Experimental Investigation into Wire Electrochemical Micro-Machining for Reduction of MicroSparks and Overcut

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1 Introduction

Wire electrochemical micromachining (WECMM) is such an advanced machining process that dissolves material by required electrochemical reactions between cathode wire and anode workpiece dipped inside suitable electrolyte solution separated by a narrow inter-electrode gap (IEG). The WECMM is a transport-limited electrochemical dissolution process. The continuous removal of dissolved products and sludge becomes more difficult in the tiny IEG due to frequent microsparks and unstable machining [1]. Moreover, of the several research works for investigating the influence of various process parameters, no effort has been focused to control the effect of microsparks and reduction in overcut on wire electrochemical micromachining process considering most of the influencing parameters which is a primary requirement during machining. During the process, there may be a possibility of unusual sludge and dissolved products in narrow IEG causing microsparks which in turn reduces homogeneity and machining stability. Feed rate of tool wire has a great influence on corresponding micromachining criteria [2]. The machining stability and slot profile investigated with DP-WECMM are considerably better than those with traditional WECMM where frequent microsparks occur [3]. A proper combination of voltage and pulse period and pulse duration results in outstanding machining accuracy for a thick workpiece [4]. The axial and intermittent feed-direction vibrations combination are capable of improving the maximum feed rate [5]. A lower initial IEG can decrease the stray current results in a better entrance shape [6]. Proper feed rate leads to a small machined roughness surface without any microsparks [7]. High precision micro features can be achieved with the vibration of cathode wire [8]. Low frequency and small amplitude improve machining stability, accuracy, and

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improve overcut reduction [9]. The influence of voltage on wire feed rate was also investigated for achieving the maximum feed rate. Enhancement of mass transport and micro-vibration of wire improves the machining quality of WECMM [10]. The stray-current attack was identified to reduce stray current attack with wire insulating methods [11]. The effect of microspark and stray current on machining accuracy was experimentally investigated during electrochemical micromachining [12]. However, WECMM is still under investigation and microsparking in the IEG due to inappropriate flushing and accumulation of machining products, namely, sludge and gas bubbles and the effect of stray current deteriorates, degrades, and distorted homogeneity and stability of process as well as dimensional characteristics generated microfeatures which leads to increase in overcut.

The present experimental investigation is paying attention to the development of a proper WECMM for fabricating microfeatures for investigating the number of microsparks generation and overcut during micromachining. For this, a suitable axial flushing system has been implemented and the piezoelectric transducer (PZT) tool vibration has been used which results in a decrease in microsparks during machining. This paper, therefore, emphasizes finding out the effect of various controllable parameters such as feed rate, pulse voltage, pulse voltage frequency, and wire vibration frequency and amplitude with PZT on corresponding slit width for microspark effect as well as the formation of overcut. Numbers of micro-sparks are measured with the help of an oscilloscope. Also, after the experiments, the generated microslits have been carefully analyzed under the optical microscope. The influence of most influencing parameters on microspark generation and overcut is represented graphically to investigate the effect on the fabricated microslits by determining suitable ranges within which the WECMM process can get better control over the generation of microsparks and reduction in overcut which ultimately result in stable, accurate, and homogeneous micromachining.

2 Experimental Setup

An experimental setup for wire electrochemical micromachining (WECMM) is developed having various subsystems and mechanical machining units. The XYZ movement stage is power driven by three stepper motors. The XYZ movement represents three principle Cartesian axis directions of X, Y, and Z for positioning. It helps in workpiece location, holding the tool wire properly, and moving that wire precisely and accurately. Also, the power supply unit, electrolyte flow system; etc. along with various sub-systems like Perspex machining chamber, Perspex wire holding, and tensioning block and worktable connected to the stage. The position control unit is operated by a computer. The machining chamber is positioned on the stage during experiments. The worktable is used to hold the machining chamber and to restrict its movement during experimentations. A wire is held vertically straight with proper tension in the mentioned block. It has the arrangement to attach the PZT for introducing a small frequency and amplitude of wire vibration during machining. A

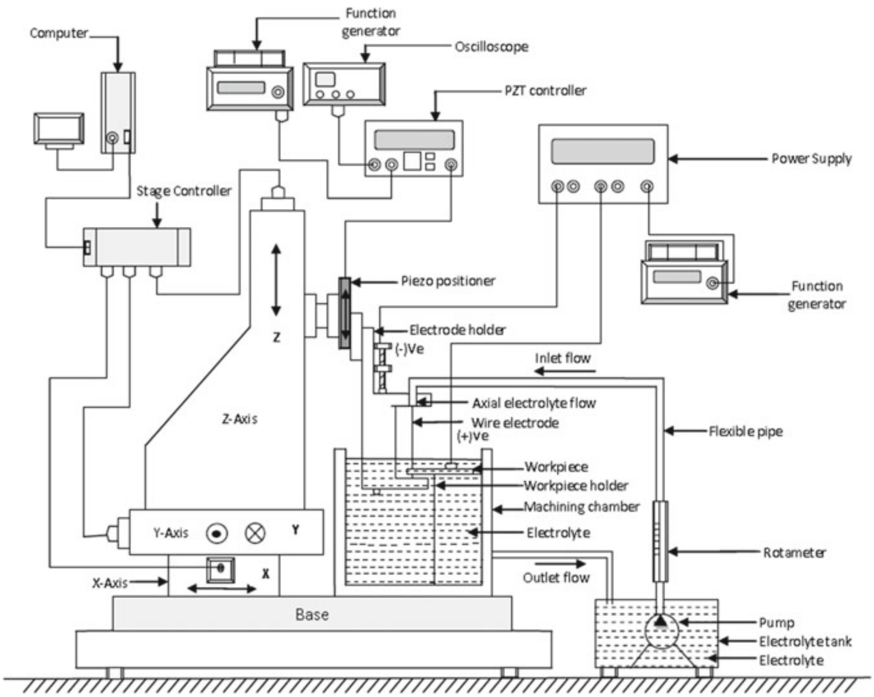

Fig. 1 Schematic diagram of the WECMM experimental setup

suitable axial electrolyte flow system has been developed for regulating proper flow. The flow system consists of a pump, electrolyte supply chamber, flow control valve, rotameter, etc., to control the flow. The DC pulse generator is used to generate different pulse nature of variable voltage, pulse period, and duty ratio. The oscilloscope has been used for monitoring different pulse power parameters during experiments and the measurement of micro-sparks. Also, multimeter, stereo zoom microscope, optical camera, and microscope, etc., have been used for carrying out the experiments. A schematic diagram of the WECMM experimental setup has been shown in Fig. 1.

3 Experimental Planning

In the present work, a tungsten wire of Ø50μm with a very thin layer of coating of synthetic enamel on a non-machining area is used as a tool electrode. The workpiece specimens were 15 mm × 15 mm × 0.1 mm stainless steel 304 sheets were used for better understanding the effect for micro sparks generation and overcut in machined slit width. The electrolyte used for experimentation was 0.1 M H_2SO_4. Experimentations are done with a variable rectangular DC power supply. Microslits were machined and the effect of micro-sparking and overcut were considered for experimental analysis. To investigate experimental results and to improve the machining quality, numbers of micro sparks are counted with the help of an oscilloscope at each stage of varying conditions of process parameters during machining of microslits and overcut measured with an optical microscope for each operating conditions by considering the mathematical model, as follows:

$$\text{Overcut} = 2\Delta \text{s} = 2\Delta \text{b}\sqrt{\frac{2\text{d}}{\Delta b} + 1} \tag{1}$$

where Δb, inter-electrode frontal gap; Δs, inter-electrode side gap; d, the diameter of wire electrode.

The experimental setup was prepared for microwire tool mounting and holding, workpiece mounting, and electrolyte flow system. All the experiments maintained the required amount of inter-electrode gap, i.e., 100 μm by forwarding the motion of wire and checking the IEG with a continuity tester to avoid any contacts between wire and workpiece material. The process parameters have been set according to the planning and given the feed rates in the stage controller to move the wire electrode toward the workpiece. On completion of machining, switch off all the machine types of equipment in sequential order. The influence of various parameters on the generation of micro sparks and is responsible for the production of overcut while machining is considered for investigation. Sketch of side gap for overcut in WECMM machining process shown in Fig. 2.

In this experimental study, feed rate, pulse voltage, pulse voltage frequency, PZT tool vibration frequency, and amplitude were identified to carry out the experiments keeping other parameters fixed for all experiments, and working ranges were selected based on data given in the literature survey, review of experiences and trial experiments for microslits machining to understand the effect for generation of microsparks

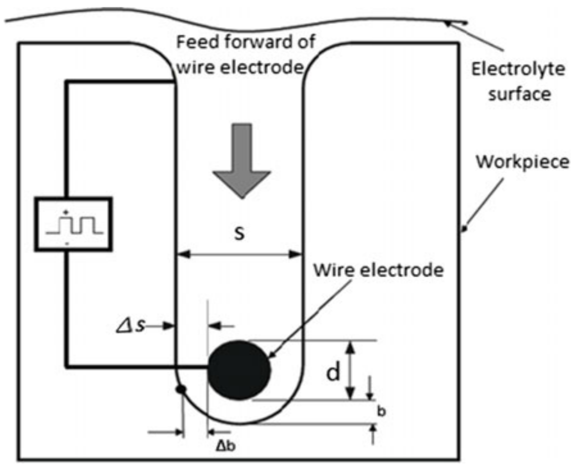

Fig. 2 Sketch of side gap for overcut in WECMM process

Table 1 Operating conditions

Working condition	Value
Workpiece material	Stainless Steel 304
Workpiece thickness	100 μm
Wire electrode Material	Tungsten
Diameter of wire Electrode	Ø50μm
Applied pulse Voltage	4–12 V
Wire feed rate	1.0 μm/sec to 1.8 μm/sec
Duty ratio	50%
Voltage pulse frequency	50 kHz to 500 kHz
Type and concentration of Electrolyte	0.1 M H_2SO_4
Electrolyte flow rate	35lph
IEG	100 μm
PZT tool vibration frequency	0–100 Hz
PZT tool vibration amplitude	0–50 μm
Insulating material for wire	Synthetic Enamel

and as well as the formation of overcut. Operating conditions for all the process parameters with their ranges used in experimentations are shown in Table 1.

4 Results and Discussion

4.1 Influence of Feed Rate on MicroSpark and Overcut

Experiments were conducted for the machining of microslits with 4 V applied voltage, 200 kHz voltage pulse frequency, 40 Hz PZT vibration frequency, 12.94 μm PZT vibration amplitude, and 1–1.8 μm/sec ranges of feed rate. It is discovered that average current is increased with an increase in tool feed rate and micro sparks occur at higher currents, but overcut is reduced with an increase in feed rate. Microslits fabricated with lower feed rates are homogeneous as controlled dissolution occurred and due to the absence of a microsparks effect. If the wire feed rate was too high, it was difficult for the flow system to remove the sludge and dissolved product from narrow IEG, leading to microsparks. It is observed that wire feed rate in the range of 1.4–1.6 μm/sec gives better control for the reduction of average current and overcut. Moreover, the average overcut is at a bit higher side regarding the fact that tungsten wire of diameter 50 μm and IEG of 100 μm have been used during experiments due to the application of such a low feed rate. To achieve better machining quality, as well as to prevent the occurrence of microsparks and to reduce overcut, the influence

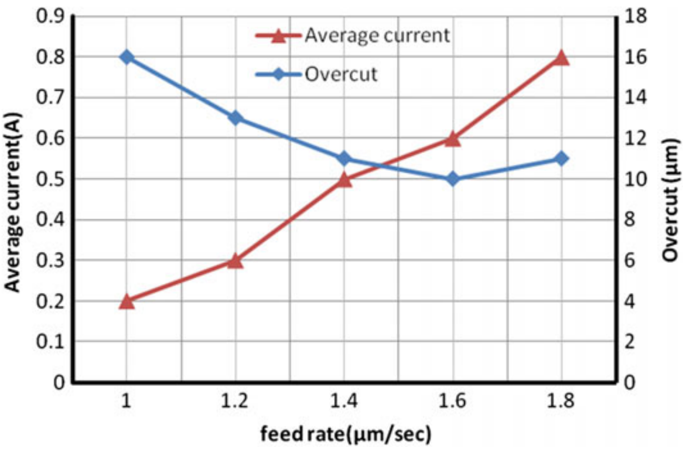

Fig. 3 Influence of tool feed rate on average current and overcut

of feed rate with quantity microsparks and overcut was investigated and plotted on a graph as shown in Fig. 3.

4.2 *Influence of Machining Voltage on MicroSpark and Overcut*

The effect of pulse voltage on overcut without vibration and with PZT tool vibration was investigated at 1.4 µm/sec tool feed rate, 50% duty ratio, 250 kHz voltage pulse frequency, 35lph electrolyte flow rate, 100 µm thick SS304 workpiece, Ø50µm tungsten wire electrode, 0.1 M H_2SO_4 and 60 Hz frequency with 12.94 µm amplitude of PZT vibration and with a range of 4–12 V applied voltage. It is observed that overcut is much less using PZT wire vibration during machining as shown in Fig. 4.

Further experimental trials are conducted to investigate the effect of applied voltage on overcut and the number of microsparks produced with the same above parametric conditions with PZT vibration. It is seen that when the applied voltage is on the lower side, the inter-electrode gap narrows and, micro-sparks occur more frequently due to poor removal of sludge and dissolved products from narrow IEG. It is eliminated with PZT vibration due to pressure created in the electrolyte. Also, it promotes the renewal of fresh electrolytes and the removal of dissolved products from the narrow IEG. It is again observed that the overcut and number of micro sparks increases with an increase in applied voltage and decreases with a decrease in applied voltage. A large voltage leads to a high current density, which induces a high material removing rate. Then a wide side gap is obtained which ultimately increases the overcut. Microsparks were observed during the initial machining process. As the machining process continued, microsparks vanished while the average current

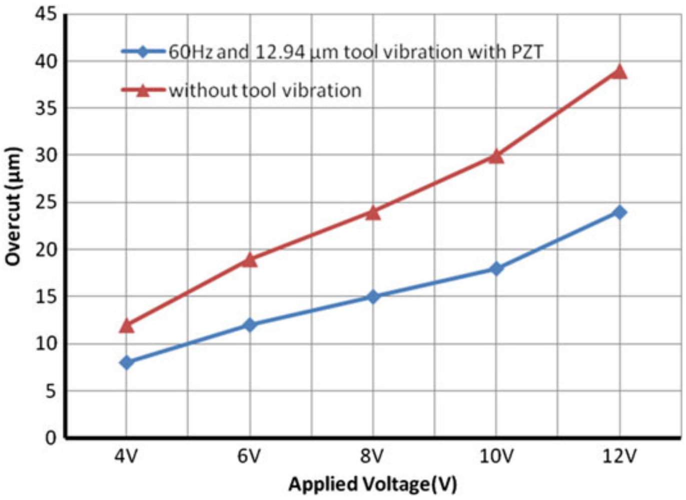

Fig. 4 Influence of applied voltage on overcut with and without PZT vibration

decreased. Furthermore, the wire loses its straightness and tension and resulting insufficient electrolyte flushing along the wire electrode in narrow IEG. As a result, the machining goal could not be accomplished. As per Faraday's and Ohm's laws, greater machining current into the machining gap created with higher applied voltage which increases the MRR leads to an increase in overcut and more number of micro-sparks which reduces homogeneity and accuracy of machining. It is found that applied voltage in the range of 4–6 V gives better control on the reduction of a number of microsparks and overcut. The applied pulse voltage effect on overcut and the number of micro-sparks are plotted graphically as shown in Fig. 5.

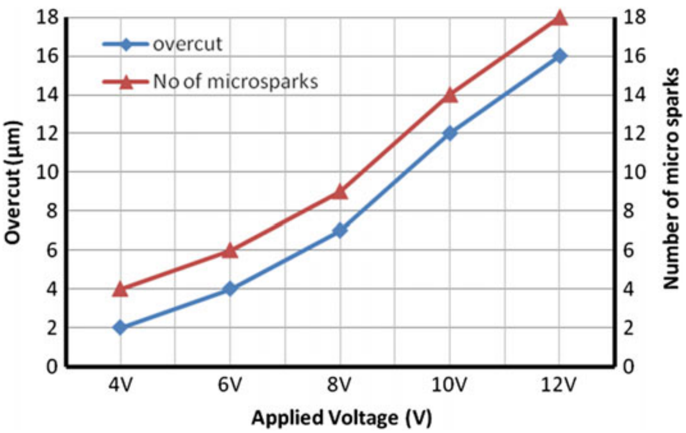

Fig. 5 Influence of applied voltage on overcut and number of microsparks

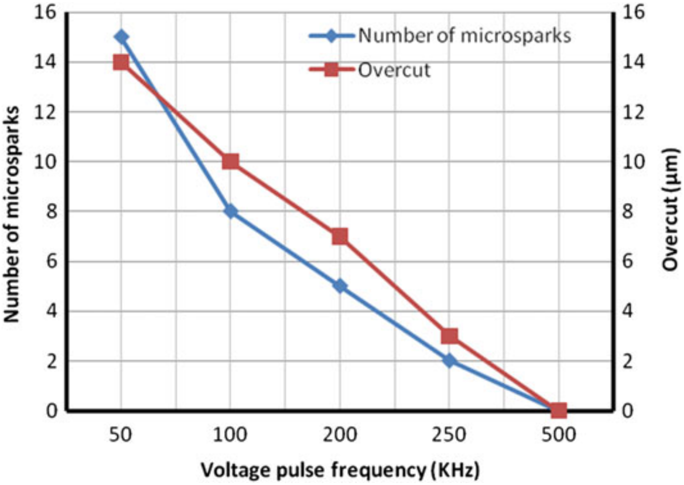

Fig. 6 Influence of voltage pulse frequency on overcut and number of micro sparks

4.3 Influence of Voltage Pulse Frequency on MicroSpark and Overcut

The experiments reveal the effect of applied voltage pulse frequency on overcut and a number of sparks produced during machining of microslits with 6 V applied voltage, 1.4 µm/sec feed rate, 40 Hz PZT vibration frequency, 12.94 µm PZT vibration amplitude, and 50–500 kHz range of voltage pulse frequency. It is observed that the value of the overcut of the microslit decreases almost linearly with the increase in applied voltage pulse frequency. Moreover, with a further increase in frequency beyond 500 kHz, then no machining will occur. It is also observed that with a decrease in the frequency value which may be up to 50 kHz, generation of more heavy microsparks occurs and the machining product will fully block the narrow IEG. As a result, machining will stop after starting. A voltage pulse frequency of 250 kHz is optimal for the reduction of microsparks and overcut. The graph for the influence of voltage pulse frequency on overcut and number of microsparks is plotted as shown in Fig. 6.

4.4 Influence of PZT Tool Vibration Frequency on a Micro Spark

The influence of micro-tool vibration frequencies on a number of micro sparks generated is investigated by conducting experiments with 6 V applied voltage, 1.4 µm/sec feed rate, 200 kHz voltage pulse frequency, and 12.94 µm PZT vibration amplitude. It is observed that for vibration frequencies of 0–5 Hz, it is not enough to remove

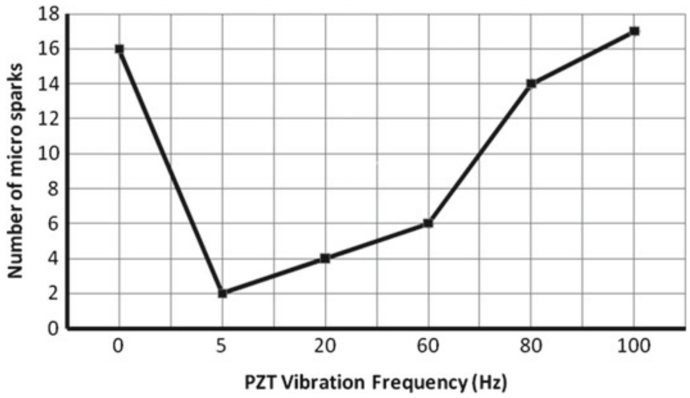

Fig. 7 Influence of PZT vibration frequency on a number of micro-sparks

the dissolved products from narrow IEG, and a number of micro spark generations are quite large which leads to unstable process stability. When the PZT frequency of vibration is higher than 40 Hz, the number of micro-sparks increases quickly due to wire electrode radial vibration which is more frequent at 80 Hz frequency. It is observed that vibration frequencies of 5–20 Hz have better control for the reduction of micro-sparks as shown in Fig. 7. Therefore, a proper range of PZT vibration frequency has a considerable effect on the better renewal of fresh electrolytes. It also improves the machining stability and accuracy.

4.5 Influence of PZT Vibration Amplitude on Micro-Sparks

An experimental trial has been conducted with 6 V applied voltage, 1.4 μm/sec wire feed rate, and 200 kHz voltage pulse frequency, 20 Hz PZT vibration frequency with 0–50 μm range of PZT vibration amplitude of wire vibration. It is observed that when vibration amplitude is lower than 10 μm, renewal of electrolyte was difficult due to less pressure in narrow IEG. On the other hand, micro-sparks occur with high frequency with unstable machining. The range of 10–20 μm micro-tool vibration amplitudes generates quite fewer micro-sparks which leads to better processing stability during micromachining. However, At PZT amplitude higher than 20 μm, the number of micro-sparks increases due to the more wire electrode radial swing, resulting in unstable machining. The influence of PZT vibration amplitude on a number of micro-sparks was observed as shown in Fig. 8.

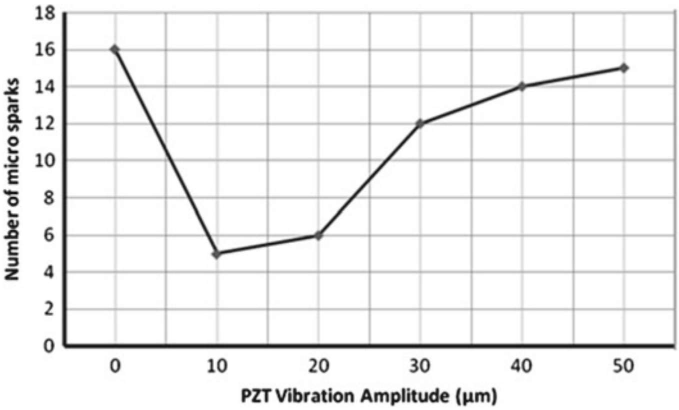

Fig. 8 Influence of PZT vibration amplitude on number of micro sparks

5 Controlled Parametric Micro-Slit Fabrication

After finding out the influence of various predominant machining parameters and using a controlled parametric combination of 6 V voltage, 1.4 μm/sec feed rate, 250 kHz voltage pulse frequency, 20 Hz PZT vibration frequency, and 10 μm PZT vibration amplitude, micro-slit has been fabricated. As IEG is 100 μm which is quite large, it has taken a considerable amount of time to overcome the effect of micro sparks and to reduce the chances of overcut at the entry point of machining, but micro-slit is quite smooth and homogeneous as shown in Fig. 9.

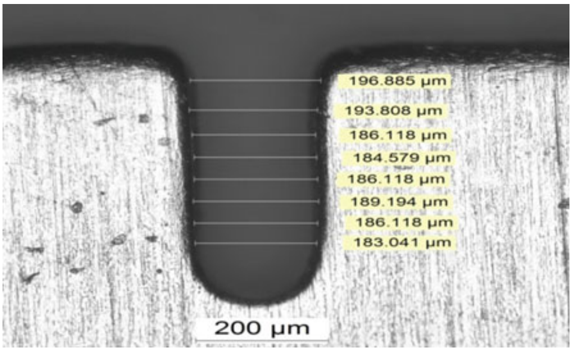

Fig. 9 Micro-slit fabricated with controlled parametric condition

6 Conclusions

The present experimental investigation highlights that effect of micro-sparks and overcut on dimensional characteristics of the microslit during wire electrochemical micromachining is greatly influenced by the various influencing process parameters. The influence of different process parameters on the generation of a number of micro-sparks and overcut were exhibited through graphical plots. Based on the above graphical plot representations and observations, the following conclusion has been drawn.

(i) Experiments with increasing feed rate have resulted in a decrease in overcut and with higher value of feed rate started showing abrupt change and increasing trend in overcut problem due to coagulation of reaction products in the IEG due to uncontrolled micromachining process. Average current increases with an increase in feed rate and micro-sparks occur at higher currents. It is observed that wire feed rate in the range of 1.4–1.6 μm/sec gives better control for the reduction of average current and overcut.

(ii) The overcut and a number of micro-sparks increase as applied voltage increases. Again it is observed that overcut is less when the micromachining operation is performed with a tool vibration PZT system. It is found that applied voltage in the range of 4–6 V gives better control on the reduction of a number of microsparks and overcut.

(iii) Experimental results reveal that with the increase in applied voltage pulse frequency, the value of the overcut of the micro-slit decreases almost linearly but at the very low frequency, the number of micro-sparks increases which reduces the process stability and homogeneity. A voltage pulse frequency of 250 kHz is optimal for the reduction of micro-sparks and overcut.

(iv) It can be concluded that low frequency and small amplitude vibration of wire electrodes with PZT significantly improves processing stability by reducing the generation of micro sparks and overcut. It is observed that vibration frequencies of 5–20 Hz with 10–20 μm micro-tool vibration amplitudes of wire vibration with PZT has better control over the reduction of microsparks.

WECMM plays a crucial role in machining desired complex microfeatures. However, an in-depth research is still required to improve the potential and effectiveness of the process by determining suitable machining conditions as well as strict control of operating parameters in the future.

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