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Precision manufacturing of convex off-axis aspheric mirror in space optical system

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We study a convex off-axis aspheric mirror which works as secondary mirror in space optical system. The parameters of the mirror are described. In order to test the surface error, the mirror is made up of fused silicon and is tested by the backside transmission type. The shape accuracy while grinding is controlled using coordinate measuring machining testing. The distortion of the measurement is corrected by affine transformation. The ion beam figuring is used for surface finishing and to achieve root mean square of 0.015λ ($\lambda = 632.8$ nm).

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The three-mirror anastigmation (TMA) off-axis aspheric optical systems were widely used in space remote optical sensors[1]. This configuration can obtain good resolution and wide field of view. Meanwhile, the structures of off-axis TMA optical system are divided into Cook-TMA and Rug-TMA. In Rug-TMA structure, the primary mirror is the aperture stop of the optical system. The fields stop can be placed at the position of intermediary image to reduce the stray lights. The Rug-TMA structure is widely used in space optical system. But the secondary mirror is usually designed as convex off-axis aspheric mirror and is very difficult to manufacture.

In this letter, we study testing and manufacturing of convex off-axis aspheric mirror. The mirror is about 176×110 (mm), which works as secondary mirror in Rug-TMA space optical system. It is a convex and off-axis hyperboloidal asphere, and the other side is a perfect plane, which also act as the reference position of the mirror. These types of mirrors are difficult to fabricate and test because of their off-axis and convex characters. The mirror is made up of fused silicon with good uniformity. So the surface is tested by transmission method. The manufacturing of the mirror is studied, especially using ion beam figuring (IBF).

The curvature radius of the aspheric surface $R = 895.27$ mm, the conic coefficient $K = -4.256$, and the off-axis-amount $H = 69.5$ mm. The diameter of its parent mirror is about 310 mm. The requirement of surface error is 0.02λ root mean square (RMS) ($\lambda = 632.8$ nm).

The convex mirror was usually tested by aberration-free point methods or compensation methods[2]. According to the aberration-free point method, a big perfect sphere is needed. The diameter of sphere should be as large as 1100 mm. It is very expensive and time-consuming. According to the compensation method, the cost is also too much to employ null lens methods directly to test mirrors bigger than 300 mm.

Here the backside transmission type was used to test the mirror (Fig. 1). The mirror was part of null lens compensating optical system. The shape accuracy was restricted precisely. Firstly, the nonuniformity of the refractive index should be less than 0.5×10^{-6}. The center thickness of mirror is 33.18 ± 0.02 mm. This value should be monitored through the fabrication. The requirement of surface error of the plane side is 0.015λ RMS, the testing set-up of the plane is shown in Fig. 2.

The mirror was manufactured from blank by DMG Ultrasonic 100-5 milling device. The machine can work as five-axis computer numerical control (CNC) milling and the tool can be used in Ultrasonic mode to improve the efficiency and surface quality. The initial shaping of the mirror should be completed in the machine together including the plane side and the convex off-axis aspheric surface.

The plane processing should be good enough before the fabrication of the convex off-axis aspheric surface, in our case it is about 1/20λ RMS. The mirror can position as part of the parent symmetrical asphere while milling the convex surface. The center thickness of mirror should be decided seriously. We evaluated

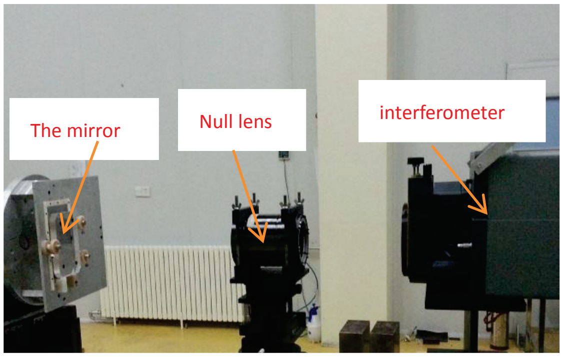


Fig. 1. Testing the aspheric surface by backside transmission type.

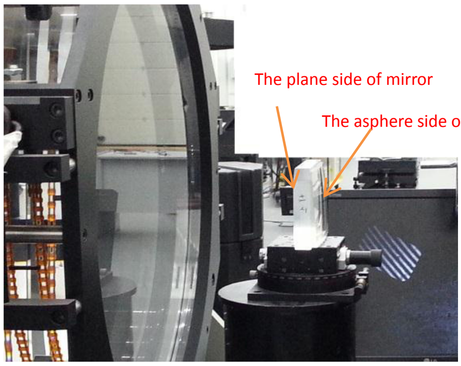


Fig. 2. Testing set-up of the plane side of the mirror.

the additional removal value as 0.1 mm, so the center thickness of mirror was milled as 33.28 mm.

After the shape milling process, the mirror was grinded by computer-controlled small tool which was referred to as computer-controlled optical surfacing (CCOS). At this stage, the shape precision should be tested all the time using coordinate measuring machining (CMM). The PRISMO navigator (ZEISS) was used for testing the shape precision and the aspheric surface error together. In our case, the position adjustment aberration errors cannot be eliminated. So the testing error results should be totally removed to ensure shape precision and aspheric surface error accuracy even tilts. The precision of the PRISMO CMM is about 0.9 μm/m, which is good enough for our testing at grinding stage.

In polishing stage, the IBF[3–5] was used for the high-accuracy processing of both the side surfaces. The IBF uses a beam of high-energy ions directed toward a target substrate in a controllable way and removes material from an optical surface by physical bombardment of surface. Because of noncontact figuring, IBF avoids the problems such as edge effects and load press. The shape of the removal distribution is like Gaussian function, and it is very beneficial to make the surface error converge coherently with high accuracy.

Firstly, the surface error of plane side is corrected by IBF. The polishing cannot damage the aspheric surface at the same time. The full-width at half-maximum size of the removal function is 8.4 mm, the remove rate is 5.14 nm/s, and the volume rate is 0.025 mm^3/min. As shown in Fig. 3, the surface error is 0.007λ RMS after IBF, which is good enough for the aspheric surface testing.

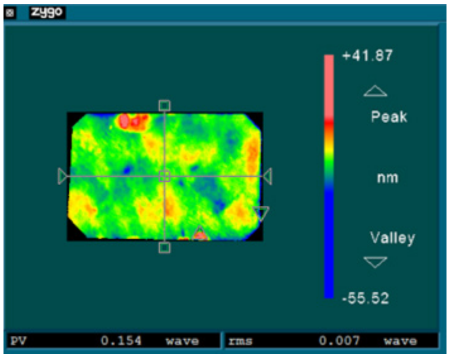


Fig. 3. Polishing result of the plane of the mirror.

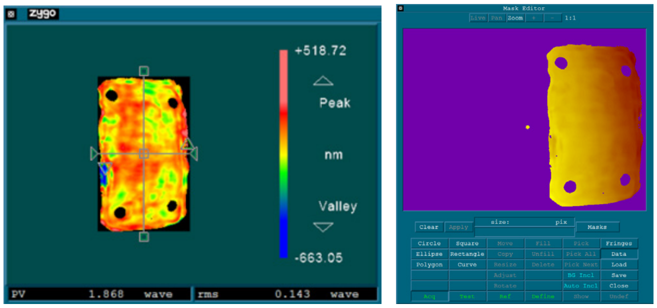


Fig. 4. Initial surface error of the aspheric side with distortion.

In null lens compensation, the distortion was not compensated in the measure system. So the relative positions of interferogram and mirror surface were non-linearly mapped. The mapping distortion in the measurement of off-axis aspheric mirror was corrected by the affine transformation model[6]. Figure 4(left) shows the initial surface error and Fig. 4(right) shows the interference fringe, in which the distortion is obvious.

There are four marks on the mirror, which can reduce the position errors. The transformation precision is about 0.56 mm obtained by mutual calibration. The position error is about one-thirtieth of the removal function, which is precise enough for polishing. The correction results are shown in Fig. 5.

Similar to the typical CCOS method, the material removal procedure used were convolution of ion beam

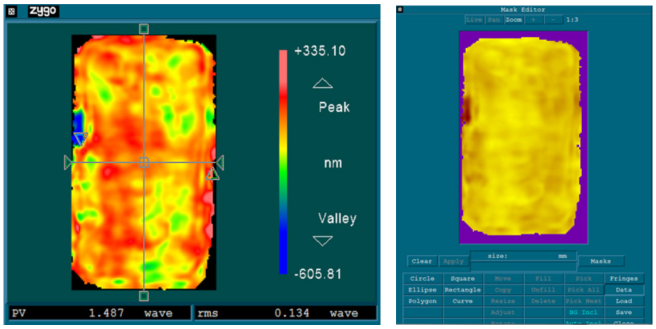
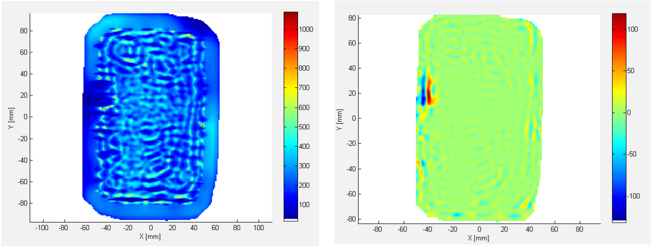


Fig. 5. Surface error of the aspheric side after distortion correction.



(a) (b)

Fig. 6. Simulation results by IBF software (a) dwell distribution (in ms) and (b) result (in nm).

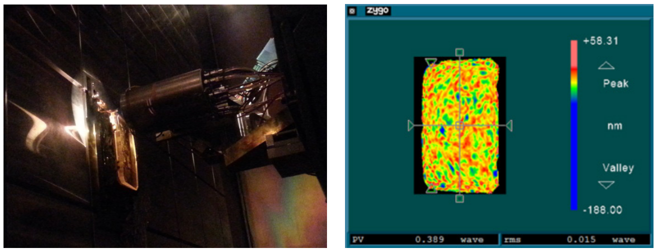


Fig. 7. Final fabrication results of the IBF.

removal function and fabrication dwell-time function. In the off-axis aspheric surface figuring, the compensation of the removal function changing was calculated using dwell-time computation software (Fig. 6). The simulation obtained is 5.6 nm RMS.

The aspheric surface was figured twice, the total polishing time was about 14 h divided into six cycles. The final accuracy of the convex off-axis aspheric surface was 0.015λ (Fig. 7).

As a result, only ripples which achieve the removal frequency limitation of IBF removal spot remain. The results are good enough and restricted by the testing optical systems.

In conclusion, we study the convex off-axis aspheric mirror which usually works as secondary mirror in space optical system. The mirror is tested by transmission type method. In polishing process, the distortion of the measurement is corrected by affine transformation. The IBF is used for convex off-axis aspheric surface finishing and achieves RMS of 0.015λ in the end. We carry out the precision manufacturing of convex off-axis aspheric mirror effectively.

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