Electrochimica Acta 75 (2012) 94–100

Contents lists available at SciVerse ScienceDirect

Electrochimica Acta

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

Study of a novel cathode tool structure for improving heat removal in electrochemical micro-machining

Jing Wu, Hong Wang*, Xiang Chen, Ping Cheng, Guifu Ding, Xiaolin Zhao, Yi Huang

Science and Technology on Nano/Micro Fabrication Laboratory, Research Institute of Micro/Nano Science and Technology, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China

ARTICLE INFO

Article history:
Received 7 February 2012
Received in revised form 20 April 2012
Accepted 20 April 2012
Available online 4 May 2012

Keywords:
EMM
Hollow electrode
Heat removal
Multi-physics
Pulse rate

ABSTRACT

In this paper, the effects of a hollow structure of cathode tool and radial flow of electrolyte on heat removal are studied using COMSOL software. A multi-physics (electrical field, flow field and heat transfer) model, which implement the bilateral interactions with customized PDE, is proposed to simulate the EMM process with a moving cathode tool. The ALE method is used to track the moving interface. The simulations show that the electrolyte flow rate and flushing time are the most important factors for the heat removal. A hollow structure of the cathode tool is proposed to improve the stability of flow rate, which will remove the heat generated during the EMM process effectively.

1. Introduction

The growing demand for micro parts and molds has increased the importance of micro-machining technologies such as micro electrical discharge machining, micro electrochemical machining, and micro-electrochemical discharge machining. Among these processes, electrochemical micro machining (EMM) is used widely as it allows manufacturers to shape hard metals at a high material removal rate, without affecting the tensile strength of the workpiece material and its other physical properties, while ensuring a low surface roughness [1]. Although the process of EMM is difficult to predict, many mathematical approaches such as boundary elements method (BEM), finite difference method (FDM) and finite element method (FEM) have been used to analyze the electrical and fluid properties in the process. And many numerical models have also been proposed, ranging from the most commonly used potential models to multi-ion transport and reaction models [2,3].

Deconinck et al. [4] simulated the influence of the temperature on the uniformity or copying quality of the removal rate. Hourng et al. [5–7] calculated the temperature distributions in the electrolyte in one or two dimensions. Bhattacharyya and Munda [8] demonstrated that a significant metal removal rate and minimal overcutting could be obtained with the proper operating potential and electrolytic concentration and sufficient processing time. Kock et al. [9] verified the effects of pulse width on fabrication accuracy. Lee et al. [10] demonstrated the effect of pulse rate and the inter-electrode gap (IEG) value on the concentration distribution in IEG during the EMM process. It is well known that the EMM process is influenced by numerous factors such as temperature, IEG, electrolytic concentration, and operating potential. In the process, several physics are involved and flow field play an important role in the conduction of current between electrodes and maintaining the stability of the environment. The structure of cathode is a critical factor for the flow field excepting for the machining shape. The literatures mentioned above all used a solid cathode tool in the process. However, these solid tools have several disadvantages such as low copying accuracy and asymmetry. A hollow structure of the cathode tool, resulting in high copying curacy and enhanced symmetry, has been adopted in traditional large scale machining. Since the adverse influence of decrease in flow rate is more serious in EMM, the adoption of hollow cathode tool would be a significant improvement.

In the following sections, the paper discusses a multi-physics model that presents some comparative simulations to study their sensitive relevance on temperature distribution in EMM process.

2. Theoretical model

EMM is a current controlled electrolytic process. Typically, a workpiece (anode) is connected to a tool (cathode) and immersed in an ionic solution in a reactor. When a potential difference is applied between electrodes, the oxidation and reduction reaction

* Corresponding author.
E-mail address: qfwj10@163.com (H. Wang).

0013-4686/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.electacta.2012.04.078

will take place on anode and cathode, respectively. The metallic ions of the anodic dissolution will migrate toward the cathode and form the metallic hydride and oxide after reacting with the OH^-. At the same time, oxygen is generated on the anode while hydrogen is generated on the cathode. By feeding the shaped cathode toward the workpiece, the reverse shape of the tool is copied. In order to attain a more specialized study of the temperature variation in the EMM process, the aspects of concentration and gas evolution are not considered here. As the electrode reaction and current density are strongly dependent on temperature, and heat, generated by the electrochemical reaction, is mainly removed by the electrolyte flow. It was reasonable to consider the electrolyte only in the view of obtaining the temperature distribution. Electrodes are usually good heat conductors, approximately 100 times better than the electrolyte and it is logical to regard the electrode–electrolyte interface as outer boundaries (reference temperature).

During this process, several controllable parameters such as, operating potential, flow rate of electrolyte, IEG, and electrolyte composition, play an important role on the copying quality. The structure of cathode tool, which is a critical factor for maintaining flow rate in the process, is transformed to hollow from solid.

2.1. Model assumptions

The EMM process involves several interactive physics, such as flow field, electric field and heat transfer. First, a model of electrodes with given dimensions is needed to attain the potential distribution. And then an electrolyte model with potential U, temperature T and electrolyte velocity v is developed according to the experiments. An established heat transfer model acts as a bridge coupling the two mentioned above. In order to obtain coupling physics results, a multi-domain method is used.

To simplify the proposed model, several assumptions are made as follows:

(1) The EMM process is ideal. The anodic dissolution will take place as long as a potential difference is applied between electrodes, and it depends only on temperature.
(2) The model is isothermal. The thermal conductivity of the electrolyte was assumed to be a constant.

2.2. Geometry model

The geometry used in this study is presented in Fig. 1, a 2D channel, comprised a cathode surface (no. 3, 4, 5, 7, 8 and 9), an anode boundary [12], containing the electrolyte flowing between them. The channel is 150 μm in width and has a length of 600 μm. The inter-electrode gap (IEG), is set to 20 μm. Radius of the hollow structure is 50 μm. In addition, the hollow tool feeds down with a constant rate v_c in the process.

The anode surface, which is in contact with the electrolyte, is fully active with a constant potential applied to it; while the cathode tool is side-insulated, i.e., boundaries 3 and 9 are electrically insulated from the electrolyte.

The electrolyte flows in radial flow at a uniform rate profile, i.e., flows in from $\overline{AB}$ and exits from $\overline{CD}$ and $\overline{EF}$. In order to avoid the convergence in the solving process, the Heaviside function [10] of the velocity distribution is set as the initial value at the inlet, $\overline{AB}$.

2.3. Electrical model

The potential between the electrodes comply with Laplace equation,

$$\nabla^2\phi = 0 \tag{1}$$

i.e., the potential field is a steady current field.

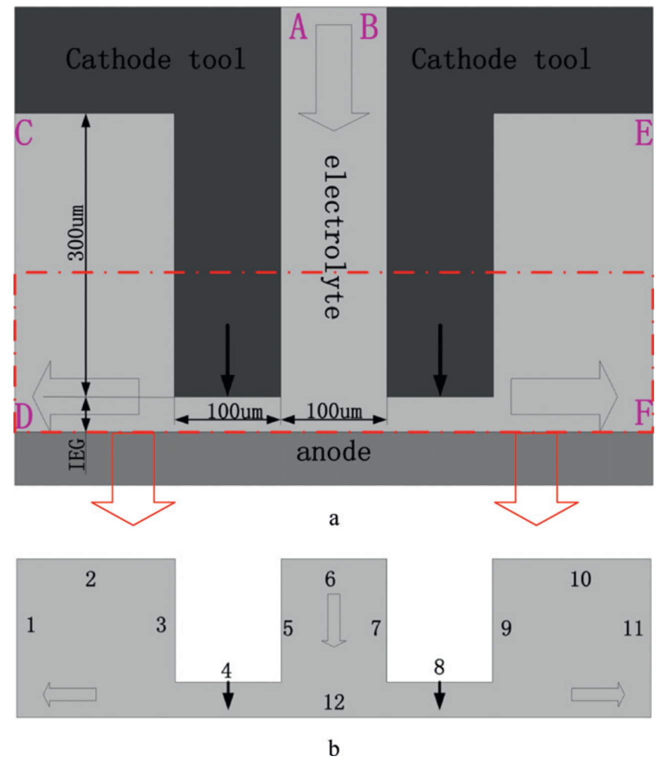

Fig. 1. Geometry model with a downward feeding cathode tool; the electrolyte flow region is noted as gray area: (a) initial model and (b) simplified simulation model.

The anode interface and cathode interface are taken as equipotential surfaces, denoted as V_a and V_c, for solving the charge conservation

$$\nabla \cdot (\kappa \nabla U) = 0 \tag{2}$$

V_a, V_c are imposed as constant potential (V). Meanwhile, a temperature dependent model, in which the electrical conductivity is linearly related to temperature T, is selected to obtain the potential distribution. The relation between κ' and T is introduced:

$$\kappa' = \kappa[1 + \alpha(T - T_{ref})] \tag{3}$$

where T_{ref} is the reference temperature and a conductance constant α indicates the degree of temperature dependence.

A typical potential distribution is obtained, shown in Fig. 2. In order to decrease the influence of stray current density in processing, the sidewall insulation is adopted.

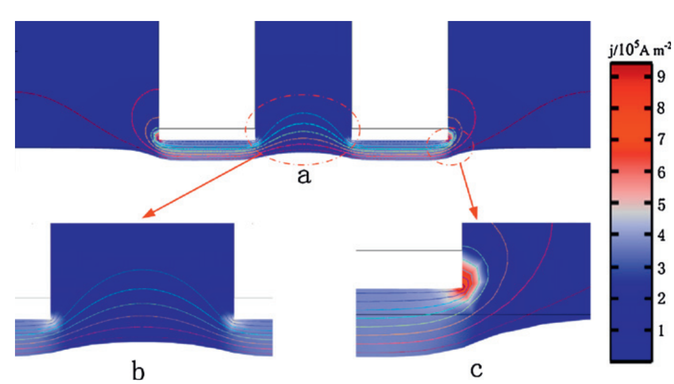

Fig. 2. Potential (V) distribution in the vicinity of the cathode tool after 1 s of metal dissolution processing; colored curves represent isopotential curves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)