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ORIGINAL ARTICLE

Electrochemical micromachining using vibrating tool electrode

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Abstract This paper proposes an electrochemical micromachining method that makes use of a vibrating tool electrode. An equation of the dynamic voltage caused by a vibrating tool electrode is deduced. Using this equation, the dynamic voltage and its changes, along with system parameters, are investigated. This paper also describes an etching experiment on a steel plate, performed with an electrochemical micromachining system that uses a vibrating tool electrode. The results show that this type of electrochemical micromachining technique can significantly increase machining localization of the electrochemical micromachining.

Keywords Electrochemical micromachining · Vibrating tool electrode · Machining localization · Dynamic voltage

1 Introduction

There is a strong potential for developing electrochemical micromachining (ECM) in the micromachining fields because, during ECM, the material transfers on ion scales and the metal ion scales are smaller than 10 % of nanometer [1–4]. The micromachining ability of conventional ECM has been limited due to a shortcoming in machining localization; however, a great deal of work has been done in the attempt to overcome this shortcoming [5–8]. One such improvement effort resulted in an important breakthrough in which ultrashort voltage pulses—of nanosecond duration—were used and the ECM machining localization was increased significantly [9]. Further research was completed regarding this technique [10, 11]. Regarding electrochemical microdrilling, the effects of applied frequency and duty cycle on nickel plate were investigated [12]. A mathematical model for predicting the diameter of the microtools fabricated by pulse ECM was presented and confirmed by experimental results [13]. Results show that the machining localization of the ultrashort-pulse ECM depends primarily on the ultrashort-pulse power supply.

In 2011, Jujhar investigated the process of electrical discharge machining (EDM) by applying continuous and discontinuous vibrations to the workpiece; this was discovered to improve the microhardness of the workpiece [14]. Referencing this method, we propose a means of ECM by which the machining localization can be increased without an ultrashort-pulse power supply. Our suggested method of ECM uses a vibrating tool electrode. For the micromachining method, an equation of the dynamic voltage caused by a vibrating tool electrode was deduced. Using this equation, we investigated the dynamic voltage and its changes, along with system parameters. We developed an ECM system that uses a vibrating tool electrode by which we conducted an etching experiment on a steel plate. The results show that the ECM method we propose can substantially increase machining localization of the electrochemical micromachining.

2 Potential difference from vibrating electrode

An equivalent circuit of two electrodes immersed in electrolyte is given in Fig. 1. From Kirchhoff's voltage law, we know

$$\varphi + R_e\left(C_d\frac{d\varphi}{dt} + \frac{\varphi}{R_r}\right) = \Phi \tag{1}$$

where φ is voltage of the double layers on the electrode, R_e is electrolyte resistance, $R_e=\rho_L d$, ρ_L is electrolyte resistivity, d is separation between the electrodes, R_r is resistance of the

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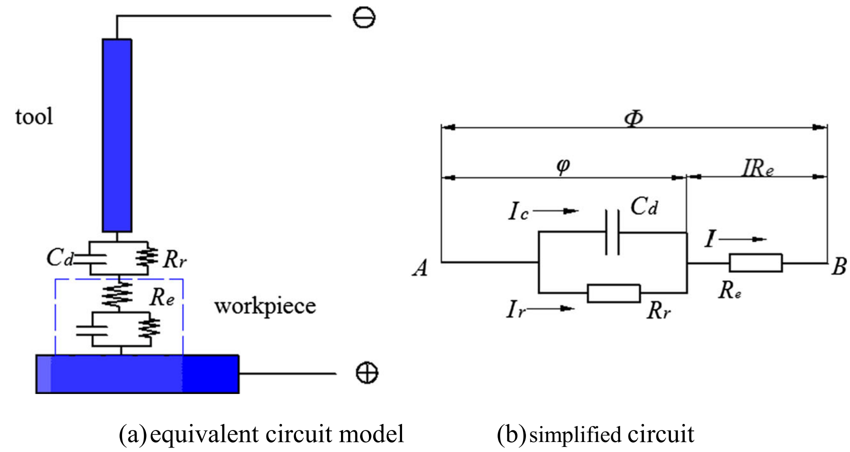


Fig. 1 An equivalent circuit of two electrodes immersed in electrolyte. **a** Equivalent circuit model and **b** simplified circuit

electromechical reaction, C_{d} is capacity of the double layers on the electrode, and Φ is voltage between two electrodes.

When the electrode tool vibrates, separation d periodically changes. It causes periodical change of the electrolyte resistance R_{e} and voltage of the double layers. Thus, we can give

$$d = d_0 + \Delta d \tag{2-a}$$

$$R_{\mathrm{e}} = R_{\mathrm{e}0} + \Delta R_{\mathrm{e}} \tag{2-b}$$

$$\varphi = \varphi_0 + \Delta\varphi \tag{2-d}$$

where d_0 is initial separation between the electrodes, Δd is separation change, $R_{\mathrm{e}0}$ is initial electrolyte resistance, ΔR_e is electrolyte resistance change, φ_0 is initial voltage of the double layers, and $\Delta\varphi$ is voltage change.

Substituting Eq. 2 into Eq. 1, yields

$$(\varphi_0 + \Delta\varphi) + (R_{e0} + \Delta R_e)\left[C_{\mathrm{d}}\frac{d(\varphi_0 + \Delta\varphi)}{dt} + \frac{\varphi_0 + \Delta\varphi}{R_{\mathrm{r}}}\right] = \Phi \tag{3}$$

From Eq. 3, we obtain

$$\varphi_0 + R_{e0}\left(C_{\mathrm{d}}\frac{d\varphi_0}{dt} + \frac{\varphi_0}{R_{\mathrm{r}}}\right) = \Phi \tag{4-a}$$

$$R_{e0}C_{\mathrm{d}}\frac{d\Delta\varphi}{dt} + \Delta\varphi\left(1 + \frac{R_{e0}}{R_{\mathrm{r}}}\right) + \Delta R_e C_{\mathrm{d}}\frac{d\Delta\varphi}{dt} + \Delta R_e\frac{\varphi_0}{R_{\mathrm{r}}} + \Delta R_e\frac{\Delta\varphi}{R_{\mathrm{r}}} = 0 \tag{4-b}$$

In Eq. 4-b, $R_{\mathrm{e}0}$ is much smaller than R_{r}, so $R_{\mathrm{e}0}/R_{\mathrm{r}}$ is taken as zero. Neglecting the higher-order term, Eq. 4-b can be changed into following form

$$R_{\mathrm{e}0}C_{\mathrm{d}}\frac{d\Delta\varphi}{dt} + \Delta\varphi = -\frac{\varphi_0}{R_{\mathrm{r}}}\Delta R_{\mathrm{e}} \tag{5}$$

Letting $\Delta d = \Delta d_{\mathrm{m}}\sin\omega t$, and substituting it into Eq. 5, yields

$$R_{e0}C_{\mathrm{d}}\frac{d\Delta\varphi}{dt} + \Delta\varphi = -\varphi_{\mathrm{c}}\sin(\omega t) \tag{6}$$

where Δd_{m} is vibrating amplitude of the tool electrode, ω is vibrating frequency of the tool electrode, t is time, and φ_{c} is equivalent exciting voltage, $\varphi_{\mathrm{c}} = \frac{\varphi_0}{R_{\mathrm{r}}}\rho_{\mathrm{L}}\Delta d_{\mathrm{m}}$.

The solution of Eq. 6 is

$$\Delta\varphi = \frac{\varphi_{\mathrm{c}}}{\sqrt{1 + (R_{e0}C_{\mathrm{d}}\omega)^2}}\sin(\omega t - \theta) \tag{7}$$

Letting reaction voltage of the workpiece be φ_{r}, the condition occurring for electrochemical reaction is

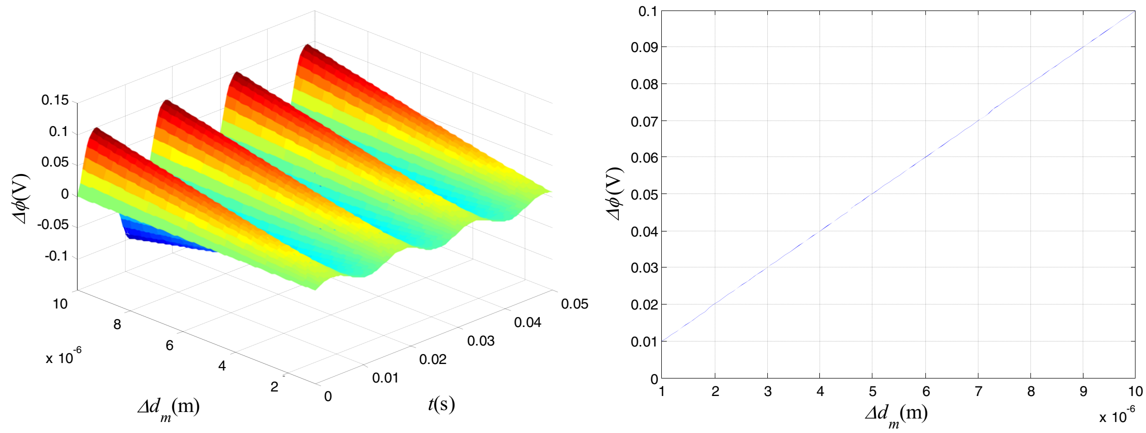
$$\varphi_0 + \Delta\varphi \geq \varphi_r \tag{8}$$

Substituting Eqs. 7 into 8, yields

$$\Delta d_{\mathrm{m}} \geq (\overline{\varphi} - 1)\sqrt{1 + (R_{e0}C_{\mathrm{d}}\omega)^2}\frac{R_{\mathrm{r}}}{\rho_{\mathrm{L}}} \tag{9}$$

Table 1 Parameters of the numerical example

ρ_{L} (Ωcm)	S (cm^2)	R_{r} (Ω)	C_{DL} (μF/cm^2)	ω (Hz)
50	1	5	13	420



(a) *t* changes (b) *t*=const

Fig. 2 $\triangle\varphi$ as a function of $\triangle d_{\mathrm{m}}$ and $t(\varphi_0=10$ V, $d_0=10$ μm). **a** *t* changes and **b** *t*=const

where $\overline{\varphi}=\frac{\varphi_r}{\varphi_0}$.

For a given Δd_{m}, the condition occurring for electrochemical reaction becomes

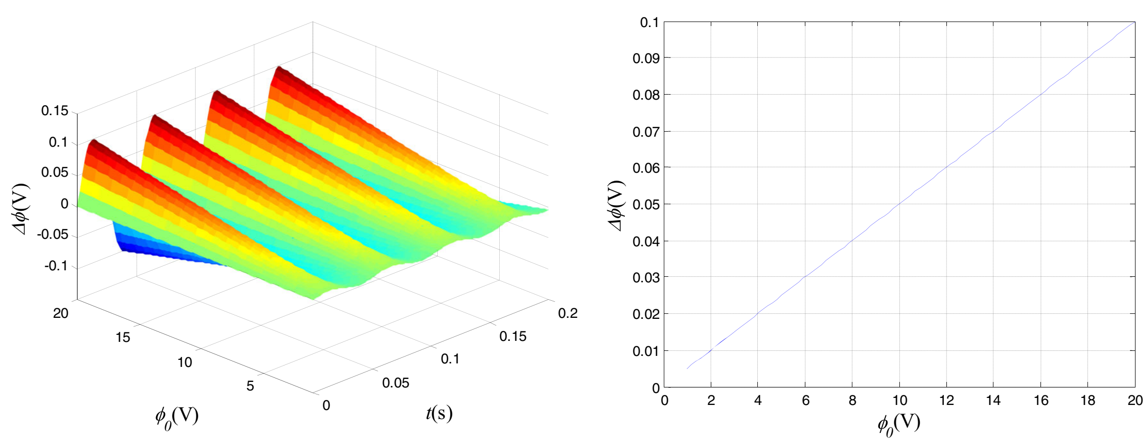
$$d_0\leq\frac{1}{\rho_{\mathrm{L}}C_{\mathrm{d}}\omega}\sqrt{\left[\frac{\rho_{\mathrm{L}}\Delta d_{\mathrm{m}}}{R_{\mathrm{r}}(\overline{\varphi}-1)}\right]^2-1} \tag{10}$$

3 Results and discussions

The equations in this paper are used for analyzing the potential differences from a vibrating electrode. The parameters of the numerical example are shown in Table 1 (here, *S* is section area of the tool pole). Figures 2 and 3 give the voltage changes with the main parameters. Figures 2 and 3 show the following:

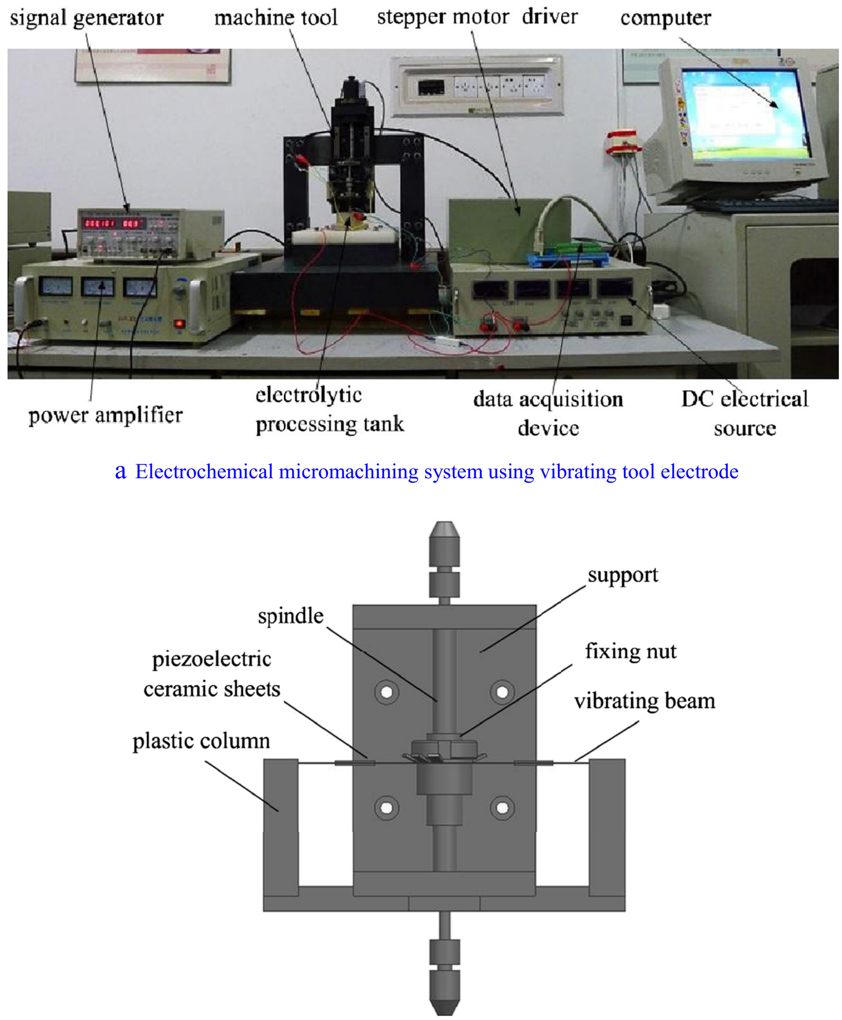
(1) As the tool electrode vibrates periodically, a periodical voltage change occurs. Based on the occasional changes in the distance between the tool electrode and workpiece, the electrolyte resistance periodically changes as well. Therefore, when a static voltage is applied between two electrodes, a voltage change that improves machining localization of ECM can be produced.

(2) The voltage change from the vibrating electrode is proportional to the vibrating amplitude of the tool electrode. As the vibrating amplitude is 1 and 10 μm, respectively, the amplitude of the voltage change becomes 10 and 100 mV, respectively. This shows that the tool electrode



(a) *t* changes (b) *t*=const

Fig. 3 $\triangle\varphi$ as a function of φ_0 and $t(\triangle d=5$ μm, $d_0=10$ μm). **a** *t* changes and **b** *t*=const



a Electrochemical micromachining system using vibrating tool electrode

b Vibration excitation mechanism

Fig. 4 **a** Electrochemical micromachining system using vibrating tool electrode. **b** Vibration excitation mechanism

vibration at micron dimension can cause considerable voltage change.

(3) When the vibrating amplitude of the tool electrode is given, the initial voltage between two electrodes can bring about vibrating electrode voltage change. As the initial voltage increases from 2 to 10 V, the vibrating electrode voltage change increases by five times.

The vibrating electrode voltage change is additionally dependent on the initial separation between the electrodes and the frequency of the exciting voltage. When other parameters are constant, the discussed voltage change decreases nonlinearly, with increasing initial separation between the electrodes and the frequency of the exciting voltage. When the frequency of the exciting

Table 2 Changes of the voltage along with the vibrating displacement of the tool electrode

Δd_m (μm)	2	4	6	8	10	12	15
$\Delta\varphi$ (mV) measure	6.25	12.75	19.85	21.45	26.50	31.35	38.55
$\Delta\varphi$ (mV) calculate	6	12	18	24	30	36	45
Error (%)	4.0	5.9	9.3	11.9	13.2	14.8	16.7

voltage is relatively low, effects on voltage change from the initial separation and the frequency are not obvious and can be neglected. When the frequency of the exciting voltage is high, the aforementioned effects on voltage change should be considered.

4 Electrochemical micromachining system and test

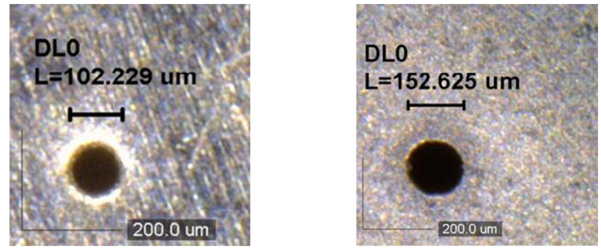
An ECM system using vibrating tool electrode is developed (see Fig. 4). It consists of a machine tool, control system, and the exciting part of tool electrode vibration. The exciting part of vibration includes a tool electrode fixture, exciting vibration beam, and piezodrive power supply (see Fig. 4b). By the reverse piezoelectric effect, a beam on which piezoelectric ceramic pieces are adhered is excited to vibrate vertically. This process drives the tool electrode to vibrate vertically.

Using the ECM with vibrating tool electrode, we measured periodic voltage change caused by the exciting beam of vibration. A partial voltage circuit was used to apply a static voltage between two electrodes, an oscilloscope was used to measure voltage change caused by the exciting beam of vibration, and a vibrator was used to measure vibrating displacement of the tool electrode.

The initial separation between the electrodes was 20 μm, the initial voltage between them was 6 V (it means $\varphi_0=3$ V), the area of the electrode was 100 mm^2, and the exciting frequency of the vibration-exciting power supply was 100 Hz. The measured and calculated changes of voltage, along with the vibrating displacement of the tool electrode, are shown in Table 2.

The results show that a periodic voltage change occurs as the tool electrode vibrates periodically, and that the voltage change is approximately proportional to the vibrating amplitude of the tool electrode. The measurement results approximately agree with calculative values. When the vibrating amplitude is relatively large, the errors between measurements and calculative values are relatively large. This most likely occurs based on effects of the nonlinearity factors. At $\Delta d_m=15$ μm, the error is 16.7 %. The results justify our abovementioned findings. The effects of the nonlinearity on the voltage change should next be considered for a relatively large vibrating amplitude of the tool electrode.

To justify our findings further, we conducted an etching experiment on a 0.2-mm-thick steel plate.



(a) vibrating tool electrode (b) static tool electrode

Fig. 5 Hole etched by electrochemical micromachining system. **a** Vibrating tool electrode and **b** static tool electrode

For this experiment, we used a cylindrical W wire, 30 μm in diameter, as a tool. The electrolyte was $NaNO_3$, and the concentration was 6 %. A static voltage (3.5 V) was applied between two electrodes. The exciting frequency of the vibration-exciting power supply was 100 Hz, and the exciting voltage amplitude was 100 V. The feed speed of the tool was 0.1 μm/s. It took 60 min to etch through the steel plate. The diameter of the hole etched was 102.2 μm (see Fig. 5a). An etching experiment on a 0.2-mm-thick steel plate was also performed, making use of static voltage without vibrating tool electrode. The diameter of the hole etched was 152.625 μm (see Fig. 5b).

The results show that an ECM technique that uses vibrating tool electrode can significantly increase machining localization of the electrochemical micromachining. These results illustrate the effectiveness of our method because the vibrating tool electrode can potentially cause a dynamic difference that increases machining localization in a same manner as pulse-current ECM. Furthermore, the vibrating tool electrode was found to be favorable for diffusion of the electrolytic product.

5 Conclusions

In this paper, an electrochemical micromachining method using vibrating tool electrode has been proposed. Such a system was developed and then used for an etching experiment on a steel plate. The results showed that an ECM technique using vibrating tool electrode can increase the machining localization of the electrochemical micromachining substantially.

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