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Ultrasonic Vibration Assisted Micro Electrochemical Discharge Drilling Technology*

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Abstract - Electrochemical Discharge Machining (ECDM) is an effective way to fabricate micro holes, channels and kerfs on non-conductive materials. In this paper, material removal mechanism of ECDM was discussed and model for gas film formation was established. Meanwhile, a series of experiments for micro drilling were carried out to demonstrate the advantages of Ultrasonic Vibration Assisted Electrochemical Discharge Machining（UAECDM）. Results have shown that the machining voltage is significantly reduced while ultrasonic vibration is applied to the tool electrode, and both accuracy and stability of the machining process are improved consequently. Finally, 3 *3 array holes were fabricated with small thermal crack area around the inlet and no breakage at the outlet.

Index Terms - electrochemical discharge machining; ultrasonic vibration; micro drilling.

I. Introduction

Electrochemical Discharge Machining (ECDM) is one of the main methods that aim to deal with non-conductive materials. With relatively high accuracy and flexibility, it has attracted great attention in recent years.

Ultrasonic vibration assistance in traditional electrical machining is proven to be effective in promoting electrolyte circulation, increasing the machining efficiency and accuracy. Thus, Ultrasonic Vibration Assisted Electrochemical Discharge Machining (UAECDM) has emerged.

Hu Jianhua found that by applying ultrasonic vibration assistance to the EDM process, the interelectrode circulation of electrolyte is significantly improved; With appropriate parameters of ultrasonic vibration, machining efficiency is effectively improved. Hu also established a curve relation between the excitation voltage of supersonic wave, vibration frequency and machining time [3]. Chang Weijie conducted a simulation with FLUENT to analyze the effects of ultrasonic vibration on inter-electrode pressure field, flow field and particle concentration. Results have shown that with ultrasonic vibration assistance, the gradient of pressure distribution is optimized and the circulation of electrolyte enhanced, which contributes to the removal of machining debris, the reduction in arc discharge and short circuit, and eventually the improvements of machining efficiency [4].

In 2016, Goud reviewed the mechanisms of material removal of ECDM. Possible measures to improve the removal rate are discussed and future research trends are pointed out in his work [1]. In order to improve the efficiency of the ECDM process, Singh has made several technical improvements to the structural system of ECDM, and developed a Hybrid Machining Method to further enrich the process [2].

Elhami explored the characteristic of a single discharge in the ECDM process and the effects of ultrasonic vibration [5]. Further experiment has shown that with the assistance of ultrasonic vibration, current signal is significantly changed as an increased number of discharges is observed in unit time period; Material removal rate is promoted by 35% and tool wear reduced by up to 14%. The thickness of gas film is found to drop by 65% as ultrasonic vibration is applied, which is benefit to machining localization. Besides, a vibration amplitude of 10μm proves to be optimum for a uniform current signal, which has a positive effect on the material removal [6].

In this paper, glass is selected as the workpiece material, and an ultrasonic vibration assisted micro-electrochemical discharge drilling process is carried out. The influence of ultrasonic vibration assistance on the machining principle, and machining effects is discussed.

II. Principle and Simulation of Machining Process

A. Machining Principle

A set of basic Electrochemical Discharge Machining (ECDM) system is demonstrated in Fig. 1, which includes a tool electrode and an auxiliary electrode, electrolyte (typically aqueous solution with a specified concentration), a pulse power supply and a workpiece. The immersed surface area of the tool electrode should be significantly smaller than that of the auxiliary electrode.

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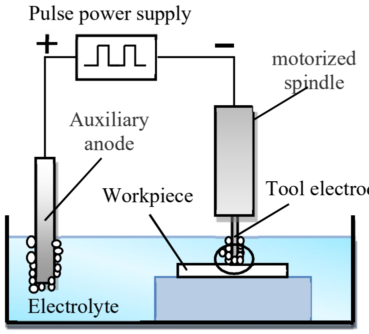

Fig. 1 Basic Electrochemical Discharge Machining (ECDM) System.

As shown in Fig.2, due to electrolysis reaction, a large number of bubbles are produced around the cathode and a thin gas film is gradually formed which isolates the tool electrode with electrolyte. When the applied voltage reaches the critical value, electrical discharges will occur. The energy of a single discharge can be calculated by a basic formula, that is:

$$Q = \int_0^T UIdt \tag{1}$$

Where U is the pulse voltage, I is the mean current, T is the duration of a single discharge.

As the state of discharges is volatile [7], an average discharge current is used as follow:

$$I \cong \lambda_d Aq\tau \tag{2}$$

Where λ_d is the number of discharges per unit time, A is the area of discharges, q is the number of charges and τ is the time constant.

With the voltage U between the tool electrode and the gas film boundary determined, the average discharge energy per unit time is:

$$Q_i = UI \cong \lambda_d Aq\tau U \tag{3}$$

When the workpiece is close enough to the discharge area, materials will be heated and melt locally. Ignoring part of the energy loss by the possible gasification and chemical reaction at high temperature, the amount of melting materials is:

$$n \cong \frac{Q_i}{\lambda} \tag{4}$$

Where λ is the melting heat of glass.

The volume of melting glass per unit time is:

$$V \cong \frac{n \cdot M}{\rho} \cong \frac{\lambda_d Aq\tau UM}{\lambda\rho} \tag{5}$$

Where M is the molar mass of glass, ρ is the density of glass. It is obvious from the formula that the volume of melted glass workpiece increases with the increase of λ_d, A and U. As these parameters can be regulated directly or indirectly in electrochemical discharge drilling, the control of the whole process is realized.

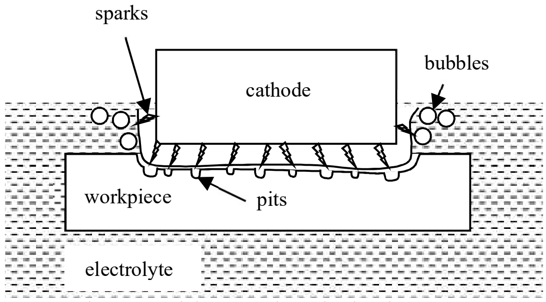

Fig. 2 Material Removal Mechanism in ECDM.

With the assistance of ultrasonic vibration, the coalescence of gas bubbles is promoted, the formation of gas film is hastened and its thickness reduced, leading to a decline in the critical voltage of electrochemical discharge. As a result, machining could be conducted at a relatively lower terminal voltage and the smaller discharge energy for each spark. Besides, the appearance of gas film along the tool electrode is more uniformly distributed, so that the taper of the cavity is relieved. Ultimately, machining accuracy and stability is improved

B. Simulation Analysis

In this section, the finite element analysis software FLUENT is used to analyze the process of gas film formation in ECDM process.

It is assumed that the electrolyte is an incompressible fluid and H_2 gas satisfies the approximate ideal gas equation of state. Mass and momentum conservation equations were used and the standard k-ε model is selected for calculation.

In order to simplify the computing process, the tool electrode is set up as a 300μm long cylinder with 100μm diameter and a 2D transient model is established. The model, as shown in Fig. 3, consists of the tool electrode and the electrolyte. Γ_1 is set up as a pressure-outlet and Γ_2 a velocity-inlet (H_2 gas with a speed of 0.005m/s). UDF files which control the frequency and amplitude of ultrasonic vibration are loaded at Γ_2. Γ_3 is set as no sliding wall of the container. Finally, the gas-liquid two-phase distribution in the machining area is obtained.

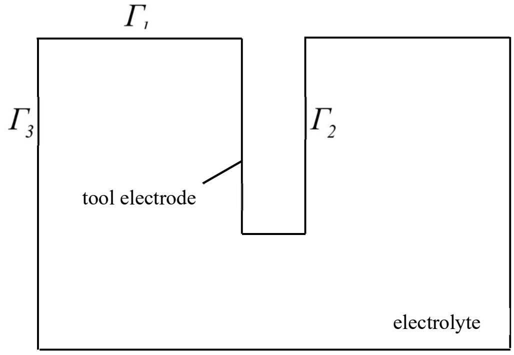

Fig. 3 the finite element model of gas film formation.

As shown in Fig. 4, the gas-liquid distribution of ECDM (without loading UDF files) is compared with that of UAECDM. The blue area represents liquid and the red area is gas. It can be seen from the diagram that the external diameter of gas film formed without the assistance of ultrasonic vibration is 210μm near the surface of electrolyte, and 161μm near the tip of the electrode, with a conicity of 0.22. The maximum thickness at bottom is 48μm. For UAECDM, the external diameter of gas film is 190μm near the surface of electrolyte, and 154μm near the tip of the electrode, with a conicity of 0.16. The maximum thickness at bottom is 38μm.

The simulation results show that the overall thickness of the gas film decreases to a certain extent, and its taper is obviously reduced when applied with ultrasonic vibration on the electrode, demonstrating the advantages of UAECDM over standard ECDM, which is consistent with the theoretical analysis in previous section.

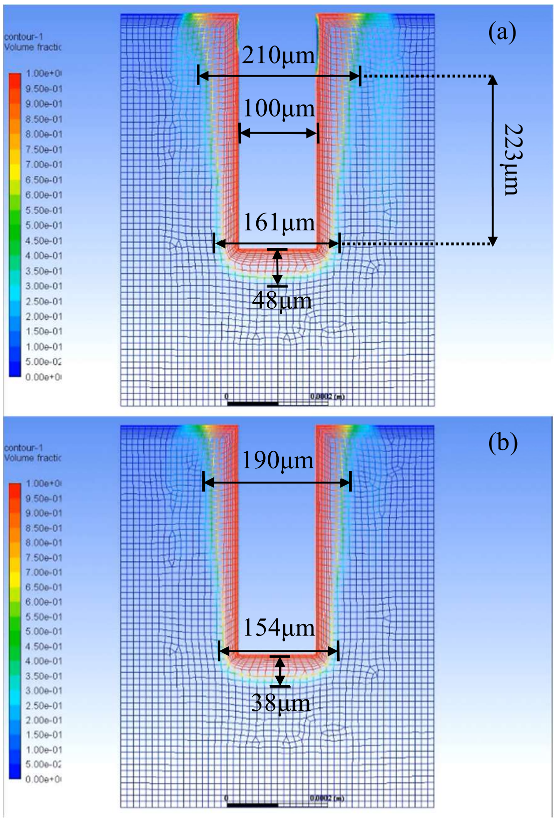

Fig. 4 Gas-liquid two-phase distribution. (a) ECDM; (b)UAECDM

III. Experiments and Discussion

In this chapter, experiments of ultrasonic vibration-assisted electrochemical discharge drilling on sheet glass is carried out. Machining parameters are listed in TABLE I. Through variable-controlling approach, the effects of ultrasonic vibration amplitude, pulse voltage and tool feed rate on machining process are investigated. Each trial on a single parameter is repeated at least three times for the reliability of experimental data. Based on comparative analysis, a set of optimized parameters are determined to implement a drilling process of array holes. Note that the tool electrode used here is a spiral electrode of Tungsten Carbide with 100μm diameter and the electrolyte is potassium hydroxide solution.

TABLE I
Machining Parameters

	Parameter	Value
Ultrasonic Wave	Vibration amplitude	0~10 (μm)
Power Supply	Pulse voltage	27~41 (V)
	Pulse frequency	1000~4500 (Hz)
	Duty factor	60~90 (%)
	Feed rate	0.3~2.0 (μm/s)

A. Effect of Vibration Amplitude on Hole Quality

The effect of ultrasonic vibration amplitude on the inlet diameter of the micro-holes is illustrated in Fig. 5. A vibration frequency of 26000HZ is used according to the natural frequency of the system, and the amplitude is adjusted by controlling the energy input of the ultrasonic vibration (0%, 25%, 50%, 75%, 100%). The average diameter of micro-holes decreases first and then increases as the ultrasonic vibration is amplified. The minimum value of hole diameter is 134.54μm, which appears as the amplitude of ultrasonic vibration reaches 7.5μm (75% of the maximum value), with a minimal standard deviation level, indicating that machining process is at the most stable state.

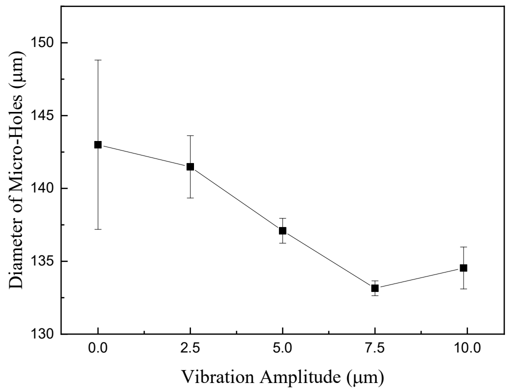

Fig. 5 Effect of Vibration Amplitude on the Diameter of Micro-holes.

B. Effect of Pulse Voltage on Hole Quality

As shown in Fig. 6, the average inlet diameter of micro-holes changes accordingly with the pulse voltage of power supply. As the pulse voltage increases, the characteristic size of micro-holes gradually gets larger. This is because the electrolysis reaction is enhanced when a higher voltage is applied, thus the formation of the gas film is quickened. Meanwhile, the average discharge energy per unit time Q increases, as in (3). Therefore, more material is melted away at the discharge area, as in (5). In other words, the material removal rate of the ECDM process is increased while tool feed rate still stays constant, resulting in a larger inlet diameter of the drilling hole.

In the experiment assisted with ultrasonic vibration, the inlet diameter of the micro-holes is generally smaller than that of standard ECDM. The reason is that in UAECDM, the coalescence of bubbles is refined. The thickness of gas film gets smaller, and its distribution along the electrode becomes more homogeneous, thus lowering the critical voltage required for the electrochemical discharge. As lower voltage is adopted for UAECDM, not only the characteristic size of micro-holes gets smaller, but the overall stability and accuracy of machining process is promoted with less thermal cracks around the inlet.

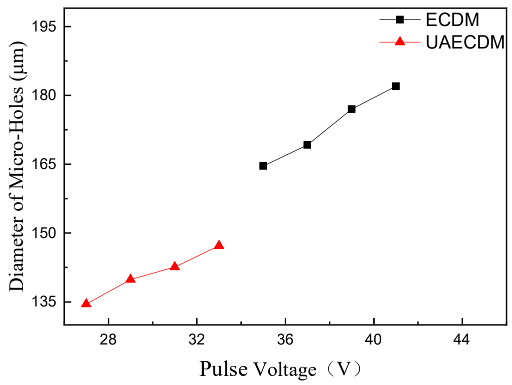

Fig. 6 Effect of Pulse Voltage on the Diameter of Micro-holes.

C. *Effect of Tool Feed Rate on Hole Quality*

As shown in Fig. 7, the average inlet diameter of micro-holes changes in counter with the feed rate of the tool electrode. When the same workpiece is machined at a larger feed rate, the drilling time becomes shorter. Repeated discharges at the inlet of the drilling hole is reduced. As a result, inlet diameter delines.

Compared with the standard ECAM, the average inlet diameter of micro-holes in UAECDM is generally smaller. The main cause is that, with the assistance of ultrasonic vibration, gas film becomes thinner, and critical voltage is declined significantly. For better accuracy and stability, a lower pulse voltage is adopted and the feed rate need to be reduced correspondingly. With smaller machining gap and energy input, hole diameter become thinner.

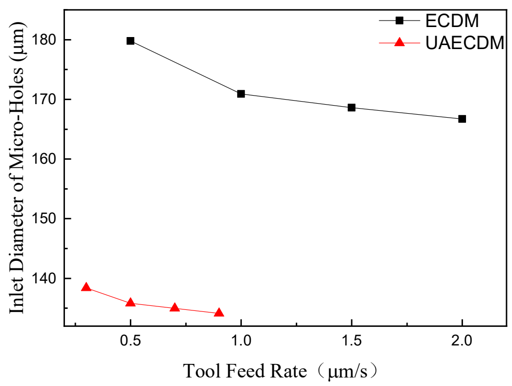

Fig. 7 Effect of Feed Rate on the Diameter of Micro-holes.

It is important that feed rate matches with the pulse voltage, otherwise defects are prone to appear. With a deficient pulse voltage and excessive feed rate, mechanical collision will occur which may cause tearing even mechanical collision; with excess pulse voltage and insufficient feed rate, there will be more thermal cracks around the inlet of the micro-hole and breakage at the outlet.

D. *Experimental Results*

According to the theoretical analysis and experiment results in the previous chapter, appropriate parameters are selected to carry out electrochemical discharge drilling. Two sets (for ECDM and UAECDM each) of 3×3 array holes were successfully fabricated on high quality sheet glass. Depicted in Fig. 8, the micro-holes drilled by standard ECDM have an inlet diameter of 172μm and an outlet diameter of 167μm.

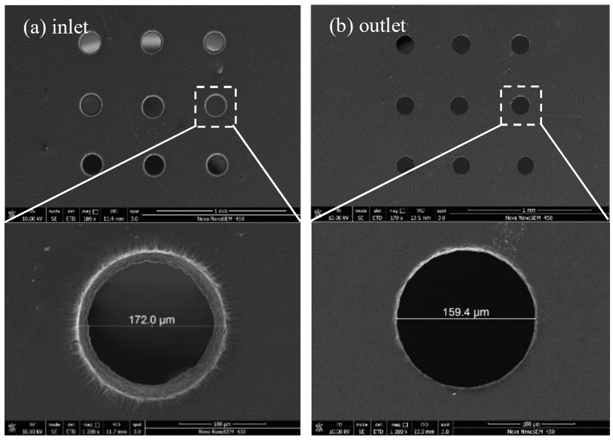

Fig. 8 Microporous array drilled by ECDM

Assisted with ultrasonic vibration, the diameter reaches down to 130.8μm at the inlet and 126.5μm at the outlet (Fig. 9). Compared with the standard ECDM, the characteristic size of the micro-holes is significantly reduced, and thermal crack around inlet is modified, and the outlet is rounded, proving that UAECDM has higher machining capability, reliability and repeatability.

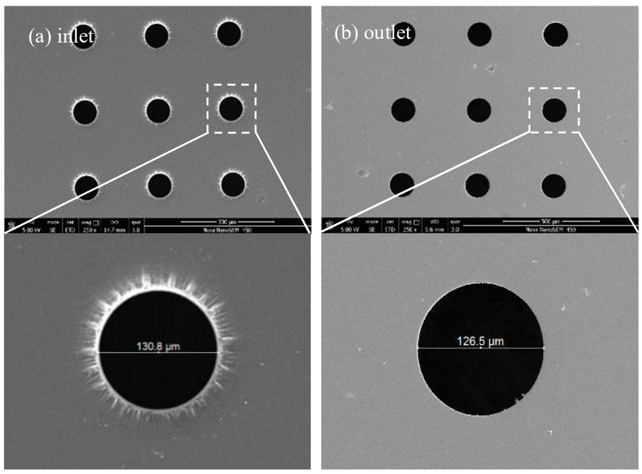

Fig. 9 microporous array drilled by UAECDM

IV. CONCLUSION

The present study established a finite element model to estimate the thickness of gas film in electrochemical discharge drilling. Experiments were conducted to demonstrate the advantages of the UAECDM over the standard ECDM. The influence of ultrasonic amplitude on the quality of micro-hole drilling was explored, and the optimum ultrasonic amplitude (7.5 micron) was obtained; the critical voltage (voltage from 35V to 27V, a 22.86% reduction) is significantly reduced by adding ultrasonic vibration assistance, and the machining accuracy (average diameter of micro-holes from 163.2 to 135.6μm, a 16.9% reduction) is improved, and the machining stability is optimized.

Experiments of electrochemical discharge drilling were carried out. With machining principles summarized, proper combination of parameters was found. Eventually, with selected parameters, 3 *3 array holes with less thermal crack area around the inlet and no breakage at the outlet was fabricated.

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