Development of the eroded opening during electrochemical boring of hole

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1 Introduction

Electrochemical machining (ECM) was first introduced in 1929 by Gusseff, later it was found that ECM is 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 [1]. An electrical current passes between the cathode tool and the anode workpiece through an electrolyte solution. The workpiece is eroded in a way that can be described by Faraday’s law of electrolysis. ECM is suitable for the machining of components of complex shape and high strength alloys, as typically found in the semiconductors industries [2–4].

Micro-machining refers to material removal that ranges from several microns to millimetres in dimensions. Advanced micro-machining has shown various machining activities performed on very small and thin workpieces. ECM has been used widely in manufacturing semiconductor devices and thin metallic films. ECM processes were also recognized in the aerospace and electronic industries for shaping and finishing operations of a variety of parts with opening windows that are a few microns in diameter [5].

A few studies of precision micro-ECM have been conducted by the consumer products industries [6]. However, except for electrochemical jet machining, electrochemical etching and wire electrochemical grinding, ECM still lags far behind other processes such as electric discharge machining (EDM) in the precision and micro-machining fields [7–10]. For the purpose of precise micro-machining, it is necessary to predict the final shape formed by the process when the machining parameters are given. The prediction also serves to save both material and time by the process design. Unlike the conventional cutting process, the control of dimension and shape is particularly difficult for micro-machining. This paper proposes a method to predict the machined profile of the workpiece. The prediction describes the development of the machined profile as a function of time and the changing gap opening. The results are verified experimentally.

2 Mathematical model

Figure 1 shows the geometry of the ECM process. The electrode of diameter \( d \) is placed above the workpiece with gap \( \delta \). Coulomb’s law says that the electric field intensity \( E \) applied to the workpiece by a point charge \( P(x') \) on the electrode is inversely proportional to the square of the distance \( R \) between \( P(x') \) and the considered point on the workpiece \( Q(x) \).

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

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

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

The amount of material erosion found on the workpiece caused by a single charge on the electrode is further assumed to be pro-
portional to $E$. In the two-dimensional model, the electrode is considered a line and is divided into infinitely many point charge sources. One point on the workpiece is influenced by all point charges on the line electrode. To add up all the erosion effects, an integral of the charge sources from one edge to another along the line electrode is carried out. The actual eroded depth caused by the equivalent line electrode at each time increment can be calculated by an iteration

$$y_1(x) = \delta$$

$$y_{i+1}(x) = y_i(x) + \Delta t \cdot m_i(x) \quad (i \geq 1)$$

where

$$m_i(x) = -\int_{-d}^{d} \frac{c}{R^2} dx' = -\int_{-d}^{d} \frac{c}{(x-x')^2 + y_i(x')^2} dx'$$

and $c$ is a constant of electrical efficiency.

At the first moment of the electromachining, the equation draws an initial eroded profile of the workpiece. When the first iteration is done, the shape of the workpiece was eroded into an indent so that the gap distance from the electrode to the new surface of workpiece has widened. Every point on the new machined surface of workpiece has a renewed gap value after the first time step. Substituting the new value of gap into the model to do the second iteration, one can renew the profile and the gap distance between electrode and workpiece. With the iteration operation, the method can describe the development of the eroded surface of the workpiece during the ECM process. Figure 2 shows the formation of the final shape calculated by the iterations in the model. At the beginning, the erosion goes faster in depth, while the width of the hole shows less erosion during the processes.

Once the eroded profile touches the bottom of the workpiece, a hole is bored. At this moment, the hole enlargement at the bottom will be faster than previously predicted, as there is no more material underneath the bottom plane to be removed. The electrical current before and after the formation of the through hole was monitored and showed approximately on the same level (see Fig. 3), which indicates that the same amount of material is removed. Hence the electric charge will be consumed to increase all the electric charges on the line electrode.