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Experimental study on electrochemical machining of titanium alloy TC4 twisted blades

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Abstract: Titanium alloy TC4 is widely used as the material of aero-engine blade, which is a typical difficult-to-process material. Electrochemical machining (ECM) is the preferred processing technology for titanium alloy TC4 because it does not depend on the strength and hardness of the material itself, high processing efficiency, and good surface quality. In this paper, the flow field characteristics and experiments of ECM of titanium alloy TC4 twisted blades are studied. According to the characteristics of the blade itself, the lateral flow tangential inlet flow field and the corresponding complex fixture and tool electrode are designed. The theoretical and geometric models of the flow field simulation are established, and the finite element simulation analysis of the flow field is carried out. The results show that the electrolyte flow rate in the new flow field is high and evenly distributed, and there is no shortage of liquid and vortex defects, which can meet the needs of ECM. The experiments of ECM parameters optimization are carried out, and it is found that pulse frequency and duty cycle have a key effect on the surface quality of titanium alloy TC4 blade. The experimental results show that the machining process is very stable under the new flow field mode and optimized machining parameters. The surface of the titanium alloy TC4 blade is bright and without defects. The surface roughness of the concave and the convex are Ra 0.44 μm and Ra 0.47 μm, respectively. The profile accuracy of concave and convex were -0.008 ~ +0.057 mm and -0.002 ~ +0.059 mm, respectively.

Keywords: Electrochemical machining; Titanium alloy TC4 blade; Surface quality; Lateral flow tangential inlet flow field; Parameter optimization

1. Introduction

Titanium alloy TC4 has good heat resistance, low specific density, high strength, excellent corrosion resistance, and other characteristics are widely used in the aerospace field of blade materials, but its high hardness and high strength characteristics make traditional mechanical cutting technology face many challenges, such as tool wear, blade deformation, fracture, micro cracks, low processing efficiency, high processing costs[1,2]. Therefore, titanium alloy TC4 is a typical hard-to-cut material. ECM is very suitable for precision and efficient machining of titanium alloy TC4 blade because of its outstanding advantages such as no cutting force, no dependence on the mechanical properties of the anode material itself, no loss of the tool cathode, high processing efficiency, and good surface quality[3-5].

In ECM, flow field is the key factor affecting machining stability, surface quality, and machining efficiency. Reasonable flow field design is the basic condition to ensure the smooth progress of ECM titanium alloy TC4 blade. Wang et al. studied the flow field of ECM of large-size blades, and the surface roughness of the processed stainless steel 304 blades is about Ra 0.6 μm[6]. Zhu et al. proposed a dynamic additional electrolyte flow mode for the ECM of the blisk cascade passage, which effectively eliminated the local poor electrolytic flow area and improved the machining stability and surface quality[7]. Guo et al. proposed a four-way electrolyte flow mode to improve the stability of electrolyte flow on the leading and trailing edges of the blade in ECM[8]. Cao et al. proposed a new mode of cyclic change of electrolyte flow direction for counterrotating ECM casing, which improved the symmetry of the convex structure[9]. Xu et al. used the tube electrode with slit on the side wall as the tool cathode to process the blisk channel, analyzed the electrolyte flow, and greatly improved the processing efficiency[10]. Chen et al. used pulsating flow field for electrochemical milling of deep and narrow groove structures[11]. Yue et al. improve the machined surface of the workpiece by adjusting the electrolyte flow field in electrochemical milling-grinding[12]. Deng et al. improved mass transfer in electrodeposition by trapezoidal anodes[13].

In addition, due to some characteristics of titanium alloy TC4, such as high breakdown potential, easy to form passive film on the surface, and different elements in the matrix material have different electrochemical dissolution rates, it is easy to produce defects such as pitting on the surface of the workpiece if inappropriate electrolyte type and processing parameters are used. In order to improve the surface quality of titanium alloy TC4 parts by ECM, domestic

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and foreign scholars have carried out a lot of research. Jiang et al. improved the surface quality (Sa 7.028 μm) of the blade of the electrochemical trepanning by using an auxiliary anode in sodium chloride solution[14]. Wang et al. studied the effect of the tool cathode feed rate on the taper of the convex structure in sodium chloride solution. The surface roughness of the machined part is about Ra 0.65 μm (measuring length 0.4 mm)[15]. Wang et al. reported the mechano-electrochemical milling of TC4 titanium alloy grooves in sodium nitrate solution at different feed rates, and the surface roughness of the sample ranged from Ra 6.19 μm to Ra 27.16 μm[16]. Lei et al. reduced the surface roughness of the titanium alloy TC4 blade from Ra 2.621 μm to Ra 1.815 μm in sodium chloride solution by optimizing the flow field of the electrochemical trepanning[1].

In this paper, ECM of titanium alloy TC4 twisted blade was carried out to achieve high quality and high precision machining of the blade. Firstly, the method of bidirectional feed ECM blade was introduced, and the characteristics of blade itself and the possible flow field mode were analyzed. Secondly, based on the characteristics of blade and traditional lateral flow field, a new lateral flow tangential inlet flow field was designed. Moreover, the corresponding complex fixture and tool cathode were also designed. Thirdly, the finite element simulation theory and geometric models of flow field were established, and the flow field simulation analysis of titanium alloy TC4 twisted blade was carried out. The results show that the flow rate of the new flow field is high and uniform in the processing area of titanium alloy TC4 blade, and there are no liquid shortage, vortex, and obvious uneven shunt defects. After that, the ECM experiments of titanium alloy TC4 twisted blade were carried out in sodium chloride solution, and it was found that the pulse frequency and duty cycle had key effects on the surface quality of the blade, and optimized machining parameters were obtained. Finally, several titanium alloy TC4 twisted blades were machined under the designed lateral flow tangential inlet flow field and optimized processing parameters. The surface roughness of the blade is less than Ra 0.5 μm, and the profile error is less than 0.07 mm. The high quality and high precision manufacturing of titanium alloy TC4 twisted blades were realized.

2. Bidirectional feed ECM method for blades

In ECM, the blade profile usually adopts the bidirectional feed ECM method of concave cathode and convex cathode, as shown in Fig. 1. During processing, the blade is connected to the positive pole of the power supply, while the concave cathode and convex cathode are connected to the negative pole of the power supply. At the beginning of the process, high-pressure and high-speed electrolyte rapidly flows into the machining area. The concave cathode and the convex cathode gradually approach the blade surface with a certain feed speed. Simultaneously, under the applied voltage, anodic workpiece oxidation reactions occur, causing the blade blank to dissolve. The flocs, Joule heat, and hydrogen bubbles generated during processing are swiftly washed away by the rapid flow of electrolyte. With the continuous feed of the concave cathode and the convex cathode, the profile of the blade is gradually formed.

3. Lateral flow tangential inlet flow field

In ECM, the flow field, fixture, and tool cathode are fundamental and essential for achieving stable processing and high surface quality of blades. This section will first introduce the characteristics of titanium alloy TC4 blade, analyze several electrolyte flow modes that may be suitable for the blade, and carry out flow field design.

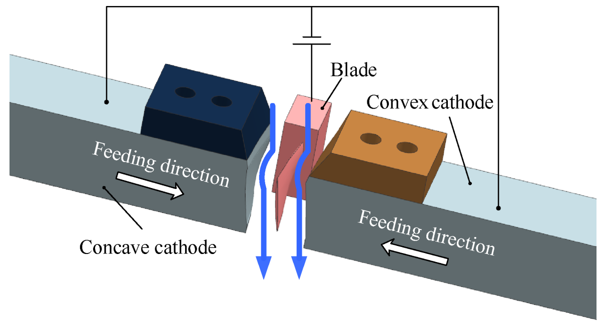


Fig. 1 Schematic diagram of bidirectional feed ECM for blade.

After that, the complex fixture and tool cathode are designed based on the blade characteristics and the electrolyte flow.

3.1. Characteristics of titanium alloy TC4 blade

Fig. 2 is the standard model of titanium alloy TC4 blade, which is constrained by six control lines, the length and width are about 42 mm and 28 mm respectively, and the total area of the concave and convex is about 20.3 cm^2. It can be seen from the figure that the direction of the blade from the root to the tip is very distorted, showing the characteristics of wide at the top and narrow at the bottom, which increases certain difficulty for flow field design, tool cathode design, and ECM.

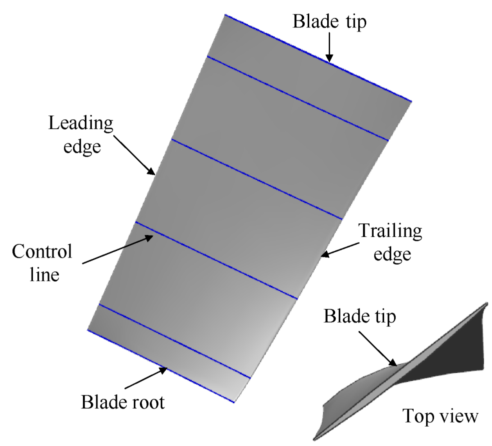


Fig. 2 Titanium alloy TC4 blade standard model.

In order to better analyze the profile characteristics of the blade, six control lines are extracted, and the center arc of each control line is drawn by connecting the center of the inner circle. It can be seen from Fig. 3 that the tangential direction of the leading edge of the blade is relatively consistent, while the tangential direction of the trailing edge is greatly different. In addition, it can be clearly seen that the distortion degree of the 1st, 2nd, and 3rd control lines is small, and the distortion degree gradually increases from the 4th control line. The torsion angle of the leading and trailing edges changes from 184° of the 1st control line to 139.6° of the 6th control line, and the maximum change angle is about 44.4°, and the degree of distortion change is very obvious. Compared with the straight blade of the same section, the machining of the blade is more difficult.

3.2. Analysis of electrolyte flow mode of titanium alloy TC4 twisted blade

In ECM, the pattern of electrolyte flow is very important for machining stability, surface quality, and machining accuracy. Reasonable flow field design and optimization can make the electrolyte flow at high-speed wash away the electrolytic products and the heat generated during processing, so as to avoid short circuit caused by product accumulation. At the same time, the designed flow field should also have the characteristics of stable and uniform flow rate, no lack of liquid phenomenon, so as to ensure the stability of ECM. For titanium alloy TC4 blade, there are three possible flow field modes: (1) Positive flow. As shown in Fig. 4 (a), the electrolyte flows into the blade tip and is divided into two ways, flowing through the concave and the convex respectively, and finally flows out from the root and platform of the blade. The flow mode has the advantage of simple channel design. However, due to the long size of the blade and the distortion of the profile, the electrolyte flow path is very long, and the passive shunt mode makes the electrolyte uneven shunt for the concave and the convex, which is prone to product accumulation and flow mark defects, resulting in poor processing stability and processing quality. At the same time, the flow direction of the flow mode at the blade root suddenly changes at a large angle, which increases the flow resistance and weakens the velocity. Moreover, due to the thin profile of the blade, the impact of high-pressure electrolyte will lead to blade tip flutter during actual machining, resulting in short-circuit burns and other defects, which seriously affect the machining stability and machining accuracy. (2) Reverse flow. As shown in Fig. 4 (b), two streams of electrolyte flow into the processing area from the platforms of the concave and the convex respectively, through the concave and the convex, and finally converge and flow out from the blade tip. The flow mode divides the concave and the convex into two channels for liquid supply, which can actively control the flow rate and pressure of the two channels of electrolyte, avoid the disturbance caused by passive shunt, and ensure the uniformity and stability of the flow field. However, this flow mode also has disadvantages such as long flow channel and sudden change of electrolyte direction at blade root. (3) Lateral flow. As shown in Fig. 4 (c), lateral flow is a more widely used flow mode in blade ECM due to its short flow path and good stability. The electrolyte flows in from the leading edge or trailing edge, is passively divided into the concave and the convex, and then gathers and flows out from the trailing edge or leading edge. This flow mode is suitable for the blade whose profile is not twisted. For the titanium alloy TC4 blade in this paper, because the profile is very twisted, there are disadvantages of uneven shunt and flow field disorder at the inlet flow.

3.3. Lateral flow tangential inlet flow field design

Based on the analysis in the previous section, lateral flow is more suitable for titanium alloy TC4 blades due to short and gentle flow channels, but improvements need to be made to improve the stability and uniformity of flow field. In order to ensure the stability of the inflow of electrolyte and the uniform shunt between the concave and the convex, the inflow angle of electrolyte should be similar. Fig. 5 shows the tangential angles of the leading and trailing edges corresponding to the 10 sections of the blade. It can be seen that the tangential angle of the leading edge is consistent, while the tangential angle of each section of the trailing edge

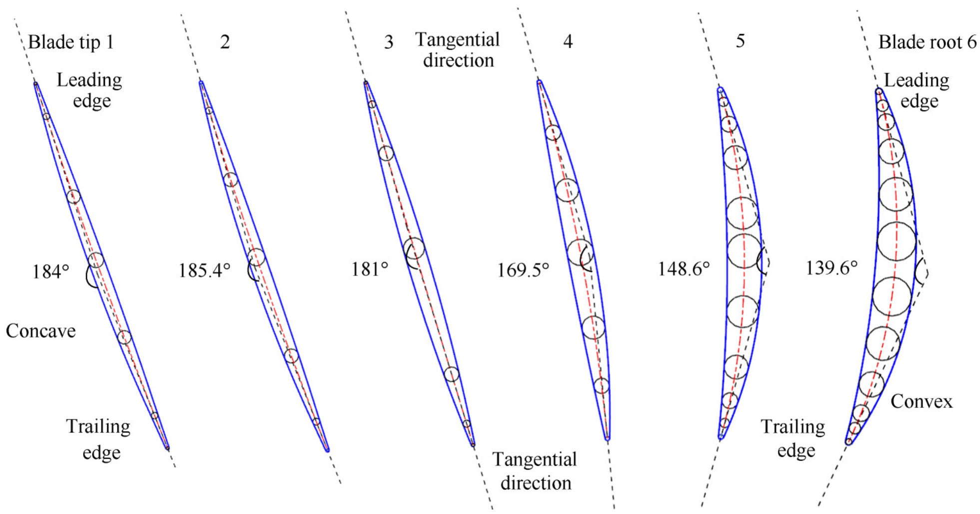


Fig. 3 Details of six control lines of titanium alloy TC4 blades.

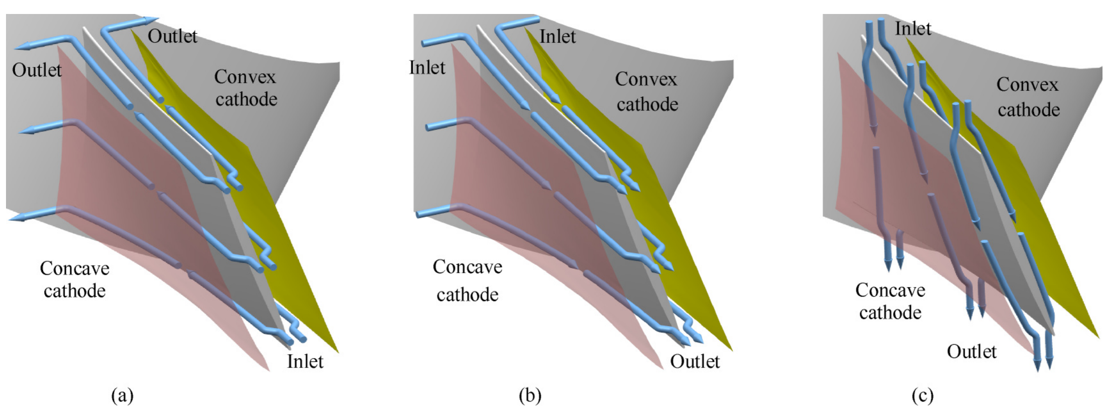


Fig. 4 Several electrolyte flow modes for titanium alloy TC4 twisted blades.

changes greatly. In this paper, therefore, the liquid is injected tangentially from the leading edge to make the electrolyte enter the processing zone more smoothly and the shunt more evenly.

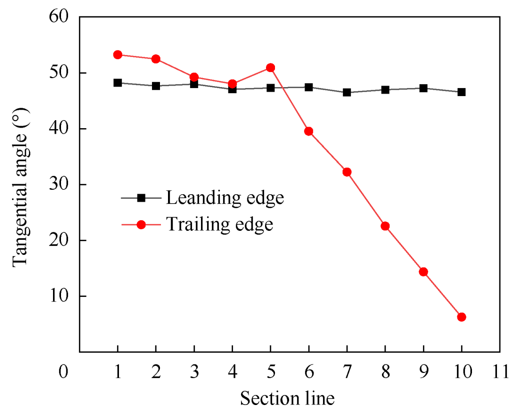


Fig. 5 Distribution of tangential angles at leading and trailing edges.

Fig. 6 is a schematic diagram of the lateral flow tangential inlet flow field for a titanium alloy TC4 blade. As shown in the figure, the electrolyte flows in the tangential direction along the middle arc line of the blade itself, and is divided into two streams at the leading edge with similar tangential angles, which flow through the concave and the convex surface respectively, and then converge at the trailing edge and flow out along the tangential direction[6]. The flow field mode electrolyte has a short flow path and is easy to discharge electrolytic products quickly. At the same time, it can effectively improve the stability of the flow field and the uniformity of the shunt at the leading edge, and improve the processing quality.

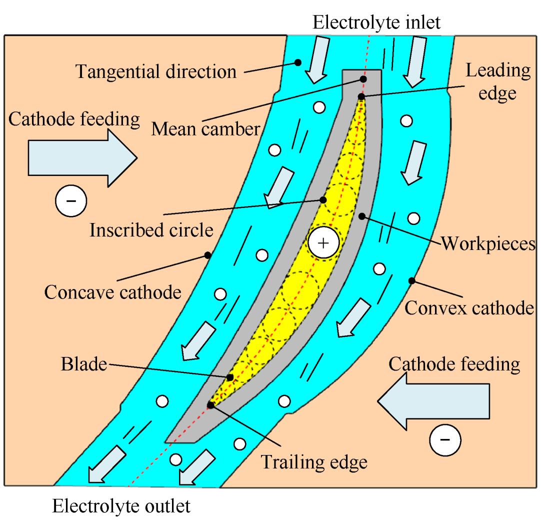


Fig. 6 Schematic diagram of lateral flow tangential inlet flow field.

In ECM, the fixture is a very important component, which provides the installation platform and positioning reference for the workpiece, and interacts with the tool cathode. There is also a predesigned flow channel inside the fixture to improve the stability of the electrolyte flow, and can also play a role in sealing and preventing electrolyte leakage to ensure the high pressure and flow rate required for titanium alloy TC4 blade processing. Based on the lateral flow tangential inlet flow field, the corresponding fixture for titanium alloy TC4 blade is designed in this paper. As shown in Fig. 7, the fixture comprises: inlet, flow guide block, upper cover, fixture base, copper bar, etc. Fig. 8 shows the designed concave cathode and convex cathode with complex surface structure, made of stainless steel 304.

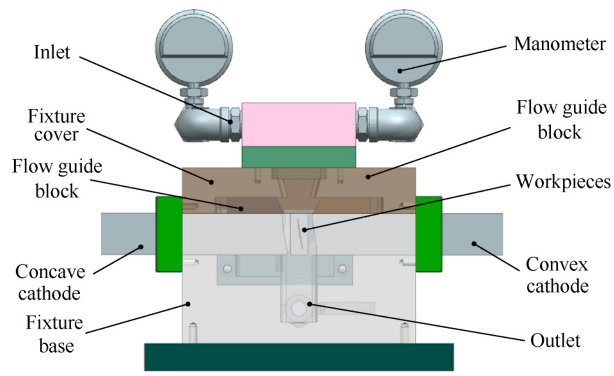


Fig. 7 3D model of fixture for titanium alloy TC4 blade.

4. Lateral flow tangential inlet flow field simulation

In order to further analyze the rationality of the designed lateral flow tangential inlet flow field, this section will carry out finite element simulation analysis for the flow field.

4.1 Flow channel model

According to the designed flow field and fixture, the flow channel model of the lateral flow tangential inlet flow field in the equilibrium state is established for finite element simulation, as shown in Fig. 9 (a). In the process of ECM, the most concerned is the flow rate and pressure distribution of the electrolyte in the machining area between the workpiece and the tool cathode, which has a direct impact on the surface quality and the machining accuracy of the workpiece. Therefore, in order to more intuitively observe the flow rate and pressure distribution of the electrolyte in the machining gap, the corresponding section is selected in the processing area in the vertical direction of the flow channel model, and the local enlarged image of the machining region (area ‘a’) is further selected. Fig. 9 (b) shows the result of tetrahedral mesh division of the flow channel. It can be seen that the mesh is relatively dense to ensure the accuracy and reliability of the simulation calculation.

4.2 Mathematical model

In the actual ECM, the processing area is very complicated be-

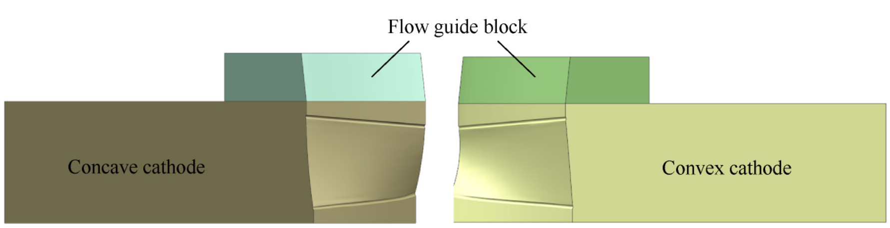


Fig. 8 3D model of tool cathode for titanium alloy TC4 blade.

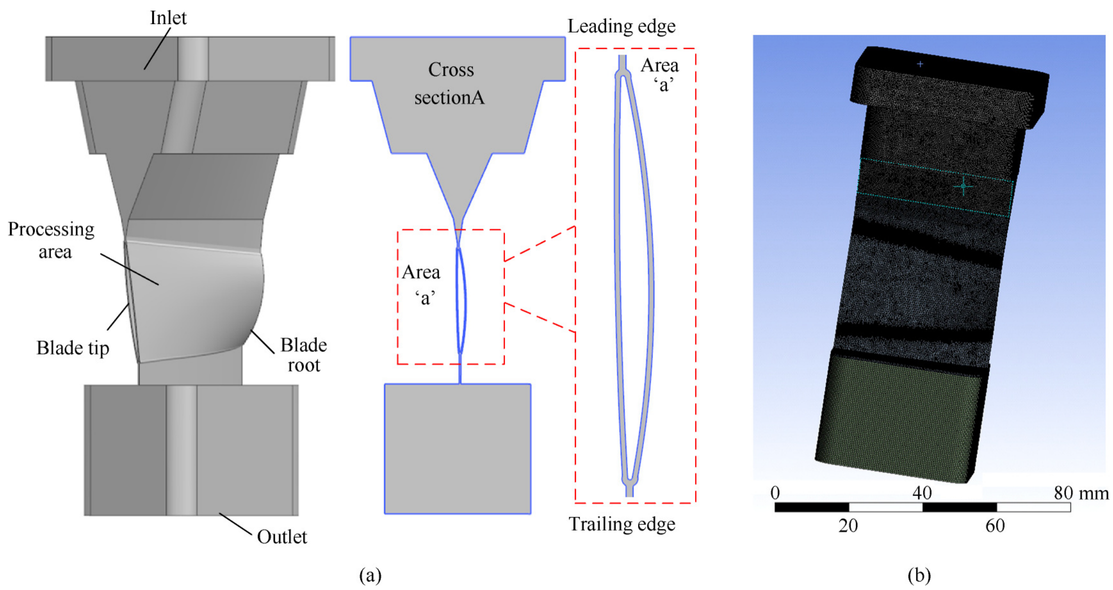


Fig. 9 3D model and meshing of the flow channel: (a) 3D model and (b) meshing.

cause of the presence of high-speed flowing electrolyte, bubble, and flocculent sludge, which is a solid-liquid-gas three-phase flow. Generally, bubbles and flocculent sludge are ignored in flow field simulation to simplify calculation. In addition, for the ECM of titanium alloy TC4 blades, neutral sodium chloride salt solution is usually used, which is an incompressible, continuous Newtonian fluid. Therefore, the flow of the electrolyte conforms to the mass conservation equation and the momentum conservation equation[7]:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+F_i \tag{2}$$

where ρ represents the density of the electrolyte in the flow field, u_x, u_y, and u_z denote the velocity components in the x, y and z directions respectively, x_i and x_j are coordinates in the Cartesian coordinate system, p stands for the pressure of the electrolyte, F_i is the ith component of the volume force, τ_{ij} is the ijth element of the stress tensor.

In ECM, the electrolyte in the processing area is generally required to be turbulent to ensure the rapid removal of flocculent sludge, bubbles, and Joule heat. At the same time, it can reduce the influence of concentration polarization and improve the processing stability. In this study, RNG κ-ε model is used for finite element simulation of flow field. The model is mainly aimed at the high Reynolds number flow problem and is very suitable for ECM of titanium alloy TC4 blades. The transport equations of turbulent kinetic energy k and dissipation rate ε are as follows[17]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\alpha_k\mu_{\text{eff}})\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\alpha_\varepsilon\mu_{\text{eff}})\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

$$\mu_{\text{eff}}=\mu+\mu_t,\quad \mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{5}$$

where G_k is the generation of turbulent kinetic energy due to the mean velocity gradient, and α_k and α_ε are the reciprocal of effective Prandtl number of turbulent kinetic energy and dissipation rate, respectively.

4.3 Simulation results analysis

For the lateral flow tangential inlet flow field simulation of titanium alloy TC4 blade, the inlet pressure and outlet pressure of electrolyte are set as 0.8 MPa and 0.2 MPa respectively. Fig. 10 (a) shows the electrolyte flow rate and pressure distribution in the machining region (region 'a') in the blade tip, the middle of the blade, and the blade root section. It can be seen that the electrolyte flow rate is high in the machining gap, and there is no liquid shortage area. It can also be seen that the electrolyte flow rate and pressure distribution of the concave and the convex are relatively uniform, and no obvious defects of uneven distribution are found. This helps to ensure the stability of the processing and the consistency of the processing of the concave and the convex. In addition, the pressure of the electrolyte decreases slightly along the flow direction from the leading edge to the trailing edge, which is mainly due to the pressure loss of the fluid.

In order to more clearly analyze the flow rate and pressure of the electrolyte in the machining area, 1000 sampling points are uniformly selected in the machining gap area (area "a" in Fig. 9). Fig. 10 (b) and (c) show the distribution intervals of electrolyte flow rate and pressure at sampling points respectively. It can be obviously found that the electrolyte flow rate of these sampling points is mostly distributed between 16-20 m/s, and the pressure is mostly distributed between 0.35-0.55 MPa. It can also be obviously found that the flow rate of these sampling points in the processing area is greater than 10 m/s, the average flow rate is about 18.53 m/s, and the variance is 9.02. This indicates that the electrolyte flow rate is fast and the distribution is more uniform, which can meet the needs of ECM[3]. It also preliminarily proves that the designed lateral flow tangential inlet flow field is feasible for twisted titanium alloy TC4 blades.

5. ECM experiments of titanium alloy TC4 blade

5.1 ECM experiments

Based on the designed lateral flow tangential inlet flow field, fixture, and tool cathode, ECM experiments of titanium alloy TC4 blade are carried out. Fig. 11 (a) and (b) show the actual images of fixture and tool cathode respectively. A 10wt% neutral sodium chlo-

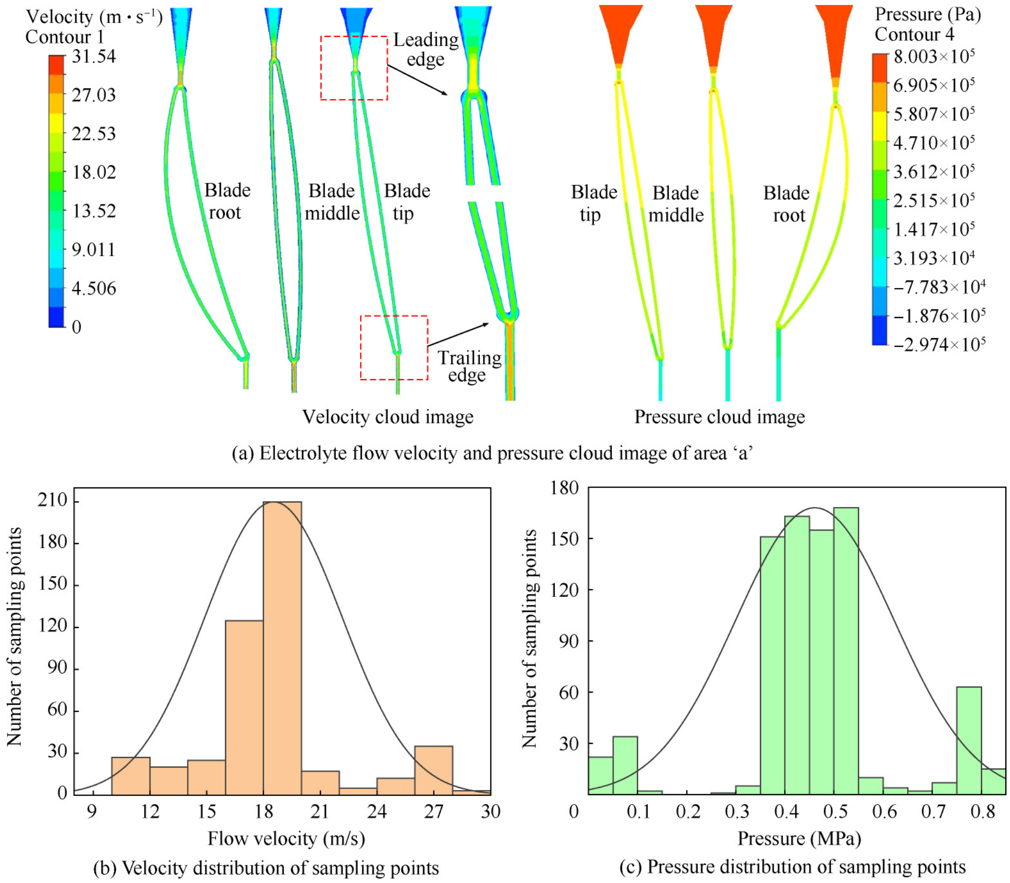


Fig. 10 Simulation results for area 'a'.

ride solution is used as the electrolyte, and the electrolyte inlet and outlet pressures are consistent with the above simulation. According to several pre-experiments, the influence of power pulse frequency and duty cycle ratio on the surface quality of titanium alloy TC4 blade is emphatically explored, and better machining parameters are obtained. This study mainly introduces five groups of ECM experiments on titanium alloy TC4 blades, and the specific processing parameters are shown in Table 1.

In the process of ECM, the machining current is recorded and analyzed with the change of the tool cathode feed distance to judge the stability and progress of the machining. As shown in Fig. 12, the processing currents of the five groups of experiments showed a similar change trend, that is, the processing currents gradually increased in the initial stage due to the gradual increase of the processing area, and then remained almost unchanged due to the processing entering the equilibrium state, and the processing currents slightly decreased in the final stage due to the dissolving of the leading and trailing edges. It can also be clearly seen from the figure that the processing current changes gently in the whole process of machining, and there is no mutation. This means that the process is very stable and there is no short circuit.

In Fig. 12, three groups of experiments (a), (b), and (e) mainly explored the effects of different pulse frequencies on titanium alloy TC4 blades under similar duty cycle. It can be seen that under the same duty cycle (80%), the size and variation trend of processing currents at 500, 1500, and 1000 Hz are similar. At the same time, three groups of experiments (c), (d), and (e) mainly explored the effects of different duty cycles on titanium alloy TC4 blades at similar pulse frequencies. It can be seen that under the same pulse frequency (1000 Hz), the processing current gradually increases with the increase of duty cycle. The main reason is the increase of pulse width in pulse current.

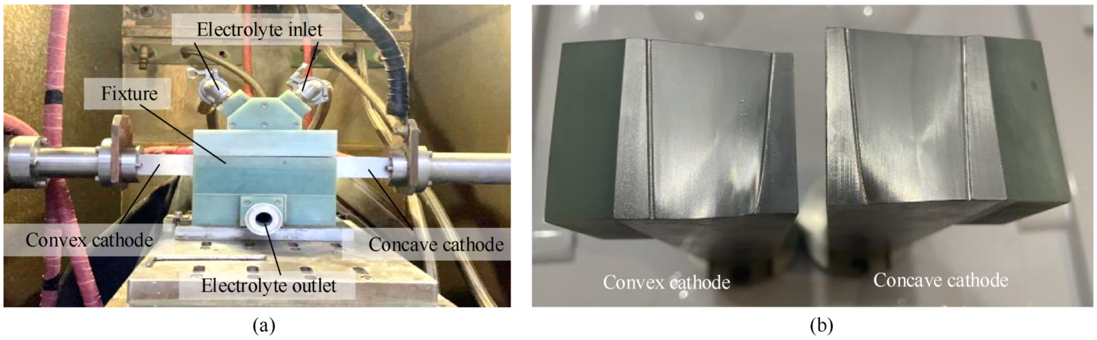


Fig. 11 ECM device for titanium alloy TC4 blade: (a) processing site and (b) tool cathode.

Table 1 ECM parameters.

Group	(a)	(b)	(c)	(d)	(e)
Machining voltage (V)	38				
Pulse frequency (Hz)	500	1500	1000	1000	1000
Duty cycle	80%	80%	40%	60%	80%
Feed rate (mm/min)	0.8				
Feed distance (mm)	11.2				
Electrolyte temperature (°C)	32				
Inlet pressure (MPa)	0.8				
Outlet pressure (MPa)	0.2				

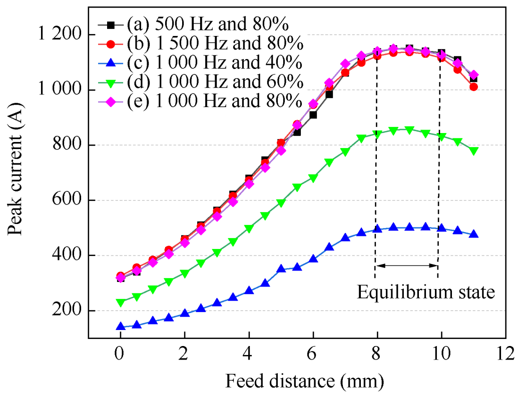


Fig. 12 The relationship between the machining current and the feed distance.

5.2 Results analysis

Fig. 13 shows five sets of manufactured titanium alloy TC4 blades through ECM. Firstly, the effects of different pulse frequencies in groups (a), (b), and (e) in Fig. 13 are analyzed. From these figures, it is obvious that: (1) When the pulse frequency is 500 Hz and the duty cycle is 80%, there are obvious flow mark defects on the surface of titanium alloy TC4 blade near the blade root, which seriously affects the surface quality. This may be attributed to the fact that the profile at the blade root is very distorted and the pulse period is large, and more electrolytic products cannot be discharged in time within a single pulse period. (2) When the pulse frequency is 1500 Hz and the duty cycle is 80%, it can be seen from the local enlarged image that there is white and black texture on the surface of the titanium alloy TC4 blade, which has an adverse effect on the surface quality. A possible explanation is that the pulse period is small, the product generation is more and faster, and the electrolytic product cannot be discharged in time when the power-off. (3) When the pulse frequency is 1000 Hz and the duty cycle is 80%, it can be found that the surface of the titanium alloy TC4 blade is very smooth, and there is no flow mark, texture, and other defects.

From the above analysis, it can be seen that compared with 500 and 1500 Hz, a smoother and defect-free surface can be obtained when the pulse frequency is 1000 Hz. Therefore, the pulse frequency of 1000 Hz is selected to carry out follow-up experimental analysis. In Fig. 13, (c), (d), and (e) are titanium alloy TC4 blades with different duty cycles when the pulse frequency is 1000 Hz. From Fig. 13 (c), it can be clearly found that there are many micro-bulges at the trailing edge of the blade, which cannot meet the processing requirements. This may be due to the small duty cycle, which makes the processing current density small and the electrolytic products converge and flow out at the trailing edge, resulting in uneven dissolution of the trailing edge materials. It can be seen from Fig. 13 (d) and (e) that the surface of titanium alloy TC4 blade is very smooth and without defects when the duty cycle reaches 60% and 80%. In order to further compare the surface quality of titanium alloy TC4 blades with a duty cycle of 60% and 80%, their surface roughness is measured, as shown in Fig. 14. It can be seen from the figure that the surface roughness value of titanium alloy TC4 blade when the duty cycle is 60% is slightly lower than that when the duty cycle is 80%, but the surface roughness of the two is almost similar.

Based on the above analysis, the titanium alloy TC4 blade can obtain better surface quality when the pulse frequency is 1000 Hz and the duty cycle is 60%. Fig. 15 shows several titanium alloy TC4 blades under optimized ECM parameters, it can be seen that the surface of the blades is very smooth, without defects such as flow marks and bulges.

The surface roughness of the concave and the convex is measured using a roughness meter, and the results are shown in Fig. 16. It can be seen that the surface roughness values of the concave and the convex are about Ra 0.44 μm and Ra 0.47 μm, respectively, which have good surface quality. A coordinate measuring machine is used to detect the machining error of the blade, and the results

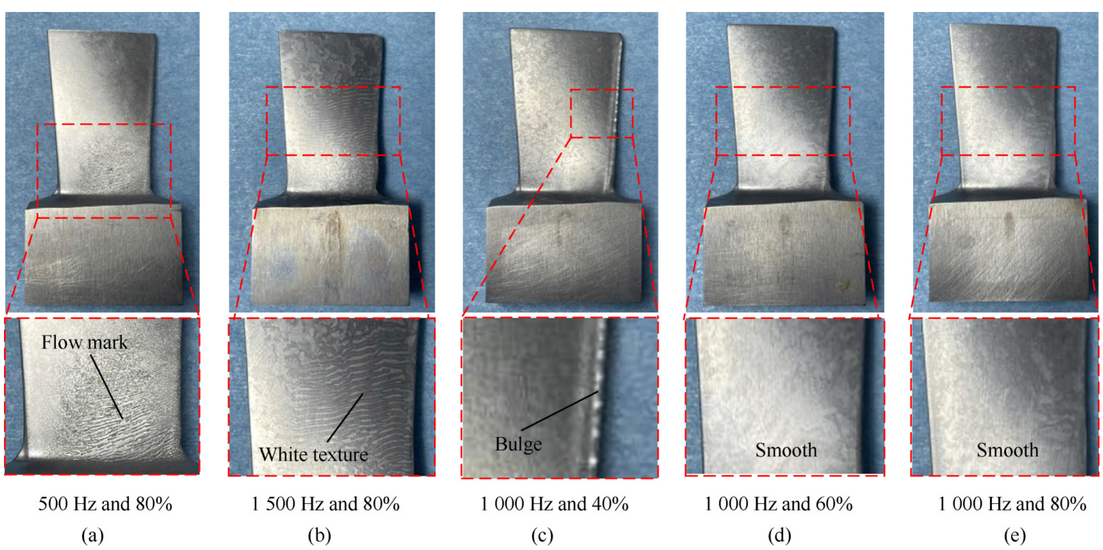


Fig. 13 Titanium alloy TC4 blades under different ECM parameters.

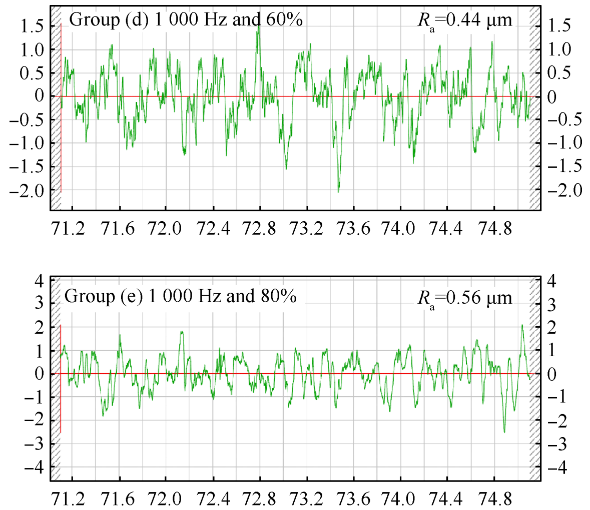
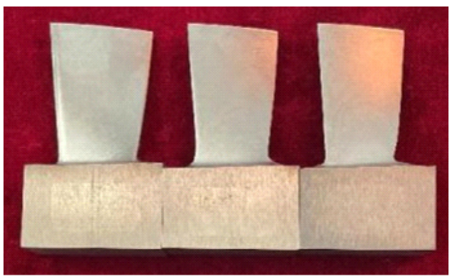
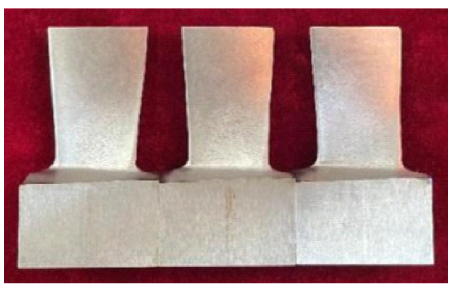


Fig. 14 Surface roughness measurement results of blades for group (d) and group (e).



(a)



(b)

Fig. 15 Titanium alloy TC4 blades through ECM: (a) concave and (b) convex.

are shown in Fig. 17. It can be seen that the error of the concave profile is -0.008 ~ +0.057 mm, and the error of the convex profile is -0.002 ~ +0.059 mm, which has a high machining accuracy. Through the above series of studies, it is also verified that the designed flow field, fixture, and tool cathode can be used in engineering practice.

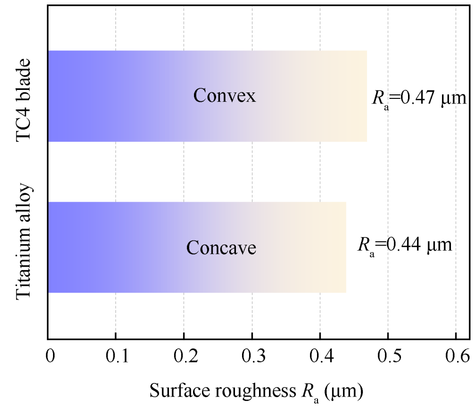


Fig. 16 Surface roughness value of titanium alloy TC4 blade.

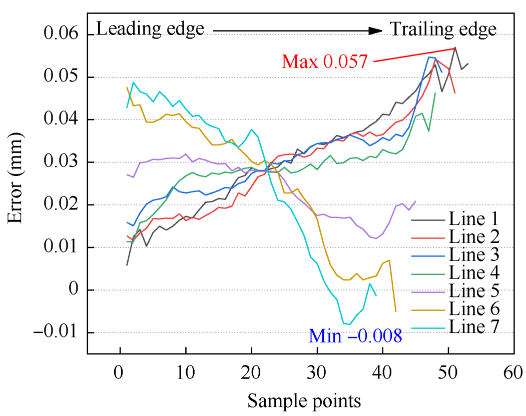
6. Conclusions

In this paper, ECM experiments were carried out on titanium alloy TC4 blades, including flow field design, finite element modeling and simulation, fixture and tool cathode design, and the influence of different frequencies and duty cycle on blade surface quality, etc., to achieve high quality and high precision machining of titanium alloy TC4 blades. Some conclusions are as follows:

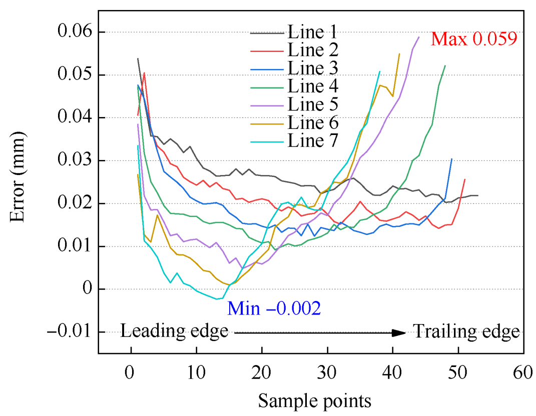
(1) Based on the characteristics of titanium alloy TC4 twisted blade and the traditional lateral flow field, the lateral flow tangential inlet flow field, fixture, and tool cathode were designed. The flow field mode has the advantages of uniform distribution between the concave and the convex, stable inflow, and short flow path.

(2) The finite element simulation analysis of lateral flow tangential inlet flow field was carried out, and the results showed that the electrolyte flow rate in the processing area of lateral flow tangential inlet flow field was high and uniform, and there were no defects such as liquid shortage area and obvious uneven shunt.

(3) The experiments of ECM of titanium alloy TC4 blade were carried out, and it was found that pulse frequency and duty cycle had important effects on the surface quality of titanium alloy TC4 blade, and better machining parameters were obtained, and high quality (Ra < 0.5 μm) and high precision manufacturing (profile error < 0.07 mm) of titanium alloy TC4 blade were realized.



(a) Concave



(b) Convex

Fig. 17 Profile error of titanium alloy TC4 blade.

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References

1. Lei GP, Zhu D, Li JB. Optimization of flow field in electrochemical trepanning of integral cascades (Ti6Al4V). *Chinese J. Aeronaut.* 2022; 35(10):354-364.
2. Hong Y, Sun C, Guo Q, et al. High-performance Ti6Al4V surface manufacture by laser carburising-assisted grinding. *Tribol. Int.* 2024; 198:109912.
3. Xu ZY, Wang YD. Electrochemical machining of complex components of aero-engines: Developments, trends, and technological advances. *Chinese J. Aeronaut.* 2021;34(2): 28-53.
4. Wang YD, Xu ZY, Meng DM, et al. Study on surface roughness of large size TiAl intermetallic blade in electrochemical machining, *J. Manuf. Process.* 2022;76:1-10.
5. Geng TY, Xu ZY. Electrochemical discharge machining for fabricating holes in conductive materials: A review. *J. Adv. Manuf. Sci. Technol.* 2021;1(3) 2021006.
6. Wang YD, Xu ZY, Liu J, et al. Study on flow field of electrochemical machining for large size blade. *Int. J. Mech. Sci*. 2021;190:106018.
7. Zhu D, Zhang J, Zhang K, et al. Electrochemical machining on blisk cascade passage with dynamic additional electrolyte flow. *Int. J. Adv. Manuf. Technol.* 2015;80:637-645.
8. Guo JW, Zhu D, Zhu D. Flow field design and experimental investigation of electrochemical machining on blisk. *Chinese J. Aeronaut.* 2022; 35(8) 295-303.
9. Cao WJ, Wang DY, Guo HT, et al. Improvement on profile accuracy of convex structure during counter-rotating electrochemical machining by periodically changing electrolyte flow direction. *J. Manuf. Process.* 2023;102:79-94.
10. Xu ZY, Xu Q, Zhu D, et al. A high efficiency electrochemical machining method of blisk channels. *CIRP Ann. - Manuf. Technol*. 2013:62: 187-190.
11. Chen XL, Ye ZS, Li GJ, et al. Electrochemical milling of deep-narrow slots with a pulsating electrolyte flow field. *CIRP J. Manuf. Sci. Technol*. 2022;39:244-260.
12. Yue XK, Qu NS, Niu S, et al. Improving the machined bottom surface in electrochemical mill-grinding by adjusting the electrolyte flow field. *J. Mater. Process. Technol*. 2020;276:116413.
13. Deng X, Zhang Y, Zhou X, et al. Mass transfer enhancement through trapezoidal anode in dynamic mask electrodeposition of metal micropillar. *J. Adv. Manuf. Sci. Technol.* 2024;4:1-12.
14. Jiang T, Zhu D, Lei GP. Electrochemical trepanning with an auxiliary electrode. *Chinese J. Aeronaut*. 2021;34(5):183-194.
15. Wang DY, Cao WJ, He B. Formation of a convex structure during the counter-rotating electrochemical machining of TC4 titanium alloy in NaCl solution. *Int. J. Electrochem. Sci*. 2019;14:9042-9057.
16. Wang ML, Qu NS. Investigation on material removal mechanism in mechano-electrochemical milling of TC4 titanium alloy. *J. Mater. Process. Technol.* 2021;295:117206.
17. Zhu HJ. *FLUENT CFD engineering simulation practical guide*. Beijing: Posts and Telecom Press; 2014.