Electrochemical Machining with Nonsymmetric Suction of Electrolyte Flow

M. Hashiguchi[1], D. Mi[1]
1. Keisoku Engineering System Co.,Ltd.,Tokyo, Japan

Introduction

Electrochemical machining(ECM), which is a kind of machine processing method, removes metal by the electrochemical process[1]. Although the use of this method is limited to electrically conductive materials, it can be used for working extremely hard materials, even for the metal which cannot be easily machined by traditional methods.

ECM is an anodic dissolution process and utilizes an electrolytic cell formed by a cathode tool and an anode workpiece with a suitable electrolyte flowing between them. During ECM process, slug due to dissolved workpiece disturbs the continuation of ECM. Therefore , it is very important to control electrolyte flow field to remove contamination such as slug, or gas to be generated by the machining process as well as heat control for electrolyte, machining tool and workpiece. The anode workpiece is dissolved according to Faraday's law and the machining state of speed and shape depends on the electric potential distribution in electrolyte. To reduce the overcut of workpiece, special consideration is also needed for electric potential field within the electrolyte.

An electrochemical machining system with electrolyte flow suction has already been proposed by Endo and Natsu[2] ,and it is very interesting because that it can remove slug or gas efficiently ,while it can reduce the area of flowing electrolyte. Finite-element analysis for drilling holes based on ECM has been investigated by Mi and Natsu[3] and the effectiveness of numerical computation on this field has been reported by them.

In this paper, electrochemical machining tool with suction devices for electrolyte is investigated numerically. The numerical solutions have been obtained and visualized by using commertial finite-element analysis software: COMSOL Multiphysics® of Ver.5.3.

Method of approach

Electric potential in electrolyte can be determined based on the conservation law of electric current density $\boldsymbol{i_l}$:

$$\nabla \cdot \boldsymbol{i}_l = 0 \; .$$

When electrolyte is fully mixed and the condition of electroneutrality holds within the electrolyte, the current density can be represented by

$$\boldsymbol{i}_l = -\sigma_l \nabla \phi_l \; ,$$

where $\boldsymbol{\sigma_l}$ and $\boldsymbol{\phi_l}$ are the electric conductivity and electric potential of electrolyte, respectively.

This form of electric current resembles the Ohm's law and the consevation law of electric current poses the Laplace equation governs the electric potential distribution $\boldsymbol{\phi_l}$ within the electrolyte.

In order to get the numerical solution of electric potential $\boldsymbol{\phi_l}$, we need boundary conditions as well as the govering equation. The surface of tool or workpiece faced to electrolyte becomes an electrode of solid phase electric potential $\boldsymbol{\phi_s}$. As we cannot measure the elertric potential of electrolyte $\boldsymbol{\phi_l}$ at the interface of electrode and electrolyte, we have to estimate the electrolyte potential $\boldsymbol{\phi_l}$ along the interface. The common way to estimate it is the use of overpotential $\boldsymbol{\eta}$ which is defined by $\boldsymbol{\phi_s - \phi_l - E_{eq}}$, where $\boldsymbol{E_{eq}}$ is the standard equilibrium potential and can refer to the experimental data handbook.

For simplicity we assumed thermodynamic equilibrium holds along the interface of the tool, that is, set $\boldsymbol{\eta}$ to zero. Therefore we can determine the boundary condition for electrolyte electric potential $\boldsymbol{\phi_l}$ only if we prescribe the solid phase electric potential $\boldsymbol{\phi_s}$ and prepare the standard equilibrium potential $\boldsymbol{E_{eq}}$. For cathodic tool, the boundary condition $\boldsymbol{\phi_s = 0}$ is set on the solid electrode potential and $\boldsymbol{E_{eq}}$ for Cu. This means that the Dirichlet condition of $\boldsymbol{\phi_l}$ was set to $\boldsymbol{-E_{eq}}$ on the tool surface.

For the anodic workpiece an positive electric potential va (=O(10V)) of solid electrode $\boldsymbol{\phi_s}$ is set as the Dirichlet boudary condition. Assuming steel (Fe) for the material of the workpiece, the corresponding overpotential is so high that we can assum the anodic Tafel expression for the anodic dissolution :

$$i_{Fe} = i_{0,Fe} \times 10^{\frac{\eta_{Fe}}{A_{Fe}}} \; ,$$

where $\boldsymbol{i_{0,Fe}}$, $\boldsymbol{A_{Fe}}$ are the exchange current density and anodic Tafel slope, respectively. The overpotential $\boldsymbol{\eta_{Fe}}$ is expressed by $\boldsymbol{\eta_{Fe} = v_a - \phi_l - E_{eq,Fe}}$.

Faraday's law gives the machining rate on workpiece of metal (denoted by suffix m) as normal direction speed $\boldsymbol{v_n}$:

$$v_n = \{M_m/(\rho_m z_m F)\} i_n ,$$

where $\boldsymbol{M_m, \rho_m, z_m}$ are molar mass, mass density, number of participating electrons of workpiece metal m, respectively ,and $\boldsymbol{F}$ is the Faraday constant (96485 $\mathbf{C/mol}$).

The normal electric current density $\boldsymbol{i_n}$ is defined by

$$i_n = \boldsymbol{i_l} \cdot \boldsymbol{n} ,$$

where $\boldsymbol{n}$ is the normal vector on the workpiece wall surface. This relation can be rewritten by the directional derivative of electrolyte electric potential $\boldsymbol{\phi_l}$ as follows:

$$i_n = -\sigma_l \nabla \phi_l \cdot \boldsymbol{n} = -\sigma_l \frac{\partial \phi_l}{\partial n} .$$

By putting $\boldsymbol{i_n}$ equals to $\boldsymbol{i_{Fe}}$, we set the Neumann boundary condition for $\boldsymbol{\phi_l}$ on the workpiece.

During the machining process, the surface position of the workpiece is dissolved according to the Faraday's law and we have to model the movement of the surface shape. By using the moving mesh interface of COMSOL Multiphysics®, this can be realized easily, that is, we merely set the already mentioned $\boldsymbol{v_n}$ into "Normal mesh velocity" of the moving mesh interface. Also, smoothing for the mesh arrangement to be varied can be automatically done by the moving mesh interface.

Chemical species of electrolyte are advected by the fluid flow of the electrolyte. In the present study, unsteady laminar flow of electrolyte is assumed and the numerical solutions of velocity vectors and pressure field are obtained by solving the incompressible unsteady Navier-Stokes equations. The boundary conditions applied to the present study will be explained later.

Although, for simplicity, transport of chemical species were ignored in this study, we think the possibility of the removal of the contamination of slugs or gases during ECM process can be discussed within the present framework because such contamination is considered to be passive scalar.

Computational results and discussions

Firstly, we verified the present computation of electric current density together with moving mesh by tailoring a simple model of parallel plates configuration shown in Fig.1. The width of the plates is 800μm and the initial gap is 40μm. For tool plate, a downward speed is applied by using "prescribed displacement" of the moving mesh interface. The workpiece is moved based on the "prescribed normal velocity" of the moving mesh interface. For anodic workpiece, solid phase electric potential v_a of 15Vdc is uniformly applied. In this case it can be expected that the surface of workpiece will be dissolved uniformly and maintain its flatness. Thermodynamic equilibrium are assumed for both of tool and workpiece. In this case, we can derive an exact solution of the electric current density within the electrolyte as:

$$i_{exact} = \frac{v_a - E_{eq,work} + E_{eq,tool}}{|y_{work} - y_{tool}|} .$$

Here y_{work} and y_{tool} are the vertical displacement of the surfaces of workpiece and tool, respectively. These are sampled during time-dependent computation. On the other hand, we can obtain the numerical electric current density simultaneously on the surface of tool or workpiece as a prescribed variable of COMSOL Multiphysics®. The present numerical results agree with the exact expression as shown in Fig.1. Although not shown here we also confirmed the conservation of electric current density by observing the same results of electric currnt density for both surfaces of tool and workpiece .

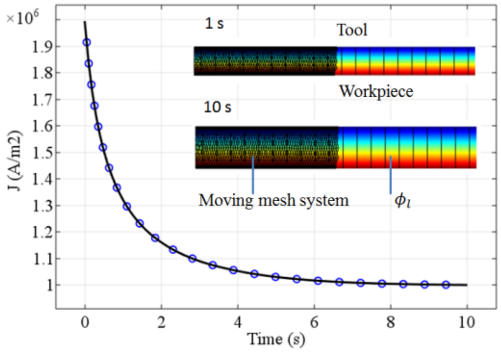


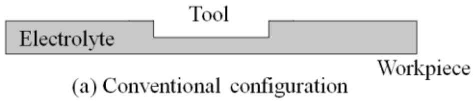
Figure 1. Verification of numerical results for electric field and electric current density with moving mesh system; color shading: $\boldsymbol{\phi_l}$, exact : solid line, numerical: circles.

Secondly we studied the realistic configuration of ECM sysytem. The configuration propsed here is shown in Fig.2(b). In order to examine the effect of distribution of electric potential over surface of cathodic tool on the electric field within the electrolyte, conventional tool (Fig.2 (a)) was also studied.

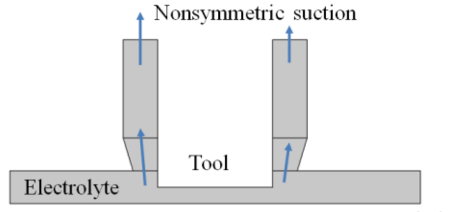
In this study, electric potential v_a applied to the surface of workpiece was 5Vdc. The material of workpiece is steel (Fe), which the equilibruim electric potential $E_{eq,Fe}$ is -0.44V.

The Tafel expression was used as already mentioned. The exchange current density and Tafel slope are assumed as $7.1 \times 10^{-5}\ A/m^2$ and 0.41V, respectively.

The dissolved metal ion is Fe^{2+}, so the number of participating electrons z_{Fe} is 2, M_{Fe} 55.85 g/mol and ρ_{Fe} 7.874 g/cm^3 and they are used for the Faraday's law.



(a) Conventional configuration



(b) Proposed configuration

Figure 2. Proposed configuration for electrochemical machining.

Copper (Cu) is assumed for the material of tool.

As already denoted, thermodynamic equilibrium is assumed and the equilibrium potential $E_{eq,Cu}$ of 0.521 V was used over tool surface.

Electrolyte is represented by describing the equivalent electric conductivity σ_l of 5 S/m. The temperature of the electrolyte was 25 degC.

Here we fixed the tool position and the time variations of the electric potential field were studied. Fig.3 shows the differences of the arrangement of the electric potential applied over the tool surface between the conventional configuration and proposed one.

In this examination, no flow of electrolyte is taken into consideration. Fig.4, therefore, only compares the electric field (using color shading, and envelope curves of electric field vectors which are called by "stream lines") of the proposed system (defined as Fig.2 (b)) with the conventional one (defined as Fig.2(a)). These figures corresponds to the states at 4 s after the starting of ECM process. This figure shows that the proposed electrode of the tool reduced the width of dissolved portion over the workpiece. In the proposed configuration, both sides of the central part of the tool have a clearance which forms flow channel and are insulated there. This results suggest that modification of solid phase electric potential distribution over the cathodic tool could increase machining precision of ECM.

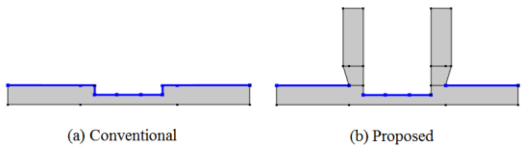
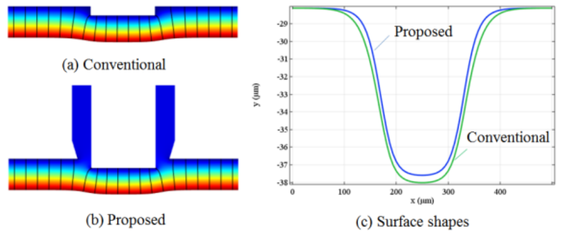

(a) Conventional (b) Proposed

Figure 3. Copmarison of the electrode arrangement for the cathodic tool surfaces of coenventional and proposed configuration; blue-colored lines denote the application of the solid phase electric potential $\phi_s = 0$.



(a) Conventional (b) Proposed (c) Surface shapes

Figure 4. Comparison of electric field and surface shape of the workpiece at 4s after the starting; for comparison convenience, the y-value of conventional case (green line) is shifted by 0.31 μm.

Fig.5 shows the results of the computation coupled with laminar flow. The purpose of this computation is to investigate whether the flow field of electrolyte could be controlled by the modification of suction pattern at the electrolyte flow exits, which are illustrated in Fig.2(b). The left suction speed is 5m/s and the right suction speed is 2m/s.

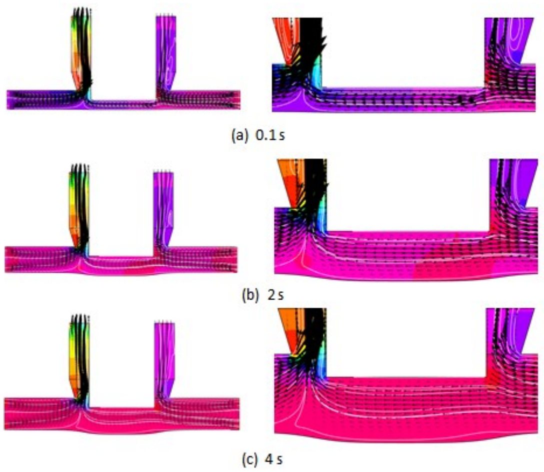
We can observe no reversal flow beneath the central part of the tool surface during the time goes as shown in Fig.6. Within the electrolyte region developed under the central part, hydrogen gas could be generated. The observed no reversal flow field can sweep out the hydrogen gas easily. Furthermore, it is plausible to expect that the flow channels prepared for the present configuration can lead the hydrogen gas to the flow exit region. Along surface of the workpiece, slug by dissolving the metal could be accumulated when there is no flow of electrolyte.

As it can be observed quantitatively in Fig.6, the left-going flow speed is strong when the gap between the tool and the workpiece is small. This suggests that the flow near the workpiece can be kept to be strong when we move the tool downward and keep the gap small.

Conclusion

In this paper, electrochemical machining tool with suction devices for electrolyte liquid was investigated numerically.

A modification of the shape of tool electrode was discussed based on finite-element analysis.


(a) 0.1 s

(b) 2 s

(c) 4 s

Figure 5. Time evolution of the flow field (left colums: whole field, right colums: the enlargement); color shading: pressure field, white lines: instanteneous stream lines, vectors: instantaneous flow vectors.

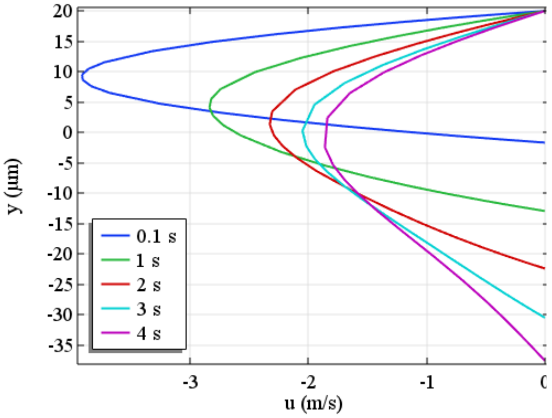


Figure 6. Time evolution of the x-component of flow velocity along the vertical line through the center of the tool.

At first we proposed a modification of electrode configuration which can improve the arrangement of electric lines and reduce the overcut of workpiece. Secondly, we also proposed nonsymmetric flow suction of electrolyte and the resulting flow field shows the possibility to efficiently sweep out slug from the surface of the maching tool.

Electric field within electrolyte was analyzed based on the conservation of current. The deformation of solid surface of workpiece due to electrochemical machining was treated by moving mesh technique with the normal mesh speed prescribed by Faraday's law. The governing equations are solved by using general purpose multiphysics analysis software, COMSOL Multiphysics® of Ver.5.3.

Due to finite-element analysis by using COMSOL Multiphysics®, we proposed here a modification of electrode configuration in electrochemical machining system with suction device, which improves the machining accuracy of the workpiece and can be expected to sweep out slug or gas to be developed over the surface of electrodes.

References

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