Fabrication and testing of optical free-form convex mirror

Feng Zhang (张 峰)

Key Laboratory of Optical System Advanced Manufacturing Technology, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

Corresponding author: zhangfjyz@sina.cn

Received March 30, 2014; accepted July 16, 2014; posted online January 19, 2015

In order to obtain precise optical free-form convex mirror, we present a perfect process specification for fabricating and testing optical free-form convex mirror. Some technical requirements of 84×84 (mm) optical free-form convex silicon carbide (SiC) mirror are introduced. Firstly, the SiC blank is milled to the best-fitting sphere by means of DMG Ultrasonic 100-5 computer-controlled machine. Secondly, the best-fitting sphere is grinded and polished to optical free-form surface with certain figure accuracy by computer-controlled small tool fabrication. Finally, in order to meet the requirement of design, the optical free-form convex mirror is fabricated by advanced ion beam figuring. The contour testing technique is used for measuring the optical free-form convex mirror in milling and grinding processes, and the computer-generated hologram null testing technique for measuring the optical free-form convex mirror in polishing process is studied. The final testing result indicates that the figure accuracy of the optical free-form convex mirror is 0.02λ (root mean square).

OCIS codes: 220.4610, 220.4840, 220.5450, 220.1250.
doi: 10.3788/COL201513.S12202.

With the promotion of the idea of optical design, optical free-form components are becoming more and more popular, because the optical free-form components can improve flexibility of optical design, increase degrees of freedom of optical design, correct off-axis aberrations of optical system better, extend the field of view of optical system, and then improve the image quality of optical system[1–3]. However, the fabrication and testing of optical free-form convex mirror is more difficult than that of sphere or asphere. In order to make optical systems based on optical free-form components to be used widely, the fabrication and testing technologies of optical free-form components must be solved firstly. And also, the fabrication and testing of convex component is more difficult than that of the concave component. Here the fabrication and testing technologies of optical free-form convex mirror are studied.

At present, optical fabrication methods mainly used include traditional classical fabrication, computer-controlled small tool fabrication[4,5], stressed lap fabrication[6], magnetorheological finishing (MRF)[7], ion beam figuring(IBF)[8,9], etc. Traditional classical fabrication is suitable for plane, spherical, and coaxial aspheric fabricating. Usually large aperture aspheric surface is fabricated by stressed lap. MRF cannot be used in optical component grinding process, and mid-frequency error in component surface is produced easily during MRF process. Usually, optical free-form surface is asymmetric, and the radius of curvature at each point is different. Therefore, only small tool should be used for optical free-form component fabrication. Computer-controlled small tool fabrication can complete the optical components fabricating process from grinding to polishing by changing the tools and abrasives. IBF is a high-precision deterministic polishing, especially for component figure error correction in final polishing process. Therefore, precise optical free-form convex mirror can be fabricated effectively by combining computer-controlled small tool fabrication with IBF.

Testing technologies of optical free-form surface are very challenging. According to the figure characteristic and the figure error of optical free-form mirror at different stages of fabrication process, contour testing technique and computer-generated hologram (CGH) null testing technique are adopted for testing optical free-form convex mirror in grinding process and polishing process, respectively.

The optical free-form convex mirror to be manufactured is the secondary mirror of an optical system. The size of the mirror surface is 84×84 (mm), the material of the mirror is silicon carbide (SiC), and the technical requirement of the figure error of the mirror is better than 1/50λ (root mean square (RMS)) (λ = 632.8 nm).

The mathematical model descriptions of free-form surface are diversified, such as Zernike polynomial, XY polynomial, and Gauss polynomial, and each has its advantages and disadvantages. The model description put to use should be dependent on practical application and optical design. The mathematical model description of optical free-form convex mirror given by optical designer is expressed as

$$z = \frac{cs^2}{1+\sqrt{1-c^2s^2}} + \sum_{i=1}^{N} A_i Z_i(r,\theta), \tag{1}$$

where $c = 1/R_0$, $R_0 = -1562.3$ mm, $s^2 = x^2 + y^2 = r^2$. The second term in Eq. (1) is Zernike polynomial, and its expression is shown in Table 1.

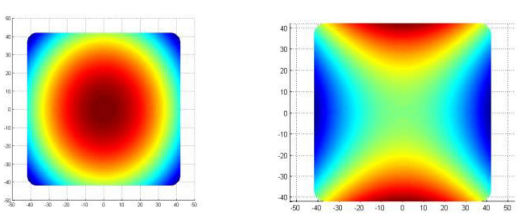
Table 1. Expression of Zernike Polynomial

N	A_i	$Z_i(r, \theta)$
4	-4.0750×10^{-5}	$r^2 \cos 2\theta$
9	3.775×10^{-10}	$3r^3 \cdot \sin\theta - 2r \cdot \sin\theta$
10	-3.6773×10^{-9}	$r^3 \cdot \sin 3\theta$
11	2.45×10^{-11}	$r^4 \cdot \cos 4\theta$
12	1.201×10^{-12}	$4r^4 \cdot \cos 2\theta - 3r^2 \cdot \cos 2\theta$
13	-3.65×10^{-13}	$6r^4 - 6r^2 + 1$
19	1.39×10^{-14}	$10r^5 \cdot \sin\theta - 12r^3 \cdot \sin\theta + 3r \cdot \sin\theta$
20	-1.57×10^{-14}	$5r^5 \cdot \sin 3\theta - 4r^3 \cdot \sin 3\theta$
25	-4.4185×10^{-13}	$20r^6 - 30r^4 + 12r^2 - 1$

The surface map of optical free-form convex mirror is analyzed (Fig. 1(a)). The shape of the free-form mirror surface looks mainly like a convex sphere, peak-to-valley (PV) value of the sag is 0.89 mm. The deviation between the best-fitting sphere and the free-form surface is shown in Fig. 1(b), PV value of the deviation is 0.1441 mm. The characteristic of free-form surface is shown in Fig. 1(b).

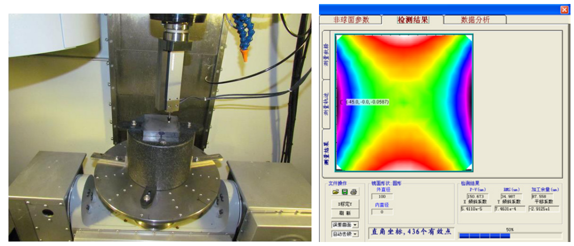
According to the characteristic of the free-form surface, the SiC blank surface is milled to the best-fitting sphere, and then the best-fitting sphere is grinded and polished to high-precision free-form surface. The main fabrication process of the optical free-form convex mirror includes the best-fitting sphere milling and free-form surface grinding and polishing. The contour testing and the CGH null testing are adopted in fabrication process.

The milling of SiC blank is carried out on DMG Ultrasonic 100-5 five-axis linkage processing machine. The machine has three translational degrees of freedom and two rotational degrees of freedom, and can realize the milling of planar, spherical, and aspherical surfaces. The SiC blank is milled to best-fitting sphere by the machine, and then the figure of mirror is tested by contour testing technique. The photo of contour testing and the testing result are shown in Figs. 2(a) and (b), respectively. Figure 2(b) shows the deviation between the milling best-fit sphere and the designed free-form surface, the PV value of deviation is 0.150 mm, which is very close to 0.144 mm (Fig. 1(b)).



(a) (b)

Fig. 1. Schematic of (a) surface map of optical free-form convex mirror and (b) its deviation from sphere.



(a) (b)

Fig. 2. Contour testing of the mirror after milling: (a) photo of contour testing and (b) result of contour testing.

The mirror is grinded from best-fit sphere to free-form surface by means of computer-controlled small tool equipment. The photo of computer-controlled small tool equipment is shown in Fig. 3.

The equipment is a six-axis synchronous vertical computer numerical control (CNC) gantry machine center. Six degrees of freedom are three translational degrees of freedom (X, Y, Z) and three rotational degrees of freedom (U, V, W), representing the table translation in the x-axis direction, the tool translation in the y-axis direction, lifting in the z-axis direction, the rotation of the table, the tool swing, and rotation, respectively. The table and the tool are driven by driver system. Combined six degrees of freedom, the function of machine for grinding, and polishing free-form convex mirror can be realized.

The idea of free-form convex mirror grinding depends on computer-controlled optical surfacing technique. On the basis of quantitative testing data, a small tool controlled by computer moves on the surface of the mirror, the figure error of the free-form surface is corrected through controlling the dwell time of the small tool at different positions on the mirror surface.

The selection of small tool is key factor in grinding process. The material of small tool is stiff SiC, so it is difficult to change the shape of small tool in grinding process. According to the experience, if the agreement between the small tool and the workpiece surface is less than 10 μm, the figure error can be corrected effectively. By means of studying characteristic of free-form convex mirror, it is found that the agreement between the small tool and free-form convex mirror is good if the

Fig. 3. Photo of computer-controlled small tool machine.

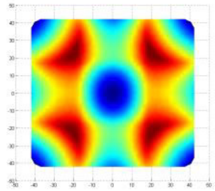


Fig. 4. Distribution function of the agreement.

size of small tool is less than Φ10 mm. The distribution function of the agreement between the small tool with the size of 10 mm and free-form convex mirror is shown in Fig. 4. The PV value of deviation is 9.7 μm, which is less than 10 μm.

Therefore, the strategy of free-form convex mirror grinding is as follows: at the beginning of grinding, because of large figure error on the mirror surface, in order to grind the mirror efficiently, the big tool is adopted; at the end of grinding, in order to correct figure error efficiently, only small tool with the size of 10 mm is used. The figure error of freeform convex mirror is tested by contour testing technique. The convergence of the figure error of the free-form convex mirror in grinding process is shown in Fig. 5. Figure 5 indicates that the final figure errors in grinding process are 1.8 μm (PV value) and 0.23 μm (RMS value), which can meet the technical requirement of grinding.

After grinding, in order to remove subsurface damage produced in grinding and improve the figure accuracy of the optical free-form convex mirror, the optical free-form convex mirror should be polished. CGH null testing technique is adopted for testing optical free-form convex mirror in polishing process.

In recent years, with the development of lithography technology, manufacturing accuracy of CGH is promoted evidently. The interferometric method with CGH has been wildly used to test aspheric optical components[10,11].

Because of the particular characteristic of free-form surface, such as multi-extremes and inflection points, CGH technique is the only effective technique for testing high-precision optical free-form surface in polishing process as of now.

In the light path of optical free-form convex mirror testing, CGH is used as null compensator. The schematic diagram of optical free-form convex mirror tested by CGH is shown in Fig. 6.

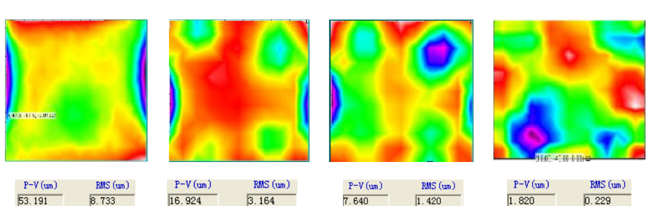


Fig. 5. Convergence of the figure error of the free-form convex mirror.

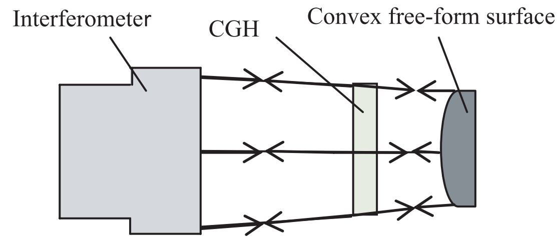


Fig. 6. Schematic diagram of optical free-form convex mirror tested by CGH.

Standard spherical wave coming from interferometer occurs on CGH, then diffraction occurs. The other diffraction light is removed, only +1 diffraction light is allowed entering testing path. The +1 diffraction light will produce theoretical free-form wavefront. The wavefront incidents on optical free-form convex mirror, it travels along the normal direction of the surface. The light reflected from the free-form surface, carrying figure error information, goes back to interferometer along original path, and interferes with reference spherical wave. Surface figure error of the optical free-form convex mirror is obtained by analyzing interference fringes.

As shown in Fig. 6, in testing light path, interferometer, CGH, and free-form mirror must be in the correct spatial location. Otherwise, testing result will contain extra error caused by maladjustment[12–14]. The complex function CGH is designed to remove maladjustment error, which consists of three segments, main zone, fiducial section, and alignment section. The complex function CGH is shown in Fig. 7. Main zone is testing area, which can produce diffraction light to test surface figure errors of the optical free-form convex mirror. Fiducial section can project fiducial marks around the optical free-form convex mirror. According to these marks, the relative position between CGH and the optical free-form convex mirror can be adjusted accurately. Alignment section is used to align CGH to interferometer. Therefore, the complex function CGH can eliminate maladjustment error.

The main error sources that influence the accuracy of CGH include glass substrate error σ_1, CGH calculation error σ_2, and CGH platemaking error σ_3. Glass substrate error σ_1 is the largest error. In order to decrease error σ_1,

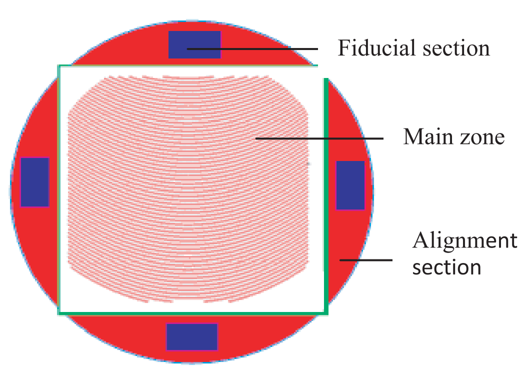


Fig. 7. Complex function CGH.

Table 2. Accuracy of CGH

Error Source	**Value of Error ($\lambda = 0.6328\ \mu$m)**
Glass substrate error σ_1	0.005λ
CGH calculation error σ_2	0.001λ
CGH platemaking error σ_3	0.003λ
Other errors σ_4	0.001λ
Total error σ	0.006λ

not only high-precision glass substrate should be chosen but also the testing result of glass substrate should be presented to the CGH designer to compensate the error. The accuracy of the CGH is shown in Table 2.

The final accuracy of the CGH is 0.006λ. The technical requirement of the figure accuracy of the optical free-form convex mirror is 0.02λ. Therefore, CGH can meet the requirement for the optical free-form convex mirror testing.

Firstly, the optical free-form convex mirror is polished on computer-controlled small tool machine as shown in Fig. 3. After 12 periodic polishing, the figure accuracy of the optical free-form convex mirror tested by CGH is shown in Fig. 8.

The figure accuracy of the optical free-form convex mirror is 0.044λ (RMS), which is better than 0.05λ (RMS), so the mirror can go to IBF.

IBF is a highly stable, highly deterministic, and non-contact technology for ultra-precise optical elements polishing. IBF is the last process of optical free-form convex mirror fabrication. The optical free-form convex mirror is fabricated on IBF1500 machine.

According to the size of mirror and the distribution of figure error, 10/10/30 ion source grid is chosen, the value of full-width at half-maximum is 7.4 mm, and the volume of removal rate is 0.015 mm^3/min. After 72 min IBF, the figure error of the optical free-form convex mirror is tested by CGH (Fig. 9). The figure accuracy

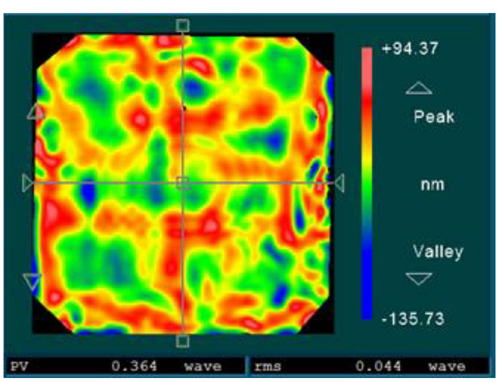


Fig. 8. Testing result of the mirror after computer-controlled small tool polishing.

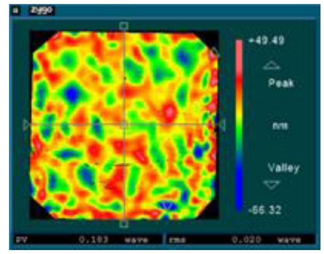


Fig. 9. Final testing result of the mirror after IBF.

of the optical free-form convex mirror is 0.02λ (RMS), which can meet the design specification.

In conclusion, we present a perfect process specification for fabricating and testing optical free-form convex mirror. The process specification include the blank milling to the best-fitting sphere by DMG machine, the best-fitting sphere grinding and polishing to optical free-form surface by computer-controlled small tool fabrication, and correction of the figure error of the optical free-form convex mirror by IBF. The contour testing technique is used for measuring the optical free-form convex mirror in milling and grinding processes, and the CGH null testing technique for measuring the optical free-form convex mirror in polishing process is studied. The 84×84 (mm) optical free-form convex mirror is fabricated by the process specification. The final testing result indicates that the figure accuracy of the optical free-form convex mirror is 0.02λ (RMS). The experiment verifies that the fabricating and testing specification is suitable for manufacturing optical free-form mirror.

References

1. W. T. Plummer, J. G. Baker, and J. V. Tassell, Appl. Opt. **16,** 3572 (1999).
2. A. Y. Yi and T. W. Raasch, Appl. Opt. **44,** 6869 (2005).
3. D. Xue, L. Zheng, and F. Zhang, Opt. Precis. Eng. **19,** 2813 (2011).
4. R. A. Jones, Appl. Opt. **6,** 1247 (1977).
5. J. Zhang, L. Dai, F. Wang, and L. Wang, Acta Opt. Sin. **33,** 0822002 (2013).
6. B. Fan, Y. Wan, C. Wei, Y. Li, Z. Zeng, F. Wu, and S. Wu, Chin. J. Laser **33,** 128 (2006).
7. S. Yin, Z. Xu, F. Chen, and J. Yu, J. Mech. Eng. **49,** 33 (2013).
8. Y. Dai, W. Liao, L. Zhou, S. Chen, and X. Xie, Appl. Opt. **49,** 6630 (2010).
9. M. Demmler, M. Zeuner, A. Luca, T. Dunger, D. Rost, S. Kiontke, and M. Kruger, Proc. SPIE **7934,** 793416 (2011).
10. Y. Xie, Q. Chen, F. Wu, Hou Xi, J. Zhang, and G. Wu, Acta Opt. Sin. **28,** 1313 (2008).
11. S. Cao, Y. Sui, and H. Yang, Acta Opt. Sin. **33,** 0612003 (2013).
12. F. Li, X. Luo, J. Zhao, D. Xue, L. Zheng, and X. Zhang, Opt. Precis. Eng. **19,** 709 (2011).
13. Y. Gu, E. Miao, S. Gao, Y. Sui, and H. Yang, Chin. J. Lasers **38,** 1208005 (2011).
14. J. Feng, C. Deng, and T. Xing, Laser Optoelectron. Prog. **49,** 110902 (2012).