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An investigation of factors affecting surface generation in ultrasonic vibration assisted diamond cutting of hard-brittle materials

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Abstract
Ultrasonic Vibration Assisted (UVA) machining is being used for direct diamond turning of hard-brittle materials to obtain optical-quality surfaces. It largely reduces the processing time and cost to produce the high accuracy surface on hard-brittle materials. However, our understanding of the cutting mechanics and surface generation in UVA diamond cutting of these materials is still far from complete. In this paper, an experimental investigation has been conducted to study the effect of the factors affecting the surface generation in UVA diamond cutting of hard-brittle materials. A series of tapered grooving experiments were conducted on optical glass (BK7), tungsten carbride (WC), and Silicon Carbide (RB-SiC). The factors under control in this investigation included vibration amplitude of the UVA system, cutting speed, cooling conditions and depth of cut. With appropriate selection of cutting parameters, the experimental results show that it is technically feasible to achieve ductile cutting of hard-brittle materials by UVA diamond cutting. The results provide an important means for better understanding the cutting mechanics and surface generation of UVA diamond cutting of hard-brittle materials.

Keywords: Ultrasonic vibration, hard-brittle materials, surface generation, ultra-precision machining, surface integrity

1. Introduction

In recent years, hard-and brittle materials have been widely used in many industrial fields, such as optics, aerospace, automotive, electronics, etc. [1]. Many high precision moulds are made from these kinds of materials, such as tungsten carbide, to maintain high accuracy and provide thermal resistance during the moulding process. However, these materials are difficult to process due to their high hardness. Grinding and polishing methods are usually used to process those types of materials to obtain an optical-quality surface. Direct diamond turning is not possible since it easily wears the cutting tool and cannot produce a good surface quality. This can make the fabrication process expensive and time consuming. An ultrasonic vibration assisted (UVA) diamond machining method has been developed [2-4], which may provide an alternative solution for this.

As shown in Fig.1, UVA diamond machining makes use of a small amplitude of high-frequency vibration added to the tool cutting direction [5]. The high frequent oscillation of the tool in the cutting direction leads to an intermittent contact between the tool and the workpiece. This provides a number of technological advantages over conventional turning methods, such as reduced cutting forces [6,7], extended tool life [8], better surface roughness and form accuracy [9], suppression of burr formation [10], and greater critical cutting depth of brittle-ductile transition during the cutting of brittle materials [11]. There have been some previous studies on ultrasonic vibration assisted cutting of materials such as hardened steel, titanium alloys and ceramics [12-15]. However, the understanding of the material removal mechanisms for UVA diamond machining of hard and brittle materials is still far from complete.

In this paper, a pilot study has been carried out to investigate the factors affecting surface generation in UVA diamond turning of hard and brittle materials, including optical glass (BK7), tungsten carbide (WC), and silicon carbide (RB-SiC). Tapered grooves were cut on those materials while the cutting mechanics and integrity of the surface generated were analysed.

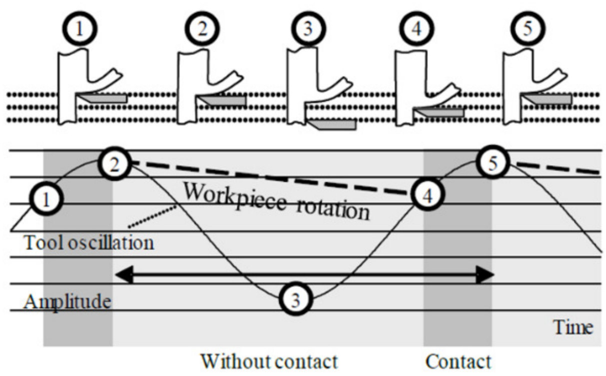

Figure 1. Principle of ultrasonic vibrastion assisted diamond turning [5]

2. Experimental setup

Fig. 2 shows the experimental setup to conduct the tapered groove generation experiments. A UVA system (UTS 1 from son-x GmbH) was integrated on a Moore Nanotech 350 FG ultra-precision machine. A single crystal diamond tool provided by Contour Fine tooling Ltd. was used in this experiment. The workpiece materials included optical glass (BK7), Tungsten Carbide (WC) with 10%wt. of Cobalt (WC/Co), and reaction bonded silicon carbide (RB-SiC). The workpiece was mounted on a fixture with a tapered angle of 0.04 degree as shown in Fig. 3. Tapered grooves were machined through a linear motion along the Y axis. Table 1 summarizes the experimental conditions. The workpiece surface was polished to be mirror-like surface before the grooving experiments so as to avoid any effects caused by the initial surface roughness of the workpiece. The generated tapered grooves were measured using a Zygo white light interferometer (Nexview, Zygo Ltd.), scanning electron microscope (TM3000, Hitachi Ltd.) and optical microscope (BX60, Olympus Corp.)

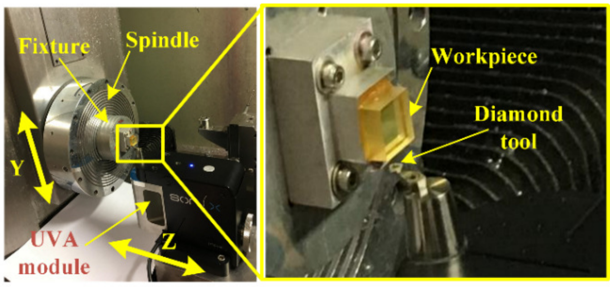

Figure 2. Snapshot of the experimental setup

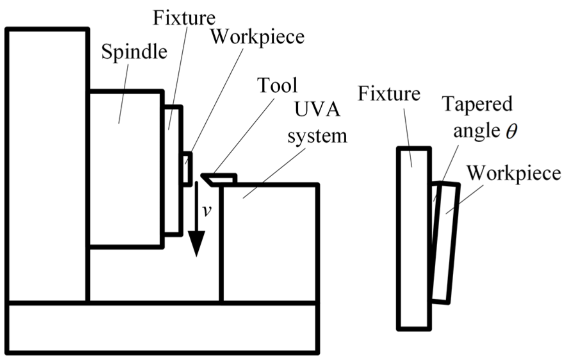

Figure 3 Graphical illustration of grooving experimental setup

Table 1 Experimental conditions

Workpiece material	BK7, WC/Co, RB-SiC
Vibration frequency (kHz)	80
Vibration amplitude (μm)	0, 0.5, 1
Cutting speed (mm/min)	150, 1000
Coolant	With mist oil, without mist oil
Tool parameters	1 mm tool nose radius, -25° rake angle and 10°clearance angle

3. Results and discussions

3.1. Grooving on optical glass (BK7)

Fig 4 shows the result of UVA diamond cutting of optical glass (BK7) using an ultrasonic vibration amplitude of 1 μm and cutting speed of 150 mm/min. Three regimes with different removal characteristics were observed which include ductile regime, brittle/ductile regime and brittle regime. The critical depth of cut is defined as the depth at the boundary between the ductile regime and the brittle /ductile regime. It is important to note that the undeformed depth of cut should be kept to be less than the critical depth of cut to order to obtain a crack free surface.

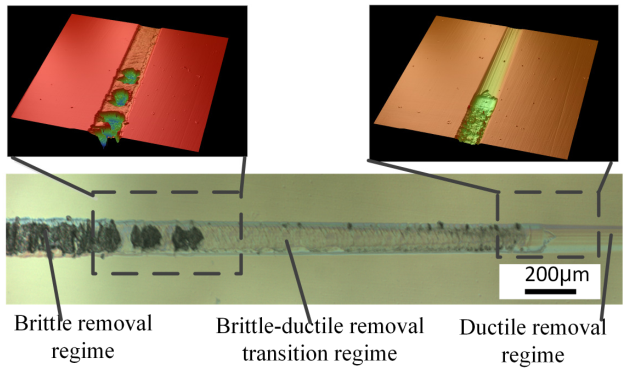

Figure 4. Optical microscopy of the groove on BK7 glass sample (Vibration amplitude: 1 um, Cutting speed: 1000 mm/min.).

3.1.1 Effect of UVA machining on surface generation in diamond cutting of BK7

Fig. 5 shows the generated tapered grooves on the BK7 surface with and without UVA. The grooves were generated without coolant. It is found that the generated surface quality in the groove can be divided into three regimes induced by different cutting depths, these are brittle removal region, brittle-to-ductile transition region and ductile removal region, respectively. The brittle removal region almost covers the whole groove in diamond machining of optical glass under no vibration conditions (see Fig. 5(a), As shown in Fig. 5(b), the brittle-to-ductile transition region and ductile removal region takes place along most of the length of the grooves when the groove was cut with ultrasonic vibration and a vibration amplitude of 0.5 μm. It shows the effectiveness of UVA machining in improving the surface quality in diamond cutting optical glass.

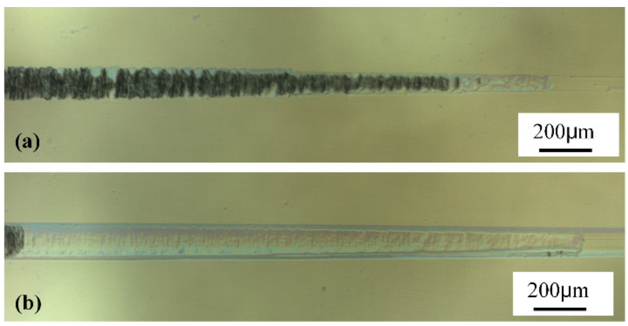

Figure 5. Tapered grooves generated on BK7 optical glass under different conditions: (a) without ultrasonic vibration and cutting speed of 150 mm/min, (b) with ultrasonic vibration of amplitude of 0.5 μm and cutting speed of 150 mm/min.

3.1.2 The influence of vibration amplitude on the critical depth of cut

To better understand the influence of vibration amplitude on the critical depth of cut, the tapered grooving experiment was conducted under different vibration amplitudes. Fig. 6 and Fig. 7 show the profile of grooves cut with a vibration amplitude of 1 μm and 0.5 μm, respectively. The critical depth of cut of the groove cut with an vibration amplitude of 1 μm is 0.75 μm while the critical depth of cut with an vibration amplitude of 0.5 μm is 0.5 μm. The results indicate that UVA cutting possesses better performance than conventional cutting and a larger vibration amplitude allows a larger depth of cut in the ductile cutting regime.

In diamond cutting hard-brittle material, the critical depth of cut can be expressed as:

$$d_c = 0.15 \cdot \left(\frac{E}{H}\right)\left(\frac{K_c}{H}\right)^2 \quad (1)$$

Where d_c is the critical depth of cut, H is the material hardness, E is the elastic modulus and K_c is the fracture toughness. According to Eq. (1), the critical depth of cut for BK7 glass cut by conventional cutting method is calculated as only 18.12 nm. Therefore, the UVA cutting process is able to considerably increase the critical depth of cut.

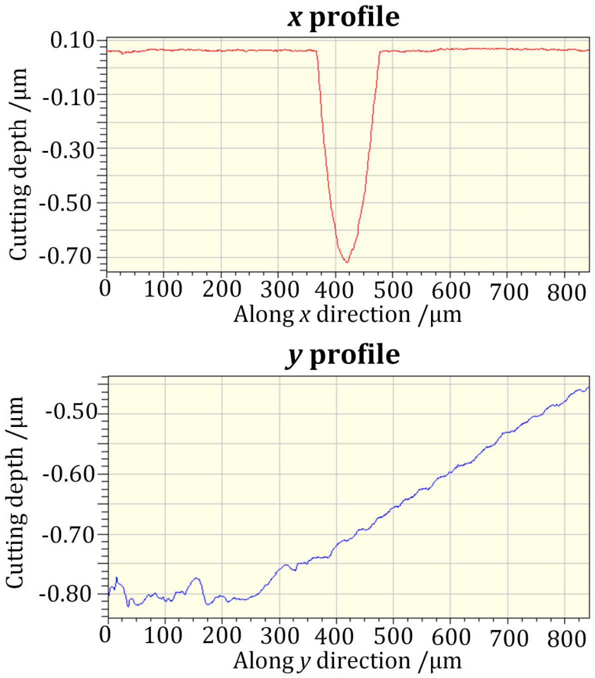

Figure 6. Profiles of the grooves on the BK7 sample. The X profile is in the border profile in terms of the critical depth of cut with an vibration amplitude of 1μm while the Y profile is along the cutting direction

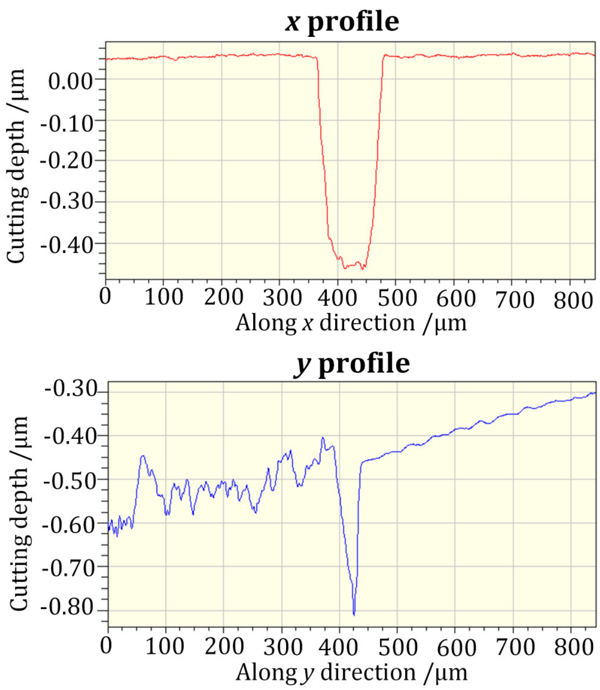

Figure 7. Profiles of the grooves on the BK7 sample. The X profile is the border profile in terms of the critical depth of cut with an vibration amplitude of 0.5 μm while the Y profile is along the cutting direction.

3.2. Grooving on tungsten carbide

Fig. 8 shows a comparison of the results of tapered grooves generated on a tungsten carbide (WC/Co) surface without coolant. As was the case with optical glass BK7, the brittle removal region almost covers the whole of the groove surface when the cutting is undertaken without the UVA process, while the surface quality of the whole groove is much better when it is cut with the UVA process. The effect of the coolant in UVA diamond machining of WC/Co was also compared as shown in Fig. 9. It is important to note that the surface quality can be significantly improved with the use of coolant. This is due to the fact that the coolant oil is helpful for the lubrication during cutting, which assists in reducing the cutting forces.

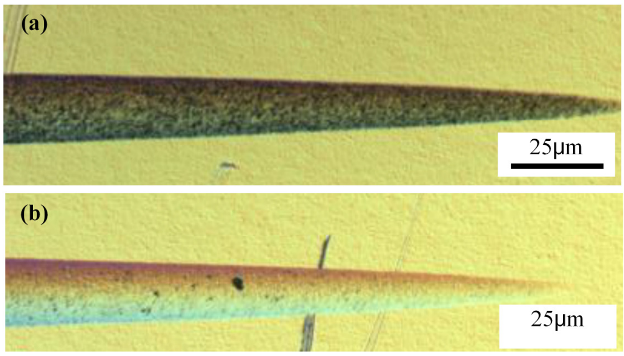

Figure 8. Tapered grooves generated on WC/Co surface with and without ultrasonic vibration. (a) With ultrasonic vibration, (b) without ultrasonic vibration. The cutting speed is 150 mm/min, and the vibration amplitude is 1 μm (with UVA).

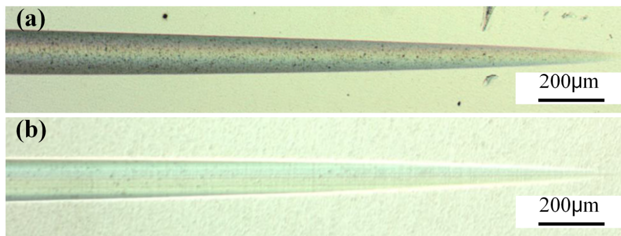

Figure 9. Tapered grooves generated on WC/Co surface with and without mist coolant.(a) No coolant, (b) with coolant.

3.3. Grooving on reaction bonded silicon carbide

The surface quality of the tapered grooves on silicon carbide (RB-SiC) under different vibration amplitudes were compared as shown in Fig. 10. These grooves were generated with mist oil coolant. It is found that the surface quality with 1.0 μm vibration amplitude is better than that of vibration amplitude of 0.5 μm when other conditions are kept the same.

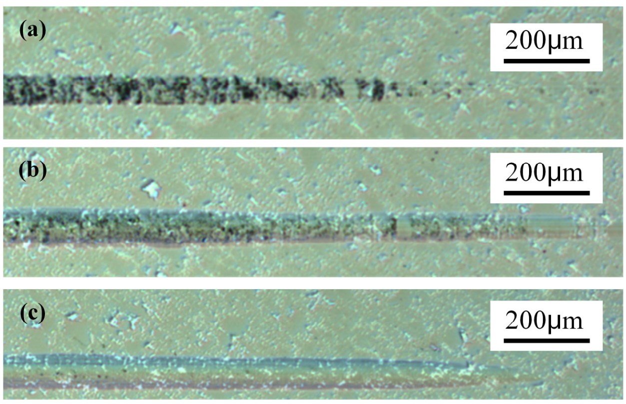

Figure 10. Tapered grooves generated on RB-SiC surfaces with different vibration amplitude. (a)No vibration, (b) vibration amplitude of 0.5 μm, (c) vibration amplitude of 1.0 μm.

The tapered grooves generated with different cutting speeds were also compared in Fig. 11. It is important to note that the surface quality in terms of the proportion of the ductile removal region with a cutting speed of 150 mm/min is much higher than that with a cutting speed of 1000 mm/min. This is likely due to the fact that a lower cutting speed when using the UVA system can reduce the tool-workpiece contact ratio, which is beneficial to obtain high-quality cutting [17]. Figure 12 shows the generated tapered grooves on RB-SiC with and without coolant, and the result is similar to that for WC/Co, which further demonstrates that the coolant is a critical factor to obtain good surface-quality in UVA diamond turning of hard-brittle materials.

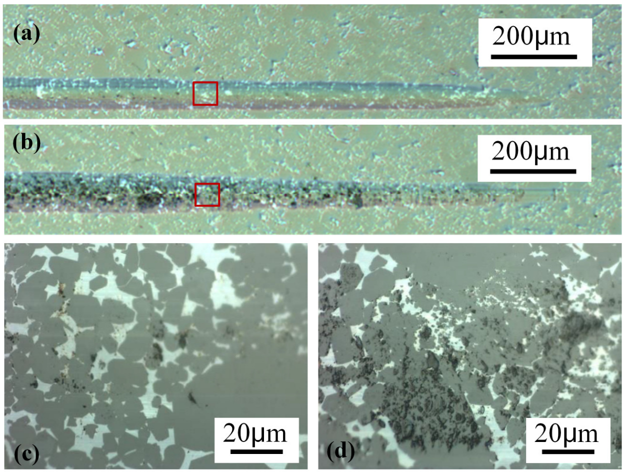

Figure 11. Tapered grooves generated on RB-SiC surfaces with different cutting speeds. (a) Cutting speed of 150 mm/min, (b) cutting speed of 1000 mm/min, (c) magnified zone in (a), (d) magnified zone in (b).

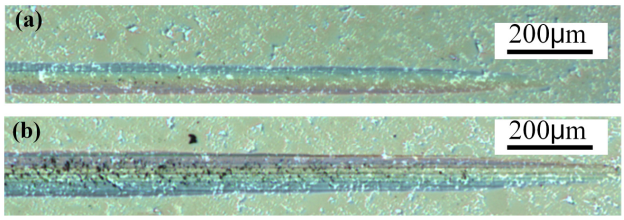

Figure 12. Effect of coolant to the tapered grooves generated on RB-SiC surfaces. (a) with coolant, (b) without coolant

4. Conclusions

In this paper, an investigation of the factors affecting the surface generation in ultrasonic vibration assisted (UVA) diamond cutting of hard-brittle materials were carried out under different cutting conditions including vibration amplitude of UVA, cutting speed, with and without coolant and depth of cut . A series of tapered grooving experiments were conducted on BK7 optical glass, tungsten carbide, and silicon carbide.

The experimental results show that UVA machining is effective to obtain good surface quality in diamond cutting hard-brittle materials. With the use of the UVA process, it is possible to achieve ductile mode cutting unlike with conventional diamond cutting of hard-brittle materials. The cutting mechanics in terms of ductile-brittle transition after UVA diamond cutting varies with different conditions such as the vibration amplitude, cutting speed, and cooling conditions. The critical depth of cut in diamond cutting of BK7 optcal glass can also be increased. The use of coolant is found to be a positive factor affecting the quality of surface generation in UVA diamond cutting.

The results of the investigation not only provide an important means to better understanding the cutting mechanics and surface generation mechanism but also sheds light on the optimization of cutting parameters for improving the surface quality in UVA diamond cutting of hard-brittle materials.

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