# Improving the efficiency and quality of mechanical polishing in sapphire aspherical surface production by ultra-precision grinding

**Qingliang Zhao[1, #], Sheng Wang[1]**

1 Center for Precision Engineering, Harbin Institute of Technology, Harbin, 150001, China
# Corresponding Author / Email: zhaoqingliang@hit.edu.cn , TEL: +86-0451-86402683, FAX: 86-0451-86415244

KEYWORDS: Sapphire aspherical surface, Ultra-precision grinding, Mechanical polishing, Uniform removal

***Abstract:*** *The traditional aspheric manufacturing process consists of grinding, lapping, and polishing. The high hardness and high brittleness of sapphire makes it difficult to remove brittle fracture damage and grinding marks from the grinding process by subsequent lapping and polishing. The use of ultra-precision grinding to reduce the damage depth and marks amplitude of sapphire aspheric surfaces is a recommended solution. Meanwhile, ultra-precision grinding can also provide better profile accuracy, which will also significantly reduce the time required to correct the profile accuracy during the polishing stage. From the above, this paper studies the uniform removal polishing process of the preserved profile accuracy after ultra-precision grinding of sapphire. First, the strategy and experiment of uniform removal of sapphire spiral polishing were studied. Then, the polishing process of profile accuracy preservation after ultra-precision grinding of sapphire aspherical surfaces was realized. The research can significantly improve the production efficiency and quality of sapphire aspherical surfaces, thus expanding their applications in optical systems.*

**NOMENCLATURE**

$Zi_1$ = Profile height at position *i* of the radius after polishing at constant feed speed;

$Zi_0$ = Profile height at position *i* of the original workpiece.

## 1. Introduction

Sapphire ($\alpha$-$Al_2O_3$), as a physically and chemically stable single-crystal material with excellent mechanical properties, such as high hardness (Mohs hardness 9), corrosion resistance, high temperature resistance, and excellent optical properties for transmission in the infrared and visible wavelength bands, has gained wide acceptance in the defense industry and civil optics [1]. Sapphire aspheric surface is better adapted to serve in harsh environments, in addition to improving the performance of the optical system, the imaging quality of the optical system and the compactness of the system [2].

However, on the one hand, the high hardness and brittleness make the sapphire grinding process extremely susceptible to brittle fracture damage. On the other hand, the high hardness contributes to the poor polishing efficiency of sapphire, which makes it difficult to remove the grinding damage and grinding marks during the polishing process. The unstable and immature connection between the two core processes of grinding and polishing due to high hardness and high brittleness in the sapphire optical manufacturing process significantly restricts the processing quality and manufacturing efficiency of sapphire aspheric surface, thus limiting their wide application and service in optical systems [3].

To break through the high-efficiency and low-damage machining process for sapphire aspherical surfaces, ultra-precision grinding is used instead of the traditional rough grinding an d lapping process, and a uniform removal strategy for spiral polishing of rotationally symmetric elements is proposed for the entrance cond ition of high profile accuracy and low damage after ultra-precision grinding. Finally, the uniform removal strategy is applied to the ultra-precision grinding and mechanical polishing process chain for sapphir e aspherical surfaces.

## 2. Material and method

The experimental system for ultra-precision grinding and polishing of sapphire aspherical surfaces is sho wn in Fig. 1, the experimental parameters are listed in Table 1. The gr inding process of aspherical surfaces adopts the classical cross grindin g method. Notably, the whole grinding system is hydrostatic bearing, which provides high damping and closed-loop high stiffness. In addition, the grinding process uses rough grinding, semi-precision grinding and ultra-precision grinding to suppress subsurface damage, which helps to reduce the subsequent polishing time. Mechanical polishing is performed using an elastic polishing tool with a normal force applied load, which consists of a polyurethane, polymer foam support and an elastic unit. Mechanical polishing is carried out by means of a spiral feed.

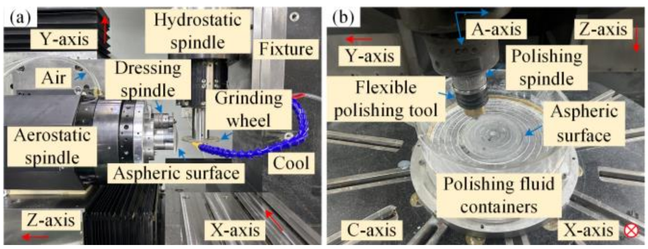


Fig. 1 Aspherical surface ultra-precision grinding and polishing experiments. (a) Ultra-precision grinding, (b) Mechanical polishing

Table 1 Experimental parameters of ultra-precision grinding and polishing sapphire aspherical surface

| | |
|---|---|
| Ultra-precision grinding | Rough grinding, Semi-precision grinding, and Ultra-precision grinding |
| Grinding wheel | D25, D15, and D7 |
| Wheel speed | 8000 r/min |
| Feed speed | 2, 3 mm/min |
| Grinding mode | Cross grinding |
| Mechanical polishing | Uniform removal |
| Feed mode | Spiral |
| Polishing liquid | Polycrystalline diamond polishing solution, 1 μm |
| Compression depth | 1 mm |
| Tool speed/Workpiece speed | 1000/15 r/min |

The correspondence between the material removal volume and the radius of gyration must be precisely established. The material removal volume is equal to the convolution of the removal function and the dwell time. To achieve uniform removal, the material removal volume needs to be constant. The variation of dwell time in the spiral polishing process is determined by the feed rate, which is inversely proportional to the feed rate, and the variation of the feed rate is related to the trend of material removal at different rotary radii. Through the above analysis, Fig. 2 shows the flow chart of the spiral polishing uniform removal strategy. First of all, a constant feed rate and workpiece speed are used for spiral polishing experiments to obtain the material removal volume at different rotary radii. The material removal volume $Z_i$ at different rotary radii satisfies Eq. (1):

$$Z_i = Z_{i1} - Z_{i0} \tag{1}$$

Assuming that the removal amount at the most edge is $Z_0$ and the constant feed rate is $F_0$, the feed rate $F_i$ to realize uniform removal at different rotary radii should be satisfied:

$$F_i = \frac{Z_i}{Z_0} \times F_0 \tag{2}$$

where the edge removal $Z_0$ is used as the basis for calculating the coefficient of variation of the feed rate.

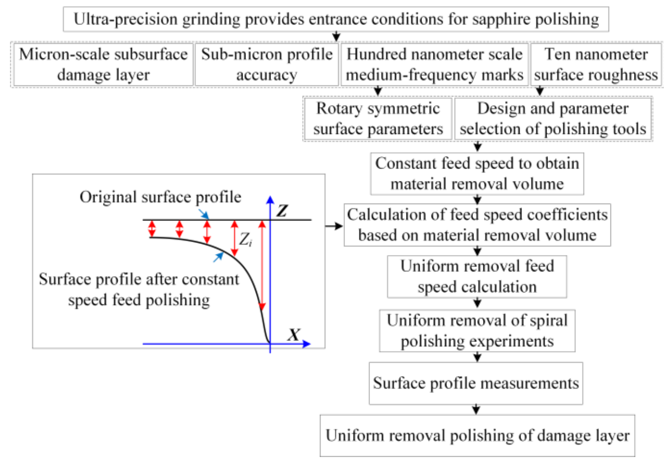


Fig. 2 Spiral feed uniform removal polishing strategy.

The prerequisite for achieving uniform removal through spiral polishing is to obtain the material removal volume of spiral polishing at a constant speed. Table 2 shows the parameters of the material removal acquisition experiment for spiral polishing at constant speed. The surface profile after spiral polishing was measured by a laser interferometer.

Table 2 Experimental parameters of constant feed rate spiral polishing

| | |
|---|---|
| Tool speed/Workpiece speed | 1000/15 r/min |
| Feed speed | 2 mm/min |
| Polishing time | Total 4 round, every round consists of 3 times polishing |
| Feed mode | Spiral |
| Compression depth | 1 mm |

## 3. Results and discussion

### 3.1 Uniform removal of mechanical polishing spiral feed path

Fig. 3a shows the interferometer measurement results of spiral polishing. Multiple rounds of polishing are designed to evaluate the stability of the material removal volume in spiral polishing. From the interferometer results, the edge material removal volume is much lower than the center, and the center of some results cannot be measured by the interferometer due to the high steepness of the surface profile and the high profile height. The change in material removal volume of spiral polishing at constant feed speed and workpiece rotation speed can be accurately measured by using interferometer.

Fig. 3b shows the material removal volume of spiral polishing. The cumulative removal height increases with the increase of polishing time. For the material removal volume of different rounds, the material removal volume curves of spiral polishing basically match together, which fully demonstrates the stability of the material removal rate of the elastic polishing tool during spiral polishing, which is a necess ary condition for subsequent uniform removal and polishing. The feed speed coefficient calculation for subsequent uniform removal polishi ng experiments uses the average of the material removal volume of fo ur rounds of polishing.

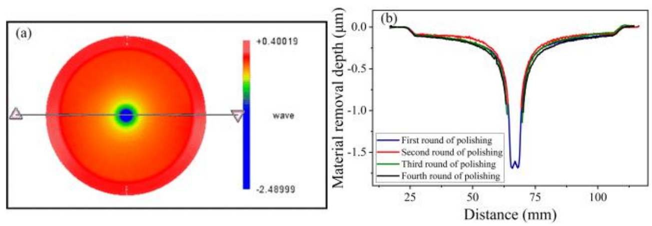


Fig. 3 Constant feed rate spiral polishing to obtain material removal volume. (a) Profile, and (b) Material removal depth.

Fig. 4 shows the surface profile by spiral polishing with increasi ng polishing time. After 968 min of polishing, the surface contour acc uracy increased from PV0.151 wave to PV1.98 wave. The central feat ure amplitude increases with the increase of polishing time. The centr al feature amplitude is 1.98 wave, which contributes to the entire surf ace contour accuracy PV value. In addition, the outline of the planar c ross-section except the central area is gradually tilted, with a tilt amplitude of 0.7 wave.

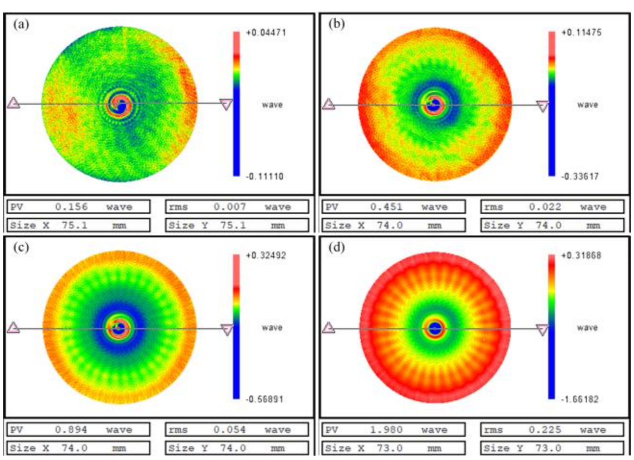


Fig. 4 Surface profile of uniform removal spiral polishing. (a) Polishi ng time=23 min, (b) Polishing time=113 min, (c) Polishing time =315 min, and (d) Polishing time=968 min.

### 3.2 Profile accuracy of sapphire aspherical surface ultra-precision grinding and polishing experiments

The surface profile accuracy, mid-frequency marks amplitude and surface roughness of ultra-precision grinding and polishing of sapphire aspheric surfaces are shown in Fig. 5. The surface profile accuracy after ultra-precision grinding is PV2.58 wave, and the profile accuracy after uniform removal polishing is reduced to PV1.54 wave. The surface roughness decreased from Ra 9.39 nm to Ra 0.58 nm. The marks amplitude after ultra-precision grinding is about 50 nm, and the marks amplitude after mechanical polishing is reduced to 1 nm.

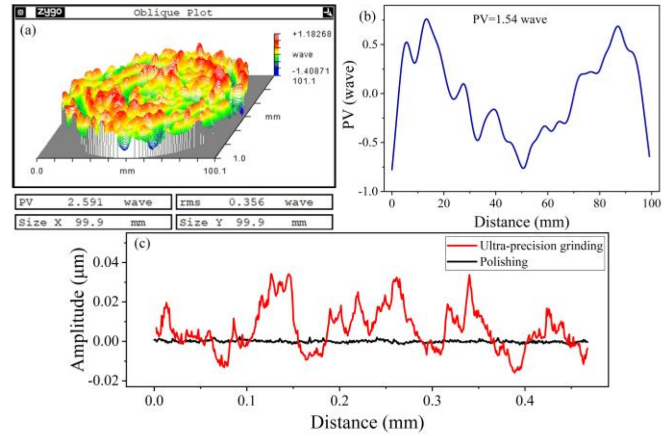


Fig. 5 Profile of sapphire aspherical surface ultra-precision grinding and polishing. (a) Profile of ultra-precision grinding, (b) Profile of polishing, and (c) Medium frequency marks amplitude.

## 4. Conclusions

Ultra-precision grinding provides low surface profile accuracy, mid-frequency marks amplitude and surface roughness. After uniform rem oval polishing, full-frequency error can be further converged. The ultra-precision grinding and polishing process chain can efficiently prepare sapphire aspherical surface optical elements in the infrared field, it ca n also provide a front process for subsequent optical elements requirin g higher precision.

## ACKNOWLEDGEMENT

The authors would like to thank the National Natural Science Fou ndation of China [Grant No. 52305460].

## REFERENCES

1. Dobrovinskaya E R, Lytvynov L A, Pishchik V. Sapphire: material, manufacturing, applications[M]. Springer Science & Business Media, 2009.
2. Yamanashi T. Design of a wide angle zoom lens using an asphere to achieve superior solutions[C]//Zoom Lenses V. SPIE, 2015, 9580: 172-185.
3. Wang S, Tie G, Shi F, et al. Effect of different grinding strategies on subsequent polishing processes of sapphire[J]. Journal of Manufacturing Processes, 2024, 112: 339-357.