Machining Guidelines for Fabricating Microgrooves of Varied Cross Sections by Electrochemical Micromachining

V. Rathod, B. Doloi and B. Bhattacharyya

Abstract Increased surface area at the cross section of varied cross-sectional microgroove improves the product performance; hence, complex microgrooves of different cross sections are machined on various micro-products. Fabrication of straight microgroove on metallic surfaces is simple, whereas machining of varied cross-sectional microgroove on metallic surfaces becomes the challenging task from the aspects like fabrication of complex shaped microtool and suitable microgroove manufacturing process. Very few methods are capable to machine such complex shaped microgrooves. This chapter explores the potential of machining varied cross-sectional microgrooves on metallic surfaces by electrochemical micromachining. Important process parameters such as applied voltage, duty ratio and machining time have been controlled along the depth while machining the microgrooves. Influences of these parameters on width have been investigated, and results have been applied to devise the machining guidelines to fabricate varied cross-sectional microgrooves. The guidelines for machining straight, reverse tapered, barrel-shaped, double stepped, spherical based and microgroove with internal pocket have been developed. Finally, fabrications of these microgrooves have been demonstrated successfully by following developed guidelines. The developed guidelines can be applied for machining complex microgrooves for micro-coolers, micro-reactors and micro-mixers that need definite shape and size for their working.

Keywords EMM · Complex microgroove · Guidelines · Cross sections
Reverse taper · Barrel shape · Double step · Spherical base · Internal pocket

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Nomenclatures

h	Inter-electrode gap
ρ_s	Specific electrolyte resistivity
τ	Charging time constant
c	Specific capacitance of double layer
V_m	Volume of material removed
C	Electrochemical constant of a material
E	Applied voltage
A	Active microelectrode surface area
t	Machining time
t_{on}	Pulse on-time
T	Total machining time
n	Total number of scans
L	Microgroove length
V_x	Scanning speed
σ	Standard deviation

1 Introduction

Micro-devices such as micro-actuators, micro-pumps, micro-mixers and micro-dies need microgrooves as one of the essential micro-features fabricated on it to fulfil their functional requirement. Recently, the demand for microgrooves with internal features has been increased, specifically in the applications of microthermal devices such as micro-coolers, micro-heat exchangers and micro-reactors. Specific cross-sectional shape, i.e. geometry of microgrooves, improves product functionality as well as product performance because of augmented inner surface area, which improves heat transfer rate well as rate of chemical reaction. The micro-products like microthermal devices and micro-reactors demand high mechanical strength at elevated temperature and higher thermal conductivity for effective heat transfer. Corrosion resistant is the main criterion in biomedical applications. Hence, properties like wear resistance, corrosion resistance, thermal conductivity and mechanical strength at elevated temperature are the important aspects in material selection of the micro-products. Advance engineering metals such as superalloys, titanium, nickel base alloys and stainless steel are most suitable for fabrication of the micro-products to fulfil such requirements. Microgrooves of various geometries are to be machined on various micro-products to fulfil their functional requirements. Hence, precise manufacturing of microgrooves with internal features forming different cross sections of the microgroove on metallic surfaces has become research issue that requires additional developments.

1.1 Literature Survey

Fabrication of plain microgrooves is comparatively easy and can be achieved by various traditional as well as non-traditional micromachining methods. Whereas the machining of varied cross-sectional microgroove becomes the challenging task from the aspects like development of complex shaped microtool and suitable microgroove manufacturing process. Chern et al. (2007) and Yan et al. (2009) fabricated various microgrooves on metal surfaces by traditional machining methods such as micro-end milling, shaping, fly cutting and diamond turning to explore the burr formation mechanism during machining. Authors observed microtool wear and burr formation as the significant issue in during machining of microgrooves. Nageswara and Kunzru (2007) applied photolithography or wet chemical etching for manufacturing of fine grooves on silicon. Authors find the various issues in controlling the depth of microgroove of different shapes, as well as the requirements of special equipment. Oh et al. (2006) applied laser beam micromachining for machining of high aspect ratio microgrooves on metallic surfaces. During the investigation, authors reported an issue of unavoidable heat affected zone and the challenges in regulating uniform cross section along the depth of microgrooves. Presently, very few micromachining methods such as micro electro-discharge machining (μ-EDM) are capable to machine microgrooves of different cross sections on metallic surfaces. Yan et al. (2010) developed microtools of different end shapes by wire-EDM and applied these microtools to fabricate the varied cross-sectional microgrooves on metallic surfaces by μ-EDM. Authors focused the requirement of individual end shaped microtools for each cross-sectional shape of the microgroove and microtool wear as the significant problem in this process, which restricts the use of developed microtool for machining of multiple micro-features.

Therefore, the potential of fabricating varied cross-sectional microgrooves by electrochemical micromachining (EMM) has been explored in this chapter. Important process parameters such as applied voltage, duty ratio and machining time are regulated while fabricating microgrooves using enveloped EMM setup. Influences of these parameters on width overcut have been investigated, and investigational results have been applied to devise the machining guidelines to fabricate varied cross-sectional microgrooves. The guidelines for machining straight, reverse tapered, barrel-shaped, double stepped, spherical based and microgroove with internal pocket have been developed. Finally, fabrications of these microgrooves have been demonstrated successfully by following developed guidelines. The developed guidelines can be applied for fabricating complex microgrooves suitable for micro-coolers, micro-reactors and micro-mixers that require specific geometry for product working.

2 Mathematical Analysis for Generation of Different Internal Features by Electrochemical Micromachining (EMM)

To machine the microgrooves of various cross-sectional shapes on metallic surfaces, principle of EMM has been studied. Material removal mechanism of the process has been analysed, so that material removal can be controlled during machining of microgroove.

2.1 EMM Principle

EMM works on the principle of anodic material dissolution, in which microtool and workpiece are immersed in an electrolyte with very small inter-electrode gap as cathode and anode, respectively. To improve the machining accuracy, ultrashort pulse power supply with minimum IEG is preferred. Stagnant electrolytes are used during machining because of micron-sized tools. During machining of micro-features, microtool moves with constant tool feed rate towards the workpiece, following the predetermined path (Kirchner et al. 2001).

In EMM, as the potential is applied between the microtool electrode and workpiece immersed in an electrolyte with small IEG. At the interface between electrode and electrolyte, a very thin layer exists called as double layer. The potential profile in the double layer becomes similar to that of an equivalent circuit which consists of capacitors and resistors. Electrolyte resistance is the product of the inter-electrode gap (h) and the specific electrolyte resistivity (ρ_s). Therefore, charging time constant (τ) of the double layer having specific capacitance (c) is

$$\tau = \rho_s ch \tag{1}$$

When IEG is small, the time constant for double layer charging is small. When applied pulse duration is longer than the charging time constant, the double layer becomes charged high enough for dissolution. However, at other places where the charging time constant is larger than the pulse duration, the double layer is not charged sufficiently for material dissolution. Hence, material dissolution occurs in areas where electrolyte resistance is lower during each pulse.

The volume of material dissolved in EMM can be determined by combining Faraday's first law and Ohm's law as (McGeough 1974)

$$V_{\mathrm{m}} = \frac{CEA}{\rho_s h} t \tag{2}$$

where V_{m} is the volume of material dissolved, C is the electrochemical constant of a material, E is applied voltage, A is active microelectrode surface area which takes part in machining, t is the machining time, ρ_s is specific electrolyte resistivity and h is inter-electrode gap. From above equation, it can be said that volume of material removed by EMM depends upon applied voltage, electrode size, type of electrolyte and its concentration, inter-electrode gap and machining time.

In EMM, double layer is charged and discharged frequently during every pulse at both the electrodes. Considering that, material dissolution takes place during pulse on-time only, and pulse off-time is kept long enough for heat dissipation and to flush away the dissolved materials from the machining zone. Therefore, Eq. (2) can be modified as

$$V_{\mathrm{m}} = \int_0^{t_{\mathrm{on}}} \frac{CEA}{\rho_s h} \mathrm{d}t \tag{3}$$

In fabrication of micro-features using sidewall insulated microtool of suitable size with specific parameter settings, the values of electrochemical constant, active electrode surface area, specific electrolyte resistivity and inter-electrode gap can be assumed as constants, and then, Eq. (3) can be further modified as

$$V_{\mathrm{m}} = \frac{CA}{\rho_s h} \int_0^{t_{\mathrm{on}}} E \mathrm{d}t \tag{4}$$

From Eq. (4), it can be concluded that during electrochemical micromachining of micro-features, volume of material removed, i.e. machining gap across front and side of the microtool, can be regulated by applied voltage, pulse on-time and machining time, which can be used in machining of complex micro-features.

For machining microgroove of desired depth microtool has to scan number of times for complete scan length, followed by down feed at the end of each scan which takes total machining time T, which can be given as

$$T = \frac{nL}{V_x} \tag{5}$$

where n is the total number of scans, L is the microgroove length and V_x is scanning speed. Hence, volume of material removed in total machining time T can be given as

$$V_{\mathrm{m}} = \left[\frac{CA}{\rho_s h} \int_0^{t_{\mathrm{on}}} E \mathrm{d}t \right] \frac{nL}{V_x} \tag{6}$$

From Eq. (6), it can also be concluded that scanning speed of the microtool also has a significant role in regulating volume of material removed and, in turn, regulates the front and side machining gap in layer-by-layer machining of microgrooves. Increased scanning speed reduces the total machining time, decreasing the total volume of material removed, that results in reduced machining gap at front and side, even though numbers of scans are same. Similarly, the reduced scanning speed requires longer machining time, increasing total volume of material removed and generating higher machining gap at front and side.

3 Experimental Details

Experiments have been performed utilizing in-house developed EMM setup which consisted of various subsystems. The same setup has been utilized for the development of disc microtool, required for the further machining of complex microgrooves.

3.1 Experimental Setup

Figure 1 depicts the photographic view of the EMM setup that has been utilized for the development of disc shape microtool, as well as in machining microgrooves of varying cross sections. Developed EMM setup consists of various subsystems integrated together such as mechanical machining unit, controller unit, desktop computer, piezoelectric transducer (PZT), pulse power supply, digital storage oscilloscope and machining chamber with work holding arrangement. The basic function of the mechanical machining unit is to provide the movements to microtool in *X*, *Y* and *Z* directions by combining three separate units of long travel linear stages arranged in gantry type structure, and also to hold microtool and workpiece. Each of the linear stage has a stepper motor of 0.3125 μm resolution and is controlled through machine controller unit through a desktop computer. PZT has been mounted on vertical stage, and microtool tool holder has been mounted on PZT, so that longitudinal vibrations can be transferred to the microtool. Amplitude of vibration and vibrational frequency of PZT has been regulated through power supply of PZT. Pulse generator provides the pulsed power supply with different parameters such as voltage amplitude, pulse frequency and duty ratio to the microtool and workpiece. Digital storage oscilloscope has been utilized for observing the nature of pulse being supplied, for online monitoring and during IEG setting. Microgrooves have been machined on stainless steel, measured and analysed utilizing measuring microscope and SEM micrographs, respectively.

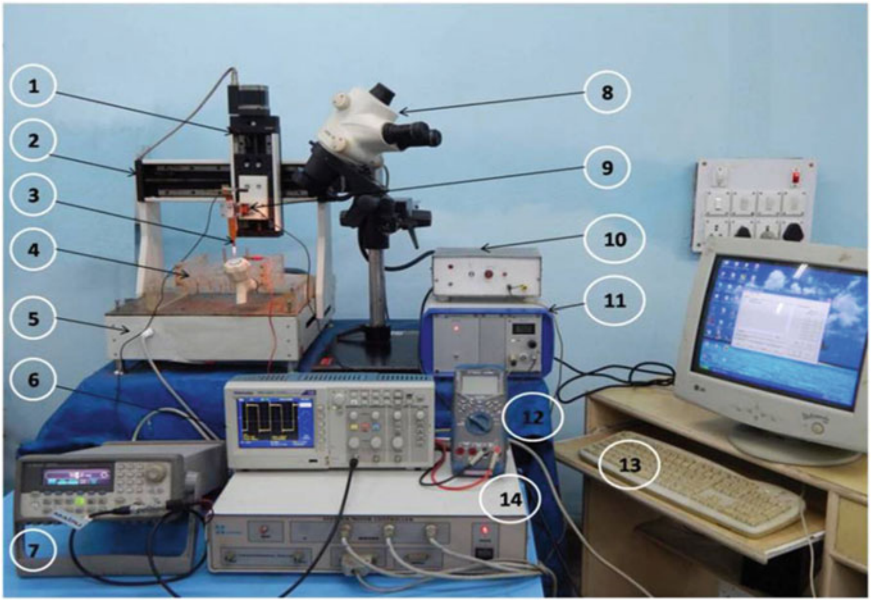


Fig. 1 Photographic view of developed EMM setup. *1* Long travel linear stage, *2* gantry bridge, *3* microtool holder, *4* machining chamber, *5* mechanical machine unit, *6* digital storage oscilloscope, *7* pulse generator, *8* steoreozoom microscope, *9* PZT, *10* PZT power supply, *11* amplifier, *12* digital multimeter, *13* desktop computer and *14* machine controller unit

3.2 Planning of Experiments

In-house developed sidewall insulated disc microtool has been utilized for machining of complex microgrooves by EMM. EMM characteristics such as side machining gap and linearity of microgroove have been studied to develop the strategy for machining the various cross-sectional shapes of the microgrooves. Varied cross-sectional microgrooves have been machined by layer-by-layer machining by scheming the important process parameters while machining the microgroove. Microtool vibration system has also been utilized during machining to ensure the supply of fresh electrolyte at IEG.

To study the influence of process parameters such as applied voltage, duty ratio and machining time over side machining gap and linearity, microgrooves have been machined on stainless steel using sidewall insulated disc microtool by layer-by-layer machining. Scanning type machining also takes care of supply of fresh electrolyte at narrow IEG during each scan. Therefore, layered machining strategy for microtool movement has been followed, in which microtool moves with horizontal tool feed of 109 μm/s for complete scan length and down feed of 0.625 μm at the end of each scan. Fabricated microgrooves have been analysed for the measurements and shape accuracy. Widths of the microgroove have been measured at different locations along its length, and side machining gap has been determined. Standard deviation (σ) for width of microgroove has been analysed to appraise the uniformity of microgroove along its length. Side machining gap characteristics have been analysed and applied for machining of different micro-features inside the microgrooves by controlling the process parameters during machining of microgrooves.

While machining deep microgrooves by EMM, continuous supply of fresh electrolyte at machining zone and taking away the process by-products from narrow IEG are the main challenges. Longitudinal vibrations of the microtool with few microns of amplitude of vibration help to improve the supply of fresh electrolyte by removing sludges from machining region. Vibration frequency of 88 Hz and 4–5 μm amplitude of vibration result in best machining performance, which has been decided through trial experiments (Bhattacharyya et al. 2007). Finally, SEM micrographs of the machined microgrooves with different internal micro-features have been analysed for measurements and for further analysis.

3.3 Layer-by-Layer Machining Strategy

In layer-by-layer machining, microtool moves for complete machining length with full scanning speed and feeds vertically downward by short distance at the end. Hence, for fabricating the microgrooves of desired length and depth, microtool has to scan to and fro along the full length of microgroove for 'n' number of times to complete total depth, with vertical down feed by small distance, i.e. scan depth, each time.

3.4 Disc Shape Microtool and Its Sidewall Insulation

Microtool is the vital element in EMM. In EMM, microtools with finished surface quality are preferred because the characteristics of microtool such as shape, size and surface finish are conveyed to the workpiece. For microtool fabrication, tungsten is one of the best suitable materials, because of its various important properties like hardness and corrosion resistance. Figure 2 shows the microscopic image of fabricated disc shape microtool of diameter 200 μm and height 70 μm, developed from tungsten micro-rod specimen of diameter 200 μm by reverse EMM (Rathod et al. 2013). Machining conditions during fabrication of disc shape microtool are given in Table 1.

In EMM, use of disc microtool confines the dissolution of workpiece to disc region and reduces the taper formation at the sidewalls of micro-features as shown in Fig. 3 (Rathod et al. 2014). To confine the dissolution of workpiece material along the disc region, the radial difference between the disc radius and shank radius of the microtool electrode (d) must be greater than the difference between the

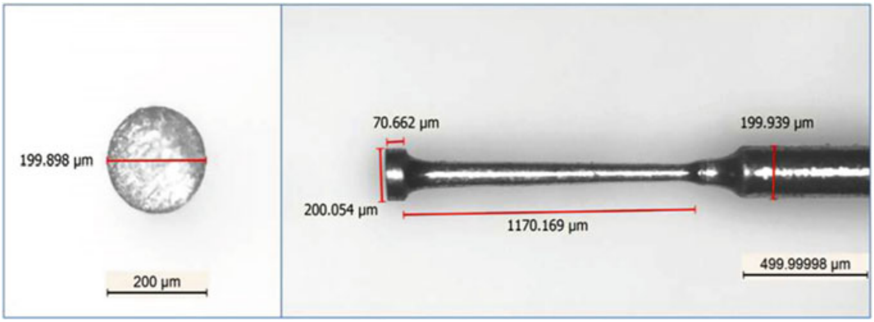


Fig. 2 Disc shape microtool fabricated by EMM

Table 1 Machining parameters in fabrication of disc 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 V
Pulse frequency	1 MHz
Duty ratio	80%
Machining time	15 min

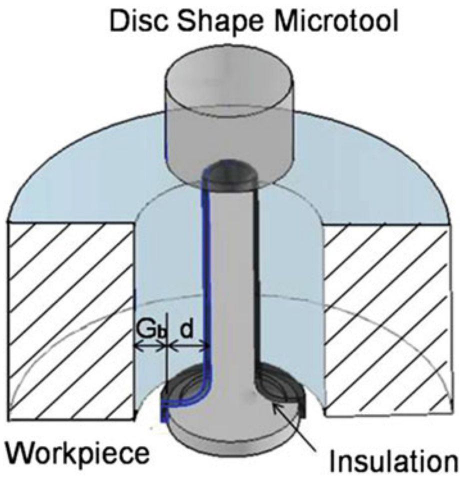


Fig. 3 Influence of disc shape on sidewall profile of micro-feature (Rathod et al. 2017)

machining gap, i.e. $d > G_b$ (Kim et al. 2005). Machining gap depends upon machining parameters; ultimately, the desired radial difference between the disc and shank of the electrode also depends on the machining parameters. Fabrication of complex microgrooves of varied side machining gaps along its depth needs various disc microtools with various combinations of disc and shank diameters that is practically impossible, or utilizing the same disc microtool with sidewall insulation by varying machining conditions. Therefore, to avoid the over dissolution, to reduce the stray current effects and to minimize the taper formation along the sidewalls of microgroove while machining complex micro-features with varied side machining gaps, disc microtool sidewalls are insulated. Sidewall insulation of disc microtool makes the EMM non-sensitive to the microtool length during machining micro-features of higher depth; hence, uniform side machining gap can be obtained irrespective of depth of micro-features. Use of disc microtool assures the presence of fresh electrolyte at machining zone along with easy removal of EMM by-products from very small machining zone as compared with straight cylindrical microtool due to smaller shank diameter and smaller disc height that enhances the overall machining performance.

4 Results and Discussions

Machining of perfect micro-features of required dimension by EMM desires to know the accurate amount of side machining gaps, which may generate during machining. Therefore, to investigate the side machining gap characteristics, microgrooves have been machined utilizing developed EMM system setup, and influence of the major process parameters such as applied voltage, duty ratio and machining time on side machining gap and uniformity of microgrooves has been analysed. Experimental outcomes have been graphed to reveal the effect of various factors on side machining gap.

4.1 Influence of Applied Voltage on Side Machining Gap and Linearity

To study the effect of applied voltage on side machining gap and uniformity of the microgroove along its length, microgrooves have been fabricated with applied voltage 2.8–4.0 V, pulse frequency 5 MHz, 30% duty ratio and 0.15 M H_2SO_4 as an electrolyte. Figure 4 depicts the microscopic images of microgrooves machined at different applied voltages. Widths of the machined microgroove have been measured at various points of the microgroove as shown in the figure. Microgroove widths obtained at various voltages of 2.8, 3.2, 3.6 and 4.0 V are 305, 344, 356 and 425 μm, respectively. The increase in length of the machined microgrooves can also be seen as 2269, 2281, 2356 and 2332 μm, at various applied voltages.

Figure 5 plots the influence of applied voltage on side machining gap and standard deviation of machined microgrooves. From the figure, it can be observed

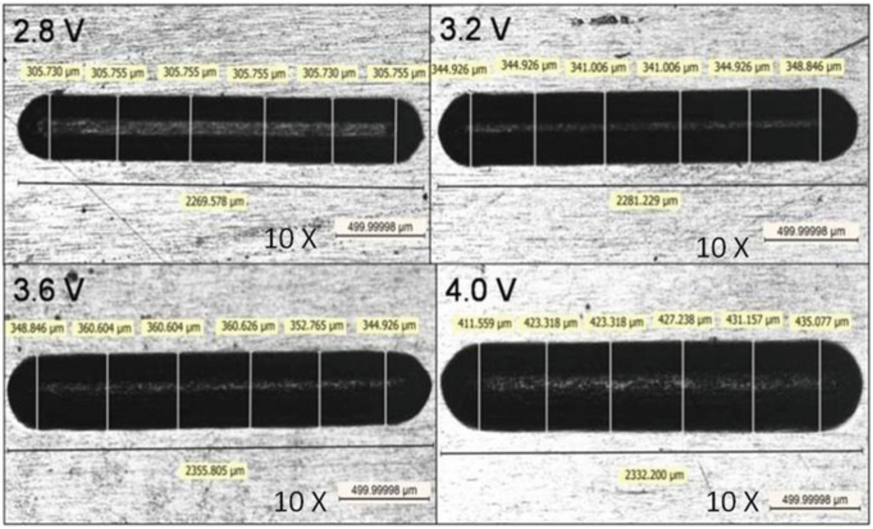


Fig. 4 Microgrooves machined at various applied voltages (Rathod et al. 2017)

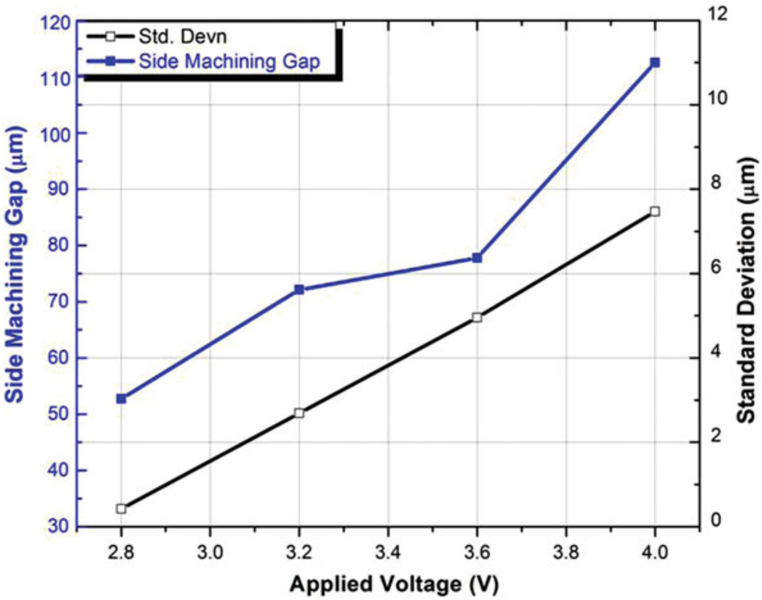


Fig. 5 Variation in machining gap and standard deviation with applied voltage (Rathod et al. 2017)

that with increase in applied voltage, side machining gap increases and linearity of microgroove decreases. The reason behind this is increased machining current at higher applied voltage that increases the current density and in turn reduces the machining localization. Finally, side machining gap increases with increase in applied voltage due to increased material dissolution as per Eq. (6). From above experiments, it can be said that applied voltage has a key role in regulating the side machining gap in EMM, and this factor can be utilized for fabricating microgrooves of varied side machining gaps.

4.2 *Influence of Duty Ratio on Side Machining Gap and Linearity*

The ratio of pulse 'on' time to the total pulse period is the duty ratio, and it implies the percentage of time for which pulse remains 'on'. Material dissolution occurs during the pulse 'on' time only; hence, pulse 'on' time is very important parameter in EMM. To examine the influence of pulse 'on-time' over side machining gap and uniformity of machined microgrooves, duty ratio has been varied from 30 to 60%, i.e. pulse 'on' time from 60 to 120 ns, with pulse frequency 5 MHz, applied voltage 2.8 V and 0.15 M H_2SO_4 as an electrolyte. Figure 6 shows the microscopic images of machined microgrooves at different duty ratios. Microgroove widths obtained at different duty ratios of 30, 40, 50 and 60% are 297, 367, 418 and 583 µm, respectively. The length of machined microgroove can also be observed as 2230, 2277, 2332 and 2371 µm, at different applied voltages. Figure 7 demonstrates the change in side machining gap and standard deviation of microgrooves machined at different duty ratios. Increase in side machining gap and reduction in linearity of microgroove with increase in duty ratio can be seen from Figs. 6 and 7. This can be explained with the help of nature of pulse waveforms observed during machining.

Figure 8 shows the digital images of pulse waveforms obtained by digital storage oscilloscope. Pulse parameters as can be seen from Fig. 8a are applied voltage 5 V, pulse frequency 5 MHz, pulse period 200 ns, duty ratio 30% and pulse width, i.e. pulse on-time 60 ns. Single pulse consists of pulse on-time and pulse off-time, and pulse on-time increases with increase in duty ratio. Dissolution of workpiece occurs during pulse 'on' time, and process by-products like sludge and heat are taken out from machining region during pulse 'off' time mainly. Increased pulse on-time with increases in duty ratio increases the volume of material removed as per Eq. (6). Increased machining current at higher duty ratio reduces machining localization, which increases material dissolution that increases machining gap finally. From these experiments, it is observed that duty ratio also has an important role in regulating side machining gap in EMM and can be used for machining of micro-features having different machining gaps.

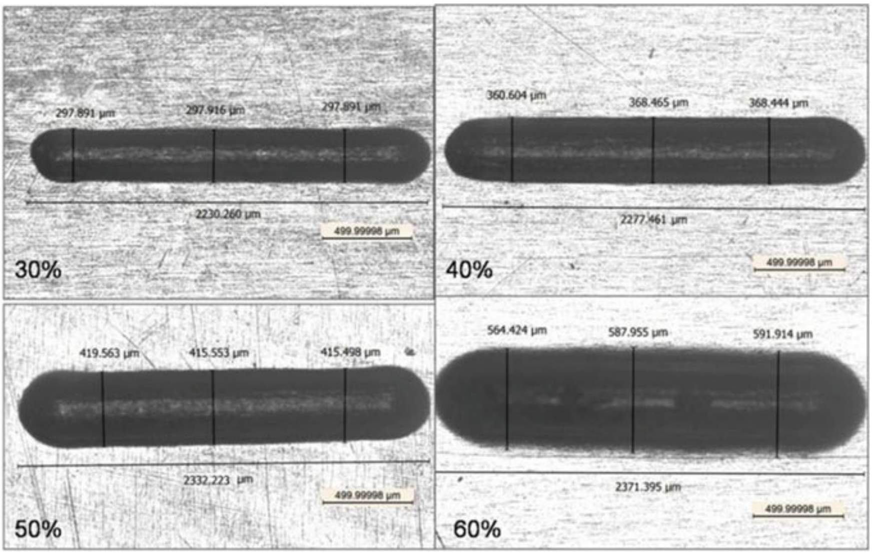


Fig. 6 Machined microgrooves at different duty ratios (Rathod et al. 2017)

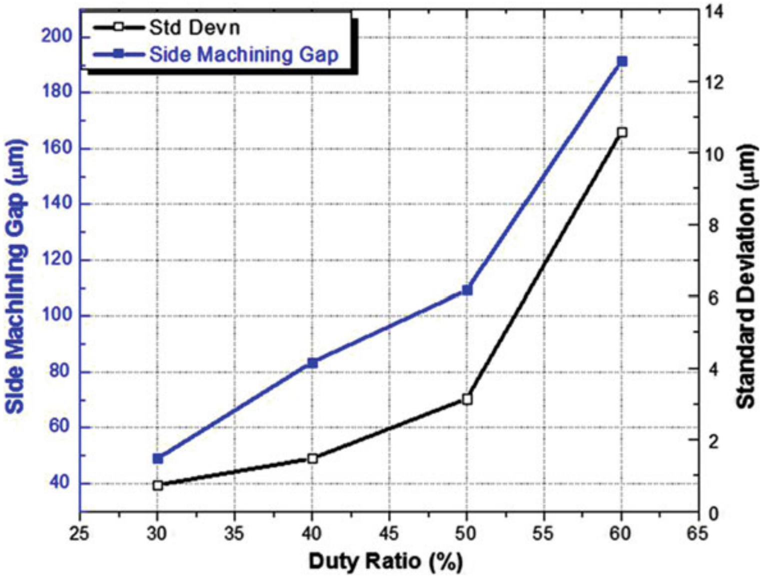


Fig. 7 Variation in machining gap and standard deviation with duty ratio (Rathod et al. 2017)

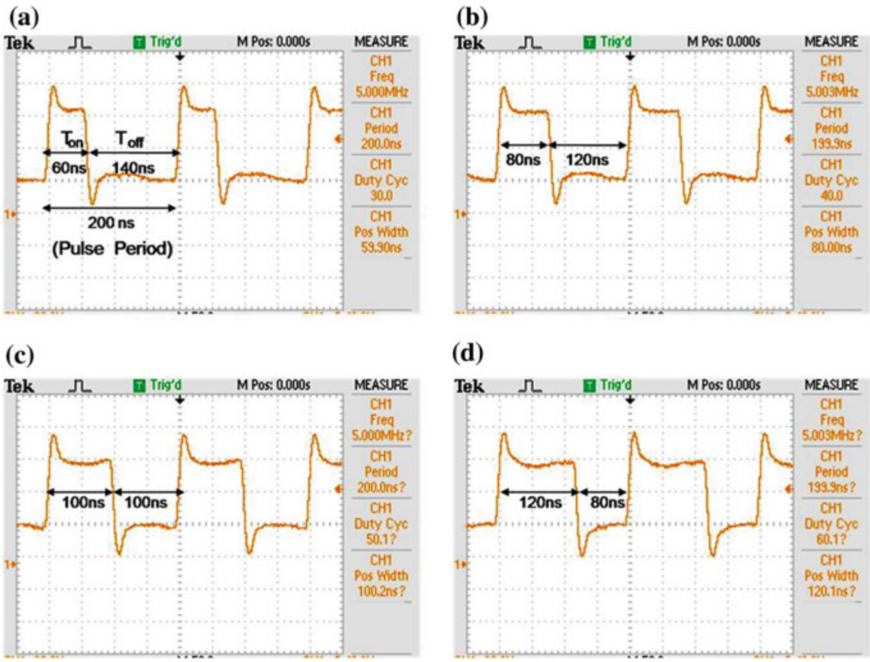


Fig. 8 Pulse waveforms at: **a** 30%, **b** 40%, **c** 50% and **d** 60% duty ratio (Rathod et al. 2017)

4.3 Influence of Machining Time on Side Machining Gap and Linearity

To study the effect of total machining time over side machining gap and linearity, microgrooves have been machined to various machining times from 3 to 12 min, with applied voltage 2.8 V, pulse frequency 5 MHz, duty ratio 30% and 0.15 M H_2SO_4 as an electrolyte with inter-electrode gap of 10 µm with no vertical microtool feed. Figure 9 depicts the microscopic images of the machined micro-grooves at various machining times. Microgroove widths obtained at different machining time of 3, 6, 12 and 15 min are 260, 272, 292 and 313 µm, respectively. Similarly, the lengths of machined microgroove obtained are 2054, 2114, 2198 and 2223 µm, respectively. Figure 10 shows the variation in side machining gap and linearity of the microgroove machined at various machining times. From the figure, it can be observed that side machining gap rises with machining time, and linearity of microgroove enhances initially with increase in machining time, and afterwards, it diminishes. This is due to the continuous dissolution of workpiece with increased machining time, which ultimately increases the side machining gap. Inter-electrode gap increases with progress of time that diminishes the machining localization, and finally reduces the linearity and increases the side machining gap of the

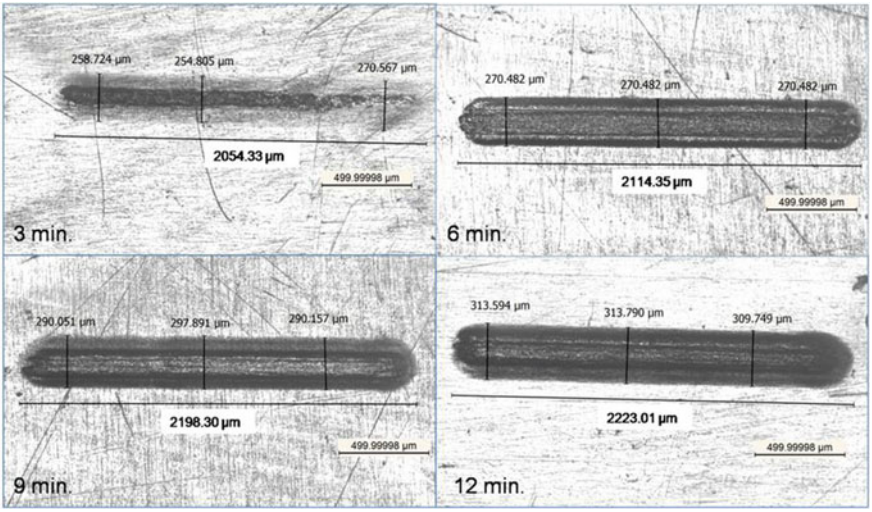


Fig. 9 Machined microgrooves at various machining times (Rathod et al. 2017)

microgroove. From these experiments, it can be said that machining gap varies also with machining time and can be used for machining of micro-features with different side machining gaps.

5 Machining of Varied Cross-Sectional Microgrooves

Influence of various process parameters on side machining gap has been analysed through the experiments. Variation in machining gap with process parameters offers the possibility of machining different micro-features inside the microgrooves to generate various cross-sectional microgrooves. Utilizing sidewall insulated disc microtool with longitudinal vibrations, adopting layer-by-layer machining strategy and by varying the process parameters during machining of microgroove, fabrication of various cross-sectional microgrooves has been demonstrated (Rathod et al. 2017).

5.1 Machining of Reverse Tapered Microgroove

Microgrooves with reverse taper are very much difficult to be machined by various present micromachining techniques, whereas such microgrooves can be machined without any difficulty by increasing duty ratio gradually along the depth of microgroove during machining. Figure 11 illustrates the planned profile of reverse

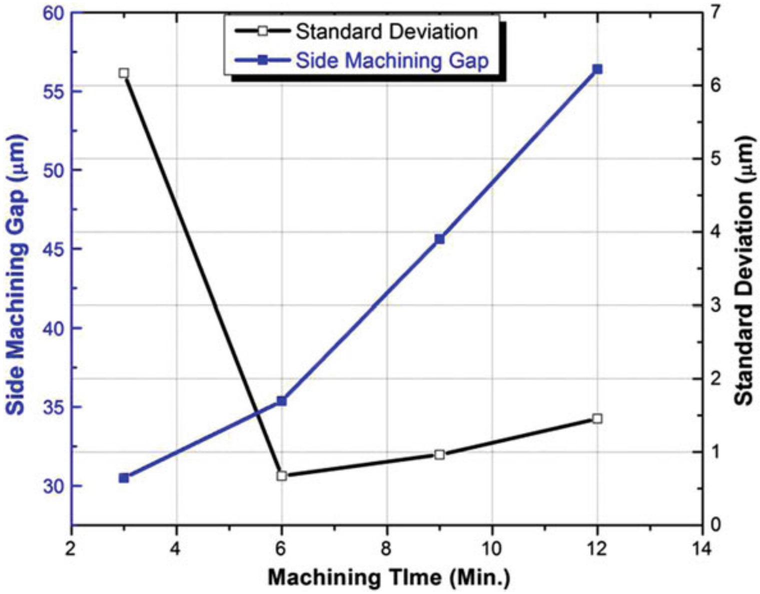


Fig. 10 Deviation in machining gap and standard deviation with machining time (Rathod et al. 2017)

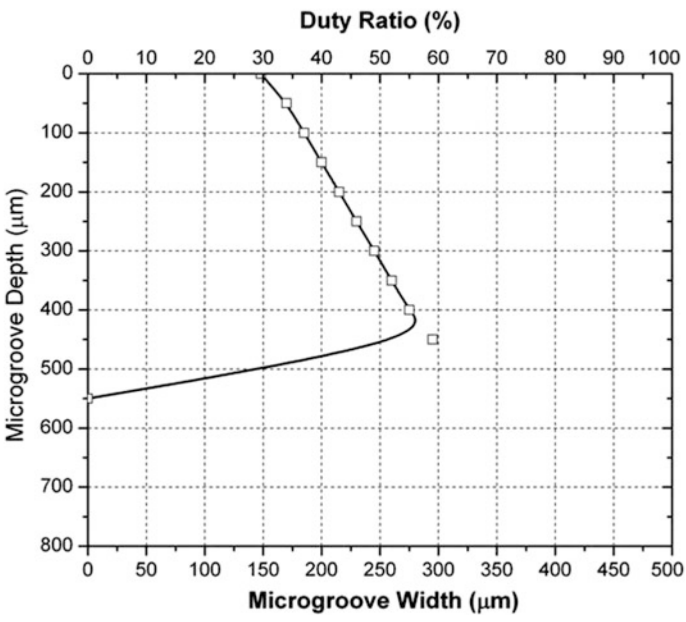


Fig. 11 Planned profile for reverse tapered microgroove (Rathod et al. 2017)

tapered microgroove as per the experimental findings, with machining parameters as applied voltage 3.2 V, pulse frequency 5 MHz, 0.15 M H_2SO_4 as an electrolyte and scanning speed of 109 µm/s with tool feed of 0.625 µm at the end of each scan by varying duty ratio gradually from 30 to 60% along the depth during machining.

Increase in duty ratio during machining of the microgroove leads to the more material dissolution, i.e. higher width of microgroove that gives the reverse tapered microgroove. Application of insulated disc-shaped microtool controls over dissolution of workpiece material along sidewalls of the microgroove, as well as stray current effects even at higher duty ratio. Thus, when duty ratio increases with respect to the depth during machining of microgroove, the width increases only at front end of the microtool and top face width, i.e. entry width of microgroove remains unchanged. Hence, microgroove having gradual increase in width towards the bottom can be fabricated by this method. It is also possible to fabricate the microgrooves of various reverse taper angles by controlling the duty ratio during machining of microgroove. Figure 12 depicts the SEM images of machined reverse tapered microgroove. From the figure, entry width 354.14 µm and bottom width 553.20 µm with reverse taper angle of 55° for total depth of 534.94 µm can be seen clearly. Curved surface is generated at the bottom of the microgroove, due to the nature of the current distribution. In disc shape microtool, more current flows through the core of the disc, in comparison with the periphery because of shorter path of current flow at core. Higher current at core dissolves more material in central portion, i.e. bottom of the microgroove as compared to periphery, leading the curved surface at the bottom of the microgroove.

5.2 Machining of Barrel-Shaped Microgroove

Applied voltage directly influences the material removal in EMM. Hence, varying cross-sectional microgrooves can also be obtained by regulating the applied voltage during microgroove machining. Barrel-shaped microgroove that has increased

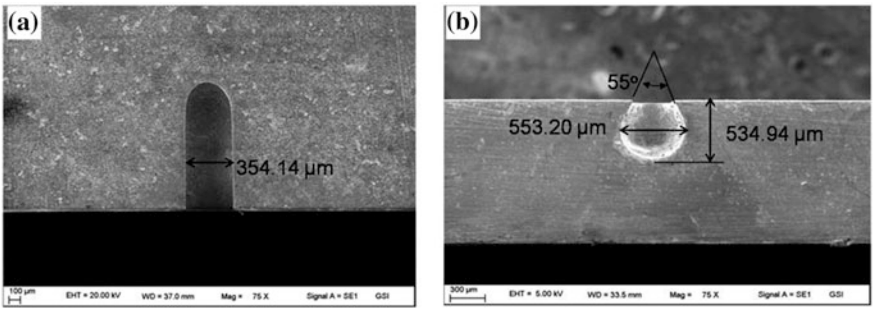


Fig. 12 SEM micrograph of machined microgroove (Rathod et al. 2017)

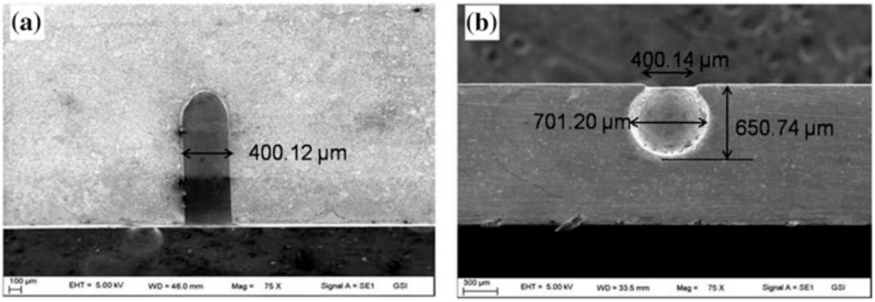


Fig. 13 SEM micrograph of barrel shape microgroove (Rathod et al. 2017)

width up to mid and reduced width for remaining depth can be machined by varying applied voltage from 3.2 to 3.8 V up to midsection of microgroove and again decreased from 3.8 to 3.2 V for remaining depth with pulse frequency 5 MHz, duty ratio 30% and 0.15 M H_2SO_4. Figure 13 shows the SEM micrographs of machined microgroove with entry width 400 µm with increasing width. It can also be seen that maximum diameter of 701 µm at the mid of microgroove, with total depth of 650.74 µm.

Increase in applied voltage enlarges side machining gap at front face of the microtool resulting in increased width of microgroove; further continuation of machining with reduced applied voltage leads to the reduced machining gap. Therefore, a microgroove of increasing width up to desired depth and reducing width for remaining depth can be machined. Microgrooves of different opening widths as well as different internal widths can be fabricated by combination of applied voltage and other parameters during machining of microgroove. Reduced scanning speed enlarges the opening width that also supports the fabrication of microgrooves of required dimension.

5.3 *Machining of Spherical-Based Microgroove*

In EMM, machining gap can be regulated not only by changing the pulse parameters but also by changing the machining time. Microgrooves with uniform width up to required depth having spherical base are challenging to machine by the present techniques. Such microgrooves can be fabricated easily by machining microgrooves up to desired depth with constant parameters and further prolongation of machining at higher duty ratio, with no microtool down feed for generation of spherical base. Figure 14 shows the SEM micrograph of microgroove machined with applied voltage 3.2 V, pulse frequency 5 MHz, duty ratio 30%, 0.15 M H_2SO_4 as an electrolyte and scanning speed of 109 µm/s with 0.625 µm vertical feed at the end of scan up to 250 µm depth. After that, microgroove has been machined with increased duty ratio of 50% for 10 min with no vertical down feed.

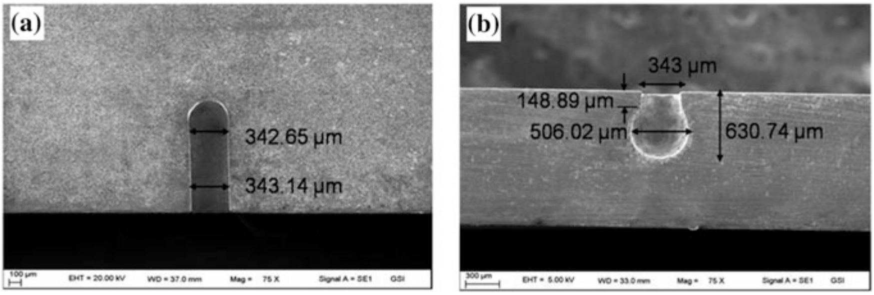


Fig. 14 SEM micrograph of microgroove with spherical base (Rathod et al. 2017)

The figure shows the entry width of 343 µm up to 149 µm depth with having spherical base of 506 µm diameter, machined for the total depth of 630.74 µm.

Sidewall insulated disc microtool limits over dissolution of material even at higher machining time and higher duty ratio. Therefore, at increased machining time and duty ratio, width of microgroove, i.e. machining gap, increases at front end of microtool only, and width at an entrance of microgroove remains unchanged. Hence, a microgroove with constant width up to required depth with spherical base of higher diameter can be machined. Because of the nature of current distribution at the front end of the disc shape microtool, spherical base is generated at base of straight microgroove. Increased duty ratio reduces machining localization, which results in material dissolution from wider area and generates sphere of higher diameter at bottom of machined microgroove, since there is no vertical tool feed. Microgrooves of different widths with spherical base of various diameters can be generated on metallic surfaces by regulating different process parameters during machining.

5.4 *Machining of Stepped Microgroove*

Microgrooves of very complex profiles can be machined by devising process parameter along the depth during machining of microgrooves. Schematics of the profile planned for stepped microgroove are as shown in Fig. 15. Machining of stepped microgroove has been planned into two steps. Microgroove of desired depth ‘Z_1’ has been planned with higher duty ratio of 60% for depth of 300 µm, and microtool travels for distance ‘Z_2’, i.e. 100 µm without machining to overcome the depth overcut generated at higher duty ratio. Afterwards, microgroove at the base has been planned with lower duty ratio of 30% for required depth of ‘Z_3’, i.e. 200 µm. Other process parameters have been kept identical during machining for both steps of the microgrooves as applied voltage 3.2 V, pulse frequency 5 MHz, 0.15 M H_2SO_4 as an electrolyte and scanning speed of 109.375 µm/s.

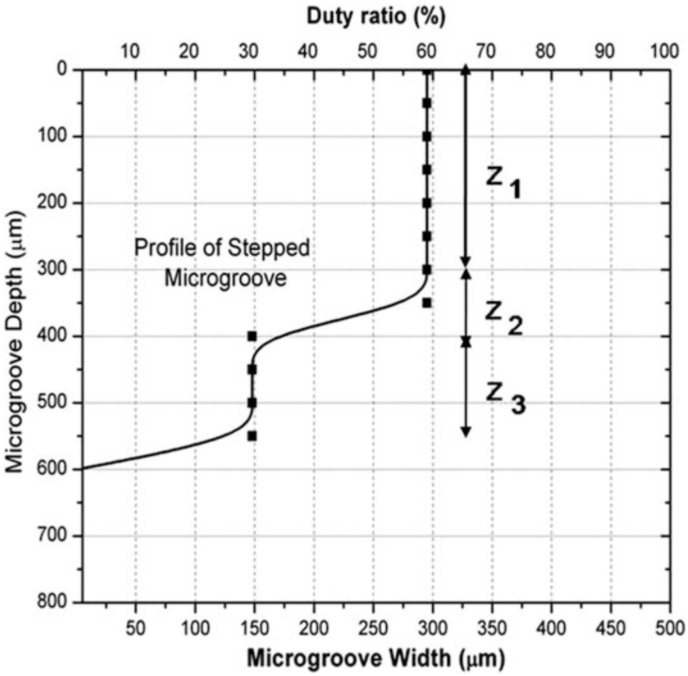


Fig. 15 Profile planned for stepped microgroove

Figure 16 depicts the SEM image of double stepped microgroove fabricated by EMM using disc microtool. The figure shows the average microgroove width of 561 μm at the top face and inner microgroove of 323 μm width. Total depth of the microgroove is 602 μm, with inner groove depth of 241 μm. Machining with increased duty ratio results in higher machining gap due to increased pulse 'on' time, in first step. Afterwards, material dissolution with reduced duty ratio results in smaller side machining gap. From Figs. 15 and 16, it can be seen that, by adopting scanning type strategy of microtool movement during machining, microgrooves with multiple steps of desired shape and size can be fabricated by EMM utilizing the same disc shape microtool by controlling the EMM parameters. Rounded surface is formed at the base of fabricated microgroove in comparison with the planned flat base of the microgroove. This is due to the nature of the current distribution through the microtool and poor machining localization at the front face of the microtool. However, flat surfaces can also be obtained by improving the process parameters, i.e. with lower applied voltage, and ultrashort pulses.

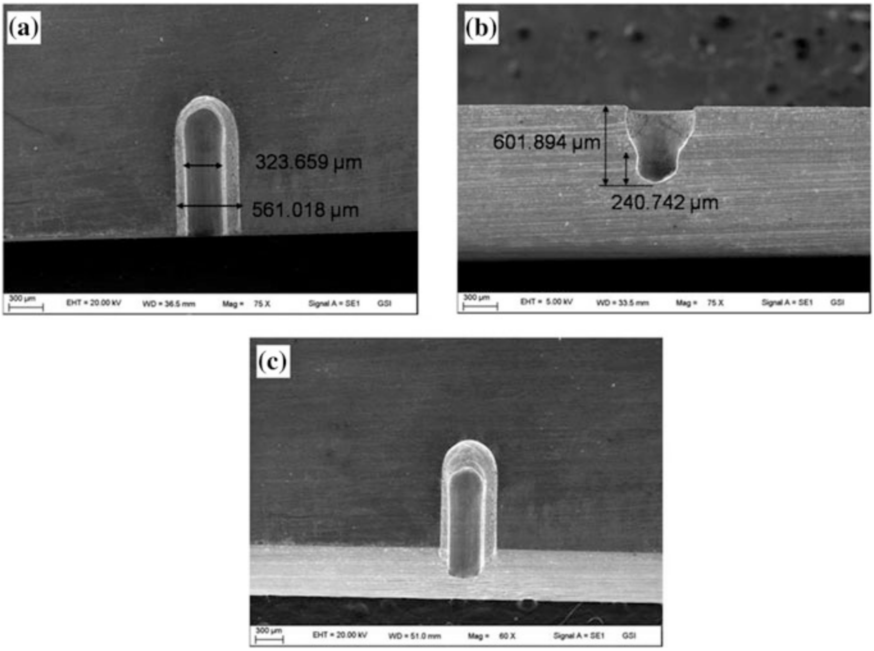


Fig. 16 SEM micrograph of stepped microgroove (Rathod et al. 2017)

5.5 Machining of Microgroove with Internal Pocket

Figure 17 shows the planned profile for machining the microgroove having internal pocket. Microgroove with narrow opening is intended to be fabricated with smaller duty ratio for desired depth as indicated by 'Z_1', followed by the fabrication with increased duty ratio for internal pocket of desired dimension as shown by 'Z_2' with other identical parameters.

Figure 18 depicts the SEM images of fabricated microgroove with internal pocket using disc microtool with applied voltage 3.2 V, pulse frequency 5 MHz, 30% duty ratio for 200 μm depth and 60% duty ratio for 400 μm depth, 0.15 M H_2SO_4 as an electrolyte and scanning speed of 109.375 μm/s with 0.625 μm vertical feed to the microtool at the end of each scan. Average opening width of 325 μm with the depth 121 μm. The internal pocket of 527 μm × 671 μm can be seen for the total depth of 794 μm. From the figures, it can be seen that by following this scheme of machining, microgrooves with varied opening width and internal pocket of desired dimensions, i.e. width and depth, can be fabricated utilizing the same disc shape microtool.

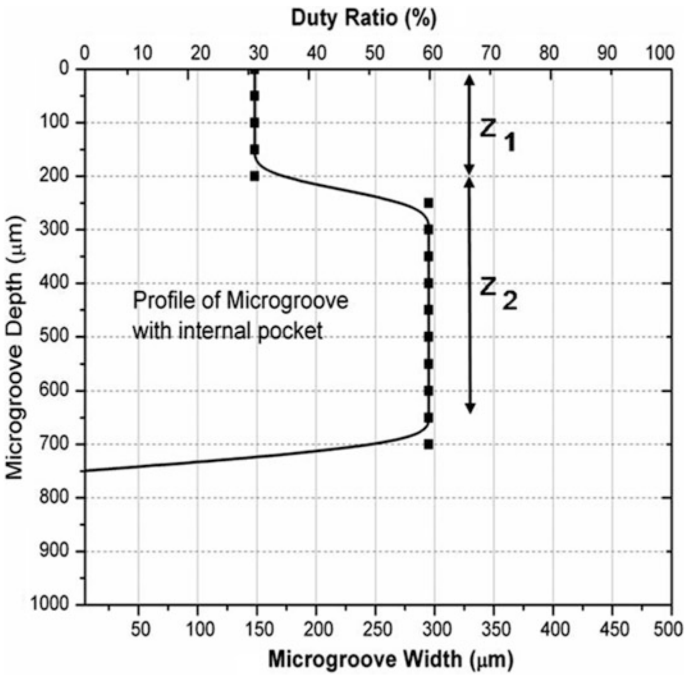


Fig. 17 Planned profile of microgroove with internal pocket

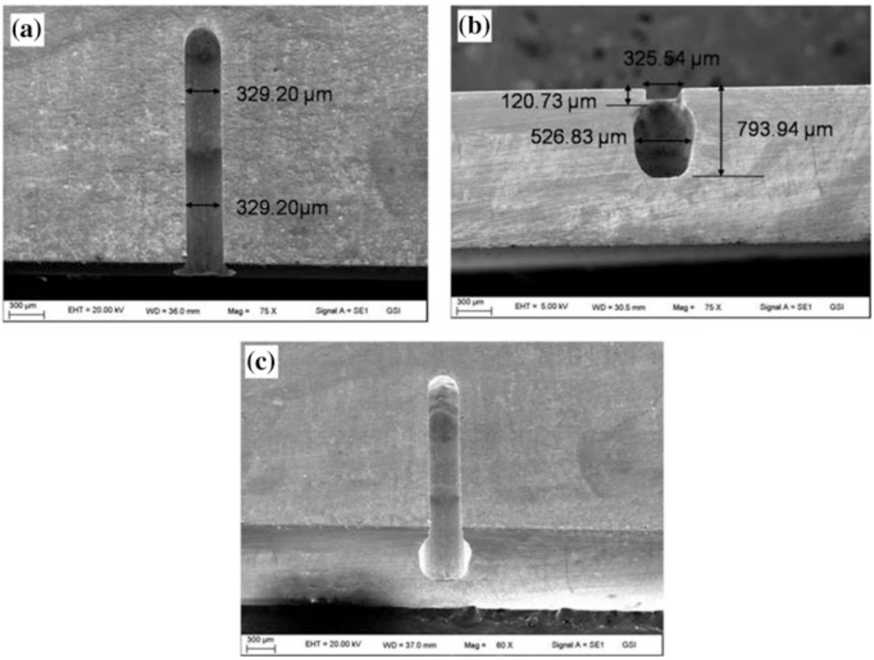


Fig. 18 SEM micrograph of stepped microgroove

6 Guidelines for Machining Varied Cross-Sectional Microgrooves

Investigational outcomes have been used for planning the desired cross section of the microgroove. Tables 2, 3, 4, 5, 6 and 7 provide the guidelines for machining microgrooves with different internal features forming different cross-sectional microgrooves, machined at applied voltage 3.2 V, pulse frequency 5 MHz, 0.15 M H_2SO_4 as an electrolyte and scanning speed of 109 µm/s with tool feed of 0.625 µm at every scan by varying duty ratio gradually from 30 to 60% during machining of microgroove. Use of sidewall insulated disc microtool with microtool vibrations has been considered in process. Tabulated data will be helpful to plan and machine different features inside the microgroove.

Table 2 provides the guidelines for controlling the duty ratio during fabrication of straight microgrooves of required depth. The total depth of microgroove considered is 700 µm. For machining straight microgroove of required depth, duty ratio is maintained constant throughout the machining depth. When the duty ratio is kept 30%, i.e. DR_1, with other constant parameters as mentioned above, the width of microgroove predicted from the experimental results is W_1, i.e. 296 µm. Similarly, by varying duty ratio to different values ranging from 40, 50 and 60%, i.e. DR_2, DR_3 and DR_4, microgrooves of different widths 368, 418 and 582 µm can be machined for required depth.

Table 3 presents the guidelines of varying the duty ratio in fabrication of reverse tapered microgrooves of required taper angle and depth. Total depth of the microgroove considered is 700 µm. Machining is started with 30% duty ratio, and it is increased gradually by 1° for every 20 µm depth, i.e. with vertical tool feed, to get the reverse tapered microgroove. In this way, microgrooves with different reverse taper angles can also be machined by changing the duty ratio at the start of machining of microgroove, as well as by varying the rate of change of duty ratio along the depth.

Table 4 gives the guidelines of varying the duty ratio along the depth of microgroove to machine barrel shape microgrooves of required dimensions. Total depth of the microgroove considered is 700 µm. Duty ratio is increased up to the mid-depth of microgroove and is reduced gradually after the mid-depth, to get the barrel shape of microgroove. Machining is started with 30% duty ratio and increased gradually by 1° for every 10 µm of vertical tool feed up to 400 µm, and duty ratio is gradually reduced with the same rate for remaining depth. Likewise, microgrooves of various barrel dimensions can also be fabricated by changing the duty ratio at the start of microgroove machining, as well as by varying the rate of change of duty ratio along the depth.

Table 5 illustrates the guidelines of varying the duty ratio during fabrication of V-shaped microgrooves. Total depth of the microgroove considered is 700 µm. Duty ratio is reduced gradually up to the required depth to achieve the *V* shape of microgroove. Machining is started with 60% duty ratio and is gradually reduced by 1° for every 20 µm of vertical tool feed required depth. Likewise, microgrooves of

Table 2 Guidelines for machining straight microgroove

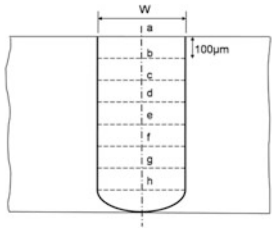
Pt.	Microgroove depth	Duty ratio				Microgroove width				Microgroove shape
		DR_1	DR_2	DR_3	DR_4	W_1	W_2	W_3	W_4	
a	00	30	40	50	60	296	368	418	582	
b	100	30	40	50	60	296	368	418	582	
c	200	30	40	50	60	296	368	418	582	
d	300	30	40	50	60	296	368	418	582	
e	400	30	40	50	60	296	368	418	582	
f	500	30	40	50	60	296	368	418	582	
g	600	30	40	50	60	296	368	418	582	
h	700	30	40	50	60	296	368	418	582	

Table 3 Guidelines for machining reverse taper microgroove

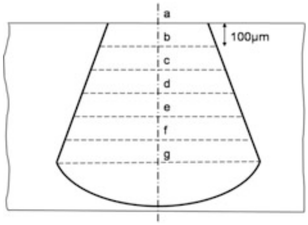
Pt.	Microgroove depth	Duty ratio	Microgroove width	Microgroove shape
a	00	30	296	
b	100	35	332	
c	200	40	368	
d	300	45	393	
e	400	50	418	
f	500	55	500	
g	600	60	582	

Table 4 Guidelines for machining barrel shape microgroove

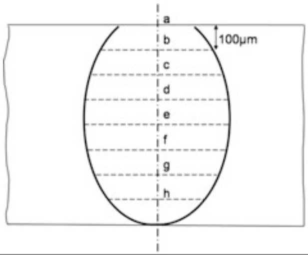
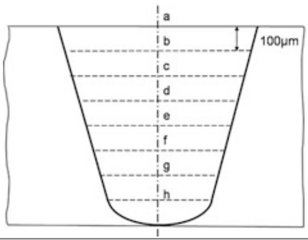
Pt.	Microgroove depth	Duty ratio	Microgroove width	Microgroove shape
a	00	30	296	
b	100	40	368	
c	200	50	418	
d	300	60	582	
e	400	50	418	
f	500	40	368	
g	600	30	296	

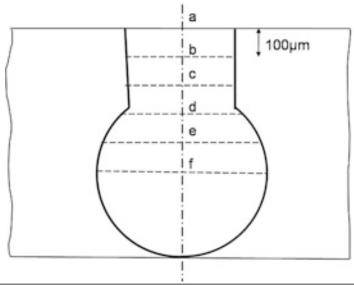
Table 5 Guidelines for machining *V* shape microgroove

Pt.	Microgroove depth	Duty ratio	Microgroove width	Microgroove shape
a	00	60	582	
b	100	55	500	
c	200	50	418	
d	300	45	393	
e	400	40	368	
f	500	35	332	
g	600	30	296	

various *V* angles can also be fabricated by changing the duty ratio at the start of microgroove machining, as well as by varying the rate of change of duty ratio along the depth.

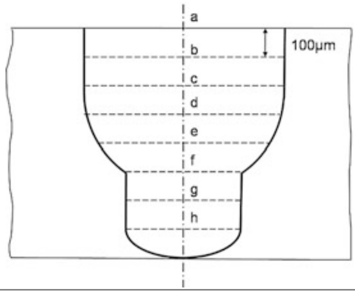
Table 6 offers the guidelines of varying the duty ratio during fabrication of straight microgrooves with spherical base. Microgroove is machined with fixed duty ratio up to certain depth to generate straight microgroove, and afterwards, duty ratio is increased to higher value and machined for predetermined time without

Table 6 Guidelines for machining spherical base microgroove

Pt.	Microgroove depth	Duty ratio	Microgroove width	Microgroove shape
a	00	30	296	
b	100	30	296	
c	200	30	296	
d	300	30	296	
e	400	30	368	
f	500	50[a]	520	

[a]Machining for 10 min without any vertical feed

Table 7 Guidelines for machining double microgroove

Pt.	Microgroove depth	Duty ratio	Microgroove width	Microgroove shape
a	00	60	582	
b	100	60	582	
c	200	60	582	
d	300	60	582	
e	400	00	430	
f	500	30	296	
g	600	30	296	
h	700	30	296	

vertical tool feed, to achieve the spherical base. Microgroove is machined with 30% duty ratio up to 400 μm depth, and at the end, duty ratio is increased to 50% and machined for 10 min with no vertical tool feed to generate the spherical base. Likewise, microgrooves of various base diameters can also be fabricated by regulating the duty ratio at the start of microgroove machining, as well as by changing the duty ratio and machining time at the end.

Table 7 presents the guidelines of varying the duty ratio during fabrication of double stepped microgrooves. Outer microgroove has been fabricated with higher duty ratio up to desired depth, microtool is fed down for short distance without machining to clear depth overcut and inner microgroove is machined with reduced duty ratio for the remaining depth to achieve double stepped microgroove. Outer microgroove is machined with 60% duty ratio up to 300 μm depth, and then, microtool is fed down for 100 μm without any material dissolution to clear depth overcut, and finally, inner microgroove is machined with 30% duty ratio for the remaining depth to generate double stepped microgroove. Similarly, microgrooves having number of steps with different dimensions of outer and inner microgrooves can be machined by changing the duty ratio at appropriate depth, during machining.

7 Conclusions

An application of sidewall insulated disc microtool with longitudinal vibration has been proposed in fabrication of various cross-sectional microgrooves by EMM. Machining characteristics, viz. side machining gap and linearity of microgroove, have been analysed through experiments. From experimental results, it has been concluded that

(i) Side machining gap, i.e. width of microgroove, varies with process parameters such as applied voltage, duty ratio and machining time. By regulating these process parameters along the depth of microgroove, it is possible to plan and fabricate different internal micro-features inside the microgrooves.
(ii) To develop the machining guidelines for various cross sections of the microgrooves, duty ratio has been regulated from 30 to 60%, with other process parameters as applied voltage 3.2 V, pulse frequency 5 MHz, 0.15 M H_2SO_4 as an electrolyte and scanning speed 109 μm/s, with tool feed of 0.625 μm at every scan. Guidelines have been developed for straight, reverse tapered, barrel shape, *V* shape, spherical base and double stepped microgrooves.
(iii) Insulation of lateral surface of disc microtool prevents the over dissolution of workpiece during fabrication of complex microgrooves, minimizes the stray current effect and also makes EMM process non-sensitive to the microtool depth.
(iv) Layer-by-layer machining in addition to the microtool vibration assists in removing slush and process by-products from IEG ensuring the presence of fresh electrolyte at machining zone and enhances the machining performance while machining complex microgrooves.
(v) Finally, fabrication of reverse tapered microgroove having reverse taper angle 55° for total depth of 534.94 μm, barrel shape microgroove of 400 μm entry width, 701 μm wide at mid, for total depth 650.74 μm, spherical base microgroove having width 343 μm for 149 μm depth, and spherical base of 506 μm dia. for total depth 630.74 μm, stepped microgroove with double steps having 561 μm width at top for 361 μm depth and inner groove 323 μm wide for 241 μm depth, microgroove with internal pocket with straight opening of 325 μm for 121 μm depth and internal pocket of 527 μm × 671 μm for the total depth of 794 μm has been demonstrated successfully.

Designed guidelines can be used for practicing engineers and researchers in this field for planning and machining varied cross-sectional microgrooves as per the requirement. Machining guidelines have been designed considering variation of duty ratio along the depth to obtain required cross-sectional shaped microgroove. However, other parameters such as applied voltage and machining time can also be considered for designing machining guidelines, which may help to combine the effect of variation of more than one parameter to minimize the total machining time.

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