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Configuration Design and Experimental Verification of Flow Field in Electrochemical Machining of Blisk Profiles

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Abstract. Electrochemical machining (ECM) is widely applied in aerospace and other industries, and has become one of the core technologies for blisk manufacturing. Flow field stability is a key factor affecting the machining stability and surface quality of ECM. In view of the structural characteristics and machining difficulties of blisk blade surfaces, four three-dimensional flow modes with additional electrolyte flow at the leading and trailing edges were designed, and finite element simulations were conducted for these four flow modes. The results show that the flow mode with an additional electrolyte inlet length of 12 mm achieves better performance, with higher electrolyte velocity and more uniform flow field distribution. In addition, cathode deformation caused by pressure difference was also analyzed to evaluate the rationality of the flow field under the four flow modes. Verification experiments were carried out, and the experimental results are consistent with the simulation results. With the optimized flow field model, the machining process is stable and high surface quality can be obtained.

Keywords Electrochemical machining (ECM); Blisk; Flow Field; Simulation

1. Introduction

Blisk is a key component of aero-engines, integrating blades and disks into a single structure to simplify engine design, reduce weight, and improve reliability^[1]. However, due to its complex structure, twisted blade profile, and the adoption of difficult-to-machine materials such as nickel-based superalloy, great challenges are posed to its manufacturing^[2]. Among various machining technologies, electrochemical machining (ECM) is a non-traditional machining technology that achieves material removal based on the principle of electrochemical dissolution. With its unique advantages including no tool wear, high machining efficiency, low processing cost, and independence from the mechanical properties of metal materials, it has become one of the main methods for blisk manufacturing^[3-5]. In-depth research on blisk ECM has been carried out at home and abroad, and a large number of achievements have been obtained. General Electric (GE) of the United States, MTU Aero Engines of Germany, and Russia all take this technology as a key research direction^[6]. In China, favorable research progress has been made in tool cathode design^[7], vibrating electrochemical machining^[8], flow field design^[9] and other related fields.

The flow field is critical for ECM stability, directly impacting machining efficiency and surface quality^[10]. Previous studies have advanced flow field design: Wu et al. applied hydrodynamic methods to cathode flow field design^[11]; Zhu et al. proposed a W-type flow field to reduce cathode deformation and improve machining accuracy^[12]; Xu et al. enhanced cascade channel machining quality with a Π -type electrolyte flow mode^[13]; and Xu et al. improved flow field uniformity using small-aperture outlets and group-hole tubular electrode^[14].

This study focuses on blisk blade profile ECM flow field design. Four three-dimensional flow configurations with auxiliary electrolyte supply at leading/trailing edges were designed, and finite element simulations were performed to identify the optimal flow scheme. Cathode deformation under

pressure difference was analyzed to evaluate flow rationality, followed by process experiments to verify simulation accuracy.

2. Three-Dimensional Flow Field Model Establishment

The electrochemical machining process of blisk is generally divided into two stages: rough machining and finish machining. In rough machining, a blank roughly similar to the blade shape is mainly machined to provide cascade channels for placing the sheet-formed cathode in finish machining. Finish machining is carried out with a formed electrode to realize the precise forming of the blisk. The machining method is shown in Fig. 1. The electrochemical machining of blisk profiles involved in this paper belongs to the finish machining stage. Sheet cathodes for the blade basin and blade back are fed into the pre-machined cascade channels. The blisk blank is usually placed obliquely, and the blisk is formed by the opposite feeding of two cathodes. After one machining cycle is completed, the blisk is rotated according to the angular relationship between blades, and the machining of the next blade is continued.

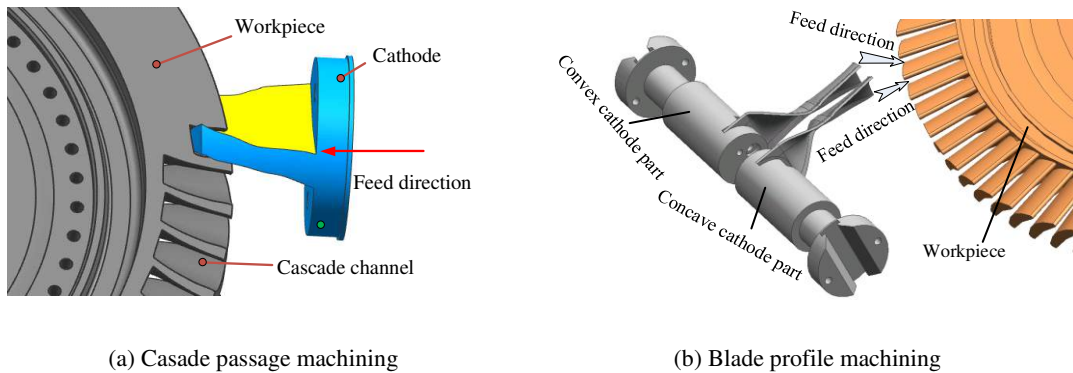


Fig. 1 Steps of blade profiles electrochemical machining

The stability of the electrolyte flow field is fundamentally governed by flow channel design, and the flow field directly determines the machining accuracy and surface integrity of electrochemical machined components. Non-uniform flow fields induce random distribution of electrolytic by-products within flow channels, resulting in stochastic fluctuations of electrical conductivity in the inter-electrode gap. This in turn triggers flow anomalies such as flow starvation, vortex formation and cavitation in the flow channel, and may even lead to catastrophic process failures including short-circuiting and workpiece ablation during machining. A rational flow field design is the cornerstone of successful electrochemical machining operations. In accordance with the characteristics of blisk blade profile ECM, four three-dimensional flow field configurations with auxiliary electrolyte supply structures at the leading and trailing edges are proposed. Specifically, four streams of electrolyte are introduced into the machining zone from four inlets respectively located at the blade root of the suction side, the blade root of the pressure side, the leading edge, and the trailing edge of the blade blank, and finally discharged from the blade tip. The common feature of the four configurations is that independent electrolyte supply is implemented for the leading and trailing edges, enabling active control of process parameters such as electrolyte pressure and flow rate in the machining regions of the leading and trailing edges. This design ensures timely removal of electrolytic by-products, improves flow field uniformity in the inter-electrode gap, and consequently enhances the machining efficiency and process stability of the full-profile blisk. The key geometric parameters of the leading/trailing edge inlets are cross-sectional length L and width W (Fig. 2a). Constrained by the tooling fixture and workpiece geometry, the value of W is fixed at 3 mm. Since the inlet length directly affects the electrolyte flow rate at the leading and trailing edges, an optimization study is carried out with four different length levels: $L=6, 12, 18, 25.6$ mm. Four

corresponding flow channel models are established under the cross-sectional dimensions of 3mm×6mm, 3mm×12mm, 3mm×18mm, and 3mm×25.6mm, respectively. To comparatively investigate the flow velocity variations in the machining zone during blade ECM under the four flow field configurations, three cross-sections are selected at three typical positions along the blade span — blade root, blade mid-span and blade tip — in each flow channel model (Fig. 2b) for analysis. The distances from these cross-sections to the root of the blade mid-span flow channel are 3 mm, 12 mm and 24 mm, respectively, and the remaining portion is defined as the flow guiding section.

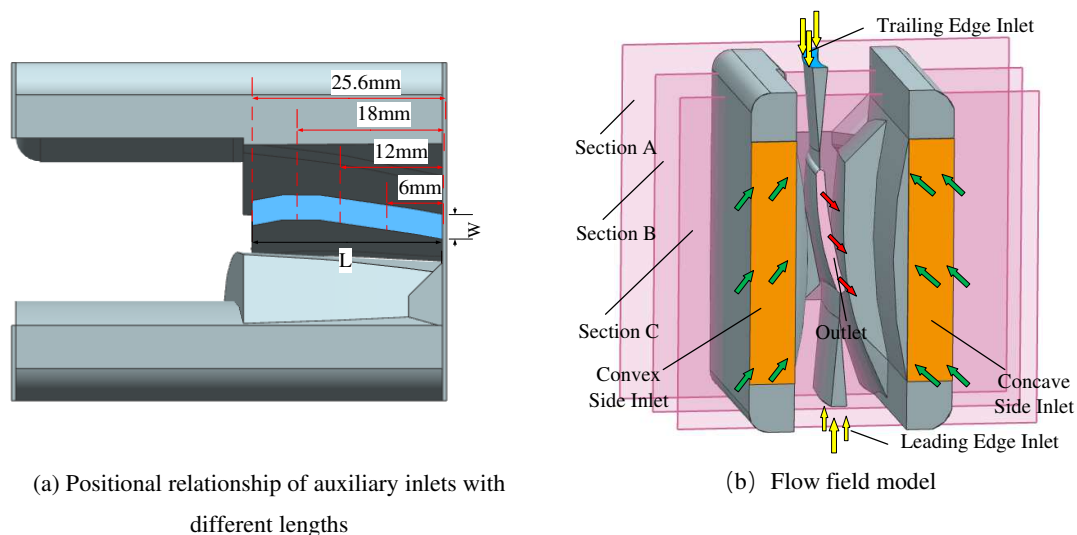


Fig. 2 Four three-dimensional flow field configurations

3. Flow Field Simulation and Analysis

3.1. Selection of Flow Field Mathematical Models

During the electrochemical machining (ECM) of blisk blade profiles, the electrolyte flows at high velocity through the inter-electrode gap (IEG), carrying away the heat, gas bubbles, and electrolytic by-products from anodic dissolution of the workpiece generated in the machining zone. The flow field within the IEG is highly complex in ECM. To simplify the flow field simulation, the following assumptions are adopted ^[15]:

- (1) The fluid is incompressible. At the interface between the fluid and the solid boundary, adjacent fluid layers exhibit no relative motion or slip with respect to the boundary.
- (2) The electrolyte is treated as in a turbulent flow state, and temperature rise as well as the energy loss induced by temperature rise are neglected.
- (3) The shear stress between adjacent flow layers of infinitesimal thickness is considered proportional to the shear rate perpendicular to the direction of motion ^[12].

Owing to the complex flow field behavior in the present study, the RNG $k-\varepsilon$ two-equation model is adopted for the turbulent, incompressible fluid, to better resolve flows with high strain rates and significant streamline curvature. The equations for turbulent kinetic energy and dissipation rate are given as follows ^[16].

$$\begin{aligned} & \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} \\ &= \frac{\partial}{\partial x_j} \left[a_k \mu_{eff} \frac{\partial k}{\partial x_j} \right] + G_k + \rho \varepsilon \end{aligned} \quad (1)$$

$$\begin{aligned} & \frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} \\ &= \frac{\partial}{\partial x_j} \left[a_k \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \end{aligned} \quad (2)$$

where: ε is the turbulent dissipation rate, k is the turbulent kinetic energy, μ_i is the time-averaged velocity, μ_{ef} is the effective viscosity, $a_k = a_\varepsilon = 1.39$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, and $C_\mu = 0.0845$, The turbulent kinetic energy production term G_k induced by the mean velocity gradient and the turbulent viscosity μ_i are calculated according to Equations (3) and Equations (4):

$$G_k = \mu_i \left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} \right) \frac{\partial u_i}{\partial x_j} \quad (3)$$

$$\mu_i = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4)$$

3.2. Simulation Results and Analysis

In the finite element analysis, the electrolyte flow channel model formed by the workpiece, cathode, and fixture in the ECM of blisk blade profiles is meshed, as shown in Fig. 3.

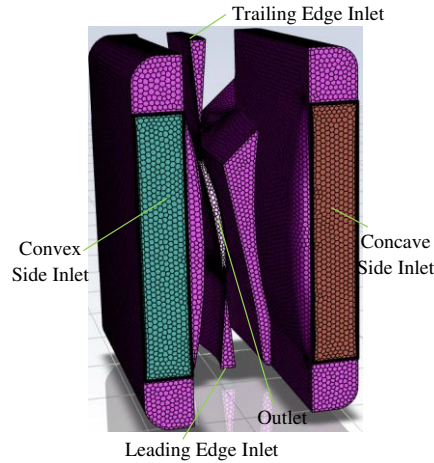


Fig. 3 Mesh generation of the electrolyte flow channel

Initial and boundary conditions are set for the mesh division model in Fig. 3. In the flow field models of the four configurations, all parameters are constant except for the cross - sectional length of the liquid inlet at the leading and trailing edges, which is a variable. The liquid inlet and outlet of the flow field model are both pressure - type. The pressure at the liquid inlets on the suction and pressure sides is 1.0 MPa, the pressure at the liquid inlets on the leading and trailing edges is 0.6 MPa, and the pressure at the liquid outlet is 0.15 MPa. The RNG k - ε turbulent model is adopted for the finite element solution. The flow field condition is judged by analyzing the velocity cloud diagrams of the trailing edge at sections A, B, and C of the root, blade body, and blade tip of the flow channel model, as shown in Fig. 4.

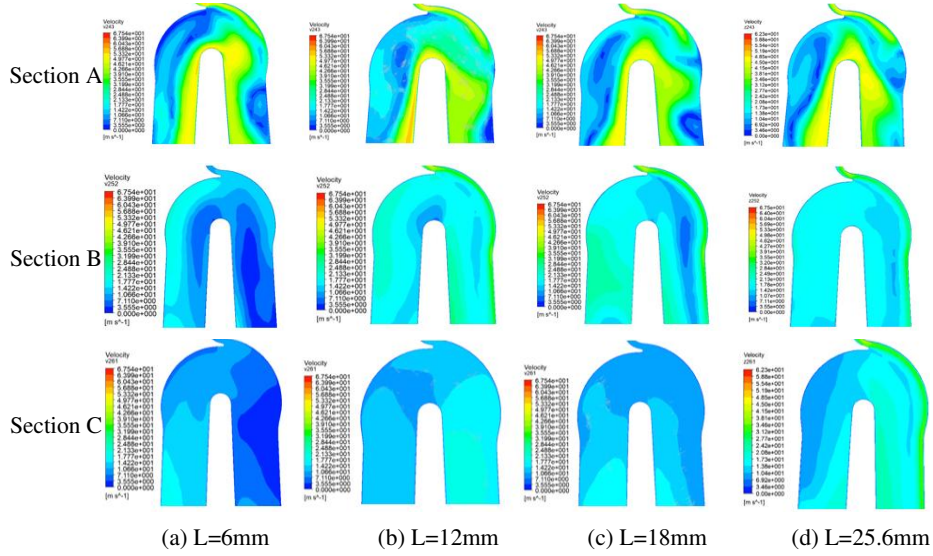


Fig. 4 Velocity cloud diagrams of the trailing edge at sections A, B, and C (root, blade body, and blade tip) of the flow channel model

From the velocity cloud diagram in Fig. 4, it can be seen that in the entire processing area of the blade, the flow velocity increases gradually along the flow path. A low - velocity region exists at the root of the blade. This is because when the electrolyte enters the flow channel of the processing area, the electrolytes in the pressure side flow channel and the suction side flow channel meet at the leading and trailing edges, resulting in mechanical energy loss and a decrease in flow velocity, which makes the flow field environment here relatively harsh and the flow field uniformity poor. At the same time, the flow velocity increases at the blade body and the blade tip, as the electrolyte after meeting gradually stabilizes, the energy loss decreases, and the electrolytic products can be quickly taken away from the processing area. In Fig. 4(a), the low - velocity area along the flow path is obvious and large in area. Due to the small size of the liquid inlets at the leading and trailing edges and the high flow velocity, the intersection area of the electrolyte is far from the leading and trailing edges area. But due to a large impact with the electrolyte from the suction and pressure sides, a large - area low - velocity area is formed. As a result, a liquid - shortage area is easily formed in the suction side area near the leading and trailing edges. During processing, the electrolytic products of the anode cannot be taken away quickly, and bosses are likely to appear on the processed workpiece or a short circuit may occur. In Fig. 4(b), the flow velocity changes uniformly along the flow path, and the overall flow velocity is also significantly increased, further improving the stability of the flow field. In Fig. 4(c), the low - velocity area at the root of the blade is obvious. At the same time, a flow velocity sudden change area appears on the suction side of the blade body. The overall flow velocity is relatively low compared with that when $L = 12 \text{ mm}$. In Fig. 4(d), the low - velocity area at the root of the blade is large, and the flow field is prone to liquid shortage or short circuit, with poor flow field stability. By comprehensive comparison, the flow field when $L = 12 \text{ mm}$ is optimal.

A quantitative analysis is performed on the flow velocity distribution in the trailing-edge flow channel of the blisk blade. As shown in Fig. 5, equally spaced profile lines are defined at a distance of 0.35 mm from the center of the trailing-edge flow channel along the flow path, with 200 data points sampled on each line. The electrolyte flow velocity at each point is extracted along the flow path, and the variation and distribution of electrolyte velocity at 1000 sampling points on the trailing edge under different configurations are analyzed. The mean velocity $\bar{v}$ and variance σ^2 are calculated, and the percentage of

points with a velocity below 4.68m/s relative to the total number is defined as pp . Taking the above three parameters as evaluation indicators, the statistical results are listed in Table 1. To more intuitively analyze the velocity variation of sampling points under different configurations, the relationship curves of the average electrolyte velocity, variance, and low-velocity point percentage versus the cross-sectional length L are fitted respectively, as shown in Fig. 6.

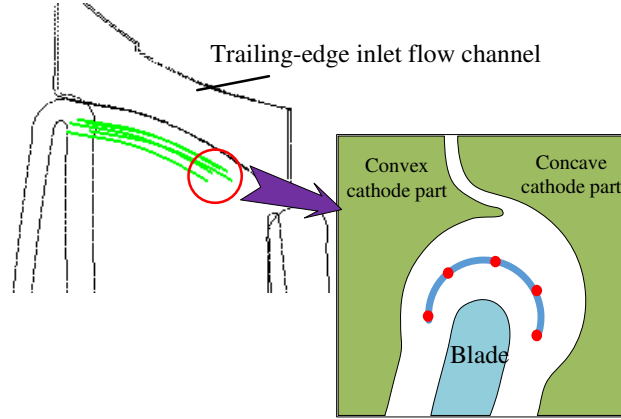


Fig. 5 Schematic diagram of sampling point positions along the flow path in the leading-edge flow channel of the blade

Table 1 Flow velocity analysis results of the trailing edge under different configurations

L (mm)	pp (%)	σ^2 (m ²)	$\bar{u}$ (m/s)
6	7.5	107.20	14.65
12	0	61.36	19.28
18	0.5	88.31	19.25
25.6	0.5	70.30	18.82

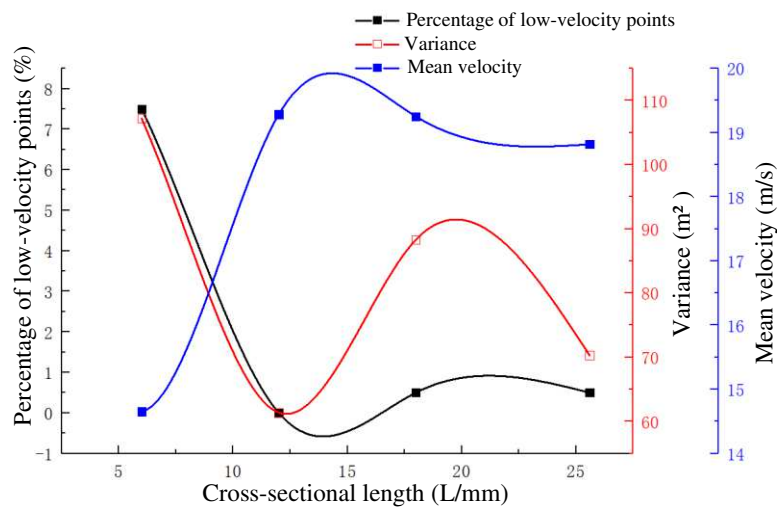


Fig. 6 Variation curves of electrolyte flow velocity under different configurations and different cross-sections

As can be seen from the results in Table 1 and Fig. 6, when the cross-sectional length $L = 6$ mm, the average electrolyte flow velocity is 14.65 m/s, which is the lowest among the four configurations. Meanwhile, the percentage of low-velocity electrolyte points accounts for 7.5%, and the variance reaches the maximum value of 107.20 m²/s² among the four configurations, indicating that the flow velocity at the trailing edge of this configuration varies greatly, the flow field is unstable, and the low-velocity region

is relatively large, which is highly likely to cause sparking and short circuits during the machining process. With the increase of the cross-sectional length L , the trailing-edge machining zone is supplied with sufficient electrolyte. Although a small-area low-velocity zone of electrolyte still exists, the average electrolyte flow velocity has been greatly improved, and the percentage of the number of low-velocity electrolyte points has also been significantly reduced. When the cross-sectional length $L = 12$ mm, it reaches the minimum value of 0, and the variance of electrolyte flow velocity also reaches the minimum value of $61.36 \text{ m}^2/\text{s}^2$, indicating that the flow field stability is significantly improved. Accordingly, it can be concluded that in the electrochemical machining of blisk blades, changing the cross-sectional length L has a significant effect on improving the electrolyte flow velocity and flow field stability at the trailing edge, and the optimal cross-sectional length is 12 mm.

3.3. Cathode Deformation Analysis

In the precision machining of blade profiles, the cascade passage of blisk is narrow, so the cathode tool must be designed as a thin-sheet structure. Therefore, the deformation of the finishing tool cathode under high-speed and high-pressure electrolyte environment becomes particularly critical. To verify the feasibility of the above flow field configurations, flow field simulations are re-conducted on the results, and the electrolyte hydraulic pressure obtained from the flow field simulation is applied to the cathode. The optimized cathode deformation distribution is shown in Fig. 7. When the cross-sectional length $L = 12$ mm, the total cathode deformation reaches the minimum value of 0.0084 mm, which has a negligible effect on the machining accuracy of electrochemical machining. The simulation results demonstrate that the proposed design method of flow field configurations is reasonable and effective.

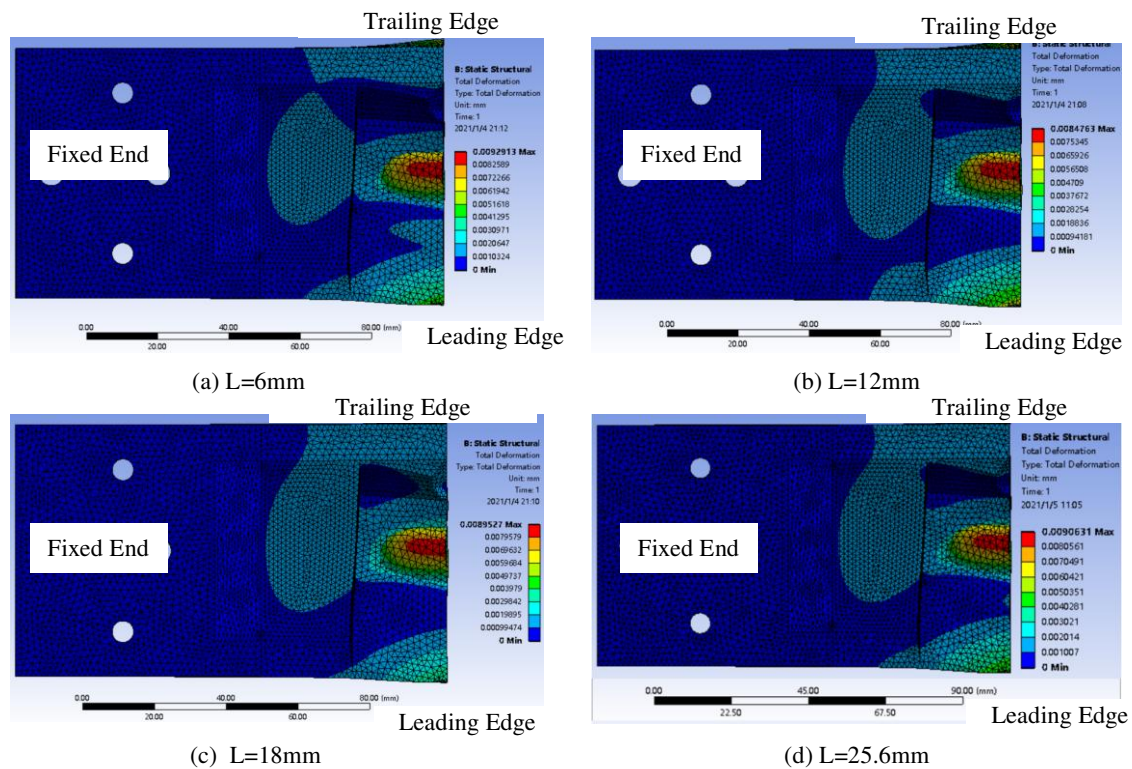


Fig. 6 Deformation of the cathode under different flow mode configurations

4. Experimental results and discussion

To verify the rationality and effectiveness of the mathematical model and simulation results, comparative experiments under four flow field configurations are carried out on a self-developed six-axis four-linkage electrochemical machining machine tool for blisk profile machining, so as to analyze

the influence of different flow field configurations on machining quality.

According to the previous simulation results, configuration plugs with different dimensions are fabricated using polyurethane as the material, as shown in Fig. 8. These plugs are installed inside the inlet and trailing-edge flow passages to form different flow field configurations. The workpiece is a fan-shaped segment with rough-machined cascade passages, made of superalloy. The cathode is a self-designed thin-sheet electrode made of stainless steel. The electrolyte is a 20% sodium nitrate solution with a temperature of 30 °C and a machining voltage of 20 V. The electrolyte pressure at the inlet of the convex part and concave part is 1.0 MPa, the pressure at the inlet of the leading edge and trailing edge is 0.6 MPa, and the pressure at the outlet is 0.15 MPa. The special experimental ECM setup is shown in Fig. 9, and the experimental parameters are listed in Table 2. The anode workpiece and cathode tool are sealed inside the fixture body, which is made of epoxy resin.

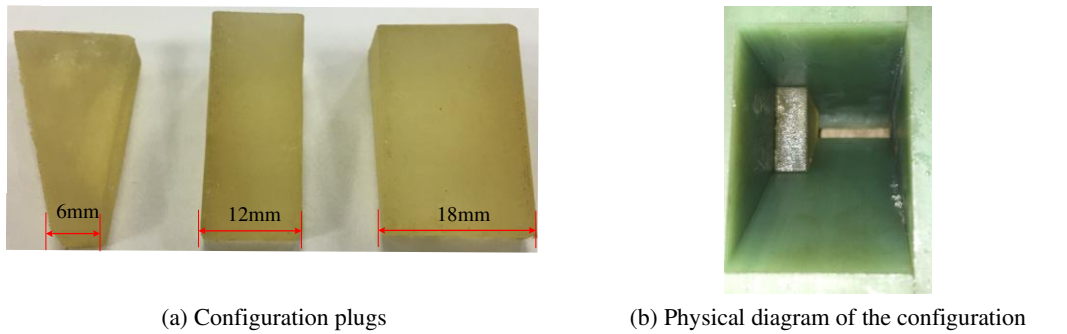


Fig. 8 Flow field configurations with different flow field types

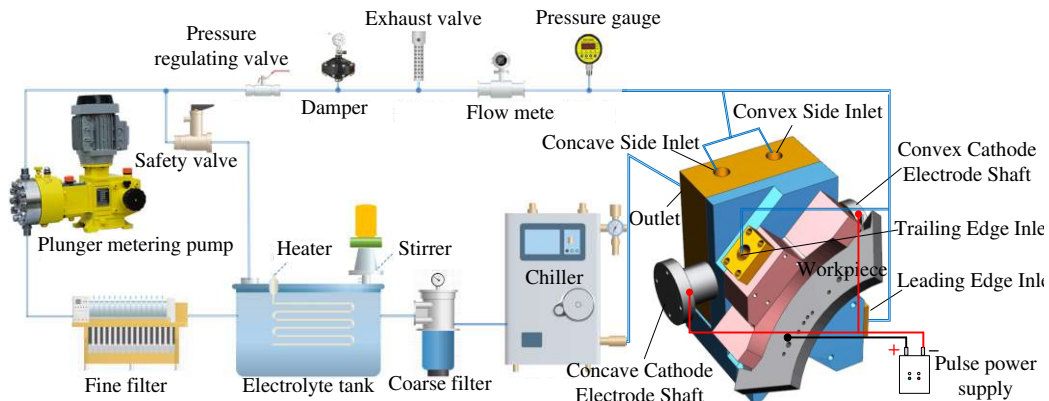


Fig. 9 Electrochemical machining experimental system for blisk

Table 2 Experimental parameters

Conditions	Setting
Workpiece material	GH4169
Electrolyte	20 wt% NaNO ₃
Electrolyte temperature	30°C
Machining voltage	20 V
Duty ratio	74%
Feed rate	0.8 mm/min
Pressure of convex part and concave part	1.0 MPa
Pressure of the leading edge and trailing edge	0.6 MPa
Outlet pressure	0.15 MPa

In the experiments, the cathode feed rate of 0.8 mm/min is adopted for all four flow field configuration models. The machining process is stable under the above feed rate, with no unexpected machining

failures observed. However, as can be seen from the machined samples in Fig. 10, when $L=6$ mm, a wide range of prominent flow marks appear on the blade body and blade tip, indicating that the flow velocity at these positions is relatively low and the flow field uniformity is poor, which is consistent with the simulation results. When $L=18$ mm and $L=25.6$ mm, only a few flow marks are detected, suggesting that the flow field is improved and its uniformity is enhanced. When $L=12$ mm, no flow marks are observed. Compared with the other three configurations, this flow field configuration exhibits better flow field uniformity, which verifies the accuracy of the finite element flow field simulation.

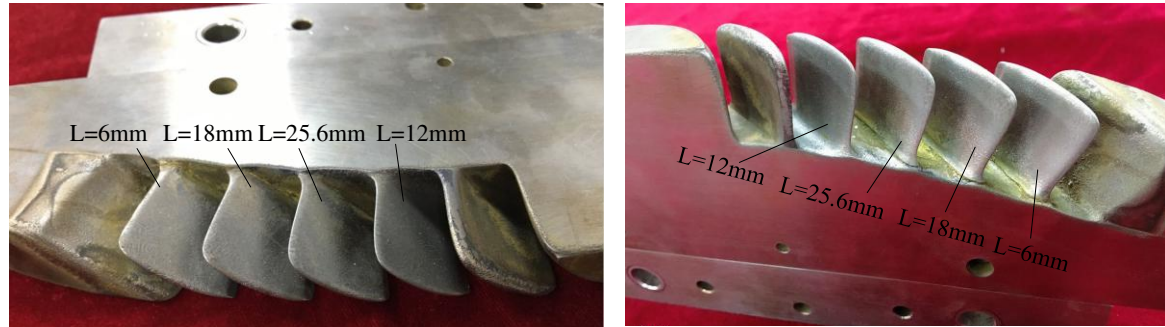


Fig. 10 Machined samples of electrochemical machining with different flow field configurations

Surface roughness of the machined blades is measured using a profilometer (Perthometer M1; Mahr, Germany), and the measurement results are shown in Fig. 11. The surface roughness of the blade back profile is $R_a = 0.397 \mu\text{m}$, while that of the blade basin profile is $R_a = 0.404 \mu\text{m}$. It can be concluded that the flow field configuration with a cross-sectional length of $L = 12$ mm yields favorable surface quality of the component.

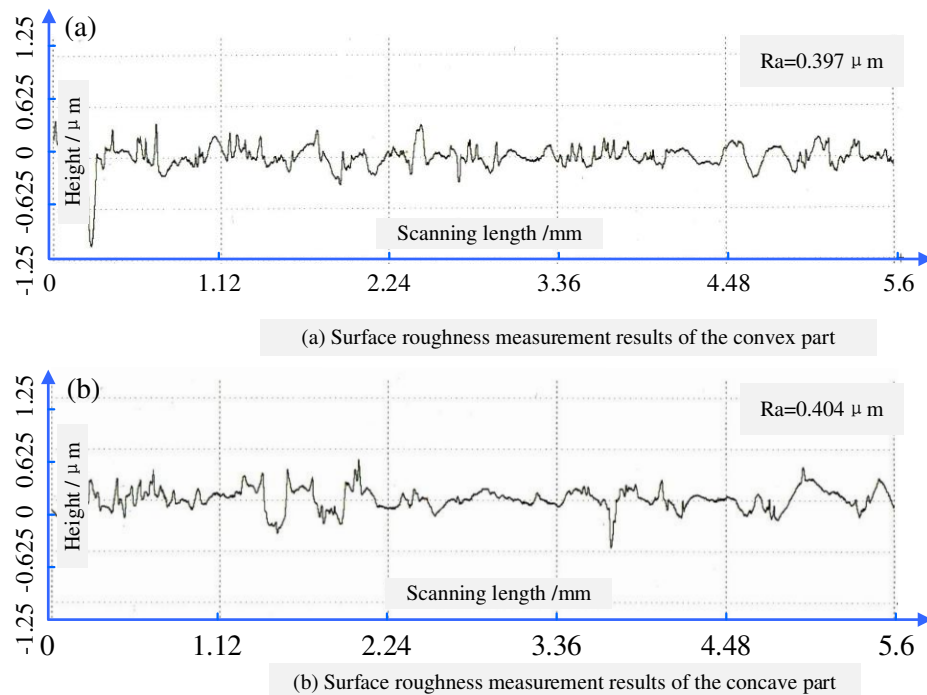


Fig. 11 Surface roughness measurement results of the blade

To further investigate whether intergranular corrosion occurs in the machined and non-machined regions of the test piece after electrochemical machining, blade No. 6 and the non-machined region of its hub are cut by wire electrical discharge machining (WEDM). Cross-sectional samples are prepared

from the blade body, flow passage and non-machined region of the hub, and then subjected to etching. Metallographic observations under an optical microscope reveal no intergranular corrosion or microcracks on the sample surfaces (Fig. 12), indicating favorable surface integrity of the test piece.

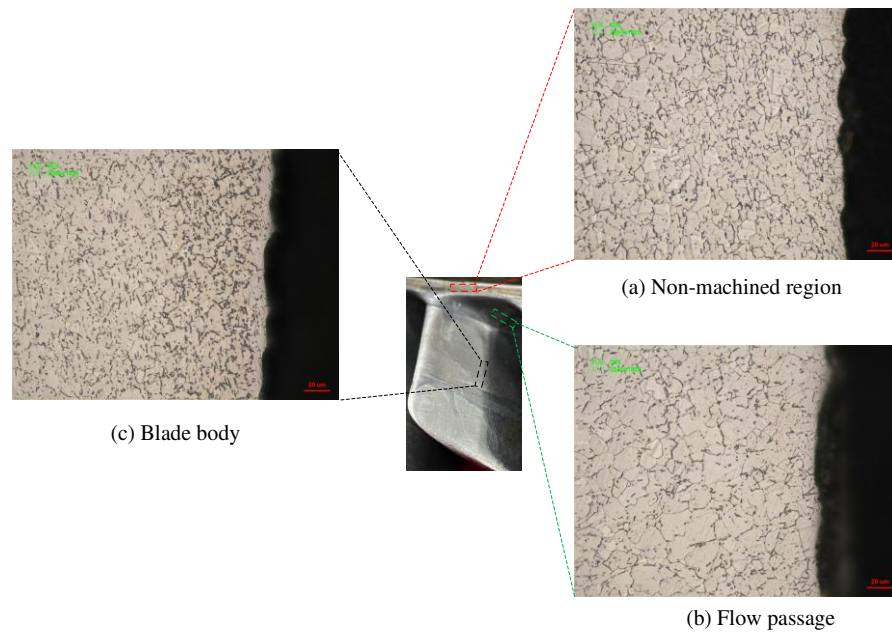


Fig. 12 Intergranular corrosion detection of the test piece

In summary, favorable blade allowance distribution and surface quality are obtained through machining experiments on the test piece, which effectively validates the feasibility of the proposed machining process scheme.

6. Conclusion

(1) Three-dimensional flow field models with four types of leading and trailing edge auxiliary liquid supply configurations are established, and finite element simulations are carried out for the four flow field models respectively. Simulation results show that the flow channel model with a cross-sectional length of $L = 12$ mm at the leading and trailing edge liquid inlets exhibits favorable flow field uniformity, which meets the flow field requirements of electrochemical machining.

(2) Cathode deformation induced by pressure difference in the four flow field configurations is analyzed. The maximum cathode deformation of the flow channel model with $L = 12$ mm is 0.0084 mm, which has a smaller impact on electrochemical machining accuracy compared with the other configurations, indicating that the proposed flow field configuration design method is reasonable and effective.

(3) To verify the accuracy of the simulation results, blade electrochemical machining experiments at the same feed rate are carried out. For the optimal flow field configuration, the surface roughness of the blade back profile is $R_a = 0.397 \mu\text{m}$, while that of the blade basin profile is $R_a = 0.404 \mu\text{m}$. Experimental results demonstrate that the optimal flow field configuration presents better flow field stability.

Authors' contributions Conceptualization: Jianwei Guo; data curation: Jianwei Guo; formal analysis: Jianwei Guo, Erhao Jiao; funding acquisition: Jianwei Guo and Long Chao; methodology: Jianwei Guo and Erhao Jiao; project administration: Jianwei Guo; resources: Jianwei Guo; simulation: Jianwei Guo; Supervision: Erhao Jiao; experimental: Jianwei Guo and Erhao Jiao; writing - original draft preparation: Jianwei Guo; writing - review and editing: Jianwei Guo

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Data availability The manuscript has no associated data or the data will not be deposited.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval This paper is new. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal as well.

Consent to participate Not applicable.

Consent to publish Not applicable.

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