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Modelling of precision steady-state and non-steady-state electrochemical machining by wire electrode-tool

V.P. Zhitnikov*, N.M. Sherykhalina, A.A. Zaripov

Ufa State Aviation Technical University, 12 K. Marx Str., 450000 Ufa, Russia

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ABSTRACT

The methods of the theory of functions of a complex variable are applied for investigation of the electrochemical machining process. The steady-state and non-steady-state processes of workpiece cutting using a wire electrode-tool are considered. For modelling of the precision process of electrochemical machining the stepwise function of current efficiency is used. The function determines the movement velocity of the anode boundary. The machining surface at steady-state process is divided into three parts: an active dissolution area, an area where there is no dissolution (for low current density) and a transition area in which the current density is equal to a critical value. At non-steady-state process a jump-like dissolution turn on and turn off and dynamical ascertainment of workpiece shape takes place in the transition area. The numerical investigation of solutions of non-steady-state problems shows quick formation of the solution coinciding with the steady-state solution obtained independently up to accuracy 0.001.

1. Introduction

The investigation of electrochemical shaping is of great interest in connection with the wide application of electrochemical mechanical machining (ECM) in different branches of industry; see, for example, McGeough (1974). Today the technologies of precision machining of different metals and alloys are being actively developed, including nanotechnologies, with the help of pulse ECM by a vibrating electrode-tool (ET), as described by Zhitnikov and Zaytsev (2008).

The modelling of ECM is based on Faraday's law:

$$V_{ecm} = \frac{k}{\kappa}\eta j,\ \mathrm{k} = \kappa\varepsilon/\rho, \tag{1}$$

where V_{ecm} is the dissolution velocity, ε is the electrochemical equivalent, ρ is the density of the dissolved material; κ is the conductivity of the electrolyte; j is the current density on the anode boundary; $\eta = \eta(j)$ is the current efficiency (the current fraction taking part in the material dissolution reaction).

The precision technologies of pulse cyclic ECM are being applied at present to achieve increased accuracy. In this case, an oscillating constituent (usually sinusoidal) is imposed on the ET translation movement, and the current is given as rectangular pulses at the time of the maximum approach of the ET and the detail. The completed electrolyte is substituted at the moment when the ET is removed from the detail. The shift of the workpiece surface in one period is assumed to be a small quantity in view of the small velocities of ECM (several mm/min) and the short pulses (about 1–3 ms). Then it is possible to use a discrete-continuous model of the process for which the dependence (considered above) of the dissolution velocity on the current density is valid, and the proportionality coefficient k decreases by Q times, where $Q = T/t_p$, T is the oscillation period, t_p is the pulse duration.

In view of the shortness of the pulses, it is possible to neglect the electrolyte heat and gas filling. So, the ideal process in a standard electrolyte is considered here.

For a given dependence of the current efficiency $\eta(j)$ on the current density j and constant electrode potentials, the process localization is determined by the coefficient introduced by Idrisov et al. (2004):

$$k_{loc} = \frac{j}{V_{ecm}}\left|\frac{dV_{ecm}}{dj}\right| = \left(1 + \frac{j}{\eta}\frac{d\eta}{dj}\right). \tag{2}$$

So, the greater the value of $d\eta/d\eta$ the greater the value of k_{loc}.

In this paper, the dependence of the current efficiency on the current density is modelled by the stepwise function suggested by Zhitnikov et al. (2011):

$$\eta(j) = \begin{cases} \eta_0, & j > j_1, \\ \forall\eta \in [0, \eta_0], & j = j_1, \\ 0, & j < j_1. \end{cases} \tag{3}$$

* Corresponding author.
E-mail addresses: zhitnik@mail.ru, zhitnik@ugatu.ac.ru (V.P. Zhitnikov).

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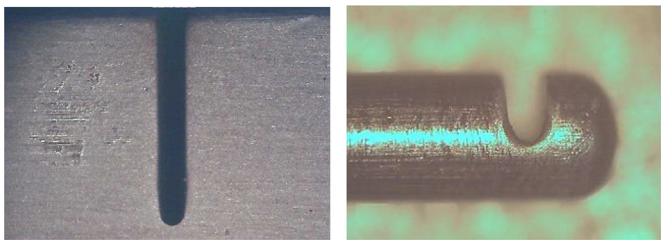

Fig. 1. Profile patterns obtained by cutting of grooves.

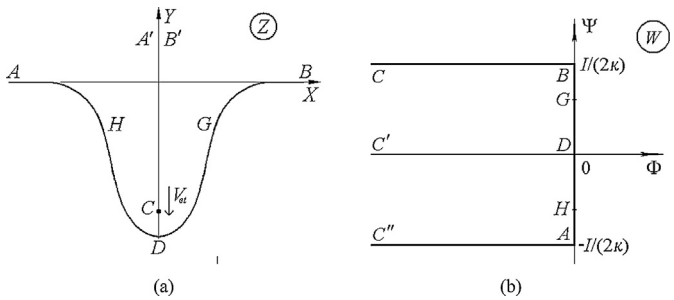

Fig. 2. IES images shapes: (a) physical plane; (b) complex potential plane.

Note that this model does not contradict the experimental results of Mannapov et al. (2011), because the real dependence for passivate electrolytes for rather short pulses contains a segment where there is sharp changing of the current efficiency if the current density approaches some critical value. The qualitative experimental justification of this dependence presents in Zhitnikov et al. (2011).

It is important that the dependence (3) has a vertical segment (where the derivative tends to infinity), which provides the most localization according to Eq. (2).

Karimov et al. (1990) and Zhitnikov and Zaytsev (2008) have solved the problems of the steady-state shaping by a point ET and a round ET for $\eta = const$. For non-steady-state problems with a point and plane ET, the dependence $\eta = const$ was used by Zhitnikov et al. (2004). The non-steady-state shaping by a plane ET with stepwise dependence of the current efficiency was investigated by Zhitnikov et al. (2011). The non-steady-state problem of the copying of a round ET with hyperbolic dependence of current efficiency was solved by Minazetdinov (2009). The cutting by a round ET for different changes of ET trajectory for $\eta = const$ was investigated by Volgin et al. (2014) using the boundary element method. The boundary element method was also applied by Purcar et al. (2004) for ECM problems solving for $\eta = \text{const}$. The authors of these two papers notice that solving of the problems by numerical methods one can obtain uncontrolled grid nodes rapprochement in some regions. This process leads to the deceleration or to the computational error increase (Pandey, 1980). The complex approaches of location control of grid nodes are required to avoid such problems.

We can fix nodes on the border of the region on some parametric plane χ (for example a band). In this case the conformal mapping is used and the partial time derivative is calculated $\partial Z/\partial t(\chi, t)$, ($Z = X + iY$, X, Y are the Cartesian coordinates, t is the time) This modification simplifies non-steady-state problems solution (Zhitnikov et al. (2004)). Particularly, the form of integrated functions allows application of uniform spatial grid on all time steps in spite of the essential variation of inter-electrode space.

2. Problem statement

Let us consider a non-steady-state problem of electrochemical machining with the help of a wire ET.

Photos of experimental patterns with grooves obtained by cutting of the produced details are shown in Fig. 1. The width of the slots in these experiments varied in the range of 50–200 μm.

The wire ET, represented by a point at the cut, moves into the depth of the initially plane workpiece with velocity $V_{et} = -\mathrm{d}Y_c/\mathrm{d}t$ (Y_c is the ordinate of the point C, t is the time) at a right angle to the surface. The initial gap between electrodes (the distance CD) is equal to S_0. The current in a unit width cell is equal to I. The inter-electrode space (IES) shape is shown in Fig. 2a. Here HDG is the dissolution area, and AH and GB are insoluble ($\eta = 0$) boundaries.

The methods of the theory of functions of a complex variable can be used under the assumption of medium ideality. The considered problem is a variety of the Hele-Shaw problem with a free boundary (Howison (1992)).

Let us consider the complex potential $W = \Phi + i\Psi$, where Φ is the electrical field potential, Ψ is the stream function. The magnitude of the electrical field strength is determined by the derivative $E = \overline{(\mathrm{dW/dZ})}$, and the current density is $j = \kappa|\mathrm{dW/dZ}|$ according to Ohm's law, $Z = X + iY$. The problem is reduced to determining the conformal mapping of the IES area of the physical plane onto the area in the plane W at every moment.

The potential Φ is assumed to be constant (equal to zero) on the boundary corresponding to the machining surface; the stream function Ψ has constant values on any streamline. Therefore, a semi-band with the width I/κ (Fig. 2b) is a domain corresponding to the IES in the complex potential plane.

Let us come to the dimensionless magnitudes z, τ and w:

$$z = \frac{Z}{l},\ \ \mathrm{x} = \frac{X}{l},\ \mathrm{y} = \frac{Y}{l},\ \tau = \frac{V_{et}}{l}\mathrm{t} = \frac{k\eta_0 I}{l^2\kappa}\mathrm{t},\ \ w = \frac{\kappa}{I}\mathrm{W},\ \varphi = \frac{\kappa}{I}\Phi\,\psi = \frac{\kappa}{I}\Psi, \tag{4}$$

where $l = k\eta_0 I/(\kappa V_{et})$ is a typical dimension. For $\eta = const = \eta_0$ this magnitude is equal to the asymptotical width of the groove appearing when the ET moves into the workpiece.

We denote the dimensionless ordinate of the point C by y_C, the dimensionless velocity of ET by v_{et}. Then

$$v_{et} = -\frac{dy_C}{\mathrm{d}\tau} = -\frac{1}{l}\frac{l}{V_{et}}\frac{\mathrm{d}Y_C}{dt} = 1.$$

Then the equality (1) takes the form

$$\frac{\mathrm{d}z}{d\tau} = \frac{l^2\kappa}{lk\eta_0 I}\frac{dZ}{dt} = \frac{l\kappa}{k\eta_0 I}k\eta\overline{\left(\frac{\mathrm{d}W}{\mathrm{d}Z}\right)} = \frac{\eta}{\eta_0}\overline{\left(\frac{\mathrm{d}w}{\mathrm{d}z}\right)}, \tag{5}$$

where $\eta = \eta\left(\kappa V_{et}/\mathrm{k}\eta_0|\mathrm{dw/dz}|\right)$ according to Eq. (3).

The equality (5) allows us to compute the evolution of the free boundary of the machining surface in time and it is used in solving of the non-steady-state problem.

Let us consider the steady-state solution forming on the most part of workpiece surface in machining zone with time increase. In this case the boundary shift along the normal caused by electrochemical dissolution is equal to the projection of the ET's moving velocity on the normal. Note that the strength vector is directed along the normal to the electrodes' boundaries (from cathode to anode) for equipotential electrodes. In this connection, the steady state condition can be written in the form

$$|\frac{\mathrm{d}Z}{dt}| = k\eta|\frac{\mathrm{d}W}{\mathrm{d}Z}| = -V_{et}\sin\theta,$$

where θ is the inclination angle of the strength vector to the X-axis.

This formula for dimensionless variables has the form

$$\frac{\eta}{\eta_0}|\frac{\mathrm{d}w}{\mathrm{d}z}| = -\sin\theta. \tag{6}$$

Note, that for application of the function (3) the Eqs. (5), (6) remain valid for any value of η. Particularly, the equality $\mathrm{d}z/\mathrm{d}\tau = 0$ follows from (5) for $\eta = 0$ and the equality $\sin\theta = 0$ follows from Eq. (6).