Effect of step pulse waveform in electrochemical micromachining for dimension control

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KEYWORDS

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ABSTRACT

Electrochemical micromachining is becoming a popular technique for structuring ultra-precision micro-components. Incorporating the discharging effect of double layer capacitor during faradic time of step pulse waveform, potential transmission has been controlled during machining. In addition, by applying another technique of dimension control, stray current effects have been minimised significantly, which is clearly understood from simulation and polarization results. As a result, electrolyte potential and current density have been minimised by 23% and 63%, respectively. Thus, at the voltage of 14V, 51.49% of overcut reduction has also been obtained as compared to non-coated workpieces. For coated workpieces, the transpassive state appears quickly which can remove the obstacle of current flow during the passive state. From machined microholes images, it has been observed that edges are uniform, pitting effects are negligible, sidewalls are smooth and profiles of microholes are almost circular.

1. Introduction

Electrochemical micromachining technology is expected to play a promising role in the fabrication of micro-components for various applications. Landolt et al. (2003) has given a brief overview of the basic prospect of EMM for biomedical, electronics and micromechanics applications. Recently, various pulse pattern techniques have been used to enhance the machining performance and ultra-precision structures. Ghoshal and Bhattacharyya (2014) showed that machining accuracy has been enhanced by utilising the tool vibration technique. Xu et al. (2019) found that machining resolution can be improved by using sinusoidal signals. Patel et al. (2020) investigated the triangular pulse waveform in EMM and found that utilising this waveform overcut can be minimised dramatically. Sharma et al. (2022) studied the faradic current through electrochemical impedance spectroscopy under the application of triangular, rectangular, and sinusoidal waveforms. The results revealed that better anodic dissolution can be achieved by using the triangular voltage waveform and better machining efficiency is obtained by applying the rectangular voltage waveform. Panda et al. (2022) showed that the accuracy of EMM can be increased significantly by using step pulse waveform instead of rectangle pulse waveform.

From the research works, it has been understood that the proper potential transmission during machining is very essential to achieve better accuracy and precision shape of machine products. To reach this aim, step pulse waveform (SPW) has been designed as a new pulse pattern technique. As the tool-tip area is very small compared to the workpiece, the potential transmission and current density play a significant role in stray current. To reduce the stray current effects, dimension control technique has been applied under the step pulse waveform. In dimension control technique, except for the machining zone, fully coated workpieces are working as an insulator, which may restrict potential transmission in the electrolyte during micromachining. Hence, the effects of electrolyte potential and current density have also been investigated through simulation and experimental processes. The effect of both techniques on overcut and ultra-precision microholes machining have been investigated for different voltages. Finally, the characteristics of machined microholes have been analysed in depth.

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2. Working Principle of Step Pulse Waveform in EMM

The design strategy of SPW is that the potential variation can occur during the faradic time. It is caused by discharging effect of the double layer capacitor (DLC).

The pulse on time of SPW has been broken into two parts with different peak voltages such as V_{Smax}, and V_{Shalf} as shown in Fig.1. Thus, the discharging of DLC can occur when the pulse voltage drops down from maximum to the second peak during pulse on time. As a result, the potential transmission can be controlled during micromachining. Hence, anodic dissolution rate can also be controlled, and accuracy of EMM is improved.

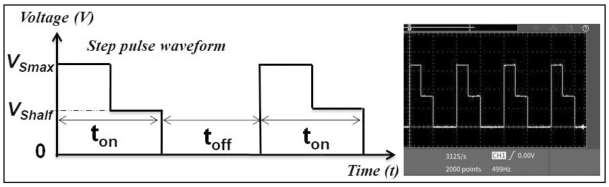

Fig. 1. Step pulse waveform in schematic and oscilloscopic view.

3. Experimental Setup and Planning

EMM set-up has been designed indigenously with three different sub-components, such as mechanical unit, power supply unit, and stepper motor control unit as shown in Fig.2. The gantry type stage has been used as a mechanical unit, where the microtool is connected with the Z axis. Machining chamber has also been incorporated into the mechanical unit for micromachining. The ultra-precision movement of Z-axis has been controlled by stepper motor controller. Programmable DC pulse power supply (Matsusada, Japan) has been used for voltage pulse power supply. Digital oscilloscope TBS2000 (Tektronix, USA) has been utilised for the measurement of waveforms during machining.

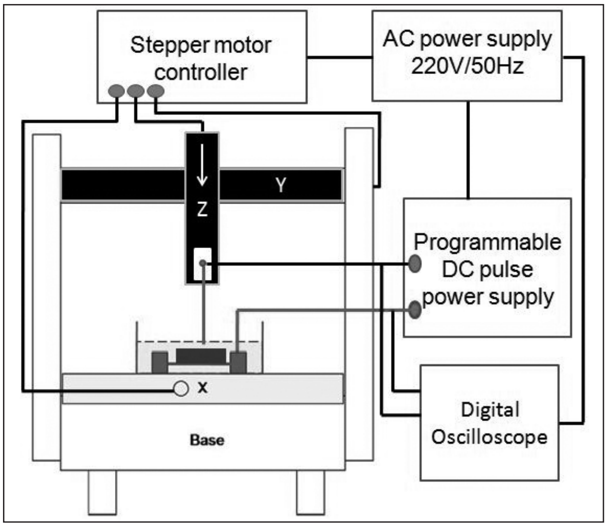

Fig. 2. Schematic view of experimental setup of EMM.

Tungsten (W) rod with 200µm diameter and 200µm thickness of stainless steel (SS304) has been chosen as tool and workpiece, respectively. The sidewalls of microtool and except machining zone total workpiece have been coated with synthetic enamel to minimise the effect of stray current. 0.1 M H_2SO_4 solution has been used as an electrolyte because it can dissolve the sludge during machining from the machining zone, which is most effective for the stagnant electrolyte. The applied voltages 13V to 16V have been selected for a better understanding of the potential distribution in the electrolyte. To avoid the unstable condition of electrolytes at higher voltage, pulse frequency has been selected at a lower value, i.e., 500Hz. As the stagnant electrolytes have been used, higher pulse-off time is required to remove the sludge during machining. Thus, 50% of duty cycle has been selected for micromachining. The initial inter-electrode gap, and tool feed rate have been selected at 20µm, and 0.5µm, respectively. Using Scanning Electronic Microscope (SEM) and digital microscope (Leica), the condition of the machined micro-holes has been observed.

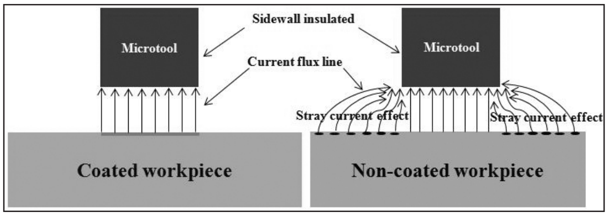

Fig. 3. Effect of stray current for coated and non-coated workpiece.

4. Simulation Results of Potential Transmission and Current Density for Dimension Control

The electric field distribution plays a significant role in EMM because the tool-tip area is very small compared to the workpiece. From Fig.3, it has been noticed that except machining area, current cannot flow through the surface areas of coated workpieces. Thus, potential transmission in the electrolyte has been restricted during micromachining. Hence, to get a better idea of potential distribution and current density for coated and non-coated workpieces, simulation

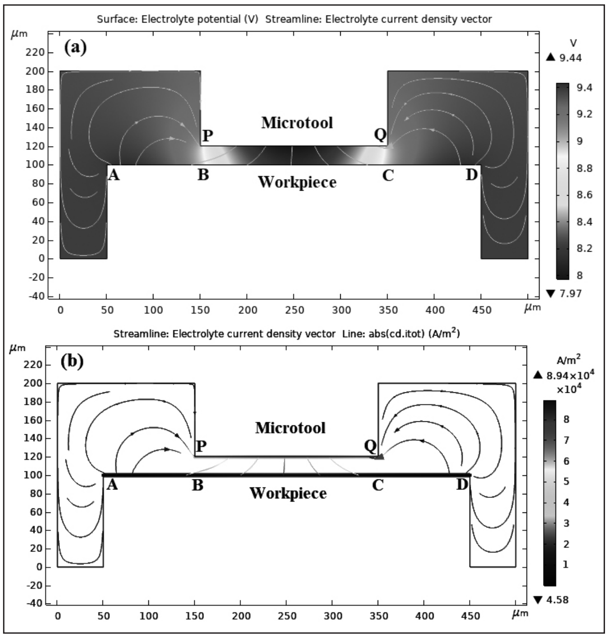

Fig. 4. Simulation results of non-coated workpiece for (a) electrolyte potential (b) electrolyte current density.

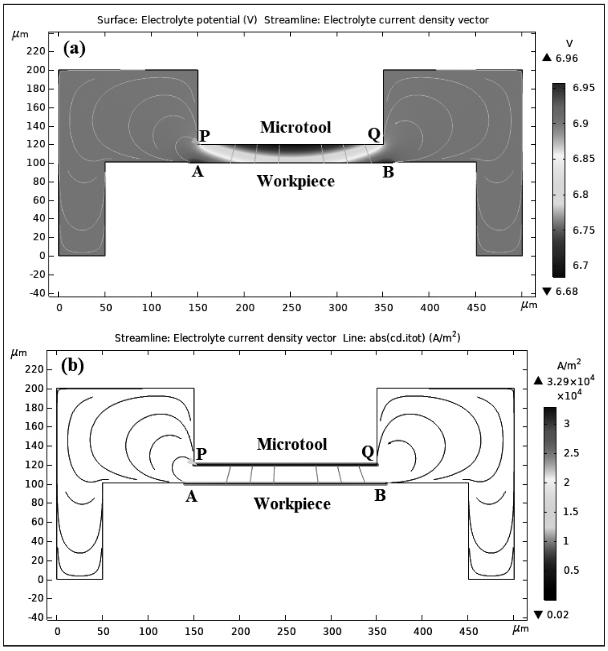

Fig. 5. Simulation results of coated workpiece for (a) electrolyte potential (b) electrolyte current density.

has been done through COMSOL software. The total tool-tip area is not considered for simulation process because 3D geometry is very complicated for understanding current density and potential distribution in the electrolyte. Simulation process has been carried out at the applied voltage of 14V. For non-coated workpiece, the maximum electrolyte's potential is 9.44V as shown in Fig.4(a). Furthermore, it has been noticed that the maximum current density is 8.94x10^{4}A/m^2 as shown in Fig.4(b). Streamline or electric flux line

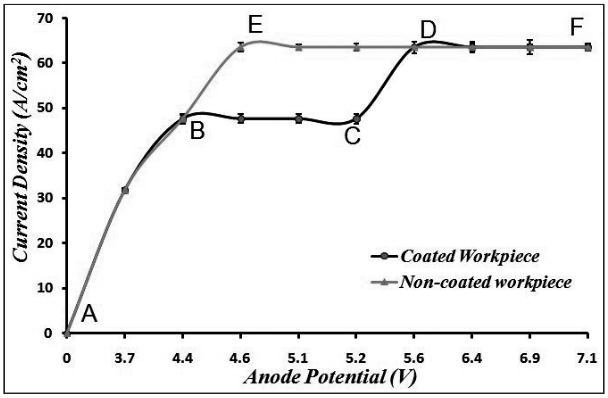

Fig. 6. Anodic polarization curve for non-coated and coated workpiece at 14V.

exhibit that stray current passes from PQ to AB and CD regions. As a result, pitting and etching effects have appeared in these regions.

But, when workpieces have been coated on all surfaces except machining zone, i.e., AB region, the electrolyte potential can be obtained at 6.96V, which is 26.27% less than the non-coated workpiece as shown in Fig.5(a). Similarly, electrolyte current density has been obtained at 3.29x10^{4}A/m^2, which is reduced by 63.19% as shown in Fig.5(b). As a result, by applying dimension control technique stray current effects have been minimised significantly.

5. Results and Discussion

5.1. Effect of dimension control on polarization under SPW

In coated workpiece, current density varied in a moderate range and transpassive state appeared quickly as shown in Fig. 6. The active state belongs in the region of AB, where the current density accelerated up to 47.62 A/cm^2. In this region, metal surfaces are etched with a high rate of anodic dissolution. Next, the passive state, i.e., BC region, becomes accompanied by an oxide layer on the anode surface, which interrupts further current flow. Hence, anodic dissolution rate decreases suddenly. But, this passive state does not sustain for a long duration because when anodic potential increases more than 5.2V, the transpassive state of CD appeared with higher current density i.e., 63.49A/cm^2. As a result, the interrupted current can further flow through the oxide layer because during this state oxide layer becomes thinner than the passive state. In consequence, the anodic dissolution rate increases with polishing action which can improve the profile of microholes and reduce pitting effects. But, for non-coated

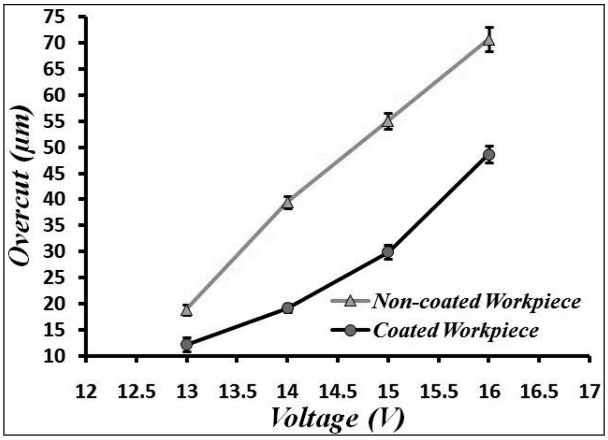

Fig. 7. Overcut reduction by SPW for coated and non-coated workpiece.

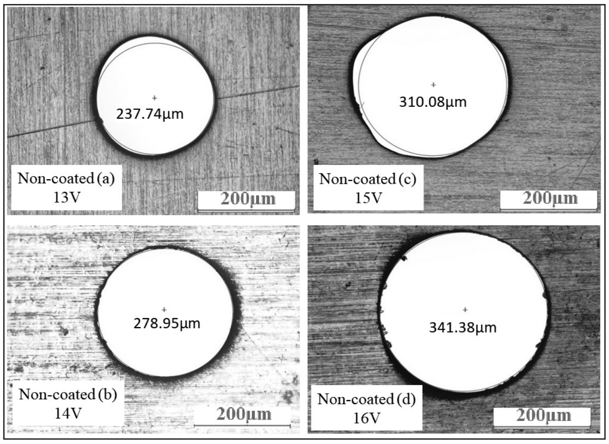

Fig. 8. Images of machined microholes for non-coated workpiece.

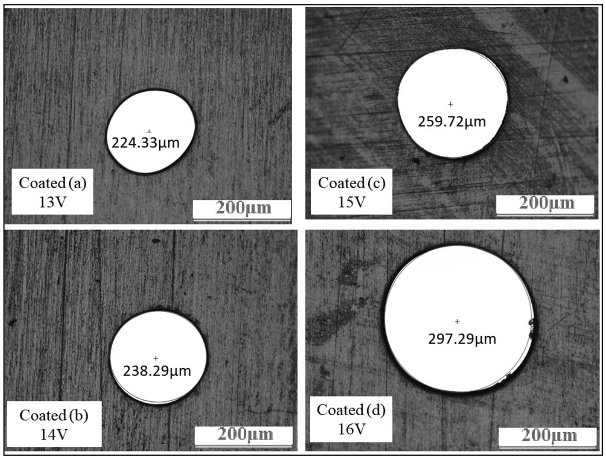

Fig. 9. Images of machined microholes for coated workpiece.

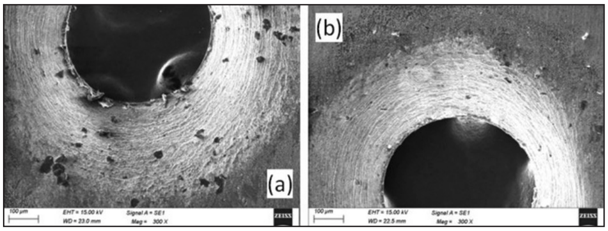

Fig. 10. SEM images of machined microholes at 14V for (a) non-coated (b) coated workpiece.

workpieces, it has been observed from machined microholes that edges are irregular, and have more pitting effects.

The reason behind this phenomenon is that for non-coated workpieces, the active state, i.e., AE region, is longer and the current density rises to 63.49A/cm^2. Hence, anodic dissolution rate is greater than coated workpieces during the active state. As an effect, overcut and error of circularity of microholes increase. In addition, another factor is that thought out the total passive state of EF, a larger current density is obtained, resulting in more currents being developed which are engaged to generate the excessive gas bubble. When these gas bubbles are broken, micro-sparks are generated, resulting in unwanted metals removed from the machining zone. Thus, overcut increases and sidewalls become rough surfaces. The minor current can penetrate through the oxide layer and create pitting effects across the entry side of microholes. According to experimental results, it has been noticed that the trend of current density variation is similar to simulation results.

5.2. Effect of SPW on overcut for dimension control

Experiments have been carried out at four different pulse voltages, i.e., 13V, 14V, 15V and 16V. In non-coated workpieces, the electrolyte potential and current density are higher as compared to the coated workpiece, which is clearly understood from simulation and polarization results. Hence, larger overcut of microholes has been obtained than coated workpieces as shown in Fig.7. From Fig.8, it has also been observed that the profile of machined microholes is not circular and edges are not uniform.

But, for coated workpiece, proper circle shape of machined produced has been obtained as shown in Fig. 9. It has also been noticed that minimum overcut has been obtained at 13V, but maximum overcut reduction i.e., 51.49%, and proper circular shape, better uniform edge are obtained at 14V due to proper potential distribution in the electrolyte of machining zone.

From the machined micro-holes, it has also clearly been noticed that in non-coated workpieces, edges are not uniform; more pitting effects have appeared as shown in Fig.10 (a). But, for coated workpieces, edges are uniform, and pitting effects are negligible as shown in Fig.10 (b).

6. Conclusions

Applying step pulse waveform and dimension control techniques the accuracy of EMM has been enhanced significantly and ultra-precision microholes have been fabricated. A few noteworthy conclusions are as follows:

- The potential transmission has been controlled significantly by step pulse waveform because the partial discharging effect of DLC has been incorporated during the faradic time. Thus, anodic dissolution rate has been controlled. As a result, overcut has been minimised significantly.
- From simulation results, it can be concluded that by utilising SPW in coated workpieces, electrolyte current density and potential have been reduced by 63% and 26.37%, respectively. As a result, the stray current has been minimised.
- Another observation from the experimental results is that the trend of current density reduction is similar to simulation results. The polarization curve exhibits that in coated workpieces, current density varied in a moderate range, i.e., 47.62 A/cm^2, during active state and transpassive state appears quickly which can increase the further current flow rate. In consequence, the obstructed anodic dissolution rate further increases with polishing action which can improve the smoothness of the sidewall and the circularity profile of microholes.
- Applying SPW in coated workpieces; overcut has also been reduced significantly as compared to non-coated workpieces. Furthermore, it has been noticed from machined images that the profile of microholes is almost circular, edges are uniform, and pitting effects are negligible. But in non-coated workpieces, these effects are prominent.

Thus, utilising SPW with dimension control technique, overcut and stray current effects have been minimised, as well as ultra-precision microcomponents can also be fabricated. In other words, these techniques are applicable for better shape control management of EMM operations.

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