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Modeling of wire electrochemical micromachining

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Abstract

Wire electrochemical micromachining (WECMM) is a promising method for the fabrication of various metal parts. In recent years, WECMM has attracted increasing interest, especially for treatment of complex-shaped microworkpieces. By now, the regularities of electrochemical shaping for the complex-shaped workpieces have not been adequately investigated, because the majority of the works, which are devoted to WECMM, are experimental.

In this work WECMM is studied theoretically. The Laplace equation for the electric potential and the equation of workpiece surface evolution are used as the mathematical model of the process. A scheme of computer simulation involves the numerical solution of the Laplace equation by the boundary element method; the determination of a new position of workpiece surface with regard for possible topological changes; and the motion of wire tool-electrode along a prescribed trajectory. Various schemes of shaping for the tool-electrodes with various cross-section shapes and various types of motions are analyzed. As a result of simulation, the dependences of the front and side interelectrode gaps on the machining parameters are obtained. They can be used for determining the path of wire tool-electrode in order to obtain the prescribed shape and sizes of workpiece surface.

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Keywords: Electrochemical micromachining; Wire tool electrode; Numerical simulation

1. Introduction

For cutting the complex-shaped parts made of difficult-to work materials, various methods of machining (diamond wire cutting [1], wire electrical discharge machining [2], laser beam cutting [3], plasma arc cutting [4], fluid jet machining [5]) are widely used. Along with the methods of mechanical, chemical, and physical treatment, various schemes of electrochemical machining (ECM) are used to fabricate complex-shaped and microstructured surfaces. The ECM offers several advantages: the absence of mechanical and heat effect on the workpiece, absence of tool-electrode (TE) wear, a possibility of controlling the shape and dimensions of workpiece surface by varying the machining conditions and trajectory of TE movement [6]. The following schemes of electrochemical machining are widely used to fabricate the complex-shaped and functional surfaces:

(1) With the use of a stationary non-profiled TE and a mask placed on the anode or cathode.

(2) With a profiled TE moving towards the workpiece surface.

(3) With non-profiled TE, which moves along the workpiece surface by the prescribe trajectory with the aid of numerically controlled system. The term “non-profiled” means that the shape and sizes of TE do not correspond to those of workpiece surface.

Nomenclature

B_{TE}	dimensionless length of TE cross-section
d_{TE}	diameter of the circumcircle for the TE cross-section
E	electrode potential
H	dimensionless width of slit
H_{TE}	dimensionless height of TE cross-section
i	current density
L	natural parameter of workpiece surface

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L_{TE} natural parameter of TE surface
n unit vector of outer normal to surface
R_0 dimensionless radius entry hole
S_F dimensionless frontal interelectrode gap between plane electrodes
U^* characteristic applied voltage
v^* characteristic TE feed rate
V_{TE} dimensionless feed rate of tool-electrode
Wa Wagner number
X, Y dimensionless coordinates
α angle of rotation of TE
ε_V volumetric electrochemical equivalent
η current efficiency
τ dimensionless time
χ conductivity of electrolyte solution
Ω_{TE} dimensionless TE angular rate
Φ dimensionless potential
C subscript, which characterizes the location of the center of TE
TE subscript, which denotes tool-electrode
x, y subscripts, which denote the projections on the corresponding axis of coordinates
WP subscript, which denotes workpiece
0 subscript, which characterizes the initial values (before machining)

The application of non-profiled TE enables one to improve the conditions of removal of machining products, because the instantaneous machining surface area is only a small fraction of the total machining surface area. The required shape and sizes of workpiece surface are provided by the motion of TE along a certain trajectory. By now, the technologies of fabrication of tool-microelectrodes with rather complicated cross-section shape have been developed [7]. The application of such wire TE enables one to enhance the efficiency of machining by combining the merits of profiled and non-profiled TE. This method significantly extends the capabilities of electrochemical machining for fabricating complex-shaped surfaces and the microelements of various shapes and sizes.

Though the schemes of wire electrochemical cutting have been known rather long [8], insufficient accuracy of the machining limited its application. However, in recent years, the wire electrochemical cutting has attracted increasing interest, especially for treatment of microworkpieces [9]. At present, the possibilities of WECMM are significantly extended due to improved mass transfer [10] and the application of short pulses [11]. It was shown experimentally that the vibration of TE has a pronounced effect on the mass-transfer rate [12] providing high cut width accuracy in the machining using curved micro-cantilever beams [13]. The majority of the works devoted to this problem are experimental. To predict the geometry of workpiece surface and study the regularities of surface machining with moving TE, it is advantageous to use the methods of mathematical modeling. Various modes of ECM are frequently simulated using a mathematical model involving the Laplace equation for the electric potential and the equation of workpiece surface evolution [14]. The equations of mathematical model are solved numerically by the finite elements method [15] or by the boundary elements method [16]. In the majority of the works devoted to the modeling of ECM, the schemes of machining with stationary electrodes or electrodes moving towards the workpiece surface are considered. Frequently, the simplest cases of machining, when the topological changes of workpiece surface are absent, are considered.

In the works devoted to the modeling of wire ECM, as a rule, approximate mathematical models are used, which are based on the linear approximation of distribution of electric potential along the interelectrode gap [17]. This approximation may be used only in the cases that the interelectrode gap is significantly smaller than the characteristic size of TE or workpiece. However, in many cases, especially in the WECMM, the gap is comparable to the characteristic size of TE. In this case, the distribution of current density should be calculated by using the Laplace equation. Earlier [18], we developed a method of modeling ECM with a wire TE, which moves by an arbitrary trajectory along the workpiece surface, using the boundary element method.

Here, the earlier-proposed method is further developed in order to predict the shape and sizes of complex-shaped surfaces and microstructures, which form on the workpiece surface machined with a moving wire TE with various shapes of cross-section; the tool-electrode can move forward, rotate, and execute transverse oscillations.

2. Mathematical Model

The model of the wire electrochemical machining (Fig. 1) involves the Laplace equation for the electric field potential, equation of workpiece surface evolution, and equations of motion of wire TE. Let us present the mathematical model in the dimensionless form. The diameter of the circumcircle for the TE cross-section (d_{TE}) was taken as a unit length; the characteristic applied voltage (U^*), as a unit electric potential; and the characteristic TE feed rate (v^*), as a unit rate. Then, the following system of dimensionless equations is obtained:

$$\begin{aligned}
&\operatorname{div}(\operatorname{grad}\Phi) = 0,\\
&\frac{dX_{WP}}{d\tau} = \eta S_F \frac{\partial\Phi}{\partial X}, \quad \frac{dY_{WP}}{d\tau} = \eta S_F \frac{\partial\Phi}{\partial Y},\\
&\frac{dX_C}{d\tau} = V_{TE,x}(\tau), \quad \frac{dY_C}{d\tau} = V_{TE,y}(\tau), \quad \frac{d\alpha}{d\tau} = \Omega_{TE}(\tau),\\
&\bar{X}(L_{TE},\tau) = X_0(\tau) + X_{TE}(L_{TE})\sin[\alpha(\tau)] - Y_{TE}(L_{TE})\cos[\alpha(\tau)],\\
&\bar{Y}(L_{TE},\tau) = Y_0(\tau) + X_{TE}(L_{TE})\cos[\alpha(\tau)] + Y_{TE}(L_{TE})\sin[\alpha(\tau)].
\end{aligned} \tag{1}$$

Equations (1) involve the dimensionless parameter S_F, which characterizes the machining conditions. This parameter is calculated by the following equation:

$$S_F = \frac{\varepsilon_V \chi U^*}{d_{TE} v^*}. \tag{2}$$