Study on the Surface Integrity of Micro-Ultrasonic Machined Glass-ceramic Material

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Abstract. Ultrasonic machining (USM) technique has long been used for fabricating various patterns and drilling holes on brittle materials. However, the surfaces generated by USM are normally rather rough and covered by deep penetrated cracks. This has greatly limited USM being used in micro-machining and fine machining. This research aimed to study the surface integrity of the USMed surface and develop a feasible way to minimize the scattered cracks so that good surface finish could be achieved. Machining parameters such as type and concentration of abrasive particles, grit size, and feed rate were systematically investigated to check their influences on the surface obtained. A ‘multi-stage’ micro-USM process was developed in this study and surface with Ra value better than 0.2μm was achieved using the proposed process.

Introduction

Owing to the excellent optical and mechanical properties, materials such as glass, Zerodur, Fused quartz, SiC and silicon are widely used in industry. These materials are hard and brittle. As a result, they are extremely difficult to machine, especially when there is micro-structures fabrication involved. Grinding, lapping and polishing are normally used to deal with bigger sized work-pieces. Laser ablation, micro-EDM (electro-discharge machining) can only effectively produce micro-structures on polymers and electrical conductive materials respectively. As to the FIB (focused ion-beam) process, it is expensive and more suited for research and development. Micro-ultrasonic machining (MUSM) is considered to be a promising alternative for efficiently and accurately fabricating microstructures on brittle materials [1-5]. Being a non-thermal, non-chemical and non-electrical machining, it has the advantages of no heat affected zone. However, the obtained surfaces are in general rough and full of micro-cracks. That was caused by the micro-chipping dominated material removal mechanism of MUSM[2][7][8]. This research aimed to investigate the surface integrity of the MUSMed glass-ceramic material and subsequently improve it by modifying the MUSM process.

Experimental

A Sonic-Mill^{SM} Stationary process USM machine was employed in this study. The vibration frequency of the oscillating system was fixed at 20kHz in the present study and the feed rate ranged from 0.1mm/min to 0.5mm/min. The glass-ceramic material Zerodur, having a very low thermal expansion coefficient around 0.02×10^{-6}/K, was selected as the material to be machined. Zerodur is easily fractured during machining leaving deep-penetrating cracks inside the material. All Zerodur specimens were pre-polished to a surface roughness better than 5nm Ra to minimize the fracture caused by the pre-existed surface/sub-surface cracks. Machining parameters, such as type of abrasive, grit size, feedrate and concentration of abrasives were systematically investigated to check their influences on the surface obtained. The MUSM parameters used in the experiments were listed in Table 1. Surface profilometer (Alfa-step) was used to measure the surface roughness. The wedged polishing and etching technique was used in this study to reveal the sub-surface cracks of the machined surface (Fig. 1). Optical microscope and scanning electron microscope were utilized in conjunction with etching technique to examine tool wear and machined surface.

Table 1. MUSM machining parameters investigated in this experiment.

SiC (μm)	**Feed rate (mm/min)**	**Concentration (%)**
60	1.5、1.0、0.5	5
12	1.5、1.0、0.5	5
5	0.5、0.1	5、10、20
2	0.1、0.05	20、33
1	0.1	20、33
Al_2O_3 (μm)	**Feed rate (mm/min)**	**Concentration (%)**
0.3	0.1	33

Surface integrity of the machined specimens

The experimental results showed that the surface integrity of the MUSMed specimen was profoundly influenced by the USM parameters. A rough surface with scattered chipping and deep penetrated cracks are normally found when large grit size abrasives and/or fast feedrate are used. As shown in Table 2, bigger grit size of abrasives resulted in deeper sub-surface cracks. The sub-surface cracks generated while using large abrasive could be improved if it was followed by a MUSM process using finer abrasives. However, it could be very difficult to remove all sub-surface cracks if the cracks had penetrated too deep into the substrate.

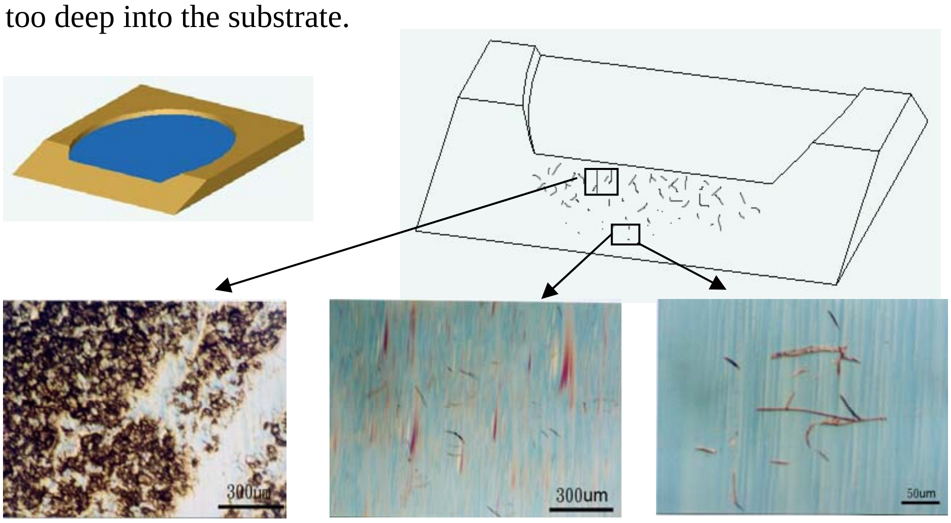


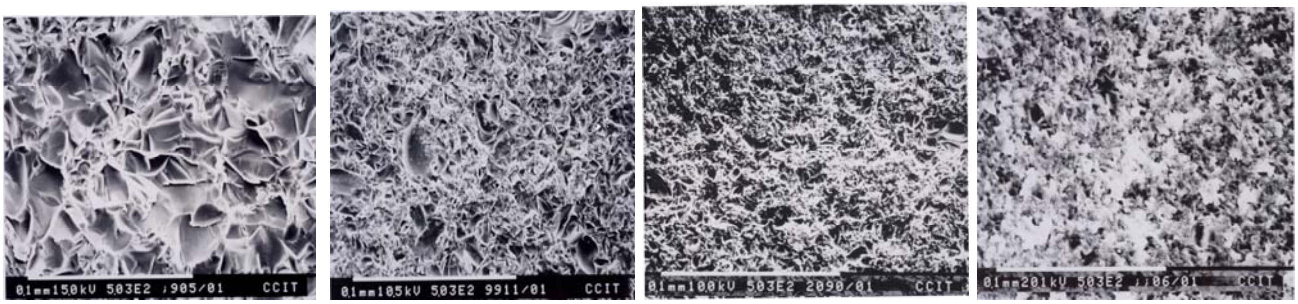
Fig.1 Sub-surface cracks and microstructures induced by 60μm SiC investigated by oblique polishing and etching techniques.

Table 2. Influence of abrasive size on the sub-surface crack involved during USM.

SiC abrasive particle size (μm)	Depth of sub-surface crack (μm)
60	15.0
5	8.4
2	5.0
60 followed by 2	12.0

As to the concentration of abrasives, it was found that too high an abrasive concentration would normally result in a poor surface finish due to abrasives got too "crowded" and, instead of removing material by excited abrasive particles, abrasives were often pressed against the work-piece to remove material. The best abrasive concentrations found in this study were 5% for 60 μm SiC, 10% for 5 μm SiC, 20% for 2 μm SiC and 33% for 0.3 μm Al_2O_3.

Under the same oscillation amplitude/frequency and using the same abrasives, slower feedrate generally means better surface roughness and shallower sub-surface cracks. This could be clearly seen in Fig.2 where SiC abrasives of 5μm in grit size and 5% in concentration were used to machine Zerodur under various feedrate.

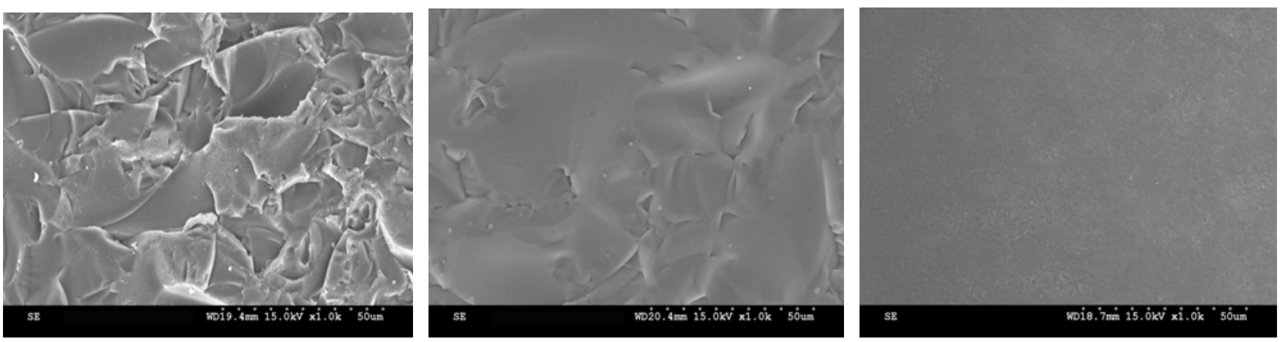


(a) (b) (c) (d)

Fig.2 Effect of feedrate(f_r) on the surface roughness of MUSMed Zerodur using SiC abrasives of 5μm in diameter and 5% in concentration, (a) f_r =1.5mm/min, Ra=1.25μm, (b) f_r =1mm/min, Ra=1.16μm, (c) f_r =0.5mm/min, Ra=0.96μm, (d) f_r =0.2mm/min, Ra=0.75μm.

Improving surface integrity by 'multi-stage' MUSM process

A multi-stage MUSM process combining coarse/fine abrasives and fast/slow feed rate was developed to improve the surface finish and overall machining efficiency. Specimen was firstly machined by coarse SiC abrasives (60μm) at 0.5mm/min for mass and swift material removing. It was subsequently machined by 5μm and 2μm SiC abrasives at 0.2mm/min and 0.1mm/min for accurate dimension control and better surface finish. To further improve the surface finish, a "dwelling" process which held the tool oscillating without in-feeding into the workpiece for several minutes was conducted. Shown in Fig. 3 were the scanning electron micrographs of the surfaces obtained at various stages of the MUSM process. The corresponding surface roughness values of the obtained surfaces were shown in Fig. 4. A surface with Ra value better than 0.2μm was achieved using this multi-stage process. Unlike those "typical" fracture/chipping distributed surface generated by MUSM process, the obtained surface was smooth and translucent.



(a) (b) (c)

Fig.3 SEM micrographs of the surface obtained by MUSM using (a) 60μm SiC abrasive, 5 % concentration and feedrate of 0.5mm/min, (b) 2μm SiC abrasive 20 % concentration and feedrate of 0.1mm/min (c) 2μm SiC abrasive 20 % concentration and dwelling (zero feedrate) for five minutes.

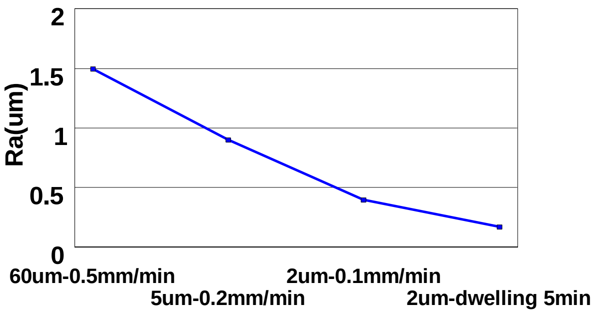


Fig.4 Surface finish (Ra) of the machined surfaces at different stages

Conclusions

(1) The surface integrity of the MUSMed specimen was profoundly influenced by the oscillation amplitude, frequency and feed rate of the MUSM tool, and the type, grit size and concentration of abrasives used.

(2) A rough surface with scattered chippings and deep penetrated cracks were normally found when large grit size abrasives and/or fast feed rate were used.

(3) Too high an abrasive concentration would normally result in a poor surface finish. The best abrasive concentrations found in this study were 5% for 60 μm SiC, 10% for 5 μm SiC, 20% for 2 μm SiC and 33% for 0.3 μm Al_2O_3.

(4) Under the same oscillation amplitude/frequency and using the same abrasives, slower feedrate generally means better surface roughness and shallower sub-surface cracks.

(5) It was found that good surface finish can be achieved without surrendering too much efficiency by the proposed 'multi-stage' micro-USM process where coarse abrasives/large feed, fine abrasive/small feed and fine abrasives/dwelling were carried out step by step.

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