Experimental Investigation into micro-ultrasonic machining of zirconia using multiple tips micro-tool

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ABSTRACT

The usage of micro products has grown significantly over the past ten years in a variety of industries, including engineering, automotive, health care, and electronics. Materials that are hard and brittle is frequently used to make microproducts like microreactors, microfluidic devices etc. Micro ultrasonic machining (μ-USM) is most excellent micro machining process to produce micro features on ceramic materials. The multiple tips micro-tool has been fabricated to generate multiple micro-channel on zirconia by μ-USM process. The effect of process parameters such as power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut and material removal rate (MRR) of micro channels generated on zirconia were investigated. By using multiple tips micro-tool, micro-channels were produced using μ-USM which increases productivity of μ-USM. The higher value of MRR and lower width overcut achieved as 3.970mm^3/min and 26μm respectively during multiple micro channel fabrication.

KEYWORDS

μ-USM,
Zirconia,
MRR,
Width Overcut,
Micro-Channels,
Multiple Tips Micro-Tool.

1. Introduction

Over the past ten years, the use of micro products in industries such as engineering, automotive, health care, optical components, and electronics has rapidly increased (Jauregui et al., 2010). The micro products like micro reactors, micro fluidic devices etc are commonly made of hard and brittle materials like ceramics, glass, silicon etc. Due to their exceptional qualities, including strong corrosion resistance, high hardness, high strength, wear resistance, and high thermal resistance, these materials are ideal for the aforementioned product (Tsuboia et al., 2012). Because of these characteristics, these materials are particularly challenging to process. μ-USM is the most excellent micro machining technique for producing miniature features on fragile and hard materials. The ability to process both conductive and nonconductive materials is μ-USM's main benefit. μ-USM is quite same to the USM except the tool tip dimension, abrasive size which are used into micron range (Egashira & Masuzawa, 1999). A vibrating micro tool is used in this procedure to repeatedly pierce the work surface as abrasives constantly flow through the machining zone. The mechanical, chemical, and physical properties of the workpiece material are not altered, just like in other micro machining methods including electric discharge machining (EDM), electro chemical machining (ECM), and laser beam machining (LBM). Due to the fact that this procedure does not need a clean room environment, it is also a cost-effective method for micro-machining of extremely hard and brittle materials.

The micro-diamond tools have been developed using electroless composite plating and further micro-machining operation performed on silicon to observe the tool life (Park et al., 2010). Ultrasonic machining has been utilised to generate hexagonal hole on alumina ceramic and also find the optimum parametric combination (Lalchhuanvela et al., 2012). Ultrasonic machining has been utilised to generate stepped hole on zirconia ceramic and develop the mathematical model (Das et al., 2016). Longitudinal-torsional coupled rotary ultrasonic machining to generate the hole on ZrO_2 ceramics to investigate the cutting force and machined surface roughness (Chen et al., 2022). Micro hole and 3D micro cavity generated on silicon by micro USM also

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applying the tool wear compensate method to reduce the tool wear and accuracy of hole (Park et al., 2010). Three advanced ceramic materials (silicon carbide, zirconia, and alumina) are used for drilling operation by using ultrasonic machining. The tool of stainless steel (diameter 0.7 mm to 3 mm) was used to observed the hole integrity at entrance of hole (Tsuboia et al., 2012). The MRR achieved during micro channel generation on glass by rotary ultrasonic machining at optimal condition was 1.30 mm^3/min. The tool used for this experiment was tungsten carbide of 600 µm (Yu et al., 2004).

In the present research work, multiple tips micro-tool has been developed by using wire-cut electro discharge machining (W-EDM) for generation of multiple micro-channels on zirconia materials. The fabrication of micro channels using single tip micro-tool of circular cross section is taking more time for generation of multiple micro-channels. It also hampers the accuracy of micro-channels by repetition of same tool during successive machining and also due to tool wear. To solve this problem multiple tips micro tool has been designed and developed by wire-EDM process. By using multiple tips micro tool productivity can be increased in µ-USM for micro channel fabrication. The effect of process parameters such as power rating, abrasive slurry concentration, tool feed rate and slurry flow rate on width overcut and material removal rate (MRR) of multiple micro-channels generated on zirconia were investigated.

2. Experimental Setup and Planning

Micro ultrasonic machining setup consist of different components namely power supply, vibration unit, controller and slurry supply unit. Fig. 1 shows the schematic view of micro ultrasonic machining setup ("AP 1000 sonic mill") which is used for experiments. In µ-USM, transducer is employed to convert electrical energy into ultrasonic vibration. The ultrasonic vibration is further transfer to micro-tool through horn. The abrasive slurry is supplied between micro-tool and work surface, and abrasive particles accelerated by ultrasonic vibration of micro tool.

For micro-tool, SS304 (stainless steel) is chosen because it is extremely efficient for µ-USM which is ductile and very much suitable material for ultrasonic micromachining. It is also economical and easily available. Fig. 2 shows the optical image of developed multiple tips micro-tool used for experiments. The width of each micro-tool tip is 180µm. The micro-tool has been developed with the help of wire EDM process. This micro-tool has been silver brazed on hexagonal bolt and screw fitting to horn. Zirconia ceramic has been used as workpiece on which multiple micro-channel are generated. The physical properties of zirconia materials have been given

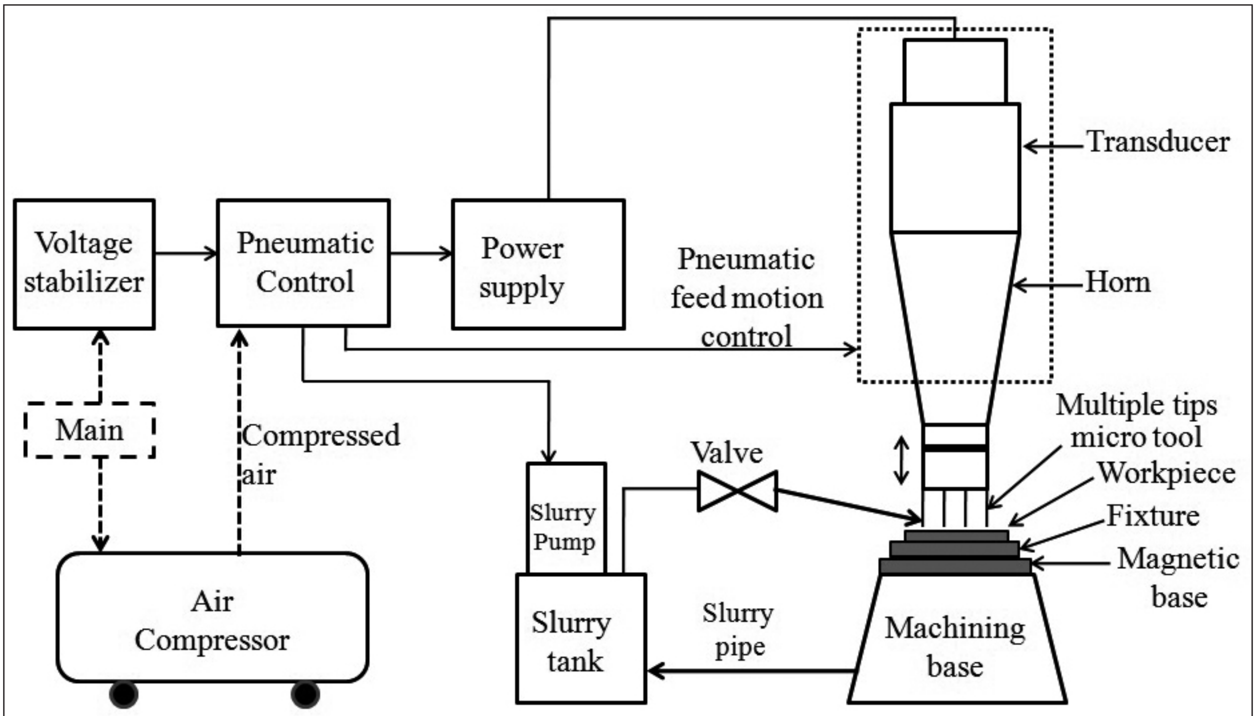

Fig. 1. Schematic view of micro ultrasonic machining setup.

in table 1. Zirconia material has been paste on the fixture made of mild steel and fixed on the magnetic base. Silicon carbide has been used as abrasive which is mixed with water and continuously supplied during machining. For this investigation developed multiple tips micro tool is used for generation of multiple micro channels. Each experiment has been conducted for three times. The widths of each micro-channel have been taken at five different places and average width is taken.

The average width at top surface of micro channels is measure by measuring microscope (made: Leica DM2500 M). After the measurement of average width at top surfaces of micro channel, width overcut and MRR are calculated by using equation (1) and (2) respectively.

The width overcut (WOC) of machined micro-channels is given as:

$$\textit{Width overcut} = w_c - w_t \qquad \text{......................(1)}$$

Where, w_c : Average width of micro channel, and
w_t : Average width of tool tip.

The MRR is calculated by:

$$MRR = {}^{lbd}/_{t} \qquad \text{.....................(2)}$$

Where, l : The total length of micro-channels,
b : Width of micro channel,
d : Depth of micro channel and
t : Machining time.

3. Results and Discussion

Micro channels have been generated on zirconia by using multiple tips micro-tool in micro-USM. Multiple micro-channels generated by changing one parameter at a time i.e. power rating, abrasive slurry concentration; tool feed rate and slurry flow rate. At the same time other process parameters are maintained at an intermediate level. The impact of each process parameter on width overcut and material removal rate has been investigated and discussed subsequently.

3.1. Effect of power rating on MRR and width overcut

Figure 3 shows the effect of power rating on MRR and width overcut of micro channel. The micro channels fabricated on zirconia by micro ultrasonic machining. At lower value of power rating MRR is 1.13 mm^3/min and up to 300 W MRR increases slowly. But at 400 W power rating, MRR suddenly increased to 2.34 mm^3/min. When power rating increases the impact energy onto work material through the abrasive

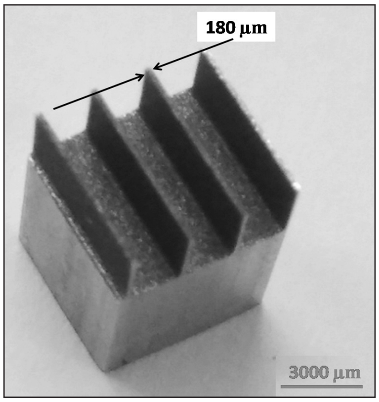

Fig. 2. Optical image of developed multiple tips micro-tool.

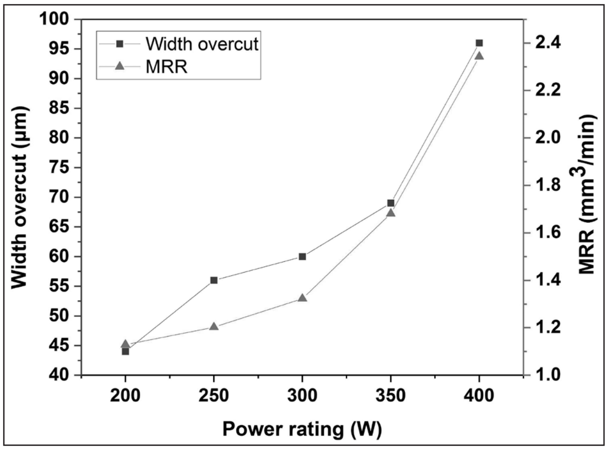

Fig. 3. Effect of power rating on MRR and width overcut.

Table 1
Physical properties of zirconia.

Parameters	Zirconia	Units
Chemical Composition	ZrO_2	--
Density	6.49	gm/cm^3
Hardness	9	Mohr’s scale
Tensile Strength	330	MPa
Compressive strength	1200	MPa
Coefficient of thermal expansion	10.5 X 10^{-6}	K^{-1}
Thermal conductivity	2.7	W/m K
Poisson’s ratio	0.31	--

particles is more. So erode more material from the work and hence MRR is more. At higher value of power rating, more is the striking force of the abrasive particles. Due to higher striking energy, larger size of indentation is formed. So, more materials are removed from the work surface which in turn increases width overcut. Hence, width overcut is more at higher power rating.

3.2. Effect of abrasive slurry concentration on MRR and width overcut

Figure 4 shows the effect of abrasive slurry concentration on MRR and width overcut. Abrasive slurry concentration is an significant process parameter for micro ultrasonic machining. At 5% slurry concentration MRR is 1.306 mm^3/min. More abrasive particles are present on the micro tool's bottom face when the slurry concentration is increased. Due to this, number of impact is more and hence more material is removed. At 25% slurry concentration MRR is 3.91 mm^3/min during micro channel generation on zirconia by micro ultrasonic machining. At 5% slurry concentration the width overcut of 42 µm is obtained. After increasing the slurry concentration, extra abrasive particles participates 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 as abrasive slurry increases.

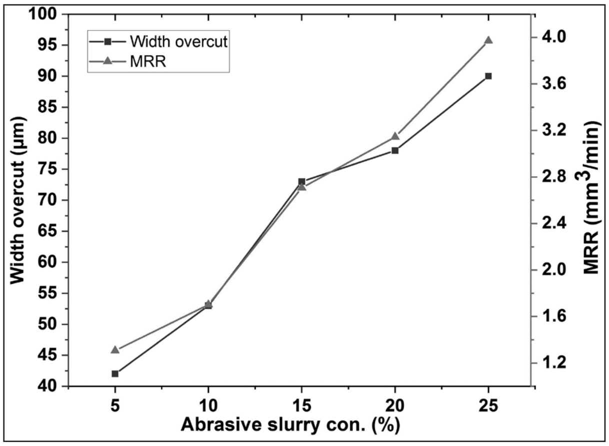

Fig. 4. Effect of abrasive slurry concentration on MRR and width overcut.

3.3. Effect of tool feed rate on MRR and width overcut

Figure 5 show the effect of tool feed rate on MRR and width overcut. Tool feed rate is crucial process parameter for micro ultrasonic machining. At 0.8 mm/min tool feed rate MRR is 1.833 mm^3/min. If increases the tool feed rate, the impact force act the front face of micro tool, is becoming more so crater depth of indentation is more on the workpiece surface and hence MRR increases. However, as tool moves faster, removal of material from side wall is less which reduces the width overcut. At 1.2 mm/min tool feed rate, MRR is 3.065 mm^3/min of zirconia. Width overcut of 26 µm is obtained at 1.2 mm/min tool feed rate.

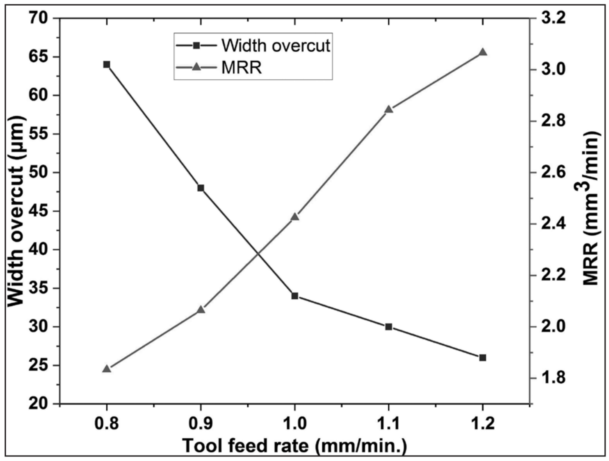

Fig. 5. Effect of tool feed rate on MRR and width overcut.

3.4. Effect of slurry flow rate on MRR and width overcut

Figure 6 shows the effect of slurry flow rate on MRR and width overcut during micro channel fabrication on zirconia. At low slurry rate (40 ml/sec) the MRR is 1.464 mm^3/min. After increasing the slurry flow rate MRR also increases. Due to increasing slurry flow rate, availability of fresh abrasive particles at tool work interface is more. Due to presence of fresh abrasive particles at tool-workpiece interface penetrations into

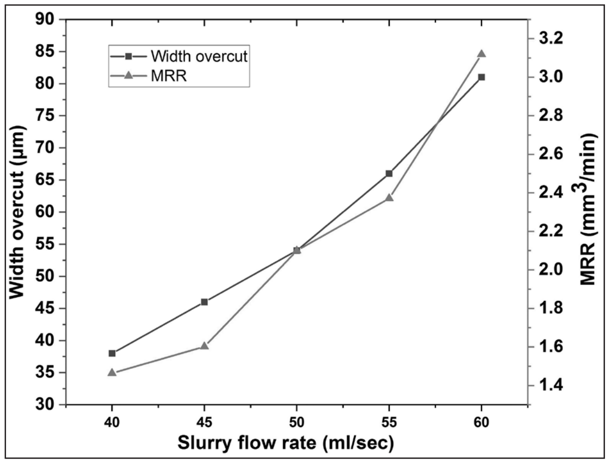

Fig. 6. Effect of slurry flow rate on MRR and width overcut.

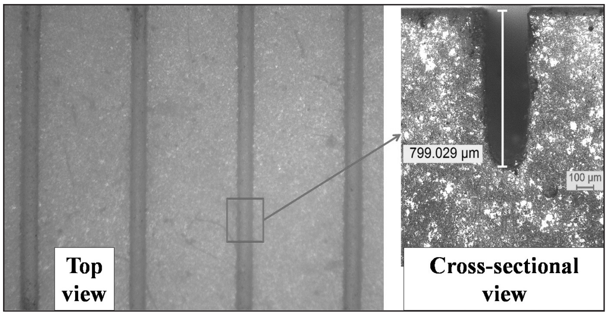

Fig. 7. Microscopic view of micro channels on zirconia.

workpiece is more. Hence, MRR increases for increase of slurry flow rate. However, width overcut increases due to more material removal from the side walls. At higher slurry flow rate MRR is 3.118mm^3/min for zirconia micro channels. The lower width overcut (38 µm) has been obtained at 40 ml/sec slurry rate

The top view of microscopic view of multiple micro channels fabricated on zirconia material is shown in fig. 7. In this fig. also indicate the cross-sectional view of a machined micro channel for observing depth of micro channel.

4. Conclusions

For the purpose of fabricating multiple micro-channels on zirconia, multiple tips micro-tool has been design and developed for µ-USM. The following conclusion has been drawn through experiments:

- Utilizing a developed multiple tips micro-tool, micro-channels were produced on zirconia using micro ultrasonic machining (µ-USM) which increases the micro machining productivity of µ-USM.
- The micro-channel is 6 mm in length and 180 µm in width. The maximum depth of a micro channel is observed as 799 µm.
- The aspect ratio of the generated micro-channel is observed as 4.5.
- All process variables, such as power rating, abrasive slurry concentration, tool feed rate, and slurry flow rate, have a substantial influence on MRR as well as width overcut of micro-channels fabricated on zirconia.
- The higher value of MRR during micro channels fabrication on zirconia is 3.970 mm^3/min at 25% abrasive slurry concentration and the lower width overcut of micro-channels is 26 µm at 1.2 mm/min tool feed rate.

Very few research studies have been carried out on micro machining on zirconia by µ-USM process. However, further study has to be done in the field of machining array of micro channel, array of microholes on zirconia by µ-USM. The study of surface roughness, taperness and other factors during the fabrication of micro-channels on zirconia by µ-USM may be another area of interest for research with potential for wider use in the present micro manufacturing sector.

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