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Experimental Study on Ultrasonic Vibration assisted Electrochemical Grinding of Small Holes*

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Abstract - Electrochemical grinding, as a composite machining method, is currently widely used for drilling and milling of hard-to-machining materials. Based on the electrochemical grinding method, the ultrasonic vibration assists the hole enlargement process to improve the machining quality of small holes. In this paper, an experimental platform for ultrasonic assisted electrochemical grinding was set up, and a mathematical model for hole enlargement in ultrasonic assisted electrochemical grinding is established. The effects of ultrasonic vibration, electrical parameters and rotation speed of electrode on the machining quality of 304 stainless steel were studied.

Index Terms - Ultrasonic assisted; electrochemical grinding; 304 stainless steel; small hole machining.

I. INTRODUCTION

Electrochemical Grinding (ECG) technology is a composite machining technology that combines electrochemical and mechanical grinding. It belongs to the field of electrochemical machining. The technology was first proposed by American scholar G. F. Keeleric in 1952 and applied to the machining of cemented carbide tools [1]. In the process of electrochemical grinding, metal workpiece is mainly eroded by electrochemical reaction. Mechanical grinding assists the process by scraping the passive film on the surface of anode workpiece to accelerate electrochemical reaction.

Ultrasound assisted electrochemical machining (UAECM) technology is a composite machining technology that combines ultrasonic vibration and electrochemical machining (ECM). In order to ensure the precision requirements of electrochemical machining, micro-electrochemical machining is generally carried out at a low current density. The passivation film formed on the surface of the workpiece hinders the continuation of electrochemical reaction when the passivation zone of the workpiece metal material is at a lower current density [2]. Ultrasound assisted electrochemical machining technology can optimize the environment of ECM by adding ultrasonic vibration in the machining area, effectively removing the passive film on the workpiece surface and promoting the circulation of electrolyte and the discharge of electrolyte products by using the cavitation effect of ultrasonic vibration, so as to improve the machining efficiency and stability of ECM [3].

Ultrasonic Assisted Electrochemical Grinding (UAECG) technology combines ultrasonic vibration on the basis of electrochemical grinding, and uses the negative pressure cavitation of ultrasonic vibration to promote the gas and other electrolysis products in the machining area. It discharges and promotes the circulation renewal of the electrolyte and makes the flow field of the electrolyte more uniform, thereby optimizing the effect of electrochemical machining in electrochemical grinding to improve machining efficiency, repeated machining precision and surface machining quality. In addition, the introduction of ultrasonic vibration into the electrochemical grinding can also effectively avoid or reduce the machining short circuit in the electrochemical grinding. In 2017, Zhao Bo [4] of Henan University of Technology proposed ultrasonic assisted electrochemical on-line dressing grinding technology for the machining of nanocomposite ceramic materials, the research shows that the material removal rate increases significantly with the increase of cutting depth and axial feed rate. In 2018, Sisi Li [5-7] of Akita Prefectural University in Japan proposed ultrasonic assisted electrochemical grinding technology and ultrasonic assisted pulse electro-grinding technology and conducted experiments, the results show that the normal stress and tangential stress in ultrasonic assisted electrochemical grinding are reduced by 57% and 56% respectively compared with traditional grinding. In 2018, Indian scholar H. Singh [8] et al. put forward the technology of ultrasonic vibration assisted electrochemical honing for bevel gear machining, through experiments, it is found that the average surface roughness and maximum surface roughness of bevel gear can be optimized by 91.04% and 71.98% by ultrasonic assisted electrochemical honing. In 2019, Wenjie Zhai [9-11] et al. of Harbin Institute of Technology conducted ultrasonic assisted electrochemical mechanical polishing test and simulation analysis on silicon carbide materials, and conducted orthogonal comparison experiments on ultrasonic vibration, DC voltage, abrasive suspension and other factors, the results show that the surface machining quality is the best when using semi-fixed abrasive polishing disc, but the material removal rate is lower; Fenton reaction solution has the best effect on improving the material removal rate of the specimen; when the specimen retaining ring is applied with ultrasonic vibration, the material removal rate increased by 91.7%.

II. PROCESSING PRINCIPLE AND TEST PLATFORM

A. Machining Principle

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In the ultrasonic assisted electrochemical grinding process of this paper, the effect of the tool electrode on the workpiece is mainly divided into electrochemical machining, electrochemical grinding and secondary electrochemical machining. In the area of electrochemical machining and secondary electrochemical machining, because of the large gap between electrode and the passivation layer formed on the workpiece surface cannot be scraped by mechanical grinding, the continuation of electrochemical machining is hindered, as a result, the current density is low and the material removal is slow, so the material removal mainly occurs in the electrochemical grinding area.

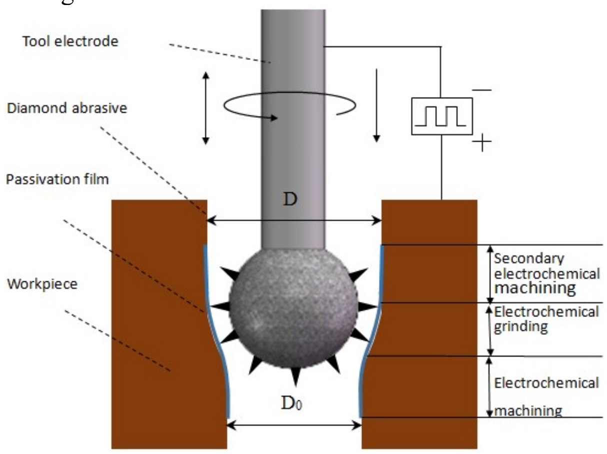


Fig. 1 Schematic diagram of ultrasonic assisted electrochemical grinding

As shown in Fig. (2), in the hole enlargement process by ultrasonic assisted electrochemical grinding, the machining gap S_0 of workpiece surface at Q Area（Q Area is the current machining area）can be approximately expressed as follows:

$$S_0 = \overline{S_0} - A\cos(\frac{2\pi}{T}t - \varphi)\cos\theta \qquad (1)$$

In Eq. (1), S_0 is the machining gap of workpiece surface at Q Area, $\overline{S_0}$ is the balanced machining gap of the workpiece surface at the Q Area when machining is stable; A is the ultrasonic vibration amplitude of the tool electrode in the vertical direction; T is the ultrasonic vibration period; φ is the initial phase; t is the machining time; θ is the angle between the ball center of tool electrode and the connecting line of Q Area and the vertical axis, it mainly related to the ball electrode diameter d, pre-hole diameter D_0, electrical machining parameters and electrolyte conditions. It can be obtained by observing the wear marks on the ball head of the tool electrode, which is generally 58°-59° in this paper.

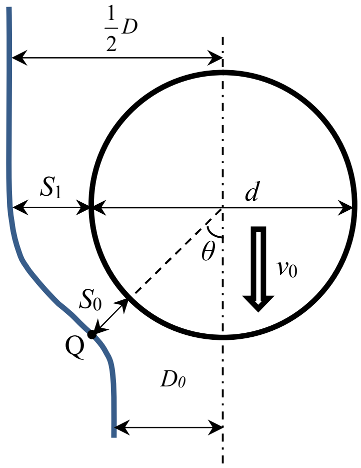


Fig. 2 Geometry diagram of ultrasonic assisted electrochemical grinding machining gap

Therefore, according to the actual machining conditions of this paper, when using the high-frequency pulse power supply for ultrasonic assisted electrochemical grinding, Eq. (2) can be obtained:

$$V = \eta\omega i\Delta S t = \eta\omega\Delta S\frac{t}{t_p}\int_{t_1}^{t_2} i dt = \eta\omega\kappa\Delta S\frac{t}{t_p}\int_{t_1}^{t_2}\frac{U}{S_0}dt \quad (2)$$

In Eq. (2), V is the workpiece erosion volume, η is the current efficiency, ω is the volume electrochemical equivalent, i is the current density, ΔS is the area of Q Area, t_2 and t_1 are the upper and lower limits of the effective machining range of a single pulse period, t is the machining time, t_p is the power pulse period, κ is the electrolyte conductivity, both the machining potential U and the machining gap S_0 are functions of time.

When the machining is in a stable state, the feed rateof the tool electrode is matched with the electrochemical erosion rate of the surface of the workpiece, and the machining gap is basically stable. Therefore, the normal electrochemical erosion rate of the workpiece surface at Q Area v can be expressed as:

$$v = v_0\cos\theta = \frac{\eta\omega}{t_p}\int_{t_1}^{t_2} i dt = \frac{\eta\omega\kappa}{t_p}\int_{t_1}^{t_2}\frac{U}{S_0}dt \qquad (3)$$

In Eq. (3), v_0 is the tool electrode feed rate.

In the paper, since the ultrasonic vibration amplitude of the tool electrode A is only about 5μm, thus $A\cos\theta \ll \overline{S_0}$ when the machining is stable, S_0 is approximated by $\overline{S_0}$. And $\overline{S_0}$ can be gained from Eq. (3).

$$\overline{S_0} = \frac{\eta\omega\kappa U'}{v_0\cos\theta} \qquad (4)$$

In Eq. (4), U' is the equivalent potential.

In the electrochemical grinding machining area, there are:

$$\frac{dS}{dt} = \frac{\eta\omega\kappa U'}{S} \qquad (5)$$

Integral Eq. (5) to obtain:

$$\int SdS = \int \eta\omega\kappa U' dt \tag{6}$$

From the initial conditions $t = 0$ and $S = \overline{S_0}$, it is concluded that:

$$S = \sqrt{2\eta\omega\kappa U' t + \overline{S_0}^2} \tag{7}$$

Therefore, the balance machining gap $\overline{S_1}$ in the widest area of the ball electrode is:

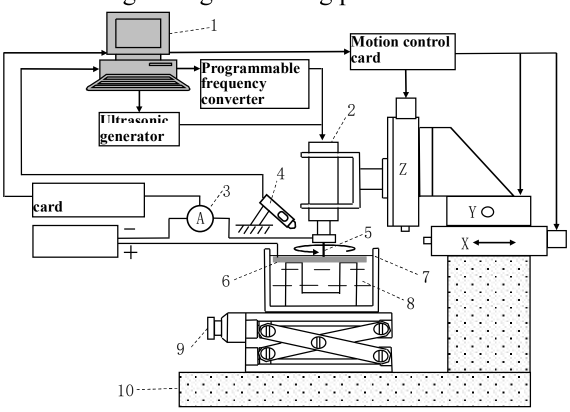
$$\overline{S_1} = S_1 = \sqrt{2\eta\omega\kappa U' \frac{\left(\overline{S_0} + d\right)\cos\theta}{v_0} + \overline{S_0}^2} \tag{8}$$

In the non-electrochemical grinding machining area, since the electrode gap is too large and the passivation film formed on the surface of the workpiece cannot be removed by mechanical grinding, the electrochemical machining is hindered, resulting in a small current density, and the removal rate of the workpiece by electrochemical machining is slow. Ignoring the effect of secondary electrolysis on small holes, the diameter of small holes machined by ultrasonic assisted electrochemical grinding can be expressed as follows:

$$D = d + 2\overline{S_1} = d + 2\sqrt{2\left(\frac{\eta\omega\kappa U'}{v_0}\right)^2 + \left(\frac{\eta\omega\kappa U'}{v_0\cos\theta}\right)^2 + \frac{2\eta\omega\kappa U' d\cos\theta}{v_0}} \tag{9}$$

B. *Experimental Platform*

In order to ensure the machining accuracy and stability of ultrasonic assisted electrochemical grinding, the experimental platform should have excellent geometric accuracy, motion accuracy, transmission accuracy and strong overall stiffness. The ultrasonic assisted electrochemical grinding machining platform built in this paper mainly includes three-axis linkage machine bed, high-frequency pulse electrolysis machining power source, ultrasonic generator, ultrasonic electric spindle, motion control system, measurement and control system, working electrode and clamping device thereof. Manual lifting platform and electrolyte tank, etc. Fig. (3) is a schematic diagram of the structure of the ultrasonic assisted electrochemical grinding machining platform.



1、 computer, 2、 ultrasonic motorized spindle of machine tool, 3、 Hall current sensor, 4、 CCD visual monitoring, 5、 tool electrode, 6, workpiece、7、electrolyte tank, 8、electrolyte, 9、manual lifting platform, 10、marble platform.

Fig. 3 Schematic diagram of ultrasonic assisted electrochemical grinding machining platform

The ultrasonic electric spindle machining system is the core component of the test platform, which mainly includes the ultrasonic generator, the ultrasonic electric spindle, the electric spindle circulating cooling module and the tool electrode clamping module, etc. It can make the tool electrodes to vibrate along the axis of the spindle while rotating at high speed. The ultrasonic motorized spindle used in this test platform is a traditional motorized spindle with an ultrasonic module on the spindle. Through the piezoelectric inverse effect of the transducer, the frequency electrical signal is converted into high-frequency ultrasonic vibration. Then the amplitude of the ultrasonic vibration is adjusted by the horn and the ultrasonic energy is concentrated on a smaller area.

The machining control system of the experimental platform is composed of hardware and software parts. It can realize three-axis linkage, machining three-dimensional shape of workpiece, and has high positioning accuracy and reciprocating positioning accuracy. Because of the need for real-time monitoring, the experimental platform uses a detection system composed of ammeter, Hall current sensor, oscilloscope, data acquisition card and CCD visual monitoring. In order to ensure the measurement accuracy, optical microscope, scanning electron microscope and white light interferometer are mainly used as measuring instruments because of the need to measure the diameter of the hole and the surface roughness of the inner wall.

III. Experiments And Discussion

A. *Experiments Arrangement*

Machining of small holes is carried out in two steps: (1) ultrasonic assisted electrochemical drilling for pre-holes machining; (2) ultrasonic-assisted electrochemical grinding for hole enlargement. Ultrasonic assisted electrochemical drilling for pre-hole and ultrasonic assisted electrochemical grinding for hole enlargement are performed on the same experimental platform. In order to avoid positioning errors, on-line tool changing operation is carried out after pre-hole machining. At the same time, the machining power and electrolyte are replaced and the machining parameters are reset for hole enlargement machining.

By means of ultrasonic assisted electrochemical drilling, the pre-hole with good repetitive machining accuracy was machined on 304 stainless steel sheet (500μm thickness) by using spiral electrodes (800μm diameter), which meets the dimension accuracy requirement of ultrasonic assisted electrochemical grinding. The pre-hole machining parameters are shown in Table 1, and the diameter of pre-hole is 0.87±0.01 mm.

TABLE I

Pre-hole machining parameters

Peak voltage	Pulse period	Pulse Width	Electrolyte	Electrode speed	Feed rate	Ultrasonic amplitude
7V	10μs	2.5μs	10%$NaNO_3$	6000r/min	0.4μm/s	5μm

B. *Effect of ultrasonic vibration on machining quality*

In order to explore the effect of different ultrasonic vibration amplitude on the surface quality of the inner wall of the small hole under the condition of reasonable matching between electrochemical machining and mechanical grinding, a series of comparative tests was carried out, as shown in Fig. (3). The experimental parameters are as follows, machining voltage: 3.3V, tool electrode rotary speed: 12000r/min, mesh of abrasive particles on tool electrodes: 1200#, ultrasonic vibration amplitude variation range 0-10μm. When the amplitude is 0, no ultrasonic vibration is applied, and the frequency of the ultrasonic vibration is a resonance frequency obtained by sweep frequency of the tool electrode, and is generally at 24.9-25.1 kHz.

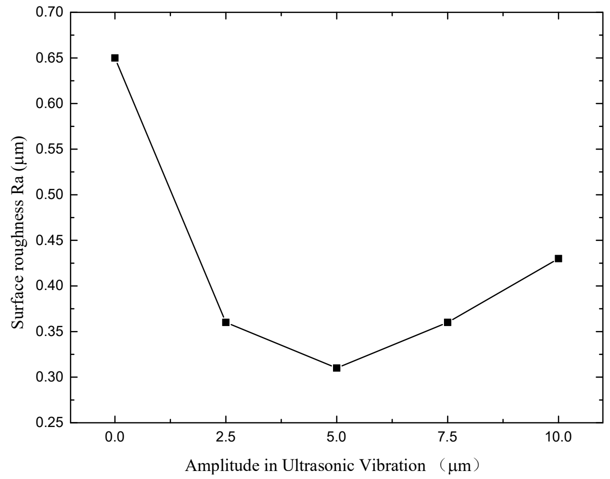


Fig. 4 Surface roughness of the pore wall under different ultrasonic vibration amplitudes

As can be seen from Fig. (4), the ultrasonic vibration applied to the tool electrode can significantly improve the surface quality of the small hole compared with the electrochemical grinding without ultrasonic vibration.

C. Effect of Electrical Machining Parameters on Machining Quality

Under the conditions of different electrical machining parameters, in order to achieve precise matching between electrochemical machining and mechanical grinding, the feed rate of the tool electrode should be adjusted accordingly to achieve high machining accuracy and surface quality. A series of comparative experiments were conducted to investigate the optimal feed rate of tool electrodes for different peak voltage and duty cycle conditions. The experimental parameters are as follows, power pulse frequency: 50kHz, tool electrode ultrasonic vibration amplitude: 5μm, mesh of abrasive particles on tool electrodes: 1200#, tool electrode rotary speed: 12000r/min, peak voltage variation range: 3-5V, duty cycle range of variation: 0.6-1, when the duty ratio is 1, the machining power supply is DC regulated. The optimal feed rate of the tool electrode under different electrical machining parameters is shown in Fig. (5).

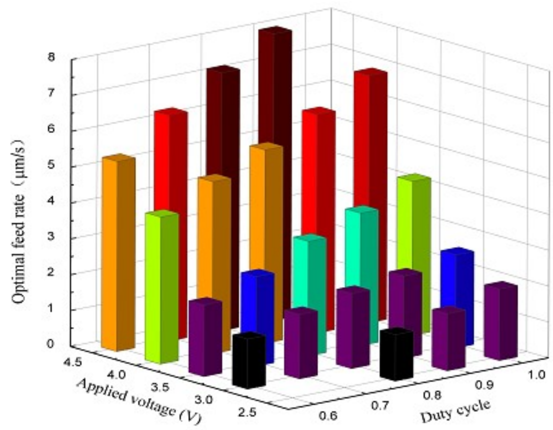


Fig. 5 Optimal feed rate of tool electrodes under different electrical machining parameters

As can be seen from Figure 5, the optimum feed rate of the tool electrode increases as the machining voltage and duty cycle increase.

In order to investigate the influence of machining voltage and workpiece feed rate on the precision of ultrasonic assisted electrochemical grinding process, the experiment on the small holes' diameter of different machining voltage and feed rate was carried out. As shown in Fig. (5). The experimental parameters are as follows, the ultrasonic vibration amplitude of the tool electrode: 5μm, mesh of abrasive particles on tool electrodes: 1200#, the rotary speed of the tool electrode: 12000r/min, and the range of the feed rate: 2.5-4.5μm/s.

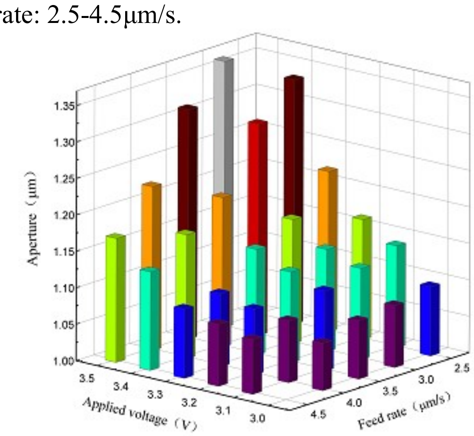


Fig. 6 Effect of machining voltage and feed rate on the small holes' diameter

The test results show that in the ultrasonic assisted electrochemical grinding for hole enlargement, the small holes' diameter increases with the increase of the machining voltage, and decreases with the increase of the feed rate of the tool electrode.

D. Effect of electrode rotation speed on machining quality

In order to explore the effect of tool electrode rotation speed on machining efficiency, a series of tests were carried out in 8000-16000r/min rotation speed, as shown in Fig. (7). The test parameters are as follows, machining voltage: 3.3V, ultrasonic vibration amplitude of the tool electrode: 5μm, mesh of abrasive particles on tool electrodes: 1200#.

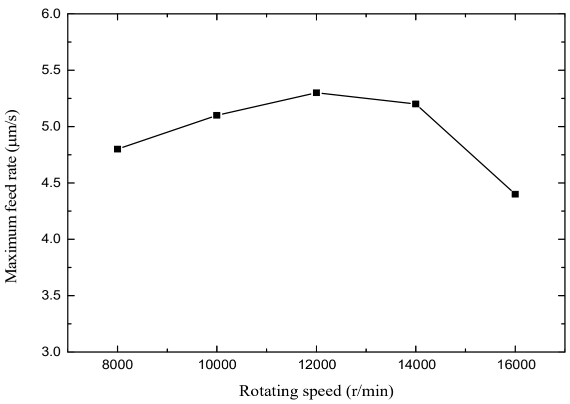
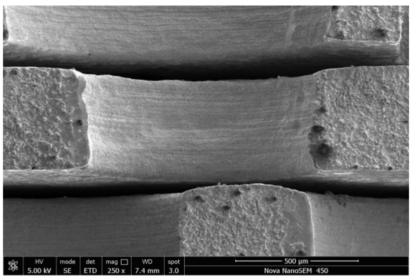


Fig. 7 Maximum feed rate of tool electrode at different speeds

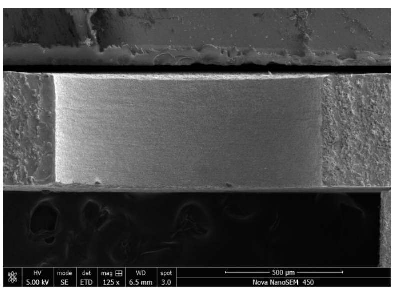
It can be seen from Fig. (7) that the maximum feed rate of the tool electrode increases at first, and then decreases with the increase of the electrode rotation speed. When the electrode rotation speed is 12000r/min, the tool electrode can obtain the maximum feed rate and the machining efficiency is the highest.

E. Experimental results

It can be seen from Fig. (8), the inner wall's morphology of the small hole before and after the ultrasonic assisted electrochemical grinding. Compared with the pre-hole, the wall of the small hole machined by ultrasonic assisted electrochemical grinding is obviously steeper, and the surface quality is improved significantly. By adjusting and matching the machining parameters such as electrical machining parameters, feed rate, electrode speed, ultrasonic vibration amplitude and diamond abrasive particle size, Finally, small holes with a diameter of 1.1+0.01mm, a surface roughness of Ra=0.31μm and a taper of less than 0.6 degrees can be obtained, as shown in Fig. (8b). The optimized machining parameters are as follows: machining voltage: 3.3V, feed rate: 4μm/s, electrode rotation speed: 12000r/min, ultrasonic vibration amplitude: 5μm, mesh of abrasive particles on tool electrodes: 1200#.



(a) Pre-hole's inner wall after UAECM



(b) Final-hole's inner wall after UAECG

Fig. 8 Pre-hole's inner wall after UAECM and final-hole's inner wall after UAECG

IV. Conclusions

Ultrasonic vibration assisted electrochemical grinding of small holes can effectively improve the machining accuracy and surface quality of the hole, and can effectively improve the machining efficiency under the reasonable matching with the electrical machining parameters. Especially, the surface roughness of the final hole obtained by ultrasonic assisted electrochemical grinding can be decreased from 1.51μm to 0.31μm by reasonable selection of electrical parameters, and repeated machining accuracy is better than 10μm.

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