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Parametric Analysis on Ultrasonic Micro Machining of Quartz

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Abstract

Ultrasonic micromachining (USMM) is a non-conventional mechanical material removal process which is extensively applied for generating micro features on parts of hard and brittle materials such as silicon, glass and quartz. The advantage of ultrasonic micromachining is that there is no thermal damage to the work-piece and there is also no limitation due to electrical or chemical properties of substrate materials. Quartz has been widely useful in industries such as optical, communication, high quality imaging system, beam wave front measurements, multiple beams shaping etc and the market for quartz components is vast. Being hard and brittle material, quartz is difficult to machine. USM process is able to make micro hole on quartz of thickness 1mm. A micro tool of stainless steel having diameter 330µm has been utilized for USM process for micro drilling operation. Experiments have been done by using different types of abrasives like boron carbide, silicon carbide and aluminum oxide of average grain size 15µm. Experiments have been performed under different parametric setting of abrasive slurry concentration, power rating and tool feed rate. The abrasive slurry concentration varies from 10 to 40 % by weight, power rating from 200 to 500 W and tool feed rate from 0.8 to 1.1 mm/min. Micro hole has been generated on quartz and volumetric material removal rate have been considered as response of ultrasonic micromachining. The effects of various types of abrasives, slurry concentration, power rating and tool feed rate on volumetric material removal rate (MRR) have been analyzed in this present research.

Keywords: Ultrasonic micromachining, quartz, MRR, micro hole, Boron carbide, silicon carbide and aluminum oxide.

1. INTRODUCTION

Hard and brittle materials like quartz, glass, silicon, and ceramics are progressively used in MEMS because of their material properties such as resistance to high temperature, chemical erosion and wear. Most of the nontraditional machining processes have difficulty in machining these materials. Micro Electrical discharge machining (µEDM) and electrochemical micromachining (EMM) are not used for machining these materials because of most of these hard and brittle materials are not electrically conductive. Cracks are easily formed when machined by laser beam due to thermal effects of laser beam machining. Ultrasonic micromachining (USMM) is one of nontraditional micro machining process, which is mainly used to machine hard and brittle materials. Ultrasonic micromachining (USMM) is the downscaling of conventional USM for generation of micro features by utilizing micro sized tool and fine abrasive particles of micrometer even nanometer order for achieving very good surface finished and high accuracy [1].

The trend towards miniaturization of industrial products is inevitable. This trend is presently realized in light weight, miniaturized products of high functionality. Quartz is extensively used in resonators, filters and sensors, optical instruments, semiconductors and precision equipments because of its exceptional properties like transmission ability in both ultraviolet and infrared spectra, good corrosion resistance, high compressive strength, and excellent wear resistant properties. [2-4].

In ultrasonic machining, the material is removed due to erosion by impacting abrasive particles at an ultrasonic frequency. In Ultrasonic micromachining, micro features can be generated using easy shaped micro tools [5]. The ultrasonic machining result from the conversion of high frequency electrical energy into mechanical longitudinal vibrations, which is transmitted via a horn to the cutting tool and the abrasive slurry is fed between the tool and the workpiece. The frequency of tool Vibration is generally set at 20 kHz. The tool is fed into the workpiece under a constant static load and accelerates the abrasive particles against the workpiece surface at high velocity, causing them to erode the material from the workpiece material by micro chipping, leaving a precise reverse form of the tool shape. The fundamental mechanisms of the micro chipping action in ultrasonic micromachining have been well-known to be mainly localized hammering and free impact by abrasive grains in the slurry. Cavitation can also occur during material removal. Sometimes, it is possible to assist the mechanical erosion due to the presence of an aggressive slurry medium inducing chemical effects accompanying the hammering process.

Z. Yu et al. studied the influence of machining parameters on the performance and reported that the machining speed was decreased after the application of a certain value of static load, similar to the phenomena in macro USM. The debris accumulation was identified as the dominant reason, which caused a part of static load to be consumed in impacting the debris instead of the abrasive particles [6]. A. Schorderet et al. reported that the net machining speed was evaluated for a wire tool and a twist drill with two different diameters (100 and 200 µm). The results showed that the use of twist drill as micro tool to drill deep holes with a constant speed. With cylindrical WC tools, the speed obtained at the start of the drilling is almost 6 times higher than the average drilling speed [7]. S. Cherku et al. presented the results of micro ultrasonic machining using oil based abrasive slurry and reported that machining with water based slurry is suitable only for finer particles sizes with higher concentration or medium particles sizes with medium concentration or coarser particle sizes with lower particles where as machining with oil based slurry is always suitable for all the particle sizes with low concentration and also concluded that machining with oil based slurry gives good surface finish compared to the water based slurry [8]. Sandeep Kuriakose et al. investigated for the machining of micro features on metallic glass by micro hole drilling operation using micro-USM and reported that micro-USM can be used to machine micro holes in metallic glass in room temperature without any heat generation

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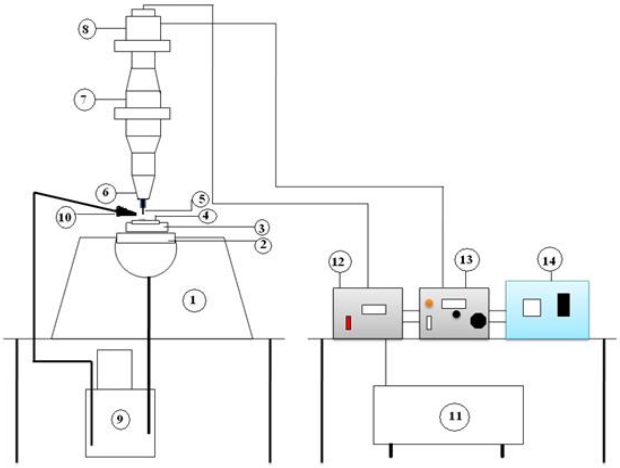
and crystallization. The metallic glass has a very good machinability for micro-USM with high MRR and with very low TWR, with very less overcut, minimum edge deviation and near zero taper angle [9]. W. Pei et al. reported that abrasive particles are distributed randomly in the machining area and their movement affects the profile of the machined surface. It was found that machined surface profiles show convex or concave shapes. The profile is affected by amplitude of vibration, diameter of tool and the depth of hole [10].

In the present research work micro holes have been generated on quartz material of thickness 1 mm by using different type of abrasives. The influences of process parameters on volumetric material removal rate (MRR) during the ultrasonic micromachining have been investigated and discussed.

2. EXPERIMENTAL SETUP

In Ultrasonic micromachining (USMM) high frequency electrical energy is converted into mechanical ultrasonic vibration by transducer. This vibration is transferred to the horns via coupler. The horn amplifies the amplitude of vibration and transfers this vibration to the tool. This causes the vibration of tool along its longitudinal axis at high frequency, usually 20 kHz with amplitude of 25 µm. The maximum power rating is 500 W and a constant static load is applied on the micro tool. At the same time, feed rate is applied in the longitudinal direction. Abrasive material such as boron carbide, silicon carbide and aluminum oxide of 15 µm is suspended in water and continuously flows across the gap between the tool and workpiece. Stainless steel of grade SS304 has been used as micro-tool material as it is highly efficient tool material for USMM which is tough, but not hard. Fig. 1 shows the schematic diagram of USMM setup.



1.Machine Base, 2.Magnetic Base, 3. Work Holding Plate, 4. Workpiece, 5. Micro Tool, 6. Horn, 7. Coupler, 8 Transducer, 9. Recirculating Pump, 10. Slurry Supply Nozzle, 11. Compressor, 12 Control Unit, 13. Tool Vibration Control Unit, 14. Electrical Power Supply Unit .

Fig. 1 Schematic diagram of USMM setup

3. EXPERIMENTATION

The experiments were carried out in stationary Sonic Mill machine (Model: AP-1000). The frequency of vibration of ultrasonic micromachining is about 20 kHz. The square flat quartz workpiece of thickness 1 mm thick was fixed on the work holding plate made of mild steel. Tool feed rate was varied along the longitudinal axis of mill module. Boron carbide, silicon carbide and aluminum oxide abrasives of 15 µm average grain size separately mixed with water at room temperature was used as abrasive slurry solution. Then, stainless steel (SS-304) of tool diameter 330 µm and 18 mm long was used for micro hole generation on quartz. In manufacturing point of view, high MRR is desired. Based on the previous research work and some pilot experiments, the range of process parameters has been selected for experimentation. Abrasive slurry concentration varies from 10 to 40 %. Power rating varies from 200 to 500 W during experimentation. Tool feed rate varies from 0.8 to 1.10 mm/min during experimentation.

Table 1 represents the experimental conditions of ultrasonic micromachining of quartz. The machined micro hole dimension as shown in Fig. 2 was measured in microscope. A rough edge of the hole surface at entry side was observed due to scattered chipping and deep penetrated cracks when large grit size abrasives and/or fast feed rate are applied. Hole surface finish can be improved by using finer abrasives. Too high concentration of abrasive slurry would normally result in a poor surface finish because the circulation and of abrasives are not proper and abrasives are concentrated at the machining zone.

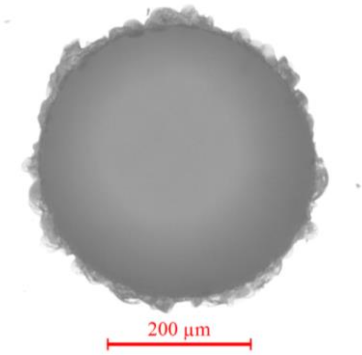


Fig. 2 Micro hole on quartz

Table 1. Experimental Conditions of USMM

Experimental Conditions	Description
Workpiece material	Quartz (Thickness 1 mm)
Tool material	SS-304 (Diameter 330 µm)
Tool geometry	Cylindrical
Abrasive material	Boron carbide, Silicon Carbide, Aluminum oxide
Abrasive size (Average diameter)	15 µm
Frequency of vibration	20 kHz
Amplitude of vibration	25 µm
Slurry concentration	10-40 % by weight
Power rating	200-500 W
Feed rate	0.8-1.1 mm/min
Slurry media and temperature	Water at room temperature

3.1 Measurement of volumetric material removal rate

Diameters of micro hole at entry and exit side were measured after machining and then the volume of the material removed was calculated. Then the volume of material was removed was divided by total machining time to calculate the volumetric material removal rate.

$$MRR = \frac{V}{T} \quad (mm^3/min.)\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (1)$$

The volume of micro hole has been calculated with the help of following equation (2) assuming shape of micro hole as a frustum of cone.

$$V = \frac{\pi t}{3}\left(R_1^2 + R_1R_2 + R_2^2\right)\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

Where V is the volume of micro hole, R_1 is the radius of micro hole at entry and R_2 is the radius of micro hole at exist and t is the thickness of workpiece i.e. length of micro hole.

3.2 Influence of process parameter on MMR

Influence of process parameters such as abrasive slurry concentration, power rating and tool feed rate on volumetric material removal rate (MRR) are investigated and discussed in the following sub-section.

3.2.1 Influence of abrasive slurry concentration on MRR

In ultrasonic micro machining process the abrasive slurry concentration is one of the significant parameters. The effect of abrasive slurry concentration on MRR has been observed and presented through figures and analyzed.

Fig. 3 shows that as abrasive slurry concentration is increasing, the MRR is increasing gradually in case of B_4C and SiC. Since there will be a significant numbers of abrasive grains under the tool, the condition for circulation of abrasive in the machining zone are satisfactory. If abrasive slurry concentration is less, then the number of abrasive grains available at the machining zone becomes less. Hence, the penetration rate becomes also less. Thus due to less number of abrasive grains taking part in the material removal, the MRR is less. When the abrasive slurry concentration is 10 % then the MRR is very less and when concentration is 40 % MRR is more. In case of Al_2O_3 abrasives when concentration increased from 10 to 20 % MRR is suddenly increased and then gradually increases. From figure it is clear that MRR is more when using B_4C abrasive because of its higher hardness as compare to SiC and Al_2O_3 abrasives.

3.2.2. Influence of power rating on MRR

Power rating is also one of the important parameter in USMM process. The effect of power rating on MRR has been observed and analyzed through graphs. Fig. 4 shows power rating Vs MRR graph. When the power rating is 500 W then the MRR is high. Generally low power rating gives the low MRR. As the power rating increases then MRR also increases because with more ultrasonic power, abrasive particles in slurry were striking with more momentum and kinetic energy hence eroding more material. And at low power rating abrasive particle in slurry are striking with low momentum and kinetic energy and it increases with increase in power rating and hence, material removal rate also increases. With the increment power rating after a certain value, crack formation started at surrounding of entrance of micro hole which is not desirable for accuracy aspects.

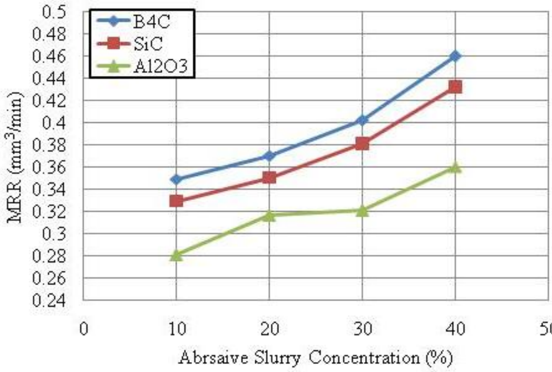


Fig. 3 Influence of abrasive slurry concentration on MRR

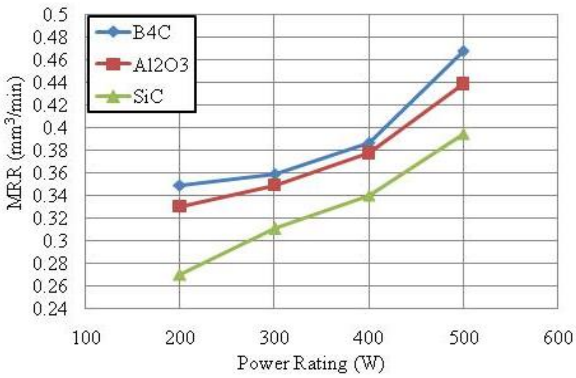


Fig. 4 Influence of power rating on MRR

3.2.3. Influence of tool feed rate on MRR

Tool feed rate is also one of the important parameter of USMM process. The effect of tool feed rate on MRR explained in the subsequent discussion.

Fig. 5 shows that the variation of MRR with the tool feed rate. Figure shows that when tool feed rate is increasing the MRR first increases gradually and then slowly increases while B_4C abrasive are used. MRR reaches higher value at tool feed rate of 1.1 mm/min. When tool feed rate is low, MRR is also low because abrasive particle striking at small force on work piece. When tool feed rate increases, the striking force of abrasive particle at workface also increases, hence MRR also increases. When using Al_2O_3 abrasive the MRR is low because of low hardness of abrasive and also low sharpness as compared to B_4C and SiC.

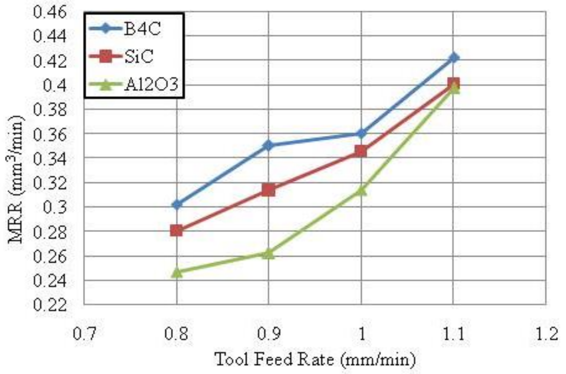


Fig. 5 Influence of tool feed rate on MRR

4. CONCLUSION

Ultrasonic machining process has been applied for generation of micro hole with shaped micro tool. The experimental investigation explore that volumetric material removal rate is influenced by machining parameters such as abrasive slurry concentration, power rating and tool feed rate for generating through micro hole on quartz. It has been found that performance criteria MRR has very much influenced by abrasive slurry concentration compared to power rating which is about same as compared to tool feed rate. Out of the observed experimental results maximum material removal rate 0.4681 mm^3/min is obtained using B_4C abrasive with 500W power rating. Microholes on quartz are fabricated, by using micro tool with 330μm diameter and different types of abrasives during ultrasonic drilling. It is concluded that for achieving maximum material removal rate, all the process parameters i.e. power rating, tool feed rate and abrasive slurry concentration should be set at higher values. This present parametric analysis is very much effective for better setting of process parameters in order to achieve higher material removal rate during USM micro drilling on quartz.

Few research works are reported on micro hole drilling on quartz by micro-USM process. But, further analysis needs to be carried out in the area of optimization of micro-USM process, micro hole drilling on silicon wafer. Study of tool wear rate and surface roughness etc during micro hole generation on quartz and other hard and brittle materials are also the area of research interest for wide application of micro ultrasonic machining process in modern micro manufacturing industry.

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