Effect of ultra-precision grinding of sapphire on polishing performance

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ABSTRACT
Sapphire optics holds significant promise for several applications, while machining challenges associated with high hardness and brittleness have limited its widespread service. Introducing ultra-precision grinding instead of conventional grinding/lapping processes to improve efficiency and suppress damage is interesting to investigate. The damage evolution laws of the polishing process on the sapphire after ultra-precision grinding were investigated, the ion beam polishing was used to eliminate Bell layer and subsurface damage. The grinding strategy of rough grinding, semi-precision grinding, and ultra-precision grinding was used to acquire different degrees of grinding damage, the influence of different grinding damage on the roughness and surface morphology of the polished process was studied. The results indicated that the time required for polishing to remove ultra-precision grinding damage was only 1/3 of that required for rough grinding. The KOH etching was employed to characterize the subsurface damage of polyurethane polishing, the subsurface damage was predominantly intertwined scratches, and no scratches were observed after ion beam polishing. In addition, ion beam polishing will reduce the surface roughness variation induced by etching. The process route that consists of ultra-precision grinding, polyurethane polishing, and ion beam polishing facilitates the efficient manufacture of damage-free sapphire optical components.

1. Introduction

Sapphire optical elements are widely used in extremely harsh environments such as defense industry. Surface and subsurface quality affects the long-term stability, component lifetime, imaging quality and laser damage threshold of optical elements[1, 2]. Therefore, it is crucial to suppress or eliminate any damage that may occur during the manufacturing process of the optical elements.

Grinding and polishing are two key techniques in the manufacturing process of optical elements made from hard and brittle materials. Damage mainly arises from the stress and cracks generated by abrasive action on the material, and this damage is primarily removed through subsequent polishing. The current manufacturing process of optical elements mainly includes rough grinding, lapping, and polishing. The lack of control in the lapping process can potentially cause significant damage to the surface profile accuracy as the lapping time increasing[3]. In the lapping process of aspheric and freeform surfaces, the loss of contour accuracy is particularly severe due to the difficulty in achieving uniform material removal with free abrasive particles. The high position accuracy of ultra-precision grinding systems allows for the convergence of aspheric or freeform surface contours to sub-micron levels, while the high rigidity and damping of the spindle provide significant advantages in suppressing damage[4, 5]. Compared to rough grinding, ultra-precision grinding allows the use of smaller grit sizes, grinding depths and feed speeds, resulting in superior grinding quality. Compared to lapping, ultra-precision grinding also uses fixed abrasives instead of free abrasives, which offers a huge advantage in terms of profile retention and correction. By employing ultra-precision grinding in optical manufacturing, replacing traditional rough grinding and lapping processes, advanced damage suppression and improved surface finish can be achieved, which is expected to reduce the overall manufacturing cycle of optical components.

This study focuses on the influence of damage characteristics on subsequent polyurethane polishing during the ultra-precision grinding process of sapphire. The evolution of polishing process, including surface roughness and damage morphology, was investigated under different levels of grinding damage. Chemical etching was used to characterize subsurface damage during polyurethane polishing, and ion beam polishing was employed to remove the subsurface damage layer. This work contributes to the development of an efficient and damage-free processing chain for sapphire optical elements.

2. Material and method

Fig. 1 illustrates the experimental setup of the sapphire combined processing technique, consisting of ultra-precision grinding, polyurethane polishing, and ion beam polishing. In Fig. 1a, grinding experiments were conducted using an ultra-precision machine equipped with a hydrostatic axis system. The ultra-precision grinding system includes liquid hydrostatic linear guides, an air hydrostatic spindle, and a liquid hydrostatic grinding spindle (HYPROSTATIK). To investigate the influence of different levels of grinding damage on the polishing process, a grinding strategy combining rough grinding, semi-fine grinding, and ultra-precision grinding was employed. More details about grinding strategies can be found in Table 1.

Fig. 1 Ultra-precision grinding and polishing system.

(a) Ultra-precision grinding system with full hydrostatic module,

(b) Polyurethane polishing systems, and (c) Ion beam polishing system.

Table 1 Ultra-precision grinding parameters.

Contents	Test A	Test B	Test C	Test D
Abrasive size	D25	D15	D7	D5
Bond type	Resin	Resin-metal	Resin	Ceramic
Workpiece speed	97 r/min			
Wheel speed	8000 r/min			
Feed speed	2 mm/min			
Grinding depth	1 μm, 0.5 μm			
Grinding strategy	D25	D25-D15	D25-D15-D7	D25-D15-D5

In the polyurethane polishing experiment (Fig. 2b), the polishing tool (OPTOTECH) was mounted on a high-speed electric spindle and set at an angle of 10°. Poly-crystalline diamond polishing slurry with a particle size of 1 was used, and the evolution of grinding damage was investigated at different polishing times. Specific parameters for the polishing process are provided in Table 2. To investigate the subsurface damage induced by polyurethane polishing on sapphire, a molten KOH etching technique was employed. After polyurethane polishing, ion beam polishing was used to uniformly remove the subsurface damaged layer. The removal depth for ion beam polishing was set at 1μm. Moreover, the surface profile of the grinding and polishing surfaces was observed using a white light interferometer (ZYGO). Furthermore, the surface morphology was examined using a laser microscope (KEYENCE VHX3000).

Table 2 Polyurethane polishing parameters.

Types	Contents
Polishing pad	Polyurethane
Polishing mode	Spiral
Tool speed	1000 r/min
Compression depth	0.1, 0.3 mm, 0.5 mm, 0.7 mm
Polishing slurry	Polycrystalline diamond 1 μm
Workpiece speed	17 r/min
Single polishing time	5 min

3. Results and discussion

3.1 Ultra-precision grinding surface characteristics

Fig. 2 illustrates the surface roughness and surface morphology of sapphire after ultra-precision grinding using different grinding strategies. The surface roughness follows a law with different grinding strategies: D25 > D15 > D7. It is worth noting that using D15 hybrid bond and D7 resin bond wheels can reduce the surface roughness. Specifically, the workpiece achieves roughness values of Ra 14.2 nm and Ra 8.09 nm, respectively. As for surface morphology, the grinding surface of the D25 wheel exhibits brittle fracture pits, and the surfaces of the D15 and D7 wheels grinding predominantly show ductile characteristics, with only small pits visible on the surface. These different surface features have an impact on the subsequent polishing process, as deeper pits are not conducive to the polishing process.

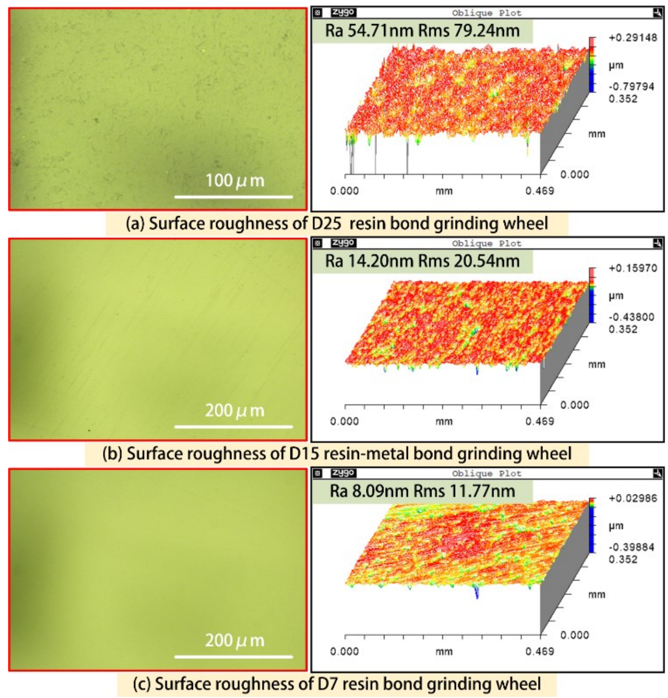

Fig. 2 Surface characteristics for sapphire ultra-precision grinding with different grinding wheels.

3.2 Evolution of surface roughness in polishing process

Fig. 3 demonstrates the evolution of surface roughness during the polishing process under different grinding strategies. As the polishing time increases, the surface roughness shows a decreasing trend. At a polishing time of 125 minutes, the surface roughness of the D15, D7, and D5 wheels grinding converges to less than 2nm. Subsurface cracks and defects generated by grinding gradually become exposed during the polishing process, thus influencing the surface roughness. After 225 minutes of polishing time, all the damages have been eliminated, and the surface roughness of all the workpiece converges to 1nm. The rate of roughness reduction varies for different grinding strategies, with the D25 wheel exhibiting the most significant reduction. This is attributed to the difference in contact area between the grinding surface and the polishing pad.

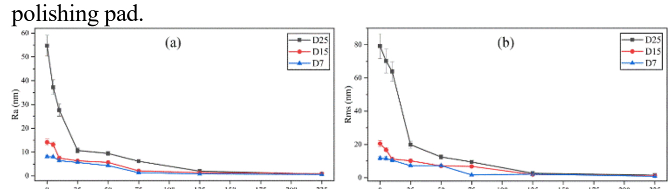

Fig. 3. Evolution of surface roughness during polishing process under different grinding strategies.

3.3 Evolution of grinding damage in polishing process

The polishing efficiency for sapphire is low, and different grinding surface characteristics have varying effects on the removal of damage during the polishing process. Fig. 4 illustrates the influence of different grinding strategies on the evolution of damage. The main observed evolution features during polishing are damage and marks. When using a D25 wheel, the focus of polishing is to remove the large pits generated by grinding. Initially, due to severe surface brittle fracture, the grinding marks are sheltered. With increasing polishing time, the ductile surface features increase, gradually revealing the grinding marks. Additionally, the scale of damage decreases, with larger damaged pits transforming into micro-pits. Eventually, after 225 minutes of polishing, all grinding damage is removed. The remaining pits on the polishing surface are the residual grinding damage. For D7 and D15 wheels, the focus of polishing is to remove marks. The amount of material removal during polishing is related to the depth of subsurface damage caused by ultra-precision grinding. When the removal depth of polishing exceeds the depth of subsurface damage, the polished surface becomes completely free of micro-pits and marks.

Fig. 4. Damage evolution during polishing process under different grinding strategies.

Table 3 Time required for damage removal of different grinding strategies.

Types	Time
D25 grinding wheel	225 min
D15 grinding wheel	125 min
D7 grinding wheel	75 min
D5 grinding wheel	125 min

Table 3 presents the removal times for different grinding strategies. The order of damage removal times is as follows: D7, D15, D25. Specifically, the D7 wheel grinding requires only 1/3 of the time by the D25 wheel. Therefore, the ultra-precision grinding strategy reduce the subsequent polishing time. The D7 ultra-precision grinding reduces the subsequent polishing time primarily due to the generation of lower damage scales. Additionally, pits formed by intertwined cracks are not easily eliminated during the polishing process. On the contrary, the ductile grinding surface can quickly reduce the surface roughness.

3.4 Subsurface damage in polyurethane polishing

It is important to note that prior to ion beam polishing, certain areas of the workpiece are protected to prevent treatment in specific regions. KOH etching is performed to verify the removal of subsurface scratches. Fig. 5 demonstrates a clear morphological contrast between the ion beam polishing surface and the untreated surface, even under etching, where no scratches are observed on the ion beam polished surface. The untreated surface is covered with scratches. This confirms the effectiveness of ion beam polishing in eliminating the Bell layer and subsurface scratches caused by polyurethane polishing.

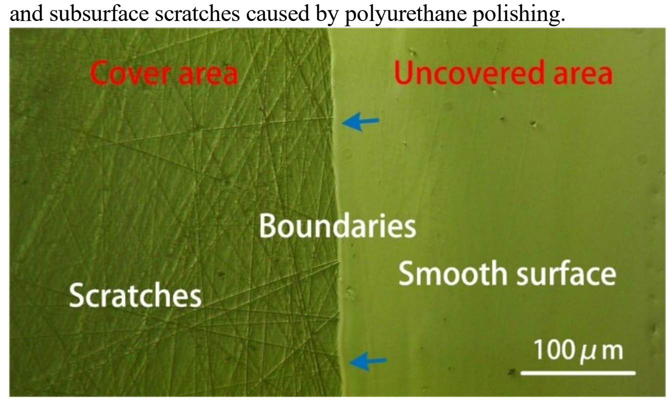

Fig. 5. Effect of ion beam polishing on subsurface scratches.

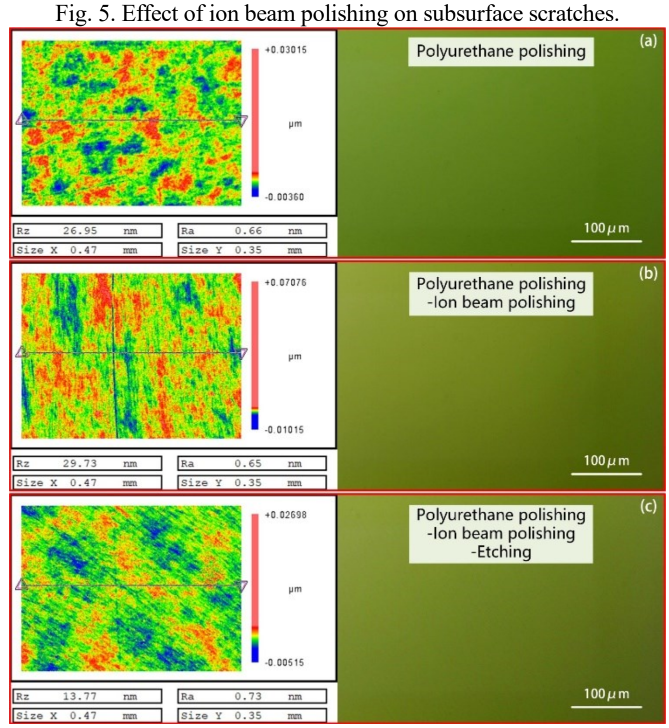

Fig. 6. Removal of subsurface scratches in polyurethane polishing used ion beam polishing. (Workpiece C)
(a) Polyurethane polishing, (b) Polyurethane polishing-Ion beam polishing,

and (c) Polyurethane polishing-Ion beam polishing-Etching.

Fig. 6 provides further details on using ion beam polishing to eliminate subsurface scratches. After polyurethane polishing, the surface roughness Ra is measured at 0.66nm. Following ion beam polishing, the surface roughness reduces to 0.65nm, indicating that ion beam polishing can further decrease the surface roughness caused by polyurethane polishing. Both the polyurethane polishing surface and the ion beam polishing surface do not exhibit significant damage. Furthermore, no noticeable scratches are observed on the etched surface of the ion beam polished sample, as shown in Fig. 6c, suggesting that ion beam polishing can remove the subsurface damage layer induced by polyurethane polishing. The surface roughness Ra of the ion beam polished sample after etching does not significantly increase, further supporting this observation.

4. Conclusions

This work focuses on investigating the efect of ultra-precision grinding on the polishing process of sapphire, aiming to develop a combination process of ultra-precision grinding, polyurethane polishing, and ion beam polishing to achieve damage-free sapphire optic. Ultra-precision grinding can achieve a ductile surface with a roughness of Ra 8.09nm. The damage evolution during polishing process varies for different grinding surfaces, time to damage removal by the polishing process is dependent on the subsurface damage scale for different grinding strategies, and ultra-precision grinding can save the polishing time by 1/3. Molten KOH etching is employed to reveal the subsurface scratches under polishing surface, and the ion beam polishing has the capability to eliminate subsurface scratches.

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