Research on The ECM of Inner Copper Alloy of Bimetal Composite Part Based on Flow Field Simulation

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Abstract: The high efficiency electrochemical machining (ECM) of inner copper alloy in bimetal composite part composed of copper and tungsten was taken as the research object. The cathodes with positive flow, reverse flow and side flow electrolyte flow were designed. The flow field simulation geometric model was established, and the flow field simulation and flow field uniformity analysis were carried out by COMSOL Multiphysics, the general structure of tool cathode was designed based on side flow type. The results show that the uniformity of the flow field in the side flow machining area is better, and the stability of the machining process can be improved by using the structure design of the front and rear positioning plates.

1. Introduction
Tungsten metal has the characteristics of high hardness, high strength, high melting point and high boiling point, which is often used in modern industry, aerospace and other fields[1]. The bimetallic composite composed of copper and tungsten is shown in figure 1. Its outer contour is hexagonal and its inner contour is circular. The inner layer of copper alloy needs to be removed during processing.

![Figure 1. Schematic diagram of workpiece.](image)

It is hard to remove the inner copper alloy completely and efficiently without affecting the tungsten surface quality and precision by the traditional machining. ECM is a process that uses the principle of metal electrochemical anodic dissolution to process the workpiece into a specific shape and size. It has the characteristics of high machining efficiency, good surface quality and no tool electrode loss[2].

Li et al.[3] designed a positive cathode structure with independent working teeth to solve the difficult
machining problem of rifling of gun barrel, which achieved high machining accuracy and accelerated the development cycle of cathode. Ai et al.\(^4\) used nanosecond pulse power supply to complete the ECM of copper, solved the problem of forming the soft material brass, and improved the localization ability.

COMSOL Multiphysics software can be used to solve the flow field, electric field and other multiphysical field problems in the process of ECM, and optimize the process parameters of ECM. Wang et al.\(^5\) simulated the inter hole of the tube electrode flow field in ECM, and optimized the machining parameters and improved the stability of the machining process by analyzing the flow field distribution. Mu\(^6\) simulated and analyzed the flow field distribution under different electrolyte flow forms in order to improve the defects such as "holes" in the flow field of ECM, which effectively improved the uniformity of the flow field. Chen et al.\(^7\) used the turbulent SST model to solve the electrolyte flow velocity and temperature distribution, the effects of flow rate, and the electrolyte temperature distribution and the anode current density were analyzed.

In this paper, take the ECM of the inner copper alloy of the bimetallic composite part as the research object, the cathode structure is designed and the flow field simulation and analysis are performed based on the standard turbulent \(k-\varepsilon\) model.

2. Cathode structure design and flow field simulation

2.1 Cathode structure design
Assuming that the machining is reached in a balanced state, the balance machining gap is 0.5 mm. According to the characteristics of the workpiece, the machining requirements and the principle of ECM, the corresponding structure of tool cathodes of the forward flow, reverse flow and side flow are preliminarily designed, as shown in Figures 2 and 3.

![Schematic diagram of tool cathode structure.](image)

2.2 Flow field simulation mathematical model
It is assumed that the fluid is in an ideal state: the electrolyte is incompressible and the dynamic viscosity does not change with the change of velocity gradient\(^8\). The electrolyte is turbulent and the machining process is steady. It can be described by mass conservation equation and momentum conservation equation:

\[
\begin{align*}
\text{div}(\vec{v}) &= 0 \\
\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} &= \frac{1}{\rho} \text{grad} p + \mu \nabla^2 \vec{v}
\end{align*}
\]

Where, \(\vec{v}\) is the velocity vector, \(p\) is the pressure, \(\rho\) is the density, \(\mu\) is the dynamic viscosity.

The electrolyte is NaNO\(_3\) solution with 20% mass fraction at the temperature of 293.15K, and the
outlet back pressure is standard atmospheric pressure. Selection the standard turbulence $k$-$\varepsilon$ model simulates the flow field, where $k$ is the turbulent kinetic energy, $\varepsilon$ represents the turbulent dissipation rate. The transport equation is:

$$
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\rho k}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \tag{2}
$$

$$
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\rho k}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + G_{1\varepsilon} - C_{2\varepsilon} \rho \frac{k}{\varepsilon} \tag{3}
$$

Where, $\rho_k$ and $\rho_\varepsilon$ are empirical constants, $G_k$ is the production term of turbulent kinetic energy $k$ caused by changes in the average velocity gradient. $G_{1\varepsilon}$ and $G_{2\varepsilon}$ are empirical constants.

According to the Reynolds number $Re$ calculation formula:

$$
Re = \frac{u D_h}{v} \tag{4}
$$

Where, $u$ is the flow rate. When $Re<2300$, the flow state is laminar flow, when $Re>2300$, it is turbulent flow, and the turbulent flow velocity $u_T$ needs to meet the formula as:

$$
u_T > 2300 \frac{v}{D_h} \tag{5}
$$

The electrolyte kinematic viscosity coefficient $v$ can be replaced by the kinematic viscosity coefficient of water at 293.15K, which is $1.01\times10^{-6}$ m$^2$/s, the hydraulic diameter $D_h$ is 0.5 mm, and the turbulent flow velocity $u_T$ should be greater than 4.646 m/s.

### 2.3 Flow field simulation geometric model

The geometric model of flow field is established by Solidworks as shown in figure 4 ~ 6.

![Figure 4. Geometric model of forward flow field.](image)

![Figure 5. Geometric model of reverse flow field.](image)
2.4 Flow field simulation analysis

Using COMSOL Multiphysics simulation software, the standard $k$-$\varepsilon$ model is used to simulate the uniformity of the flow field in the processing area of forward flow, reverse flow and side flow, and analyze the uniformity of the flow field. The uniformity of flow field refers to that the electrolyte flow on the machining surface is uniform and sufficient in the process of ECM, and there are no flow field defects such as streamline intersection. The uniformity of flow field is a key index to evaluate the stability and performance of flow field.

Set the flow rate at the entrance of 5 m/s to obtain the flow velocity distribution in three flow modes, the figure 7 is the velocity distribution figure after the flow field solution.

![Velocity distribution figure](image)

(a) Positive flow type    (b) Reverse flow    (c) Side flow type

Figure 7. Velocity distribution.

According to the symmetry of the flow field simulation model, one sixth of the symmetry center plane of the flow field geometry model is selected to observe the flow field uniformity in the machining area. Choose the flow velocity of 10 points in the section for observation, and the location of selected points are shown in the Figure 8. The velocity data of each point under the three flow forms are processed by percentage transformation, Change value of velocity percentage as shown in table 1 and Figure 9 is the data curve of Table 1.
Figure 8. Location of observation point of simulation section.

Table 1. Change value of velocity percentage of observation point.

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Positive | 0.60 | 0.73 | 0.89 | 1   | 0.95 | 0.93 | 0.90 | 0.84 | 0.79 | 0.88 |
| Reverse  | 0.68 | 0.87 | 1   | 0.93 | 0.91 | 0.92 | 0.91 | 0.92 | 0.81 | 0.97 |
| Side    | 0.74 | 0.91 | 1   | 0.99 | 0.98 | 0.97 | 0.95 | 0.93 | 0.87 | 0.91 |

Figure 9. Flow rate percentage transformation value of observation point.

It can be seen from the Table 1 and Figure 9. that the change trend of flow velocity of the three kinds of electrolyte in the gap is roughly the same. The flow velocity increases rapidly at the entrance of the gap, and has a small fluctuation in the gap, and increases slightly at the outlet due to the rapid drop of electrolyte pressure.

The standard deviation of 2 ~ 10 points in Table 1. are shown in Table 2.

Table 2. Standard deviation of percentage transformation value.

| Flow form      | Standard deviation |
|----------------|--------------------|
| Positive flow  | 0.82               |
| Reverse flow   | 0.55               |
| Side flow      | 0.44               |

It can be seen from Table 2. that the velocity fluctuation of the positive flow type in the processing area is the largest, the uniformity of the flow field is the worst. The side flow type has the least fluctuation of velocity and has the best uniformity of flow field.

3. General structure design of cathode

The general structure of the cathode was designed based on the side flow type. In order to avoid the disadvantages of cathode vibration caused by high-speed electrolyte impact when the cathode is feeding in the composite part, the front and rear positioning plates of the cathode are designed. The front positioning plate is circular in outline, and the rear positioning plate is hexagonal in outline. The positioning plates are with liquid through holes. The guide section is designed so that the electrolyte is
turbulent when it enters the processing area. The general structure of the cathode is shown in Figure 10.

![Figure 10. General structure of cathode.](image)

The front positioning plate, the rear positioning plate and the diversion section are all made of insulating epoxy resin, and the cathode material is stainless steel.

4. Conclusion

This paper had researed the electrolytic processing method of copper alloy in the inner layer of copper tungsten bimetal composite part. Three kinds of tool cathode are designed. The flow field geometry model of three cathode structure is established and simulated with standard turbulence model in the COMSOL. The results show that the flow field uniformity is better under the side flow mode. The structure of tool cathode, the guide section, front positioning plate and rear positioning plate can effectively improve the ECM stability.

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