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Ultraprecision Diamond Turning of Glass with Ultrasonic Vibration

J. Gan, X. Wang, M. Zhou, B. Ngoi and Z. Zhong

Precision Engineering and Nanotechnology Centre, School of Mechanical and Production Engineering, Nanyang Technological University, Singapore 639798

By applying ultrasonic vibration to a single-crystal diamond tool-tip, ductile machining of fused silica can be achieved even for 2 μm depth of cut. The increase in the critical depth of cut is significant and is a function of the ratio of vibration speed to cutting speed. Surface roughness Ra *of 100 nm was obtained for up to 2 μm depth of cut.*

Keywords: Brittle–ductile transition; Diamond turning; Ultrasonic vibration

1. Introduction

Some brittle materials have found wide applications because of their excellent thermal, chemical, and wear resistance characteristics. Impeding the use of these brittle materials in precision engineering applications is the fact that currently it is very difficult for them to be machined in a way that ensures high precision in form and to a good surface finish.

A non-traditional or unconventional machining technique incorporating ultrasonic technology [1] has been introduced to enable easier machining of otherwise hard-to-machine materials, and there exist various reports on ultrasonic abrasive machining and slurry drilling [2–4].

It is well known that the present machining technology using a diamond tool cannot be applied to steels because of excessive wear of the diamond cutting tool owing to high chemical activity of the carbon with the iron. However, Moriwaki and Shamoto [5] reported successful diamond-turning of stainless steel by applying ultrasonic vibration to the tool tip by which they obtained an optical quality mirror surface with an R_{max} as low as 0.026 μm and high-quality surfaces with a roughness less than R_{max} 0.1 μm and this could be done stably up to a cutting distance of 1600 m. They also diamond-turned soda-lime glass by applying ultrasonic vibration to the tool tip, and obtained a smooth transparent surface on the soda-lime glass with surface roughness R_{max} 0.03 μm [6].

Fused silica (vitreous silica) has an excellent resistance to most chemicals and to radiation damage. It is widely used in optical systems and is thought to be an ideal "glass" for windows in space-vehicles and wind-tunnels. This paper reports the results of our work on the ductile machining of fused silica by applying ultrasonic vibration.

2. Experimental Equipment and Workpiece

Figure 1 shows the ultrasonic vibration system and workpiece mounted on an Optimum 2400 ultraprecision lathe system, USA. Figure 2 shows the various parts of the ultrasonic vibration system. Table 1 shows the workpiece and tool conditions and ultrasonic vibration conditions.

3. Groove Cutting Experiments

The groove cutting experiments were carried out at two different cutting speeds, 1.98 m min^{-1} and 3.11 m min^{-1}. The

Table 1. Experimental conditions.

Workpiece material	Fused silica
Tool Conditions	Single crystal diamond Rake angle: 0° Clearance angle: 11° Tool nose radius: 0.8 mm
Cutting and ultrasonic vibration conditions	Cutting speed: 1.1–4.24 m min^{-1} Feedrate: 5 μm rev^{-1} Spindle speed: 90 r.p.m. Vibration amplitude: 3 μm Vibration frequency: 40 kHz Maximum vibration speed: 45 m min^{-1}

Correspondence and offprint requests to: Ms X. Wang, Precision Engineering and Nanotechnology Centre, School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore. E-mail: swangxj@ntu.edu.sg

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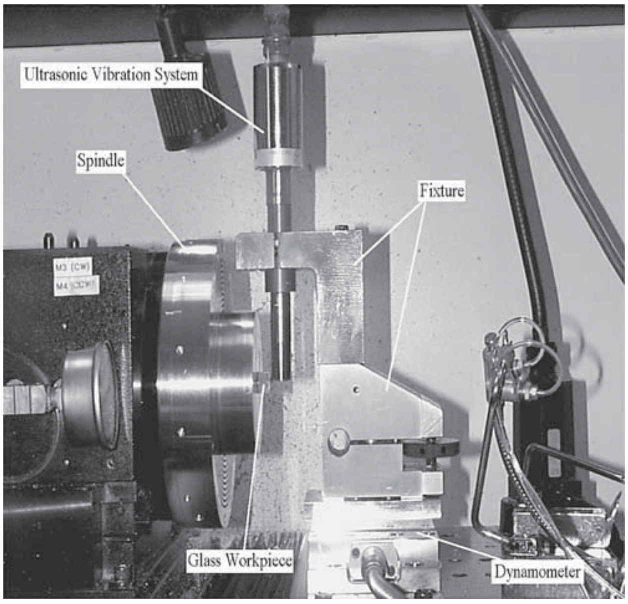

Fig. 1. Ultrasonic vibration system and workpiece on Optimum 2400.

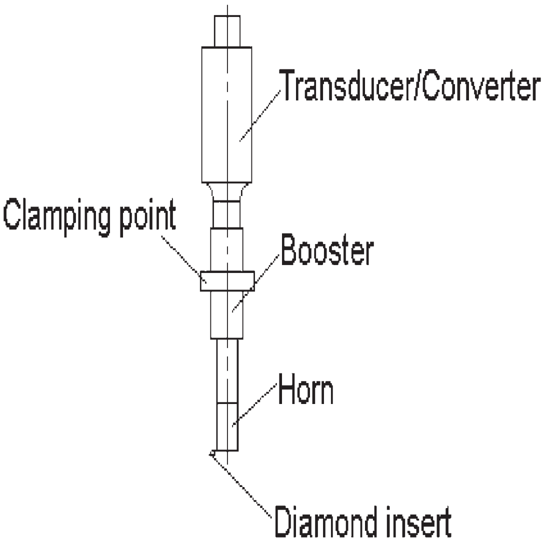

Fig. 2. Diagram of ultrsonic vibration system.

workpiece of fused silica was inclined by a small angle to the mounting plate so that the depth of cut could be varied continuously in one revolution. These experiments were performed using the same cutting tool with ultrasonic vibration at a maximum vibration speed of 45 m min^{-1}. Figure 3 shows microphotographs and profiles of grooves in the vicinity of the transition boundaries. The line A–A in Fig. 3(*a*) was drawn across a groove cut at 1.98 m min^{-1} and line B–B in Fig. 3(*b*) across a groove cut at 3.11 m min^{-1}. These lines were selected so that ductile machining (where the cutting depth is below the critical depth) occurs to one side of each line and brittle machining (where the cutting depth is above the critical depth) occurs to the other side. The depths shown in the cross-sections through the lines are therefore approximately the corresponding critical depths of cut. It can be seen that the groove shown in Fig. 3(*a*) has a smoother profile and a deeper critical depth of cut than that in Fig. 3(*b*).

According to Chao [7], the critical depth of cut of fused silica in conventional diamond turning is in the region 0.5–0.9 μm. The results of the groove cutting experiments suggest that the critical depth of cut was increased as a result of ultrasonic vibration of the tool tip. Furthermore, it can be deduced that the critical depth of cut varies with the ratio of vibration speed to cutting speed; in particular, the critical depth of cut increases when the ratio of vibration speed to cutting speed increases.

4. Face Turning of Fused Silica with Ultrasonic Vibration by Continuously Varying Depth of Cut

In this experiment, a fused silica workpiece was mounted at a slight inclination so that on one side of the workpiece, the depth of cut varied continuously from 0 near the centre of the workpiece to 10 μm at the periphery of the workpiece.

Figure 4 illustrates the transition area between brittle and ductile machining. It was taken using a Zeiss optical microscope at 200 magnification. Region A shows regular feed marks without any fracture and it is apparent that ductile machining takes place in region A. A few small fractures, shown as dark spots, are found where the depth of cut is around 2 μm in region B. This area is a transition region between ductile and brittle machining. At a deeper depth of cut in region C, very irregular fracture takes place.

The surface quality of the ductile machining area in section A was measured using a WYKO surface profiler. Figure 5 shows the 3D plot of the surface near the transition area in region A as shown in Fig. 4. The measured area is approximately 120 μm × 91 μm and the magnification was 51.6 × in the VSI mode. The surface roughness *Ra* of this area is almost 100 nm. The very regular feed marks can be seen clearly in the picture.

Figure 6 shows the 2D subregion profiles in the feed direction and cutting direction as shown in Fig. 5. The distance between every two peaks of the wave in the feed direction (as shown in Fig. 6 (*a*)) is approximately 5 μm, which corresponds to the feed per revolution of the turning process. The distance between two peaks in the cutting direction (as shown in Fig. 6(*b*)) is 1.5 μm, which corresponds to the calculated $l_T \approx 1.4$ μm, given by

$$l_T = vT = \frac{v}{f} = \frac{2\pi n r}{f}$$

where,

l_T = the distance that the workpiece covers in one period T of the vibration of the tool
T = one period
n = spindle speed

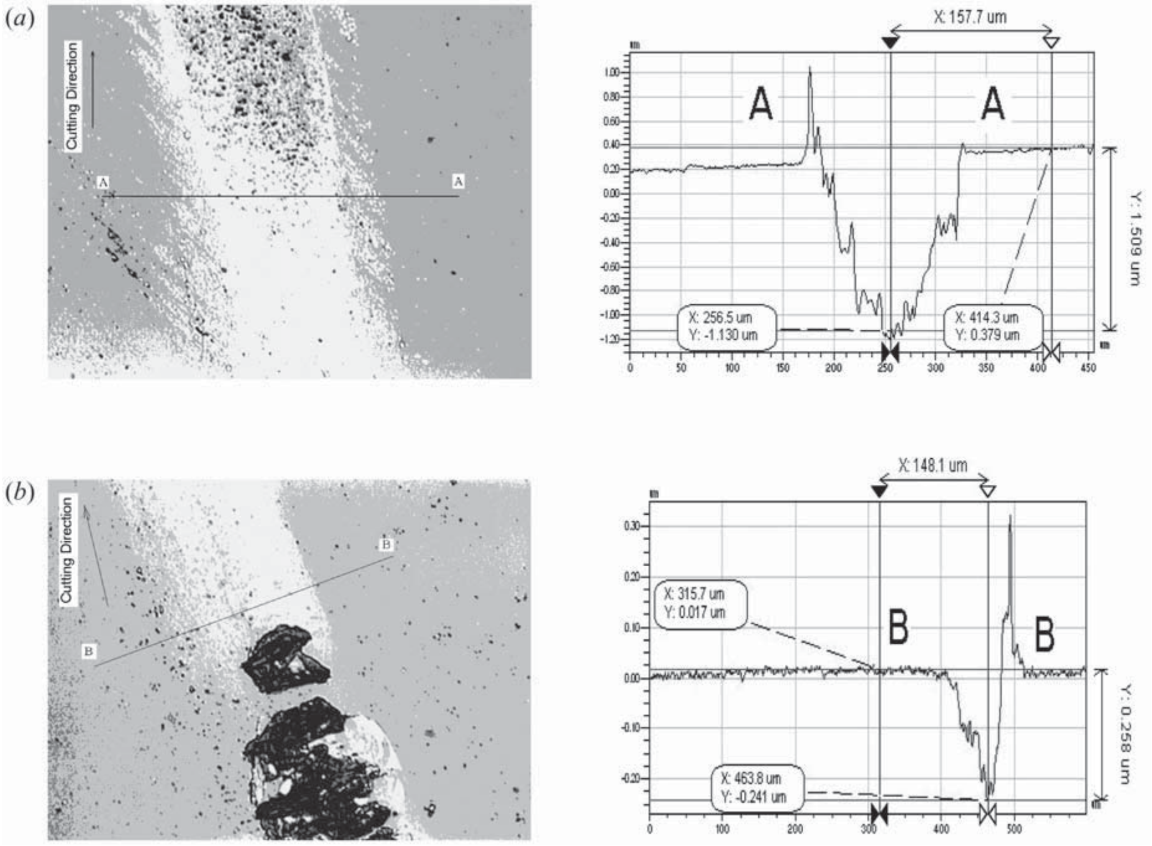

Fig. 3. Photographs of cut grooves taken with a Zeiss Microscope and profiles of grooves near transition boundaries measured by a W 2000 interferometer. (*a*) Cut groove and its section profile at cutting speed 1.98 m min^{-1}. (*b*) Cut groove and its section profile at cutting speed 3.11 m min^{-1}.

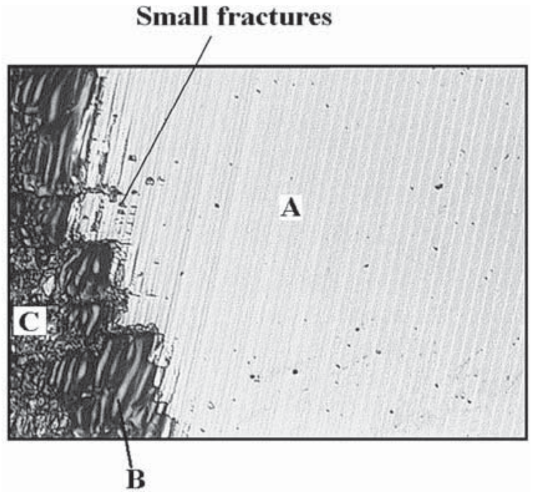

Fig. 4. Photograph of transition area between brittle and ductile machining.

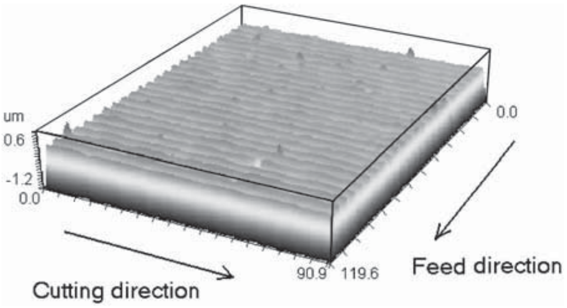

Fig. 5. 3D plot of dutile machining area taken by a WYKO surface profiler.

r = radius of the cutting area of the workpiece
v = velocity of workpiece, $v = 2\pi nr$
f = vibration frequency = 40 kHz

Surface quality improves with a smaller cutting length L_T in one period. Because $l_T = vT = v/f = 2\pi nr/f$, to reduce L_T it is

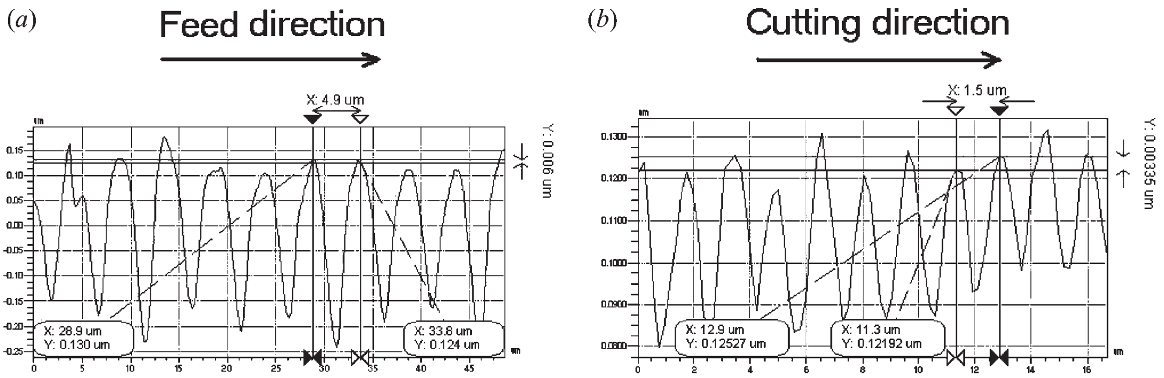

Fig. 6. 2D subregion profiles in feedrate direction and cutting direction of Fig. 5.

necessary to decrease the cutting speed of the workpiece and/or to increase vibration frequency.

5. Conclusions

1. The critical depth of cut in the ultrasonic vibration cutting process is related to the ratio of cutting speed of workpiece and the maximum vibration speed of the tool. The critical depth of cut was found to be approximately 1.5 μm at a cutting speed of 1.98 m min^{-1} and a maximum ultrasonic vibration speed 45 m min^{-1}. At a cutting speed of 3.11 m min^{-1} the critical depth of cut was smaller ($\approx$ 0.3 μm) and the profile of the groove was rougher.
2. The critical depth of cut was found to be even larger (2 μm) in face turning of fused silica with ultrasonic vibration. The surface roughness *Ra* near the transition area is almost 100 nm and the very regular feedrate (5 μm rev^{-1}) marks were observed in the ductile machining part.

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