High precision grinding of large-aperture off-axis aspheric mirror with form-damage controlling methodology

Guoyan Sun[1,#], Xiabin Ji[1], Hang Cheng[1], Jigong Zhang[1]

Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, NO.17 Xinxi St., Xi'an, 710119, PR China
Corresponding Author / Email: sunguoyan@opt.ac.cn TEL: +81-029-88887560

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The demand for Large-Aperture Off-axis Aspheric Optical Elements (LAOAOE) has grown substantially in space/ground-based large-aperture telescopes, aerial optoelectronics, and ground tracking and sighting instruments. Moreover, the increasing aperture of elements and the shortening processing cycle make high-efficiency and high-precision manufacturing the core problem of LAOAOE processing. Precision grinding is an efficient material removal process for LAOAOE. The surface form accuracy and subsurface damage depth directly affect the removal volume and the difficulty of precision convergence in subsequent polishing. These two parameters are the key to improving the processing quality and shortening the processing cycle of elements. Therefore, the study on high-precision grinding of LAOAOE is carried out to improve the surface form accuracy, reduce the depth of grinding damage, and perform collaborative numerical approximation, which is of great value for applications. In terms of surface form accuracy improvement, a kinematic model of aspheric grinding is established. The main factors of the machine tool structure affecting the low-frequency surface shape and accuracy are identified. Several factors are explored to achieve collaborative control and accuracy optimization of process parameters, including the A-axis zero error, Y-axis centering error, grinding wheel shape and size error, grinding wheel path, and Z-axis surface compensation. In addition, a mathematical analysis and simulation model for the medium-frequency texture of the aspheric grinding surface is proposed. The texture and surface roughness of the grinding surface can be significantly reduced by uniformly optimizing the grinding texture. In terms of grinding damage suppression, the variation rule of the grinding damage depth with the grinding parameters is obtained. Moreover, the mapping relationship between the grinding damage depth and the grinding surface roughness is established. A subsurface damage suppression strategy for LAOAOE is presented. The surface form accuracy PV (Peak-Valley) can reach 3 μm after the grinding test of the 640 mm off-axis aspheric lens, with the surface roughness Ra of less than 24 nm and Rz lower than 0.2 μm. According to the mapping relationship between surface roughness and subsurface damage layer depth, the estimated subsurface damage layer depth is approximately 5 μm, similar to the PV value. Engineering verification of actual optical element processing shows that the subsequent polishing duration can be significantly shortened, which is important for the efficient high-precision processing of large-aperture optical elements.

1. Introduction

With the increasing demand for high-resolution detection and imaging, the development of large aperture optical components with complex surface forms and lightweight structures has become increasingly important [1, 2]. For example, the primary mirror diameter for the European Extremely Large Telescope (E-ELT) project is 42 m, comprising 984 hexagonal sub-mirrors with a diameter of 1.45 m each. Furthermore, all sub-mirrors are off-axis aspheric surfaces made of microcrystalline glass Zerodur or optical glass ULE. The completion of all sub-mirrors is required within 4.5 years [3]. However, the large aperture and complex surface forms significantly increase processing difficulty and cycle time, posing an urgent need to expedite processing cycles and enhance efficiency for manufacturing large aperture optical components.

As a highly efficient and precise machining process [4], precision grinding plays a crucial role in the production of large-aperture optical components. However, precision grinding unavoidably introduces low-frequency grinding surface form inaccuracies, medium-frequency grinding textures as well as subsurface damages. These surface form errors and subsurface damages determine the difficulty and duration of subsequent polishing processes. Consequently, numerous studies have been conducted by scholars to investigate grinding processes for large-aperture optical components. Zhang et al. [5] processed a Φ372 mm high-steep off-axis SiC aspheric mirror using variable-axis single-point grinding, achieving a surface form accuracy (PV) of 7.8 μm after grinding. Comley et al. [6] achieved shape accuracy RMS better than 1 μm for a low-steepness Φ1450 mm caliber mirror through precision grinding. Mario et al. [7, 8] investigated the influence of grinding parameters on medium-frequency errors on machined surfaces and confirmed the correlation between medium-frequency errors and grinding texture uniformity. In addition to the grinding surface form accuracy, the grinding damage depth is another important factor affecting the polishing cycle. The most ideal control is that the value of grinding surface form accuracy is approximately equal to the grinding damage depth. In this paper, precision grinding experiments were conducted on large-aperture aspherical surfaces to explore the formation mechanism, influencing factors, and suppression methods for low-frequency surface shape errors and subsurface damage depths in the grinding process. This study aims to provide theoretical support for efficiently and precisely processing large-aperture optical components.

2. Design indexes for off-axis aspherical surface

The optical component was a Φ 640mm off-axis aspherical surface with uniform thickness, and its mother mirror equation was as follows:

$$z(x,y)=\frac{\left(x^2+y^2\right)}{18000} \tag{1}$$

in which *x, y*, and *z* represent the surface form coordinates of the off-axis aspherical surface with an off-axis amount of 700 mm. The high-precision grinding of the large-aperture off-axis aspherical surface required multiple iterative processes, as shown in Fig. 1. Firstly, the mirror surface was rough ground and then precision ground. It was necessary to suppress the error of the surface form accuracy and the depth of subsurface damage during precision grinding.

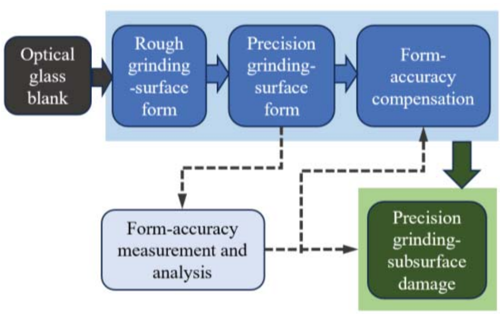

Fig. 1 Process flow of precision mirror grinding

3. Grinding surface form accuracy improvement

3.1 Influence factor analysis of low-frequency surface form error

The OptoTech MCG 500 CNC-Compact high-precision 5-axis milling and grinding machine was adopted for the machining of the Φ560 mm off-axis aspherical optical components in this paper, as illustrated in Fig. 2. It consisted of linear motion axes in three directions, a workpiece revolving platform (C axis), a grinding spindle, and a workpiece swing axis (A axis). The CNC linear motion axis had positioning and repeated positioning accuracies of ≤5 μm and ±2 μm, respectively, while the positioning accuracies of the A axis and C axis were ≤9″ and ±5″, respectively. The perpendicular grinding mode was employed.

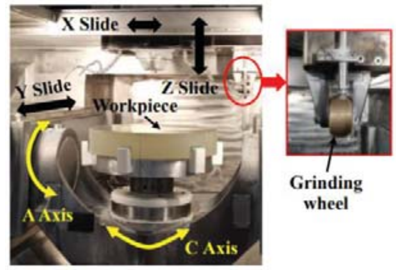

Fig. 2 Illustration of grinding machine

Grinding surface accuracy can be significantly influenced by different grinding methods and motion paths. The effects of three-axis spiral grinding, four-axis spiral grinding and grating grinding on the surface accuracy of the off-axis aspheric mirror were compared. The grinding parameters for spiral grinding and grating grinding are designed as illustrated in Table 1 and Table 2 respectively. The surface form accuracy PV after Y, Z and C-axis three-axis linkage grinding is 12μm as shown in Fig. 3(a), the surface form accuracy PV after X, Y, Z and C four-axis linkage grinding is 10μm as shown in Fig. 3(b), while the surface shape accuracy PV after three-axis grating grinding is 6μm as shown in Fig. 3(C). According to the comparison, the grating grinding method with three-axis linkage can obtain the highest surface accuracy, followed by the spiral grinding method with four-axis linkage.

Table. 1 Grinding parameters with spiral scanning-path

Grinding path	Grinding depth /μm	Workpiece rotary speed/rpm	Feed rate mm/min	Grinding wheel rotary speed/rpm
Spiral	10	22	1.8	3000

Table. 2 Grinding parameters with raster scanning-path

Grinding path	Grinding depth /μm	Feed speed /mm/min	Feed Distance /mm	Grinding wheel rotary speed/rpm
Raster	10	700	0.1	3000

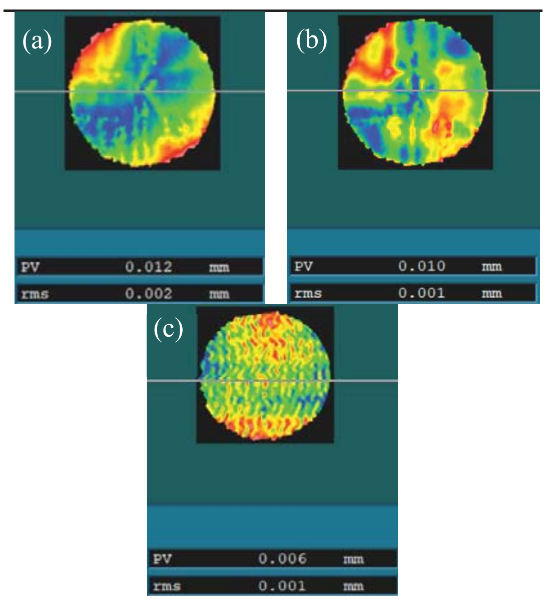

Fig. 3 The experimental results of the surface form accuracy (PV): (a) three-axis spiral scanning-path, (b) four-axis spiral scanning-path, (c)

three-axis raster scanning-path

The grinding machine accuracy will lead to the inherent surface form accuracy error of the ground aspherical surface, which can be reduced by the real-time compensation of Z-axis feed depth. Firstly, the aspheric surface form accuracy after grinding is measured, and then the Z-axis feed depth is adjusted according to the residual error analysis of the surface form to achieve the real-time compensation grinding. As shown in Fig.4, after grinding with metal-based D20 grinding wheel through Z-axis accuracy compensation, surface form accuracy PV of off-axis aspheric mirror was significantly reduced from 8μm to 3μm, basically close to the limit of accuracy detection capability of three coordinate measuring machine.

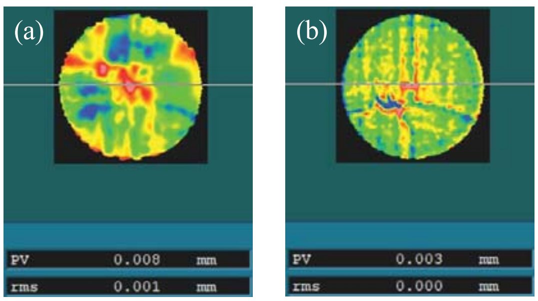

Fig. 4 The experimental results of the surface form accuracy (PV): (a) without accuracy compensation, (b) with accuracy compensation

3.2. Medium -frequency error suppression method

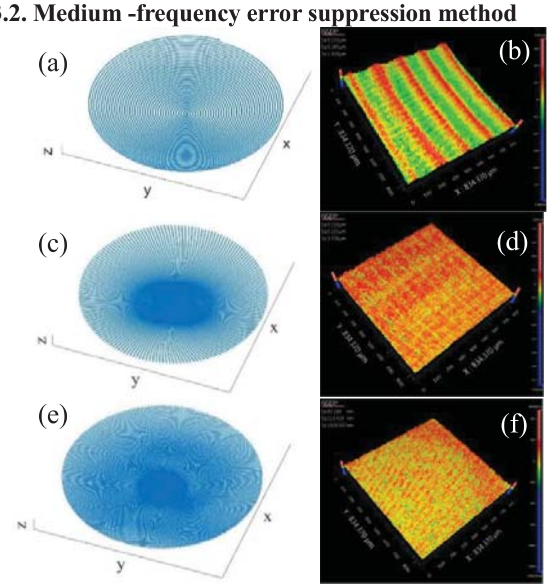

Fig. 5 The simulation results and experiment results of grinding surface marks:(a) simulation result-circular spiral pattern, (b) experiment result-circular spiral pattern, (c) simulation result-radial spiral pattern, (d) experiment result-radial spiral pattern, (e) simulation result-uniform pattern, (f) experiment result- uniform pattern

Since there was a direct relationship between medium frequency errors and grinding marks, the suppression of medium frequency errors could be achieved by modulating the evenness of grinding marks [7, 8]. The grinding point distribution equation was established for the aspherical grinding in this paper, and the simulation of grinding marks could be achieved for the aspherical surface grinding according to the equation. Based on the simulation results of grinding marks, further optimization of grinding parameters was achieved by moderately increasing the grinding wheel rotation speed, reducing the workpiece feed speed, and adjusting the workpiece rotation speed, which improved the grinding surface texture, and the evenness of grinding marks could be adjusted. As illustrated in Fig. 6, the trajectory patterns of the grinding surface could be adjusted through the optimization of grinding parameters. With the increasing density of grinding points, they formed circular spiral patterns, radial spiral patterns, and uniform patterns, as shown in Fig. 5 (a), Fig.5 (c), and Fig. 5 (e), respectively. Correspondingly, the grinding verification test was carried out according to the simulation parameters. A white-light interferometer was adopted to observe the appearance of the grinding surface and measure surface roughness. The experiment showed that the texture pattern of the grinding surface was consistent with the simulation result. As shown in Fig. 5 (b), Fig. 5 (d), and Fig. 5 (e), the grinding surface roughness of circular spiral patterns, radial spiral patterns, and uniform patterns were 133 nm, 110 nm, and 83 nm, respectively. This suggests that the simulation optimization of grinding parameters can achieve the evenness of grinding marks and reduce surface roughness.

4. Design indexes for off-axis aspherical surface

Based on the fracture mechanics of hard-brittle materials, the subsurface damage depth and surface roughness Rz are considered to be approximately equal to the indentation median crack depth and indentation lateral crack depth, respectively. There is a certain mathematical relationship between the subsurface damage depth and the surface roughness Rz. Therefore, 18 groups of grinding experiments were carried out in order to obtain the relationship between subsurface damage depth and surface roughness, as well as the variation rule with grinding parameters. The grinding parameters are designed as shown in Table 3.

Subsequently, the white light interferometer was used to observe the surface morphology and roughness, and the scanning electron microscope was used to observe the grinding subsurface cracks. According to the experimental results, as illustrated in Fig. 6 and Fig. 7, the variation law of surface roughness (Ra and Rz) and subsurface damage depth with grinding wheel and machining parameters are basically consistent. Compared with the metal-based grinding wheel, the ground surface roughness and subsurface damage depth by using the resin-based grinding wheel are lower. Besides, the smaller the grinding grain size, the lower the surface roughness and subsurface damage depth. Therefore, the metal-based grinding wheels can be used for early precision grinding stage to quickly achieve high-precision surface shape of the off-axis aspheric mirror, and the small-grain resin-based grinding wheels can be used to ultimately improve the ground surface and subsurface quality. In addition, the surface roughness and subsurface damage depth increase with the grinding depth and feed speed, but decrease with the grinding wheel speed. In the engineering grinding, it is necessary to balance the grinding efficiency and quality comprehensively, that is, the grinding efficiency can be improved by using larger grinding depth and feed speed in the early stage, and the surface and subsurface quality can be improved by reducing the grinding depth and feed speed in the final stage.

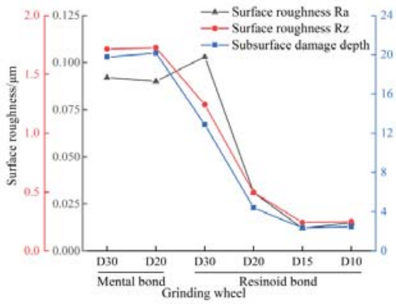

Fig. 6 Surface roughness and subsurface damage depth after grinding with different grinding wheels

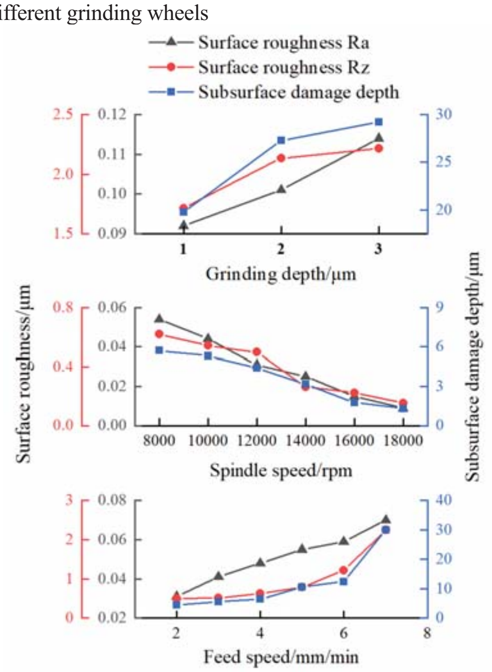

Fig. 7 Surface roughness and subsurface damage depth under different grinding parameters

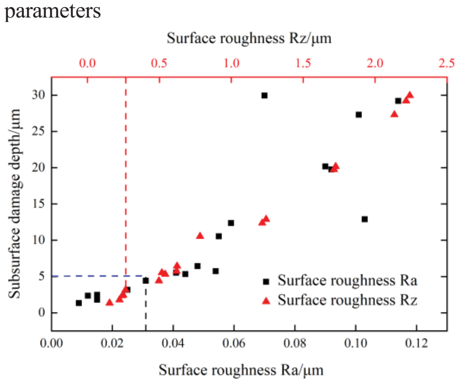

Fig. 8 Surface roughness and subsurface damage depth under different grinding parameters

Moreover analysis based on indentation fracture mechanics revealed that there was a corresponding relationship between the grinding subsurface damage depth and surface roughness. When the damage depth was less than 5 μm in the experiment, the surface roughness Ra was below 30 nm and Rz lower than 0.25 μm, as shown in Fig. 8, all of which could be used as the basis to control the grinding damage. Finally, after the shape and property-controlled grinding of off-axis aspheric lens with an aperture of 640 nm, the surface form accuracy could reach 3.1 μm with the surface roughness Ra less than 24 nm, Rz lower than 0.2 μm. According to the relationship between the surface roughness and the depth of the subsurface damage, the estimated depth of damaged layer lower than 5 μm. It was verified that the subsequent polishing duration had been significantly shortened.

5. Conclusions

For the LAOAOE, the grinding surface form accuracy can be efficiently improved by the deterministic analysis, control and compensation on the various factors affecting surface form accuracy. By mastering the mapping law between the grinding subsurface damage depth and surface roughness, the measurement on surface roughness can realize the indirect control of subsurface damage depth. Also, the combinatorial optimization of grinding process can achieve the collaborative control of form precision and subsurface damage to less than 5μm, which will lead to the significant reduction of polishing period for the optical elements with large aperture. It will be of great reference value for the efficient high-precision processing of optical elements with large aperture.

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