Analysis of Surface and Subsurface Damage Morphology in Rotary Ultrasonic Machining of BK7 Glass

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Abstract. This paper investigates the formation process of surface/subsurface damage in the rotary ultrasonic machining of BK7 glass. The results show that during the milling using the end face of the tool, the cutting depth and the residual height between the abrasive grains constantly change with the high-frequency vibration, generating lots of cracks on both sides of the scratches. The high-frequency vibration accelerates the chips falling from the surface, so that the chips and thermal damage are reduced, causing the grinding surface quality better. A plastic deformation area is formed during the grinding, due to the non-uniform cutting force on the material surface, and the residual stress is produced in the deformation area, inducing the median/lateral cracks.

1. Introduction
During the process of rotary ultrasonic machining (RUM) of BK7 glass, the material usually produces plastic deformation and brittle fracture, and the median and lateral cracks are generated on the surface. The median cracks propagate downwardly in the loading direction to form subsurface damage (SSD), while the lateral cracks extend upwardly parallel to the surface of the workpiece, when it is extended to the surface, the material falls off in the form of chip debris. Markov AI proposed that the repeated impacts of diamond abrasive grains cause a large number of microscopic and macroscopic cracks to nucleate and extend, which are interwoven into a network, forming a weakened layer in the material [1]. Prabhakar D investigated the forward motion and rolling of the abrasive grains can cause the brittle fracture of the weakened layer [2]. Spur G et al. found that the real contact time was reduced by 50% due to the sinusoidal motion of the workpiece with ultrasonic assistance, resulting in an enormous reduction in frictional effects and normal forces [3]. Qu W et al. found that the lateral cracks would inhibit the formation of subsequent median cracks if the tangential displacement of abrasive grains is less than the extended length of the lateral crack, so the SSD depth is decreased [4]. Lv et al. did the scratching tests with a gradient load on the BK7 glass. The results showed that with a small scratching depth the scratches on the surface were discontinuous, and there were a few of cracks at the bottom of the scratches. As the scratching depth increasing, there were lateral cracks and median cracks on the both sides of the scratches, and the overlapped cracks caused the formation of the chips, which indicated the removal of the material in RUM is mainly caused by the crack propagation [5, 6].

As described above, in the RUM process, the abrasive grains have a great transient acceleration with the assistance of ultrasonic vibrations. Therefore, it is necessary to study the influence of high-frequency vibration on the surface and SSD characteristics in RUM of BK7 glass, in order to perfect the mechanism of RUM.

2. Formation process of BK7 glass surface by RUM
The RUM of BK7 glass is essentially a micro-cutting process on the surface of the workpiece using a large number of diamond abrasive grains. Abrasive grains press and scratch on the surface, ultimately
forming the machined surface. The RUM with different cutting depths is shown in figure 1, with increase of the cutting depth, not only the cutting takes place at the end face of the tool, the grains at the lateral of the tool are also involved in cutting. When the back engagement \( (a_p) \) at the end face of the tool is less than maximum protrusion height of grain \( (h_e) \), machining only occurs at the end face of the tool and the material is removed by milling (figure 1a); When \( a_p \) is greater than \( h_e \), the grains at the lateral of the tool will cut the lateral surface of the workpiece, at the same time, the horizontal surface of workpiece is milled by grains at the end face of the tool (figure 1b).

![Figure 1. Illustrations of the RUM with different cutting depths.](image)

It can be seen from figure 1, the RUM produces two machining surfaces, the milling surface perpendicular to the spindle axis and the grinding surface parallel to the spindle axis. Because the grains at the end and lateral faces have different trajectories, so it is necessary to do a separate investigation on the cutting effects of the grains on the end and lateral faces, and analyze the formation process of BK7 glass surface by RUM.

![Figure 2. Illustrations of the end face milling.](image)

The cutting process of grain at the end face is shown in figure 2, and it can be seen that the axial high-frequency vibration has an influence on the motion of grain, causing the cutting depth constantly changing. At the same time, the milling residual height \( (h_r) \) between the adjacent abrasive grains is also constantly changing, and resulting in a large number of microscopic cracks on the both sides of the scratches, and then they develop into the surface and subsurface damage.

![Figure 3. Illustrations of lateral face grinding.](image)
The cutting process of grain at the lateral face is shown in figure 3. The axial high-frequency vibration causes the abrasive grains to move in a sinusoidal trajectory, and there are interferences between the adjacent abrasive grains causing the grinding residual thickness ($t_r'$) to be less than the average grinding residual thickness ($t_r$), reducing the roughness of the lateral grinding surface.

3. Morphology of surface damage

In order to study the characteristics of surface damage in RUM, the milling experiments for BK7 glass were carried out. The experiments were performed on a RUM machine, and used hollow nickel-based electroplating diamond tool (outer diameter is 8mm, inner diameter is 6mm grain size is 91μm, grain concentration is 100%). The dimensions of the specimens are 30mm×15mm×6mm. Other experimental conditions are listed in table 1.

| Parameter            | Unit   | Value  |
|----------------------|--------|--------|
| Spindle speed        | [rpm]  | 6300   |
| Feed rate            | [mm/s] | 20     |
| Cutting depth        | [μm]   | 200    |
| Vibration frequency  | [kHz]  | 20.689 |
| Vibration amplitude  | [μm]   | 5      |

In order to obtain the surface damage morphology, the specimens were observed by three-dimensional super-depth optical microscope (VHX-1000E). Figure 4 shows the morphologies of milling surface machined by end face and grinding surface machined by lateral face. Figure 4a shows the brittle fracture area is small on the milling surface (produced by end face), and there is a large amount of fine collapses and a small amount of pulverizable areas.

![Figure 4. Morphologies of the surface produced by end face and lateral face (by VHX-1000E).](image)

![Figure 5. Morphologies of the surface produced by end face milling (by SEM).](image)
The morphology of surface damage produced by lateral face of the tool is shown in figure 4b, and the grinding surface has more small plate shaped pits rather than large plate shaped pits, causing fewer chips and better surface quality. This is due to the grains at the lateral face have high-frequency axial vibration, impacting the grinding surface and accelerating the separation of the chips and the workpiece. Thereby effectively reducing the thermal damage on the grinding surface. In addition, the periodic change of the contact area between the abrasive and the workpiece reduces the wear of the grain. In order to further reveal the effect of RUM on the surface damage, the microscopic surface morphologies produced by end face milling were observed by SEM (figure 5). As shown in figure 5(a), the pulverizable areas are stacked with small fragments of cluster distribution, and the pulverizable areas are less than the fractured areas.

4. Morphology of subsurface damage
Prior to the formal machining tests, a bonded interface sectioning technique was selected to examine the morphology of subsurface damage [7]. In this method, the surfaces of two specimens (15mm×15mm×6mm) were first ground and polished until the surface roughness was 10nm or less in order to remove the subsurface damage caused in the preparation of the specimen. Subsequently, the two specimens were bonded together with an epoxy resin adhesive. To minimize edge chipping of the bonded surfaces, the clamping pressure was applied to ensure that a thin adhesive thickness was achieved. In order to investigate the influence of RUM, the bonded specimen was machined by RUM. After the machining they were separated by melting the adhesive and then cleaned with acetone in the ultrasonic cleaner. The SSD morphologies were observed by VHX-1000E (figure 6).

Figure 6 shows the SSD caused by RUM mainly includes chipping layer and cracking layer. The chipping layer was composed of irregular surface defects mainly generated by chips falling; the cracking layer was composed of lateral cracks and median cracks. At the bottom of the shell-like defect there was a median crack extending downwardly perpendicular to the surface, at the lower right of the shell-like defect there was a lateral crack at the beginning of the extension, and there was a bright area above the lateral crack, which was a potential damage area. There were a large number of lateral cracks in the interior of the material under the potential damage area (shown in figure 6b). At the right side of the large chipping shown in figure 6b, there was a lateral crack extending downwardly under the potential damage area. This phenomenon is because in the RUM process a plastic deformation area was formed, and the cutting force was changing during the RUM process. Thus the residual stress was in the deformation area, which eventually induced median/lateral cracks.

5. Subsurface damage depth measurement
In this paper, we use an advanced finishing technique (magneto-rheological finishing or MRF), causing no SSD, to create a shallow groove on the BK7 glass surface to obtain the distribution of SSD. SSD depth is calculated by the deepest distance from the crack tip to the surface and the size of the groove. This method can measure the SSD depth by the measurement of the horizontal extension distance of SSD in millimeter instead of the measurement of the vertical depth of the SSD in micrometer in tens of
microns, in other words, it can amplify the SSD depth in small scale, which is suitable for precise detection of SSD depth [8, 9].

The BK7 glass specimens (30mm×15mm×6mm) were polished by a RUM machine (DMG Ultrasonic70-5) with a hollow nickel-based electroplating diamond tool (outer diameter is 8mm, wall thickness is 1mm, grain size is 76μm, grain density is 100%), and other experimental conditions are shown in table 2.

Table 2. Experimental conditions.

| Parameter               | Unit | Value |
|-------------------------|------|-------|
| Spindle speed           | [rpm]| 8300  |
| Feed rate               | [mm/s]| 75    |
| Cutting depth           | [μm] | 10    |
| Vibration frequency     | [kHz]| 20.689|
| Vibration amplitude     | [μm] | 5     |

The procedures of the measurement method are briefly described here. (1) Using the MRF machine (shown in figure 7a), the specimen was polished a groove on the surface, and the middle of the groove must penetrate the entire SSD in order to ensure the deepest SSD can be observed; (2) etched in the 5% HF solution for 15min until the subsurface cracks exposed, and the etched specimens were cleaned by ultrasonic cleaner; (3) using the contourgraph to obtain the morphology of the groove, and observing the cracks by the optical microscope; (4) analyzed by image and morphology of the groove to determine the depth and length of SSD. The polished specimens are shown in figure 7b.

Obtained by the contour graph and microscope, the cross-sectional profiles of the groove along the horizontal and vertical directions are shown in figure 8, and the morphologies and distributions of cracks are shown in figure 9.

![MRF equipment and polished specimens](image)

Figure 7. MRF equipment and the polished specimens.

![Cross-section profiles produced by MRF](image)

Figure 8. Cross-section profiles produced by MRF.
Figure 9. Cracks distributions at different depth.

It can be seen from figure 8 that the profiles of the head and the end of the groove were not the same, so the magnifications of SSD depth were different (75.47 times in head and 279.96 times in end). The polished groove were tested from head and end respectively, and the average value of the results was taken as the SSD depth. Finally, the maximum SSD depth of the BK7 glass specimen was 26.8 μm.

6. Conclusion
(1) The formation process of BK7 glass surface by RUM was investigated. It was found that the cutting depth and the residual height ($h_r$) between the adjacent abrasive grains changed with the high-frequency vibration, causing a large number of cracks on the both sides of the scratches, and the interferences between grains caused the roughness of the lateral grinding surface reduced.
(2) There are a large amount of chips produced on the milling surface, the brittle fracture area was small, and there were a small amount of pulverizable areas. The grinding surface had a better surface quality, because the high-frequency vibration accelerated the chips falling and reduced the large chips and thermal damage at the same time.
(3) The morphology of SSD by RUM was analyzed, and there was a median cracks extending downwardly at the bottom of the fracture. At the right of the fracture there was a lateral crack which is parallel to the surface. The lateral and median cracks were induced by the residual stress, and the accumulation of these cracks formed SSD.

7. References
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