Study on Cathode Design Method for Electrochemical Machining of Turbine Blade

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Abstract—**Electrolytic machining technology is one of the main machining methods of turbine blade, which is the core component of aerospace engine. The standardization and uniformity of the angle between the cathode feed direction and the clamping angle of the workpiece and the normal direction of the workpiece profile are the important factors that affect the accuracy of the cathode design. In this paper, the turbine rotor blade model of a small engine is analyzed, the distribution law model of machining clearance between cathode tool surfaces corresponding to each sampling point on blade profile is established , the cathode feed angle and blank clamping angle are optimized, and the design method of electrolytic machining cathode surface model to improve the design accuracy of cathode surface is studied.**

Keywords-Electrochemical Machining; Blade; Cathode Surface Design; Angle Optimization

I. FOREWORD

With the development of aerospace field, most of the engine blades have the characteristics of twisted three-dimensional complex profile, thin wall and light weight. Titanium alloy, superalloy and other difficult cutting materials are often used in the material, which poses a new challenge to the machining and manufacturing technology of the blade. Electrolytic machining (Electrochemical Machining, ECM) is a kind of special machining method, which is a processing method to remove excess materials from workpiece by anodic dissolution of metal in electrolyte. Different from the traditional cutting process, the cathode tool does not have direct contact with the anode workpiece in the process of electrolytic machining. Compared with other machining technologies, electrolytic machining has obvious advantages in some aspects,such as no loss of cathode tools, machinable three-dimensional complex shape, high machining productivity, low cost of complex parts with complex mass production structure and no machining stress in the machining process, which has gradually become one of the key technologies in aero- engine blade manufacturing[1].In this paper, the blade basin and blade back of turbine rotor of a certain type of engine are taken as the research object of machining. The structure of blade body surface is analyzed, the cathode tool for machining the blade basin and blade back is designed, and the feed direction is parallel to the plane of blade edge plate, so as to ensure the machining accuracy of blade basin and blade back.

In the electrochemical machining of blade, the design of tool cathode is always the difficulty and difficulty for people to study. The accurate design of the tool cathode is the basic guarantee of the dimensional accuracy and the shape accuracy of the workpiece[2]. The main method of the tool cathode design is to find out the distribution of the machining gap δ in different spatial positions. For the cathode design of three-dimensional workpiece, the usual method is to slice the workpiece to be processed and transform the three-dimensional space problem into two-dimensional plane problem. At present, there are two kinds of cathode design methods: theoretical calculation method and experimental verification correction method[3]. The most famous and widely used theoretical calculation method is cos θ method. Cosθ method (schematic diagram is shown in Figure 1) is a method to obtain the cathode surface model by analyzing the spatial distribution law of the machining gap based on the simplified electric field model in the machining gap.

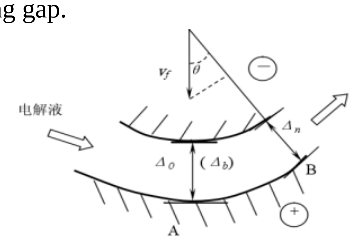


Figure 1. Forming law of cosθ method

The method of the cathode design adopted in this paper is based on the blade model, and the three-dimensional digital modeling of the processing blade is carried out, the coordinate of the sample point of the profile is uniformly obtained through the method of equal- height and equal-arc length and the like, and then, according to the distribution law of the machining gap, the analysis is carried out, the distribution of the space included angle between the normal direction of the sampling point profile and the cathode feeding direction distributed in the machining gap is optimized, the blade profile data is offset to a certain normal gap in a three-dimensional space in combination with the cos method, and the cathode profile of the two processing electrodes is finally calculated, The solid shape of the cathode can be made by the three-dimensional drawing software. So that the preparation period of the cathode can be greatly shortened.

II. DATA ACQUISITION OF AIRFOIL PROFILE OF AVIATION TURBINE BLADE

A. *Blade modeling*

The key point of blade model building process is digital modeling of blade surface line. According to the influence on all aspects of turbine blade, the section line of blade body is constructed from the main parameters such as the influence on energy loss and air flow outlet angle, the influence on determining blade strength and auxiliary parameters[4]. Determine the type value points according to the parameters. After importing these type value points, model the engine blades with the help of nx11.0 software platform, and a group of section curve layers of blade body can be obtained, as shown in Figure 2(a). Build the blade surface with the command of generating surface by curve in UG, as shown in Figure 2(b).

(a) curve group (b) blade body surface

Figure 2. Blade modeling

The curvature distribution of the obtained leaf basin and leaf back profile is shown in Figure 4. It can be seen that the curvature of the front and rear edge of the blade surface is larger, and the curvature of the place where the basin, back and front and rear edge are connected changes greatly.

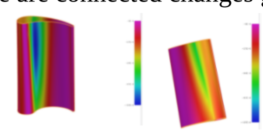


Figure 3. Curvature distribution of blade body

B. *Blade profile data acquisition*

The blade profile is a complex surface. at present, there are three main types of complex surface sampling methods: uniform sampling method, random sampling method and adaptive adjustment sampling method[5]. the measured points of these sampling method distributions are too concentrated at the maximum and minimum gaussian curvature to express the complete shape information of the surface. In order to solve the similar problems, this paper combines the contour method with the NURBS curve discrete algorithm[6] Based on the equal arc length principle proposed by Jia Chunyang and others of Central South University to analyze the surface features of the blades to be machined and plan the distribution of sampling points. In the z-axis direction, the section plane of the contour method is used to transform the blade shape features into a group of section curves with a certain step distance. For each layer of section line, the arc length method is used to divide the sampling points, and then the coordinates of these sampling points are read with the aid of UG software. This method is from surface to curve to measurement point set and then to coordinate reading of each point. It can transform the complex 3D surface shape feature of blade body into 2D curve for research. Taking the leaf basin profile sampling as an example, the coordinates of some sampling points shown in Table 1 are obtained.

TABLE I. COORDINATES OF DATA POINTS

Order	X	Y	Z
1	-11.327597571	1.661770489	20.110790766
2	-10.351043957	1.662203021	19.896334107
3	-10.672991293	1.662076857	19.978119904
4	-10.998521519	1.661932655	20.049594930
5	-11.327597571	1.661770489	20.110790766
6	-9.390668894	1.662528839	19.618280644
……	……	……	……

III. DISTRIBUTION LAW OF MACHINING GAP AND DESIGN OF BLADE CATHODE

A. Distribution rule of machining clearance

In this paper, the blade blank is fixed on the fixture, the clamp is still, and the tool cathode is fed from both sides of the blade respectively. in the process of feeding, the machining of the blade basin and the back of the blade is completed. The cathode feed direction is parallel to the edge plate, and there is no velocity feed component for the edge plate. The research on the theory and forming law of electrolytic machining is carried out on the premise that electrolytic machining enters the equilibrium state . When the electrochemical machining process enters the equilibrium state, the dissolution of anode workpiece and the feeding of cathode tool will reach a dynamic balance, that is, the part speed of cathode feeding speed vfin the normal direction of workpiece surface and the dissolution speed of anode workpiecevaare equal[7]. When electrochemical machining enters the balance state, the distribution of machining gap reaches a stable state. The angle θ in the figure is the angle between the cathode feed direction and the normal direction of blade surface, Δb is the balance machining gap[8].

It is assumed that the potential gradient in the gap does not change in the flow direction of the electrolyte, and the conductivity is also a fixed value. Combined with Faraday's law, we can get:

$$\begin{cases} U_R = U - \delta U \\ i = \kappa \frac{U_R}{\Delta} \\ v_a = \eta \omega i \end{cases} \tag{1}$$

In style：U—Processing voltage，V;
δU —Polarizing voltage，V;
U_R —Electrode voltage，V;
κ —Conductivity，$\Omega^{-1} \bullet mm^{-1}$;
η —Current efficiency;
ω —Volume electrochemical equivalent，$mm^3/(A \bullet \min)$;
i —Current density，A/cm^2;
Δ —Machining gap，mm;
v_a —Electrolytic removal rate of anode surface，$mm/\min$.

With the progress of machining, the anode dissolving speed and cathode feeding speed are gradually equal. At this time, it can be considered that electrochemical machining is in a balanced state, and the corresponding machining gap is called balance gap[9]. The shape of the anode profile is irregular, and the cathode feed rate is not always perpendicular to the anode surface. The normal balance gap at a certain point of the anode profile can be expressed as follows:

$$\Delta_n = \eta \omega \kappa \frac{U - \delta E}{v_a} = \frac{\Delta_b}{\cos \theta} \tag{2}$$

When the included angle θ=0°, the end face balance clearance Δ_b can be expressed as:

$$\Delta_b = \frac{\eta \omega \kappa U_R}{v_f} \tag{3}$$

In style: v_f —Cathode feed rate, $mm/\min$.

It can be seen from the above formula that there is a cosine relationship between the end face balance gap Δ_b and the normal balance Δ_n in the electric field model, which is the same when applied to the two-dimensional simplified electric field model. Some processing parameters are determined according to the processing experience, as shown in Table 2. When all the parameters of ECM are selected, the corresponding balance clearance Δb of bottom surface can be calculated.

TABLE II. PROCESSING PARAMETERS

Parameter	Value
Conductivity(S m^{-1})	6.72
Processing voltage（V）	15
Electrolyte density(kg m^{-3})	1100
Feed rate（mm/min）	0.3
Processing current(A)	200

Combined with the above formula, the balance clearance of the bottom surface is 0.32mm, and after Δ_b is determined, the gap distribution of ECM can be obtained according to the θ angle of each point of the workpiece and the calculation formula of above machining balance state. According to the cos θ method, the coordinates of the corresponding points on the back of the blade and the cathode surface of the blade basin are obtained by offsetting Δ_n along the normal direction of the respective space of the sampling points on these blade surfaces. The coordinates of the corresponding points on the cathode surface of the tool and the corresponding sampling points on the standard blade surface are as follows:

$$\begin{cases} x_c = x_a - \Delta_n \cos\theta \\ y_c = y_a - \Delta_n \cos\beta \\ z_c = z_a - \Delta_n \cos\gamma \end{cases} \tag{4}$$

B. *Influence of angle θ between normal direction of blade surface and cathode feed direction on electrochemical machining*

After the balance clearance of the bottom surface is determined, only the change of θ angle of each point needs to be considered. The practice of ECM proves that when the angle between the normal direction of workpiece surface and the feed direction of cathode is smaller, the forming accuracy is higher. As shown in the figure above, the angle θ=0°between the normal direction of point a on the workpiece profile and the cathode feed direction$v_f$corresponds to the machining clearance Δ_b of the bottom surface. When electrochemical machining enters the equilibrium state,point a on the workpiece surface will dissolve with the constant feeding of cathode tools, and its dissolution speed is equal to the feeding speed of cathode, so the balance gap $\Delta_b$of the bottom surface will not change, and point a has a good forming accuracy[10]. The corresponding gap at point B is a normal gapΔ_n. From the geometric relationship shown in the figure, $\Delta_n = \Delta_b / \cos\theta$ can be seen that the gap distribution is affected by the angle θ between the normal direction of the point profile and the cathode feed direction. Because the normal direction of the surface is not the same, the machining gap distribution is not uniform, which will affect the forming accuracy of ECM[11]. Therefore, the angle θ between the normal direction and the cathode feed direction of all parts of the workpiece profile is required to be less than 45°. The processing practice proves that the requirement is reasonable and necessary[12].

C. *Influence of blank clamping angle on included angle θ*

The results show that the factors influencing the angular distribution of the workpiece are two: the feeding direction of the cathode and the normal direction of the surface of the workpiece, in particular the angle of the cathode feeding angle and the angle of the clamping angle of the blade, can influence the included angle, and further influence the processing precision. In order to improve the processing precision of the blade, it is necessary to optimize the different combinations of the blade and the blade in order to improve the precision of the blade . Because the blade is not provided with a flange plate, the problem of the accuracy of the flange plate can not be taken into account when determining the cathode feeding angle and the blank clamping angle. The following guidelines are used to optimize the clamping angle of the blank.

Criterion 1: the angle θ between the normal direction and the cathode feed direction of all blade profile sampling points is less than 45°.

$$\theta_i \le 45°, 1 \le \mathrm{i} \le \mathrm{n} \tag{5}$$

(where n is the number of sampling points)

Quasi side 2: when 1 is satisfied, the mean value E of the included angle θ is minimized, as shown in the following formula:

$$\mathrm{E}\left(\theta_{\beta_0}\right) = Min\{E\left(\theta_{\beta_i}\right)\} \tag{6}$$

Criterion 1 mainly takes into account the forming accuracy of the blade body, and the theta angle value corresponding to each point on the blade profile must be strictly controlled. According to the technological characteristics of electrolytic machining and long-term engineering practice experience, the application range of theta angle is less than 45 °.

Guideline 2 takes into account the overall distribution of the corner. It is known that the mean value of all sampling points obey the normal distribution, and in the combination of the angle satisfying the criterion 1, the smaller the average value of the machining gap, the smaller the average fluctuation amount of the machining gap, and the better the machining accuracy. When the cathode parallel edge plate is fed, the rotation angle of 0 ° is a constant value. The clamping angle of the blank is in the range of 0°-180°, and the back of the blade basin and the blade are respectively calculated. The aim of the optimization is to find the best combination of angles in the tens of thousands of combinations, so that the corners of the profile conform to a certain standard. The section calculation method is adopted, as shown in Table 3 below.

TABLE III. B ANGLE SECTION VALUE SCHEME

	β value	**βIncrement of value**	**Combination number of α and β**
Leaf back	0 °~180 °	5 °	1×37
Leaf Basin	0 °~180 °	5 °	1×37

In the geometric relation, the clamping angle of the back and basin of the blade is complementary in the same plane, as long as one side of the optimal solution is selected. Taking the obtained optimal solution as the center, the range of the original value increment is 2 times, and the 1 °increment is used instead of the original increment. The piecewise value scheme is shown in table 4 below.

TABLE IV. B ANGLE SECTION VALUE SCHEME

	β value	**βIncrement of value**	**Combination number of α and β**
Leaf back	$\beta \pm 5^{\circ}$	1 °	1×10
Leaf Basin	$\beta \pm 5^{\circ}$	1 °	1×10

With this method, the calculation times will be greatly reduced. According to the above optimization criteria and calculation methods, part of the data obtained by the segmental calculation method for the leaf basin is shown in Table 5 below. It can be seen from the preliminary screening that the angle combination of 85 °/ 95 °clamping is adopted for the blank, and the calculation results are relatively ideal. The extreme value, overall distribution and variance of θ angle all meet the requirements of the optimization criteria.

TABLE V. ANGLE DATA OF LEAF BASIN OBTAINED BY ROUGH SCREEN CALCULATION IN SECTIONS

β（Leaf Basin）	θ_{max}	$\bar{\theta}$	σ_{θ}
70°	36.4°	21.3°	3.99
75°	37.5°	23.3°	3.96
80°	39.1°	26.1°	3.78
85°	39.7°	28.8°	3.63
90°	46.7°	31.8°	4.44
……	……	……	……

According to the results of the preliminary screening, the "fine" screening is carried out according to the segmented calculation method. Table 6 shows some data obtained through the segmented calculation method.

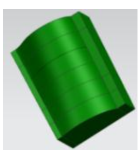
TABLE VI. ANGLE DATA OF LEAF BASIN OBTAINED FROM FINE SCREENING BY SECTIONAL CALCULATION

β（Leaf Basin）	θ_{max}	$\bar{\theta}$	σ_{θ}
83°	38.8°	26.8°	3.11
84°	39.2°	27.3°	2.99
85°	39.7°	28.8°	3.63
86°	41.0°	30.1°	3.08
87°	42.5°	31.4°	3.46
……	……	……	……

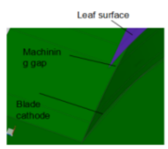
From the results of the screening, it can be concluded that the clamping angle combination with the blank clamping angle of 84 ° / 96 ° meets the requirements of optimization criteria 1 and 2, that is, the variance of θ angle is the smallest among all combinations, and its overall distribution is small and uniform. It can effectively ensure the stability and evenness of machining clearance, which is conducive to improving the forming accuracy of blade profile.

IV. CATHODE TOOL DESIGN AND 3D MODEL ESTABLISHMENT

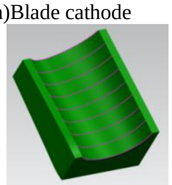
And the normal balance gap of each point can be determined, and the coordinate of the point corresponding to the cathode-type surface can be obtained by shifting the coordinate of the sampling point obtained on the blade sample piece by a certain distance along the normal direction . By means of the drawing module of the UG drawing module, the curve group is generated by the artistic spline command, and the curved surface is constructed according to the surface command generated by the curve group, namely, the tool cathode solid shape of the blade basin and the blade back of the work piece is processed, as shown in the following figure 4.



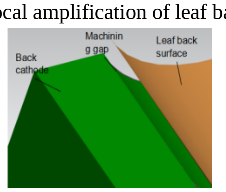
(a)Blade cathode



(b)Local amplification of leaf basin cathode



(c)Back cathode



(d)Local amplification of back cathode

Figure 4. Solid modeling of cathode tool

At this point, the initial cathode surface design of the turbine blade is completed. In the later stage, according to the solid modeling of the cathode tool, the actual cathode tool to be obtained needs to be processed on the five coordinate CNC machining center.

V. SUMMARY

Cathode design is the key link of ECM. The accuracy and automation of cathode design are related to the accuracy and production cycle of ECM. In this paper, the design of cathode for electrochemical machining of blade is discussed. Starting from the three-dimensional model of blade, the data collection of profile, the spatial distribution analysis of machining gap, the analysis and optimization of cathode feed angle and workpiece clamping angle are carried out, and the basic research on the design method of cathode for blade is carried out. For the initial cathode designed in this paper, we need to combine the processing test and the improvement of cathode correction to make the model more accurate.

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