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Short Communication

Experimental Study on Ultrasonic Assisted Electrochemical Micro-Machining of Micro-Dimple Array Structure

Ge Yongcheng, Chen wangwang, Zhu Yongwei[*]

College of Mechanical Engineering, Yangzhou University, Yangzhou, China
E-mail: ywzhu@yzu.edu.cn

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Micro-dimple array structure is a widely accepted approach for friction reduction between mechanical components. At present, there are many methods to form micro-dimple arrays on metal surface, but how to form high-quality and low-cost micro-dimple arrays is still a challenge. Ultrasonic assisted electrochemical micromachining (UAEMM) is considered to be a promising machining technology due to its advantages of high machining efficiency, high machining accuracy and no limitation of mechanical properties of work-piece materials. In this paper, the UAEMM technology is used to process the micro-dimple array structure on the metal surface. The experimental results show that the voltage is helpful to improve the machining depth, but too much voltage will also reduce the machining accuracy, and the optimal choice of voltage parameter is 2-3V voltage. Compared with DC power, pulse power used in UAEMM process can achieve better machining performance. The machining accuracy and surface quality can be further improved by modulating the synchronous relationship between ultrasonic and pulse. Finally, a better micro pit array structure was prepared according to the optimized process parameters, and its friction performance was tested. The results show that under the same conditions, the surface wear of micro-dimple array surface is less than one third of that of the plane surface.

Keywords: microdimples; ultrasonic assisted electrochemical micro-machining; friction properties; micro-structures manufacturing

1. INTRODUCTION

In recent years, the application of surface texture technology, such as micro-dimples, micro grooves, and micro-pillars, represents the advanced technology of improving functionality and performance [1,2]. Many studies have shown that, due to its good oil-storage properties, surface texturing has become a popular method in tribology to improve the friction and lubrication properties of various mechanical components [3,4]. Among the various surface textures available, the use of micro-dimple arrays to improve tribological properties is particularly effective. Recently, a number of practical methods of machining micro-dimple arrays have been reported, including conventional machining, such as micro-cutting [5] and micro-milling [6], as well as non-traditional machining methods, such as electrical discharge micro-machining [7], laser beam micromachining [8], abrasive jet micromachining [9], chemical-micro-etching [10], electrochemical micromachining [11], and ultrasonic assisted electrochemical micro-machining [12].

In the above processing methods, ultrasonically assisted electrochemical micro-machining is regarded as a promising processing technology due to its advantages of high processing efficiency, high processing accuracy, no restriction on the mechanical properties of the workpiece material, and no heat-affected layer. Ruszaj *et al*. confirmed that the surface quality of ultrasonically assisted electrochemical machining (ECM) is better than that of pulse ECM, and the surface quality of machined samples can be further improved with the addition of abrasive powder [13]. Natsu *et al*. conducted multi-dimensional ultrasonically assisted ECM experiments, and verified that the effect of composite vibration on the replication accuracy and machining speed is more favorable than the longitudinal and transverse vibration in ECM [14]. Wang *et al*. conducted research on ultrasonic-assisted electrochemical micromachining technology, and they confirmed in experiments that ultrasonic disturbance is beneficial to product elimination and has significant advantages in improving processing efficiency and stability [15]. Yang *et al*. conducted the experiment of electrochemical micro-machining with a semi-cylindrical tool. By adding ultrasonic vibration on the semi-cylindrical tool, the machining efficiency was much higher than that of electrochemical micro-machining [16]. Wang *et al*. conducted research on radial ultrasonic rolling electrochemical micromachining technology, confirmed that it is feasible to prepare micro-dimples by ultrasonic rolling electrochemical micromachining technology, and pointed out that the existence of ultrasonic vibration in the inter-electrode gap is the main reason for the improvement of machining performance [17].

The focus of this study is the experimental study of ultrasonically assisted electrochemical micro-machining of micro-dimple array structures, and the influences of applied voltage, power supply mode, and coupling relationship of ultrasound and pulses on the micro-dimple array structure is experimentally investigated. Finally, the friction properties of the micro-dimple arrays surface machined in the work reported in this study was compared with those of the plane surface

2. EXPERIMENTAL PROCEDURE

2.1 Processing principle

The principle of ultrasonic assisted electrochemical micro-machining (UAEMM) is shown in Figure 1. The cathode tool performs ultrasonic vibration, so the gap between the cathode tool and the work-piece changes periodically, and the minimum gap is about the maximum diameter of a single abrasive particle. The presence of fine abrasive particles maintains a small gap between the cathode and the work-piece, which can effectively avoid short circuit. Due to the combined effect of small current and passive electrolyte, a passivation film with extremely thin thickness and much lower strength than the base material is produced on the surface of the work-piece. The shock wave and "negative pressure cavitation" generated by the ultrasonic high-frequency vibration function can easily remove the passivation film and expel the processed products out of the machining gap in time, which improves and strengthens the electrochemical machining effect and makes the machining process stable and sustainable.

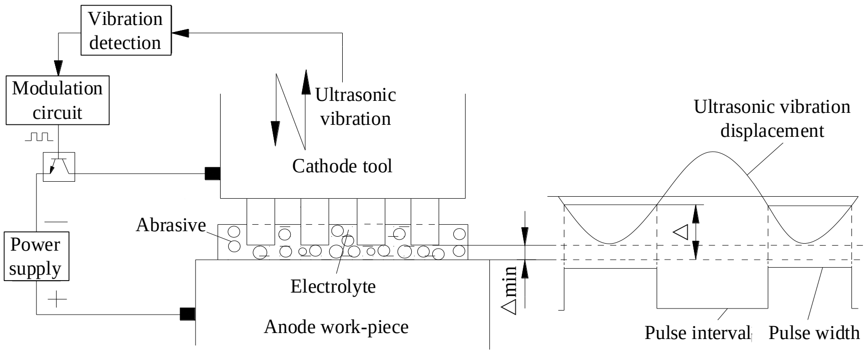


Figure 1. Principe of ultrasonic assisted electrochemical micro-machining.

2.2 Experimental set-up and procedures

Figure 2 is a schematic of the experimental setup. A laser sensor is used to detect ultrasonic amplitude and processing depth. The current, voltage, and temperature sensors detect the corresponding machining signals and transmit them to the data-acquisition card, and they are then converted into digital signals and sent to the control computer. The control computer reads the machining parameters and controls them in real time. The ultrasonic frequency range is 20 ± 4 kHz, and the ultrasonic power is continuously adjustable from 0 to 150 W. A Maglev table is used to maintain constant contact pressure between the cathode and workpiece. The cathode tool for the experiments was made of SS304 stainless steel with the different structures of a single micro-cylinder electrode, equidistant rib electrode, and micro-cylinder array electrode.

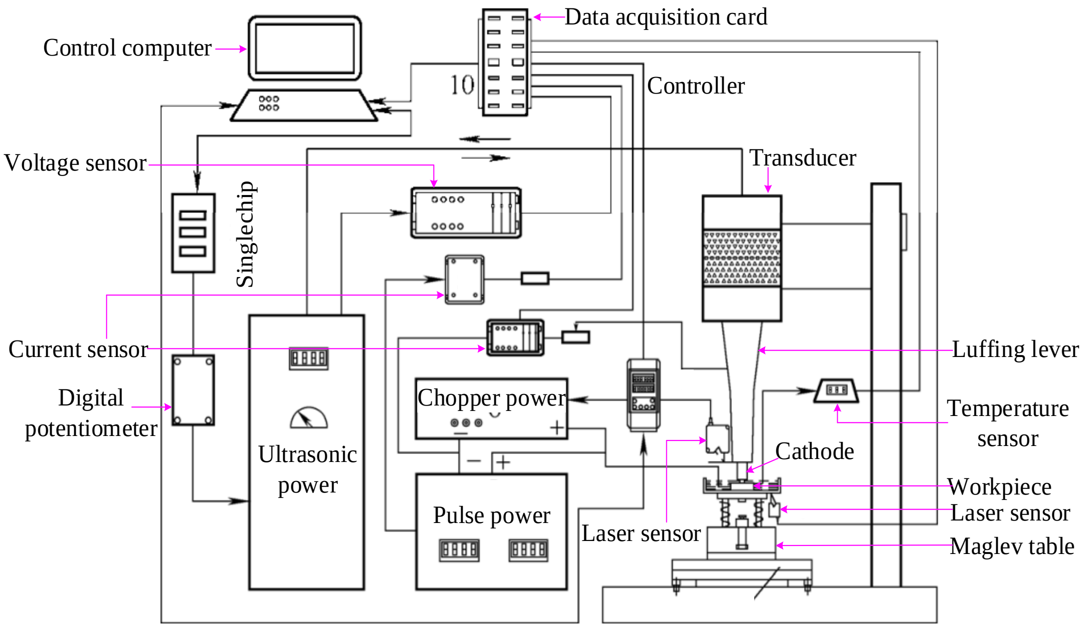


Figure 2. Schematic of ultrasonic assisted electrochemical micro-machining setup

3. RESULTS AND DISCUSSIONS

3.1 Influence of voltage parameters on machining performance

Figure 3 shows the morphology of machined samples under different voltage parameters. The tool electrode diameter is φ 0.75 mm, the abrasive is boron carbide W10, the static pressure is 0.60 N, the electrolyte is 5% $NaNO_3$ solution, and the machining time is 2 min. The depth of the micro-dimple was detected, and the relationship between the machined depth and applied voltage is shown in Figure 4.

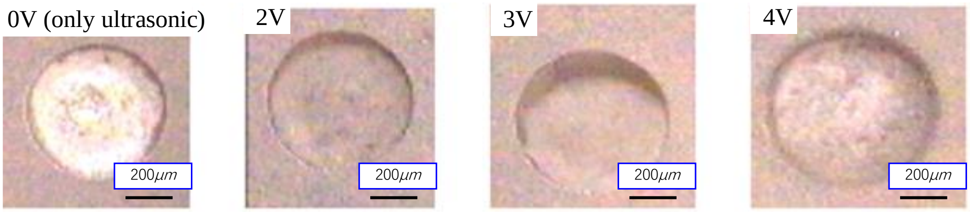


Figure 3. The morphology of machined samples under different voltage parameters.

It can be seen that, compared with the single ultrasonic method, UAEMM can obtain a greater machining depth. This illustrates that the method of UAEMM can effectively improve the low efficiency of single ultrasonic machining [18]. UAEMM under different voltages has also been studied, and the results show that when the voltage is 4 V, the depth of micro-dimple is the largest, but the diameter of the micro-dimple is also the largest, which shows that the effect of electrochemical dissolution is too strong and the machining accuracy is also reduced. When the voltage is 2 or 3 V, the machining accuracy and surface quality are relatively good. This illustrates that increasing the voltage is helpful to improve the machining depth [17,19], but too much voltage will also reduce the machining accuracy.

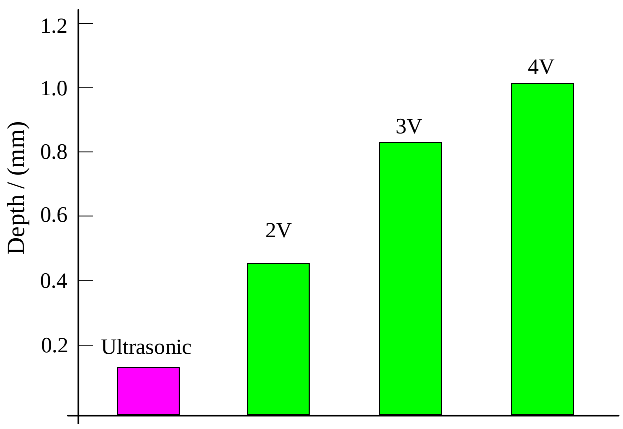
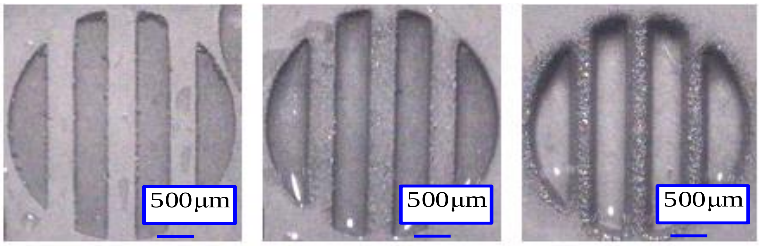


Figure 4. Variation of machined depth with different applied voltage

To further illustrate the influence of applied voltage on machining accuracy, in the work reported herein a specially designed tool electrode with equal width rib was used to conduct UAEMM experiments; the results are shown in Figure 5. It can be seen that under the voltage parameter of 3 V, a good equidistant rib size is obtained, and the rib-width accuracy can reach ±0.01 mm. When the voltage is 4 V, the surface of the equidistant ribs becomes black. When the voltage is 5 V, the sharp contour of the equidistant ribs has disappeared, and the width of the equidistant ribs also becomes significantly smaller. Therefore, to obtain better machining accuracy and surface quality, a voltage of 2–3 V is optimally selected.



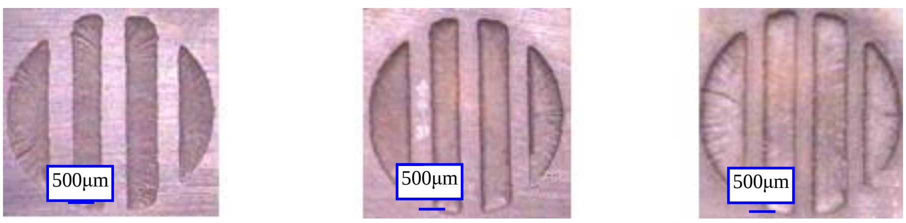
(a) 3 V (b) 4V (c) 5V

Figure 5. The morphology of machined equidistant ribs under different voltage parameters.

3.2 Influence of direct current and pulse current on machining performance

To obtain better machining accuracy, the UAEMM experiments were conducted using DC power and pulse power separately at this stage, and the machining results are shown in Figures 6 and 7.

Figure 6(a) shows an ultrasonically machined sample in which the contour of the equidistant ribs is sharp, but the depth is shallow. Figure 6(b) shows a sample processed by pulse power. The equidistance ribs have a sharp profile and uniform width, and the flow pattern at the bottom is also improved significantly. Figure 6(c) shows a sample machined by DC power in which the processing depth is improved, but the equidistant rib width is narrowed and the flow pattern at the bottom is obvious. This can be attributed to the fact that the products in the machining gap cannot be eliminated in time, resulting in the deterioration of the flow field in the machining gap [20]. Figure 7 shows the slot width between ribs after machining, which can be used to measure machining accuracy. It can be seen that the slot width is the largest when DC power is applied and the smallest when pulse power is applied. Therefore, it can be concluded that the use of pulse power in the UAEMM process can achieve better machining performance.



(a) 0V (only ultrasonic) (b) 2V pulse (c) 2V DC

Figure 6. The morphology of machined equidistant ribs under different machining conditions.

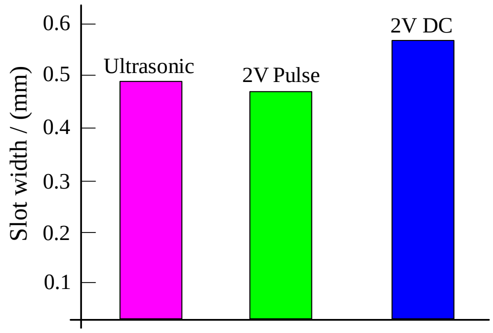


Figure 7. The slot width of machined equidistant ribs under different machining conditions.

3.3 Influence of the coupling relationship of ultrasound and pulse on the machining performance

In this stage, the UAEMM experiments in different forms were conducted by adjusting the coupling relationship between ultrasound and pulse. The electrolyte was 5% $NaNO_3$ solution, the applied voltage was 3 V, the machining time was 3 min, and the tool electrode was a micro-cylinder array electrode with a diameter of 0.5 mm. The morphology of machined micro-dimple array structures is shown in Figure 8. It can be seen that compared with the ultrasonic pulse electrochemical micromachining (UPEMM), the shape and size of micro-dimple array structures machined by ultrasonic synchronous pulse electrochemical micromachining (USPEMM) are more uniform, and the surface quality is also significantly improved. Therefore, it can be concluded that the use of USPEMM can give full play to the role of ultrasonic machining and electrochemical machining, and further enhance the advantages of ultrasonically assisted electrochemical machining [21].

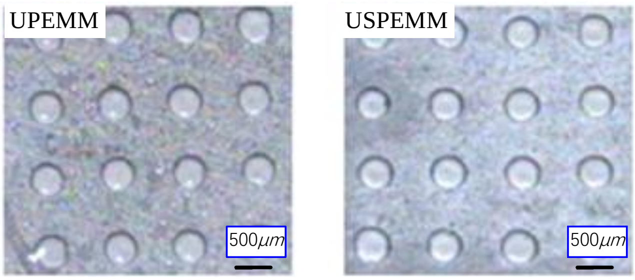


Figure 8. The morphology of machined micro-dimple array structures

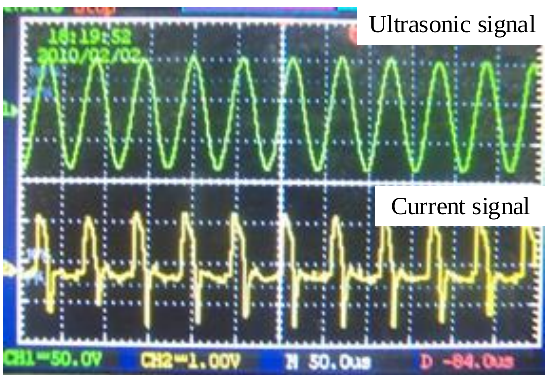


Figure 9. The parameter signals of ultrasonic and pulse during the machining process of USPEMM

The ultrasonic and pulse signal parameters during the USPEMM machining process are shown in Figure 9. It can be concluded that the USPEMM method is more suitable for micro-dimple array structures.

3.4 Comparison of friction properties of machined specimens

The frictional properties of the micro-dimple array structure surface and plane surface are compared in this stage, and the micro-dimple diameter on the micro-dimple array structures surface is 0.5 mm. The results show that the friction factor decreases from 0.12 of the plane surface to 0.11 of the micro-dimple array structure surface under the same parameters as the loading force of 0.98 N and low-concentration oil dripping on the test surface. The reason may be that the micro-dimple array structure surface is convenient for storing lubricating oil, and a stable fluid lubricating film is formed between the friction surfaces.

The surface wear is shown in Figure 10. It can be seen that the surface wear of micro-dimple array structures is approximately 0.003 mm, the surface wear of the plane is as high as 0.010 mm, and the difference between the two is greater than 3-fold. This indicates that the micro-dimple array structures machined by USPEMM can effectively improve friction performance.

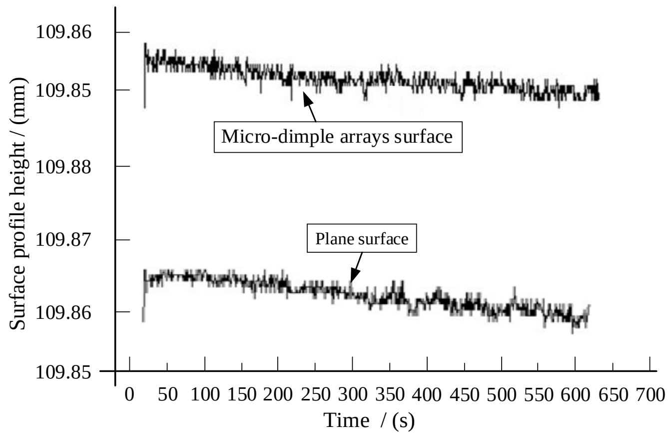


Figure 10. variation of surface wear with time

4. CONCLUSION

In this study, micro-dimple array structure was studied experimentally in detail by ultrasonic assisted electrochemical micro-machining (UAEMM) method. The conclusions can be summarized as follows:

(1) Experiments were performed and the results show that the voltage is helpful to improve the machining depth, but too much voltage will also reduce the machining accuracy.

(2) Compared with DC power, pulse power used in UAEMM process can achieve better machining performance. And the machining accuracy and surface quality can be further improved by modulating the synchronous relationship between ultrasonic and pulse.

(3) Compared with plane surface, the micro-dimple array structure machined in this paper can has better friction performance.

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