

Experimental Investigation of Subsurface Damages Made by Cup Grinding and Lapping Process of Optical Glass BK7 in Ductile Mode

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Abstract

Conventional material removal of BK7 optical glass will normally result in brittle fracture at the surface, generating severe subsurface damage and poor surface finish. Subsurface damages induced by grinding strongly influence the mechanical strength and optical quality of optical glasses. However, through ductile mode grinding it is possible to reduce the surface and subsurface cracks. It is meaningful to evaluate the depth of subsurface cracking through the measurement of surface roughness under different grinding parameters. In this research, the surface and subsurface damages during micro cup grinding and lapping process of optical glass BK7 are being investigated. In order to invest the subsurface damages, cross section polishing method is being used and the cross sections are inspected through SEM microscope. The results indicate that number of subsurface median cracks after lapping process are strongly decreased and surface lateral cracks are extended all over the sample's ground surface.

Keywords

Optical Glass BK7, Cup Grinding, Subsurface Damages, Ductile Grinding

1. Introduction

Optical glass BK7 is a typical hard and brittle material. Because of its unique superior performance, it is widely used in the fields of optics, micro-electronics, biomedicine, inertial confinement fusion (ICF), aerospace, national defense, etc [1]. The prominent character of optical glasses are high brittleness and low fracture toughness, which leads to the cracks propagation and brittle fracture in the machining process under normal conditions. These will restrict the improvement of machining precision and surface integrity [2]. Nowadays, precision machining of optical glasses are mostly performed through grinding and lapping process in order to disappear all the micro cracks produced in fabrication. However the grinding and lapping process are time consuming and machining cost is also high. Therefore, there is a crucial need for the cost-effective machining process for optical glasses [3].

To minimize the surface and subsurface damages produced in the grinding process of optical glasses, it is crucial to perform the machining process in ductile mode. In the other words, knowledge on the transition from ductile to brittle mode is essential for realizing low damage and high-precision machining of brittle materials [2].

Based on such a background, much efforts have been made to investigate the brittle-to-ductile transition behavior in terms of machining parameters in brittle materials machining. Yan et al.(2002) and Guo and Zhao (2015) stated that the ductile machining could be realized by a strict limit on the process parameters such as wheel rotational speed, wheel diameter, machining depth

and tool feed [4,5]. Li et al. (2001) defined the unformed chip thickness in grinding as the distance between two consecutive grinding surfaces formed by the adjacent abrasive grain trajectories. The critical unformed chip thickness could be determined as a function of intrinsic material properties governing the plastic deformation and brittle fracture [6]. Zhu et al. (2014) utilized the single-grit simulation to investigate the brittle-to-ductile transition in SiC grinding based on controllable maximum unformed chip thickness [7]. Bifano et al. (1991) proposed a critical cutting depth to predict the brittle–ductile transition mechanism of brittle materials machining [8]. Xiao et al. (2015) also established a model of critical cutting depth to study the brittle–ductile transition in micro-milling of KDP. The results indicated that an increase of spindle speed was beneficial for ductile cutting [9].

For bound abrasive grinding, three grinding modes (Figure 1) can be distinguished. First, (Figure 1(a)) the grinding wheel rotation plane is parallel to the rotation of the work piece and the feed direction is perpendicular to this plane. For this mode, Pei et al. studied fine grinding (grain size up to 25 μm) of Si wafers and found that feed rate and wheel rotation speed had no influence on the SSD [10]. For the second mode (Figure 1(b)), the grinding wheel rotation plane and the feed direction are parallel to the work piece plane. For this mode, Agarwal et al. showed that for rough grinding of SiC an increase in the depth of cut implies an increase in SSD depth [11]. Perveen et al. demonstrated the same phenomenon for micro grinding of BK7 glass [12]. Esmailzare et al. found out that during rough grinding of Zerodur glass, SSD depth increases with the decrease of tool's rotation speed [13]. For the third grinding mode (Figure 1(c)) the feed direction is parallel to the work piece plane but the grinding wheel rotation plane is perpendicular to that plane. In such a configuration, Maksoud et al. (for Si_3N_4 grinding) and Li et al. (for rough to finish grinding of fused silica) found that SSD depth increases when the depth of cut increases, but they observed no influence of the grinding wheel speed and the feed rate [6].

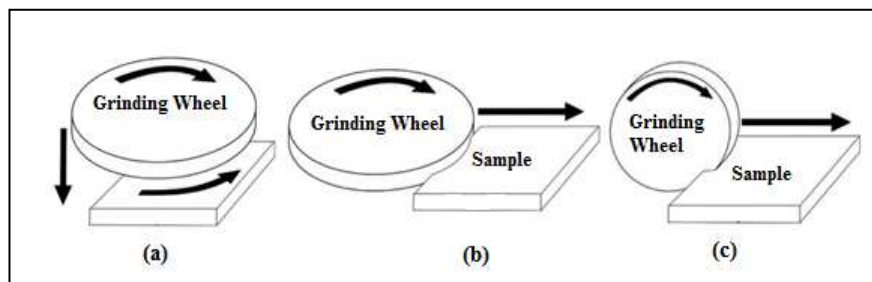


Figure 1. Grinding modes. (a) The grinding wheel rotation and work piece are parallel and the feed direction is perpendicular to this direction (b) The grinding wheel rotation and the feed direction are parallel to the work piece (c) The feed direction is parallel to the work piece and the grinding wheel rotation is perpendicular [14]

Regarding the importance of grinding parameters, a great number of researchers have been conducted on the relationship between SSD/SR and grinding parameters. The basic contributions in this field have been systematically conducted by Malkin and Guo (2008). They found out that the penetration of a sharp indenter in the brittle materials caused two principal crack system: (I) Lateral crack which is related to material removal in surface formation and (II) Median crack which generates mechanical degradation in subsurface of brittle material. Median cracks takes place under plastic deformation and are perpendicular to the ground surface of material [15].

Lambropoulos et al (1999) experimentally investigated the ratio of SSD and SR under abrasive penetration based on a sharp indenter. A model has been conducted based on SSD/SR ratio based on the assumption that median crack depth leads to SSD and lateral crack leads to SR. This model was a function of applied normal grinding force for each abrasive grain [16]. Calculating this value experimentally is hard. Li et al (2008) investigated the nonlinear relationship between SSD and SR, which is a function of material properties and grain geometry. They found that the experimental and theoretical achieved result were different. The main reason is that during grinding, the abrasive indenter move both normally and tangentially while the sharp indenter in theoretical analysis is supposed in normal direction [6].

Moreover, the experimental investigation of SSD cracks in cup grinding and lapping process of optical glass BK7 in ductile mode should also be taken into consideration. In this research, the fracture mechanism and crack formation of ductile cup grinding and lapping process are being investigated. To perform this, the specimens should be inspected destructively through section polishing method then the cross section is being inspected by LEO 435VP SEM.

2. Theoretical Analysis

2.1. Material Removal in Ductile Mode

For products, surface roughness and subsurface damage are important indexes of product quality and technical requirement. Consequently, the investigation on crack formation in ductile grinding mode is significant and necessary in order to control the desired surface roughness of product in a fast and effective manner. Based on Malkin and Hwang researches, it was found that indentation and scratch processes in normal brittle mode usually involve two principal crack systems: (I) lateral cracking responsible for material removal and surface formation, (II) radial/median cracking for strength degradation. Lateral crack leads to surface roughness (SR) and median crack leads to subsurface crack (SSD) on the surface of optical material. Normally in grinding hard materials in brittle mode, some micro cracks have been produced that reduce the final surface quality. That is why grinding in ductile mode is being crucial [14].

Producing optical glasses with low subsurface damages and surface roughness is a desire technique that grinding in ductile mode can prove. For grinding in ductile mode, the depth of cut is decreased and material removal is accompanied by elastic and plastic deformation. On the other hand, the possibility of removing material is constantly effected by machine tools capability. For grinding in ductile mode, the machine tools must be dynamically stable with low vibration ranges. For grinding optical glasses in ductile mode, critical cutting depth would be defined. Critical cutting depth $h_{id\ crit}$ is the boundary of grinding in brittle and ductile mode. The critical cutting depth for different brittle materials is listed on Figure 2 [1].

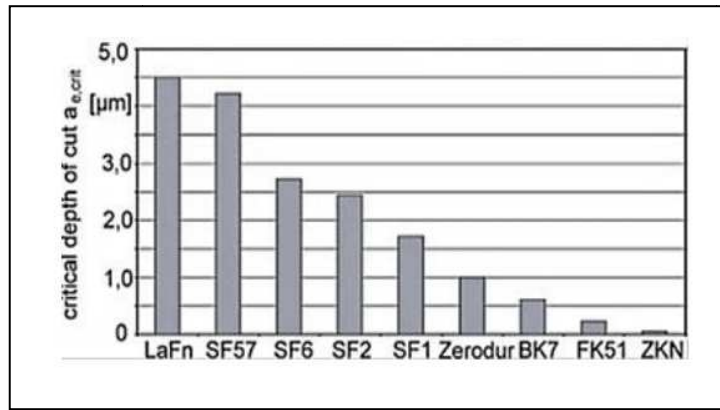


Figure2. Critical cutting depth for different brittle materials [1]

Material removal mechanism in ductile mode grinding is strongly affected by cutting depth. As a result, the machine tools rigidity is strongly affecting the critical cutting depth. The ground surface contact with diamond abrasive cup tool is caused an elastic deformation. When the depth of cut increased, elastic deformation transmitted to plastic deforms. This transmission is affected by tool's geometry and other grinding parameters specially cutting depth. Initiating the elastic deformation contact will cause micro-groove and micro-plough on the ground surface of the sample that will produce lateral crack on the surface of the material. With the increase of cutting depth, micro-plough is transmitted to micro-cut and then it produces micro median cracks on the subsurface of the sample (See Figure 3) [1].

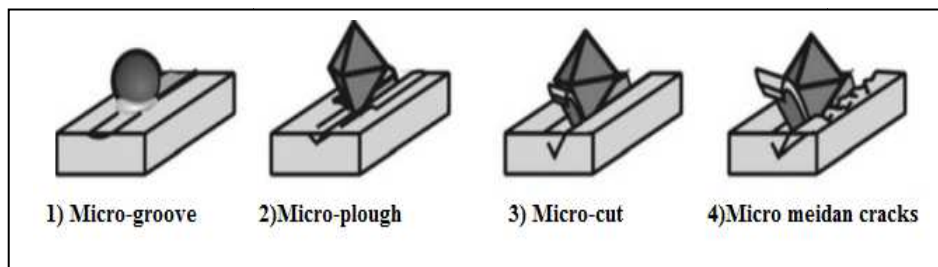


Figure3. Material removal mechanism in micro grinding of optical glasses [1]

As a result, in micro grinding of optical glasses, SSD is decreased significantly while SR is extended on the surface of the material.

Demirci et al (2010) investigated about material removal of optical glasses using different tools. To perform the experiments, they used diamond and SiC as an abrasive with metal or resin bond. The results showed that at the time of using diamond tool, the material is removed in elastic phase so the fracture will be in semi-ductile regime. While using SiC, the fracture will be completely brittle with low surface quality and high SSD rate. As a result, the best abrasive tool for grinding BK7 optical glass will be diamond [17].

2.2 Material Removal in Lapping Process

Lapping is a smooth process with high surface quality and low range of subsurface damages. The tool vibration range in lapping process is low and cause a decrease in subsurface damages. The results of performing lapping process on optical glasses show that hardness is not the only

parameter that influence surface roughness and material removal rate has a low effect on surface quality. Moreover, the number surface peaks and values on the sample's surface profile are extended but the subsurface cracks are limited that cause an increase in life cycle of the material [18].

3. Experimental Procedure

3.1. Section Polishing

To assess the SSD by cross-sectional polishing method, the samples must be properly prepared before the grinding process. Sample preparation consists of five general steps: cleaving (Cut into two equal parts), standing, polishing, adhesion and etching [13-20]. In the first step, the sample is cleaved perpendicular to the machined surface. The standing step is needed to remove the probable damages created by cleaving step. The surface of the cleaved sample is wet sanded to remove enough material from the interested cross section to ensure that any damage incurred during cleaving is removed. Third, the test surface is refined by polishing. The polished surface should also remain flat and perpendicular to the machined surface. The cleaved samples cannot be used in grinding process; since the grinding process will damage cleaved edge of samples by chipping. Hence, in adhesion step, the two parts were bonded face-to-face with a suitable adhesive. In this step, a clamping pressure was used to push the two parts tightly together, leaving a thin layer of adhesive approximately 1 μm thick. After achieving a proper bonding between the two cleaved parts, the samples are ground according to Table (2). After the grinding process, the specimens were separated by melting the glue and cleaned with acetone in an ultrasonic bath. Finally, the test surface is placed into etching solution for SEM microscopy. Then the cross sections are conducted by LEO 435VP SEM. In order to inspect the subsurface micro cracks more accurately, an etching process is required. The samples were etched for 30 seconds in 40% HF solution.

3.2. Material and Experimental Setup

Grinding experiments were performed on an Optotech MCP150 CNC milling machine. A metal bond diamond cup grinding wheel manufactured by WINTER, with an average grit size of 20 μm was used (D20 cup grinding tool). The wheel has a diameter of 50mm to perform grinding experiments in ductile mode. In this research, optical glass BK7 is used for the experiments. The chemical composition of optical glass BK7 is given by Table (1). Specimens are prepared in dia 25 mm and 10 mm thickness.

Table1. BK7 chemical composition [19]

BK7 chemical composition	SiO_2	B_2O_3	BaO	Na_2O	K_2O	Others
(%Wt)	68	15	6	6	4.9	0.1

Before the ductile grinding operation, the diamond cup tool was dressed using SiC wheel as a dresser wheel. Grinding is performed in vertical mode and both the spindle and table have rotary movements. A waterbased grinding coolant with a ratio of 1:50 was used in this study.

The critical cutting depth for different materials is mentioned in Figure 2. But as it was mentioned, the micro grinding critical cutting depth could be variable due to machine's rigidity. Ductile mode grinding could be predicted by measuring surface roughness after each grinding experiment on different cutting depths. If the surface roughness decreased significantly, the desire depth of cut could be settled. The approximate critical cutting depth for each material could be calculated by Equation (1).

$$h_{id\ crit} = \left(\frac{E}{HK} \right) \left(\frac{K_c}{HK} \right)^2 \quad (1)$$

Where E is Young modulus, K_c is fracture toughness and HK is Knop hardness. After replacing all the parameters with their values for BK7 optical glass, the critical cutting depth for BK7 is 3.52 μm . In this research, by performing the experiments on different cutting depths and observing significant change in the SR value, 5 μm is chosen as an appropriate cutting depth for grinding in ductile mode [1].

The critical cutting depth used in ductile experiments is 5 μm based on the machine stability. The other grinding parameters are cutting speed, feed rate and tables speed. The ductile grinding parameters are in Table (2). Each experiment is performed on two samples due to repeatability. After the micro grinding experiments, one sample is inspected by SEM and the other sample is prepared for lapping process.

Table2. Micro grinding parameters

No	Cutting speed (m/s)	Feed rate (mm/rev)	Depth of cut (μm)	Tables speed (rev/min)
1	9	0.003	5	50
2	9	0.002	5	50
3	9	0.001	5	50
4	13	0.003	5	50
5	13	0.001	5	50

The lapping parameters used in the experiments are shown in Table (3). After lapping process, the experiments are prepared for section polishing in order to compare the section crosses after micro grinding and lapping process. The other samples were lapped on a rotating lapping plate (240 mm diameter cast-iron plate) with a spiral groove. The center of the ring (120 mm diameter) containing a sample was positioned at 60 mm from the center of the lapping plate. For lapping process, CeO_2 abrasive slurry is used with the average size of 1-3 μm under the constant pressure. For optical glasses, SiC, Al_2O_3 and CeO_2 are common abrasive slurries used for lapping and polishing processes. Lambropoulos et al (1999) investigated about optimized slurry and grit size to perform lapping and polish process on different optical materials. They compared roughness, residual stress and material removal rate in separated experiments with different slurries and different grit sizes. The results showed that for lapping process of BK7 in ductile mode, the best slurry would be CeO_2

while the abrasive grit size is 1-5 μm . The residual stress in this condition will be on the lowest rate (2 N/m) while the final surface quality is appropriate ($R_a = 0.5 \mu\text{m}$) [16].

Table3. Lapping parameters used in the experiments

Work piece's rotary review (rev/min)	Liquid Pressure (bar)	Work piece gap (micron)	Time (min)
500	1	20	4

4. Result and Analysis

4.1. Investigation on Material Removal Mechanism

In this study, cross section polishing was used in order to investigate the material removal mechanism of optical glass BK7. Figure 4 shows BK7 samples after micro grinding experiment in which SSD is investigated by cross-sectional polishing. As it can be seen, when brittle failure is the dominant mechanism in material removal process, lateral cracks lead to chips removal and create the surface roughness and medial cracks cause subsurface damages. In micro grinding fracture (ductile mode), the penetration of indenter under grinding force causes median cracks and after unloading the abrasive tool, some median cracks start closure and are transmitted to lateral cracks. As a result, after micro grinding process, more lateral cracks could be seen on the cross section images (See Figure 4).

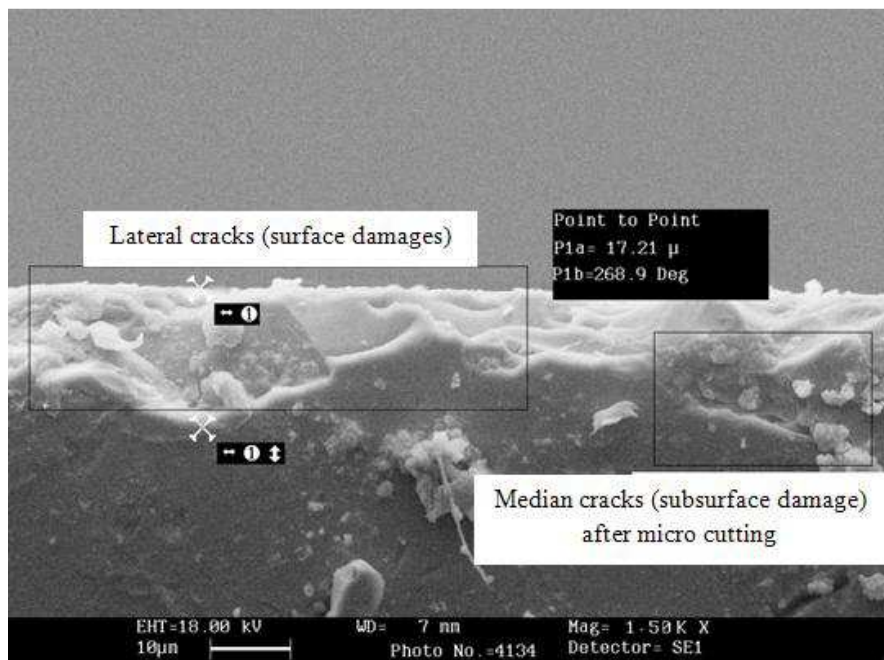


Figure4. SEM micrographs of cross section of the experiment No. 3 created by section polishing method after micro grinding process

The SEM micrographs of the specimen after lapping process are shown in Figure 5. As it can be seen, the median cracks are disappeared and the surface peaks and values are decreased which shows a better final surface quality.

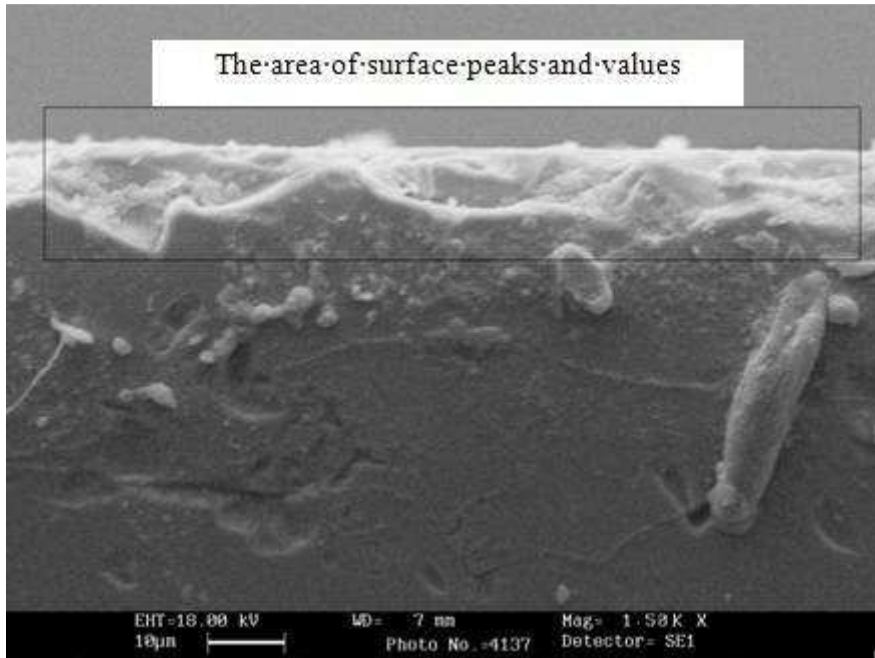


Figure5. SEM micrographs of cross section of the experiment No. 3 created by section polishing method after lapping process

4.2 Investigation on the 2D Surface Texture Profile of the Samples

Comparison of the surface texture profile of the specimens after micro grinding and lapping process shows that after lapping process, the final surface is more uniformed (See Figure 6). In micro grinding texture profile, on the edges of the specimen more valleys could be observed. On the edges of the specimen, the linear speed is higher and causes more unintegrated texture on the profile.

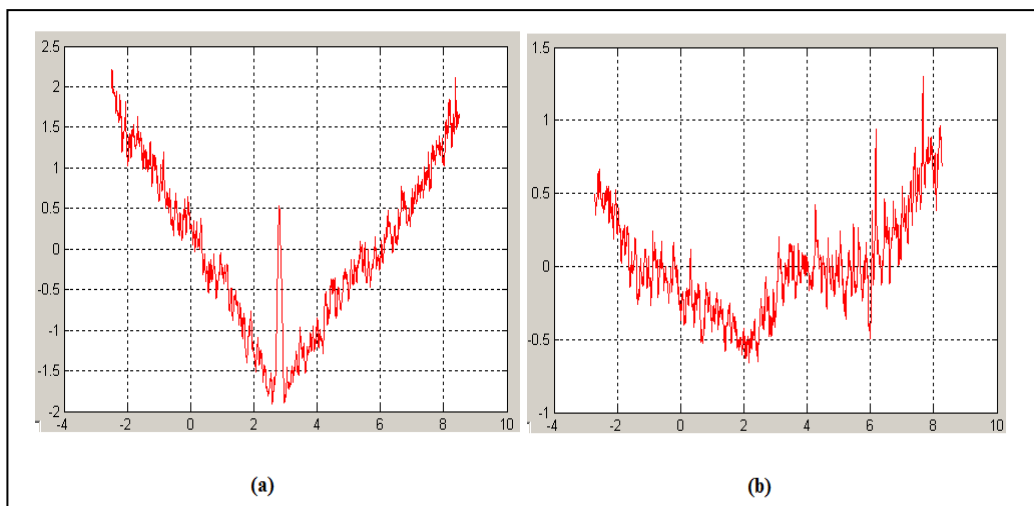


Figure6. 2D surface texture profile of the specimen after (a) micro grinding process (b) lapping process

In the middle of the specimen after micro grinding process, a peak on the surface texture profile could be observed. This peak is related to lack of concentricity between specimen and the holder which causes a peak during tools cutting path.

5. Conclusion

The main purpose of the present study was the experimental investigation of the material removal mechanism in micro cup grinding and lapping processes. Moreover, the creation of surface and subsurface damages in the cup grinding and lapping processes of optical glass BK7 was analyzed through SEM micrographs. To do this, section polishing method was conducted. In this regard, based on the theoretical studies and conducted experiments the following conclusion can be made:

- The experimental results indicate that in grinding process cutting speed, feed rate, depth of cut and tables speed have a significant effect on final surface and subsurface quality. In order to achieve grinding process in ductile mode, cutting depth is the most important grinding parameter.
- The results indicate that sub surface damages after micro grinding process have a significant decrease and after lapping process the subsurface cracks nearly disappear. But the lateral cracks which leads to surface roughness extended due to cutting tools path.
- The results of surface texture profiles indicate that the samples after lapping process have a more uniformed surface with lower ranges of peaks and values. In micro grinding process because of higher linear speed, the edges have more peaks and values on the surface texture of the specimen.

6. Reference

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