CHEMICAL ENGINEERING TRANSACTIONS
VOL. 41, 2014
Guest Editors: Simonetta Palmas, Michele Mascia, Annalisa Vacca

ISBN 978-88-95608-32-7; **ISSN** 2283-9216

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1441016

Modeling of Wire Electrochemical Machining

Vladimir M. Volgin*[a,b], Van Dong Do[a], Alexey D. Davydov[b]

[a]Tula State University, pr. Lenina 92, Tula 300012, Russia
[b]Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Leninskii pr. 31, Moscow 119071, Russia
volgin@tsu.tula.ru

The electrochemical machining with a wire tool electrode was studied theoretically. The Laplace equation for the electric field potential and the equation of workpiece surface evolution were used as the mathematical model of the process. A scheme of computer simulation of machining was developed. The scheme involved the numerical solution of the boundary integral equation, which is a consequence of the Laplace equation, by using the method of boundary elements; 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 path.
The machining of typical features (straight slits, slits with corners, openings with square and triangular cross-sections) is analyzed. It is shown that this scheme of simulation can be used for various machining regimes, including the cases of the topological changes of the workpiece surface. The results of simulation agree well with the literature data on the wire electrochemical machining. As a result of simulation, the dependences of the front and side interelectrode gaps on the machining parameters were obtained for various schemes of machining. They can be used for determining the path of wire tool electrode in order to obtain the prescribed shape and sizes of workpiece surface.

1. Introduction

For cutting the complex-shaped parts made of difficult-to work materials, various non-conventional methods of machining (laser, electro-erosion, electrochemical machining) are widely used (Rajurkar et al., 2006). In the cases of laser and electro-erosion cutting, a zone of thermal effect forms on the workpiece surface; in the electrochemical machining (ECM), such zone is not observed (Davydov et al., 2004). Though the schemes of wire electrochemical cutting have been known rather long (Metzger, 1958), insufficient accuracy of the machining limited its application (Proklova, 1976). However, in recent years, the wire electrochemical cutting has attracted increasing interest, especially for treatment of microworkpieces (Chung et al., 2011). This is caused by several reasons: the absence of considerable mechanical action on the wire tool-electrode and the workpiece (Lee et al., 2011) (as a result, low-stiff workpieces can be treated to a high accuracy); the absence of thermal action of the workpiece and tool (Speiser and Ivanov, 2013); the absence of tool-electrode wear (Rajurkar et al., 2013); the use of ultra-short voltage pulses (of several nanoseconds) and ultra-small interelectrode gaps (of the order of several micrometers) (Shin et al., 2008); the use of axial electrolyte flushing (Qu et al., 2013); the use the small amplitude vibration of tool-electrode (Wang et al., 2011), etc.
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 the wire electrochemical cutting are experimental. In the case of linear motion of wire electrode with a constant rate, the parameters of cutting can be determined by using the known analytical solutions (Zhitnikov et al., 2004); in more complex cases, the numerical methods should be used (Hinduja et al., 2013). In this case, the boundary element method (Volgin and Davydov, 2004) is more suitable than the finite element method (Rodrigues et al., 2011), because, it is easier to perform the remeshing of the computational domain.
The aim of this work is to develop the methods of numerical simulation of wire electrochemical machining with regard for possible topological changes in the workpiece surface and to study various schemes of

Please cite this article as: Volgin V., Do D., Davydov A., 2014, Modeling of wire electrochemical machining, Chemical Engineering Transactions, 41, 91-96 DOI: 10.3303/CET1441016

formation of typical features (slits and openings of various shapes).

2. Statement of problem, basic equations

The model of the wire electrochemical machining (Figure 1) involves the Laplace equation for the electric field potential, equation of workpiece surface evolution, and equation of the trajectory of wire tool-electrode. For convenience, the mathematical model is written in the dimensionless form:

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

$$\frac{dX_a}{d\tau} = A\frac{\partial \Phi}{\partial X},\quad \frac{dY_a}{d\tau} = A\frac{\partial \Phi}{\partial Y} \tag{2}$$

$$\frac{dX_c}{d\tau} = V_c(\tau)\cos[\alpha_c(\tau)],\quad \frac{dY_c}{d\tau} = V_c(\tau)\sin[\alpha_c(\tau)] \tag{3}$$

where Φ is the dimensionless potential; *X*, *Y* are the dimensionless coordinates; τ is the dimensionless time; V_c, α_c are the dimensionless feed rate of wire tool-electrode and the angle between the direction of feed rate and the abscissa axis, respectively; *A* is dimensionless parameter, which characterizes the machining conditions; *a* is the subscript, which characterizes the point on the workpiece surface; *c* is the subscript, which characterizes the location of the center of the wire tool-electrode.

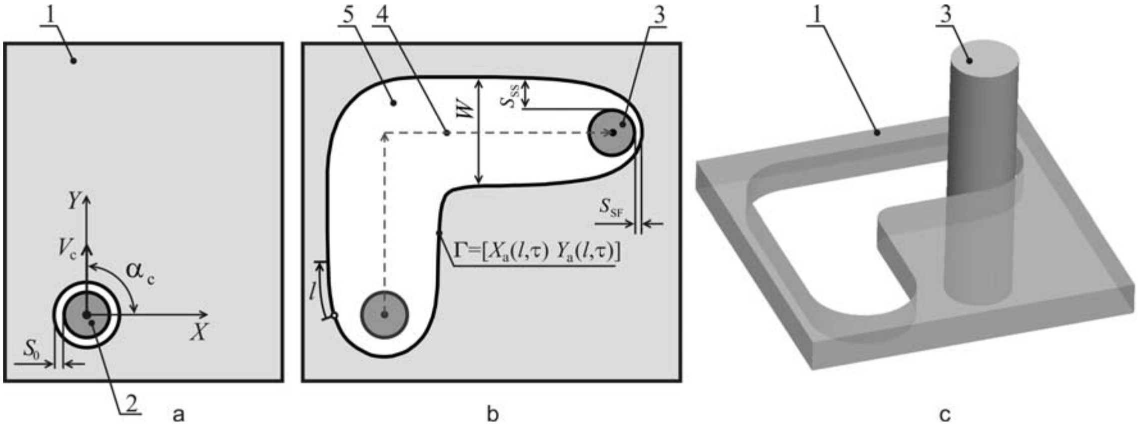

Figure 1: Scheme of wire electrochemical machining: (a) before machining, (b) and (c) during machining; (1) workpiece, (2) and (3) wire tool-electrode before and during machining, (4) trajectory of wire tool-electrode and (5) interelectrode gap filled with electrolyte solution; S_{ss} is side interelectrode gap, W is cutting width

When passing to the dimensionless variables, the diameter of wire tool-electrode (d_{WTE}) was taken as a unit length, the applied voltage (*U*) was taken as a unit electric potential, and the characteristic wire electrode feed rate (v_0) was taken as the unit rate:

$$X = \frac{x}{d_{\mathrm{WTE}}},\ Y = \frac{y}{d_{\mathrm{WTE}}},\ \Phi = \frac{\varphi}{U},\ I = \frac{d_{\mathrm{WTE}}}{\chi U}i,\ V_c = \frac{v_c}{v_0},\ \tau = \frac{v_0}{d_{\mathrm{WTE}}}t \tag{4}$$

where *x*, *y* are the dimensional coordinates; *t* is the time; φ is the potential in the solution; and χ is the conductivity of electrolyte solution.

The mathematical model (Eq. 1-3) ignores the variations in the solution concentration (Davydov et al., 2004). This is acceptable in the cases of sufficiently intense pumping or stirring of electrolyte solution.

Eq. 2 involves the dimensionless parameter A, which characterizes the machining conditions. It can be calculated by the following equation:

$$A = \frac{\eta \varepsilon_V \chi U}{d_{\mathrm{WTE}} v_0} \tag{5}$$

where η is the current efficiency and ε_V is the volumetric electrochemical equivalent.

To solve system of Eqs. 1 – 3, the boundary and initial conditions should be prescribed. For the scheme of wire electrochemical machining (Figure 1), in the case that the polarization of electrodes can be ignored, the boundary conditions for the dimensionless potential should be as follows:

$$\Phi = \begin{cases} 1, & \text{on the anode (workpiece)} \\ 0, & \text{on the cathode (wire tool - electrode)} \end{cases} \tag{6}$$

The initial conditions are prescribed under the assumptions that, at the initial instant of time, the center of wire tool-electrode is located at the origin of the coordinates, and the workpiece surface and the tool-electrode surface are separated by a dimensionless initial interelectrode gap S_0 (Figure 1 a).
Similarly to the electrochemical machining with a plane tool-electrode, which moves towards the workpiece with a constant rate, in the case under consideration, a steady-state frontal interelectrode gap can be introduced:

$$s^*_{\mathrm{SF}} = \frac{\eta \varepsilon_V \chi U}{v_0} \tag{7}$$

This enables us to present parameter *A* in the following form:

$$A = \frac{s^*_{\mathrm{SF}}}{d_{\mathrm{WTE}}} = S^*_{\mathrm{SF}} \tag{8}$$

i.e. parameter *A* is equal to the dimensionless interelectrode gap for the plane tool-electrode, all other conditions of machining being the same.

In the wire electrochemical machining, the steady-state frontal interelectrode gap (S_{SF}) will be smaller than in the machining with a plane electrode (S^*_{SF}). The relation between these frontal gaps is as follows:

$$K_{\mathrm{WTE}} = \frac{S^*_{\mathrm{SF}}}{S_{\mathrm{SF}}} \tag{9}$$

where K_{WTE} is the coefficient that monotonically decreases and approaches unity with decreasing steady-state interelectrode gap for the plane tool-electrode.

When passing to the dimensional variables, the variation of coefficient K_{WTE} from unity can be taken into account by comparing the prescribed and calculated values of steady-state frontal interelectrode gap. Using the dimensionless steady-state frontal interelectrode gap, equations (9) can be written as follows:

$$\frac{dX_a}{d\tau} = S^*_{\mathrm{SF}} \frac{\partial \Phi}{\partial X}, \quad \frac{dY_a}{d\tau} = S^*_{\mathrm{SF}} \frac{\partial \Phi}{\partial Y} \tag{10}$$

The boundary value problem for equations (1) – (3), (6) is a problem with moving boundary. Then, the equations, which describe the transport processes and the motion of computational region boundary, should be calculated simultaneously.

3. Method of numerical solution

The numerical solution is frequently simplified by using the quasi-steady state approximation. Within this approximation, the entire time of machining is divided into a number of time steps. For each step:
1) first, the distribution of electric potential is calculated (at the electrode geometry corresponding to the beginning of the step);
2) then, a new shape of the workpiece surface is determined (at the distribution of current density corresponding to the beginning of the step);

3) then, a new position of the center of the wire tool-electrode is determined.
At each time step, the boundary-value problem for Eq. 1 with the boundary conditions in Eq. 6 was solved numerically by the method of boundary elements. The system of difference equations was solved numerically by using the direct and iteration methods. As a result, the distribution of the current density over the workpiece surface was determined.
The equation of workpiece surface evolution (2) was solved numerically using the “Level Set” method, which provides the account for possible topological changes of the workpiece surface. To maintain the compromise between the accuracy and amount of computation, the remeshing of the workpiece surface was realized after each time step.

4. Results of modelling and discussion

The following values of parameters were taken for the modelling: the dimensionless steady-state interelectrode gap for plane electrode (S^*_{SF}) was taken to be 0.05 – 0.5; the dimensionless time step was chosen so that the numerical solution was stable and accurate (commonly, it was 0.002 – 0.02). From 20 to 100 boundary elements were prescribed on the initial surfaces of workpiece and wire tool-electrode. In the course of simulation, a distance between the nodes of boundary element mesh varied: it increased on the convex regions of workpiece surface and decreased on the concave regions. To provide an adequate accuracy of numerical solution and reduce the computational cost, the boundary element mesh was adapted in the course of simulation. The remeshing was realized by the following simple, but sufficiently effective method. When the length of the boundary element increased by more than 1.5 times (as compared with its initial length), the element was divided into two elements of the same length. When the length of boundary element decreased by more than 2 times (as compared with its initial length), the element was excluded; in this case, two boundary elements were replaced by one element.
At the first stage, the modelling of the wire electrochemical machining with a constant feed rate for the straight slits was performed. As a result, the cutting width and the side and frontal interelectrode gaps were determined. The calculated results agree well with the literature data (Zhitnikov et al., 2004). In particular, the frontal gap is by approximately 10 % smaller than that for a plane electrode.
Then, the machining of slits with corners was simulated for two values of steady-state interelectrode gap (S^*_{SF} = 0.1, 0.5). From the calculated results, it follows that the length of transient zone, where the cutting geometry differs from that for the straight-line motion of wire tool-electrode, depends on the steady-state interelectrode gap. With increasing gap, the length of transient zone increases, and the cutting width near the corner increases proportionally to the corner value.
Then, the effect of the machining conditions and the tool-electrode path on the accuracy of machining of the openings with square (Figure 2) and triangle (Figure 3) cross-sections was studied. The initial (round) and machined openings are shown with bold lines. The tool-electrode trajectory is shown dashed. The tool electrode just before machining is shown as gray circle.
Two schemes of shaping were considered. In the first scheme, prior to the machining, the tool-electrode is located in the center of the opening; then, it moves normally to the corresponding (square or triangle) contour. When the center of tool-electrode reaches the contour, the electrode starts to move along the contour clockwise and, then, returns to the starting point (Figures 2a, 2c, 3a, 3c). In the second scheme, prior to the machining, the wire tool-electrode is located in a corner of the contour and, then, moves along the contour with a constant rate up to returning to the starting point (Figures 2b, 2d, 3b, 3d). In contrast to the formation of straight and corner slits, in the machining of more complex elements, such as openings with square and triangle cross-sections, the topological changes of workpiece surface can take place (Figures 2 and 3). In the above cases of machining of openings, the changes can be caused by the fact that not total amount of material of the workpiece inside the opening is anodically dissolved in the course of machining. It was assumed that, when a fraction of material, which is located in the central part of the opening, is separated from the workpiece due to self-intersection of workpiece surface, it is removed from the machining zone.
In addition, sharp edges can form on the workpiece surface in the course of machining. Within the accepted parametric description of workpiece surface geometry, the disruption of workpiece surface smoothness can lead to the formation of intersections. These intersections have no physical meaning and should be eliminated in the simulation. The intersections of boundary elements, which describe the workpiece surface, were eliminated by using the following algorithm:
- the intersection point of the lines, which pass through the boundary elements, was calculated for all possible pairs of boundary elements;
- the position of the intersection point was determined and the case that the intersection point is located

inside both boundary elements, i.e. the intersection of contour takes place, was recognized;
- in the presence of contour intersection, three groups of boundary elements were formed: the elements before the first intersecting element; the elements between the intersecting elements; the elements after the second intersecting element;
- the groups of boundary elements, which really describe the workpiece surface geometry, were determined; other groups of boundary elements were excluded from further calculations;

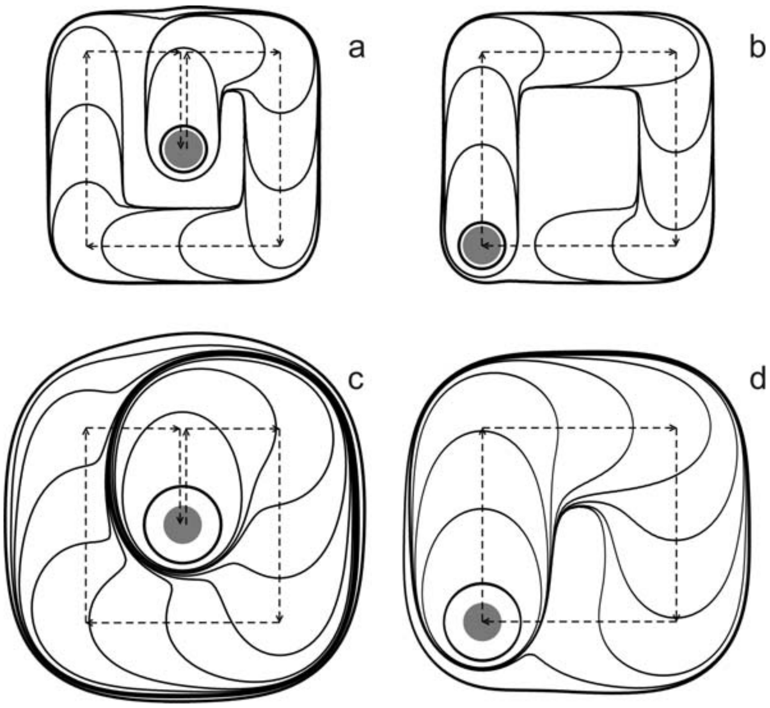

Figure 2: The results of simulation of wire electrochemical machining of square opening at (a, b) S^*_{SF} *= 0.1, (c, d)* S^*_{SF} *= 0.5 for different tool-electrode trajectories*

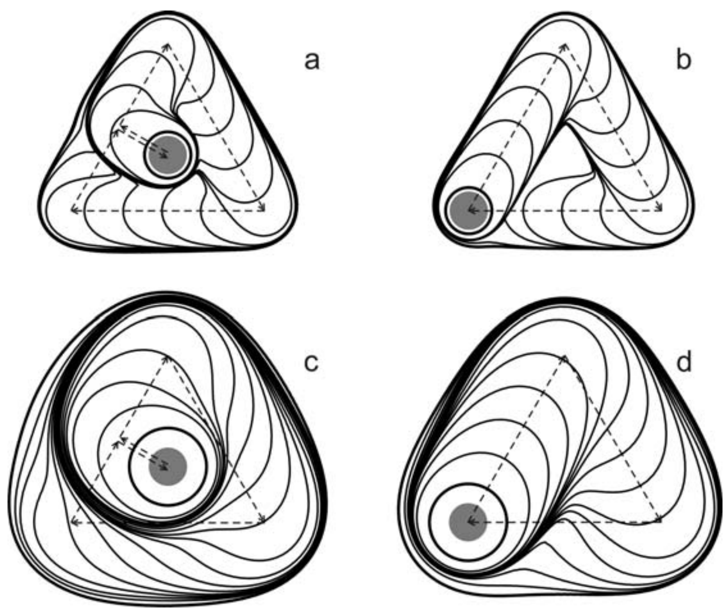

Figure 3: The results of simulation of wire electrochemical machining of triangular opening at (a, b) S^*_{SF} *= 0.1, (c, d)* S^*_{SF} *= 0.5 for different tool-electrode trajectories*

The results of modelling show that the proposed scheme of numerical simulation of wire electrochemical machining is sufficiently effective and can be used to predict the dimensions and shape of workpiece surface and to improve the trajectory of tool-electrode.

5. Conclusions

A scheme of numerical simulation of electrochemical machining with a wire tool-electrode, which enables one to predict the shape and dimensions of workpiece surface, is developed. The machining of typical elements (the straight and corner slits, the openings with square and triangle cross-sections) is analyzed. It is shown that this method of simulation can be applied to various schemes of machining, including the cases of topological changes of workpiece surface. The results of simulation agree well with the literature data. In the subsequent study, the capabilities of modelling will be extended by taking into account the dependence of current efficiency on the current density, and by taking into account the electrode polarization. In addition, the pulsed regimes of machining will be considered and the effects of charge-discharge of electrical double layer will be taken into account.

Acknowledgements

This work was supported by the Russian Foundation for Basic Research, project no. 13-08-97562 and the Ministry of Education and Science of the Russian Federation, project no. 1096 of the Basic Part of the State Program.

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