Effects of Machining Parameters on Electrochemical Multi-Field Coupling

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1. Introduction

Electrochemical machining has been widely used in the machining of a large number of precision metal parts because it has the advantages of no loss of tool cathodes and no machining deformation and internal stress on the surface of the workpiece [1, 2]. However, electrochemical machining involves multiple physical fields such as electric field, flow field, and temperature field, which brings difficulties to the accurate prediction of electrochemical machining process. In order to understand the coupling effect and processing mechanism more vividly, a large number of scholars have used experiments and simulation methods.

The relative stability of the flow velocity in the machining gap has an important influence on the results of electrochemical machining. In order to study the flow field distribution of the leaf-shaped channel, Qu et al. [3] proposed a method to increase the electrolyte inlet pressure to ensure the stability of the flow velocity in the machining gap. The results show that the electrolyte flow rate and stability in the gap between the electrodes increase with the progressive pressure, and a high cathode feed rate can be used to obtain good processing stability and improve processing efficiency. G. Mayank et al. [4] found that bubbles in electrochemical machining have an important effect on electrolyte conductivity and then affect the removal rate of materials. Manikandan et al. [5] used the gray correlation analysis method to establish a mathematical model of the influence of the tube electrode electrochemical machining feed rate, electrolyte flow rate, and electrolyte concentration on the material removal rate and machining gap, and obtained an optimized parameter combination. Zhang et al. [6] used the k-ε turbulence model to simulate the flow field of electrochemical machining, designed the tool cathode structure, and analysed the design of the cathode and the workpiece under different processing conditions through multiphysics simulation. The electric field characteristics verify that the designed cathode can meet the processing requirements. Gao et al. [7] developed and studied a quadratic polynomial model and a size analysis model to predict the width and depth of microchannels caused by abrasive-assisted electrochemical jet machining. The study found that the jet diameter affects the channel width, while the working voltage and processing time affect the channel depth. Tang et al. [8] studied the electrochemical dissolution characteristics, open circuit potential, electrochemical impedance spectroscopy and anodic polarization curve of electrochemical machining GH4169 alloy, and derived the formula of the Bode diagram of the peak phase of electrochemical polarization resistance and AC impedance and then compared

the surface defects caused by unstable flow in different electrolytes. There is obvious stray current corrosion in the sidewalls of electrochemical machining of deep narrow grooves, which limits the improvement of machining accuracy. In order to improve the machining accuracy of deep grooves, Feng et al. [9] studied the influence of the combination of pulse and oscillation on the average current density distribution on the sidewall of the deep narrow groove based on the finite element analysis of the electrostatic field. Simulation and experiment found that as the oscillation amplitude increases, the uniformity of the deep and narrow grooves is significantly improved, and a smaller average groove width and better groove width uniformity can be obtained. Chen et al. [10] proposed a conductive mask spray electrochemical machining method to reduce the overcutting of micro-pits. It is found that the conductive mask can effectively reduce the electric field at the edges of the micro-pits, and compared with the insulating mask, the outline of the pits is significantly reduced. Yang et al. [11] established a flow field model for electrochemical machining of deep spiral holes with gradually changing grooves to study the distribution of electrolyte flow field in the machining gap. By optimizing the design of the cathode model, the liquid holes on each cathode process area are increased, which can eliminate the defect of uneven electrolyte distribution in the gap, and the problem of short-circuit burns in the electrochemical machining process can also be avoided.

Electrochemical machining involves three couplings between electric field, flow field and thermal field. During the entire electrochemical machining process, the machining will be affected by the hydrogen precipitated on the surface of the cathode, which will affect the final machining quality of the workpiece. The specific distribution of electrolyte pressure, temperature, current density and bubble rate in the gap will be affected by the gas-liquid two-phase flow characteristics in the processing gap, but most simulations ignore the precipitation on the cathode surface. Therefore, the paper combined with simulation software to simulate and analyse the influence of different voltage and electrolyte inlet pressure on current density, temperature, conductivity and hydrogen volume fraction distribution.

2. Theoretical analysis of electrochemical machining

In electrochemical machining, parameters such as electrochemistry, electric field, and flow field are not only very complicated in relation to each other, but also constantly changing with time and space. It is difficult to sample and test the corresponding parameter changes in real time

during processing. Therefore, the current theoretical analysis and calculations of electrochemical machining are based on certain assumptions and simplifications, and the guiding rules given from them can only be qualitative. The testing of many parameters affecting the machining process is also limited to the macro average value obtained outside the machining gap. These average values can indirectly reflect the changing law of the internal parameters of the machining gap, so they still have a great engineering practical value. Electrochemical machining uses the principle of electrochemical anode dissolution of metals in electrolyte. The workpiece serves as the anode and the tool serves as the cathode. At the same time, apply a direct current or pulse current between the cathode and anode, and pass the electrolyte with a certain pressure or speed, so that the workpiece is formed according to the designed cathode shape and has a certain dimensional accuracy. The processing principle is shown in Fig. 1.
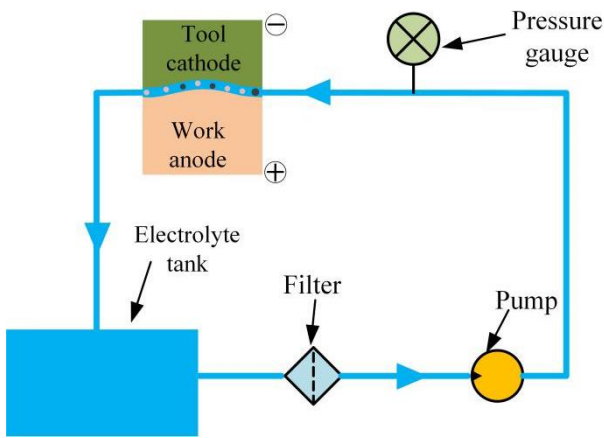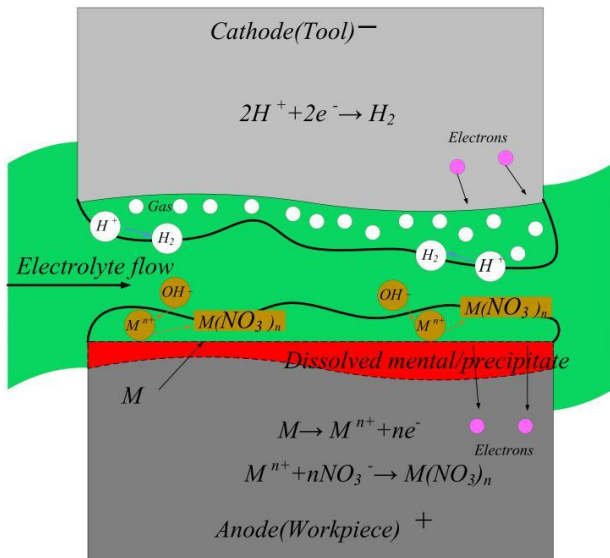

Fig. 1 Principle of electrochemical machining

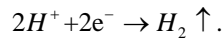Fig. 2 Principle of electrochemical reaction

The main feature of electrochemical machining that is different from mechanical machining is that it is a non-contact machining. The electrolyte flows through the gap between the electrodes, forming a conductive path between the two electrodes. Under a certain voltage, the cathode of the tool is continuously fed to the anode of the workpiece, and the electrochemical reaction occurs on the processing surface of the workpiece, which causes the workpiece material to be continuously dissolved and eroded. The

reaction product is then carried away from the processing area by the electrolyte flowing in the gap, so that the shape of the cathode is "replicated" to the workpiece, and the surface of the workpiece gradually forms a shape similar to the working surface of the tool. In electrochemical machining, redox reactions occur at the electrode-solution interface [13], as shown in Fig. 2.

Anode reaction:

$$Me - ne^- \rightarrow Me^{n+}$$
$$4OH^- - 4e^- \rightarrow 2H_2O + O_2 \uparrow .$$
$$M + nOH^- \rightarrow M(OH)_n$$
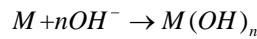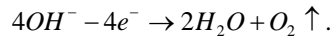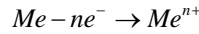
Cathodic reaction:

$$2H^+ + 2e^- \rightarrow H_2 \uparrow .$$

The anode metal loses electrons and is oxidized, and an oxidation reaction of anode dissolution occurs. Since the electrode potential of H^+/H_2 is higher than that of Na^+/Na, only hydrogen is released at the cathode and the electrode reaction of sodium deposition does not occur.

3. Multi-physics coupling simulation model establishment

3.1. Model establishment

In the simulation of electrochemical machining, the gas-liquid-solid three-phase flow, because the volume ratio of the anode product is very small, its influence can be ignored. When using COMSOL Multiphysics software to simulate, it can be simplified to a gas-liquid two-phase flow problem. In order to save computer resources and facilitate observation of the simulation results, the model is simplified into two dimensions, in which copper and titanium materials are used as tool cathode and anode workpieces, respectively. The model and meshing are shown in Fig. 3.
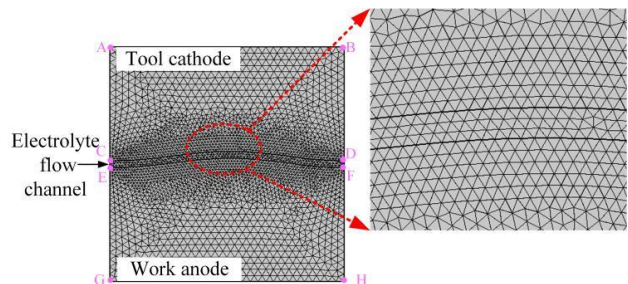

Fig. 3 Two-dimensional model and meshing

First define the relevant parameters in the software, such as the Faraday constant, the molar mass of hydrogen, and the initial conductivity of the electrolyte; Then define variables, such as hydrogen gas mass flux, electrolyte conductivity; Finally, parameters such as processing voltage and electrolyte inlet pressure are set. The relevant parameters are shown in Table 1.

In the electric field module, it is assumed that the electrochemical machining process has entered the equilibrium machining state, and the electric field parameters do not change with time. Meanwhile, assuming that the conductivity of the electrolyte remains constant and isotropic,

the current efficiency of the electrolyte is approximately constant. According to the basic theory of electric field, the distribution of electric field potential Φ in the entire processing area (referring to the processing gap in the text) conforms to Laplace Eq. [14]:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0. \tag{1}$$

Table 1

Physical properties

Physical parameter	Value
Specific heat capacity of electrolyte c_p, J·kg^{-1}·K^{-1}	3730
The initial temperature T_0, K	298.15
Electrolyte density ρ, Kg·m^{-3}	1070
Outlet pressure P_0, MPa	0
Hydrogen molar mass M_{H2}, g·mol	2
Bubble size, ×10^{-3}mm	1
Initial conductivity of electrolyte k_0, S/m	7.2

The current module, bubbly flow, $k\sim\varepsilon$ module and fluid heat transfer module are selected, and the transient state is used as a research for related simulations. In the electric field module, it is assumed that the electrochemical machining process has entered the equilibrium machining state, and the electric field parameters do not change with time. Meanwhile, assuming that the conductivity of the electrolyte remains constant and isotropic, the current efficiency of the electrolyte is approximately constant.

In the turbulent bubble flow module, it is assumed that the gas produced by electrolysis obeys the ideal gas state equation, the temperature of the electrolyte remains unchanged, and the current efficiency of the electrolyte is approximately constant. The relationship between electrolyte conductivity k, electrolyte temperature T and bubble rate β is summarized as the following formula:

$$k = k_0[1 + \alpha(T_1 - T_0)][1 - \beta]^n , \tag{2}$$

where: k_0 is the initial conductivity of the electrolyte; α is the temperature coefficient of conductivity, and the value is generally 0.02~2; T_0 is the initial temperature of the electrolyte; n is the influence index of bubble rate on conductivity, and the value is generally 1.5~2. From the formula (2), it can be seen that the increase in the hydrogen composition and the larger the bubble rate will cause the conductivity to drop.

In electrochemical machining, hydrogen mainly precipitates on the surface of the cathode. According to Faraday's law, the amount of hydrogen produced per unit time and per unit area on the surface of the cathode tool can be obtained [15]:

$$N_{H2} = \frac{\eta i}{2F} , \tag{3}$$

where: i is the current density; F is the Faraday constant; η is the current efficiency.

In the flow heat transfer module, the temperature of the electrolyte in the machining gap is affected by the interaction of the electric field and the flow field, which satisfies the convection-diffusion Eq. [16]:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p v_1 \cdot \nabla T = \nabla \cdot (k \nabla T) + Q, \tag{4}$$

where: c_p is the specific heat capacity of the electrolyte; Q is the heat generated during processing. The heat generated in the electrochemical machining process mainly comes from two aspects: Joule heat generated by the current in the machining gap; heat generated by the electrode reaction (the heat generated is small and can be ignored).

3.2. Boundary condition setting

In simulation, the setting of boundary conditions is very important and has an important influence on the results. The relevant boundary conditions are set as follows:

a) Electric field boundary conditions: $\Phi_{GH}=U$; $\Phi_{AB}=0$;

b) Boundary conditions of turbulent flow: $P_{CE}=P$; $P_{DE}=P_0$;

c) Boundary conditions of bubbles: $NH_2=i/2F$ ($F=96500$, A·s·mol^{-1});

d) Fluid heat transfer boundary conditions: $T_{CE}=T_0$; DF is set as the outlet.

4. Analysis of simulation results

In order to study the influence of different voltage, electrolyte inlet pressure and interelectrode gap on current density, temperature, conductivity and bubble rate, a controlled variable experiment method is used, as shown in Table 2. To study the influence of machining voltage on the simulation results, keep other parameters such as electrolyte inlet pressure and machining gap unchanged and change the machining voltage.

Table 2

Experimental table of controlled variables

Test	Voltage U, V	Electrolyte inlet pressure P, MPa	Inter-electrode gap Δ, mm
1	8/12/16	0.4	0.4
2	12	0.2/0.4/0.6	0.4
3	12	0.4	0.2/0.4/0.6

4.1. Distribution cloud map of simulation results

In order to visually observe the simulation results, the corresponding current density, gas volume fraction, electrical conductivity and temperature distribution cloud diagrams at a certain time are drawn when the processing voltage is 12 V, the inlet pressure is 0.4 MPa and the interelectrode gap is 0.4 mm, as shown in Fig. 4.

It can be seen from Fig. 4, a that the current density in the electrochemical machining process gradually decreases along the process direction. The maximum current density is about 2.2e^5 A/m^2 near the electrolyte inlet, and the minimum is about 1.75e^5 A/m^2 at the cathode of the electrolyte outlet. When a large amount of electrolyte flows through the machining gap during electrochemical machining, the anode material is removed and hydrogen gas is precipitated on the cathode. Part of the generated hydrogen gas disappears with the flow of the electrolyte, and the other part reaches the exit position. As shown in Fig. 4, b, the hydrogen volume fraction gradually increases from the inlet to the

outlet. The minimum volume fraction of hydrogen at the inlet is about 0%, and the maximum at the electrolyte outlet is about 14%. The proportion of hydrogen volume fraction directly reflects the change of bubble rate. The change of bubble rate affects the change of conductivity, which in turn affects the current density between electrodes. The maximum

electrolyte conductivity at the entrance is about 7.2 S/m, which gradually decreases along the flow direction, and the minimum at the electrolyte exit is about 5.2 S/m. The change of conductivity and hydrogen volume fraction shows a reverse trend, as shown in Figs. 4, b and c.
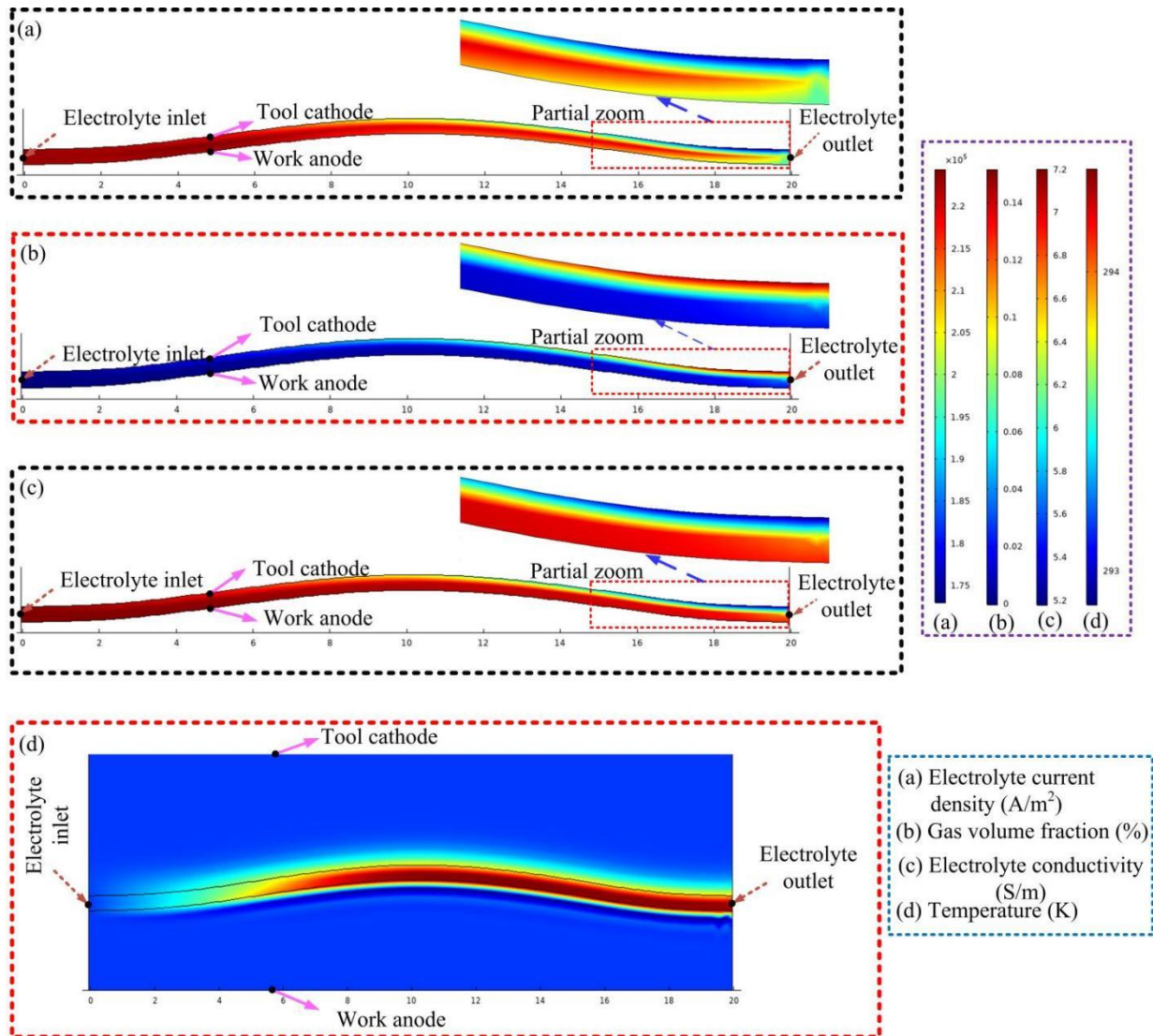

Fig. 4 Distribution cloud diagram: a - current density; b - hydrogen gas volume fraction; c - electrolyte conductivity; d - temperature

It can be considered that in electrochemical processing, the hydrogen ions in the solution obtain electrons on the surface of the cathode and undergo a reduction reaction to generate hydrogen gas and escape. Hydrogen flows with the flow of the electrolyte and gradually accumulates near the outlet, which will affect the conductivity. At the entrance, since the electrolyte is updated in time and the hydrogen content is low, the conductivity is relatively high and the current density is relatively high. Along the process direction, the hydrogen content gradually increases, so the electrolyte conductivity gradually decreases, and the current density gradually decreases. There is more accumulation of hydrogen content near the processing outlet, and the electrolyte conductivity and current density are the smallest.

It can be seen from Fig. 4, d that the minimum temperature at the inlet is about 293 K, and it gradually increases along the flow direction, and the maximum temperature at the outlet is about 295 K. It can be considered that

the flowing electrolyte will bring the products, heat and hydrogen generated during the process from the inlet to the outlet along the flow direction and accumulate at the outlet, which will lead to higher temperatures near the outlet. The temperature of the anode surface of the workpiece and the cathode surface of the tool gradually increase along the process direction, and the temperature of the anode surface is lower than that of the cathode surface. On the one hand, because the hydrogen generated on the surface of the tool cathode causes the surface electrolyte flow rate to drop, while the flow rate of the workpiece anode surface is relatively high, the heat generated in the electrolyte is less conducted to the workpiece anode, resulting in lower anode temperature rise; On the other hand, the thermal conductivity of copper material is much greater than that of titanium material, so the temperature of cathode copper is greater than that of anode titanium.

4.2. Effects of different processing voltages on the simulation results

It can be seen from Fig. 5 that when the processing voltage is the same, along the process direction, the current density gradually decreases, the hydrogen volume fraction gradually increases, the corresponding electrolyte conductivity gradually decreases, and the temperature gradually increases. At the entrance, the current density is the largest, and at the exit, the current density is the smallest. It can be considered that the electrolyte is updated in time at the entrance, and the electrolysis products and hydrogen are taken away by the flowing electrolyte, and finally accumulated at the exit, which will make the hydrogen volume fraction and temperature smaller at the entrance and maximum at the exit. The conductivity is affected by temperature and gas content. The higher the temperature, the greater the gas content, and the smaller the conductivity. This trend can also be seen from the graph. As the processing voltage increases, the current density at the same position gradually increases. As the current density increases, the heat generation in the gap will also increase, which will lead to an increase in processed products and hydrogen precipitation, resulting in a decrease in electrical conductivity.

a) Along the flow direction, mm

b) Along the flow direction, mm

c) Along the flow direction, mm
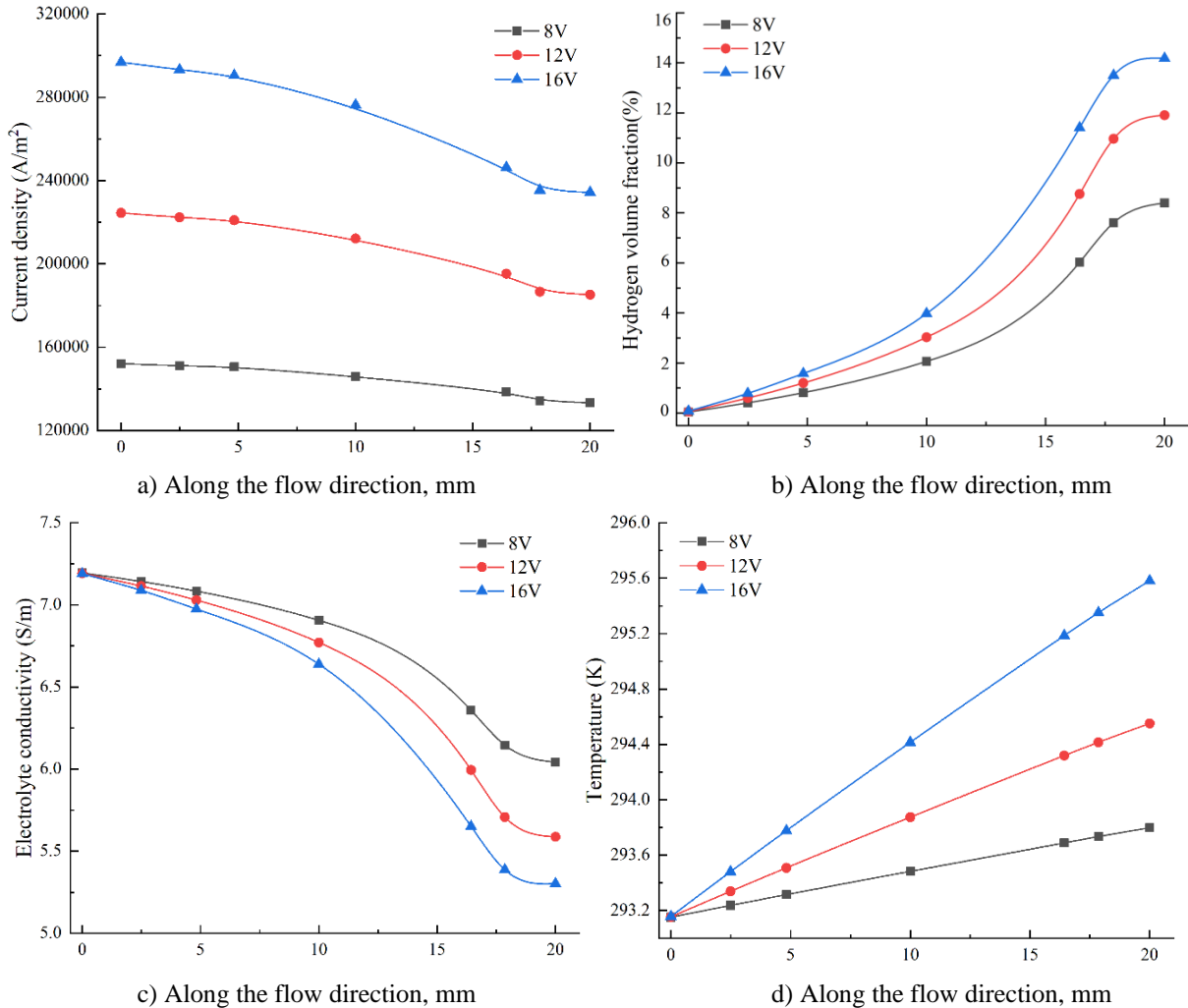
d) Along the flow direction, mm

Fig. 5 Effects of different processing voltages on the simulation results: a - current density; b - hydrogen gas volume fraction; c - electrolyte conductivity; d - temperature

4.3. Effects of different electrolyte inlet pressures on the simulation results

Fig. 6 shows the change trend of current density, temperature, conductivity and hydrogen volume fraction along the process direction obtained by changing the electrolyte inlet pressure under the same model with other processing parameters unchanged. It can be seen that the current density, temperature, conductivity and bubble change trends when the electrolyte inlet pressure increases from 0.2 MPa to 0.4 MPa are more obvious than when the pressure is 0.4 MPa and 0.6 MPa. When the electrolyte inlet pressure is the same, the current density and conductivity will gradually decrease along the process direction, the hydrogen volume fraction and temperature will gradually increase. The products, bubbles and temperature of electrochemical processing are brought to the outlet by the flowing electrolyte to accumulate, so the gas volume fraction and temperature at the outlet are larger, and the conductivity is lower, resulting in lower current density. The current density and conductivity at the same position increase with the increase of inlet pressure, and the hydrogen volume fraction and temperature gradually decrease. The analysis believes that the increase of the electrolyte inlet pressure increases the electrolyte flow rate per unit time, the electrolyte will be updated in time and the processed products in the electrolyte will be less, which increases the current density and conductivity.

a) Along the flow direction, mm

b) Along the flow direction, mm

c) Along the flow direction, mm
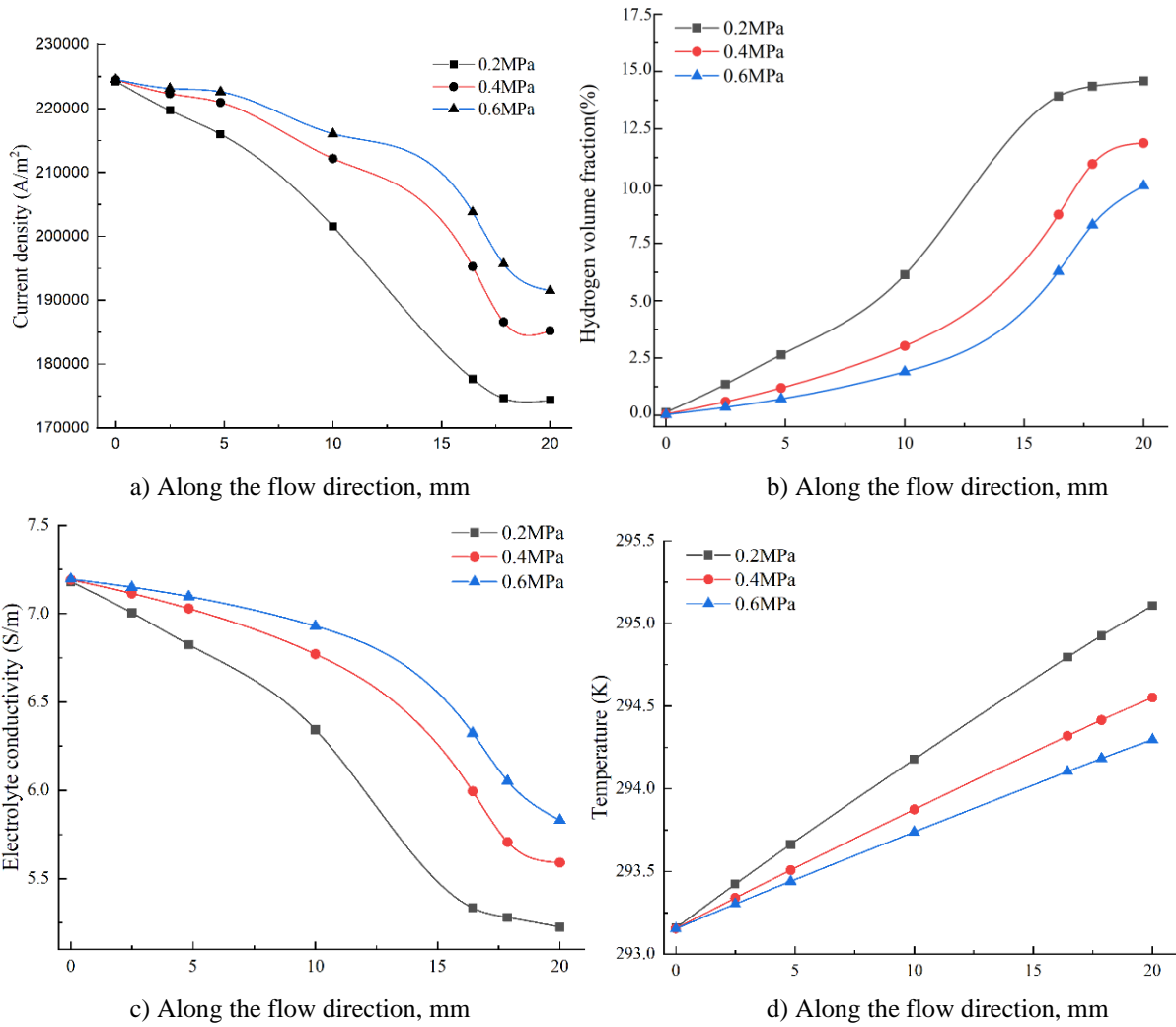
d) Along the flow direction, mm

Fig. 6 Effects of different electrolyte inlet pressures on the simulation results: a - current density; b - hydrogen gas volume fraction; c - electrolyte conductivity; d - temperature

4.4. Effects of different inter-electrode gaps on the simulation results

It can be seen from Fig. 7 that when the inter-electrode gap is 0.2 mm, the current density, hydrogen volume fraction, conductivity and temperature have a large differ-

ence between the outlet and the inlet, which are about $2.3e^5$ A/m2, 0.31, 3.7 S/m and 8 K, respectively. The change trend is more obvious than the gap between the poles of 0.4 and 0.6 mm, indicating that the machining gap has an important influence on it. Analysis shows t hat when the gap

a) Along the flow direction, mm

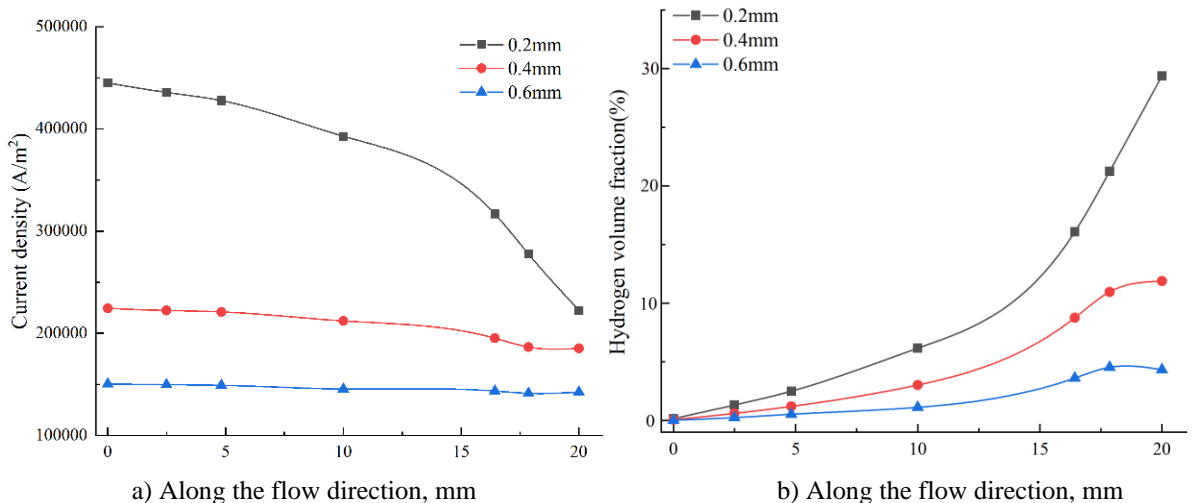b) Along the flow direction, mm

Fig. 7 Effects of different inter-electrode gaps on the simulation results: a - current density; b - hydrogen gas volume fraction; c - electrolyte conductivity; d - temperature

c) Along the flow direction, mm
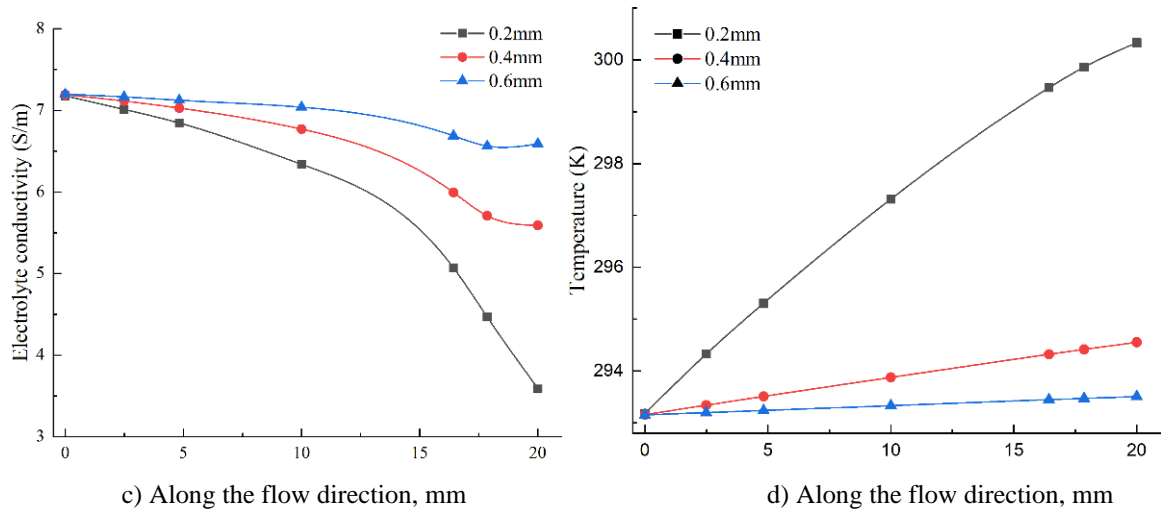
d) Along the flow direction, mm

Fig. 7 Continuation

between the electrodes is small, the current density between the anode and the cathode is larger, the electrochemical reaction in the entire gap is more intense, and the removal rate of anode surface material and the generation rate of hydrogen on the cathode surface are higher. With the increase of the inter-electrode gap, according to the principle of electrochemical machining, it can be considered that the increase of the inter-electrode gap will reduce the processing voltage between the cathode and anode. The flow rate of the electrolyte per unit time is relatively reduced, and there are fewer substances participating in the electrochemical reaction, which leads to a decrease in current density. The removal rate of anode surface material and the decrease of hydrogen generation rate on cathode surface are caused by the decrease of low current density. Therefore, as the gap between the electrodes increases, the current density, hydrogen volume fraction, and temperature difference at the outlet and inlet decrease.

5. Conclusions

Electrochemical machining is a processing method in which anode metal is continuously dissolved and finally formed. During processing, hydrogen gas is released from the cathode, which will have different effects on the electric field, flow field and temperature field. Therefore, the influence of different voltage, electrolyte inlet pressure and inter-electrode gap on current density, gas volume fraction, conductivity and temperature is studied in this paper.

1. The simulation results show that the current density increases with the processing voltage, and the maximum current density increases from 1.5e5 A/m^2 to 4.5e5 A/m^2.Because the degree of electrochemical reaction in the inter-electrode gap increases, the Joule heat increases, so the temperature and hydrogen gas fraction accumulated at the outlet also increase.

With the increase of electrolyte inlet pressure, although the current density increases, the volume fraction of outlet hydrogen decreases from 15% to 10%, and the temperature decreases from 295.3 K to 294.4 K. Because the increase in electrolyte inlet pressure is equivalent to more electrolyte inflow per unit time and the electrolyte is renewed in a timely manner, fresh electrolyte not only has a higher conductivity, but also can quickly take away the heat

and hydrogen in the gap. This reduces the hydrogen volume fraction and temperature at the outlet.

Increasing the gap between electrodes indicates that the distance between the cathode and the anode is larger. According to Faraday's law, it can be concluded that the current density between the anode and the cathode is lower, the generated Joule heat and the generation rate of hydrogen are reduced, so the volume fraction and temperature of hydrogen drop faster in the whole process.

2. The volume fraction of hydrogen is large near the cathode, and the distribution of hydrogen along the process direction is uneven. There is almost no hydrogen near the cathode at the inlet of the electrolyte, and near the cathode far from the inlet of the electrolyte, the hydrogen gradually increases and reaches the maximum at the outlet. Because the bubbles generated at the cathode near the entrance of the electrolyte are taken away by the electrolyte along the direction of the electrolyte flow before they can diffuse, they will eventually accumulate at the exit, resulting in a higher hydrogen content here. The content of hydrogen will affect the conductivity of the electrolyte, and the increase of the hydrogen content will cause the conductivity of the electrolyte to decrease, which will reduce the current density. The decrease of current density will reduce the dissolution rate of anode material, reduce the processing products and Joule heat, so the temperature will decrease accordingly.

In electrochemical machining, factors such as electric field, flow field, and electrochemistry not only influence each other, but also change with time and space, making it difficult to sample and test in real time during machining. The electrochemical theoretical analysis and simulation in the article are based on certain simplifications and assumptions, and the guiding rules given from this can only be qualitative and have certain reference value.

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EFFECTS OF MACHINING PARAMETERS ON ELECTROCHEMICAL MULTI-FIELD COUPLING

S u m m a r y

Electrochemical machining involves three couplings between electric field, flow field and thermal field. The precipitation of hydrogen on the surface of the cathode will affect the entire electrochemical machining process and the final machining quality of the workpiece. Finite element software is used to analyze the effects of different voltages, electrolyte inlet pressure and interelectrode gap on current density, hydrogen volume fraction, conductivity and temperature distribution in this article. The research results show that the increase of processing voltage will increase the current density, hydrogen volume fraction and temperature, and decrease the conductivity of the solution. As the pressure of the electrolyte increases, the current density and conductivity increase, but the hydrogen volume fraction and temperature decrease. The current density, hydrogen volume fraction and temperature decrease, and the conductivity increases when the gap between electrodes increases. At the inlet, the current density and conductivity are relatively large, and gradually decrease along the electrolyte flow direction, while the hydrogen volume fraction and temperature are the smallest at the inlet, and gradually accumulate along the electrolyte flow direction, and reach the maximum at the outlet. Through multi-physics coupling simulation, the current density, temperature, conductivity and bubble distribution in electrochemical machining can be predicted, which can provide a theoretical basis for actual electrochemical machining process parameter selection.