Chemical Engineering Science 140 (2016) 252–260

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Modeling and numerical simulation of electrochemical micromachining

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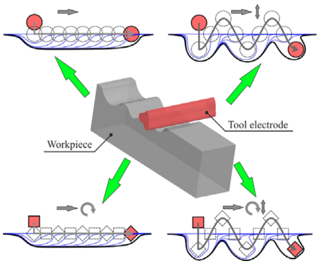
HIGHLIGHTS

- The computer simulation of electrochemical micromachining (ECMM) is performed.
- Possible topological changes of workpiece surface are taken into account.
- The schemes of ECMM by the tool electrodes with various cross-sections and motion types are analyzed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 May 2015
Received in revised form
14 August 2015
Accepted 30 September 2015
Available online 22 October 2015

Keywords:
Electrochemical machining
Numerically controlled tool-electrode movement
Computer modeling
Tool-electrodes with various cross-section shapes

ABSTRACT

The electrochemical machining using the numerically controlled motion of wire tool-electrode is studied theoretically. The Laplace equation for the electrical field potential and the equation of workpiece surface evolution are used as the mathematical model of the process. The developed scheme of computer modeling of machining involves the computation of distribution of current density over the workpiece surface using the boundary element method; the determination of new position of workpiece surface taking into account possible topological changes and the motion of tool-electrode along the prescribed trajectory. Various schemes of electrochemical micromachining using the tool electrodes with various cross-section shapes and various types of motions are analyzed.

1. Introduction

Freeform shaped parts are of great interest in many applications (Campbell and Flynn, 2001; Tapie et al., 2012; Savio et al., 2007; Lasemi et al., 2010). These parts are important components in industries such as automotive, aerospace, die/mold, electrical or electronic appliances and others. In recent years, considerable progress has been made in the development of various micro- and nano-structures consisting of complex-shaped elements. The parts with such functional surfaces are used in various fields: electronics, energetics, optics, biology, biomimetics, etc. (Evans and Bryan, 1999; De Chiffre et al., 2003; Bruzzone et al., 2008; Brinksmeier et al., 2008; Enomoto and Sugihara, 2010; Enomoto et al. 2012; Yao and He, 2014; Coblas et al., 2015).

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, a possibility of

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http://dx.doi.org/10.1016/j.ces.2015.09.034

controlling the shape and dimensions of microstructures by varying the machining modes and trajectory of tool-electrode movement (Datta and Landolt, 2000; Landolt et al., 2003; Rajurkar et al., 2006, 2013; Spieser and Ivanov, 2013).

The following schemes of electrochemical machining are widely used to fabricate the functional surfaces:

(1) With the use of a stationary non-profiled tool-electrode (TE) and a mask placed on the anode or cathode (Datta, 1995; Madore and Landolt, 1997; Qian et al., 2014; Qu et al., 2015).
(2) With a profiled TE moving towards the workpiece surface (Forster et al., 2005; Ghoshal and Bhattacharyya, 2013).
(3) With non-profiled TE, which moves along the workpiece surface by the prescribe trajectory with the aid of numerically controlled system (Kim et al., 2005; El-Taweel and Gouda, 2011; Wang et al., 2012). The term “non-profiled” means that the shape and sizes of TE do not correspond to the targeted shape of workpiece surface.

The application of masks enables one to fabricate, as a rule, only the surfaces of simple shape and 2D microstructures. Two other schemes of ECM can be used for fabricating complex-shaped surfaces and 3D microstructures, including hierarchic ones. The machining with profiled TE, principally, provides a high productivity of the process, because the metal anodic dissolution proceeds simultaneously on the entire workpiece surface. However, a high rate of electrochemical processes leads to pronounced variation of properties of electrolyte solution in the machining zone due to intense heat evolution and the formation of the products of electrochemical reactions, including the gaseous products. This decreases the accuracy of machining. The properties of interelectrode medium are restored by using pulse electrical modes (Deconinck et al., 2011; Hotoiu et al., 2013; Smets et al., 2008) and cycling variation of interelectrode gap (Davydov et al., 2004; Davydov and Volgin, 2007). The application of pulse-cycling schemes complicates the machine tools and equipment, and reduces the productivity of machining.

The variation in the properties of interelectrode medium has a weak effect on the results of nano- and micro-electrochemical shaping, because a small amount of metal is removed and relatively low currents are used.

One more limitation on the machining with profiled TE is associated with the fact that it is difficult to fabricate a TE with complex-shaped working surface.

The application of non-profiled TE enables one to improve the conditions of removal of products of electrode reactions, because the instantaneous machining surface area is only a small fraction of the total machining surface area. This feature of ECM with non-profiled TE is the reason for rather low productivity of the process. 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 (Kurita et al., 2006; Zhu et al., 2007; Fan and Hourng, 2011; Liu et al., 2014). The application of such 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.

The regularities of electrochemical machining of complex-shaped and microstructured surfaces with non-profiled (numerically controlled) TE have not been adequately investigated. 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 electrochemical machining are frequently simulated using a mathematical model involving the Laplace equation for the electric potential and the equation of workpiece surface evolution. The equations of mathematical model are solved numerically by the methods of finite and boundary elements (Davydov et al., 2004, 2014; Purcar et al., 2004; Volgin and Davydov, 2004; Pattavanitch et al., 2010; Hinduja and Kunieda, 2013). In the majority of the works devoted to the modeling of electrochemical machining, the modes 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 numerically controlled ECM, as a rule, approximate mathematic models are used, which are based on the linear approximation of distribution of electric potential across the interelectrode gap (Wei and Rajurkar, 1990; Kozak et al., 1998; Jiawen et al., 2005; Kang et al., 2009). 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 electrochemical micromachining, 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. In Fu et al. (2013), the Laplace equation was solved numerically using the finite element method. This method requires the remeshing of 3D grid of finite elements with the variation of the shape and sizes of workpiece surface due to the anodic dissolution of workpiece material. The boundary element method is more effective, it requires the remeshing only at the boundaries of computational region. Earlier (Volgin et al., 2014) we developed a method of modeling electrochemical machining with a wire TE, which moves by a prescribed 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 tool-electrode with various shapes of cross-section; the tool-electrode can move forward, rotate, and execute transverse oscillations.

2. Mathematical model

The electrochemical machining with a moving TE (Fig. 1) is simulated by a model, which ignores the variation of electrolyte solution conductivity due to the concentration changes, heat and gas evolution in the interelectrode gap. This approximation may be used provided that the electrolyte solution is stirred or pumped sufficiently intensively. The distribution of electric potential over the interelectrode space is calculated by the Laplace equation:

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

where φ is the electric field potential.

The current density can be calculated by the Ohm's equation:

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

where $\mathbf{i}$ is the current density and χ is the conductivity of electrolyte solution.

The boundary conditions on the boundary portions, which are located on the insulator or coincide with the lines of symmetry, are prescribed by the following equation:

$$\partial\varphi/\partial n = 0, \tag{3}$$

which corresponds to the condition that the electric current does not pass through the boundary.