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Application of FEM to tool design for electrochemical machining freeform surface

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Abstract

Accurate prediction of tool shape is one of the key points in electrochemical machining (ECM). This paper proposes an approach using finite element method (FEM) to design tool in ECM. This method is capable of designing three-dimensional freeform surface tool from the scanned data of known workpiece. It possesses high computing efficiency, good accuracy and flexible boundary treatment without the need for iterative procedure. An example of tool design for turbine blade is given to demonstrate this method.

Keywords: ECM; FEM; Tool design; Freeform surface

1. Introduction

In the modern science and technology, application of freeform surface parts becomes wider and wider. Some freeform surface parts, such as turbine blades and airfoils in aircraft engine industry, are made up of difficult-to-cut materials and have characteristics of complex and thin structure. When building them, no distortion or inducing residual stresses is acceptable. With traditional machining methods, it is very difficult to obtain the required machining precison. Alternatively, electrochemical machining (ECM) has been demonstrated to be an effective method for manufacturing these parts [1,2].

Compared with traditional machining methods, ECM takes many advantages in applicability such as manufacturing regardless of material hardness, no tool wear, no residual stress, high material removal rate, smooth and bright surface of complex geometry. Owing to these characteristics, ECM has been widely used in various fields, such as aerospace, automotive, national defence industry.

The main objective of ECM is to obtain required shape of the workpiece by using electrochemical dissolution process following Faraday's Law. And the tool shape is one of the key factors that determines the shape precision of the anode workpiece. Therefore, most research works on ECM were concentrated on tool design [3].

The determination of tool shape is a complicated process due to the gap configuration interactively affected by electric, thermal and flow field. To simplify this problem, the electric field was mainly taken into account and two-dimensional tools were designed in the early investigations [4,5]. For two-dimensional smooth parts, these methods were relatively accurate and could yield satisfactory results. However, for three-dimensional complex freeform surface parts, they cause remarkable errors. The larger the part surface's distortion is, the larger the error is obtained.

In theory, the tool design in ECM can be considered as an inverse boundary problem of Laplace's equation. Although an accurate analytical solution to the problem is impossible, it can be approximately tackled by numerical solutions in an iterative manner [6–8]. The procedure of numerical solutions is: a trial tool shape is calculated by the cos θ theory [9], then the tool shape is adjusted until all boundary conditions are met. The final boundary surface is the required tool geometry. Therefore, how to get excellent convergence and how to make the numerical solution method apt to deal with complex boundary conditions are the two main problems that have to be considered initally.

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Among numerical solutions, the finite element method (FEM) has abundant kinds of elements and various forms of meshes, so it is an appropriate candidate to treat complex boundary conditions.

In the present work, we developed a technique that is capable of handling three-dimensional tool design based on the Laplace's equation of the practical potential field with the FEM. The paper is structured as follows: firstly, mathematical modeling of freeform surface geometry and electric potential distribution within gap are described. Secondly, meshing and numbering and solution to the FEM are discussed. And the tool shape is selected from a group of equal-potential surfaces. At last, an example is given to show the validity of the proposed method.

2. Mathematical modeling

The freeform surfaces are usually defined as Bezier, B-spline and NURBS types. Among them, NURBS has more advantages over the other types, such as a uniform expression to all curves or surfaces and more easily controlling surface shape through modifying weight coefficient or control points. So it is popularly used in CAD softwares.

In this paper, NURBS model is used to describe freeform surface parts from the scanned data. Based on it, the trial tool shape is constructed. Meanwhile, the electric potential distribution in the gap of ECM is also modeled to determine the desired tool shape.

2.1. Modeling workpiece and trial tool shape

NURBS surface equation fitted to the scanned data can be expressed as

$$S(u, v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} \mathrm{V}_{ij} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} N_{i,p}(u) N_{j,q}(v)}, \quad u, v \in [0, 1], \tag{1}$$

where $\boldsymbol{V}_{ij}$ is the array of control points, which can be obtained by reversely calculating the scanned data. ω_{ij}-the weight factor at $\boldsymbol{V}_{ij}$, $N_{i,p}(u)$ and $N_{j,q}(v)$ the p and q powers of the base function of B spline, respectively.

Unit normal vector of the workpiece is then obtained by

$$\boldsymbol{n} = \frac{\boldsymbol{S}_u(u, v) \times \boldsymbol{S}_v(u, v)}{|\boldsymbol{S}_u(u, v) \times \boldsymbol{S}_v(u, v)|} = (n_x, n_y, n_z), \tag{2}$$

where $\boldsymbol{S}_u$ and $\boldsymbol{S}_v$ are tangential vectors along u and v directions, respectively.

The trial tool shape is calculated as follows.

Suppose that the z-axis of the workpiece coordinate system is parallel to the machine axis. It means that the tool feed rate $\boldsymbol{V}_f$ is parallel to the z-axis of the workpiece coordinate system. Thus, the unit vector of $\boldsymbol{V}_f$ can be expressed to be $(0, 0, -1)$, shown in Fig. 1. Then, the angle θ between the tool feed rate $\boldsymbol{V}_f$ and the normal vector to the anode $\boldsymbol{n}$ can be obtained as

$$\theta = \arccos \frac{\boldsymbol{n} \cdot \boldsymbol{V}_f}{|\boldsymbol{V}_f|} = \arccos(-n_z). \tag{3}$$

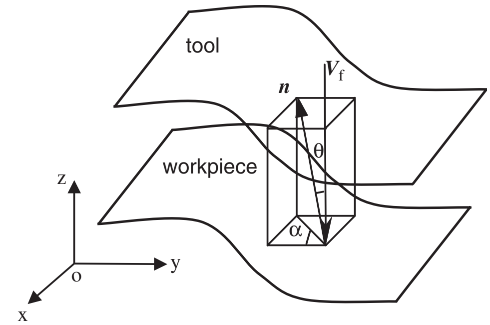

Fig. 1. The tool shape for the first trial.

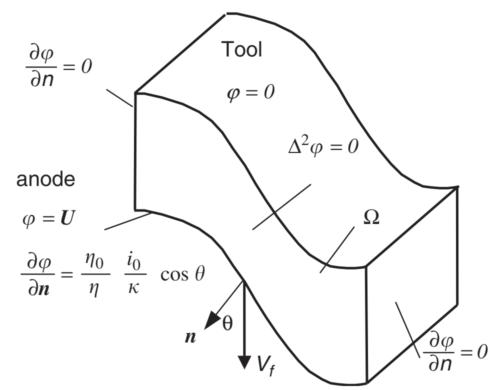

Fig. 2. Electric potential distribution within gap.

According to electrochemical law, the relationship between the coordinates of each point on the tool (x_t, y_t, z_t) and those on the workpiece (x_w, y_w, z_w) can be expressed by

$$\begin{cases} x_t = x_w - \Delta_b \cdot \sin\theta \cdot \sin\alpha, \\ y_t = y_w - \Delta_b \cdot \sin\theta \cdot \cos\alpha, \\ z_t = z_w + \Delta_b, \end{cases} \tag{4}$$

where Δ_b is the equilibrium gap at $\theta = 0$. $\alpha = \arctan n_x/n_y$, which is the angle between y-axis and the project of $\boldsymbol{n}$ on xoy plane.

Consequently, the trial tool shape is obtained with Eqs. (1)–(4) and used as the initial boundary condition during FEM calculation.

This method of obtaining the trial tool shape is different from the one in Ref. [9]. It has better initial boundary condition and then could decrease the iterative number of FEM.

2.2. Modeling electric potential distribution within gap

The workpiece profile and the trial tool shape form the gap domain Ω (see Fig. 2). According to the theories of electric field and electrochemistry, the distribution of electric potential within Ω in ECM can be described by Laplace equation:

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0. \tag{5}$$