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ORIGINAL ARTICLE

Influence of electrochemical micromachining parameters during generation of microgrooves

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Abstract Fabrication of microparts has become increasingly important with an advancement of product miniaturization in various fields. Microgrooves are used as one of the key microfeatures in many microproducts like microthermal devices, microheat exchangers, microreactors, micropumps, and micromechanical systems. Electrochemical micromachining (EMM) can be effectively utilized for the fabrication of microgrooves because of its important benefits like reusability of the tool, no stress, burr-free surfaces, and ability to cut the material irrespective of the hardness. This paper presents the influence of EMM parameters like applied voltage, pulse frequency, duty ratio, tool feed rate, and electrolyte concentration on the machining accuracy, i.e., width overcut, depth overcut, and material removal rate during fabrication of a 500 μm-deep microgroove in stainless steel. An in situ-fabricated tungsten microtool of 110 μm diameter was used to generate a microgroove using the developed EMM setup. A high-quality microgroove with 55 μm width overcut and 10-μm depth overcut with an aspect ratio of 2.31 was fabricated using the optimum setting of machining parameters.

Keywords Electrochemical micromachining · Microgroove · Overcut · MRR · Aspect ratio

1 Introduction

Product miniaturization is the recent trend in manufacturing of industrial and household products due to the multiple benefits of microproducts like low cost and less space and material, with the improved product functioning. As microcomponents are in imperative demand, fabrication of microparts became an important issue with the advancement of product miniaturization in various fields, namely, MEMS, optical systems, electronics, and biomedicine. Microgrooves of various shapes and sizes are one of the key microfeatures for many kinds of microparts like microthermal devices, microheat exchangers, microreactors, and microfuel cells. A high aspect ratio microgroove provides a large surface area for heat dissipation and reaction systems and provides high capillary force for microheat pipes and micropumps, since in microfluidics, frictional force and capillarity vary according to the shape and size of the microgroove. Microgrooves can also be used as slideways in micromechanical systems and microchannels in microdies and biomedical and biochemical applications. Microparts are made from advanced engineering materials like super alloys, titanium, aluminum alloys, copper alloys, and stainless steel, which are hard and difficult to cut by conventional machining methods. Non-conventional machining methods are more beneficial to fabricate various microfeatures like microholes and microgrooves. Even though many non-conventional micromachining techniques are available for fabrication of microfeatures on microparts, each method has some benefits and limitations like in case of micro EDM, EBM, and LBM where heat-affected zones, residual stresses, and surface cracks are unavoidable, whereas it is difficult to control the depth of the microgroove in case of wet chemical etching and LIGA. Electrochemical micromachining (EMM) has the capability to fabricate microfeatures like microholes, microgrooves, and 3-D microstructures on microproducts due to its several advantages like no tool wear, better precision, good surface finish, stress- and crack-free surface, and ability to machine complex shapes in metallic materials regardless of their hardness.

Based on present research, developments, and industrial practice in micro ECM, Bhattacharyya et al. highlighted that the dissolution of an anodic material can be restricted to the

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region very close to the electrode surface by applying ultrashort voltage pulses [1]. Liu et al. developed microelectrodes with various end shapes by electrochemical etching, single electric discharge, and electrochemical micromachining of diameters less than 6 μm and used fabricated microtools to machine microhole arrays with a diameter of less than 10 μm, microholes with no taper, and a 3-D microstructure with plane surfaces on nickel by EMM process [2]. Zhang et al. constructed a micromachining system based on electrochemical dissolution of a material, in situ fabricated a tungsten microtool electrode of 8 μm diameter, and machined the cross of a 30 μm groove width having sharp edges [3]. Munda et al. developed a mathematical model for correlating the influences of various electrochemical machining parameters, i.e., machining voltage, duty ratio, electrolyte concentration, pulse frequency, and tool vibration frequency, on the predominant micromachining criteria, i.e., the material removal rate and the radial overcut through response surface methodology, and also obtained optimal parametric conditions from developed mathematical models for higher machining rate with accuracy [4]. Liu et al. developed an EMM system for achieving a micron-sized complex structure and recommended low machining voltage, smaller pulse-on time, minor tool diameter, and higher tool feed rate to improve the machining accuracy and surface quality of microstructures [5]. Jain et al. designed and fabricated an ECMM setup to machine microholes and microchannels on stainless steel with insulated sewing needle as a tool [6]. Malapati et al. investigated the influence of EMM parameters during microchannel generation on copper foils using cylindrical tungsten microtool by scanning type movement for minimum overcut and recommended lower duty ratio, lower voltage, low electrolyte concentration, and higher frequency for accurate microchannels [7]. Kim et al. machined 3-D microstructures by restricting the dissolution of the workpiece to a very close region around the electrode by applying ultrashort pulses, introduced the use of disc-type tools to reduce the taper, and successfully fabricated high aspect ratio microstructures like microcolumns and microwalls with negligible taper [8]. Yan et al. fabricated microgrooves of various cross sections by electrodischarge machining method using different shapes of in-house fabricated rotary tungsten tool electrodes on a stainless steel surface. However, tool wear puts the limitation on the repeated use of the microtool electrodes during generation of microchannels [9]. Shin et al. minimized the side gap by applying ultrashort voltage pulses between the tool electrode and the workpiece. Changes in the side gap according to the applied voltage, pulse-on time, and pulse period were investigated, and the optimal pulse condition for stable machining was obtained. By using optimal pulse parameters, microfeatures such as microgrooves and gears were fabricated into stainless steel plates with a platinum microwire of 10 μm diameter [10]. Zeng et al. proposed different approaches for enhancing electrolysis product mass transport from a tiny machining gap between the cathode wire and anode to avoid frequent electric short circuits and improved machining stability, productivity, and the surface quality during machining of micogrooves and microstructures by wire electrochemical machining [11]. Oh et al. fabricated deep microgrooves with an aspect ratio of over 10 by applying multiple etching process parameters and adjusted the cross-sectional profile of the microgrooves between rectangular and triangular shapes by controlling laser power and etchant concentration using laser-assisted wet etching [12]. From the literature review, it is seen that fabrication of a high aspect ratio microgroove on a metallic surface by EDM puts the limitations due tool wear, and by electrochemical micromachining, it is difficult to maintain the uniform cross section of the groove for higher depth, due to the taper formation along the vertical walls. In chemical etching, it is difficult to fabricate high aspect ratio microgrooves, and by laser machining, a heat-affected zone is unavoidable as well as microgroove tapers as depth increases, since laser power decreases with depth. Because of the extensive application of microgrooves in the fabrication of microparts, microgrooves of desired shape, size, and surface quality have become the focused area of research.

In EMM, while fabricating microgrooves of high aspect ratios, removal of dissolved electrolysis products becomes more and more difficult and the machining process may stop if the suitable working parameters are not controlled. Much less information is available on the parametric analysis when depth of the groove exceeds 200 μm while fabricating microgrooves on metallic surfaces by EMM. This paper presents the influence of EMM process parameters on machining accuracy, i.e., width overcut, depth overcut, and material removal rate (MRR) during the generation of a 500 μm-deep microgroove on a stainless steel sheet by an in situ-fabricated tungsten microtool of 110 μm diameter using the developed experimental setup. After the various sets of experiments, a microgroove with a 55 μm width overcut, 10 μm depth overcut, and aspect ratio of 2.31 was fabricated with optimal machining parameters. Conditions of the machined microgroove have been analyzed through scanning electron microscope (SEM) micrographs.

2 Principle of EMM

EMM is an electrochemical anodic dissolution process in which pulsed direct current with low voltage is applied between the metallic work piece (anode) and microtool electrode (cathode) having few microns of inter-electrode gap, placed in an electrolyte. The anodic material dissolves into metallic ions by the electrochemical reactions, and hydrogen gas bubbles are formed on the cathode surface. A micron-scale electrode of desired shape and size is used as cathode. The microtool moves with constant feed rate towards the workpiece to maintain the fixed inter-electrode gap (IEG). Following the scheduled path of the microtool, the desired microgroove can be fabricated as shown in Fig. 1. An electrolyte in which electrolysis products get dissolved is generally used. The electrolyte carries away the heat generated during the machining process at the inter-electrode gap.

When a microelectrode is placed in an electrolyte with very small inter-electrode gap, R_S is the side gap electrolyte resistance and R_b is the resistance of the electrolyte at the bottom of the tool as encircled in Fig. 2. During machining when the tool is feeding downward, R_b is the shorter electrolyte resistance path between the tool bottom and workpiece; hence, the dissolved area is the region under the rear end of the tool resulting drilling operation. When the tool feed is in X/Y direction, R_s is the electrolyte resistance of shorter path, and anodic dissolution takes place around the tool sidewall, resulting grooving operation on the workpiece.

3 Experimental setup

The developed experimental setup for fabrication of microgrooves consists of various subsystems, namely, mechanical machining unit, direct current (DC) pulsed power supply, digital storage oscilloscope, and desktop computer along with a stereo zoom microscope. The mechanical machining unit consists of three long travel linear stages, assembled to form three mutual perpendicular axes. A worktable was mounted over X and Y axes and Z axis over the gantry bridge. The stepper motors of each linear stage, having a resolution of 0.3125 μm/step, were controlled by a stepper motor controller unit which was interfaced with the desktop computer using position controller software. Various feeds can be given to all or any of the three stepper motors at a time through the stepper motor controller unit. A function generator was used to generate pulsed DC supply with various parameters like pulse frequency, pulse period, voltage amplitude, and duty ratio. For online monitoring and digital storage of generated pulse, a digital oscilloscope was used. An A.C. servo voltage stabilizer was used to provide regulated power supply to the mechanical machining unit, stepper motor control unit, desktop computer, function generator, and digital oscilloscope. An electrolyte tank was fabricated from a Perspex material, with work holding arrangement. During machining, the tank was preset on the worktable. The microtool was mounted on the tool holder and positioned on the Z axis, having upward and downward movements. Figure 2 shows the schematic diagram of developed experimental setup.

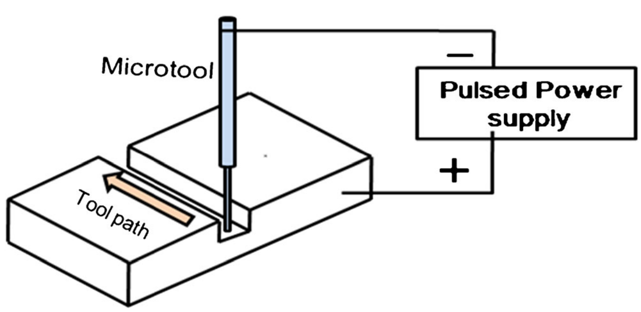


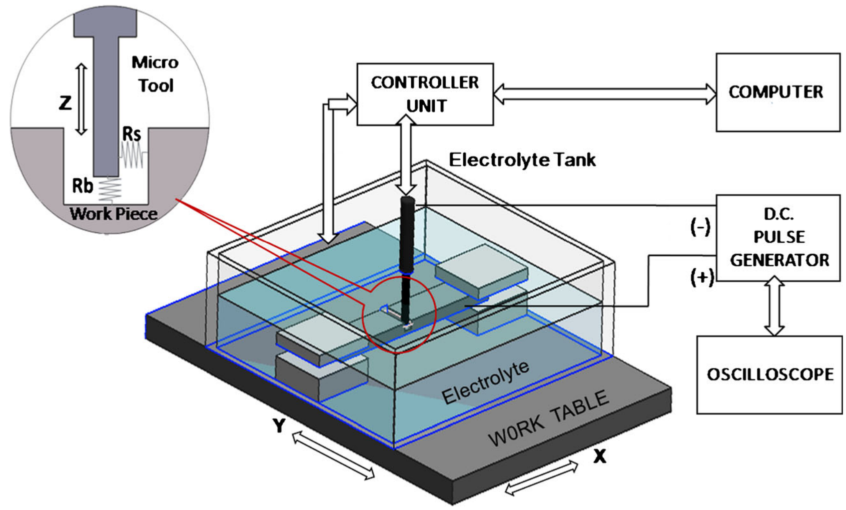
Fig. 1 Schematic diagram of microgroove fabrication

4 Experimental planning

In EMM, the accuracy of the microtool in terms of shape, size, and surface finish is very important since it directly affects the accuracy of machining; therefore, a precise microtool electrode of micron-scale size with good surface quality is required for the fabrication of accurate microgrooves. Tungsten is the best suitable microtool material to be used in EMM because of its properties like high rigidity, toughness, high melting point, and high electrical and thermal conductivities and its resistance to chemicals. A microtool was in situ fabricated by reverse electrochemical micromachining using developed EMM setup and used for the generation of a microgroove in the experiments. To fabricate a microtool, a straight tungsten microrod specimen of 200 μm diameter and 15 mm length was used. The ends of the specimen were ground, polished, and cleaned. The length and tool tip conditions were observed under the optical microscope to check the existence of flaws or cracks if any before machining. The microrod specimen was fixed to the tool holder unit, positioned vertically downward, and immersed in electrolyte at the center of the hole drilled in the stainless steel sheet. Potential difference was applied in between the tool as anode and stainless steel sheet as cathode. During machining, tungsten ions are dissolved into the electrolye at the anode and hydrogen gas bubbles are generated on cathode surface. Dissolution of ions at the microtool surface forms a non-uniform diffusion layer, which affects the electric field distribution of the electrochemical reaction and final shape of the microtool. By controlling the various machining parameters like applied voltage, pulse frequency, duty ratio, machining time, and electrolyte concentration, the microtool of desired shape, size, and surface quality can be developed. Figure 3 shows the SEM image of the in situ-fabricated straight cylindrical microtool of 110 μm diameter and 1,050 μm length with improved surface quality.

Stainless steel was selected as the workpiece material for microgrooving because of its properties like high corrosion resistance, high strength, and higher melting point, and different alloys can be obtained by varying alloying elements for any specific applications like microthermal devices and microheat exchangers. While machining a microgroove, the microtool fed downward by 500 μm from the top face with 15 μm of inter-electrode gap between the microtool and workpiece surface. To avoid any damage to the microtool

Fig. 2 Schematics of EMM setup



during IEG setting, the tool was fed with a very low tool feed rate of about 6 μm/s and low voltage of about 1 V. A set of experiments were carried out with various process parameters to investigate their influence on accuracy, i.e., width overcut (WOC), depth overcut (DOC), and MRR of the microgroove. Figure 4 shows the schematic diagram for the measurement of the fabricated microgroove. Width overcut is the excess material removed across the width of the microgroove and is calculated as

$$WOC = \frac{(W-D)}{2} \tag{1}$$

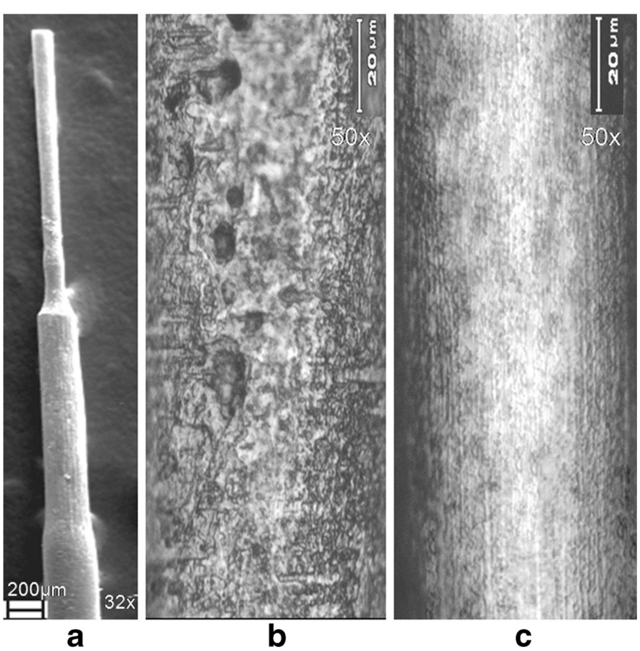


Fig. 3 **a** SEM image of the straight cylindrical microtool. **b** Surface micrograph before machining. **c** Surface micrograph of the finished microtool

where W is the average groove width and D is the microtool diameter.

Depth overcut is the extra-dimensional machining at the bottom of the groove and is calculated as

$$DOC = H_2 - H_1 \tag{2}$$

where H_2 is the total depth of the groove and H_1 is the tool feed depth.

Material removal rate is the amount of material removed per unit time and is calculated as

$$MRR = \frac{(H_2 \times W \times L)}{t} \tag{3}$$

where H_2 is the total depth of groove, W is the average groove width, L is the length of the microgroove, and t is the total time of machining.

While calculating MRR, radial curvatures at the bottom of the microgrooves were neglected.

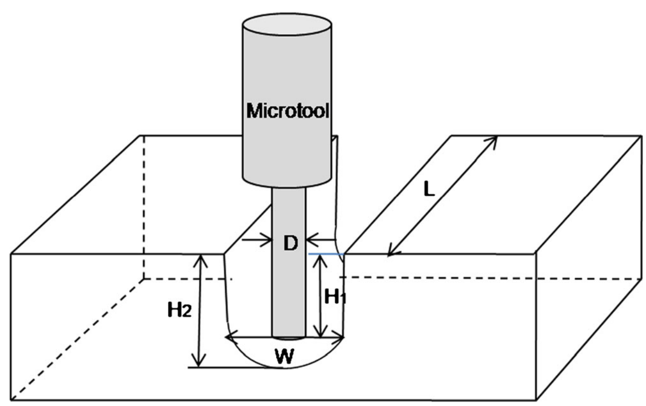


Fig. 4 Schematic illustration of the fabricated microgroove

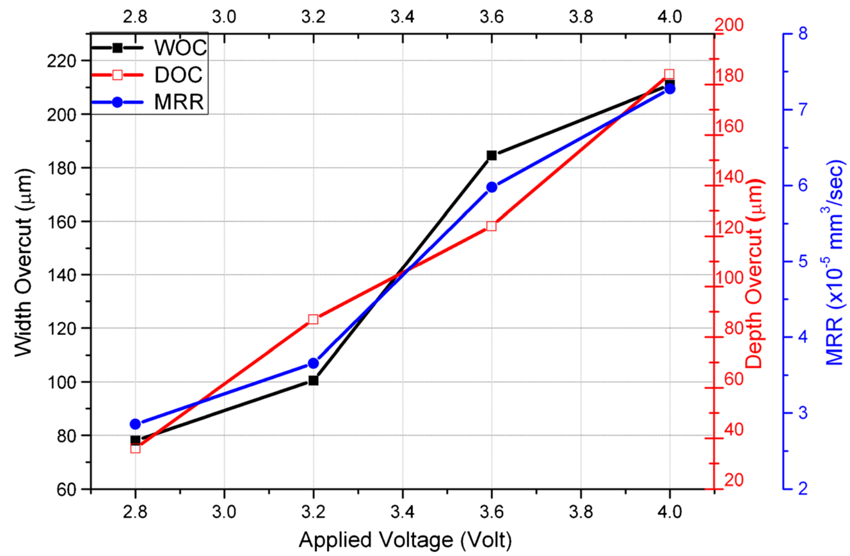


Fig. 5 Effect of applied voltage

5 Results and discussion

To investigate the influence of EMM process parameters such as applied voltage, pulse frequency, duty ratio, tool feed rate, and electrolyte concentration during fabrication of the microgroove, experiments were planned and carried out by varying one parameter at a time. The effects of process variables were measured in terms of machining accuracy, i.e., width overcut, depth overcut, and MRR. The upper and lower ranges of the machining parameters were finalized from few trial experiments and literature review.

5.1 Effect of applied voltage on machining accuracy and MRR

Experiments were conducted with an applied voltage in the range of 2.8 to 4 V, pulse frequency of 5 MHz, duty ratio of 35 %, and tool feed rate of 0.2 μm/s in an electrolyte of 0.15 M H_2SO_4.

Figure 5 shows the influence of applied voltage on width and depth overcut of the microgroove as well as material removal rate. It shows that width overcut, depth overcut, and material removal rate increase with an increase in applied voltage. In an electrochemical reaction, the total current supplied during the pulse period is the sum of faradic current and non-faradic current as shown in Fig. 6. Faradic current determines the material dissolution rate, and non-faradic current results from current flow that charges and discharges the double layer capacitance.

The amount of material removed during EMM can be determined by combining Faraday's law and Ohm's law as [13]

$$V_m = \frac{CAE}{gr} t \tag{4}$$

where V_m is the volume of the material removed, C is the electrochemical constant, A is the electrode surface area, E is the voltage, g is the IEG, r is the electrolyte resistivity, and t is the time of machining.

For the pulsed supply, material removal takes place only for the pulse-on (τ_{on}) period; hence, the volume of material removed during the pulse period can be given as

$$V_m = \int_0^{\tau_{on}} \frac{CAE}{gr} dt. \tag{5}$$

Since material removal takes place during the time corresponding to the faradic currents, hence, the better approximation

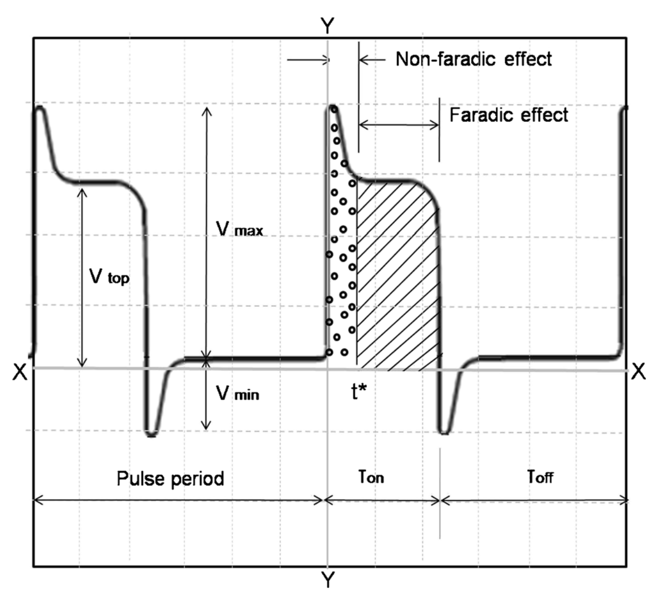


Fig. 6 Schematics for charging and discharging of waveform

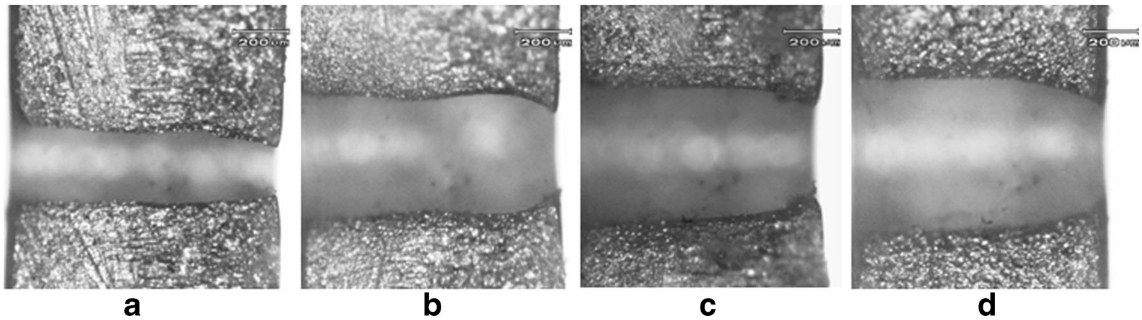


Fig. 7 Microgrooves machined at different voltages. **a** 2.8 V, **b** 3.2 V, **c** 3.6 V, and **d** 4.0 V

for the volume of material removed during pulse-on time can be given as

$$V_{on-time} = \int_{t*}^{\tau_{on}} \frac{CAE}{gr} dt \quad (6)$$

$$V_{on-time} = \frac{CAE*}{gr} (\tau_{on} - t*) \quad (7)$$

where $E*$ is the magnitude of the flat voltage from $t*$ to τ_{on}.

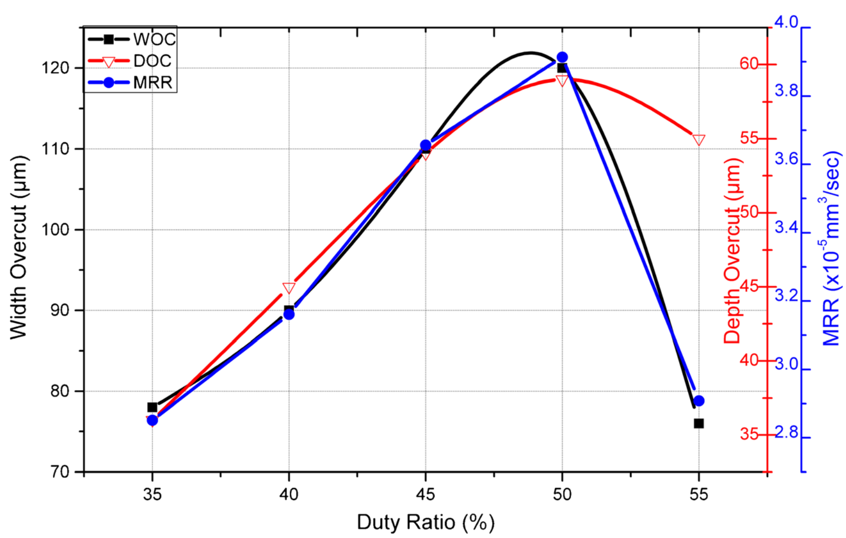
With the increase in applied voltage, there is increase in faradic current as well as duration for which it is applied, which increases in the tool polarization area and decreases localization effect, resulting in increased material removal rate and increase in width and depth overcuts of the groove. From the graph, it can be seen that overcut and MRR increase gradually with applied voltage of up to 3.2 V, and afterward, it increases rapidly; this is because at higher voltages, the magnitude of flat voltage ($E*$) and the time of faradic current (t_{on}-$t*$) increase, which leads to the increase in faradic effect causing rapid increase in overcuts and MRR. Hence, for fabricating accurate microgrooves, machining with lower voltages is recommended. Figure 7 shows microscopic images of the microgrooves machined with different voltages.

5.2 Effect of duty ratio on machining accuracy and MRR

Microgrooves were machined with an applied voltage of 2.8 V, pulse frequency of 5 MHz, 0.15 M electrolyte concentration, tool feed rate of 0.2 μm/s with duty ratios in the range of 35 to 55 %. Figure 8 shows the effect of duty ratio over the machining accuracy of microgroove and material removal rate. From the figure, it can be seen that with the increase in duty ratio, overcut and MRR increase gradually up to a certain value, and after, they decrease. This is because the pulse period is the sum of pulse-on time and pulse-off time, and duty ratio is the ratio of pulse-on time to the pulse period. Duty ratio signifies the percentage of time for which pulse remains on. With increase in duty ratio, faradic current and time of faradic current ($\tau_{ON\text{-}t*}$) increases. The amount of faradic effect which increased with the increase in current density results in more material removal and causes increase in overcuts and MRR.

When duty ratio exceeds 50 %, the amount of hydrogen gas bubbles generated on the tool surface increases considerably in a narrow inter-electrode gap. During machining of the microgroove, bubbles are attached to the lateral surface of the tool, restricting the presence of fresh electrolyte and affecting the dissolution process, and hence, width overcut,

Fig. 8 Effect of duty ratio



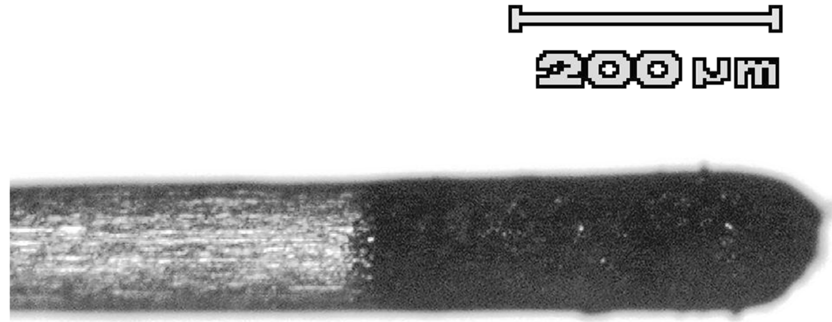


Fig. 9 Accumulated by-products on tool surface at higher duty ratio

depth overcut, and MRR decrease with irregular shape of the microgroove. Increase in duty ratio, i.e., pulse-on time, decreases pulse-off time, permitting less time for removal of metallic sludge. It thereby increases the number of short circuits and accumulation of by-products on the tool surface as shown in Fig. 9, resulting in irregularity of the generated shape. Hence, for machining microgrooves with lesser overcuts, machining with lower duty ratio is recommended.

5.3 Effect of electrolyte concentration on machining accuracy and MRR

Figure 10 shows the influence of electrolyte concentration on groove width overcut, depth overcut, and material removal rate while machining microgroove with an electrolyte concentration of 0.15 to 0.27 M H_2SO_4 with an applied voltage of 2.8 V, pulse frequency of 5 MHz, duty ratio of 35 %, and tool feed rate of 0.2 μm/s. From the graph, it is revealed that groove overcuts and material removal rate increase with increase in electrolyte concentration. This is because the number of ions available for electrochemical reaction increases with the increase in electrolyte concentration. The increased number of ions in the electrolyte increases electrical conductivity, i.e., there is a decrease in the value of electrolyte resistivity *r* in Eq. 4, resulting in the increase in volume of material removed. This is due to the fact that the faradic current increases with an increase in electrical conductivity, increasing the tool polarization area and decreasing the localization effect of the electric field. With further increase in electrolyte concentrations, more hydrogen gas bubbles are generated over the surface of the tool. The increased number of bubbles affects the dissolution process and also reduces the removal of sludge from IEG. It thereby results to less material removal with reduced width overcut and depth overcut with irregular shape of the groove. Hence, for machining accurate microgrooves with minimum overcuts, machining with lower electrolyte concentration is recommended.

5.4 Effect of tool feed rate on machining accuracy and MRR

Figure 11 plots the width overcut, depth overcut, and MRR during microgroove machining with tool feed rates in the range of 0.1 to 0.25 μm/s, applied voltage of 2.8 V, pulse frequency of 5 MHz, duty ratio of 35 %, and electrolyte concentration of 0.15 M H_2SO_4. The graph shows that width and depth overcuts decrease with an increase in tool feed rate. This is because the higher tool feed rate allows the tool to remain available for machining for a shorter time, compared to

Fig. 10 Effect of electrolyte concentration

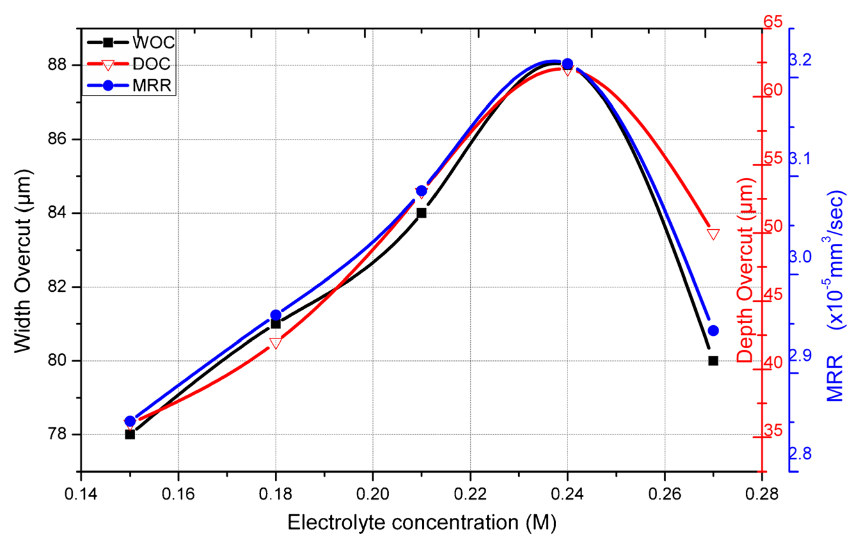
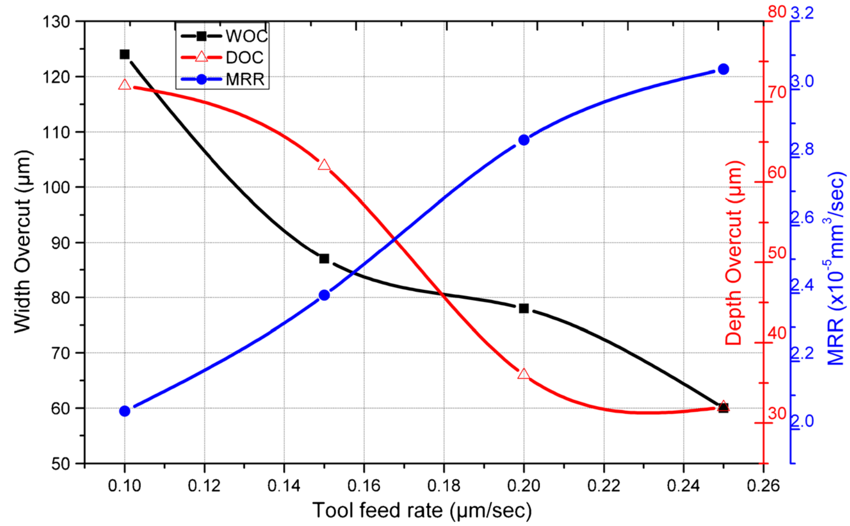


Fig. 11 Effect of tool feed rate



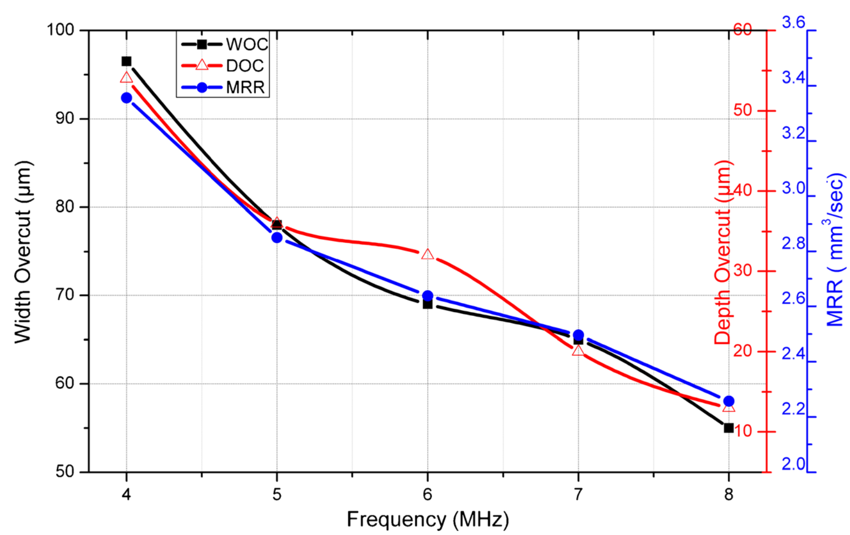
low feed rate. Increased tool feed rate reduces inter-electrode gap, and smaller IEG improves localization of the electric field over the smaller area, resulting in more accuracy in machining.

Material removal rate varies linearly with tool feed rate. At lower tool feed rate, though width and depth overcuts are higher, i.e., volume of the material removed is more and total time taken for the machining is more, overall material removal rate is lower in case of low feed rate and it increases with tool feed rate because of the decrease in total machining time. However, for stable machining, there has to be enough time for sludge removal so that material removal rate will keep the pace with tool feed rate to avoid short circuit due to frequent touching of the tool to the sludge or workpiece surface. This was verified by a trial experiment; while deciding a higher range for tool feed rate of 0.25 μm/s above, it was not possible to perform micromachining due to continuous short circuits.

5.5 Effect of pulse frequency on machining accuracy and MRR

Microgrooves were fabricated by varying the pulse frequency in the range of 4 to 8 MHz, applied voltage of 2.8 V, 35 % duty ratio, 0.15 M H_2SO_4 electrolyte concentration, and tool feed rate of 0.25 μm/s. Figure 12 shows a graphical representation for the effect of pulse frequency on groove width overcut, depth overcut, and material removal rate. It indicates that width overcut, depth overcut, and MRR decrease as pulse frequency increases. For any single pulse with fixed duty ratio, the amount of faradic current decreases with increase in pulse frequency, i.e., the duration during which pulse is applied (t_{on}-t^*) is higher for lower applied frequency and it decreases rapidly with increase in frequency. This reduces the tool polarization area by improving the localization effect, resulting in less overcuts, i.e., increased accuracy of the

Fig. 12 Effect of pulse frequency



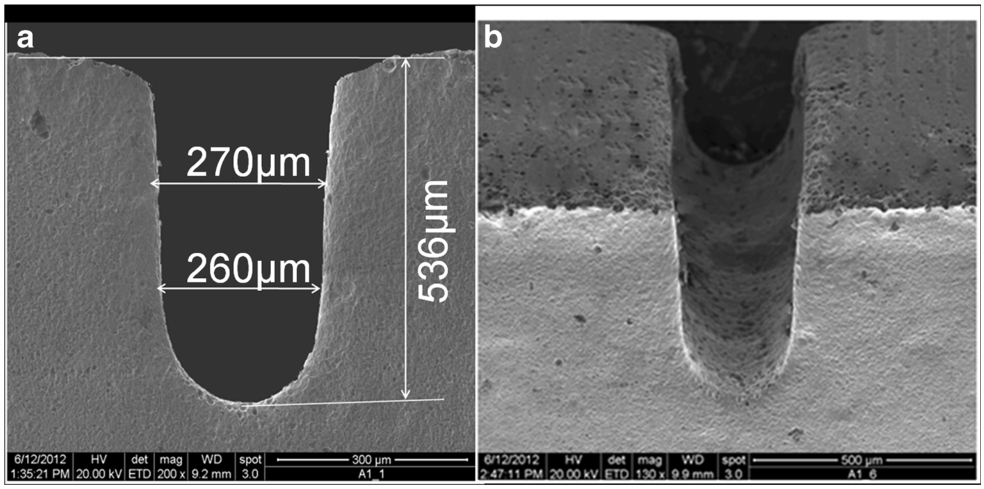


Fig. 13 SEM micrograph of the machined microgroove. **a** Front view and **b** perspective view

microgroove and reduced MRR. Hence, for fabricating accurate microgrooves with minimum overcuts, machining with higher frequency is recommended. However, a very high frequency with low voltage and high tool feed rate may cause continuous short circuit and tool breakage, resulting in very poor surface finish.

5.6 SEM analysis and fabrication of microgroove with optimal parameter settings

Figure 13 shows a SEM image of the microgroove machined with the working condition of an applied voltage of 2.8 V, pulse frequency of 5 MHz, duty ratio of 35 %, and tool feed rate of 0.2 μm/s in an electrolyte of 0.15 M H_2SO_4. It shows that during the generation of microgrooves, excess material is removed by the cylindrical surface and bottom surface of the tool causing width overcut and depth overcuts. As machining proceeds, stray current causes material dissolution from the top surface of the workpiece to the lateral surface of the tool which is above the groove depth and not insulated. Therefore, excess length of the tool needs to be insulated to minimize dissolution of the material forming a concave surface along the length of the groove over the top surface of the workpiece.

After various sets of experiments, finally, the microgroove was machined with optimal setting of machining parameters, i.e., applied voltage of 2.8 V, pulse frequency of 8 MHz with duty ratio of 35 %, and tool feed rate of 0.25 μm/s in 0.15 M H_2SO_4 electrolyte concentration and which revealed minimum overcut. Figure 14 shows the microscopic image of the microgroove machined with optimal parameter setting. A microgroove with an aspect ratio of 2.31 is successfully machined with minimum width and depth overcuts of 55 and 10 μm, respectively.

6 Conclusions

Microgrooves are one of the key microfeatures adopted on microproducts in various fields. Shape, size, and surface quality of the microgrooves affect product functionalization and

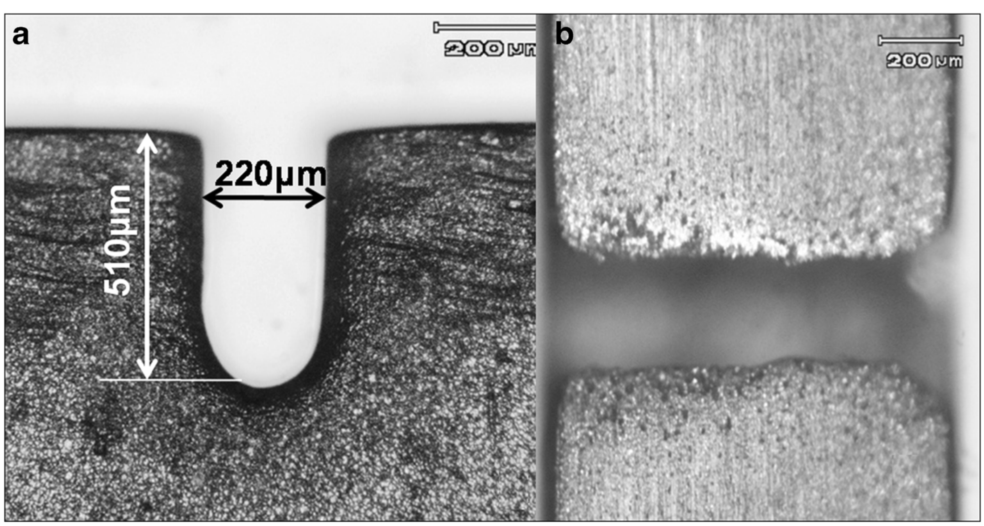


Fig. 14 Microgroove machined with optimal parameter setting. **a** Front view and **b** top view

the service life of the microproduct. In EMM, it is possible to fabricate accurate and precise microgrooves since the material is removed at ionic level. Shape, size, and surface quality of the microtool used directly affect the quality of the microgroove; hence, an in situ-fabricated microtool of better surface quality was used in the experimentation for investigating the influence of EMM process parameters on the accuracy and material removal rate. Based on the experimental results, important conclusions can be drawn as follows:

1. Machining with lower voltage, lower electrolyte concentration, higher pulse frequency, lower duty ratio, and higher tool feed rate is recommended for better accuracy of the microgroove.
2. For higher material removal rate, machining with higher voltage, lower frequency, higher duty ratio, higher electrolyte concentration, and higher tool feed rate is suggested. However, higer MRR affects the accuracy and surface quality of the microgroove. Increased number of bubbles generated at a very high voltage and higher electrolyte concentration in narrow IEG affects the dissolution process.
3. Stray current affects the accuracy and surface quality of the microproduct; hence, to minimize the stray current, excess length of the microtool needs to be insulated. During the machining of microgroove, material dissolution takes place through the lateral surface of the tool generating the microgroove along the length and also through the bottom surface of the tool generating the radius of curvature at the bottom of the groove.
4. From the experimental results, best machining parameters are found to be as follows: applied voltage of 2.8 V, pulse frequency of 8 MHz, duty ratio of 35 %, electrolyte concentration of 0.15 M, and tool feed rate of 0.25 μm/s. A microgroove with a minimum depth overcut of 10 μm and width overcut of 55 μm, having an aspect ratio of 2.31, was successfully fabricated with optimal parametric values by using an in situ-fabricated straight cylindrical microtool of 110 μm diameter and 1,050 μm length.

The present study of fabricating microgrooves by EMM will be very useful for selecting machining parameters while fabricating microgrooves of various sizes on metallic surfaces for microthermal devices, microheat pumps, microheat exchangers, etc. Circulation of fresh electrolyte in the machining area improves the accuracy of the microgroove. Hence, for better surface quality and machining accuracy, the design of a proper microtool and strategy for microtool movement need to be improved further.

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