Surface Damage Characteristics of BK7 Glass in Ultrasonic Vibration Machining Based on Scratching Experiment

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Abstract. To further explore the material removal mechanism in ultrasonic vibration machining, a diamond Vickers indenter was used to carry out scratching experiment for BK7 glass specimen. The morphologies of scratches and removal mechanism of material were analysed under different conditions. The results showed that the damage mode of scratch was plastic deformation when the scratching depth was small enough, and no crack was observed. With increase of scratching depth, the intermittent and continuous scratches appeared in plastic removal area, and plastic flow phenomenon was obvious. With further increase of scratching depth, the median/radial cracks and lateral cracks were induced, and the material was removed by plastic flow and brittle-plastic mixed mode. When the indenter arrived at the brittle fracture removal area, cracks in scratched surface became denser, the lateral cracks extended from inside of material to workpiece surface, and the material was removed by brittle fracture.

1. Introduction

BK7 glass is a typical hard-brittle material and possesses some properties such as large brittleness and high hardness, which make it extensively applied in the aerospace, optical engineering and other fields. Brittle fracture frequently during processing causes many defects such as surface/subsurface damage, micro-cracks, and residual stress. The traditional method is difficult to achieve the desired results [1]. Under the high-frequency vibration of spindle, rotary ultrasonic machining (RUM) realizes the efficient processing of BK7 glass by nickel-based electroplated diamond tools [2]. However, it is difficult to accurately observe the surface damage caused by a single abrasive during the RUM process. The interaction between a single abrasive and workpiece surface is often simulated by scratching experiments [3-5]. Bulsara V H et al. photographed the deformation and fracture of scratches in brittle solids, and indicated that the compressive stress induced the nucleation of median/lateral cracks in loading process and the tensile stress induced the nucleation of lateral cracks in unloading process [6]. Qiu Z J et al. investigated the propagation of surface/subsurface crack by single and double scratching experiments of glass–ceramics, and found that the interaction between lateral cracks and radial cracks was the main mode of material removal [7]. Lv et al. observed the scratches on BK7 glass in the scratching tests with and without ultrasonic, and revealed that the ultrasonic vibration could significantly affect the nucleation and propagation of the crack [2, 8]. Cao et al. researched the material removal behaviours in ultrasonic-assisted scratching of SiC ceramics, and concluded that the tool’s impact and cutting force on the machined surface were the main factors of removal [9].

In summary, the removal mechanisms of brittle materials have studied extensively based on the scratching experiment. However, relative movement of abrasive-material in rotary ultrasonic machining is the coupling of spindle rotary motion, linear feed motion, and axial high-frequency reciprocating motion. These alterations in movement mode have significant effect on the material removal mechanism, while no detailed investigations of these factors have been reported. To further explore the mechanism
of BK7 glass in RUM, the workpiece surface was subjected to ultrasonic vibration scratching with various depths by the diamond Vickers indenter. Subsequently, the morphology of the scratched surface was observed with the optical microscope and AFM.

2. Experimental procedures
Schematic diagram of experimental device is illustrated in figure 1. The experiments were conducted on the RUM machine (DMG Ultrasonic 70-5-linear, Germany), which equipped the tool holder (HSK63) and the ultrasonic generator (USG2000), and the frequency range of ultrasonic vibration was 18~30kHz. The indenter with the vertex radius of 0.2μm and the opposite angle of 136° was mounted on the tool holder by the spring chuck. BK7 glass was adhered on a special steel plate which was securely fixed on a three-direction dynamometer (Kistler9256C2). In order to avoid the flatness error of specimen during installation, the three-point leveling system on the machine was used to adjust the workbench. To ensure the Vickers indenter could still axial high-frequency reciprocating vibration without spindle rotation, the ultrasonic vibration mode was adjusted to the manual mode.

The BK7 glass specimens with dimensions of 30mm×15mm×6mm were selected for this investigation. Prior to the scratching experiments, the specimens were successively polished with finer abrasive to facilitate the observation of optical microscopy. In all experiments, the scratching depth increased gradually along the scratching direction. The scratching length was 2000μm and scratching speeds were 10, 20, 40, 60mm/min, respectively. Finally, the BK7 glass specimen was observed with the three-dimensional optical microscope and AFM.

![Figure 1. Experimental device for ultrasonic vibration scratching.](image)

3. Different areas of ultrasonic vibration scratching
Different areas of ultrasonic vibration scratching with various scratching depth are shown in figure 2. Apparently, the periodic fluctuation of the abrasive trajectory causes the cutting process along the feed direction to be divided into two stages: 1) intermittent cutting stage, where abrasives intermittently cut into and cut off the workpiece, leaving a series of interrupted isolated scratches on the surface; 2) continuous cutting stage, where abrasives continuously contact the workpiece, forming continuous scratches on the surface.

In the process of scratching from the starting point $S_{uvs}$ to the ending point $E_{uvs}$, the different morphologies of scratches are caused by different deformation and removal methods of the material, which are mainly composed of three ways: plastic deformation, plastic removal, and brittle fracture. In order to compare the different characteristics on surface damage morphology, the whole scratching process is divided into four areas: plastic deformation area $A_{uvs}$, plastic removal area $B_{uvs}$, brittle/plastic mixed removal area $C_{uvs}$, and brittle fracture area $D_{uvs}$. 
4. Experimental results and analysis

4.1. Surface damage of scratched surface
When the scratching speed $v=10$ mm/min, the surface damage morphology with different scratching depth is shown in figure 3, and the four areas lengths were 0.1 mm, 0.2 mm, 0.3 mm, and 1.2 mm, respectively.

The Vickers indenter intermittently cut into the specimen surface under the ultrasonic vibration, and a series of shallow pits with a certain space were impacted in the area $A_{uv}$. Because the surface material of the pits was not subjected to sufficient compressive stress and shear stress, the damage of scratch was the pure plastic deformation, and no cracks were observed. With the increase of scratching depth, there were intermittent and continuous scratches in the area $B_{uv}$. The plastic flow phenomenon was obvious on the right side of this area. The scratched surface was still relatively smooth, which indicated that the material in this area was mainly removed by plastic flow. With the further increase of scratching depth, there were large bright areas on both sides of the area $C_{uv}$. The median/radial cracks extended perpendicularly to the scratched surface and the lateral cracks horizontally extended towards the specimen surface, which indicated that the material in this area was mainly removed by plastic flow and brittle/plastic mixed removal. When the Vickers indenter reached the area $D_{uv}$, the cracks in the scratched surface area were denser. The lateral cracks on the local surface extended from the inside of workpiece to the surface under the large compressive stress and shear stress, resulting in the surface material falling from the workpiece. The material in this area was mainly removed by brittle fracture.
The AFM three-dimensional morphology in different material removal areas are shown in figure 4. In the plastic removal area (see figure 4a), the material on both sides of the scratch was extruded and deformed, resulting in plastic flow phenomenon. In the brittle/plastic mixed removal area (see figure 4b), the plastic flow of material, as well as the nucleation and propagation of cracks led to lateral cracks, ridge-like bulge and zigzag corrugation on both sides of the scratch. Simultaneously, the transition from plastic flow to brittle fracture occurred at the position C, and the scratching depth of this position was 2.23μm.

![Image of AFM three-dimensional morphology in different material removal area](image)

**Figure 4.** AFM three-dimensional morphology in different material removal area.

4.2. Change of scratch damage morphology

The three-dimensional morphologies of scratches were detected layer by layer along the scratching direction by AFM. The variations of the scratching depth with scratching length are demonstrated in figure 5.

![Image of variations of scratching depth with scratching length](image)

**Figure 5.** Variations of scratching depth with scratching length.

The repetitive positioning accuracy of machine tool was ±1μm. When the diamond Vickers indenter was mounted on the spindle and returned to the origin position again, the height error caused the theoretical scratching depth was less than the actual scratching depth. In the plastic removal area, the assistance of ultrasonic vibration changed the trajectory of indenter, which led to a slight periodic fluctuation of the scratching depth and the surface morphology. In the brittle/plastic mixed removal area, scratching depth began to fluctuate significantly at the scratching length of 500 ~ 600μm. With the further increase of scratching depth, the material produced brittle fracture and the scratching depth appeared irregular fluctuations. The increase of surface damage was induced by the propagation of radial/median cracks and the mutual overlap of many lateral cracks.
Under different scratching speeds, the cross-sectional area of the scratches increased with the scratching length (see figure 6a). The cross-sectional area first increased slowly, and then increased faster after reaching the inflection point. The width-to-depth ratio of the scratches decreased with the scratching length (see figure 6b). The width-to-depth ratio decreased at first, and then tended to be steady after reaching a certain length. When the scratching speed $v=10\text{mm/min}$, with the increase of scratching length, cross-sectional area and width-to-depth ratio of the scratches had a significant change in the position where the scratching length was about $580\mu\text{m}$. This change was in good agreement with the results of optical microscopy and the variations of the scratching depth, which indicated that the inflection point was the critical point of the transition from plastic flow to brittle fracture.

![Figure 6](image)

**Figure 6.** Variations of cross-sectional area and width-to-depth ratio with scratching length.

In addition, the scratching speed had a certain impact on the critical point of the transition from plastic flow to brittle fracture. The variations of the critical scratching depth with the scratching speed are shown in figure 7. With the increase of scratching speed, the critical scratching depth of the transition from plastic flow to brittle fracture was gradually reduced.

![Figure 7](image)

**Figure 7.** Variations of critical scratching depth with scratching speed.

5. Conclusions
The present work analyzed the morphologies of scratches under different conditions and material removal mechanism of BK7 glass in scratching experiments with ultrasonic vibration. Following conclusions can be drawn from this investigation:
1. The deformation and removal methods of the material divide the morphologies of scratches into plastic deformation area, plastic removal area, brittle/plastic mixed removal area, and brittle fracture area.

2. With the increase of scratching depth, the removal of materials was changed from pure plastic deformation to brittle/plastic mixed mode, and finally became the brittle fracture under the compressive stress and shear stress.

3. The critical point of the transition from plastic flow to brittle fracture was obtained by analyzing the variations of cross-sectional area and width-to-depth ratio, and the critical scratching depth was gradually reduced with the scratching speed.

6. References
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