Investigation on Pulsed Wire Electrochemical Machining Process Considering Machining Accuracy

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Abstract: The modeling and simulation of Pulsed Wire Electrochemical Machining (PWECM) is considered in this paper. The electrode kinetics was modeled with Butler-Volmer equation to simulate the transient current response behavior of the PWECM system. The evolution of the workpiece surface was then calculated using the machining speed which derived from the local current density. Examples of PWECM and WECM with DC voltage showed that the PWECM results in much smaller machining rate, and improved machining accuracy could be achieved with PWECM.

Keyword: Pulsed Wire Electrochemical Machining, Simulation, Machining accuracy

1. Introduction

Wire electrochemical machining (WECM) is an electrochemical machining (ECM) process which uses a thin wire as the tool electrode to cut or generate complex patterns on a plate made with any electrically conductive material. However, the machining accuracy is affected since material from zones that far away from tool wire could also be removed due to stray current. Hence, it is considered that increasing the localization of electrochemical reaction is of great importance for the micromachining with WECM.

It was reported that the localization of electrochemical dissolution can be realized by using ultra short pulse current, which takes advantage of the electrical double layer’s capacitive effect to confine the machining area. Therefore, it is thought that pulsed wire electrochemical machining (PWECM) is suitable for the machining of microgrooves or micro patterns of high accuracy.

PWECM is a result of complex interactions involving various electrical, chemical and physical effects. It is important to work out a comprehensive scientific description of the machining process so that we can design better PWECM systems and choose optimal process parameters for certain applications to obtain desired microstructures or improve surface quality, etc. Although few attempts have been made to understand the mechanism of the pulsed electrochemical machining (PECM) process, further modeling and analysis are needed to raise the knowledge on the effects of the double layer (DL), pulse characteristics and other machining parameters on dissolution localization and final shape of the machined surface.

In this study, a numerical model of the PWECM process was built to investigate the electrolyte potential, current distribution and their effects on the machining result. The influence of applied pulse on dissolution localization was also discussed by comparing with a direct current (DC) machining result.

2. Modelling of the PWECM process

2.1 PWECM process system

Table 1 Simulation conditions

<table>
<thead>
<tr>
<th>Workpiece electrode</th>
<th>50μm thick iron plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool electrode</td>
<td>Φ100μm Ti wire</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>10% NaNO3 aq</td>
</tr>
<tr>
<td>Initial gap between electrodes</td>
<td>20μm</td>
</tr>
</tbody>
</table>

Fig.1 shows the schematic of the PWECM processing system. The system mainly consists of a thin iron plate as the workpiece, a Φ100μm Ti wire tool electrode and a pulse-voltage power source. The tool wire is vertically placed near the anodic work plate. Both tool electrode and work plate are immersed in the electrolyte tank. The machining conditions are listed in Table 1, and the applied pulse voltage conditions are shown in Table 2.

Table 2 Applied pulse voltage

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Voltage Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-level voltage</td>
<td>5V</td>
</tr>
<tr>
<td>Low-level voltage</td>
<td>0V</td>
</tr>
<tr>
<td>Pulse width</td>
<td>100μs</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>50%</td>
</tr>
</tbody>
</table>

2.2 Geometry and mesh of a 2D PWECM model

The simulation process of PWECM includes: building the geometrical and physical model of the system based on the analysis of the real machining process, then meshing the model and conducting calculation. Since it is too complex to build a complete model for the real PWECM process, both the geometrical and physical model are simplified according to given conditions and data, the goal of the simulation and the capability of the computational system.

As to the geometric model of this specific problem, the PWECM process shown in Fig.1 could be reduced into a 2D model. As shown in Fig.2 (a), in the ‘XY’ plane, a small portion of the system is selected. The edge of the workpiece plate that faces the tool electrode is indicated with a dashed line. The tool wire is placed 20μm away from the workpiece plate.

Two types of mesh elements with different resolutions were used in this work. As shown in Fig.2 (b), a finer mesh was adopted around the electrode surfaces since the electrochemical reactions mainly occur at these areas. The element size of the mesh in the electrolyte was set between 90nm to 2.68μm and the element size of the mesh at the surface of the wire and the workpiece plate was set between 90nm to 0.3μm.
2.3 Physical model

The goal of PWECM simulation is to simulate the potential and current density distribution in the electrolyte and at the electrode surface, the dissolution and the profile change of the anode plate, so that it can give some intuitive descriptions about these hard-to-measure parameters to help us better understand the mechanism of the PWECM process. Finite element analysis software COMSOL Multiphysics was used to solve the physical model.

It is well known that the current in a solution relates to the net flux of the charged species. Therefore, the current density $i$ in the electrolyte can be determined as $^{(2)}$:

$$i = F \sum z_i N_i$$  \hspace{1cm} (1)

Where $F$ is Faraday’s constant, $z_i$ is the charge number of the $i$th species, and $N_i$ is the flux density of the $i$th species which is the sum of the migration, diffusion and convection effects.

Moreover, the rate of reaction, i.e. the local current density on the electrode surface can be adequately related to the surface overpotential by Butler-Volmer equation $^{(2)}$:

$$i = i_0 (\exp(\frac{\alpha_d F \eta_s}{RT}) - \exp(-\frac{\alpha_e F \eta_s}{RT}))$$  \hspace{1cm} (2)

Where $i_0$ is the exchange current density, $\alpha_d$ and $\alpha_e$ are the apparent transfer coefficients, $T$ is temperature, $R$ is the universal gas constant and $\eta_s$ is the surface overpotential, known as the driving force for the chemical reaction on the electrode.

3. Results and discussions

First, the simulation was carried out for 1000 period, 0.2s. The evolution of workpiece profile is shown in Fig.3 (a), the current density distribution at workpiece surface is shown in Fig.3 (b), and the overpotential distribution at workpiece surface is shown in Fig.3 (c). It is found from Fig.3 (a) that the machining depth at the most processed position, i.e. the center of the workpiece surface, is about 0.0065μm.

Then, the simulation was carried out under the same simulation conditions except that a 5V DC voltage was applied instead of the pulsed voltage. Also, considering the pulse off time of pulsed voltage, the DC voltage was applied for 0.1s to achieve equivalent power on time with the 0.2s pulsed voltage. The evolution of workpiece profile, current density and overpotential distribution at workpiece surface are shown in Fig.4.

It is found from Fig.4 (a) that the machining depth at the most processed position is about 0.17μm. Hence, the machining depth with the DC current is about 26 times bigger than that with the pulsed current at the same position. Therefore, it can be concluded that the machining rate is much smaller and the machining accuracy can be improved with pulsed voltage.

4. Conclusions

In this paper, the numerical model of PWECM process was built. The potential, current density distribution and the evolution of workpiece profile was investigated. Comparing with the DC voltage, the simulation results show that the dissolution rate is much smaller when the pulsed voltage is applied. Therefore, the machining area is confined and the machining accuracy is improved.

References