



Experimental investigation into ultrasonic micro machining for fabrication of micro channels on Quartz

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Abstract. Ultrasonic micro machining (USMM) process has the ability to produce micro channels on quartz materials. Fabrication of multiple micro channels on quartz is a challenging task due to brittleness of quartz. Among various materials, quartz is an attractive material for research interest because it is used for various biochemical and bio-medical applications. The developed multiple tips micro tool was used to fabricate multiple micro channels on quartz by micro USM process so that total machining time can be reduced and hence productivity can be enhanced. In the present research work, the effects of micro USM process parameters like power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut, taper angle and surface roughness of micro channel were analyzed during fabrication of multiple micro channels on quartz.

Keywords. Ultrasonic micro machining (USMM); Quartz; multiple tips micro tool; width overcut; taper angle; surface roughness.

1. Introduction

Hard and brittle materials such as quartz have outstanding thermal, chemical and wear resistant properties. The main difficulties to machine this material are its brittleness and hardness properties. The processing of quartz materials such as lithography and etching, etc. are costly. Electrically nonconductive materials cannot be machined using sophisticated machining techniques like electrical discharge machining (EDM) or electrochemical machining (ECM). For precisely cutting these brittle and hard materials, the ultrasonic micro machining process is a viable method [1]. Ultrasonic micromachining process has also no thermal damage to workpiece and it is cost effective. Because USM is a non-chemical and non-thermal process, there are no changes to the materials' physical or chemical characteristics.

Micro channels on workpiece materials are needed to hold as well as transmit liquids through passage which have applied in various areas like biomedical science, micro fuel cell and cooling of components of microelectronics. Thus, fabrication of micro channels is essential for developing micro devices. Micro channel was fabricated by using photolithography processes for micro fluidic application. A $4\ \mu\text{m} \times 1.8\ \mu\text{m}$ cross section and 1.2 mm length micro channel was fabricated and demonstrated through fluid delivery [2]. Liquid assisted femto-second laser of pulses 800 nm wavelength was used to fabricate micro holes as

well as micro-channel on glass [3]. Powder blasting is a process which is capable to generate 3D structuring on brittle materials. This process is based on the erosion of a masked substrate by a high-velocity Al_2O_3 powder beam on brittle materials [4]. A variety of design is used to developed micro channels on various engineering materials to fulfill the requirement. Because of extremely brittle and hard nature of quartz making of multiple micro channels on this material be a difficult task. Quartz is an attractive material for research interest because it is employed in various chemical and medical industries. Quartz is also used in bioscience because it has good thermal and chemical stability, high resistant to heat, cost effective, etc. [5, 6].

USM operation was performed to generate hexagonal hole on alumina ceramic and found that maximum MMR was achieved at bigger grit size and lower surface roughness was achieved at smaller grit size and power rating [7]. To reduce crack formation and enhance quality of machined entrance surface, a thin layer of wax was used on glass surface, and micro hole generated on glass using USM. It was found that crack formation occurs on wax layer instead of glass surface [8]. A new method was proposed where less than 5 % concentration of HF was added to abrasive slurry to enhance the quality of machined surface of glass [9]. Ultrasonic machining process is applied to machine silicon (100) with 200 μm cemented carbide tool. Abrasive was used for experiments as diamond (0.1 and 0.25 μm) roughness (S_a) value was obtained in the range of 5–15 nm [10]. An electric field was applied surrounding the

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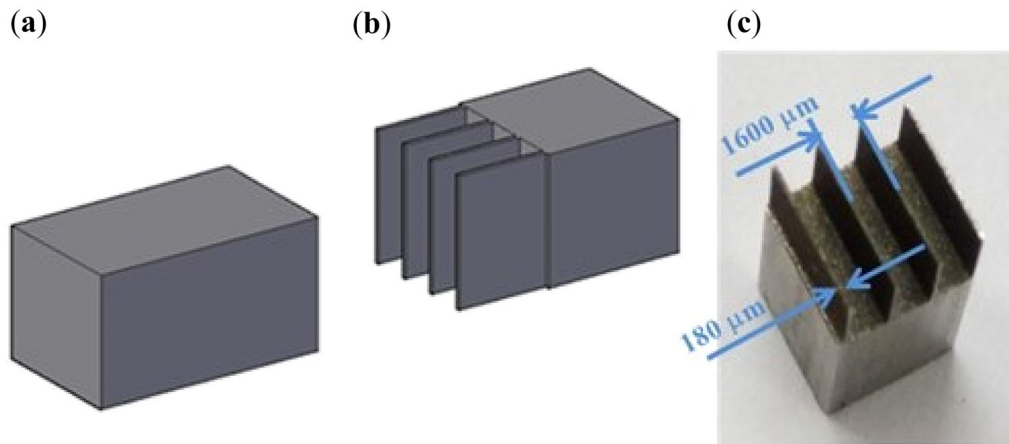


Figure 1. (a) 3D view of tool material, (b) CAD model of developed multiple tips micro tool and (c) photographic view of multiple tips micro tool.

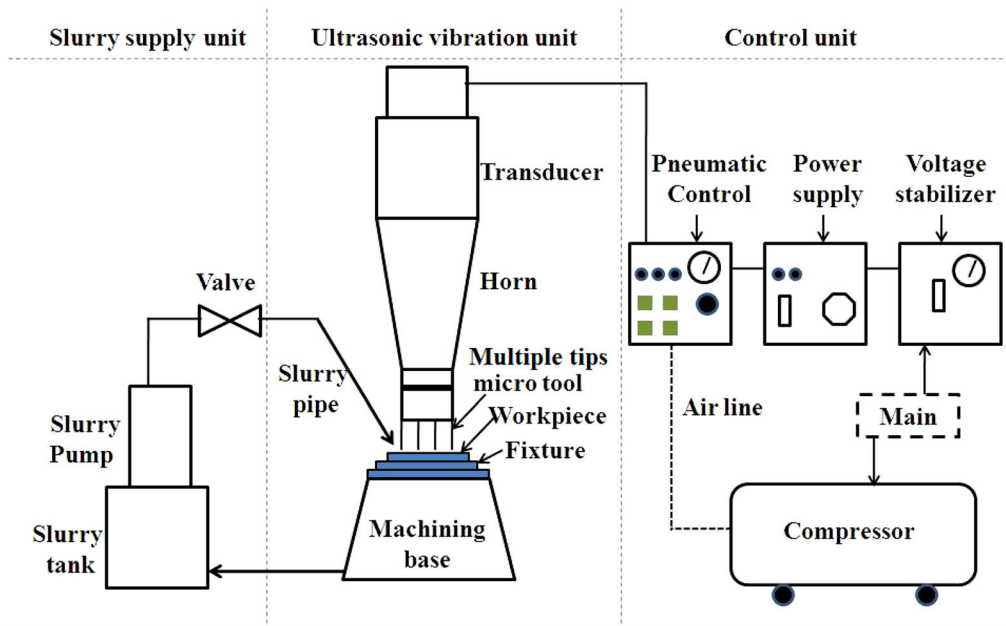


Figure 2. Schematic diagram of micro-USM system.

tool which resulted in accumulation of the abrasives around the tool and this process is called electrophoretically assisted micro-ultrasonic machining (EPAMUSM). This helped to enhance MRR as well as surface quality of hole [11]. Ultrasonic machining process was utilized to drill hole on glass using Al_2O_3 and SiC abrasive of two different shapes (Cube and sphere). Experimental as well as simulation results showed that Al_2O_3 spherical shape abrasive gave the better results [12]. USM process was used to drill micro hole on B_4C and the result was compared during machining of glass and brass [13]. It was observed that micro-rotary ultrasonic machining (μ -RUM) technique has

superior control with respect to edge chipping, taper and cutting forces compared to conventional micro-grinding and drilling process. However, effectiveness of process depends on range of machining parameters [14]. Rotary ultrasonic micro-drilling process was used to drill on zirconia, silicon and glass and it was found that machining rate and overcut was maximum for silicon, glass and zirconia sequentially [15]. Micro channel was developed on glass by using stationary micro-USM and rotary micro-USM. The experimental MRR and depth of channel were determined for both the processes [16]. Some researcher fabricated micro channel by using micro-USM process. The

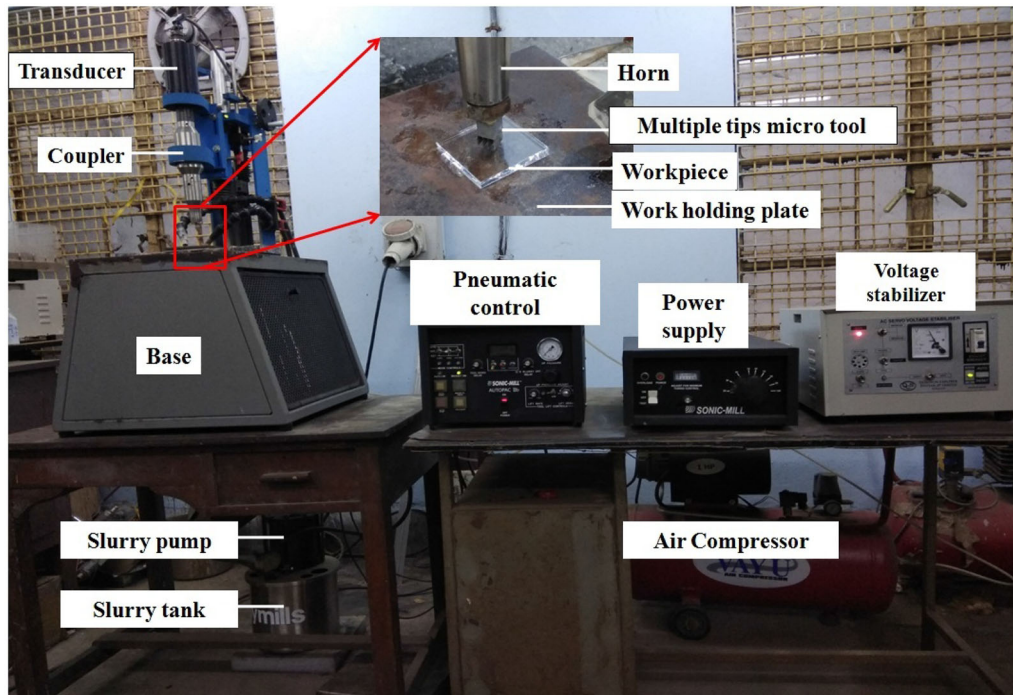


Figure 3. Photographic view of micro-USM system.

3D micro channels were produced by micro-USM method on ceramics materials [17, 18]. Micro USM process was utilized to produce the micro channel on silicon and it was reported that low viscosity fluid in abrasive slurry gave better surface finish. Higher feed rate gave better surface finish and stray cut [19]. UVAM has shown to be superior to CM for processing advanced materials because it enhances surface quality and processing efficiency [20]. A theoretical model was suggested to compute the tool-workpiece contact rate (TWCR) in ultrasonic vibration assisted milling (UVAM), where the four machining factors that impact TWCR are nominal cutting speed, ultrasonic frequency, ultrasonic amplitude, and cutting angle. The results of the experiments revealed that the UVAM approach offered clear technical benefits in terms of lowering cutting force, enhancing completed surface quality, suppressing burrs, and optimizing chip formation [21]. Ultrasonic abrasive machining technique was used to machine aluminum alloy using Al_2O_3 abrasive grains. The material is removed by mainly three modes such as hammering, impact and cavitation-erosion action [22].

So, from the literature review it is found that research work was done by using single tip micro tool of circular cross section for drilling operation or generation of single channel at a time by travelling the micro tool with the application of CNC. It hampers the accuracy of micro features by repetition of same tool during successive machining and also takes more time for operation. To solve this problem multiple tips micro tool has been designed and

developed by wire-EDM process. By utilizing developed multiple tips micro tool, multiple micro-channels have been produced by ultrasonic micro machining process. The micro channels on quartz have wide range of application in biomedical science, micro fuel cell and cooling of components of microelectronics, etc. So, fabrication of multiple micro channels on quartz at a time is very much needed using multiple tips micro tool by ultrasonic micro machining process to save time and obtain good accuracy. The influences of process parameters on width overcut, taper angle and surface roughness of micro channel have been investigated in the present research work.

2. Materials and methods

In general, micro channel, one at a time is produced by using a micro tool of circular cross section. Once single channel is created, the micro tool is worn out by some amount and it becomes short in length. So, it affects the accuracy and quality of next channel. So, when multiple channels are to be generated by a single tip tool, it is not possible to produce all channels have similar accuracy with same machining condition. Thus, new micro tool should be used every time. It also enhances the chances of misalignment of workpiece during micro tool replacement. So, to avoid these problems, multiple tips micro tool is needed to generate accurate multiple channel with same machining condition.

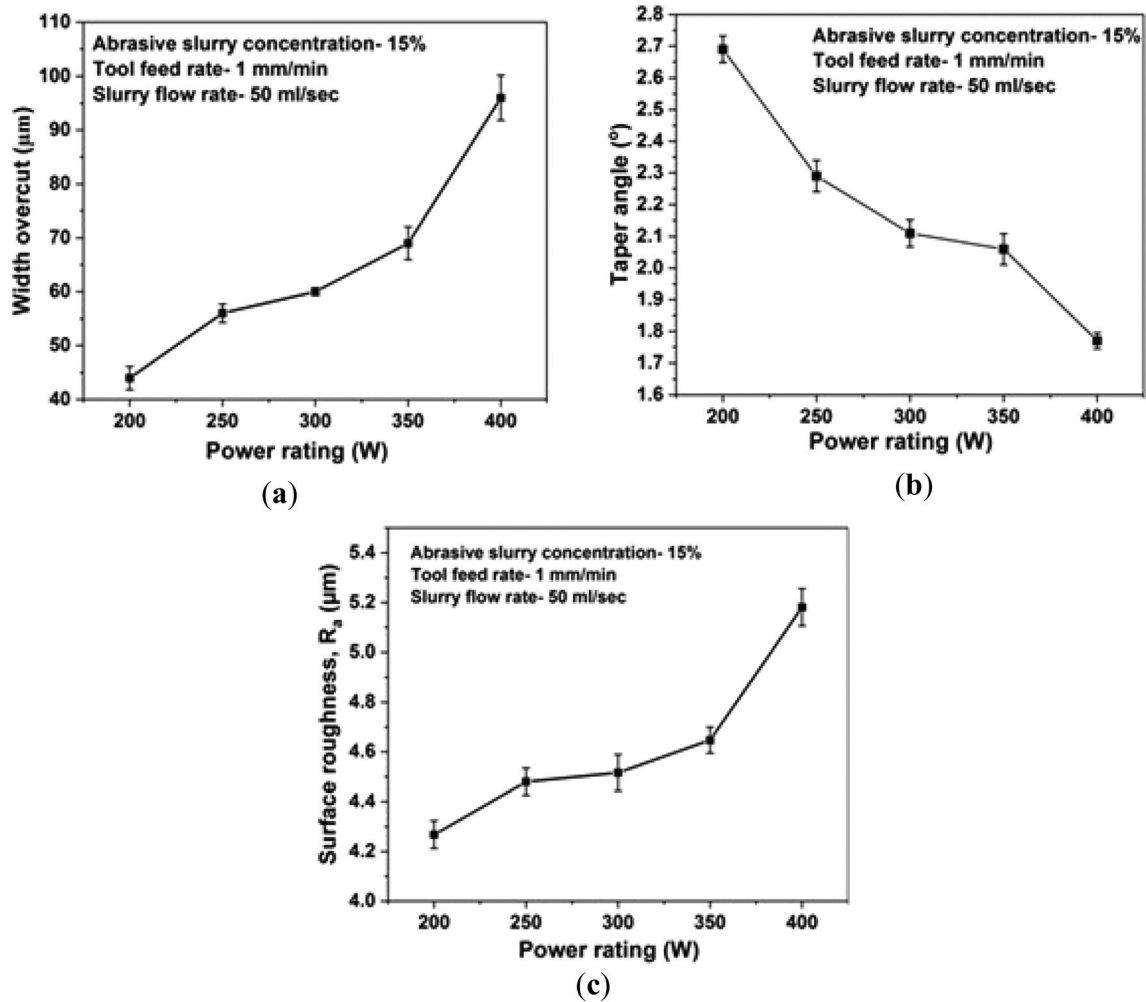


Figure 4. Effect of power rating on (a) width overcut, (b) taper angle and (c) surface roughness.

2.1 Multiple tips micro tool fabrication

The multiple tips micro tool has been developed by wire-cut EDM process. Reverse-ECM and reverse-EDM are also capable to develop multiple tips micro tool. But, wire-cut EDM was chosen over other process. Reverse-EDM and Reverse-ECM are not generally used for high aspect ratio tool. Wire electro discharge grinding (WEDG) process is used only for single tip tool. Zinc coated copper wire having diameter $250 \mu\text{m}$ is utilized as an electrode for wire-cut EDM process. Figure 1a represents the 3D view of tool material (SS304). Figure 1b represents the CAD model of developed multiple tips micro tool and figure 1c illustrates the photographic view of multiple tips micro tool developed by wire cut EDM process. The height of the tip is 4 mm and total height of tool is 10 mm. The width of each tool tip is $180 \mu\text{m}$ and length is 6 mm, the gap between two tips is $1600 \mu\text{m}$. The aspect ratio of multiple tips micro tool is obtained as 22.

2.2 Experimentation details

Micro-USM experiments were performed using USM machine “AP sonic mill 1000”. Figure 2 depicts the schematic diagram of the micro-USM system. Figure 3 shows the photographic view of the micro USM machining system indicating main component and also depict the enlarge view of developed multiple tips micro tool, workpiece and work holding plate. After the development of multiple tips micro tool, it is fixed with tool holder, by silver brazing. Then, the tool holder is mounted on horn with screw fitting. Quartz was taken as workpiece having size $25 \text{ mm} \times 25 \text{ mm} \times 2 \text{ mm}$. The workpiece is fixed with work holding plate (having size $100 \text{ mm} \times 100 \text{ mm} \times 10 \text{ mm}$) by using wax. The work holding plate further fixed at magnetic base. SiC was taken as abrasive particle. The mean size of SiC abrasive particle is $4 \mu\text{m}$. SiC is mixed with liquid media (water) to form abrasive slurry. It is continuously supplied

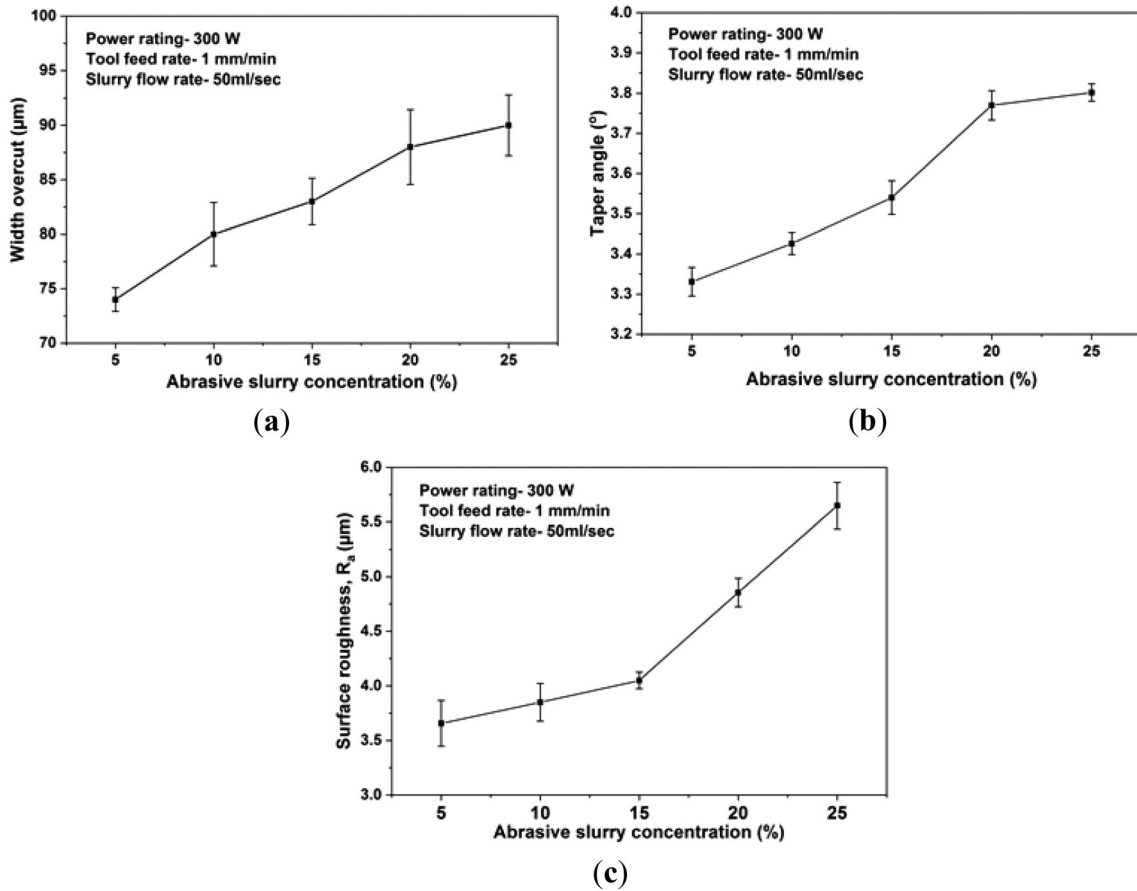


Figure 5. Effect of abrasive slurry concentration on (a) width overcut, (b) taper angle and (c) surface roughness.

between workpiece and tool. It works as coolant for tool, horn and workpiece and also takes out debris particles from cutting area.

The machining responses were considered as width overcut, taper angle and surface roughness of micro-channel. The workpiece were cleaned by ultrasonic bath after micro USM operation. The produced micro channel on quartz is 6 mm in length and 500 μm in depth. The average width at top surface and bottom surface of micro channel is measured by microscope (made: Leica DM2500 M). After the measurement of average width at top and bottom surfaces of micro channel, width overcut (WOC) is calculated by using equation (1). The taper angle is computed by equation (2). Surface Roughness Tester (SurfTest SJ-410 series) made by M/S Mitutoyo is used for surface roughness measurement of micro channel with cut-off length of 0.8 mm. Surface roughness is measured of all four channel produced at a time three times and the average value was taken.

The width overcut (WOC) of micro channel is given as:

$$\text{Width overcut (WOC)} = w_w - w_t \quad (1)$$

In the above equation, w_w : average width of micro channel on workpiece and w_t : average width of each tool tip.

The taper angle is calculated as:

$$\text{Taper angle } (\alpha) = \tan^{-1} \frac{W_a - W_b}{2h} \quad (2)$$

In above equation, W_a : average width of micro channel at top, W_b : Average width at bottom of micro channels and h : Depth of micro channel.

3. Results and discussion

Multiple micro channels are fabricated on quartz at a time by using multiple tip micro tool in micro-USM. The experiments are carried out by varying one process parameter at a time during machining. The process parameters are power rating, abrasive slurry concentration, tool feed rate and slurry flow rate. The effects of each process parameter on machining responses have been investigated and discussed subsequently.

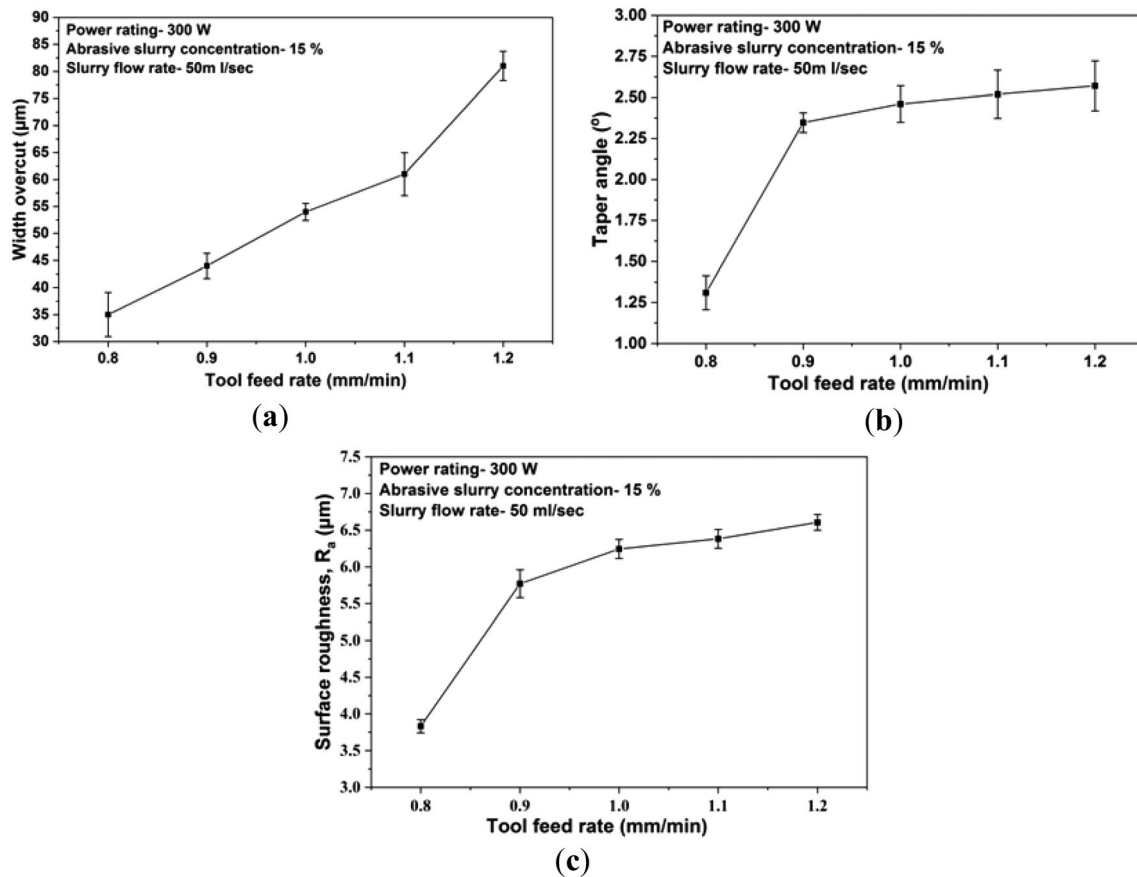


Figure 6. Effect of tool feed rate on (a) width overcut, (b) taper angle and (c) surface roughness.

3.1 Effects of power rating on width overcut, taper angle and surface roughness

Figure 4a demonstrates the effect of power rating on width overcut of micro channel. Power rating is a significant process parameter which controls the impact energy of abrasive particles striking on the workpiece. Power rating varies from 200 to 400 W. At the same time concentration of abrasive slurry, feed rate of tool and flow rate of slurry was fixed at 15 %, 1 mm/min and 50 ml/sec respectively. At low value of power rating, the striking energy of the abrasive particle is less. At higher value of power rating, more is the striking energy of the abrasive particles. Due to higher striking energy, larger size of indentation is formed. So, more materials are removed from the work surface. Hence, width overcut is more at higher power rating. As material removal increases, overcut may also increase as materials are removed from the side walls of micro channels. Overcut also depends on abrasive particle size, larger abrasive particles produce larger overcut.

At power rating of 200 W, the average width overcut is 42 μm and at 400 W, the average width overcut of 96 μm is obtained. All four micro channels during single operation have been considered for finding out the average overcut

and standard deviation was calculated and shown in figure 4a as error bar. Minimum standard deviation of overcut obtained is 0.71699 μm .

Figure 4b demonstrates the effect of power rating on taper angle of micro channel fabricated by micro USM. Taper angle decreases with the rise in power rating. Due to increase in power rating kinetic energy of abrasive particles increases so cutting rate is high. Materials are removed uniformly from the bottom part of the micro channel. The conditions for higher cutting rate/material removal rate leads to higher wear rate of the tool, which affects the dimensions of the micro-channels. As tool wear becomes more which may result in uneven machining and contribute to taper in micro-channels. Hence taper angle is less at high power rating. At power rating 200 W the taper angle 2.7 $^{\circ}$ and at 400 W taper angle 1.6 $^{\circ}$ is obtained.

The effects of power rating on surface roughness R_a value of machined surface of micro channel is demonstrated in figure 4c. At low power rating, surface roughness is low. If power rating increases, surface roughness also increases, because abrasive particles strike the work surface with higher energy. This higher energy of abrasive particles results in large indentation on the workpiece surface. So, surface roughness increases with the rise in power rating.

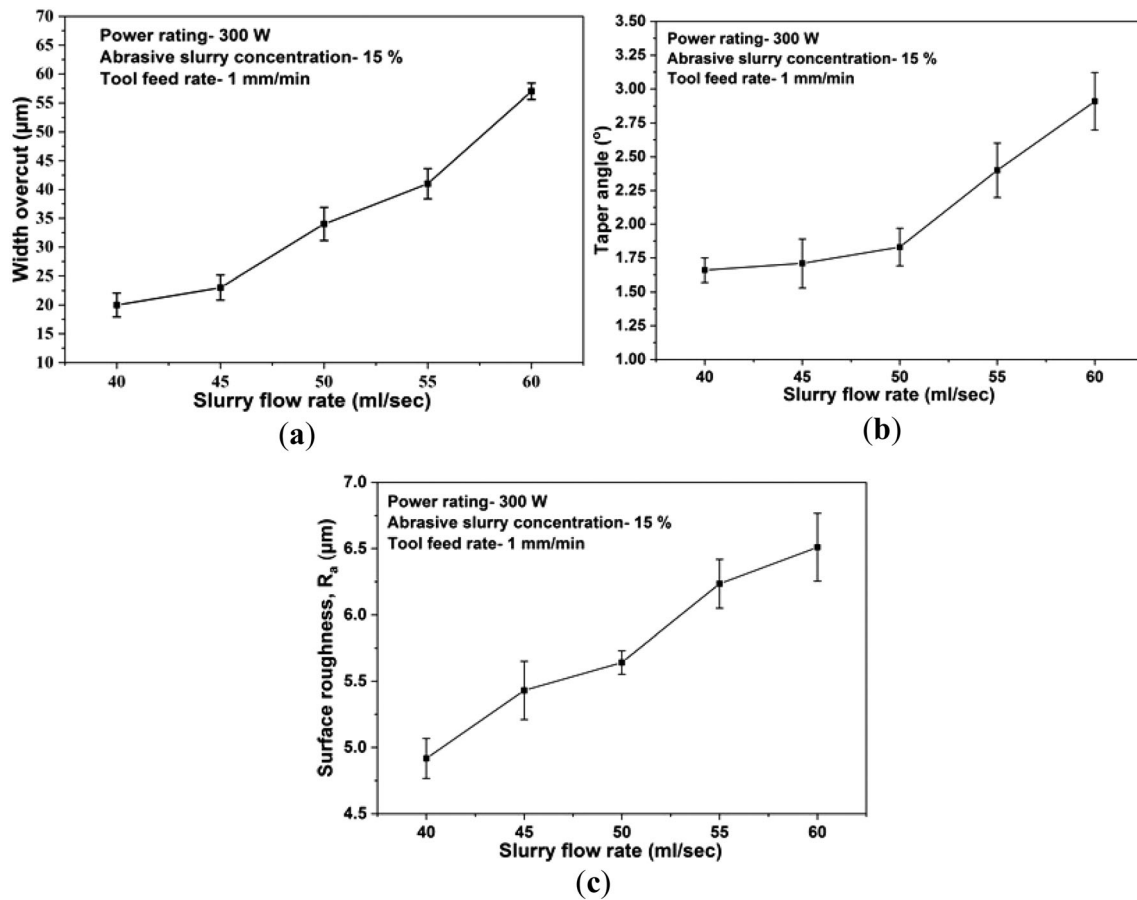


Figure 7. Effect of slurry flow rate on (a) width overcut, (b) taper angle and (c) surface roughness.

The surface roughness (R_a) is obtained as 4.268 μm at 200 W.

3.2 Effects of abrasive slurry concentration on width overcut, taper angle and surface roughness

The width overcut of micro channel on quartz is affected by abrasive slurry concentration as shown in figure 5a. Abrasive slurry concentration is an influential process parameter. Other process parameters like power rating, tool feed rate and slurry flow rate are kept constant at 300 W, 1 mm/min and 50 ml/sec respectively. At 5% slurry concentration the width overcut of 73 μm is obtained. After increasing the slurry concentration, more abrasive particles participate in machining and also these are present near the side wall of the channel. So from the side wall of channel, more materials are removed. Hence, width overcut of micro channel becomes large.

Figure 5b shows the effect of abrasive slurry concentration on taper angle of micro channel on quartz. At 5 %

abrasive slurry concentration by weight taper angle of 3.331 $^{\circ}$ is obtained. With the increase in abrasive slurry concentration, taper angle increases gradually but after 20% abrasive slurry concentration taper angle increases slowly. As abrasive slurry concentration increases, more abrasive particles are available at bottom surface of micro tool as well as side wall of micro channel. So, more materials come out from the top part of the micro channel. Hence taper angle increases as abrasive slurry concentration increases. Taper angle at 25 % abrasive slurry concentration is obtained as 3.8 $^{\circ}$.

Figure 5c shows the effect of abrasive slurry concentration on surface roughness. The better surface finish is achieved at 5% (by weight) abrasive slurry concentration. With the increase in slurry concentration, surface roughness also increases. With the increase in slurry concentration, more abrasives are present to interact with work surface which results in more number of indentations with large crater depth on the bottom surface of the micro channel, which produce rougher surfaces. At 5% abrasive slurry concentration, surface roughness, R_a value is obtained as 3.657 μm .

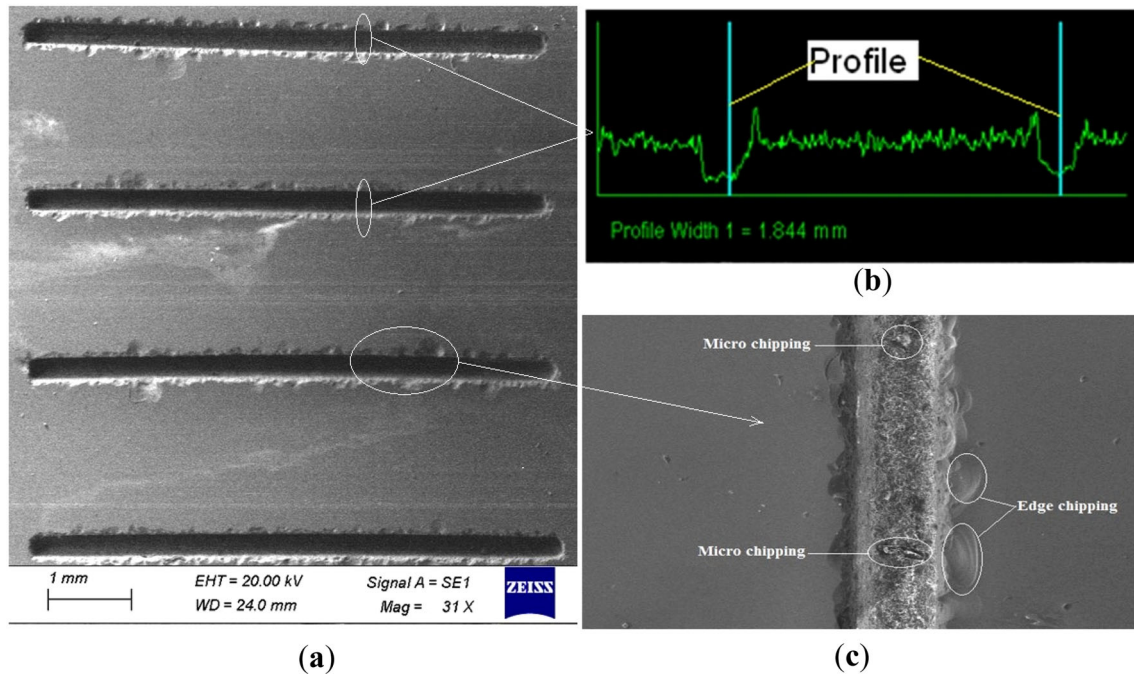


Figure 8. (a) SEM image of multiple micro channels fabricated on quartz and (b) micro channel profile on quartz after channel fabrication and (c) micro chipping and edge chipping formed on micro channel.

3.3 Effects of tool feed rate on width overcut, taper angle and surface roughness

Figure 6a shows the results of tool feed rate on width overcut. Tool feed rate means the rate of tool feed towards workpiece per unit time. The tool feed rate is varied from 0.8 mm/min to 1.2 mm/min. At the same time other process parameters such as power rating, abrasive slurry concentration and slurry flow rate are kept at 300 W, 15 % and 50 ml/sec respectively. Width overcut of 35 μm is obtained at 0.8 mm/min tool feed rate. With the increase in the tool feed rate, width overcut increases gradually. The feed rate is increased by applying higher air pressure in the tool which results in higher impact force. The energy is transmitted to the workpiece by the abrasive particle with high impact force while feed rate is increased. Impact force on the work surface is more by increasing the tool feed rate hence crater size of indentation is large. Hence, more material is removed from side wall of micro channel at large tool feed rate, so width overcut is large.

Tool feed rate also affects the taper angle which is illustrated in figure 6b. At tool feed rate of 0.8 mm/min, micro channel has less taper angle. After increasing tool feed rate, taper angle is observed as large because at higher tool feed rate, impact force on work surface increases. Material removed from the top portion of micro channel is more since more abrasive particles are available for machining in both side wall of micro channel. Due to this, top width of cut is more than that of bottom surface of the

micro channel, so taper angle increases. Less taper angle can be achieved at lower tool feed rate setting.

Figure 6c shows the effect of tool feed rate on surface roughness. From figure it is clear that surface roughness increases as tool feed rate increases. The lower surface roughness is obtained at lower tool feed rate. With the increase in tool feed rate, impact force increases and larger size craters are formed at bottom surface of micro channel which results in large surface roughness, R_a value.

3.4 Effects of slurry flow rate on width overcut, taper angle and surface roughness

Slurry flow rate also affects the width overcut of micro channel as shown in figure 7a. At low abrasive slurry flow rate, width overcut is small. With higher slurry flow rate, width overcut becomes more. With increase in slurry flow rate, availability of fresh abrasives during machining is more in the gap between workpiece and micro tool. Hence more materials are removed from side wall of micro channels. So, width overcut of micro channel increases.

The taper angle of micro channel is also influenced by slurry flow rate. The variation is shown in figure 7b. At 40 ml/sec slurry flow rate, taper angle is observed as 1.66° . Higher slurry flow rate may lead to instability in the machining process, causing uneven material removal which results in more taper angle. Taper angle increases as slurry flow rate increases. At 60 ml/sec slurry flow rate, taper angle is observed as 2.91° .

Figure 7c shows the effect of slurry flow rate on surface roughness of micro channel fabricated on quartz by micro USM. At 40 ml/sec slurry flow rate, surface roughness, R_a value is observed as 4.917 μm . Surface roughness increases as slurry flow rate increases. As slurry flow rates increases, there is increment in number of abrasive particles in the gap which lead to non-uniform removal of material and also generation of irregular surface at the bottom of micro channel. This phenomena cause higher surface roughness. The higher slurry flow rate also affects the distribution of abrasive particles in the slurry which lead to uneven abrasive distribution in the machining zone, affecting surface roughness. At 60 ml/sec slurry flow rate, roughness value R_a is obtained as 6.51 μm .

4. Analysis based on micrographs

Figure 8a shows the SEM micrograph the multiple micro channels fabricated on quartz using multiple tips micro tool utilizing micro USM process. The average width of micro channels was obtained as 254 μm and depth of micro channel was obtained as 500 μm . The micro channels fabricated by multiple tips micro tool are of rectangular shape. Figure 8b shows the profile of micro channel which is approximately mirror image of tool except overcut.

Micro chipping is observed on the bottom surface of micro channel due to fatigue failure. Some edge chipping was also observed nearby wall due to deflection of abrasive particle on the workpiece surface. Figure 8c represents the scanning electron micrograph showing micro chipping and edge chipping formed on micro channel on quartz.

5. Conclusions

Ultrasonic micro machining (USMM) process has the ability to produce micro channels on quartz materials. Multiple tips micro tool has been designed and fabricated by wire EDM process. Utilizing this multiple tips micro tool, multiple micro channels on quartz have been produced by ultrasonic micromachining process. The effect of process parameters on width overcut, taper angle and surface roughness of micro channels have been investigated. The following conclusions are drawn from the investigation:

- I. The designed and developed multiple tips micro-tools have been used effectively for ultrasonic micro machining. The average width of each tip is 180 μm and the width between two tips is 1600 μm . Wire EDM is preferred for USM micro tool fabrication because it produces high aspect ratio micro tools. The aspect ratio of developed micro tool tip is obtained as 22.
- II. Multiple micro-channels are successfully fabricated on quartz at a time by micro ultrasonic machining

process. Micro USM process parameters have a significant effect on width overcut, taper angle and surface roughness. The aspect ratio of micro channel has been obtained as 3.

- III. The low width overcut of micro channel is obtained as 16 μm at slurry flow rate of 40 ml/sec. The lesser value of taper angle is obtained as 1.31° at lower tool feed rate. The lower value of surface roughness, R_a is obtained as 3.833 μm at lower tool feed rate. Surface finish of micro channel can be improved by setting all process parameters at lower values.
- IV. The multiple micro channels fabricated by multiple tips micro tool are of rectangular shape. It is also observed that micro channel profile fabricated on quartz is approximately the mirror image of tool tip. Edge chipping is also observed at the entrance surface of channel.

For functional application of micro product in micro engineering, lower values of overcut, less taper and lower surface roughness of micro channel are always preferred. So, the micro ultrasonic machining for fabrication of micro channels on quartz is very much productive using multiple tips micro tool as the machining time is saved and good accuracy is achieved after performing this present research work.

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