Machining Removal Rate and Worn-Out for the Mesoscale Mold of Tungsten Carbide through Rotary Ultrasonic-Assisted EDM Milling

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Abstract

This paper reports the effects of a rotary ultrasonic-assisted EDM (RU-EDM) with an ultrasonic spindle of 24 kHz frequency to retrofit the EDM milling for fabrication of small molds insert at the mesoscale level. Comparison investigation includes the ultrasonic vibration effects, revolution speed, pulse-trains, removal rate, and tool wear rate for tungsten carbide molds. The fundamental studies of the pulse-trains status, gas bubble morphology and its effects on debris expelling efficiency are discussed through a transparent observation window. Experiment results reveal that RU-EDM milling is superior to conventional EDM milling in both of the removal rate and the contouring accuracy for mesoscale molds because of less tool wear. Worn-out of tooltip is also explained from the corresponding EDM pulse characteristics with or without the assistance of rotary ultrasonic vibration.
Keywords: EDM, Rotary Ultrasonic, EDM milling, Mesoscale Mold, Tungsten Carbide.

1. Introduction

EDM (Electric Discharge Machining) is a dominant popular process to overcome difficult-to-cut material and the fabricating processes of small or mesoscale precision mold. In the past, hybrid processes with ultrasonic vibration-assisted EDM (UA-EDM) and rotary ultrasonic-assisted one (RU-EDM) were reported as effective and popular methods to improve machining efficiency. In an earlier report of Ghoreishi et, al. [1], it was found that tool electrode rotation increases MRR and tool wear simultaneously, vibro-rotary EDM can improve 35% MRR by vibration tool under low frequency, and even improve 100% over the simply rotary tool EDM process (RA-EDM).

The recent reports on the effects of the vibration frequency and amplitude of the tool electrode on the removal and the dielectric flow in UA-EDM were conducted numerically in papers [2-3]. Effect of flow fields and bubbles movement to debris expulsion by a direct driven linear motor was also reported in the recent experiments [4-5]. Although some studies provided a simulation of bubble movement in the consecutive-pulse discharge of EDM [6], suggesting helpful explanation, and the fundamental heat flux effect of massive random multiple discharges of EDM is also revealed in these years [7]. But the fundamental issues on the discharging atmosphere are not comprehensively explained yet.

However, during observation of the bubble motion of conventional deep cavity EDM in our lab, we found that the fundamental EDM process in dielectric fluid, generally in oil, is discharged in the gas atmosphere at most of the time, and results in different comparison results of removal mechanism and worn-out [10]. Although there were studies on the ultrasonic EDM in gas [8], following gas EDM processes, they usually adopted high-pressure argon or oxygen. That's different gas from what is usually practical application in the industries.

For example, with ultrasonic vibration assistance, the EDM sparks are more likely to be triggered at a very different situation and result in a much higher removal rate. The typical boundary around the gas bubble formed by many foam cells with the dense wall is fulfilled with debris and oil. It reported that the boundary cell wall is the highest probability spot for the next EDM ignition, according to the works of Kunieda et al. [9]. Their paper focused on a vertical mounted transparent SiC plate. However, in a most practical situation, the die-sinking EDM was conducted in the cavity, and its discharging work-plane is horizontal. Therefore, the observation of deep cavity EDM focused on the tooltip and its periphery in this study. Especially, the effects of gas bubbles around the tooltip in EDM milling on the debris expelling and the tool wear mechanism.

This paper is aimed at the hybrid application of EDM milling for special materials, such as tungsten carbide in comparison to mold steel. Moreover, the fundamental mechanism of EDM pulse-trains and the effects on debris expelling, associated with removal efficiency are investigated. Tool wear is also explained comparatively for both EDM milling cases with and without the assistance of ultrasonic vibration.

2. Experiment Design and Setup

RU-EDM milling is composed of the high-speed rotation and the ultrasonic vibration of the EDM tool electrode. A novel rotary ultrasonic spindle of 24 kHz with an amplitude of 5-9 μm is designed and set up on a CNC EDM machine as shown in Fig. 1. The EDM machine, MoldMaster 430A, was built by a vendor in Taiwan. As shown in Fig. 1, the experimental setup of the RU-EDM, pulse-trains analyzer including voltage isolator and current probe amplifier, and transparent observation window with a high-speed camera are involved. The jump height of the tool electrode is defined as the tool draws back from the working level, according to the CNC set.

The effects of the rotary revolution speed of the tool from 1.2 to 3.6 kRPM and the ultrasonic voltage from 0 to 700 V are investigated. Finally, the performance of hybrid RU-EDM is investigated and fundamental observation for various EDM configurations and the effectiveness of the mechanism of a rotary tool and the ultrasonic vibration is further discussed.

In Fig. 2, the fundamental observation window is conducted through a 1.0 mm thick and 10 mm long glass combined with a high-speed camera shooting system (X-Stream XS-4) at the speed of 120 fps, and 2000 fps, respectively. An ultrasonic spindle and the testing bench with a fluid guideway were set up horizontally for EDM oil to flow from the left to the right side. The detailed setup of this spindle and transparent window is depicted in Fig. 2(a) and (b), respectively.

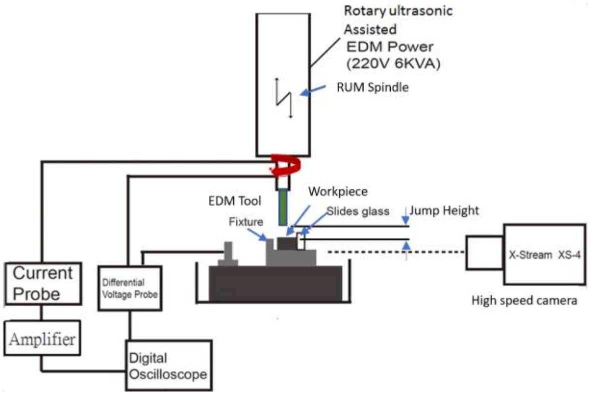


Fig. 1. Setup of the RU-EDM, pulse-trains analyzer and transparent observation window by side glass.

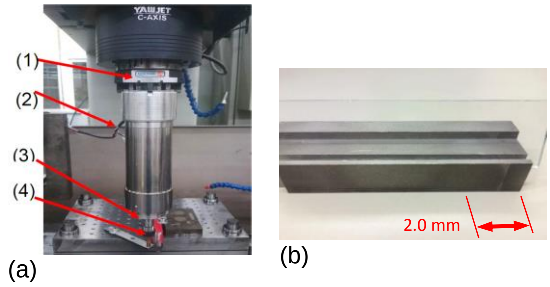


Fig. 2. (a) RUM-EDM spindle with (1) Erowa chuck, (2) ultrasonic power core (3) ultrasonic horn (4) ER collet, (b) Transparent window for observation of EDM debris and bubble along the milling path.

General EDM performance indexes including material removal rate (MRR), tool electrode wear rate (EWR) as listed in the followings.

$$\mathrm{MRR} = \frac{M_1 - M_2}{t} \quad (1)$$

$$\mathrm{EWR} = \frac{E_1 - E_2}{t} \quad (2)$$

Where, M_i and E_i denote the weight of the workpiece and the tool in mg, respectively, denoting measurement before and after the EDM processing. And a relative tool wear rate (RTWR) is usually adopted to describe the rational percentage between EWR and MRR as:

$$\mathrm{RTWR} = \frac{EWR}{MRR} \text{x100\%} \quad (3)$$

The gap status between both electrodes is important to EDM machining performance, which also contributes to machining stability. For example, in general cases, the current pulse frequency (denoted by f_I)may appear a little more than that of the voltage pulse (f_V). Then, the probability of short-circuit occurrence among the discharge pulses train is proposed to loss of the relative machining stability of gap status in this study.

Since short-circuit current pulse occurred as there was no voltage pulse, therefore, a stability index, η_s, is proposed to calculate the difference between the averaged frequency of the current pulses and voltage pulses as followed. According to the definition, more often of short-circuit pulse among EDM indicating the lower relative stability is.

$$\eta_s = (1 - \frac{f_I - f_V}{f_I}) \times 100\% \quad (4)$$

Table 1. Operation conditions for EDM testing

Tool Electrode	**∅ 3.0mm Cu-Cr**
Workpiece	Tungsten Carbide
Dielectric fluid	Kerosene
Voltage V_P(V)	200
Working Current I_L(A)	4.5 (various A)
On Time ON (μs)	65 (various μs)
Off Time OF (μs)	20.8 (various μs)
Servo Voltage S_V(V)	30
Jump Height J_H(mm)	2.4
Work time T_W(S)	0.75
Ultrasonic *Freq. f*(kHz)	24-26.5
Ultrasonic volt *Wu*(V)	0, 100, 400, 700
Vibration ampl. (μm)	5-9

3. Results and Discussion

3-1. Rotary EDM and Ultrasonic Assistance

At the very begging, a gas bubble accumulated around EDM sparks as reported in [10], as shown in Fig.3(a). It reveals the unique main bubble that remained beneath the tooltip at the first jumping stroke of the EDM spindle in Fig.3(b), with dense debris around the forms around the gas bubble. As the spindle drives the tool into revolution, the debris cloud moves along with the bubble which is always stray beneath the center of the tooltip.

The rotation effect of the spindle is compared in Fig. 3. In which, the first row is for EDM sparks, the second row is at the EDM tool jumping stage. This main bubble staying under the tooltip constrains the EDM debris flow in the velocity field. The bubble volumes are evaluated through the captured image as elliptical balls, from the geometric formula. Their volume is estimated from about 21, 44 to 54 mm^3, corresponding to the increasing speed of 1.2 kRPM to 3.6 kRPM, respectively, as shown in Fig. 3(d)-(f).

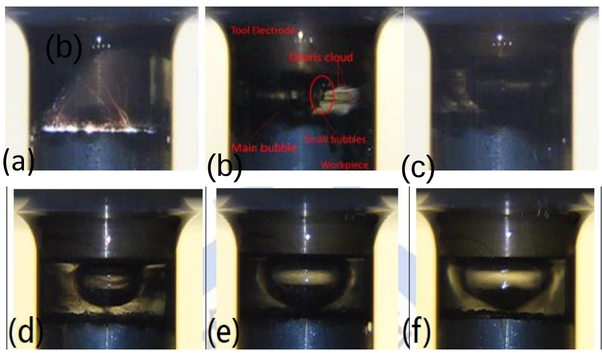


Fig. 3. (a)Gas bubble around EDM sparks, (b)main bubble observed at tool jumping, (c)the debris cloud around main bubble, (d)-(f) effect on rotary bubble at jumping stage, with spindle speed from 1.2, 2.4 to 3.6 kRPM, respectively [12].

During rotary EDM, the video image further reveals that the succeeded sparks after the jumping are initiated in the gas atmosphere as the main bubble is squeezed by the tooltip to the EDM's very narrow gap. According to this observation in mold-cavity EDM, it is claimed that sparks are initialized in a closure of the gas atmosphere rather than in dielectric fluid. Therefore, some of the understanding of material removal mechanism and the heat transfer are different from that conventionally EDM discharges submerged in oil dielectric.

3-2. Rotary EDM milling & Rotary Ultrasonic milling

As shown in Fig.4, a comparison of EDM milling with the rotary RA-EDM and the rotary ultrasonic RU-EDM milling along a slot of 1.0-mm-depth are conducted. The speed of camera shooting was 1000 fps with strong lighting. Comparing the bubble morphology during discharging in Fig.4(a) and (c) (indicated by arrow) reveals more violent turbulence caused by RU-EDM, and ultrasonic vibration splits the individual bubbles. As the EDM tool draws backward to the left, the oil flowing along with laminar layers around the tool in Fig.4(b). However, the morphology of Fig.4 (d) reveals a specific turbulent pattern. That much denser oil in Fig. 4(c) and (d) also reveals debris concentration of RU-EDM is much higher than that of conventional RA-EDM. But there is no longer a single main bubble accumulating beneath the tooltip.

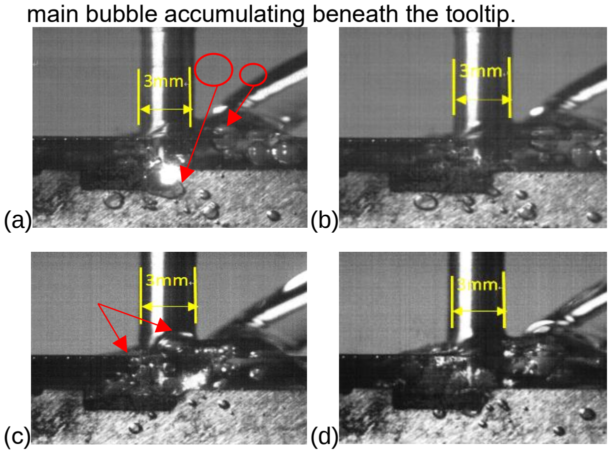
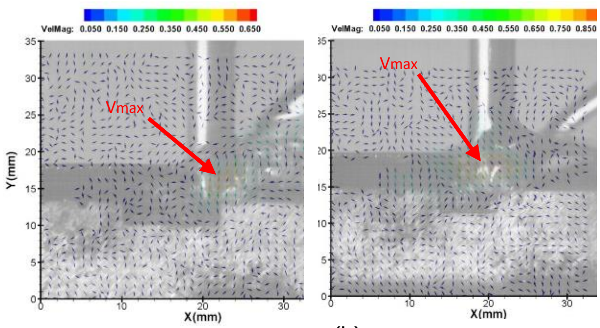


Fig. 4. Comparison on milling with RA-EDM (the first row) and with RU-EDM (second row); (a)(c) are during discharging stroke, and (b)(d) the jumping back stroke.

As shown in Fig. 5, flow velocity fields of the debris of RA-EDM milling, and vibration RU-EDM milling are compared. Although some oil smoke may cause interference, the highest velocity of RU-EDM flow reaches up to Vmax 85 cm/s is observed in Fig.5(b), which is 38% higher than that of RA-EDM in Fig.5(a), revealing the expelling efficiency of the RU-EDM.



(a) (b)

Fig. 5. Comparison on velocity fields of (a) simple RA-EDM milling, and (b) ultrasonic RU-EDM milling.

The reason for such a higher velocity is because of the amplification that ultrasonic vibration effect on the oil-debris flow around the narrow EDM gap, especially the squeezing effect of RU-EDM on the bubble cells. The pressure difference between the working gap and lateral oil is suddenly increased by ultrasonic cavitation and the amplification effect. Therefore, ultrasonic assistance increases the exchanging rate of oil and debris from the gap and the expelling efficiency of debris, as a result.

3-3. Pulse-trains of various EDM configurations

Typical pulse-trains of the rotary EDM (RA-EDM) with the spindle speed of 1.2 kRPM are shown in Fig. 6(a). Its current pulses appear some shortened rising-time compared to typical RA-EDM. The measured average frequency of the current waveform is 9.46 kHz, and the average ignition delay is shortened with ultrasonic vibration assistance.

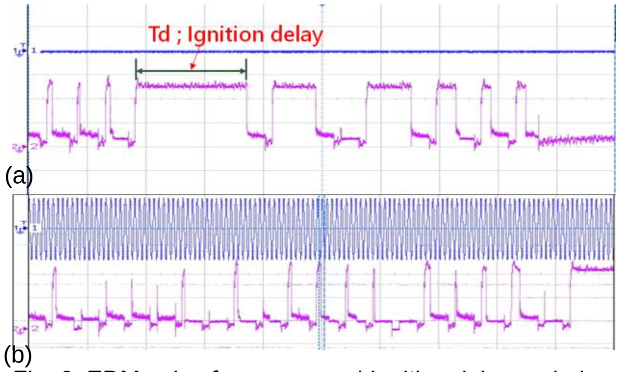


Fig. 6. EDM pulse frequency and Ignition delay period (a) without tooll vibration, (b)with vinration, Channel 1: tool's ultrasonic signal (V), Channel 2: voltage (V).

As shown in Fig.7(b), RU-EDM at 1.2 kRPM reveals that the discharge frequency is increased compared to RA-EDM, with a higher frequency of 9.57 kHz compared to the 9.45 kHz in Fig.7, due to the shorter average ignition delay period, resulting in higher removal rate. Its typical current wave (in Channel-2) shows a shorter rise time, resulting in higher energy per pulse than RA-EDM. But the averaged stability indexes η_s are 84.1% and 79.1% for RA-EDM and RU-EDM, respectively, over collecting the 10 segments of 500ms records. So, ultrasonic vibration slightly deteriorates the stability status.

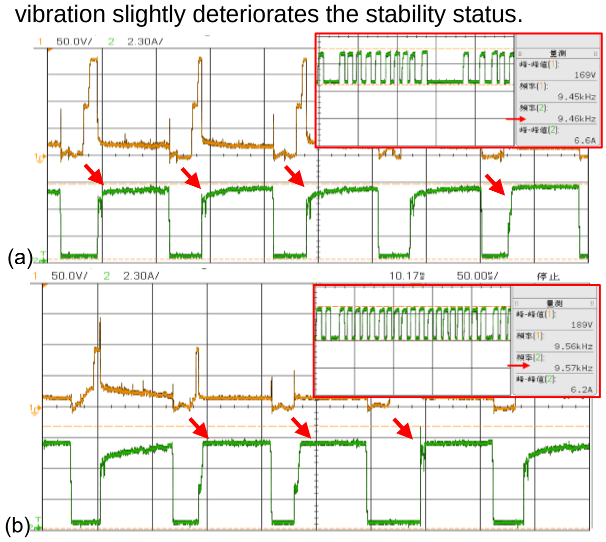


Fig. 7. Pulse-trains of the (a)RA-EDM, (b)RU-EDM (Upper channel: Voltage, and Lower channel: Current.)

As reported in the previous papers in the lab [10-11], due to rotary EDM discharge, the bubble foams rapidly accumulate around the single main bubble is tend to constrain the debris expelling. In the cases where the ultrasonic vibration is applied, associated with turbulent flow and some cavitation effect improves the debris expelling rate. Therefore, a significant improvement of removal rate by RU-EDM may contribute to the bubble-splitting into much larger cells surface, to create a much higher discharge frequency environment. Also, the turbulent flow which helps increase the removal rate by increasing the local debris expelling rate.

Fig. 8 reveals the comparison of the milling contours (9.0x9.0 mm, with 3.0mm depth) and profiles by rotary EDM and vibration assisted RU-EDM through the iso-depth contour milling. The averaged surface roughness is reduced from Ra 8.61 μm of RA-EDM to Ra 6.80 with RU-EDM, and the round errors at the bottom also reveal that RU-EDM gets much better contouring accuracy. That has resulted from different tool wear rates between these two methods. As shown in Fig.9, in comparison to the wear of the tooltip, RU-EDM preserves a better profile of tooltip with RU-EDM in both surface integrity and less tapering.

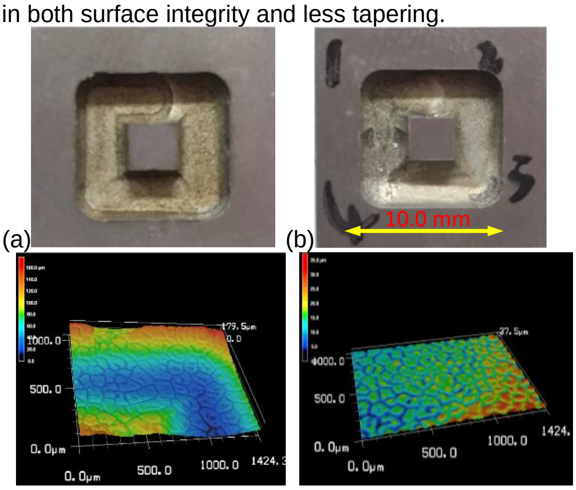


Fig. 8. The milling contours and surface profiles by (a)&(c) rotary EDM (RA-EDM) and (b)&(d) ultrasonic vibration RU-EDM.

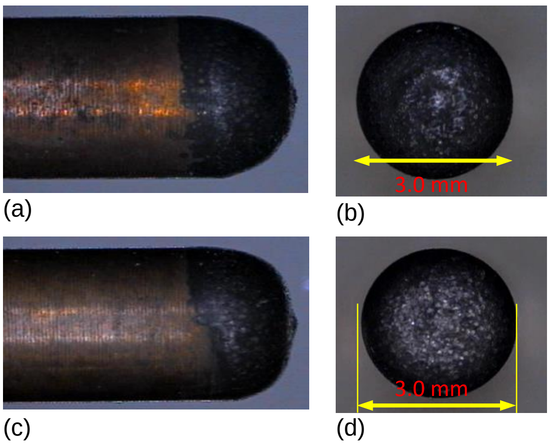


Fig 9. Comparison on views of wear of tooltip, (a)-(b) after regular RA-EDM, (c)-(d) after RU-EDM.

4. Conclusion

In EDM milling for the mesoscale mold, turbulence in RU-EDM milling is more violent than that of rotary EDM milling, and the flow velocity of RU-EDM debris is also almost 38% higher than that of RA-EDM milling. Therefore, the debris expelling rate of RU-EDM is higher than that of conventional RA-EDM milling. The effect of UA-EDM vibration involving the assistance for debris expelling, steeper rising current pulse, and also increase the discharge frequency. Therefore, with a much steeper current pulse (higher energy consumption efficiency per pulse). Besides, the morphology of the tooltip worn-out contributes to the contouring accuracy at the bottom of mesoscale mold cavities. Therefore, RU-EDM can get a much better contouring accuracy with lighter worn-out than RA-EDM. In the future study, the characteristics of ultrasonic-assisted micro-EDM milling will be involved.

Acknowledgements

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