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Original scientific paper

Limiting current density in electrochemical micromachining

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Abstract

In this paper, a method of calculating the diffusion current density on the electric pole in the electrochemical micromachining is proposed. Changes of the diffusion current with system factors are investigated from which a method of increasing the diffusion current density on the electric pole under small clearance between the hole and the tool is proposed. This is the electrochemical micromachining method using vibrating tool electrode. Using this method, an etching experiment on a steel plate is performed which shows that a reasonable machining speed and high machining accuracy are simultaneously obtained.

Keywords

Vibration tool electrode; machining accuracy; diffusion current

Introduction

Micro-electromechanical systems (MEMS) are independent intelligent systems with an internal structure in the order of micron or even nanometer. Their performance mainly depends on micro manufacturing technology [1-3]. Electrochemical micromachining has a good development potential in the micromachining field of materials because the material transfers on the ion scales during the electrochemical micromachining and the metal ion scales are smaller than 10 % of nanometer [4-6]. The conventional electrochemical machining has a shortcoming in machining localization, what limits its micromachining ability. In order to improve the machining localization of the electrochemical micromachining, a lot of work has already been done [7-11]. Among them, the use of the ultra-short voltage pulses made an important breakthrough in which ultra-short voltage pulses of nanosecond duration were used and the machining localization of the electrochemical micromachining is increased significantly [12]. For this technique, a lot of research was completed [13-16]. Improved size and shape of the electrode, together with the reduced duration of the ultra-short pulse were used to increase micromachining precision of this technique [17-19]. The simulation approaches and computational models for the pulse electrochemical machining were also reported [20].

As the pulse width of the current is further reduced, the clearance between the hole and the tool becomes smaller and smaller which causes a decrease of the diffusion current density on the electric pole. This decrease can cause obvious decrease of the machining speed and even result in electrolytic product deposition and short circuit.

Therefore, the diffusion current density on the electric pole and its change with system factors should be investigated. The way for increasing the diffusion current density under small clearance between the hole and the tool should be find out.

Here, we proposed a method of calculating the diffusion current density on the electric pole in the electrochemical micromachining and derive the corresponding equations. Based on derived equations, changes of the diffusion current with system factors are investigated. From these results, a method of increasing the diffusion current density on the electric pole under small clearance between the hole and the tool is proposed. Using this method, an etching experiment on the steel plate is performed in order to illustrate the method.

Experimental

Here, an electrochemical micromachining system is developed (see Figure 1). It consists of machine tool, control system and the exciting part of tool electrode vibration. The exciting part of vibration includes tool electrode fixture, exciting beam of vibration and piezo drive power supply. By the converse piezoelectric effect of piezoelectric ceramic piece, a beam on which piezoelectric ceramic pieces are adhered is excited to vibrate vertically, driving the tool electrode to vibrate vertically.

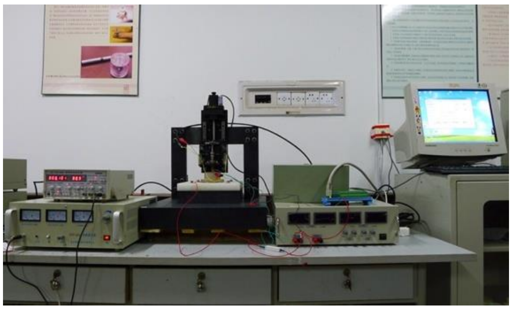

Figure 1. *Electrochemical micromachining system using vibrating tool electrode*

By the electrochemical micromachining system, we performed etching experiments on a steel plate 0.2 mm-thick. For this experiment, a cylindrical W wire of 30 µm in diameter was used as a tool. The electrolyte was 0.01 M $NaNO_3$. Static voltage of 3.5 V was applied between two electrodes. The exciting frequency of the vibration-exciting power supply was 125 Hz and the exciting voltage amplitude was 100 V. The vibrating amplitude of the tool electrode was 5 µm which means that a tool motion velocity of 2.5 mm s^{-1} is obtained during the machining. It took 30 min to etch through the steel plate. Besides it, an etching experiment on the steel plate was also performed by electrochemical micromachining system without the vibrating tool electrode.

Results and discussion

It has already been known that “in the small gap in front of the tool face, limited diffusion lowers the effective etching rate to a value significantly lower than expected from the high local overpotential with simple Tafel behavior” [12]. So, it can be concluded that diffusion or mass transport on the anode governs the rate of surface finishing in electrochemical micro machining experiments. As the gap in front of the tool face decreases, limited diffusion will lower the effective etching rate which is dependent on the limiting diffusion current I_d. Figure 2 shows a model for calculating limiting diffusion current in the gap in front of the tool face. Here, x is coordinate perpendicular to in tool pole axis; y is coordinate in tool pole axis; d_0 is gap in front of the tool face; r_0 is radius of the tool pole.

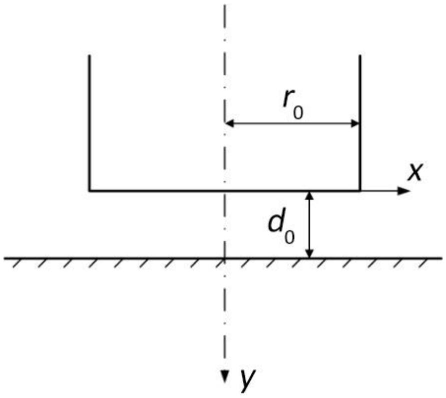

Figure 2. *Model of limiting diffusion current in the gap in front of the tool face*

The diffusion equation in the gap can be approximately defined as

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) \tag{1}$$

where C is the electrolyte concentration, D is the diffusion coefficient and t is time.

For steady-state, $\partial C / \partial t = 0$, letting $C = \varphi(x) f(y)$ and substituting it into Eq. (1), yields

$$\frac{\varphi''(x)}{\varphi(x)} = -\frac{f''(y)}{f(y)} = \omega^2 \tag{2}$$

where ω is a constant.

From Eq. (2), one can obtain following equations:

$$f''(y) + \omega^2 f(y) = 0 \tag{3}$$

$$\varphi''(x) + \omega^2 \varphi(x) = 0 \tag{4}$$

Solution of Eq. (3) gives

$$f(y) = c_1 \sin\omega y + c_2 \cos\omega y \tag{5}$$

The boundary conditions that $C = 0$ at $y = 0$ and $\partial C / \partial y = 0$ at $y = d_0$ (here d_0 is the distance between the tool face and workpiece) correspond to following conditions:

$f(0) = 0$ and $f'(d_0) = 0$

From above equations and taking $\omega = \dfrac{\pi}{2d_0}$ and $\overline{y} = y/d_0$, one can obtain the following equation:

$$f(y) = \sin\left(\frac{\pi}{2d_0} y\right) = \sin\frac{\pi}{2}\overline{y} \tag{6}$$

Solution of Eq. (4) gives

$$\varphi(x) = c_3 e^{\omega x} + c_4 e^{-\omega x} \tag{7}$$

The boundary conditions that $C=C_0$ at $x=\infty$ and $C=0$ at $x=0$ correspond to following conditions:

$\varphi(\infty) = 1$ and $\varphi(0) = 0$

From above equations and assuming $\bar{x} = x/d_0$, one can obtain the following equation:

$$\varphi(x) = 1 - e^{-\frac{\pi}{2}\frac{x}{d_0}} = 1 - e^{-\frac{\pi}{2}\bar{x}} \tag{8}$$

Thus, the electrolyte concentration is defined as:

$$C(x,y) = C_0(1 - e^{-\frac{\pi}{2}\bar{x}})\sin\frac{\pi}{2}\bar{y} \tag{9}$$

From Eq. (9), the following equation results

$$\left.\frac{\partial C}{\partial x}\right|_{x=r_0} = \frac{\pi}{2d_0}C_0 e^{-\frac{\pi}{2}\frac{r_0}{d_0}}\sin\frac{\pi}{2}\bar{y} \tag{10}$$

where $r_0$is the radius of the tool pole.

Thus, the diffusion flow rate is defined as

$$f_T = D\int_0^1 \left.\frac{\partial C}{\partial x}\right|_{x=r_0} 2\pi r_0 d_0 d\bar{y} = 2\pi r_0 D C_0 e^{-\frac{\pi}{2}\frac{r_0}{d_0}} \tag{11}$$

and the stationary current density on the electric pole is defined as

$$I_s = nFf_T \,/\, \pi r_0^2 = \frac{2nFDC_0}{r_0} e^{-\frac{\pi}{2}\frac{r_0}{d_0}} = \frac{\pi}{2} I_{co} e^{-\frac{\pi}{2}\frac{r_0}{d_0}} \tag{12}$$

where

$$I_{co} = \frac{4nFDC_0}{\pi r_0}$$

i.e., the current density on the disc electric pole at $d_0 = \infty$, defined in the cylindrical coordinate system. It shows that correction coefficient is $2/\pi$ when the current density on the electric pole is calculated by the Cartesian coordinate system.

For transient state ($\partial C/\partial t \neq 0$), letting $C = q(t)\,\varphi(x)\,f(y)$ and after substituting it into Eq.(1), one can obtain:

$$\frac{\dot{q}(t)}{Dq(t)} = \frac{\varphi''(x)f(y) + \varphi(x)f''(y)}{\varphi(x)f(y)} = -\alpha \tag{13}$$

From Eq. (13), following equations are obtained:

$$\dot{q}(t) + \alpha D q(t) = 0 \tag{14}$$

$$\frac{f''(y)}{f(y)} = -\frac{\varphi''(x) + \alpha\varphi(x)}{\varphi(x)} = -\omega^2 \tag{15}$$

From Eq. (15), one can obtain Eq. (3) together with

$$\varphi''(x) + \omega_d^2 \varphi(x) = 0 \tag{16}$$

where $\omega_d^2 = \alpha - \omega^2$.

Solution of Eq. (16) can be written as:

$$\varphi(x) = e^{\omega x} + ce^{-\omega x} \tag{17}$$

By substitution of boundary conditions $\varphi(0) = 0$ and $\varphi(r_0) = 1$ into Eq. (17) and assuming $\omega_d \approx 1/2r_0$, one can obtain:

$$\varphi(x) = e^{\frac{x}{2r_0}} - e^{-\frac{x}{2r_0}} = 2\mathrm{sh}\left(\frac{x}{2r_0}\right) \tag{18}$$

$$\alpha = \omega^2 - \omega_d^2 = \frac{1}{4}\left[\left(\frac{\pi}{d_0}\right)^2 - \frac{1}{r_0^2}\right] \tag{19}$$

Solution of Eq. (14) gives

$$q(t) = c_5 e^{-\alpha D t} + c_6 \tag{20}$$

From initial conditions $q(\infty) = 0$ and $q(0) = C_0$, it follows that

$$q(t) = C_0 e^{-\alpha D t} \tag{21}$$

Thus, the electrolyte concentration is defined as:

$$C(x,y) = 2C_0 e^{-\alpha D t} \sin\left(\frac{\pi}{2}\bar{y}\right) \mathrm{sh}\left(\frac{x}{2r_0}\right) \tag{22}$$

The transient diffusion current density on the electric pole is defined as:

$$I_\mathrm{t} = nFf_\mathrm{T} / \pi r_0^2 = I_\mathrm{co} \frac{\delta}{r_0} \mathrm{ch} \frac{1}{2} e^{-\alpha D t} \tag{23}$$

Thus, the total diffusion current density on the electric pole is defined as:

$$I_\mathrm{d} = I_\mathrm{s} + I_\mathrm{t} = I_\mathrm{co}\left(\frac{\pi}{2} e^{-\frac{\pi}{2}\frac{d_0}{r_0}} + \frac{d_0}{r_0} \mathrm{ch} \frac{1}{2} e^{-\alpha D t}\right) \tag{24}$$

After correction, the current density on the electric pole is:

$$I_\mathrm{d} = I_\mathrm{s} + I_\mathrm{t} = I_\mathrm{co}\left(e^{-\frac{\pi}{2}\frac{d_0}{r_0}} + 0.7\frac{d_0}{r_0} e^{-\alpha D t}\right) \tag{25}$$

As the motion velocity of the electric pole is considered, the diffusion equation in the gap can be approximately defined as

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - V_y \frac{\partial C}{\partial y} \tag{26}$$

where V_y is the motion velocity of the electric pole.

For stable state ($\partial C/\partial t = 0$), letting $C = \varphi(x)f(y)$ and substituting it into Eq.(26), yields

$$\frac{\varphi''(x)}{\varphi(x)} = \frac{V_y f'(y) - Df''(y)}{Df(y)} = \omega^2 \tag{27}$$

From Eq. (27), ones can obtain Eq. (4) together with:

$$f''(y) - \frac{V_y}{D} f'(y) + \omega^2 f(y) = 0 \tag{28}$$

Solution of Eq. (28) is

$$f(y) = e^{\frac{V_y}{2D}y} \sin \omega_d y \tag{29}$$

where

$$\omega_d = \omega\sqrt{1-\xi^2}\,,\ \xi = -\frac{V_y}{2D\omega}\,,\ \omega = \frac{\pi}{2d_0}\,.$$

Thus, the electrolyte concentration is defined as:

$$C(x,y)=C_0\left(1-e^{-\frac{\pi}{2}\bar{x}}\right)e^{\frac{V_y}{2D}y}\sin\omega_d y \tag{30}$$

From Eq. (30), it follows that

$$\left.\frac{\partial C}{\partial x}\right|_{x=r_0}=\frac{\pi}{2d_0}C_0 e^{-\frac{\pi}{2}\frac{r_0}{d_0}}e^{\frac{V_y}{2D}y}\sin\omega_d y \tag{31}$$

Thus, the diffusion flow rate is defined as

$$f_T=D\int_0^1\left.\frac{\partial C}{\partial x}\right|_{x=r_0}2\pi r_0 d_0 d\bar{y}=2\pi r_0 D C_0 e^{-\frac{\pi}{2}\frac{r_0}{d_0}}e^{\frac{V_y}{2D}d_0}\sin(\omega_d d_0+\lambda) \tag{32}$$

where

$$\mathrm{tg}\lambda=\sqrt{\left(\frac{\pi D}{d_0 V_y}\right)^2-1}\,.$$

The current density on the electric pole is defined as:

$$I_\mathrm{s}=nFf_T/\pi r_0^2=\frac{2nFDC_0}{r_0}e^{-\frac{\pi}{2}\frac{r_0}{d_0}}e^{\frac{V_y}{2D}d_0}\sin(\omega_\mathrm{d}d_0+\lambda)=\frac{\pi}{2}I_{co}e^{-\frac{\pi}{2}\frac{r_0}{d_0}}e^{\frac{V_y}{2D}d_0}\sin(\omega_\mathrm{d}d_0+\lambda) \tag{33}$$

For transient state, the diffusion current density on the electric pole is already defined by Eq. (23). Thus, the total diffusion current density on the electric pole is defined as:

$$I_\mathrm{d}=I_\mathrm{s}+I_\mathrm{t}=I_\mathrm{co}\left(e^{-\frac{\pi}{2}\frac{r_0}{d_0}}e^{\frac{V_y}{2D}d_0}\sin(\omega_\mathrm{d}d_0+\lambda)+0.7\frac{\delta}{r_0}e^{-\alpha Dt}\right) \tag{34}$$

Equations (23), (24), (25), (33) and (34) derived in this paper are utilized for analyzing diffusion current density on the electric pole for electrochemical micromachining. The parameters of the numerical example are shown in Table 1. Figures 3-5 present calculated diffusion current density as a function of time for different system parameters.

Table 1. *Parameters of the numerical example*

D/ cm^2 s^{-1}	*n*	*F* / C mol^{-1}	C_0 / mol
10^{-5}	2	96500	10^{-2}

Following points could be summarized from Figures 3-5:

1) In electrochemical micromachining, the diffusion current on the electric pole includes two parts: steady-state current and transient state current, *i.e.* $I_\mathrm{d}=I_\mathrm{s}+I_\mathrm{t}$. At initial condition, the transient state current, I_t, is large and drops quickly to zero with time, while the steady-state current, I_s, does not change with time. The total diffusion current, I_d, is near to the I_t, initially and then near to the I_s. As the radius of the electric pole tool drops, I_t drops quicker and the I_s becomes larger than I_t, making I_d almost equal to I_s.
2) As the ratio of the clearance d_0 to the radius of the electric pole tool r_0 drops, the total diffusion current drops quickly. The ratio d_0/r_0 determines a distance between the tool pole and the workpiece. A small ratio d_0/r_0 means a small distance between the tool pole and the workpiece. The total diffusion current, I_d, is lower and drops faster with decreasing distance between the tool pole and the workpiece. As the radius of the electric pole tool drops, the total diffusion current becomes higher and also drops faster with decreasing the ratio d_0/r_0. This is because both stable state current and transient state current drops quickly with decreasing the ratio d_0/r_0.

(a) (b)

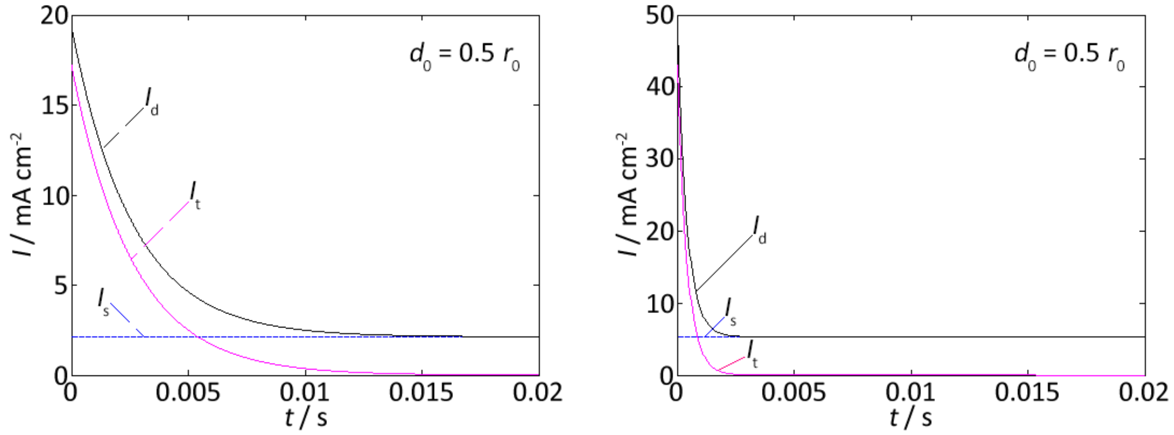

***Figure 3**. Diffusion current density (I_s, I_t and I_d) for d_0/r_0=0.5 and (a) r_0=5 µm, (b) r_0=2 µm.*

(a) (b)

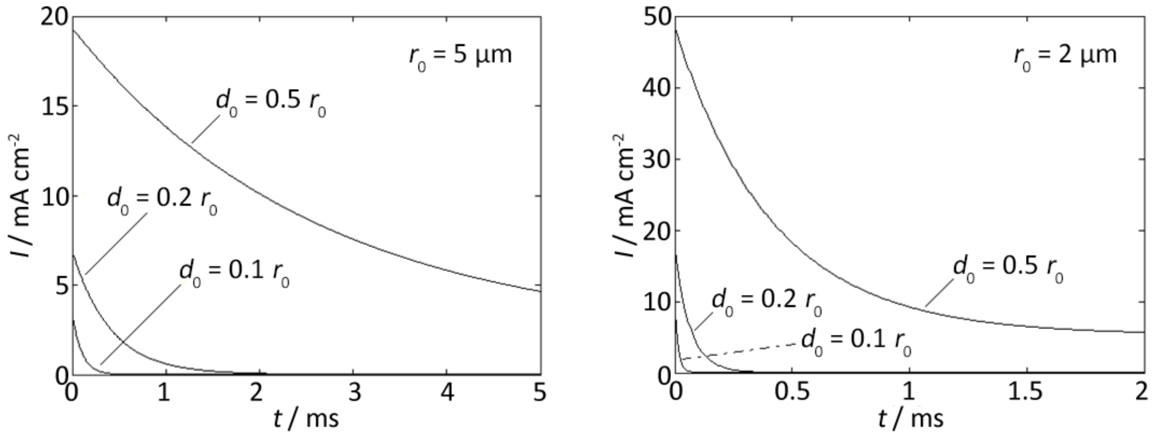

***Figure 4**. Total diffusion current density for different d_0/r_0 and (a) r_0=5 µm, (b) r_0=2 µm.*

3) When the motion velocity, V_y, of the tool electrode is considered, the stable state current changes with the velocity, but the transient state current does not change with it. If V_y increased from 0 to 2 mm s^{-1}, I_s increased from 2 to 26 mA cm^{-2}. Here, the steady-state current is much higher than the transient state current density, $I_s >> I_t$, even at the initial time, and so the total diffusion current density, I_d, is determined mainly by the steady-state current. As the radius of the electric pole tool drops, I_d becomes large, and the effects of the velocity V_y on the diffusion current become weak. However, the total diffusion current still grows obviously with increasing V_y.

All these results suggest that the motion velocity of the tool electrode can increase the total diffusion current on the electrode by which the machining speed and machining accuracy of the electrochemical micromachining can be increased.

Based on above mentioned results, a new electrochemical micromachining method is proposed. It is the electrochemical micromachining using vibrating tool electrode which can increase the diffusion current density on the electric pole under small clearance between the hole and the tool. By the electrochemical micromachining system, we performed etching experiments shown in Figure 6. It took 30 min to etch through the steel plate. As seen in Figure. 6(a), the diameter of the etched hole is about 108 µm. For comparison purpose, the etching experiment on a steel plate 0.2 mm-thick performed by electrochemical micromachining system without vibrating tool electrode is presented in Figure 6(b). The micromachining was not completed because of short circuit. As seen in Figure 6(b), the diameter of the hole etched is much larger than that obtained with the vibrating tool electrode and accumulation of the electrolytic product occurs, causing the short circuit between the tool and a work piece.

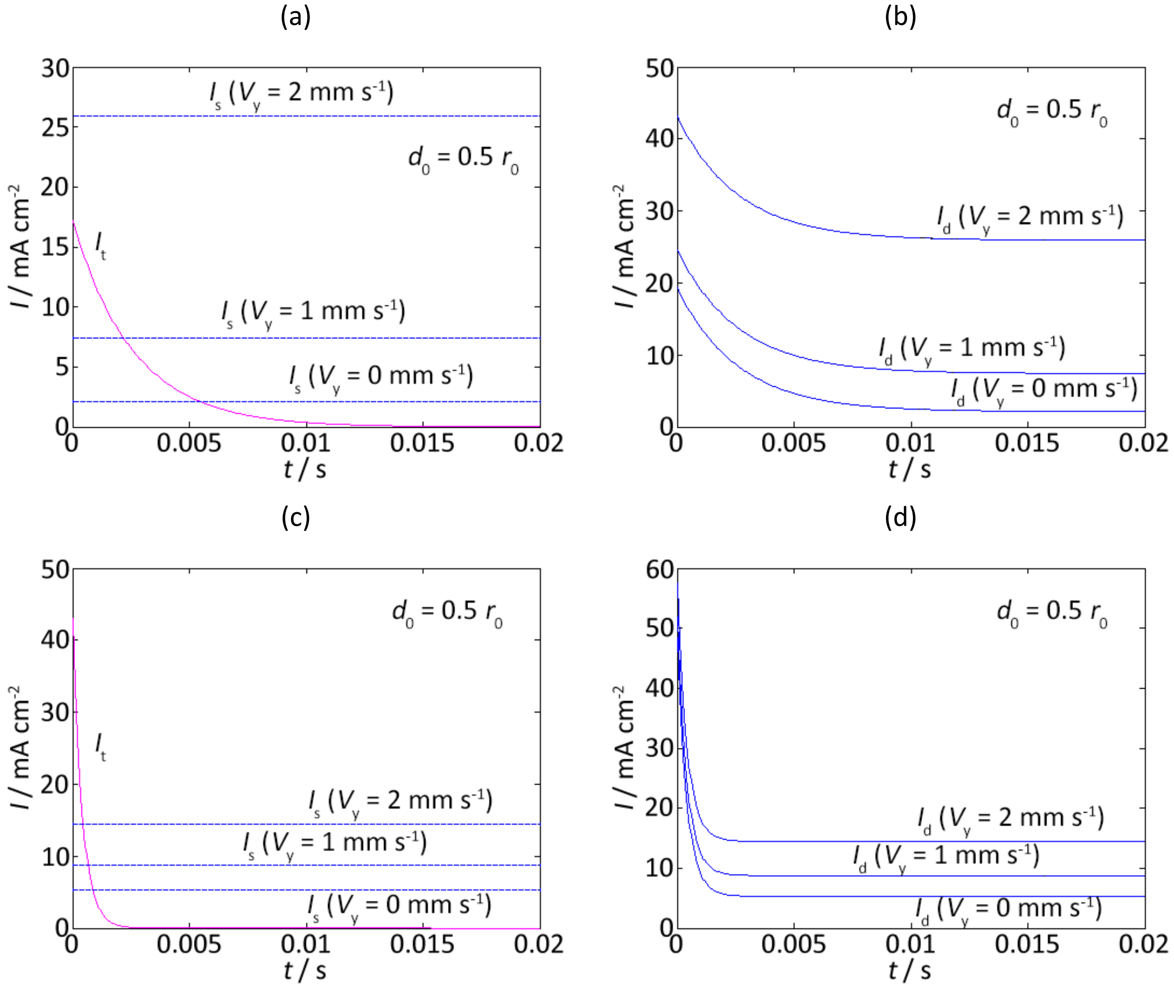

***Figure 5**. Diffusion current density,* (I_s, I_t and I_d) *for* d_0/r_0=0.5 *at different* V_y *and (a)* r_0=5 μm, *(b)* r_0=5 μm, *(c)* r_0=2 μm, *(d)* r_0=2 μm.

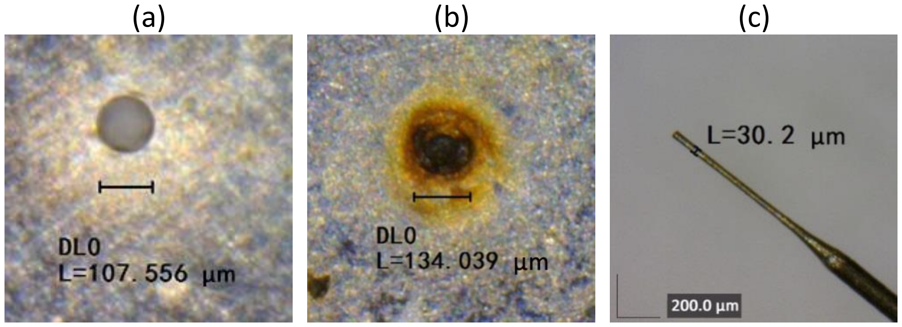

***Figure 6.** Holes etched* by electrochemical micromachining system: **(a)** vibrating tool electrode, (b) *normal* tool electrode, *(c) tool pole.*

Present results show that a reasonable machining speed and high machining accuracy is obtained simultaneously by the electrochemical micromachining technique using vibrating tool electrode, illustrating thus the effectiveness of our method and correctness of our theories. Because the vibrating tool electrode can increase the diffusion current density on the electric pole under small clearance between the hole and the tool, machining localization and machining speed can simultaneously be increased**.**

Besides it, effects of the main vibrating parameters on the machining accuracy are investigated for the electrochemical micromachining technique using vibrating tool electrode. In Figure 7, the machining resolution d_c, estimated by measuring the tool diameter and the hole diameter [(final hole diameter – tool diameter)/2] is presented as a function of vibrating frequency of the tool electrode, f, and vibrating amplitude of the tool pole, A_z.

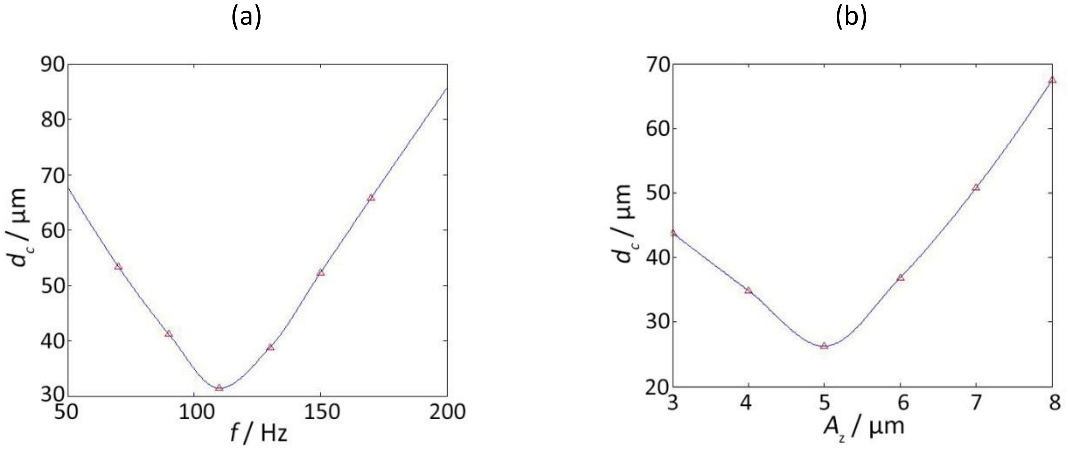
(a) (b)

Figure 7. *Machining resolution as a function of: (a) frequency change* (A_z=5 µm), *(b) amplitude change* (f =108 Hz)

Figure 7(a) shows that when the vibration frequency of the tool electrode increases, the machining resolution improves significantly, attains an optimum machining resolution at 108 Hz, and then becomes obviously bad. The same effect appears in Figure 7(b), showing the effect of the vibrating amplitude increase and an optimum machining resolution attained at 5 µm. The resultant micro holes machined at the optimum f = 108 Hz for different A_z values are shown in Figure 8.

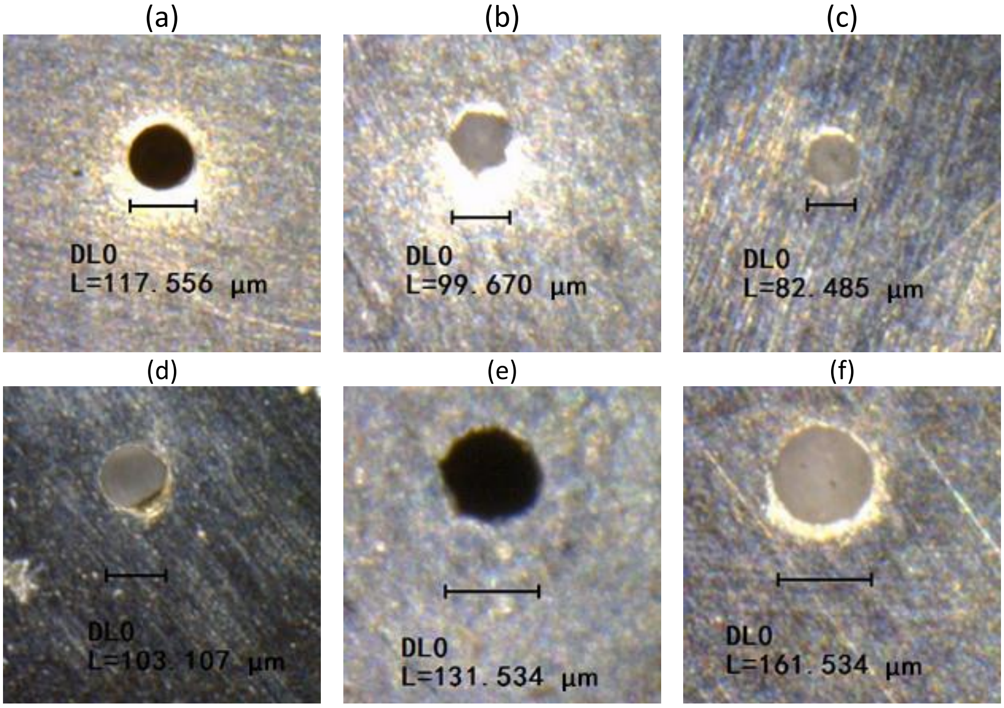
(a) (b) (c) (d) (e) (f)

Figure 8. *Micro holes machined at* f = *108* Hz *for different vibration amplitudes: (a)* 3 µm, *(b)* 4 µm, *(c)* 5 µm, *(d)* 6 µm, *(e)* 7 µm, *(f)* 8 µm.

The obtained results suggest that the machining accuracy for the electrochemical micromachining technique using vibrating tool electrode increases with vibrating frequency and amplitude, but the optimum vibration parameters exist, above which the machining accuracy becomes bad. This probably happens because the electrochemical reaction time increases and the depolarization time reduces when the vibrating frequency and amplitude is larger than the optimum values.

Conclusions

In this paper, a method of calculating the diffusion current density on the electric pole in the electrochemical micromachining is proposed. Changes of the diffusion current calculated with the system factors are investigated. Based on these results, a method of increasing the diffusion current density on the electric pole under small clearance between the hole and the tool is proposed. This is an electrochemical micromachining method using a vibrating tool electrode. Using the method, an etching experiment on a steel plate is performed which showed that a reasonable machining speed and high machining accuracy can be obtained simultaneously.

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