Research on Ultra Precision Grinding Technologies of Large Aperture and Complex Aspheric Lens

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Abstract: The computer aided programming system was developed, which could compute the coordinates and generate the CNC programs automatically. On the premise of waviness controlling, the raster grinding trajectory was optimized. To acquire the radius and form error of diamond wheel, the measurement by a corkscrew spin trajectory was proposed. By precision tool setting, the definitive position between wheel and element was established. Through on-machine measurement, the 3D form error of optics was acquired, which was combined with the theoretical coordinates of aspheric to compensation grinding. In the end the grinding experiment was carried out. The material removal rate of rough grinding, semi-fine grinding and fine grinding were about 466.7mm^3/s, 10.5 mm^3/s and 2.3 mm^3/s, respectively. The P-V of form error after fine grinding was about 3.21μm. The destination of highly active and ultra-precision grinding of large aperture and complex aspheric lens was achieved.

Introduction

Complex and off axis aspheric mirrors can eliminate the adverse effects of spherical aberration and quadrantal deviation generated by spherical mirrors in the beam transfer process. And they also can reduce the energy loss in the beam focusing, improve the focusing precision of optical system, and increase the relative aperture of the system. So this kind of optics are widely used in the field of aviation, aerospace, national defense and other large optical systems such as space telescope, high power laser system [1]. There are several technologies to fabricate large scale and precision aspheric lens. As the advantages of high material removal efficiency, surface convergence precision and easy to realize automation of manufacturing [2-3], ultra precision grinding technology is applied in a number of large optical systems (such as TMT [4], EURO50 [5], NIF [6]) as the main process of batch production. Based on the BigOptiX, a self-developed precision grinding machine with micron level compensation processing capability, the institute of precision engineering at Cranfield University machined an off-axis aspheric mirror with a diameter of about 1.45m. The rough grinding, semi-fine grinding and fine grinding were used for diamond wheels with the grit size of 76μm, 46μm and 25μm respectively. With the maximum material removal rate reaching at 187.5 mm^3/s, processing 0.5

mm thickness materials just took only 10 hours, and the P-V of final form error was about ±1μm [7]. Modeling the aspheric with reverse engineering and improving the accuracy of coordinates to 0.1μm by interpolation algorithm, the University of Chinese Academy of Sciences created the CNC grinding programs using UG software. And then an off-axis aspheric SiC lens with the dimension of 700mm×700mm was fabricated, whose P-V of final form error was about 11.3μm [8].

There is a great demand for high precision and complex aspheric lens in large optical systems these years. In order to satisfy the requirements of batch manufacturing for large scale aspheric mirrors in the construction of great optical systems, several key technologies are discussed in this paper, such as computer aided NC programming system, optimization of raster grinding steps, on-machine measurement of 3D form error of arc diamond wheel, precision tool setting of aspheric, on-machine measurement of form error of optics and error compensation, which improved the forming efficiency and precision. For a certain type of off-axis aspheric mirror, grinding experiment was carried out. Rough grinding with a diamond wheel with grit size of 160μm ~ 200μm, the maximum material removal rate reached at 466.7mm^3/s, and it just cost 6 hours to remove 12mm of thickness. The material removal rate of semi-fine grinding with the wheel grit size of 63μm ~ 80μm was 10.5 mm^3/s, and the processing time was about 10 hours. The last fine grinding process cost 12 hours with the material removal rate of 2.3mm^3/s, using the wheel with grit size of 10μm ~14μm. The P-V and RMS of final form error of element were about 3.21μm and 0.52μm respectively. The position error of aspheric was below 0.05mm.

The principle of aspheric parallel grinding

The mathematical model of aspheric surface. Aspheric is defined as the surface that is rotated by the normal line passing through the vertex. The aspheric mirror actually used is a part of the rotationally symmetric aspheric surface. For example, figure 1 is a typical 3D geometric model of the square aspheric mirror, and the rotational symmetry axis is the Y axis. The mathematical expression of aspheric surface is shown in Eq. 1.

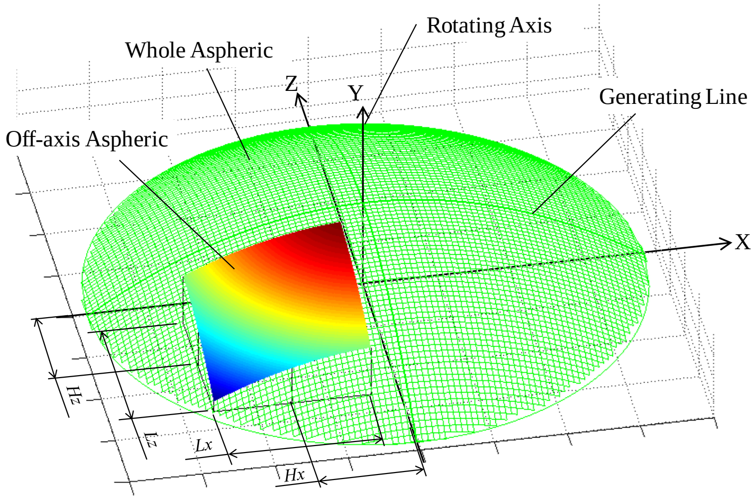


Fig. 1 3D geometric model of aspheric

$$Y(X,Z)=\frac{c(X^2+Z^2)}{1+\sqrt{1-(1+k)c^2(X^2+Z^2)}}+\sum_{i=1}^{n}\alpha_i(X^2+Z^2)^i \quad (1)$$

In the formula, c=-1/R_0, R_0 is the vertex radius of aspheric, k is the cone coefficient. $Hx-Lx/2 \leq X \leq Hx+Lx/2$, Lx is the dimension of the optics along the X direction, and Hx is the distance of off-axis at the X direction. $Hz-Lz/2 \le Z \le Hz+Lz/2$, Lz is the dimension of the optics along the Z direction, and Hz is the distance of off-axis at the Z direction. α_i is the high-order aspheric coefficient.

Principle of parallel grinding of aspheric. In the condition of acquiring the same processing efficiency and accuracy of non-rotational symmetric aspheric mirror, it can cut down the demand of equipment accuracy and stiffness when using the rectangular coordinate horizontal axis grinding machine [9]. Figure 2 shows the principle of aspheric parallel grinding. The element travels along the X axis with the work table. The diamond wheel, which is fixed on the spindle, travels up and down along the Y axis when rotating. At the same time the optic material is removed. Then the wheel travels along the Z axis discontinuously with raster trajectory, which scans the whole aspheric. In the grinding process, the direction of the linear velocity of wheel is parallel to the feed direction of element. The grinding points are circumferential on the wheel surface, which increases the useful width of wheel and manifolds the grinding edges. The wear of wheel will get less at the same material removal volume. If the aspheric equation is $y=f(x, z)$, the coordinates of diamond wheel when grinding are shown in Eq. 2. Where, (x, z, y) are the coordinates of aspheric optics surface, (xo, zo, yo) are the coordinates of wheel when grinding, R_a is the arc radius of grinding wheel, and R_w is the basic part radius of grinding wheel.

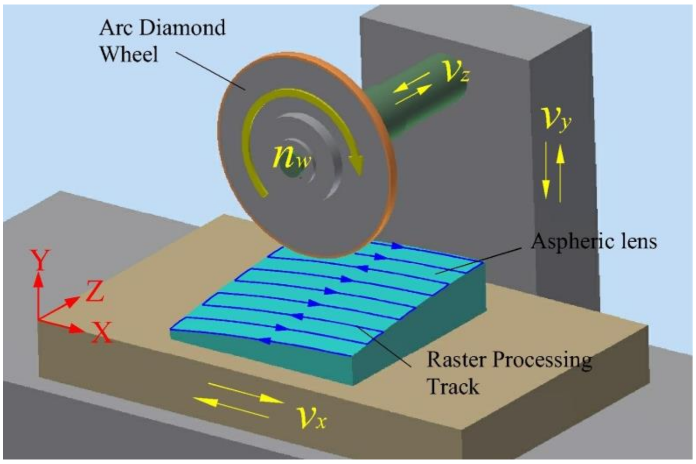


Fig. 2 Principle of parallel grinding of aspheric

$$\begin{cases} xo = x - R_a \times \dfrac{\frac{\partial f}{\partial x}}{\sqrt{[\frac{\partial f}{\partial x}]^2 + [\frac{\partial f}{\partial z}]^2 + 1}} - R_w \times \dfrac{\frac{\partial f}{\partial x}}{\sqrt{[\frac{\partial f}{\partial x}]^2 + 1}} \\ zo = z - R_a \times \dfrac{\frac{\partial f}{\partial z}}{\sqrt{[\frac{\partial f}{\partial x}]^2 + [\frac{\partial f}{\partial z}]^2 + 1}} \\ yo = y + R_a \times \dfrac{1}{\sqrt{[\frac{\partial f}{\partial x}]^2 + [\frac{\partial f}{\partial z}]^2 + 1}} + R_w \times \dfrac{1}{\sqrt{[\frac{\partial f}{\partial x}]^2 + 1}} \end{cases} \quad (2)$$

The work of ultra-precision grinding is forming a work piece from the wedge blank to the off-axis aspheric mirror directly. In order to improve the overall machining efficiency, the rough grinding, semi-finishing and finishing grinding of the components is carried out using the diamond grinding wheels with grit size of 160μm ~ 200μm, 63μm ~ 80μm and 10μm

~14μm respectively. In the rough grinding process, the wedge-shaped preform body is formed to aspheric surface. And the subsurface damage layer generated by the former process are removed at semi-finishing grinding and fine grinding. At the same time, the surface form error should be converged.

Computer Aided NC programming technology

The mathematical formula of aspheric is complex, and the height and curvature of every point on the surface are not the same. It needs rich experience and skills for workers to process a complex aspheric surface automatically by using traditional NC G codes or macros codes. There are many factors that affect the element precision in actual machining process, and many harsh requirements for machine hardware and environmental protection. In order to solve those problems, a computer aided programming system for ultra-precision parallel grinding of complex aspheric lens was developed. The flow chart of process is shown in Figure 3. According to the processing technology, machining parameters (such as wheel speed, feed speed and grinding depth) and wheel parameters (such as arc radius and basic part radius) were input in the system first. After the aspheric parameters such as curvature radius of vertex, cone coefficient and distance of off-axis were input, the system could give out the 3D modeling of aspheric and calculate the 3D coordinates of each point on the surface of components. Based on Eq. 1, the coordinates of wheel when grinding were calculated too. According to the processing information such as raster step distance, the machining trajectory was designed and movement path of wheel was simulated, which could ensure that there was no collision or interference in the actual machining process. After saving the manufacture log, including processing parameters and aspheric parameters, the CNC program was created and transported to the grinder.

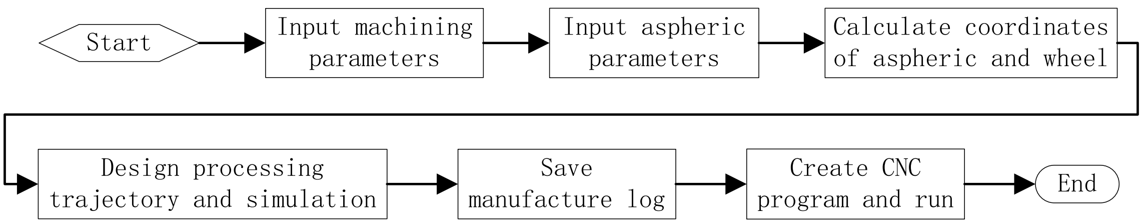


Fig. 3 Flow chart of computer aided programming system

Optimization of raster step distance

The surface accuracy is obtained based on the principle of motion copying in ultra-precision grinding. So the motion contour of the arc wheel will be copied to the surface of the components and form periodic and small scale waviness. In order to ensure the detection accuracy of element after grinding and reduce the difficulty of controlling the waviness error in the following polishing process, it is necessary to control this waviness produced in grinding. As shown in Fig. 4, the profile of arc wheel is copied to the element surface completely. The space cycle of waviness is equal to the raster step distance, and the amplitude Δh can be calculated in Eq. 3. Where, R_a is the radius of arc wheel, ΔZ is the raster step distance, and α is the tilt angle of aspheric along Z axis. When the radius of arc wheel is larger and raster step distance is shorter, the amplitude of waviness will be smaller. But if the raster step distance is too small, the efficiency of processing will be reduced evidently. Therefore, it is necessary to select the largest radius of the arc wheel. According to the principle of parallel grinding, the maximum radius of arc wheel is given in Eq. 4. Where, W is the width of the grinding wheel.

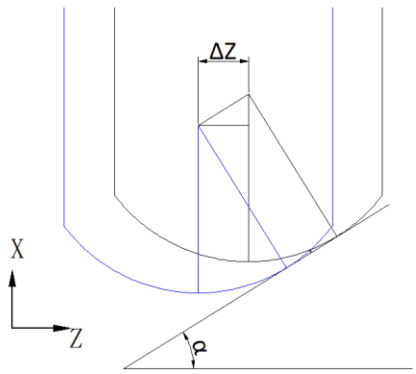


Fig. 4 Formation process of waviness in parallel grinding

$$\Delta h = \frac{R_a - \sqrt{R_a{}^2 - \dfrac{\Delta Z^2}{4\cos^2\alpha}}}{\cos\alpha} \tag{3}$$

$$R_{a\max} = \frac{W}{2\sin\alpha_{\max}} \tag{4}$$

To maximize the grinding efficiency, taking into account the controlling of waviness and sub-surface damage, the wider raster step distance is chosen in material removal stage, and finally the element is smooth grinded with narrow raster step distance. In order to ensure that the maximum actual grinding depth in smooth stage is less than the grinding depth of technical requirement, the maximum raster step distance in material removal stage is given in Eq. 5. Where, a_p is the the grinding depth of technical requirement. At this time, the maximum material removal efficiency is shown in Eq. 6.

$$\Delta Z_{\max} = 2\cos\alpha_{\max}\sqrt{R_a{}^2 - (R_a - a_p\cos\alpha_{\max})^2} \tag{5}$$

$$\mu = a_p V_f \Delta Z_{\max} = 2a_p V_f \cos\alpha_{\max}\sqrt{R_a{}^2 - (R_a - a_p\cos\alpha_{\max})^2} \tag{6}$$

On-machine measurement of 3D form error of arc diamond wheel

According to Eq. 2, in the parallel grinding of aspheric, the form error of the arc diamond wheel will affect the transfer accuracy of the wheel coordinates when grinding. This error will copy to the element surface too, and lead into machining error of component. So, it’s essential to measure the form error and acquire the radius of arc, center coordinates of arc at different phase position and radial runout error accurately before grinding. Fig. 5 shows the on-machine measurement principle of 3D geometric topography of wheel. The measurement light spot of laser displacement sensor scans on the surface of wheel with a corkscrew spin trajectory when the wheel rotates and moves along the axial direction. Meanwhile, the displacement data is acquired. By data post-processing with mathematical model of spiral scanning, the 3D geometric topography of wheel is obtained. Then the axial section profiles at different phase position are draw out to data procession with least square arc fitting, and the arc radius and center coordinates of arc are calculated. In the end, by error separation, the form error, runout error and arc error of the whole outer contour of wheel are acquired, as shown in Fig. 6.

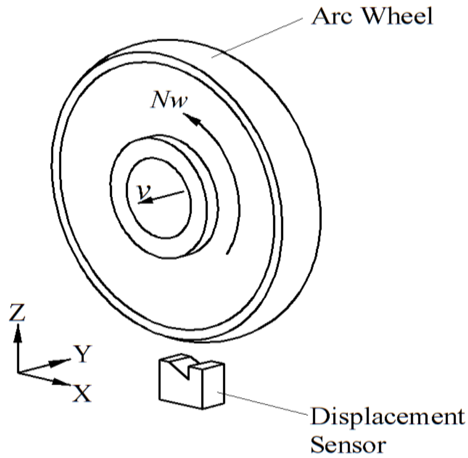


Fig. 5 on-machine measurement principle of 3D geometric topography of wheel

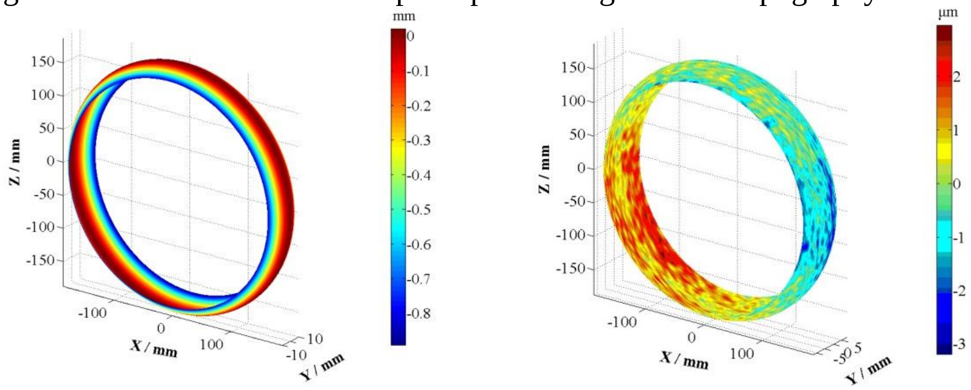


Fig. 6 3D geometric topography (left) and form error (right) of arc wheel

Precision tool setting technique for aspheric grinding

The position error of aspheric surface relative to the geometric center will affect the measuring accuracy of wave front during subsequent polishing process and the assembly accuracy during the using and assembly process of element. Therefore, it is necessary to strictly control this index in the process of form grinding. The position error of aspheric surface can be characterized by center error, that is, the lateral deviation of aspheric center relative to the geometric center of the element. Before grinding, by precision tool setting, the accurate relative position relationship between the grinding wheel and the component is established. As shown in Fig. 7, the tool setting error of the X direction and the Z direction in the horizontal plane will have a direct effect on the center error of the aspheric surface. After clamped on the work table, the horizontal position of the element in the machine coordinate system is uniquely determined, which could be obtained by measuring the coordinates of the four sides of the element by the displacement sensor. After grinding a soft oil stone, the position of wheel is copied to the pit on the surface. And the horizontal coordinates of the lowest point of the pit are measured by the displacement sensor, which was fixed on the wheel cover at the whole process. By tool setting with the accuracy higher than the technological requirements, it could achieve the idea position error without on-machine measurement and rectifying of center error, which reduces the downtime and increases the machining efficiency.

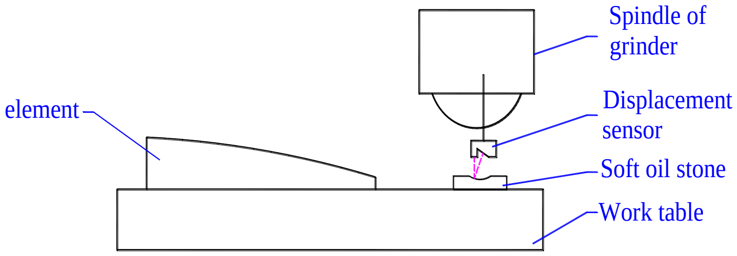


Fig7. The sketch map of precision tool setting

On-machine measurement and error compensation

The surface shape detection methods of large aperture aspheric optics mainly include off-line measurement and on-machine measurement. On-machine measurement can decrease the times of loading and unloading component, reduce the risk brought by clamping process, avoid the secondary clamping positioning errors, improve the overall machining efficiency, and greatly reduce the manufacturing cost. In addition, with the surface shape error of on-machine measurement, deterministic in-position compensation machining can be achieved, and the machining accuracy of component can be further improved. The non-contact displacement sensor is used to detect the surface shape error. It can effectively avoid the scratch on the surface of the component caused by the touch probe during the measurement process and eliminate the measurement error introduced by the wearing of probe after a long time using. The non-contact displacement sensor is fixed on the wheel cover. The movement of probe is controlled to parallel to the aspherical surface in accordance with the grating type measurement path as shown in Fig. 8. The data obtained by the displacement sensor is the surface shape error of the component. And then through the data processing shown in Fig. 9, it can obtained the 3D surface shape error distribution of component. A large caliber plane interferometer is used to detect and benchmark, and the shape distribution of the on-machine measurement is consistent with that of the interferometer. The P-V of form error is within 1 μm, and the detection accuracy is satisfied with the technological requirements.

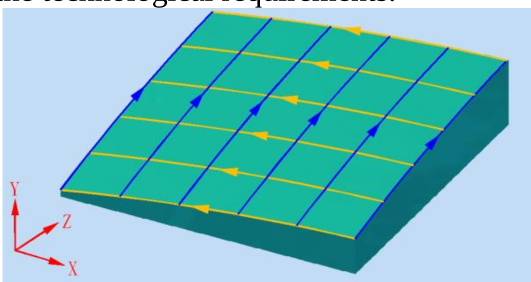


Fig. 8 Trajectory of on-machine measurement

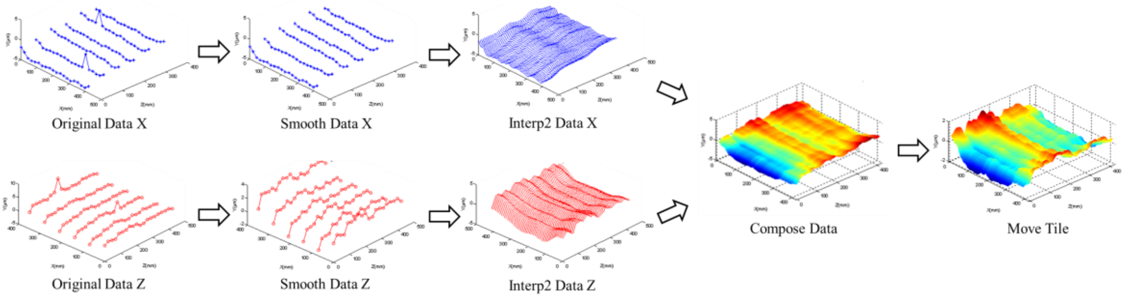


Fig.9 Data processing of form error

In the actual grinding process, after the wheel moving according to the aspheric theoretical path, due to the influence of machine precision, stiffness, temperature fluctuation of environment, and the abrasion of wheel, there is a critical shape error on the surface of component. The surface shape error of aspheric can be further reduced by compensation grinding according to the results of on-machine measurement. Fig. 10 shows the principle of compensation machining. The compensation form error is rectified from the 3D form error of previous grinding by compensation coefficient. And then it is superimposed with the theoretical points of aspheric. According to Eq. 2, the points of wheel when compensation grinding is computed out. After compensation grinding, the surface form error can be further micrified.

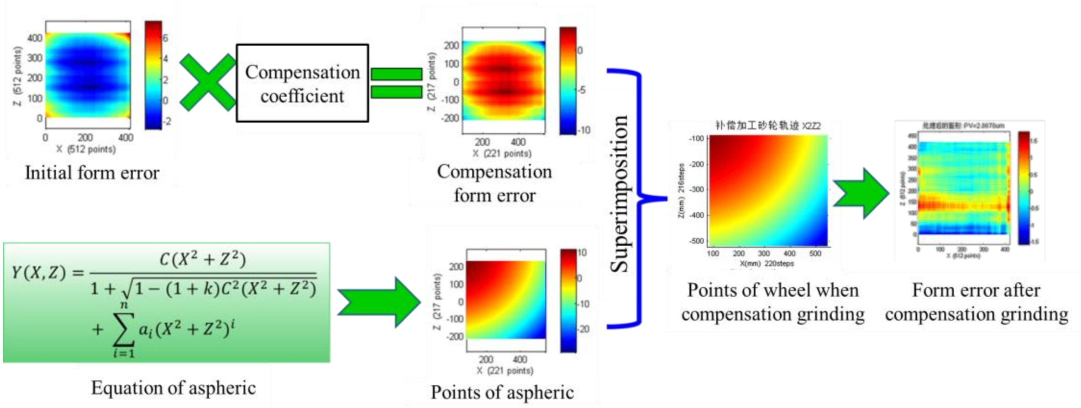


Fig. 10 Compensation Grinding Principle

Grinding experiment of large aperture complex aspheric lens

The parameters of complex aspheric lens processed in this paper are shown in Tab. 1, the distances of off-axis along the X direction and Z direction are not equal to zeros. The aspheric parameters were input into computer aided NC programming software, and the vector height of aspheric was shown in Fig. 11. The structure is irregular, with obvious non-rotational symmetry.

Tab. 1 Parameters of off-axis aspheric lens

Parameter Name	Parameter Value
Dimension $L_x \times L_z$ [mm]	430×430
Vertex Radius R_0 [mm]	4326.361422
Cone Coefficient k	-0.5129386
High-order Coefficient α_i	0
X Off-axis Distance H_x [mm]	300
Z Off-axis Distance H_z [mm]	300
Center Deviation Δ [mm]	0.1
Center Thickness T [mm]	50

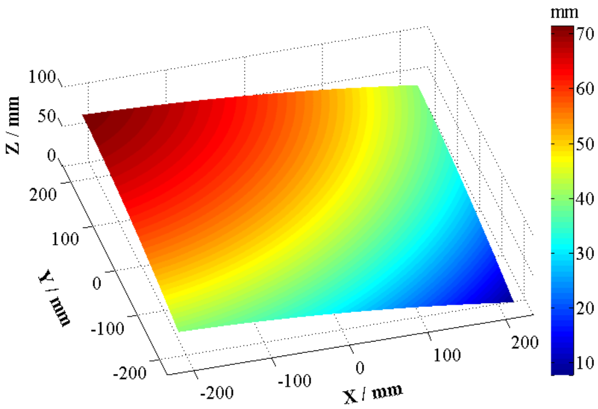
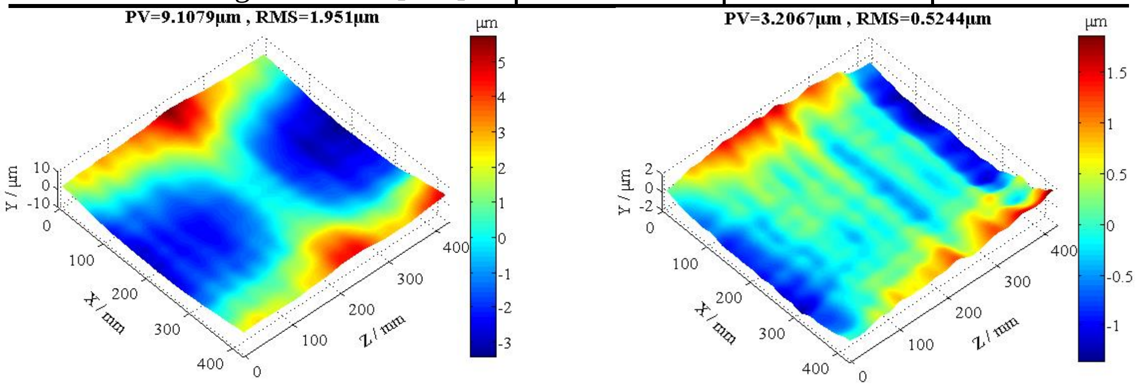


Figure 11 3D vector height map of aspheric lens

After using computer aided NC programming software to produce CNC program, the rough grinding, semi-fine grinding and fine grinding were separately performed on the ultra-precision grinding machine, and the grinding parameters were shown in Tab. 2. The maximum material removal rate of rough grinding was 466.7 mm^3/s, the maximum material removal rate of semi-fine grinding was 10.5 mm^3/s, and the maximum material removal rate of fine grinding was 2.3 mm^3/s. It took a total of 6h to rough grind the wedge blanks to aspheric surface, and semi-fine grinding and fine grinding took 10h and 12h respectively. Surface shape error was acquired after fine grinding, which was shown in Fig. 12a. The P-V value was about 9.11μm, aspheric position accuracy was better than 0.05 mm. According to the test results, after one time compensation grinding, the P-V value of shape error was micrified to 3.21μm, and the RMS value reached about 0.52μm, which was shown in Fig. 12b. Aspheric lateral position accuracy was better than 0.05 mm. The high-authority ultra precision grinding of large-diameter complex aspheric surfaces was achieved, and the element after grinding was shown in Fig. 13.

Tab. 2 Aspherical grinding parameters

Step	Rough Grinding	Sem-fine Grinding	Fine Grinding
Wheel Speed [m/s]	30	30	30
Feed Rate [mm/min]	7000	7000	7000
Grinding Depth [μm]	500	30	10
Grating Step [mm]	8	3	2
Total Grinding Thickness [mm]	12	0.9	0.2



a. Form error of initial grinding b. Form error of one-time compensation grinding

Fig. 12 Form error of complex aspheric surface

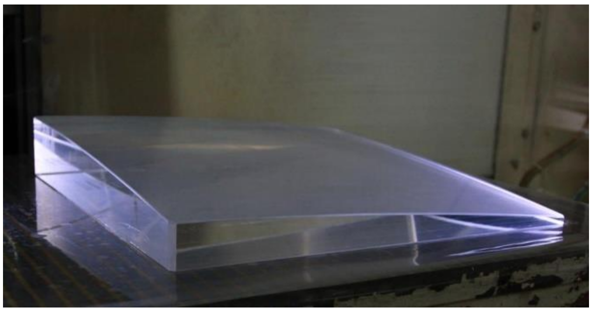


Fig. 13 Complicated aspheric optics after grinding

Conclusion

To satisfy the requirement of high-authority and precision production of large aperture and complex aspheric optics, first of all, a computer aided NC programming system for ultra precision parallel grinding of complex aspheric surfaces was developed to create the grinding CNC program automatically. According to the principle of parallel grinding, aiming at improving the material removal rate and taking into account the small scale waviness controlling, the raster step distance was optimized. In order to get the arc radius of wheel accurately, the methord of on-machine measurement of 3D geometric topography of wheel was put forward. To improve the aspheric position accuracy and reduce the subsequent machining time caused by the correction of position error, the aspheric tool setting method based on the precise detection of grinding wheel coordinates and component coordinates was proposed. By tool setting, the position accuracy of aspheric surface could be ensured to meet the process requirements. Then the on-machine measurement of aspheric form error was proposed. Based on the diplacement data, by the data procession, the 3D form error of optics was calculated. In order to diminish the form error ulteriorly, the form error of initial grinding was superimposed with the theoretical points of aspheric, and the coordinates of wheel when compensation grinding were processed out. At the end, a grinding experiment of large aperture and complex aspheric lens was carried out. The material removal rates of rough grinding, semi-fine grinding and fine grinding were 466.7 mm^3/s, 10.5 mm^3/s, and 2.3 mm^3/s respectively, and the procession time were 6h, 10h, and 12h respectively. The P-V value of final form error was converged to 3.21μm, and aspheric position accuracy is better than 0.05mm . The purpose of high-authority and precision production of large aperture and complex aspheric optics became a reality.

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