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Simulation and Experiment Study of Flow Field of Flow channel for Rectangular Hole in ECM Based on CFD

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ABSTRACT: Electrochemical Machining (ECM) is an effective method for machining the parts with the whole structure or special structure. Because the conventional machining methods are not suitable for processing these kinds of structures. In this work, taking electrochemical machining rectangular holes as the research objective, and analyzing the flow field characteristics of machined surface with three kinds of cathode channel structures. First discussing the working state of the ECM process and some equations to be complied with, then numerically simulating the models which have the same characteristics with design and simulation parameters, obtained the pressure contour and velocity contour on the machined surface. The simulation results indicated that the machining effect of long slot structure was not as good as that of arc slot and tilted slot structure, and few differences in machining effects were observed between the arc slot and tilted slot structure. A case study was presented to illustrate the effectiveness of the application of Computational Fluid Dynamics (CFD) in designing the flow field of cathode for ECM.

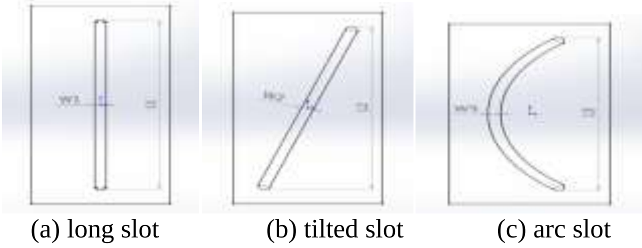
Keywords: Electrochemical Machining (ECM); rectangular hole; Computational Fluid Dynamics (CFD); flow fields

I. INTRODUCTION

Electrochemical Machining (ECM) is one of the advanced modern technologies, and used to machine electrically conductive materials and shapes that are more difficult to machine by conventional methods. ECM is generally utilized for difficult-to-cut materials such as hardened steel,including alloy and tool steel, nickel alloys, tungsten, zirconium, and otherrefractory metals. As of now, ECM is employed in many applications for automotive, aerospace, tool and die making, and electronic industries (e.g., turbine blades, engine castings, dies and molds, etc.) [1-2].

Although ECM has many advantages of having a high material removal rate, a good surface integrity, no forces and residual stresses, and has no tool wear or metallurgical defects[3]. But in industrial practices, ecm has revealed some disadvantages hampering its further development and wider acceptance [4], Among them, the design of electrode is one of the major problems, andthe design of flow field is an important part of the design of electrode. In light of this, some authors [5,6] demonstrate that computational fluid dynamics (CFD) is a promising approach to design of the flow field. The number of works [7-12] involving CFD has been increasing during recent years, but flow channel design is an important feature of cathode, as it can influence electrolyte distribution, electrolysis debris removal. These are factors that ultimately impact the performance of the machined workpiece.Thus, there is still the need to further investigate the most well-suited flow channel design for ECM.

The use of computational fluid dynamics (CFD) to simulate flow problems has risendramatically in the past three decades and become a fairly well established discipline sharedby a number of engineering and science branches[13-16]. Numericalsolution methods may be employed for CFD analysis for the simulation of fluid flow, heat andmass transport problems. Recent improvement of CFDenables researchers to visualize easily the localvelocity, and pressure fields in a domain by means ofgraphic facilities[17,18]. In the present work, a comparison of three kinds of flowfield structures of the cathode, which are long slot, arc slot and tilted slot structure(Fig.1),is madeusing 3D modeling software and Computational Fluid Dynamics (CFD).This study will allow to determine how differentflow field structures can impact the overall performance ofthe rectangular holes.



(a) long slot (b) tilted slot (c) arc slot

Fig. 1 Diagram of flow channel structure

II. NUMERICAL MODEL

2.1 Assumptions

The simulations in this work were realizedusing a standard *k-ε* turbulencemodel. To simplify the computational model and do not lose the essence of the studies, some assumptions were made for the CFDmodeling as follows:⑴ Turbulence flow; ⑵Incompressible fluids;⑶Single-phase flow, without regard to the electrolyzed products;⑷ In steady-state.

The model was implemented in ANSYS using thefollowing steps[19]:⑴ Generating themodeling in the DesignModelermodule;⑵Meshing in the Meshing module;⑶ Setting the parameters, including model configuration, domains, boundary conditions, etc.;⑷Numerical solution of the model;⑸Post-processing: visualization of results and analysis.

2.2 Model equations

The fundamental equations governing the flowfor mass and momentum for single-phase flows can be writtenas[17]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial(\rho \cdot \mathbf{u})}{\partial t} + \nabla \cdot (\rho \cdot \mathbf{u} \cdot \mathbf{u}) = -\nabla \mathrm{p} + \nabla \cdot \boldsymbol{\tau} + \rho \cdot \mathbf{g} + \mathbf{F} \tag{2}$$

where ρ is the fluid viscosity, $\mathbf{u}$ is the velocity vector, p is the static pressure, and the terms $\rho \cdot \mathbf{g}$ and $\mathbf{F}$ are the gravitational and external body forces respectively.

The standard*k-ε* turbulence model is the most widely used turbulence model. Here the *k* denotes the turbulent kinetic energy(m^2/s^2), whereas*ε* denotesthe dissipation rate (m^2/s^3). It includes two transport equations to define theturbulence scales. The model is basedon the transport equations for the turbulent kinetic energy, *k* and its rate of dissipation*ε*, and can be written asfollows[17].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_b - \rho\varepsilon - Y_M + S_k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{4}$$

Where, G_b is the generation of turbulent kinetic energy due to buoyancy, Y_M is the fluctuating dilatationto the overall dissipation rate, the turbulent viscosity is modeledas:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

Where, C_μ=0.09, $C_{1\varepsilon}$= 1.44, $C_{2\varepsilon}$=1.92and, $C_{3\varepsilon}$=0.09are constants. σ_k=1.0 andσ_ε=1.3 are the turbulent Prandtl numbers for *k* and *ε*respectively. S_κ and S_ε are source terms.

III. SIMULATION RESULTS AND DISCUSSION

It is required that the flow state is in turbulent, the electrolyte velocity $u_t$could be computed by the following equation[20]:

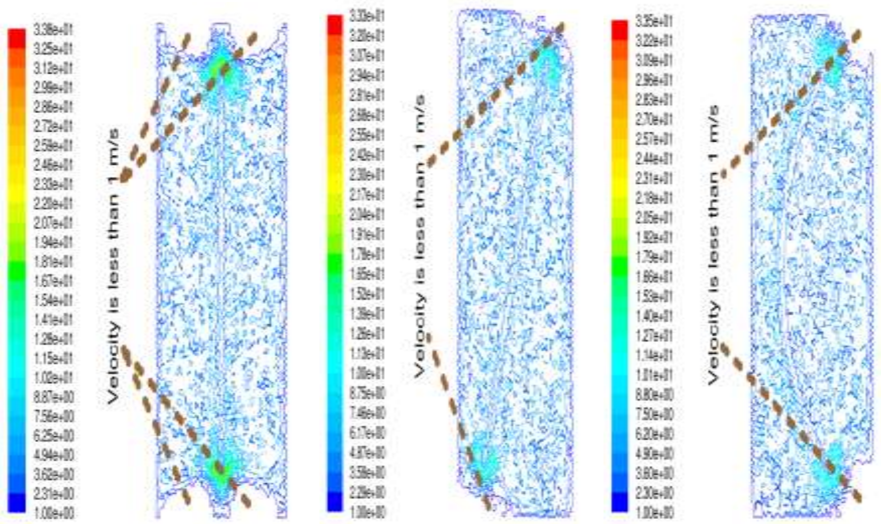
$$u_t > 2300\frac{v}{D_h} \tag{6}$$

Where, v is the kinematic viscosity coefficient of the electrolyte, D_h is the hydraulic diameter. With the equation (6), the inlet velocityof electrolyte should be u_{t1}>1.003 m/s (long slot), u_{t2}>0.996 m/s(arc slot), u_{t3}>0.999 m/s(tilted slot), respectively.

The effect of three kinds of flow structures was studied to illustrate which is suitable for electrochemical machining rectangular holes. To maintain consistency, three slot structures have the same size along the direction of length and width, that is the same size L and W, L1=L2=L3, W1=W2=W3. Moreover, this paper took the electrolyte in inter-electrode gap as the research object, and simulation analysis was done based on same parameters. In simulation, the pressure inlet and the pressure outlet were used as the boundary condition.

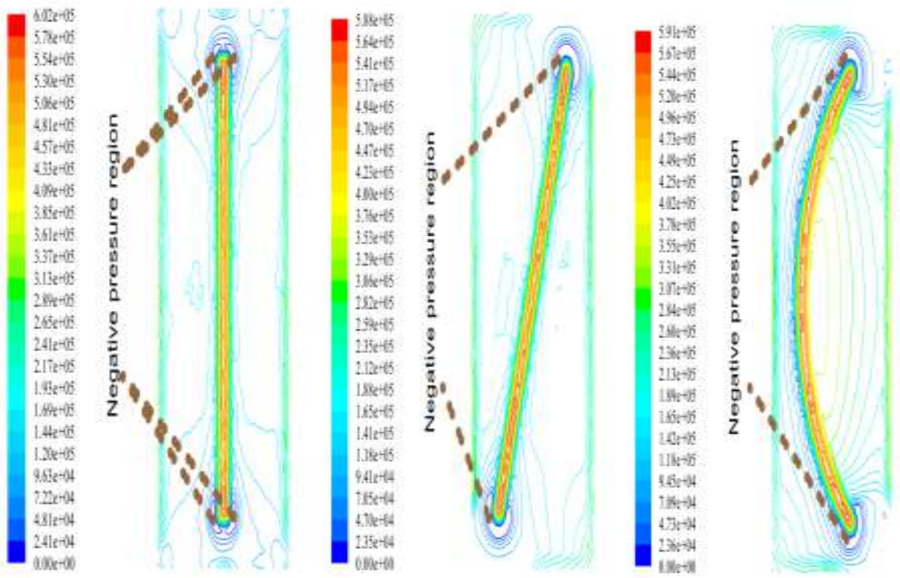
It can be observed from velocity contour (Fig. 2) that from the velocity perspective, for long slot structure (Fig. 2(a)) the areas on which the velocity was less than 1 m/s were the largest, and there were four separate small regions that were situated in the four corners. The shape of the region was somewhat similar to a quarter of an ellipse. The areas with tilted slot structure (Fig. 2(b)) and arc slot structure (Fig. 2(b)) were almost equal, and there were two separate small regions that were situated in the corners. According to the theory of ECM, the region with smaller velocity shows high possibility of machining defects. So, from the point of the view of the flow field, the long slot structure is not as good as the other two structures.

Meanwhile, negative pressure is harmful to electrochemical machining.For it maybe lead to cavitation, which will make electrolytic removal rate reducing and then the processing defects are prone to appear on some areas corresponding to the cavitation. The pressure contour (Fig.3) showed that there were negative regions in these three structures, and for both the tilted slot and arc slot structure the area of negative region was slightly larger than that of the long slot structure. But for long slot structure, the regions were scattered, and the areas of every region were smaller.These negative regions are the places that easily appear some defects.



(a) Velocity contour of long slot (b) Velocity contour of tilted slot (c) Velocity contour of arc slot

Fig. 2 Diagram of velocity contour of three channel structures



(a) Pressure contour of long slot (b) Pressure contour of tilted slot (c) Pressure contour of arc slot

Fig. 3 Diagram of pressure contour of three channel structures

IV. CASE STUDY

According to simulation results and analyses, the long slot structure was not quite fit for electrochemical machining rectangular holes than other two structures. But it is difficult to design these two channel structures because there are more design parameters such as angle relative to the length direction, radius, the position radius center, etc.So, in this paper, experimental research was carried out using the long slot structure to verify the above theory and simulated results. Some experimentalparameters were chosen as:the applied voltage was15 V, the cathode feed rate was 0.5 mm/min, the initial gapwas 0.5 mm, electrolyte inlet pressure was 0.6 MPa, the electrolytewas 22%$NaNO_3$, and its temperature was controlled at 28±1 °C.

Fig.4 shows the machined test piece. It can be seen that there were some convexities and flow marks remaining on the machined surface. There could be several reasons behind the defects. Firstly, the channel structure was not properly designed, and the experimental results justified the effectiveness of the simulation. Secondly,unsuitable processing parameters were important points that cause these defects.

Fig. 4 Photos of machined test-piece

V. CONCLUSION

In order to electrochemical machining better rectangular holes, this paper numerically simulated and analyzed the flow field of three kinds of channel structures, and had some conclusions as follows.

⑴Computational fluid dynamics can analyze the flow field of the three kinds of channel structure, so it is feasible to guide the design the flow field of the cathode.

⑵Simulation results showed that the machining effect of long slot structure was not so good as the other two channel structures, that is tilted slot and arc slot structures.

⑶Both appropriately designed flow channel structure and suitable processing parameters are key factors to obtain a good result.

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