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Effect of Current Efficiency on Electrochemical Micromachining by Moving Electrode

V.M. Volgin[a,]*, V.V. Lyubimov[a], I.V. Gnidina[a], A.D. Davydov[b], T.B. Kabanova[b]

[a]Tula State University, pr. Lenina 92, Tula 300012, Russia

[b]Frumkin Institute of Physical Chemistry and Electrochemistry RAS, Leninskii pr. 31, Moscow 119071, Russia

* Corresponding author. Tel.: +7-4872-35-24-52; fax: +7-4872-35-81-81. *E-mail address:* volgin@tsu.tula.ru

Abstract

In this work, the effect of current efficiency on the electrochemical micromachining by moving electrode 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 new scheme of solution of free boundary problem for steady-state electrochemical micromachining is proposed. According to the scheme, the initial approximation of the workpiece surface is prescribed. In the course of modeling, the workpiece surface moves in the normal direction at a rate proportional to the discrepancy of the steady-state condition. The effect of various dependences of current efficiency on the local current density is analyzed. As a result of simulation, the dependences of the shape and sizes of machined surface on the current efficiency and the machining parameters are obtained.

Keywords: Electrochemical micromachining; Current efficiency; Numerical simulation

1. Introduction

Along with the methods of mechanical, chemical, and physical treatment, various schemes of electrochemical micromachining (ECMM) are used to fabricate complex-shaped and microstructured surfaces [1]. ECMM offers several advantages: the absence of mechanical and heat effects on the workpiece (WP), no tool wear, relatively high material removal rate, smooth and bright surface, and the production of components of complex geometry [2, 3]. Therefore, ECMM is used in many industrial applications including turbine blades, engine castings, bearing cages, gears, dies and molds and surgical implants [3].

The following schemes of electrochemical machining are widely used: (1) with the use of a stationary non-profiled tool-electrode (TE) and a mask placed on the anode [4, 5] or cathode [6]; (2) with a profiled TE moving towards the workpiece surface [7]; (3) with non-profiled TE, which moves along the workpiece surface by the prescribed trajectory with the aid of numerically controlled system [8]. The term “non-profiled” means that the shape and sizes of TE do not correspond to the targeted shape of workpiece surface. In recent years, ECMM by moving electrode has attracted increasing interest, especially for machining of complex-shaped microworkpieces [9]. The shape and sizes of the machined surface depend on a large number of factors; therefore, a precise prediction of the geometry of workpiece surface is of great practical importance [10]. In the general case, the shape and sized of machined surface can be determined by solving the non-steady-state problem [11, 12]. However, the solution of non-steady-state problem requires a large volume of computation. Frequently, the quasi-steady state is reached in a short time, i.e. in the system of coordinates related to the TE, the shape and sizes of the workpiece do not change with the time. In this case, ECMM can be simulated using the models of steady-state shaping [13, 14]. Within the approximation of “ideal” ECMM process, the determination of steady-state shape of workpiece surface is reduced to the solution of free boundary problem for the Laplace equation. The condition of steady state [13] or the condition of constant current density [14] is used as an additional condition. In some cases (point, rectangular, corner

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TE, etc.), the exact analytical [14] or approximate numerical [15] solution of the problem of steady-state ECMM can be obtained. In most cases, even for the cylindrical TE, the solution of steady-state problem requires the non-steady-state methods. This complicates considerably the prediction of the shape and sizes of machined surface.

The current efficiency depends on the local current density and has a pronounced effect on the shape and dimensions of workpiece surface. In several works [16, 17], it was shown that, when the current efficiency has the form of a step function of current density, the accuracy of ECMM increases significantly. However, the effect of variable current efficiency on the electrochemical machining by moving electrode has not been adequately investigated.

The aim of this work is to develop an effective method for modeling steady-state ECMM by moving TE of arbitrary shape that takes into account the dependence of current efficiency on the current density.

2. Mathematical model

An "ideal" model for ECMM by moving TE is considered (Fig. 1a). The following basic assumptions are made: 1) there are no concentration or temperature gradients within the electrode gap due to the intense electrolyte solution flow; 2) the dependence of current on the electrode potential is ignored. Under these assumptions, the primary distribution of potential and current density takes place, Faraday's law of electrolysis can be employed to determine the rate of the workpiece dissolution:

$$\mathrm{div}(\mathrm{grad}\,\varphi) = 0\,, \tag{1}$$

$$\mathbf{i} = -\chi\,\mathrm{grad}\,\varphi\,, \tag{2}$$

$$v_n = \eta \varepsilon_V \mathbf{i}\cdot\mathbf{n}\,, \tag{3}$$

where φ is the potential; χ is the conductivity of electrolyte solution; $\mathbf{i}$ is the current density; $\mathbf{n}$ is a unit vector of outer normal to the workpiece surface; ε_V is the volumetric electrochemical equivalent of the workpiece material; η is the current efficiency; v_n is the rate of electrochemical dissolution.

The following boundary conditions are used:

$$\varphi|_{\mathrm{WP}} = u\,, \tag{4}$$

$$\varphi|_{\mathrm{TE}} = 0\,, \tag{5}$$

$$(\partial\varphi/\partial n)_{\mathrm{I}} = 0\,, \tag{6}$$

where u is the applied voltage; subscripts WP, TE, and I denote workpiece, tool-electrode and isolator, respectively.

In the two-dimensional case, in the system of coordinates related to the TE, the equation of the workpiece surface evolution $y_{\mathrm{WP}}(x,t)$ can be presented in the following form:

$$\frac{\partial y_{\mathrm{WP}}}{\partial t} = -v_n\sqrt{1+\left(\frac{\partial y_{\mathrm{WP}}}{\partial x}\right)^2} + v_{\mathrm{TE}}\,, \tag{7}$$

where t is the time; v_{TE} is the feed rate of tool-electrode.

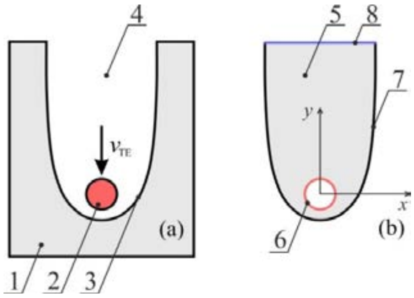

Fig. 1. (a) Scheme of electrochemical micromachining by moving tool-electrode and (b) the computational region: (1) workpiece, (2) TE that moves towards the workpiece at a rate v_{TE}; (3) workpiece surface; (4) interelectrode gap filled with the electrolyte solution; (5) computational region; (6) surface of moving TE; (7) machined surface; and (8) insulator surface that bounds the computational region.

In the steady state, equation (7) takes the following form:

$$\eta\varepsilon_V\chi\frac{\partial\varphi}{\partial n} + v_{\mathrm{TE}} n_y = 0\,, \tag{8}$$

where $n_y = -\cos\alpha = -1/\sqrt{1+(\partial y_{\mathrm{WP}}/\partial x)^2}$ is the projection of a unit vector of the outer normal to the workpiece surface onto the y axis and α is an angle between the direction of tool-electrode feed and the outer normal to the workpiece surface.

For convenient solution and analysis of the results, the mathematical model is presented in the dimensionless form. The diameter of the circumcircle for the TE cross-section (d_{TE}) is taken as a unit length; the characteristic applied voltage ($d_{\mathrm{TE}} v_{\mathrm{TE}}/(\eta^*\varepsilon_V\chi)$), as a unit electric potential; and the characteristic current density ($v_{\mathrm{TE}}/(\eta^*\varepsilon_V)$), as a unit current density:

$$X = \frac{x}{d_{\mathrm{TE}}},\; Y = \frac{y}{d_{\mathrm{TE}}},\; \Phi = \frac{\eta^*\varepsilon_V\chi}{d_{\mathrm{TE}} v_{\mathrm{TE}}}\varphi,\; \mathbf{I} = \frac{\eta^*\varepsilon_V}{v_{\mathrm{TE}}}\mathbf{i},\; U = \frac{\eta^*\varepsilon_V\chi u}{d_{\mathrm{TE}} v_{\mathrm{TE}}}\,. \tag{9}$$

Here X, Y are the dimensionless coordinates; Φ is the dimensionless potential; $\mathbf{I}$ is the dimensionless current density; U is the dimensionless applied voltage.

$$\mathrm{div}(\mathrm{grad}\,\Phi) = 0\,. \tag{10}$$

The boundary conditions:

$$\Phi|_{\mathrm{TE}} = 0\,, \tag{11}$$

$$\Phi|_{\mathrm{WP}} = U\,, \tag{12}$$

$$\left.\left(\frac{\eta}{\eta^*}\frac{\partial\Phi}{\partial N} + N_Y\right)\right|_{\mathrm{WP}} = 0\,, \tag{13}$$

$$(\partial\Phi/\partial N)_{\mathrm{I}} = 0\,. \tag{14}$$

The mathematical model (10) – (14) involves one dimensionless parameter U, one dimensionless function η/η^* that prescribes the dependence of current efficiency on the current density, and preliminarily unknown workpiece surface $Y_{\mathrm{WP}}(X)$. Dimensionless parameter U has a physical meaning: