Generation of erosion profile of through hole in electrochemical boring using a stepwise moving electrode

H. Hocheng*, P.S. Kao and S.C. Lin

Department of Power Mechanical Engineering,
National Tsing-Hua University, 300 Hsinchu, Taiwan, ROC
E-mail: hocheng@pme.nthu.edu.tw
E-mail: d863775@oz.nthu.edu.tw
E-mail: sclin@pme.nthu.edu.tw
*Corresponding author

Abstract: Electrochemical machining has been increasingly recognised for its micromachining applications. A process to erode a hole of hundreds of micrometres on the metal surface using a moving electrode is investigated in the current paper. This study provides the prediction of the produced hole enlargement and taper under the applied machining conditions during the process. A computational model is presented to illustrate how the machined profile develops as the time elapses and the electrode gap changes. The analysis is based on the fundamental law of electrolysis and the mathematical integral over a tool. The effectiveness of the model is examined by experiments using several schemes of the electrode movement.

Keywords: ECM; erosion profile; micro-hole; moving electrode.


Biographical notes: Hong Hocheng obtained his BSc from the National Taiwan University, Taiwan, in 1980, and later his Diplom-Ingenieur from Technische Hochschule Aachen, Germany. He received his PhD from the University of California, Berkeley, in 1988. Dr Hocheng is currently a Professor at the National Tsing Hua University. His field of interest is innovative manufacturing processes.

Pin-Shen Kao obtained his BSc in power mechanical engineering from National Tsing Hua University, Taiwan, in 1996, and his PhD from the National Tsing Hua University, in 2003. Dr Kao will be employed as a senior engineer at Quanta Corp. His major research field is manufacturing technique and product design.

Shih-Chie Lin obtained his BSc from the National Taiwan University, Taiwan, in 1981. He received his PhD from the University of Illinois, Urbana Champaign, USA, in 1989. Dr Lin is at present a Professor at the National Tsing Hua University. His field of interest is the monitoring of manufacturing processes.
1 Introduction

Electrochemical machining (ECM) was first introduced in 1929 by Gusseff. It was subsequently found to be particularly advantageous for high-strength and high-melting point alloys. The industrial applications have been extended to electrochemical drilling, electrochemical deburring, electrochemical grinding and electrochemical polishing (Fortuna, 1986). An electrical current is made to pass through an electrolyte solution between a cathode tool and an anode workpiece. The workpiece is eroded in accordance with the laws of electrolysis. The tool design determines the machined dimensions on the anode workpiece (Jain and Pandey, 1980).

ECM has been widely used in manufacturing semiconductor devices and thin metallic films, where high-strength alloys are frequently employed (Clifion et al., 2001; McGeough, 1974; Rajurkat et al., 1992; Riggo and Locke, 1981). ECM processes were also recognised in the aerospace and electronic industries for the shaping and finishing operations of a variety of parts with opening cuts that are a few microns in dimension (Bhattacharyya et al., 2001).

Micro-machining refers to the material removal that ranges from several microns to millimetres in dimension. Advanced micro-machining may employ various ultra-precision machining techniques to very small and thin workpieces. A few research attempts at precision micro-ECM have been made by the electro-mechanical consumer products industries (Kunieda et al., 1993). However, except for electrochemical jet machining, electrochemical etching and wire electrochemical grinding, ECM research yet falls behind other processes such as EDM in the precision and micro-machining fields (Datta et al., 1993; Hardisty et al., 1995; Jain et al., 1999; Masuzawa and Tonshoff, 1997). It is desired to predict the final shape formed by the ECM process once the machining parameters are given. A prediction also prevents material waste and saves time on design. The cost of production trial-and-error for micro-machining is much higher than for the conventional cutting process, thus there is a need for a utility to simulate the final shape of the workpiece before the micro-ECM work (Kozak, 1998). A correction factor method has been proposed for tool design of ECM (Reddy et al., 1988), which proposes an analytical model of electrochemical erosion to predict the final machined diameter of the workpiece. The material removal can be predicted based on the current density distribution semi-empirically obtained from preliminary tests (König and Humbs, 1977). The boundary element method was used which requires a significant amount of calculation (Natayanan et al., 1986). A graphical method considering local effects can achieve better dimensional accuracy (De Silva et al., 2000). The current paper proposes a simple model to describe the development of the erosion profile as a function of machining time and the changing electrode gap. The results are compared with experimental work.

2 Analytical approach

2.1 Three-dimensional method

Figure 1 shows the scheme of the three-dimensional ECM. The electrode is a cylinder electrode of diameter $d$, and is placed above the workpiece at gap $\delta$. 
Coulomb's law states the electric field intensity (E) applied on the workpiece made by a point charge \( P(x') \) on an electrode is inversely proportional to the square of distance (R) between \( P(x') \) and the considered point on workpiece \( Q(x) \).

\[
E \propto \frac{q}{R^2}
\]  

(1)

where \( q \) is the charge density, and

\[
R = \sqrt{x^2 + x'^2 - 2xx' \cos(\theta - \alpha) + \delta^2}
\]  

(2)

\( x \) and \( \alpha \) are the radial and angular coordinates on the workpiece, respectively, while \( x' \) and \( \theta \) are the angular coordinates on the electrode.

The amount of material erosion on the workpiece caused by a single charge on the electrode is assumed proportional to the electrical intensity (König and Humbs, 1977). In the model, the cathode end surface is composed of differential point charge sources. Considering one point on the anode workpiece, one finds that it is influenced by all point charges on the cathode end. To add up all the erosion effects, a double integral over the
charge sources on the entire end surface of the cathode is carried out. The actual eroded depth at the considered point on the anode produced by the cathode at each time increment can be calculated by an iteration

\[ y_i(x, \alpha) = \delta \]

\[ y_{i+1}(x, \alpha) = y_i(x, \alpha) + \Delta t \cdot m_i(x, \alpha) \quad (i \geq 1), \text{ where} \]

\[ m_i(x, \alpha) = -\int_{0}^{d} \int_{0}^{2\pi} \frac{c_1}{R^2} d\theta dx' = -\int_{0}^{d} \int_{0}^{2\pi} \frac{c_1}{x^2 + x'^2 - 2x \cdot x' \cos(\theta - \alpha) + y_i(x, \alpha)^2} d\theta dx' \]

\[ C_1 \text{ is a constant of electric efficiency determined by preliminary experiment, which differentiates the effects of the applied voltage and electrolyte concentration.} \]

### 2.2 Equivalent simplified two-dimensional method

The result of the inner integral of \( m_i(x, \alpha) \) in Equation (3) is found

\[ \int_{0}^{2\pi} \frac{c_1}{x^2 + x'^2 - 2x \cdot x' \cos(\theta - \alpha) + \delta^2} d\theta = \frac{2c_1\pi}{x^2 + x'^2 + 2x \cdot x' + \delta^2} \]

where

\[ \beta = \frac{\sqrt{x^2 + x'^2 - 2x \cdot x' + \delta^2}}{\sqrt{x^2 + x'^2 + 2x \cdot x' + \delta^2}} \]

The results show that \( m_i(x, \alpha) \) is actually independent of \( \alpha \), namely \( m_i(x, \alpha) = m_i(x) \). The erosion profile on the anode is thus found to be axis-symmetric, as can be anticipated. Furthermore, when \( \theta = 0 \), the three-dimensional model is reduced to a two-dimensional model as shown in Figure 2. A simplified model considers the erosion profile along a diametral line on the workpiece produced by all point charges on a diametral line on the electrode. \( m_i(x) \) is reduced to \( m'_i(x) \) at \( \theta = 0 \) as follows,

\[ m'_i(x) = m_i(x)|_{\theta=0} = -\int_{0}^{d} \frac{c_2}{x^2 + x'^2 - 2x \cdot x' \cos(\theta) + y_i(x)^2} dx' \]

\[ = -\int_{x}^{d} \frac{c_2}{(x-x')^2 + y_i(x)^2} dx' \]

Figure 3 shows the numerical results of \( m_i(x) \) and \( m'_i(x) \). It clearly demonstrates that \( m_i(x) \) and \( m'_i(x) \) are identical except the difference by a constant of 6.285. This constant is considered as the product of \( C_1 \) in Equation (3) and \( C_2 \) in Equation (6). Hence the simple integral of \( m'_i(x) \) along a diametral line electrode is used to replace the double integral of \( m_i(x) \) over the entire cathode end, and the whole scheme of the model can be then reduced to a two-dimensional equivalent model. The difference of the constant in between can be found by the preliminary experiment, which is also required when the three-dimensional
simulation is used. Based on Equations (3) and (6), the eroded depth produced by the equivalent line electrode at each time increment can be calculated by the following iteration equivalent to Equation (3).

\[ y_i = \delta \]

\[ y_{i+1} = y_i + \Delta t \cdot m_i \quad (i \geq 1), \text{ where} \]

\[ m_i = \int \frac{c}{2R^2} da = -\int \frac{c}{2} \frac{c}{(x-x')^2 + y'^2} da. \quad (7) \]

At the first step of machining, the equation draws an initial eroded profile on the workpiece. When the first iteration is done, the workpiece is eroded into an indent so that the gap distance across the electrode and the new generated surface of workpiece changes, thus each point on the new surface of workpiece has to renew its gap value after the first time step. Substituting the renewed gap into the model for the second iteration, one can redraw the eroded profile. In the use of the iterations continuously, the model describes the development of the erosion profile on the workpiece during the ECM process. Figure 4 shows the formation of the erosion indent calculated by the iterations (Hocheng et al., 2002).

**Figure 2** Scheme of the 2D model
Generation of erosion profile of through hole in electrochemical boring

Figure 3  Constant difference between \( m_i(x) \) and \( m'_i(x) \)

![Graph showing constant difference between \( m_i(x) \) and \( m'_i(x) \).]

\[ m'_i(x) \times 6.285 \]

\[ m_i(x) \]

Erosion in Radial Direction (mm)

Figure 4  Development of the predicted erosion profile

![Graph showing the development of the predicted erosion profile over time.]

\(--\ldots\quad 60 \text{ sec} \]
\[ --\ldots\quad 120 \text{ sec} \]
\[ \ldots--\quad 240 \text{ sec} \]

Erosion in Radial Direction (mm)
2.3 Boring-through model

Once the eroded profile touches the bottom plane of the workpiece, a hole will be bored through. Figure 5 is a photograph of the bored hole. One identifies the eroded area of diameter $2q$ on the top surface and an opening through the bottom surface at an early stage of diameter $2m$. The previous method of calculating the material removal can not be continued from the moment of boring-through, since there is no material to be eroded underneath. The electrical current before and after the formation of the through hole was monitored and showed approximately the same level (see Figure 6), which indicates that the same amount of material is removed. Hence, the electrical charge will be consumed to increase the side material removal for a wider opening of hole. The concept is presented in Figure 7. If the hole were not bored through, as shown in Figure 7(a), the electrical charge will distribute quite evenly along all the machined surface for material removal. The machined profile can be predicted by the iteration model. When the hole is bored through the bottom of the workpiece, there is no material beneath the bottom and the electric charges will be distributed to the side wall of the hole, as shown in Figure 7(b). The hole will be therefore enlarged more than previously predicted. The method considering the bottomless hole formation is introduced as follows.

Figure 5  Top view of the eroded hole after boring through
Figure 6  Electrical current rating before and after boring through (voltage = 8 V, electrolyte concentration = 5 M, initial gap = 0.25 mm, electrode diameter = 0.3 mm)

Figure 7  Schematic redistribution of electrical charge when boring through

(a) If hole were not bored through

(b) Hole is bored through
When the calculated profile reaches beyond the actual workpiece thickness (h), as described by curve \( y_i \) and the shaded area \( A \) in Figure 8, the erosion profile will be modified, based on the principle of constant amount of material removal, as elaborated below.

**Figure 8** Scheme of the converted material removal

The area \( A \) is considered a virtually removed amount of material between the bottom line and the calculated profile

\[
A = \int_{-l}^{l} (-h - y_i) \, dx. \tag{8}
\]

This part will be converted to the part in workpiece (B) to be removed, namely \( A = B \). To find B, one conducts the calculation for another profile, \( y_{i+n} \), \( n \) time steps beyond \( y_i \). In the calculation, \( y_{i+n} \) is set limited between 0 and \(-h\). B is the area between \( y_i \), \( y_{i+n} \) and \( y = -h \), the converted part of material removal.

\[
B = 2\left[ \frac{m}{n} (y_i - y_{i+n}) \, dx + \frac{m}{n} (y_i - (-h)) \, dx \right], \tag{9}
\]

where \( n \) is determined by setting the area \( B \) equal to area \( A \). Namely,

\[
A = \int_{-l}^{l} (-h - y_i) \, dx = 2 \int_{-m}^{0} (y_i - y_{i+n}) \, dx + 2 \int_{0}^{-m} (y_i - (-h)) \, dx = B \tag{10}
\]

The profile \( y_{i+n} \) is considered that actually machined, and the opening at the bottom is 2 m instead of 2 l. To calculate the bored profile at the next time step, this new profile \( y_{i+n} \) is replaced as \( y_i \) into Equation (7). The calculation procedure is shown in Figure 9.
Figure 9 Calculation of machined profile after boring through

1. Machined profile goes beyond the workpiece thickness

2. Find the profile of n time steps later, in that area A=B

3. Use the renewed profile as the current profile

4. Conduct the iteration model for the profile at next time step
3 Experimental design

The experiment is set up on a desk top CNC machine for control of the electrode movement. The gap between the electrode and the workpiece can be controlled by the Z-axis of the CNC machine within 2 μm of tolerance. The electrode is a commonly used CuZn73 alloy machined to a uniform diameter and flat end by a special technique of micro-EDM. The prepared end of the electrode is shown in Figure 10. The workpiece is SK5 stainless steel of 0.2 mm in thickness polished to the surface roughness of Ra=0.1 μm to ensure the constant initial condition of electrochemical machining. It is clamped in a tank filled with NaNO₃ electrolyte at room temperature. The circulation of the electrolyte was carefully controlled to maintain the stability of the electrical current monitored by a current meter. The flow rate of the electrolyte is 6 cm³/sec. The electrical power supply is a stable voltage source which can be adjusted from 0 to 15 V. The machined hole diameter is measured by both an optical microscope and a WYKO high-resolution surface profiler. The experimental parameters in the tests include machining time and electrode gap, while the voltage is set 8 and 9 V, the electrolyte is 5 M NaNO₃, and the diameter of the electrode is 0.3 mm. The experiment includes two parts with the stationary electrode as well as the moving electrode. Four schemes of electrode motion, A to D, with a rough and fine moving pace are designed to investigate the eroded hole profile and compared to the prediction of the model. The four schemes of electrode movement are shown in Figure 11. The movement of the electrode starts moving first after 30 seconds in consideration of the transient beginning of machining, and stops moving after 90 seconds. The gap between electrode and workpiece is kept larger than 0.15 mm throughout the experiment, or the electrical arc will occur.

Figure 10  SEM of electrode tip
4 Results and discussions

4.1 Stationary electrode

Figure 12 is an example of the experimental results of the stationary electrode (Hocheng et al., in press). One notices that the boring-through occurs at around 200 sec of machining time. The prediction agrees fairly well with the experiment by the method described in
Section 2.3. The opening at the bottom enlarges from the initial boring-through to a stable size near to 1 mm around 300 sec, while the opening at top surface settles at its final size of 1 mm earlier than the bottom opening. Further observation shows a taper of the hole forms during this development period. A desired hole taper can be achieved by careful exercise of this process with the aid of the proposed model. In ECM, the material erosion occurs beyond the transpassive zone. If the electrical intensity acting on part of the workpiece is below a threshold value, no material removal occurs and the machining profile of that part of workpiece will not change. Such a consideration is applied to the hole edge of the workpiece. A calculated erosion profile is shown in Figure 6. The points of $y_i$ in Equation (9) less than the predefined $C_i/V$ lie between the $x$-coordinates $-q$ and $q$, where $V$ is the voltage between electrode and workpiece, $C_i$ is a constant of 0.05 determined in preliminary experiments. $2q$ is correspondingly considered the machined hole diameter on the top surface of the workpiece.

**Figure 12** Predicted and experimental diameter of opening (voltage=8 V, electrolyte concentration=5 M, initial gap=0.25 mm, electrode diameter=0.3 mm)

(a) Diameter of Bottom Opening

(b) Diameter of Top Opening
4.2 Moving electrode

Once the experiment using a stationary electrode proves the effectiveness of the proposed model preliminarily, the experiment using a moving electrode is conducted. Figures 13 to 15 show the experimental results obtained from the different moving schemes of the electrode compared with the model predictions. Each experimental condition was tested three times. The comparisons of the predicted and experimental erosion opening at the bottom and top are shown in Figures 13 and 14, respectively. The experimental results lie on the predicted route of hole enlargement developing with time in all moving schemes. Higher voltage produces faster and larger erosion, as expected. The opening at the bottom enlarges drastically after boring-through at around 200 sec lasting for 50 sec, until the diameter approaches 0.8 and 0.9 mm for 8 and 9 V, respectively. The top diameter increases at a constant pace to the extent slightly wider than the bottom opening. The maximum errors between the experimental and the predicted bottom opening of moving schemes A to D are 15, 12, 17, and 18%, respectively. As to the top opening diameter, the maximum errors are 7, 7, 8 and 10%, respectively. The errors on the top are smaller than on the bottom. Since the top opening is eroded ahead of the bottom opening, it grows to a stable dimension, while the bottom opening is yet developing after being bored through. The experimental results show that the proposed model is simple to use with acceptable accuracy.

Figure 15 shows the predicted eroded taper in the model and the average of the measured taper. The taper is defined as the difference between top and bottom diameter per unit workpiece thickness.

\[
\text{Hole Taper} = \frac{\text{top opening diameter} - \text{bottom opening diameter}}{\text{workpiece thickness}}
\]

As observed in Figures 13 and 14, the top erodes earlier than the bottom until boring-through, thus the taper first drops at that moment and keeps reducing for more than 200 sec approaching the value of one, namely a straight-wall through hole. The average error of the model prediction is 8.9 and 12% for the condition of 8 and 9 V, respectively. It illustrates that the proposed model is able to predict not only the dimensions of the opening but also the taper of the hole during the electrochemical boring process. With careful design of the process, one can produce a small and tapered hole of a wide selection of taper.

The model assumes no undercut or abrupt shape changes on the electrodes, with a stable flow of electrolyte in between. The dimension of the specified ECM area is small thus the effects of the nonuniform electrolyte concentration, voltage and electrolyte flow rate are considered limited.
Figure 13  Predicted and experimental bottom hole diameter
Figure 14  Predicted and experimental top hole diameter

(a) Moving Scheme A

(b) Moving Scheme B

(c) Moving Scheme C

(d) Moving Scheme D
Figure 15  Taper prediction of moving electrode machining

(a) Moving Scheme A

(b) Moving Scheme B

(c) Moving Scheme C

(d) Moving Scheme D
5 Conclusions

The erosion profile in electrochemical boring using a flat-end moving electrode is investigated. The iteration integral shows the formation of the hole developing with time and changing gap. Once the hole is bored through, the prediction is modified to convert the virtual material removal underneath the bottom plane to the real one on the side wall. The electrical current in process is found unchanged before and after boring through, hence the same amount of material removal with the redistributed electric charges to the machined surface is applied in the analysis. The proposed model is useful in the design of electrochemical boring to make a small hole or opening, with or without a specific wall taper. It agrees fairly well with the experiment using both a stationary and a moving electrode. The future work will include the analysis of the influences of the gap voltage and the electrolyte flow.

The machining of a certain complexity, such as a composition of the spherical, cylindrical and flat surfaces, could be fairly predicted by the current model as long as there are no undercuts or an irregular flow of electrolyte caused by an abrupt change of the surface profile on the electrodes. This assumption will also be investigated in the future work.

Acknowledgement

The current research is supported by National Science Council, Taiwan, ROC under contract NSC91-2212-E-007-051.

References


