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ORIGINAL ARTICLE

Fabrication of microgrooves with varied cross-sections by electrochemical micromachining

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Abstract Microgrooves are one of the important micro-features machined on various microproducts. The demand of complex microgrooves with varied cross section has increased in various fields, since specific cross-sectional shape of microgroove improves the product performance, due to increased inner surface area. Machining of simple microgroove is relatively easy, but when the cross section of the microgroove is varying along its depth, it becomes difficult from microtool fabrication point, as well as from the process point of view. The purpose of this study is to verify the possibilities of machining varied cross-sectional microgrooves on metallic surfaces by electrochemical micro-machining (EMM). Different cross sections of the microgrooves have been machined by regulating the important EMM process parameters such as applied voltage, duty ratio, and machining time, along the depth during machining of microgrooves, utilizing developed experimental setup. This technique enables the machining of various cross sections of the microgrooves by EMM utilizing the single-disk shape microtool. Finally, machining of different cross-sectional microgrooves like reverse tapered, barrel shaped, double stepped, spherical based microgrooves, and microgroove with internal pocket has been demonstrated successfully. The experimental findings may be useful for machining of complex microgrooves suitable for micro-coolers, micro-reactors, and micro-mixers etc. which needs specific geometry for product functioning.

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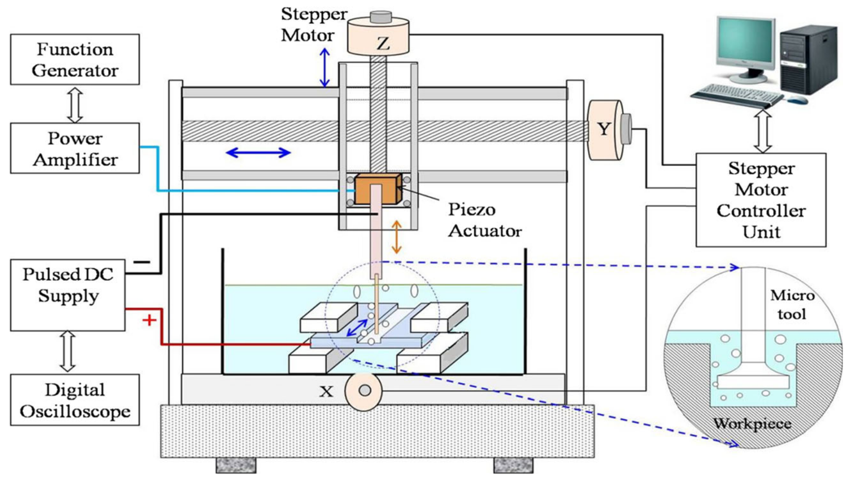
1 Introduction

Miniaturization is the principal driving force for twenty-first century's industrial technology because of the escalating demands for compact, intelligent, multi-functional, and economical engineering products. In recent years, microproducts have revolutionized the field of electronics, telecommunications, and computers, which uses silicon-based materials. With the development of MEMS and multiple benefits of the micro-systems, microproducts are widely accepted in various fields of applications like aerospace, automotive, biomedicine etc. The micro-manufacturing processes for silicon-based materials are highly developed, whereas the micro-manufacturing processes for metallic materials need further development for better applications. Applications like micro-thermal devices and micro-reactors need high mechanical strength to withstand higher thermal stresses and higher thermal conductivity for efficient heat transfer, whereas materials for micro-fluidics and biochemical applications need to be bio-acceptable, as well as corrosion resistant. Therefore, advance engineering materials like super alloys, titanium, aluminum alloys, and stainless steel are used in fabrication of micro-components because of their important properties like wear and corrosion resistant, good thermal conductivity, higher mechanical strength, and bio-acceptability. Microgrooves are one of the basic micro-features machined on the majority of the micro-devices used in various applications such as micro-actuators, micro-pumps, micro-mixers, and micro-dies etc. The demands of complex microgrooves with varied cross section have been increased, specifically for micro-thermal devices and micro-fluidics. This is because specific cross-sectional shape improves the product functionality and product performance due to increased inner surface area, which enhances heat transfer rate and chemical reaction rate.

Microgrooves can be fabricated on metallic surfaces by various conventional machining methods like micro-milling, shaping, fly cutting, and diamond turning. Chern et al. [1] machined micro-slots and micro-thin-walled structures on Al 6061-T6 utilizing tungsten-carbide microtools. Authors experimentally investigated burr formation in micromachining and suggested to maintain the axial engagement and minimum feed to avoid severe burr formation. Yan et al. [2] performed micro-grooving tests on nickel using fine end mills of noncircular cross-sectional profiles, to investigate the micromachining behavior. From the various tests, the authors concluded that suitable tool geometry and cutting edge sharpness are essential factors for eliminating burr formation in micro-cutting. In conventional micromachining, design of microtools and fixtures, burr formation, and unavoidable tool wear becomes critical issue when size of the microgrooves is smaller. T. Masuzawa [3] summarized the basic concepts and applications of major methods of micromachining. Author highlighted alternative non-conventional machining techniques which can be used to fabricate microgrooves that are micro electro-discharge machining (micro-EDM), photo-lithography or dry/wet etching, E-beam or LIGA process, laser beam machining, and electrochemical micromachining. Yan et al. [4] proposed two-step micro-EDM technique for fabricating microgrooves with varied cross sections on hard materials. Through the experiments, the authors find that this method needs separate microtools for each cross-sectional shape of microgroove and the microtools cannot be reused multiple times because of microtool wear. Rao et al. [5] applied wet etching for machining of micro-channels in stainless steel by using various etchants. From the study, the authors concluded that depth and etch factor are significantly affected by the composition of etchant, operating temperature, and initial opening width of microgroove. Photolithography or dry/wet etching can be applied for machining fine grooves on silicon, whereas it is very difficult to control depth of microgrooves with various cross-sectional shapes. Also, E-beam or LIGA process requires costly equipments to maintain special environment such as vacuum or X-ray source. Oh et al. [6] reported laser-induced thermo-chemical etching for machining of high aspect ratio microgrooves on stainless steel. From the investigations, the authors observed that high aspect ratio microgrooves can be fabricated by laser etching process; however, heat-affected zone is unavoidable and it becomes very difficult to achieve uniform cross section of deep microgrooves. Jain et al. [7] applied shaped tube electrolytic drilling (STED) process for drilling contoured holes in difficult-to-cut materials. The authors regulated voltage and feed rate to generate various types of hole profiles. During machining, the authors observed that machining current and pressurized electrolyte flow are important process parameters for continuation of the STED process. EMM is a promising technique to machine metallic surfaces irrespective of the hardness of material, without any stresses developed in workpiece or microtool, and no heat-affected zone. Also, the microtools of complex shapes can be reused because of no tool wear. Jain et al. [8] machined microtools by EMM and utilized the developed microtools for the fabrication of various micro-features. Liu et al. [9, 10] fabricated microelectrodes with various end shapes that are by different processing techniques, such as electro-chemical etching, single electric discharge, and electro-chemical micromachining. The authors applied fabricated microelectrodes in EMM process for machining of fine micro-hole array and 3D microstructure on metallic surfaces. Rathod et al. [11] machined the rectangular microgrooves on stainless steel for investigating the influence of important process parameters like applied voltage, pulse conditions, tool feed rate, and electrolyte concentration on machining accuracy of microgroove and material removal rate. Jo et al. [12] applied the EMM process for machining internal micro-features on the side wall of microhole by regulating the pulse conditions and machining time during machining. Liu et al. [13] studied the micro-electrochemical milling layer-by-layer machining process. The authors restricted the dissolution of a workpiece to very close region around electrode surface by applying ultra-short pulses and machined 2D micro-shapes and 3D complex micro-structures on metallic surfaces successfully. Spieser and Ivanov [14] reviewed recent developments and research challenges in electrochemical micromachining process. In EMM, material dissolution along the lateral surfaces of microtool results taper in the micro-structure along with the stray current effects. Hence, to minimize these effects during machining of micro-features by EMM, sidewalls of the microtool are insulated. For effective use of sidewall insulated microtools, stable, non-corrosive insulating film of few microns in thickness is required due to the micron size of the side machining gap. Rathod et al. [15] developed simple, economic, and effective sidewall insulation technique for insulating the tungsten microtools for electro-chemical micromachining of accurate micro-features such as micro-holes and microgrooves. Kim et al. [16, 17] introduced an application of disk-type electrode in electrochemical micro-machining of micro-structures of high aspect ratio to prevent the taper formation along its sidewalls. Rathod et al. [18] developed disk-shaped microtools of required dimensions by EMM and utilized it for machining of microgrooves and 3D micro-structure. Kirchner et al. [19] restricted the electrochemical dissolution of material to very confined space around the microtool, by applying ultra short voltage pulses, as well as regulating very narrow inter-electrode gap (IEG) and demonstrated machining of complex microstructures. Bhattacharyya et al. [20] introduced the microtool vibrations to improve the machining performance during machining of micro-holes on copper sheet by EMM. The

Fig. 1 Schematics of developed EMM setup



authors concluded that microtool vibration enhances electrolyte supply at narrow machining zone by effective removal of process by-products. The fabrication of simple microgrooves is relatively easy and can be machined by different conventional and non-conventional micromachining methods. But when the cross section of microgroove is varying along the depth of microgroove, the fabrication of microgroove becomes difficult not only from microtool fabrication point, but also from the process point of views. Very less literature is available for machining varied cross-sectional microgrooves on metallic surfaces. Therefore, precise machining of microgrooves of varied cross sections has become an important issue and needs further developments. Modern micromachining techniques like micro-EDM and conventional micromachining needs separate microtools for each cross sections of the microgroove. Also, the microtool wear is unavoidable, which limits the reuse of the microtool for multiple times. Proposed technique of machining different cross-sectional microgrooves on metallic surface by EMM is simple and more economical, since it utilizes the same microtool for different cross sections of the microgrooves repetitively because of no tool wear in EMM. Previous research works present an application of sidewall insulation of microtool, microtool vibration, and use of disk shape microtool separately, for improving machining accuracy and to minimize the taper formation during machining of micro-features by EMM, whereas the present work utilizes sidewall insulated disk shape microtool along with microtool vibration for machining of different cross sections of microgrooves.

This study demonstrates an application of EMM for machining of varied cross-sectional microgrooves on metallic surfaces utilizing developed experimental setup. Influence of process parameters such as applied voltage, duty ratio, and machining time on side machining gap and linearity of microgroove have been investigated to devise the strategy for machining different cross-sectional microgrooves. By regulating the process parameters along the depth of microgroove during each layer of machining, various cross sections of the microgrooves have been machined by EMM with sidewall insulated disk microtool. This technique enables the machining of different cross-sectional microgrooves like reverse tapered, barrel shaped, spherical based microgroove, stepped microgroove, and microgroove with internal pocket etc. All of these microgrooves have been machined using the single-disk shape microtool by EMM.

Table 1 Machining conditions during fabrication of disk-shaped microtool

Parameters	Details
Microtool (anode)	Tungsten specimen Ø200 μm
Workpiece (cathode)	SS sheet with central hole of Ø2.5 mm
Electrolyte	1 M NaOH
Applied voltage	1 Vt
Pulse frequency	1 MHz
Duty ratio	80%
Machining time	15 min

2 Experimental details

2.1 EMM principle

EMM is an anodic dissolution process, in which material is dissolved from metallic surface by electrochemical reaction according to Faraday's law of electrolysis. Workpiece as anode and microtool as cathode are immersed in an electrolyte with very small inter-electrode gap. Micron scale tool electrode moves with constant feed rate towards the workpiece to maintain the IEG. By following the scheduled path of microtool, desired micro-features can be machined. Anodic workpiece material is dissolved locally by electrochemical reaction to get the required micro-features. To enhance the localization of anodic dissolution and to improve

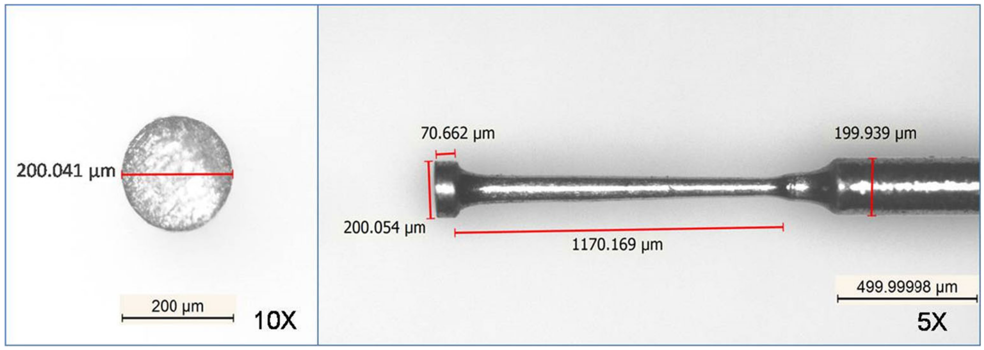


Fig. 2 Disk-shaped microtool fabricated by EMM

the machining accuracy, ultra short pulses are used. Since the material dissolves at an ionic level, very good surface quality can be achieved in EMM. Pulse parameters and machining conditions at the narrow machining zone play important role in regulating the important machining criteria of EMM.

2.2 Experimental setup

Experimental setup has been developed for the fabrication of disk shape microtool which can also be utilized for the machining of complex microgrooves. Developed setup consists of various subsystems, namely mechanical machining unit, controller unit, desktop computer, piezoelectric transducer (PZT), pulse power supply, digital storage oscilloscope, and machining chamber with work holding arrangement as shown in Fig. 1. Mechanical machining unit provides an arrangement to hold microtool and workpiece and offers movements to the tool or workpiece utilizing three units of stepper motor operated long travel linear stages arranged in gantry type structure representing *X*-, *Y*-, and *Z*-axes. Stepper motors with resolution of 0.3125 μm each have been controlled through motor controller unit using position controller software programs through desktop computer. Disk-shaped microtool along with tool holder is mounted on PZT, which can be mounted over *Z*-axis to provide longitudinal vibrations to microtool. Vibrational frequency of the PZT can be regulated by the frequency of input voltage. Pulse power supply provides DC pulses to microtool and workpiece with various pulse parameters such as voltage amplitude, pulse frequency, and duty ratio. Digital storage oscilloscope acts as data collection system, which is essential for online monitoring of EMM process as well as during IEG seting. Machining process has been monitored online through stereozoom microscope, and machined microgrooves have been measured utilizing measuring microscope.

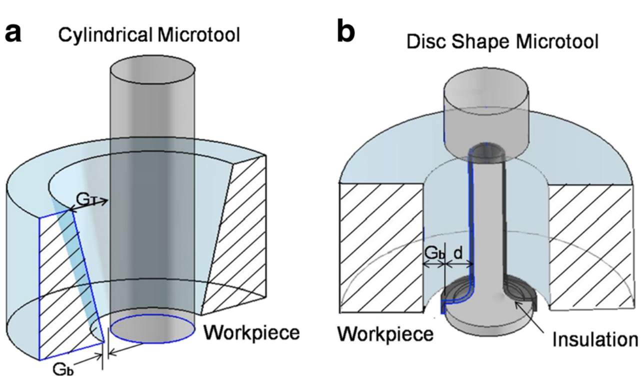


Fig. 3 Effect of microtool shape on sidewall profile machined using **a** straight cylindrical microtool and **b** disk-shaped microtool

2.3 Disk microtool fabrication and sidewall insulation

Tungsten is one of the best suitable material for microtools, because of its important properties like high rigidity and toughness, high melting point, good thermal and electrical conductivity, and corrosion resistance, which are useful to prevent microtool deformation and surface corrosion during EMM. Micron-sized tools with good surface quality are preferred in EMM, since the features of microtool such as shape, size, and surface quality are directly transferred to the workpiece. Disk shape microtool required for the machining of complex microgrooves has been developed by reverse EMM, utilizing the same experimental setup. To fabricate the disk shape microtool by reverse EMM, tool specimen of about 15 mm has been cut off from straight tungsten rod of 200 μm dia. and 150 mm long. The cut ends of the specimen have been fine ground and polished to remove end defects. The specimen length and tip conditions have been inspected under observing microscope for surface cracks and end defects if any. Front end of the tool specimen has been insulated for the required length. Stainless steel sheet of 750 μm thickness having central hole of 2.5 mm diameter insulated at top and bottom surfaces, so that only straight walls of the hole remains as current carrying part. SS sheet with cylidrical hole mounted on work holder in electrolyte tank as cathode. Front end insulated tool specimen mounted on tool holder, positioned at center of the hole in SS sheet as anode, and immersed in NaOH electrolyte. Tool specimen has been machined by EMM with various machining parameters as given in Table 1 [18], and finally, the front end insulation has been removed to get the required disk-shaped microtool. Figure 2 shows the disk-shaped microtool of disk dia. 200 μm, disk height 70 μm, average shank dia. 84 μm, and shank length 1170 μm developed by reverse EMM.

Figure 3 illustrates the effect of microtool shape on sidewall profiles of micro-features machined by cylindrical microtool and disk-shaped microtool. While machining with straight cylindrical microtool, machining gap (G_T) at top face is greater than the machining gap at bottom face (G_b) because of the machining time difference, which results taper along the sidewall of micro-feature as shown in Fig. 3a. Use of uninsulated disk-shaped microtool restricts the dissolution of workpiece to the disk region only and minimizes the formation taper along the walls of micro-features as shown in Fig. 3b. To restrict the dissolution of material along the disk region only, the radial difference between the disk radius and shank radius of the microtool electrode (d) must be greater than difference between the machining gap, i.e., $d > (G_T–G_b)$ [16]. Machining gap varies according to the pulse conditions; hence, required radial difference (d) between the disk and shank of microtool also depends upon the pulse condition. Machining of varied cross sections of microgrooves having varied side machining gaps along its depth needs machining of microgrooves with different disk microtools of different combinations of disk and shank diameters, which is practically very difficult, or machining with the same disk microtool with sidewall insulation by varying pulse conditions. Hence, to prevent the over dissolution and to reduce the taper formation along the sidewalls of micro-feature during machining of complex micro-features with varying pulse parameters, sidewalls of disk microtool have been insulated as shown in

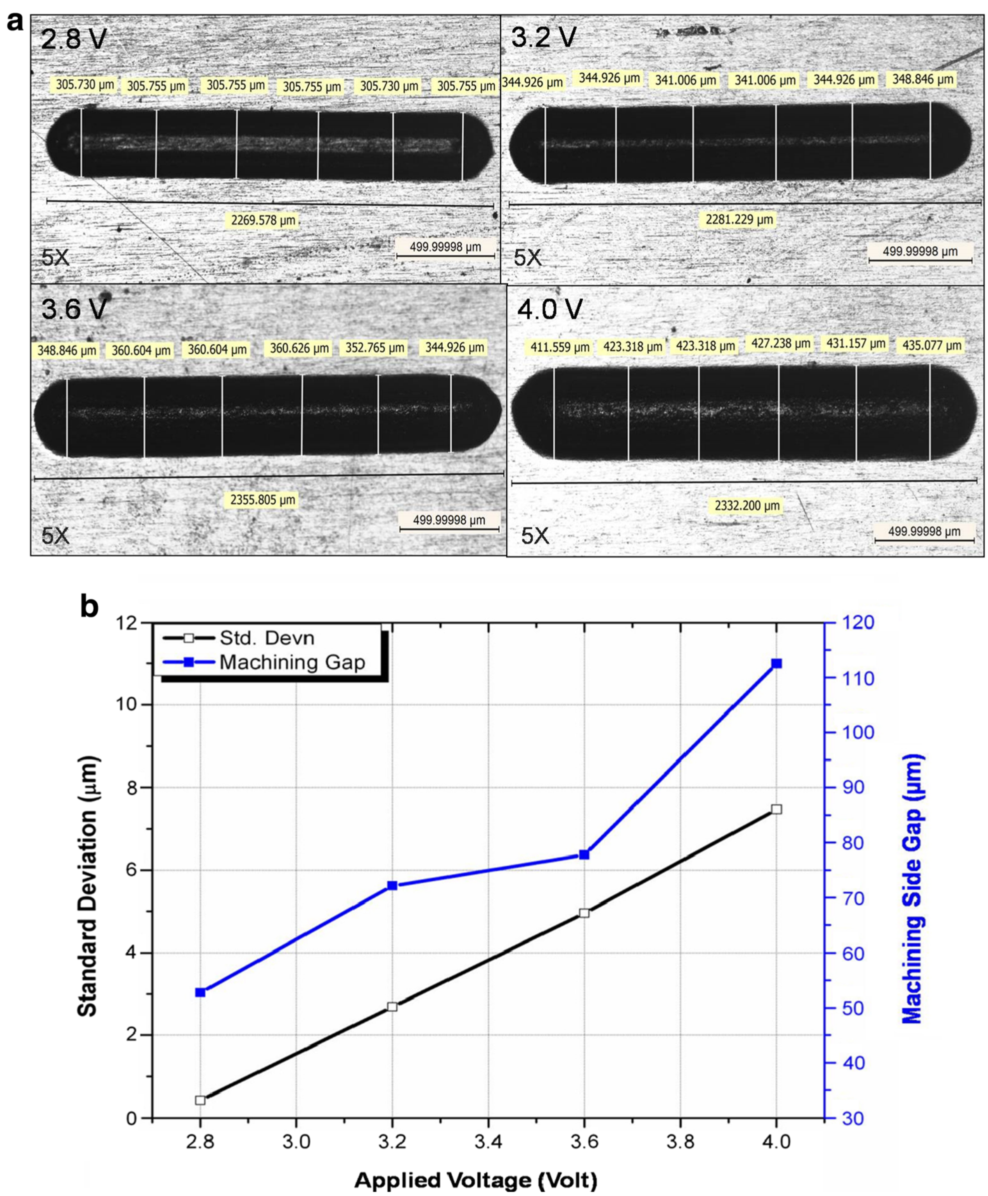


Fig. 4 **a** Microgrooves machined at different applied voltages. **b** Variation in side machining gap and standard deviation with applied voltages

Fig. 3b. Disk-shaped microtool has been insulated by dip coating using liquid solution made of polymer and resin dissolved in isopropyl alcohol. Disk shape of the microtool also ensures availability of fresher electrolyte at IEG and easy removal of process by-products from narrow machining zone, as compared to straight cylindrical microtool due to smaller shank diameter and small disk height, which also helps to improve machining performance.

2.4 Experimental plan

To investigate the influence of machining parameters like applied voltage, duty ratio, and machining time over the side machining gap, microgrooves of 2000 μm length and 50 μm depth have been machined on stainless steel using sidewall insulated disk microtool. Layer-by-layer machining ensures the supply of fresh electrolyte at narrow IEG during each scan and improves the machining accuracy; hence, this strategy for microtool movement has been followed. During machining of microgroove, microtool travels with 109 μm/s for full scanning length with vertical tool feed of 0.625 μm at the end of each scan. Supply of fresh electrolyte at machining zone and removal of process by-products from narrow IEG are the main concerns during machining of microgrooves. Longitudinal vibrations to microtool with few microns of amplitude of vibration help to enhance the supply of fresh electrolyte, by removing process by-

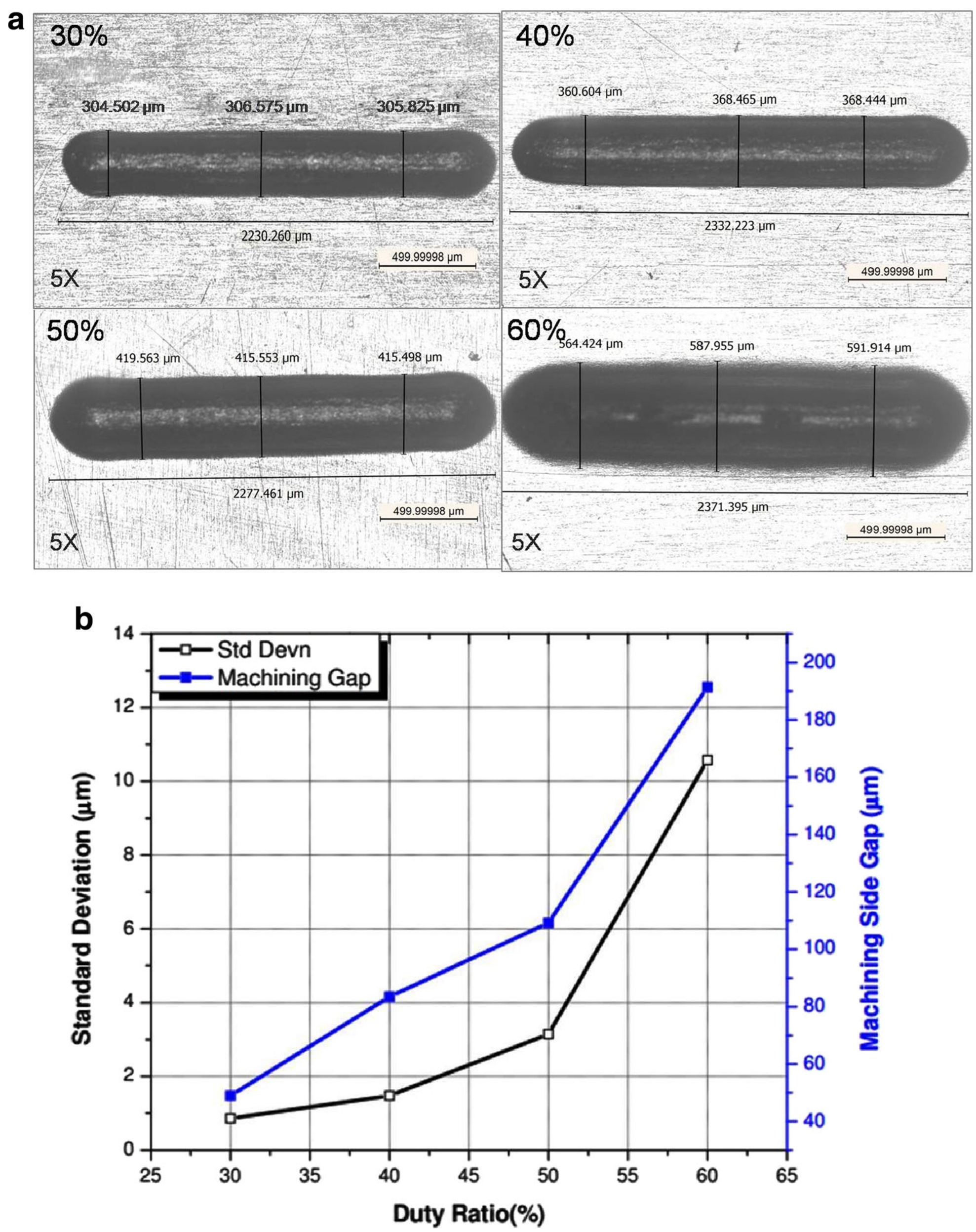


Fig. 5 **a** Microgrooves machined at different duty ratio. **b** Variations in side machining gap and standard deviation with duty ratio

products from machining region [20]. Microgroove widths have been measured at fixed intervals across the length of microgroove to determine the side machining gap.

Side machining gap is the excess material removed across the width of microgroove and is determined as follows:

$$\text{Side Machining Gap} = \frac{\sum_i^n (\text{W-d})}{2n} \quad (1)$$

where "i" = 1, 2,..., n and "n" is the number of locations where microgroove widths are measured, "W" is the microgroove width, and "d" is the disk diameter of disk microtool.

To evaluate the uniformity of microgroove along its length, standard deviation (σ) for width of microgroove is determined as follows:

$$\text{Standard Deviation } (\sigma) = \sqrt{\sum_{i=1}^{n} \frac{(W_i - Wm)^2}{n}} \quad (2)$$

where "W_i" is the microgroove width at "i" th location, "n" is the total number of locations where groove widths are measured, and "W_m" is the average microgroove width.

Side machining gap characteristics have been investigated and applied for machining of varied cross sections along the depth of microgrooves by regulating the EMM process parameters. Finally, SEM micrographs of varied cross-sectional microgrooves have been analyzed for the measurements.

3 Results and discussion

3.1 Machining characteristics of EMM

Fabrication of precise micro-features with specific dimension by EMM needs to know the exact amount of side machining gap which may generate during machining with set process parameters. Hence, to study the side machining gap characteristics, microgrooves have been machined by EMM, and influence of predominant process parameters such as applied voltage, duty ratio, and machining time on side machining gap and uniformity of microgroove have been investigated. The machined microgrooves have been measured and analyzed for side machining gap and uniformity along its length. Experimental results have been plotted to exhibit the influence of different process parameters on microgroove geometries and discussed individually as follows:

3.1.1 Applied voltage

To estimate the influence of applied voltage on side machining gap and microgroove uniformity, microgrooves have been machined with applied voltage from 2.8 to 4.0 V, pulse frequency of 5 MHz, duty ratio of 30%, and 0.15 M H_2SO_4 as an electrolyte. Figure 4a depicts the microscopic images of microgrooves machined with varied applied voltages, and Fig. 4b plots the co-relation between side machining gap

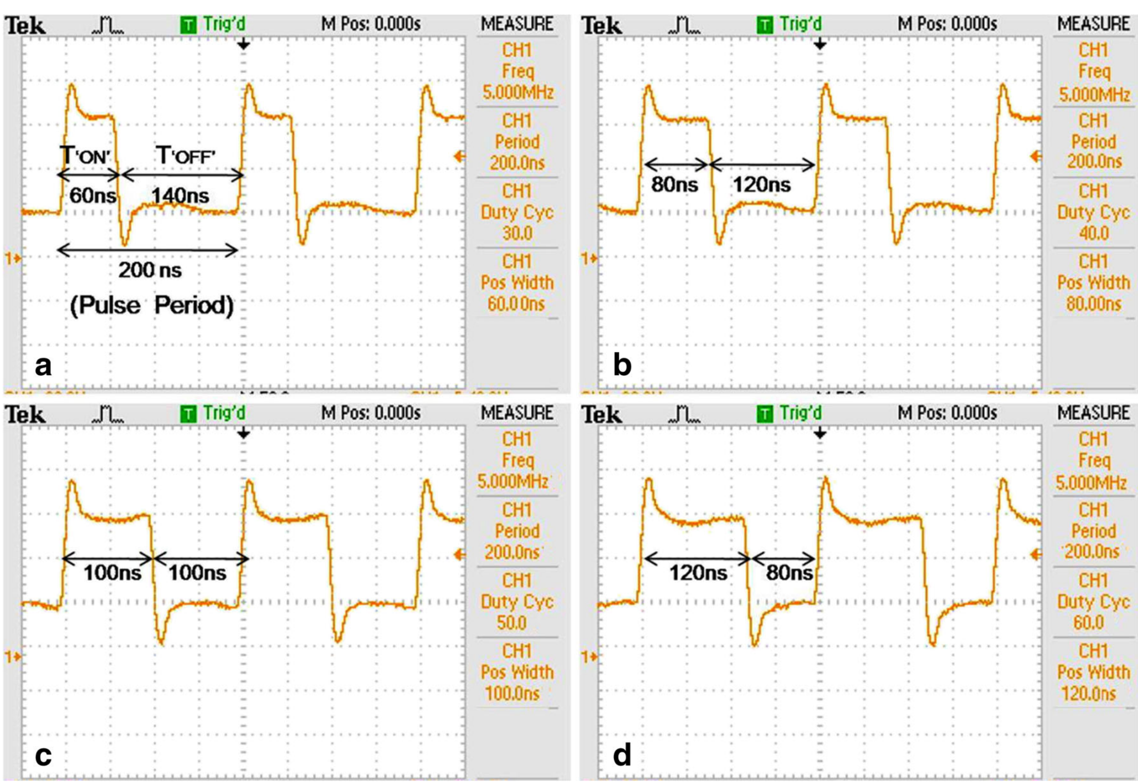


Fig. 6 Pulse waveforms at varied duty ratio **a** 30%, **b** 40%, **c** 50%, **d** 60%

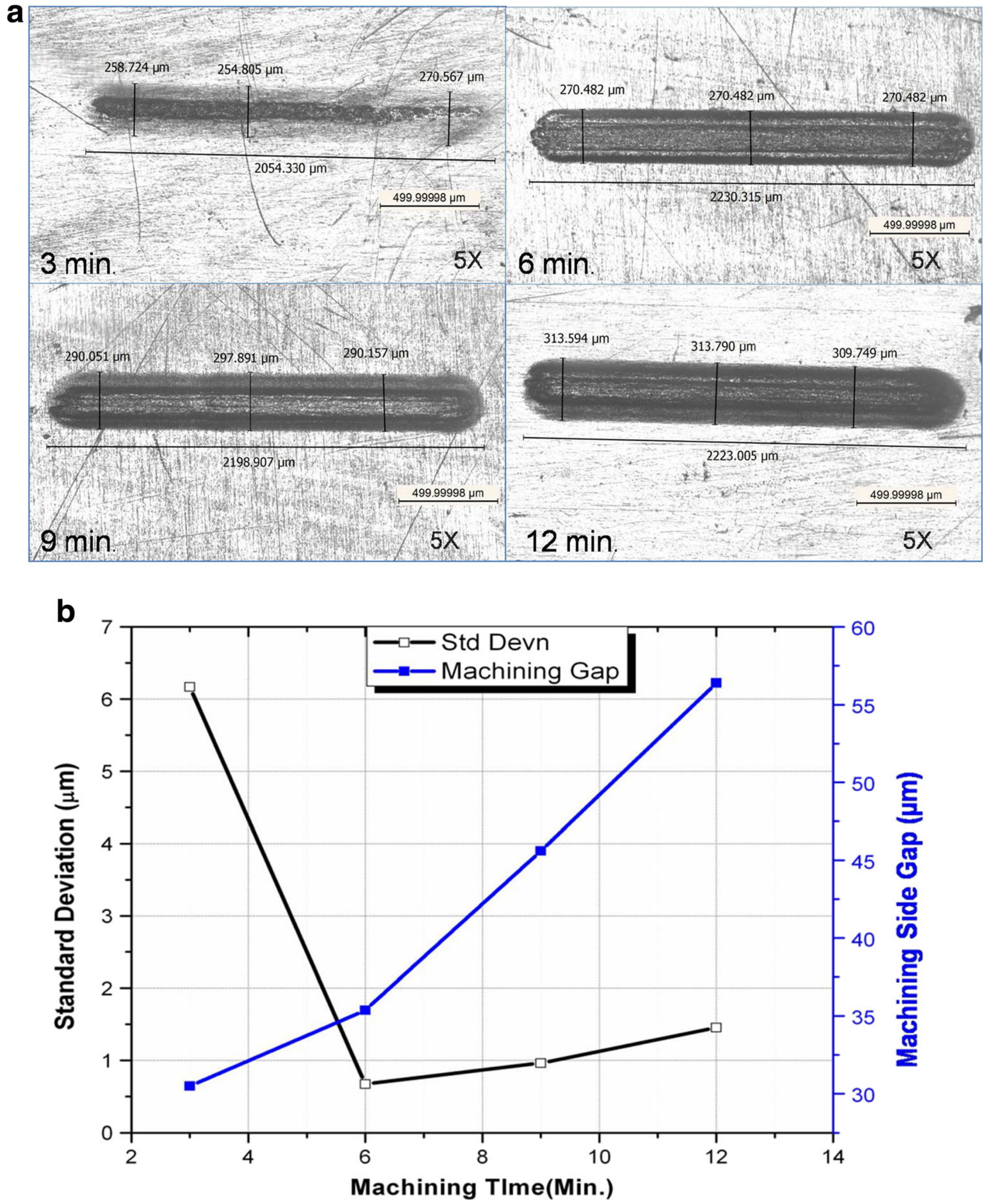


Fig. 7 **a** Microgrooves machined at different machining time. **b** Variation of side machining gap and standard deviation with duty ratio

and standard deviation with applied voltages. From the figures, it is seen that the side machining gap increases with increase in applied voltage. This is because of the increased machining current with increase in applied voltage which increases the machining current density and in turn dissolves higher amount of material. Finally, side machining gap increases with increase in applied voltage due to increased material dissolution. For investigating the uniformity of microgroove at different applied voltages, microgroove widths have been measured at different locations along the length of microgroove and standard deviation of microgroove that have been plotted as shown in Fig. 4b. From the figure, it can be seen that linearity of microgroove improves with reduction in applied voltage. This is because of the improvement in machining localization at reduced applied voltage. From these experiments, it can be concluded that applied voltage plays the significant role in regulating side machining gap and has a scope for machining of microgrooves having varied side machining gaps, i.e., varied cross-sectional microgrooves.

3.1.2 Duty ratio

Duty ratio is the ratio of pulse "on" time to the "pulse period," and it signifies the percentage of time for which pulse is "on." Pulse "on" time is one of the most important process parameters in EMM, since dissolution of material takes place during the pulse "on" time only. To investigate the influence of pulse "on" time over the side machining gap and microgroove

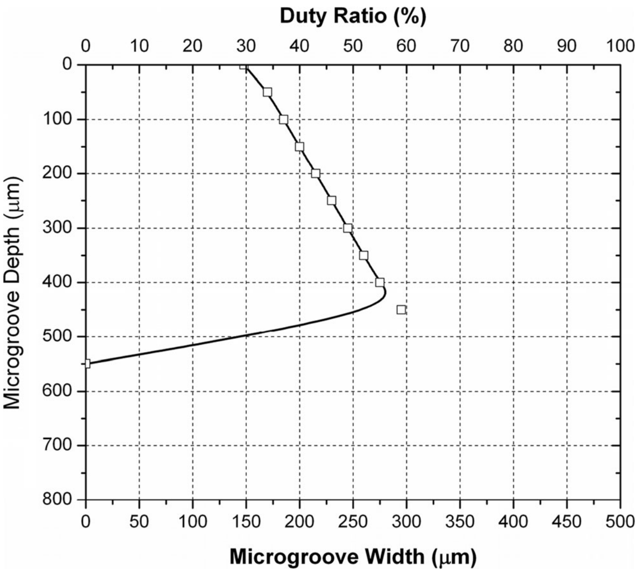


Fig. 8 Planned profile for reverse tapered microgroove

uniformity, microgrooves have been machined with varied duty ratio from 30 to 60%, i.e., pulse "on" time from 60 to 120 ns, pulse frequency of 5 MHz, applied voltage of 2.8 V, and 0.15 M H_2SO_4 as an electrolyte. Figure 5a shows microscopic images of microgrooves machined with varied duty ratios, and Fig. 5b plots the variation in side machining gap and standard deviation with duty ratio.

Increase in side machining gap with increase in duty ratio can be seen from the Fig. 5a, b. Material dissolution takes place during pulse "on" time only, and dissolution by-products like sludge and heat are carried out from machining region during pulse "off" time. Applied single pulse is the sum of pulse "on" time and pulse "off" time, and increase in duty ratio increases pulse "on" time as shown in Fig. 6a–d. Increased pulse "on" time, i.e., machining time with increase in duty ratio, increases the volume of material dissolved which in turn increases the side machining gap finally. Microgroove widths have been measured at different locations along the length of microgroove to study the uniformity of microgroove along its length, and standard deviation at different duty ratios has been plotted as shown in Fig. 5b. From the figure, it can be seen that linearity of microgroove improves with reduction in duty ratio. This is because of the improvement in machining localization at lower duty ratio due to shorter machining time. From these experiments, it can be concluded that duty ratio also plays an important role in regulating the side machining gap in EMM and can be used for machining microgrooves of varied side machining gaps, i.e., varied cross-sectional microgrooves.

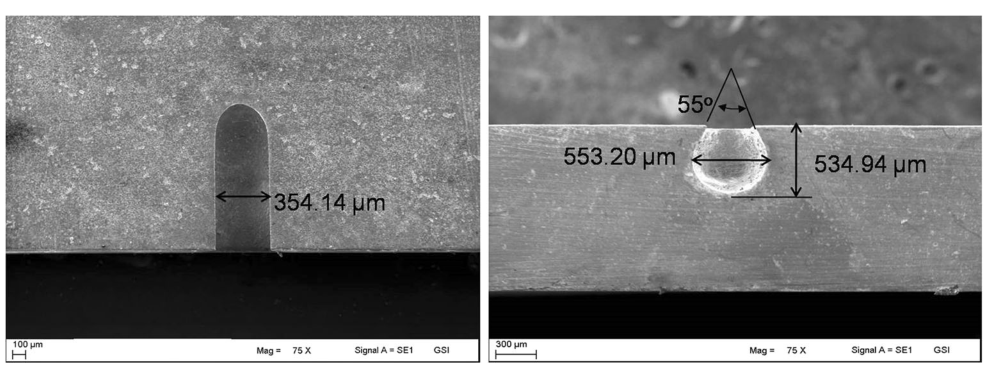
3.1.3 Machining time

To investigate the influence of machining time over side machining gap and linearity, microgrooves have been machined for different machining time ranging from 3 to 12 min, with applied voltage of 2.8 V, pulse frequency 5 MHz, duty ratio 30%, and 0.15 M H_2SO_4 as an electrolyte without any vertical tool feed. Figure 7a shows the microscopic images of microgrooves machined at different machining time. Side machining gap and linearity of microgrooves at different machining time have been plotted in Fig. 7b. From the figures, it can be clearly seen that side machining gap increases with machining time and linearity of microgroove improves initially with increase in machining time and afterward it diminishes. This is because of the continuous dissolution of material from workpiece surface with increase in machining time. With progression of time, IEG increases which in turn reduces machining localization and ultimately reduces the linearity and increases the side machining gap of microgrooves. From these experiments, it can be concluded that side machining gap varies with machining time and can also be used for machining of microgrooves having varied side machining gaps, i.e., varied cross-sectional microgrooves.

3.2 Machining of varied cross-sectional microgrooves

Side machining gap characteristics have been studied for different process parameter settings such as applied voltage, duty ratio, and machining time through basic experimentations. Variation in side machining gap with process parameters

Fig. 9 SEM micrograph of reverse tapered microgroove



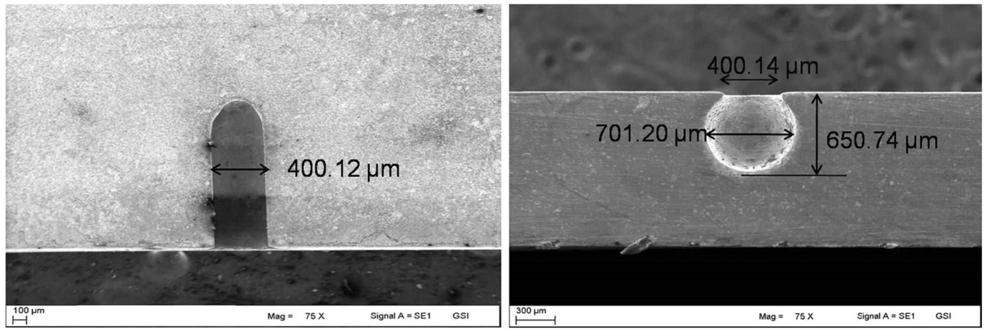


Fig. 10 SEM micrograph of barrel-shaped microgroove

offers the possibility of machining varied cross-sectional microgrooves. By regulating the process parameters along the depth of microgroove, machining of varied cross-sectional microgrooves has been demonstrated utilizing sidewall insulated disk microtool.

3.2.1 Fabrication of reverse tapered microgroove

Microgrooves with continuous increasing width towards bottom, i.e., reverse tapered microgrooves, are very much difficult to be machined by various available micromachining methods, whereas these types of microgrooves can be easily machined by the proposed method of regulating duty ratio gradually with along depth of microgrooves during machining. Figure 8 shows the planned profile for reverse tapered microgroove as per the basic experimental results. Microgroove has been machined with applied voltage of 3.2 V, pulse frequency of 5 MHz, 0.15 M H_2SO_4 as an electrolyte, scanning speed of 109 μm/s with vertical tool feed of 0.625 μm at the end of each scan, and initial IEG of 20 μm by varying duty ratio gradually from 30 to 60% along the depth of microgroove.

Gradual increase in duty ratio along the depth of microgroove results increased microgroove width generating reverse tapered microgroove. The use of sidewall insulated disk microtool restricts over dissolution of material along the sidewalls of the microgroove at increased duty ratio. As a result, when duty ratio increases along the depth of microgroove, side machining gap increases only at front end of the microtool, and the side machining gap at top remains as it is. Therefore, a microgroove whose width increases gradually along its depth can be fabricated by this method. Figure 9 shows SEM micrographs of actual machined reverse tapered microgroove. From Fig. 8 and Fig. 9, it can be seen that curved surface is generated at the bottom of the microgroove, as compared to the planned flat bottom surface. This is because of the nature of the current distribution, i.e., higher current flow through the central portion of disk, as compared to periphery of disk because of shorter path of current flow at the central part, which dissolves more material from central portion of disk as compared to periphery, resulting curved surface of machined micro-feature at the front end of disk microtool. Similarly, it is also possible to machine the microgrooves of different reverse taper angles by regulating the different duty ratios along the depth of microgroove during machining.

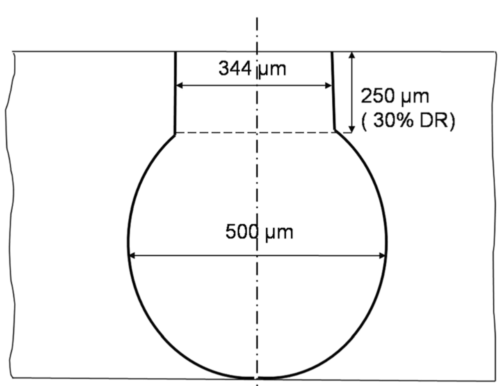


Fig. 11 Planned profile for microgroove with spherical base

3.2.2 Fabrication of barrel-shaped microgroove

In EMM, side machining gap varies with applied voltage also; hence, microgrooves of varied cross sections can also be machined by varying applied voltage along the depth of microgroove during each layer of machining. Barrel-shaped microgroove whose width increases up to the mid of microgroove and it reduces again for remaining depth has been machined by increasing the applied voltage from 3.2 to 3.8 V up to the mid-section of microgroove and reducing it gradually from 3.8 to 3.2 V for the rest of the microgroove depth, with pulse frequency of 5 MHz, duty ratio 30%, 0.15 M H_2SO_4 as an electrolyte with 20 μm IEG. To study the effect of scanning speed on opening width of microgroove, scanning speed of the microtool has been reduced to the 93.75 μm/s with 0.625 μm of vertical microtool feed at the end of each scan. Figure 10 shows SEM micrographs of the machined microgroove.

Gradual increase in applied voltage increases material dissolution due to increased machining current and in turn

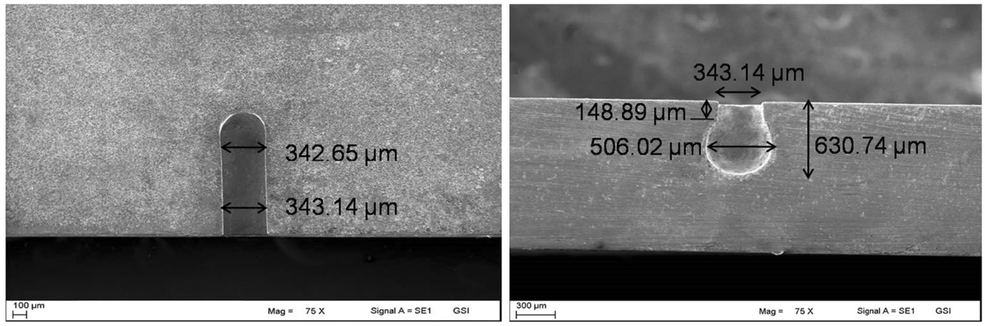


Fig. 12 SEM micrograph of microgroove with spherical base

increases the side machining gap, i.e., increased width of microgroove up to the mid of microgroove. Further continuation in machining with reduced applied voltage results reduced microgroove width, along the depth of microgroove. Sidewall insulated disk microtool restricts the over-dissolution of workpiece material along the sidewalls of the microgroove at increased applied voltages. Therefore, a microgroove whose width increases gradually up to desired depth and again its width decreases for required depth can be fabricated easily. Reduction in scanning speed increases opening width of microgroove because of the increased machining time, which may also help in machining of microgrooves of desired width for any specific application. Similarly, microgrooves of different barrel dimensions can be machined by regulating various applied voltages along the depth of microgroove during machining.

3.2.3 Fabrication of spherical based microgroove

In EMM, the side machining gap can be controlled by regulating the pulse conditions, as well as by regulating the dissolution time also. Microgrooves of uniform width up to certain depth, with spherical base at end, are difficult to be machined by any of the available micromachining methods. These types of microgrooves can be easily machined in EMM, by machining microgrooves up to certain depth with fix parameters and further continuation of process with increased duty ratio, without any vertical microtool feed. Figure 11 shows the planned profile of microgroove as per the basic experimental results. Microgroove has been machined with applied voltage of 3.2 V, pulse frequency of 5 MHz, duty ratio of 30%, 0.15 M H_2SO_4 as an electrolyte, 20 μm initial IEG, and scanning speed of 109 μm/s with 0.625 μm vertical feed at the end of each scan up to 250 μm depth. After that, machining has been continued with increased duty ratio of 50% for 10 min without any vertical microtool feed at the end of each scan.

Machining of microgroove with lower duty ratio generates microgroove of uniform width up to certain depth, whereas machining with increased duty ratio for higher machining time without any tool feed along the depth results increased side machining gap in the form spherical base. Sidewall insulation of disk-shaped microtool restricts the over-dissolution of material along the sidewalls of the microgroove for increased machining time and duty ratio. As a result, with increase in machining time and duty ratio after certain depth, side machining gap increases at front end of the microtool, whereas side machining gap at the entrance of microgroove remains unchanged. Therefore, a microgroove of uniform width up to desired depth with spherical base of higher diameter can be easily machined by this method. Figure 12 shows the SEM micrographs of the actual machined microgroove.

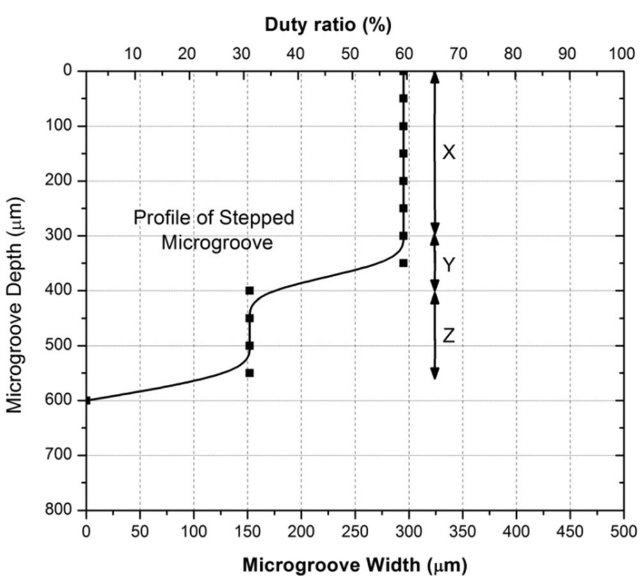


Fig. 13 Planned profile for stepped microgroove

3.2.4 Fabrication of stepped microgroove

Microgrooves of complex cross-sectional shape can also be machined by scheming the process parameters along the depth of microgroove. Figure 13 shows the profile planned for double stepped microgroove from the basic experimental results. Fabrication of stepped microgroove has been planned in two steps. In the first step, microgroove of required depth as shown by “X” has been planned with higher duty ratio of 60% for

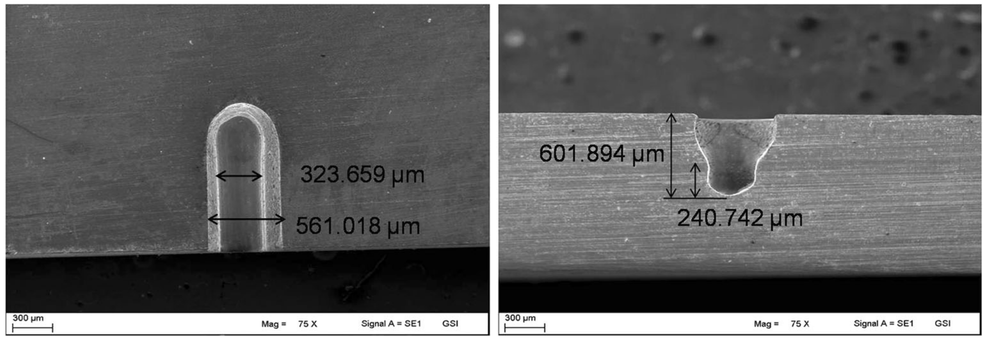


Fig. 14 SEM micrograph of stepped microgroove

depth of 300 μm, followed by down feed of microtool for "Y" distance, i.e., 100 μm without any machining to overcome the depth overcut generated at higher duty ratio. In second step, microgroove at bottom has been planned with lower duty ratio of 30% for required depth of "Z," i.e., 200 μm. Other process parameters remained identical during machining for both steps of the microgroove, as applied voltage of 3.2 V, pulse frequency of 5 MHz, 0.15 M H_2SO_4 as an electrolyte with 20 μm initial IEG, and scanning speed of 109.375 μm/s with 0.625 μm vertical feed to microtool at the end of each scan.

Figure 14 shows microscopic image of stepped microgroove machined utilizing sidewall insulated disk shape microtool. In the first step, machining with higher duty ratio results in increased microgroove width, i.e., higher side machining gap due to increased material dissolution, whereas in the second step, machining with lower duty ratio generates reduced microgroove width due to reduced material dissolution at lower duty ratio, i.e., smaller pulse "on" time. From the figures, it can also be seen that curved surface is generated at the bottom of machined microgroove as compared to the planned flat bottom surface. This is because of the nature of the current distribution and reduced machining localization at

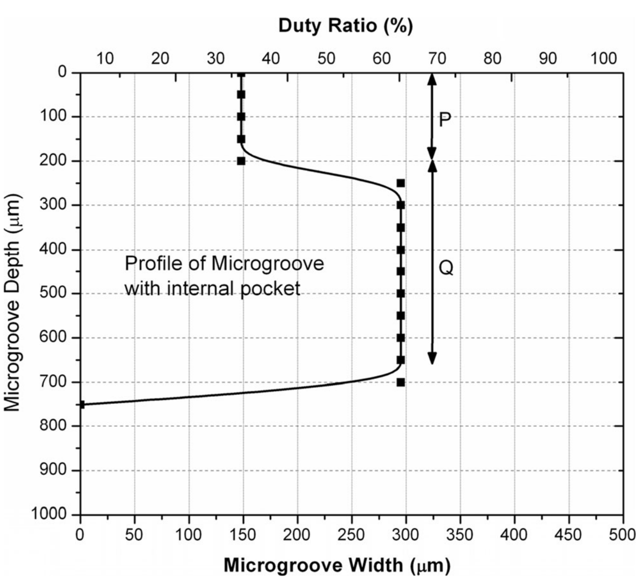


Fig. 15 Planned profile for microgroove with internal pocket

the front face of the disk microtool. Similarly, multi-stepped microgrooves of required dimensions, i.e., widths and depths, can be easily machined by regulating the process parameter along the depth of microgroove, utilizing the same disk microtool.

3.2.5 Fabrication of microgroove with internal pocket

Microgrooves having specific internal micro-features can also be machined by the proposed method of regulating the EMM process parameters along the depth of microgroove during machining. Figure 15 shows planned profile of microgroove with internal pocket from the basic experimental results. Smaller opening of the microgroove has been planned to be machined with lower duty ratio for required depth as shown by "P," and then, machining has been continued with higher duty ratio for internal pocket of required depth as shown by "Q" with remaining identical process parameters as applied voltage of 3.2 V, pulse frequency of 5 MHz, 0.15 M H_2SO_4 as an electrolyte, with 30% duty ratio for 200 μm depth, and 60% duty ratio for further 400 μm depth, 20 μm initial IEG, and scanning speed of 109.375 μm/s with vertical feed of 0.625 μm at the end of each scan.

Figure 16 shows SEM micrographs of machined microgroove with internal pocket utilizing sidewall insulated disk-shaped microtool. Machining with lower duty ratio generates microgroove of smaller width up to desired depth, whereas machining with increased duty ratio generates higher microgroove width because of increased material dissolution at increased pulse on time. Sidewall insulation of disk microtool restricts the over-dissolution of workpiece material along the sidewalls of microgroove to prevent over-sizing of opening width and dissolves the workpiece material at the front end only at increased duty ratio. Similarly, microgrooves having internal pockets of different sizes with different opening widths can be machined by regulating the different process parameter along the depth of microgroove during machining.

Microgrooves of various cross-sectional shapes such as reverse tapered, barrel shape, microgroove with spherical base, stepped microgroove, and microgroove with internal pocket have been successfully fabricated by EMM, utilizing the

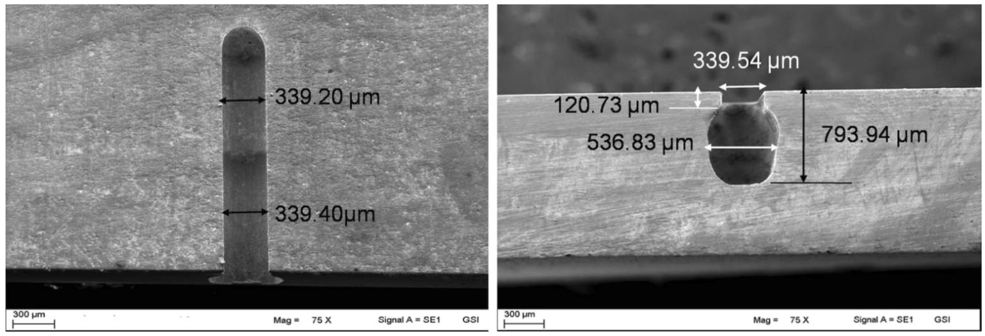


Fig. 16 SEM micrograph of microgroove with internal pocket

sidewall insulated disk-shaped microtool. By the proposed technique, microgrooves of varied cross sections of different dimensions can also be machined. Micro-EDM technique has been applied previously for machining the various cross-sectional microgrooves, which needs individual microtool for each cross-sectional shape of microgroove, with unavoidable tool wear. As compared to micro-EDM technique, proposed technique is simple and economical, since it requires single microtool for machining of varied cross sections of the microgrooves.

4 Conclusions

An application of EMM by regulating the process parameters along the depth, for machining varied cross-sectional microgrooves, has been proposed. Side machining gap characteristics have been investigated through preliminary experiments, and experimental findings have been applied to machine the various cross sections of microgrooves. From overall experiments and results, important conclusions can be summarized as follows:

(i) In EMM, side machining gap varies with process parameters such as applied voltage, duty ratio, and machining time. Hence, by varying these process parameters during each layer of machining along the depth of microgroove, and utilizing sidewall insulated disk-shaped microtool, it is possible to machine the varied cross-sectional microgrooves.

(ii) Sidewall insulation of disk-shaped microtool prevents the over-dissolution of material during machining of complex cross-sectional shaped microgrooves, minimizes the stray current effect, and makes EMM process insensitive to the microtool length during machining of deep microgrooves. Use of disk-shaped microtool also enhances the availability of fresh electrolyte at machining region during machining of deep microgrooves.

(iii) Layer-by-layer machining of microgrooves assists the machining of various cross-sectional profiles by regulating the process parameters along the depth of microgrooves. Microtool vibration system helps to remove sludge and process by-products from machining zone ensuring availability of fresh electrolyte at narrow IEG and improves machining performance during machining of complex microgrooves.

(iv) Microgrooves of different cross-sectional shapes and sizes can be machined by EMM utilizing single-disk-shaped microtool with its sidewall insulation, by strategic planning for variation in side machining gap by varying process parameters along the depth of microgroove.

(v) Machining of reverse tapered microgroove of 55° taper angle, barrel shape microgroove of entrance width 400 μm and mid-depth width 700 μm, spherical base microgroove with entrance width 343 μm and spherical base of 506 μm dia., double step microgroove with outer groove width of 561 μm and inner groove width of 324 μm, and microgroove of entrance width 340 μm, with internal pocket of 536 μm × 674 μm, by EMM has been demonstrated successfully.

Microgrooves of different cross-sectional shapes and sizes are required in various applications because of its specific shape and increased inner surface area. Novelty of this work is that this work successfully presents an application of electrochemical micromachining for machining various cross-sectional microgrooves such as reverse tapered, barrel shaped, spherical based, double steps etc. on metallic surface utilizing the disk-shaped microtool. Machining of any cross-sectional shaped microgrooves can also be planned by regulating the process parameters along the depth of microgroove during machining. However, further investigations are required for finding out optimal combination of process parameter settings to achieve different cross-sectional microgrooves, as well as to minimize total machining time.

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