as an alternative to the viscosity coefficient of the electrolyte. The electrolyte temperature is 25°C in the experiment, and the viscosity coefficient is 0.89 10^(-6) m2/s[5];Dh is the hydraulic diameter, that is, the hollow diameter of the tube electrode, which is substituted into the formula.

$$v_0 > 2300\times\frac{0.89\times10^{-6}}{0.4\times10^{-3}} = 5.1\text{m/s} \qquad (6)$$

From the formula (6), the stability of the electrochemical processing can be guaranteed only when the flow rate of the electrolyte in the processing gap is at least 5.1 m/s. From the taper tube electrode processing gap flow velocity distribution chart, when the inlet pressure is 0.5Mpa, the flow velocity in the processing gap is greater than 5.1m/s, and the velocity distribution is uniform stable. A very small number of processing areas outside the emergence of low flow rates, so need to choose import pressure parameters over 0.8Mpa.

3.3. Electric Field Characteristics of Cone Tube

Assuming that the electrolyte is isotropic, according to the electric field theory, it can be seen that the potential distribution conforms to the Laplace equation and its equation is

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0 \qquad (7)$$

Boundary conditions of anode surface

is: $$\begin{cases}\varphi_a = U \\ \frac{\partial\varphi}{\partial n} = \frac{\eta_0}{\eta}\frac{i_0\cos\theta}{\kappa}\end{cases} \qquad (8)$$

The boundary condition of cathode surface is:

$$\varphi_c = 0 \qquad (9)$$

In the formula， φ is the potential of each point in the electric field, generally φ = φ (x, y, z); U is the surface potential of the anode; n is the normal coordinates of the anode surface everywhere; θ is the angle between cathode feed rate and the normal direction of anode; is the current efficiency; η_0 is the current efficiency at θ=0; i0 is the current density in the normal direction of the anode surface at θ=0; κ is the electrolyte conductivity.

Because $\nabla\cdot i = Q$ (10) $i = -\kappa\nabla_\varphi$ (11)

The boundary between the processed material and the electrolyte is

$$-\nabla\cdot(\kappa\nabla_{\varphi_a}) = Q \quad (12) \quad -\nabla\cdot(\kappa\nabla U) = Q \quad (13)$$

Electric field simulation uses 14% sodium nitrate solution whose conductivity is 8.7 (S/m) and the anode material is 0Cr18Ni91 (304 Stainless steel), where the processing voltage 4v. From the figure 8, the current density is gradually weakened along the material to the micro-electrode direction, and the maximum value appears on the interface between the processed material and the electrolyte, and is unevenly distributed along the boundary surface. The maximum value is 6.16×10^5A, , the minimum value appears on the contact surface between the conical tube electrode and the electrolyte. The value is 0.02×10^5A, . The current density is an important parameter for electrochemical machining. Generally, with the voltage increasing, the current density increases, and the bottom surface processing effect is better. [6] However, the side current density is too large, the material removal amount increases, and the taper increases. The faster the machining speed, the less stray corrosion on the side, the smaller the taper, the closer to the taper of the forming cathode.

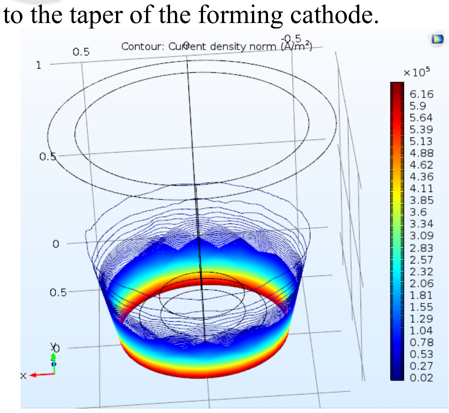

Figure 8 Distribution of electric field density.

4. EXPERIMENT OF PROCESS PARAMETERS

In order to study the influence of process parameters on the precision of the electro-processing of conical holes, a single-factor comparison test was conducted on the feed rate, processing voltage, and electrolyte concentration, keeping the other processing parameters unchanged. And taper effect of the law. The unilateral lateral clearance Δs and both sides of the taper were used as evaluation indexes. In the test, the taper hole was measured with an ultra-depth digital microscope and the hole diameter and hole taper were measured. Since the gap between the top and bottom side of the taper hole was not uniform, the three-point calculations were taken at the inlet end, the middle end, and the bottom end. Unilateral side of the average side of the gap Δ s, the formula is below.

$$\Delta s = \left[\sum\left(\frac{D-d}{2}\right)/3\right] \times \sin\theta \qquad (14)$$

In the formula (14), D is the diameter of the upper surface of the conical hole obtained by electrochemical machining, whose unit is μm and d is the diameter of the tube electrode. The main parameters are shown in Table 1.

Table 1 Selected main parameter tables.

Category	Main parameters
Electrolyte composition	$NaNO_3$
Electrolyte temperature (°C)	25
Electrolyte pressure (MPa)	0.8
Cathode taper (°)	20
Cathode speed (r/min)	200
Power type	Pulse power

4.1 The Influence of Feed Rate on Taper of Taper Hole

Select the sodium nitrate electrolyte mass fraction of 14%, the processing voltage which is 4v, change the processing speed to obtain the test data, and get the effect of the feed speed on the unilateral gap and taper. The processing quality is the basis of the electrochemical machining of the tapered hole. Appropriately increasing the feed rate helps to increase the processing efficiency and is essential for improving the productivity of electrolytic processing. As shown in the figure 9, as the feed rate increases, the side gap gradually decreases, the secondary corrosion time on the side becomes shorter, and the inlet diameter becomes smaller. However, when electrolysis is performed at a relatively fast feed rate, a short-circuit phenomenon is likely to occur, and the taper on the side surface is not uniform.

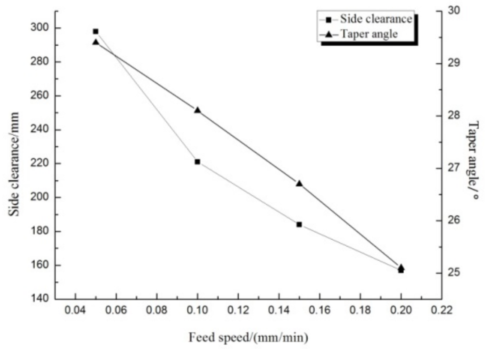

Fig. 9 Influence of feed speed on side clearance and taper.

4.2 Effect of Processing Voltage on Taper Cone Drilling

From the analysis of the electric field characteristics, it can be seen that the higher the voltage, the higher the current density at the end face and the side, and the more serious the diffusion of the tapered hole, resulting in a larger taper, an increase in the taper error with the cathode, and a lower processing accuracy.

For machining smaller conical holes, choose lower tool cathode feed rate, preferentially 0.1mm/min, 14% sodium nitrate solution for testing. As can be seen from figure 10, as the processing voltage is increased, the unilateral gap on the side becomes larger, the larger the hole diameter, the more severe the corresponding stray corrosion, and the greater the taper of the workpiece. Therefore, in the electrolysis process, the choice of processing voltage is extremely important. However, as the processing voltage decreases, the material removal rate and the machining efficiency are lower, and the radial clearance increases. Therefore, a reasonable processing voltage must be used.

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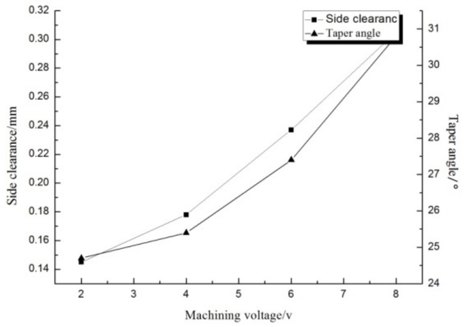

Fig. 10 Influence of processing voltage on side clearance and taper.

4.3 Influence of Electrolyte Concentration on Taper

Select 10%, 14% and 18% sodium nitrate electrolyte as a comparative test, and found that 10% sodium nitrate solution in electrochemical processing, the number of short circuit more, and the surface shown in Figure 10, select 18% sodium nitrate solution processing When the processing speed is adjustable to 0.3mm/min, the machining efficiency is better, but the taper is larger and the machining accuracy is not high. With proper increase of the electrolyte concentration, ion concentration become higher and effect of ions in the processing area become stronger. Because the localized effect of the electrochemical material removal reaction get smaller, the stray current increases removing of material. Therefore, in order to improve the processing accuracy, it is necessary to reasonably limit the electrolyte concentration. Experiments have shown that by choosing a smaller electrolyte concentration and processing voltage, the lateral clearance can be reduced. The processing gap decreases as the electrolyte concentration decreases. Therefore, the selection of a low concentration of electrolyte is advantageous for forming a small processing gap. The excessive reduction of the concentration of sodium nitrate solution leads to a decrease in the electrical conductivity and hence to a decrease in the current density. This results in a rapid decrease in the removal rate of the workpiece and a short-circuiting and burning of the workpiece.

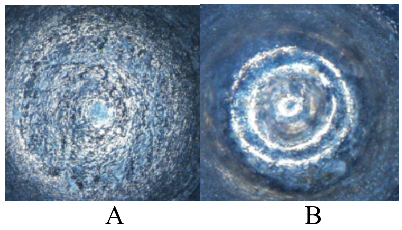

Fig. 11 Bottom map of mass fraction 10% A and 14% B sodium nitrate solution.

5. OPTIMIZATION OF TEST RESULTS

Based on the above experimental research and analysis, the optimization parameters were selected for electrolytic processing of conical tube electrodes. The $NaNO_3$ solution with a mass fraction of 14% was selected for the test, the processing voltage was 4V, and the feed rate was 0.1mm/min. Taper difference between the two sides of 0.46 ° taper, to meet the processing needs. The error in the machining results shown in Fig. 8 is small, and it can be seen from the partial enlargement that the accuracy of the shape is high, and both sides show good localization and processing capability.

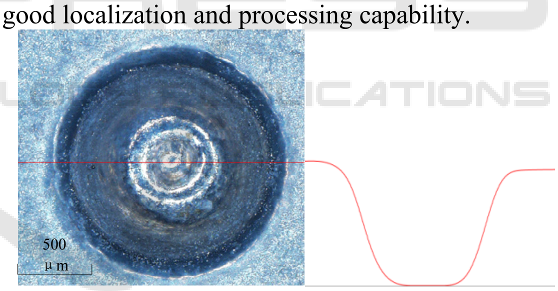

Figure 12 Conical hole profile view.

6. CONCLUSIONS

(1) An experimental study on the production of two different materials of the tube electrode by on-line electrolytic machining has been carried out, and it has been found that the stainless steel conical tube electrode can be used as a cathode for processing a tapered hole.

(2) By establishing the mathematical model and processing model of the electrolysis machining of the tapered tube electrode, the influence factors and electric field characteristics of the processing precision of the tapered tube electrode are analyzed,

and the parameter test is verified in the ECM experiment.

(3) Set up a conical tube electrode tester to analyze the effects of processing voltage, feed rate, and electrolyte concentration on the unilateral gap and taper. Select $NaNO_3$ solution with a mass fraction of 14%, the processing voltage which is 4V, and the feed rate which is 0.1mm/min and process a better tapered hole whose taper error is smaller, import roundness is better and cone burns is less.

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