Research on Improving the Taper of Hole Processing by Insulation Coating of ECM Cathode

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Abstract. Electrochemical machining (ECM) is widely used in metal parts processing because of its high processing speed, good surface quality, no stress and deformation of the workpiece after processing, and no tool wear [1]. However, ECM has the problems of high taper and low efficiency in the processing of pores due to secondary electrolysis [2-3]. Therefore, how to use ECM high-quality and efficient processing holes has become a research hotspot in many countries. Since electrolytic machining is to re-engraving the surface structure of the cathode material, the design of the cathode has a great influence on the improvement of the processing quality of the hole [4]. The use of sidewall insulating electrodes in the ECM process can improve the processing accuracy of the holes [5]. The sidewall insulation can be divided into full insulation and partial insulation, and the relationship between the degree of partial insulation and the taper of the formed profile has not been studied. In order to reduce the taper of the hole, Rolf Schuster [6] proposed using ultrashort voltage pulses to locate the processing area during electrochemical micromachining and to process some 3D microstructures on the copper plate. Fang X.L et al. [7] applied a potential difference between the auxiliary electrode and the anode to improve the accuracy of the micropore. Kim et al. [8] used disc electrodes to machine microporous structures and used array cathodes to improve processing efficiency. Yong L et al. [9] studied the ultra-short voltage pulse and high-speed rotating spiral electrode in the electrochemical drilling process to produce non-tapered small holes, and obtained the influence of process parameters on machining accuracy. In addition, in order to improve the processing quality of the holes, various electrochemical composite processing methods have been studied. This paper aims to reduce the taper of the anode workpiece hole by studying the degree of insulation of the cathode sidewall. The processing of the holes is performed by insulating coating the cathode...
structures to form different conductive radial heights $h_0$, as shown in Fig. 1. Let $\Delta S_n$ approach $X_0$ to reduce the taper of the hole. A multiphysics (electric field, flow field, temperature field and mathematical field) model for simulating ECM machining process using a moving cathode tool is proposed in different modes of conductive radial height $h_0$. And establish the mathematical relationship between $h_0$ and the taper of the machined hole to get the best processing method.

**Figure 1.** ECM processing of pores.

**Figure 2.** Electrochemical processing schematic.

### 2. Models

ECM is a processing technology that uses the principle of metal anode dissolution to complete the etching of the workpiece. During the processing, the negative pole of the power supply is connected with the tool, the positive pole of the power supply is connected with the workpiece to turn on the pulse current, and the electrolyte flows at a high speed between the two poles, at the same time keep the cathode tool at a certain speed. According to Faraday's law, the anode workpiece is continuously dissolved according to the shape of the tool of the cathode, so that the size and shape of the workpiece are re-engraved to achieve the processing purpose. Among them, the cathode is transformed from a solid to a hollow structure due to the design of the flow channel as shown in Fig. 2.

#### 2.1. Geometry model

In order to study the effect of introducing an insulated coated cathode on the machining accuracy, a physical model was constructed, see in Fig. 3. Among them, the cathode boundaries are 3, 4, 5, 7, 8, and 9. Where boundaries 3 and 9 can be partially electrically insulated from the electrolyte. The anode boundary is 12 and the entity is an electrolyte that flows between the two poles. The cathode has a diameter of 10 mm and the hollow structure has a diameter of 2 mm. The interelectrode gap (IEG) is 0.2 mm. The cathode moves downward at a constant rate $V$ during processing. A constant potential is applied to the surface of the anode in contact with the electrolyte, and the cathode is grounded. The electrolyte flows in a radial direction at a uniform rate, i.e., flows in from AB, and flows out from CD and EF.

**Figure 3.** Geometry model.
2.2. Theoretical model

According to the electric field theory, the potential distribution is given by the Laplace equation:

$$\nabla^2 \varphi = 0$$  \hspace{1cm} (1)

Where, $\varphi$ is the potential.

The relationship between current density $j$ and potential $\varphi$ is derived from Ohm’s law.

$$j = \kappa \frac{\partial \varphi}{\partial n}$$  \hspace{1cm} (2)

Where, $\kappa$ is the unit vector perpendicular to the workpiece surface; $\kappa$ is the conductivity of the electrolyte.

Because the motion of the flow field is considered as "turbulence", the velocity distribution of electrolyte in the simulation is represented by the standard model, which is called N-S equation by using continuity equation and momentum equation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$  \hspace{1cm} (3)

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}(-p \delta_{ij} + \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)) + F_i$$  \hspace{1cm} (4)

where, $i, j = 1, 2, 3$; $\rho$ is the fluid density; $t$ is the time; $u_i, u_j$ are the fluid velocity components; $x_i$ is the coordinate component; $F_i$ is the volume force component; $\sigma_{ij}$ is the stress tensor; $p$ the pressure; $\mu$ the molecular viscosity; $\delta_{ij}$ is the unit tensor, when $i \neq j$, $\delta_{ij} = 0$, when $i = j$, $\delta_{ii} = 1$.

Where, $\mu_{eff}$ represents the effective viscosity and we have $\mu_{eff} = \mu + \mu_t$, $\mu_t$ is turbulent viscosity

$$k : \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_j} \right] + G - \rho e$$  \hspace{1cm} (5)

$$\varepsilon : \frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho u_j \varepsilon) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} (C_{e1} G - C_{e2} \rho e)$$  \hspace{1cm} (6)

According to Faraday’s law, the removal rate of the anode workpiece is

$$\nu = \eta j \omega$$  \hspace{1cm} (7)

Where, $\eta$ is the current efficiency; $\omega$ is the chemical equivalent; $j$ is the current density.

3. Simulation

3.1. Simulation Parameters

It can be seen from formula 7 that the value of radial height $h_0$ can affect the current density distribution in the inner wall of the hole and further affect the anodic dissolution. Change the outline of its processing. The purpose of this paper is to study how to reduce the taper in hole electrochemical machining by improving the traditional cathode. Therefore, in order to obtain the relationship between the radial height $h_0$ and the current density and the shape of the anode profile, we studied the changes of current density and temperature in the electrochemical machining process with different values of $h_0$. And the relationship between them and the processing profile is established. The physical field of coupling simulation is electric field, flow field and temperature field. The parameters and values of the simulation model are shown in Table 1. The conductivity of electrolyte is measured by DDS-307 Conductivity Meter (Instrument and Electrical Science Instruments Co., Ltd., Shanghai, China). fig. 4 is a flow chart for simulation of anode profile forming.
Table 1. Simulation model parameters and value.

| Model parameters                  | values          |
|-----------------------------------|-----------------|
| Potential difference (V)          | 10              |
| IEG value (mm)                    | 0.2             |
| Electrolyte electric conductivity(S/m) | 1.542          |
| Thermal conductivity(W/m*kg)      | 0.58            |
| Temperature reference(°C)         | 20              |
| Inlet flow rate of electrolyte(m/s)| 0.5             |
| Electrolyte composition           | 1mol/LNaNO₃+0.1mol/LC₆H₈O₇ |
| Radial height(mm)                 | 0,0.6,1.2,1.8,2.4,3 |

3.2. Simulation results

3.2.1. Temperature distribution. In ECM, the temperature distribution is mainly affected by electrolyte convection, and the velocity at the entrance is set to be constant and vertical downward. Fig. 5 shows the distribution of temperature and velocity after 60 seconds of anodic dissolution when h₀ is 3 mm. It can be seen that the higher temperature is mainly concentrated in the gap of processing. Fig. 6 shows the temperature distribution after 60 seconds of anodic dissolution at different h₀. It can be seen that the minimum temperature is 303K when h₀ is 0.6 and 1.8mm. For other h₀ values, the gap temperature changes slightly. As a whole, the temperature changes in a small range with the change of the insulation height of the side wall. It has little effect on the accuracy of processing.
3.2.2. Current density distribution. Current density has the greatest impact on the accuracy of electrochemical machining, which directly affects the dissolution of the anode. Fig. 7 shows the current density and potential distribution of electrolyte for 60s of anodic dissolution when \( h_0 \) is 3 mm. Fig. 8 shows the current density distribution of electrolyte for 60s of anodic dissolution under different \( h_0 \). It can be seen from the fig. 8 that the current density of electrolyte for 60s of anodic dissolution is the highest when \( h_0 \) is 1.2 mm.

3.2.3. Anode profile forming distribution. As shown in Fig. 9, the anode forming profile simulated by the ALE moving grid at different \( h_0 \), it can be seen from the figure that as the \( h_0 \) continues to increase, the taper of the anode hole is continuously reduced. In order to obtain the mathematical model of the hole machining taper and \( h_0 \), the data is fitted through the matlab polynomial function model and the function relationship is obtained. The resulting mathematical model can quantitatively determine the relationship between \( h_0 \) and the taper of the machined hole.

\[
Y = 0.13589 \times h_0^3 - 2.486 \times h_0^2 + 13.13 \times h_0 + 9.0059 \quad (8)
\]

Wherein, \( Y \) is the taper of the hole.
4. Conclusions
This paper presents a cathode design method to improve the taper of electrolytic machining holes. The simulation of multi-field coupling is carried out, and the mathematical relationship between hole taper and cathode sidewall insulation is quantitatively described. The conclusions are as follows:

- Propose a partial insulation of the sidewall of the ECM cathode to machine the hole to reduce its taper.
- Establish a multiphysics model that uses mobile cathode tools to simulate ECM processing.
- Obtain a mathematical model between the different insulation heights of the cathode sidewalls and the taper of the processing holes, which can quantitatively reflect the relationship.

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