Manufacturing and testing of a cubic SiC surface

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The free surface and unrotational-symmetric surface optical elements have been applied more and more widely along with the development of optical design technology, although they are still difficult for manufacturing. In this letter, a SiC unrotational-symmetric aspheric surface whose surface equation is $z = 3\lambda(x^3 + y^3)$ ($\lambda = 0.6328$ μm) has been introduced. The tilt abstraction is adopted to minimize the material removal. The surface figures are peak-to-valley (PV) value of 0.327λ and root-mean-square (RMS) value of 0.023λ. A non-null testing method based on digital mask is proposed to test this surface. The accuracy of the method is testified by the experiment of standard sphere testing.

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The manufacturing and testing of rotational-symmetric surfaces such as spherical and conic surfaces have been well developed while the fabrication of unrotational-symmetric surface is still a difficult problem for most optical shops[1]. The recent progress of optical design and advanced imaging system, especially the wavefront coding technology for space application, calls for the unusual surface with unrotational-symmetric term[2,3]. So far, SiC is considered to be an ideal material of space mirror for its perfect mechanical and thermal properties. Based on these two reasons, a simple cubic surface $z = 3\lambda(x^3 + y^3)$ is polished on SiC material for experiment by the digital controlling manufacturing equipment (FSGJ-1). The final surface figures are peak-to-valley (PV) value of 0.327λ and root-mean-square (RMS) value of 0.023λ.

An interferometer with flat reference is applied to test this surface. Deviation between the ideal cubic surface and the flat reference is regarded as the system error and can be eliminated automatically in the testing by Metropro after the proper system error file is introduced. The accuracy of this non-null testing method is validated by the testing of an spherical model.

It is shown in Fig. 1(a) that the sag of the surface increases monotonously along the arrow direction. It can be observed that if the shape surfacing starts from a standard plane, the SiC removal of the lowest point will be 6λ ($\lambda = 0.6328$ μm), which is a tough job in polishing stage. It can also be realized spontaneously that if the fiducial plane can be tilted to a certain angle, the material removal can be reduced considerably. Although the fiducial plane of manufacturing can not be tilted, the tilt component of the surface itself can be removed instead because the tilt is just misalignment error and can be compensated easily by adjusting the direction of surface. The surface equation can be expanded by Zernike polynomial as

$$z = 3\lambda(x^3 + y^3) = 1.5\lambda(Z_2 + Z_3) \\ +0.75\lambda(Z_7 + Z_8 + Z_{10} - Z_{11}), \quad (1)$$

where $Z_2 = x, Z_3 = y$, $Z_7 = 3x^3 + 3xy^2 - 2x, Z_8 = 3y^3 + 3yx^2 - 2y$, $Z_{10} = x^3 - 3xy^2, Z_{11} = -y^3 + 3x^2y$.

After the tilt term is removed, the surface equation can be rewritten as follows:

$$z^* = 3\lambda(x^3 + y^3) - 1.5\lambda(x + y). \quad (2)$$

The material removal of the lowest point is about 3.27λ as shown in Fig. 1(b).

The digital controlling manufacturing machine (FSGJ-1) is applied to polish the surface in the first stage. The starting point is a plane with PV 0.15λ, RMS 0.02λ, and the abrasive is $0-0.5$-μm diamond slurry. The digital-control polished surface figure is shown in Fig. 2. The shape errors are PV 0.982λ, RMS 0.09λ. The FSGJ-1 is designed for manufacturing mid-aperture mirror about ϕ $300-600$ mm and the smallest polishing pad is about 30 mm[4,5]. However, there is not only convex but also concave on the surface. The surface shape will not converge if the size of polishing pad is too big. Hence some extra handwork is needed to modify the surface figure[6]. The final surface shape errors are PV 0.327λ and RMS 0.023λ, as shown in Fig. 3. The testing method will be presented in the next part.

For most rotational-symmetrical conicoid in cluding high order terms, the null testing method is most widely used, in which lenses are combined together to transform the perfect flat or sphere wavefront to asphere wavefront coincides with the asphere under test. The method is not fit for the unrotational-symmetric asphere because the combination of common lens can not create the needed special asphere wavefront. So a non-null testing method is proposed[7,8]. The Zygo interferometer with flat reference is used to test the surface and the data processing software is Metropro.

The direct testing result gives the deviation between the surface under test and the flat reference, which can be divided into three parts:

$$\Delta W = \Delta W_1 + \Delta W_2 + \Delta W_3, \quad (3)$$
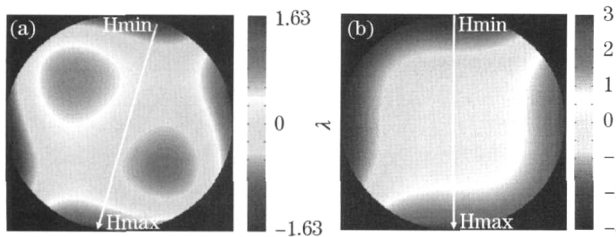
Fig. 1. (a) Surface figure before subtracting tilt; (b) surface figure after subtracting tilt.
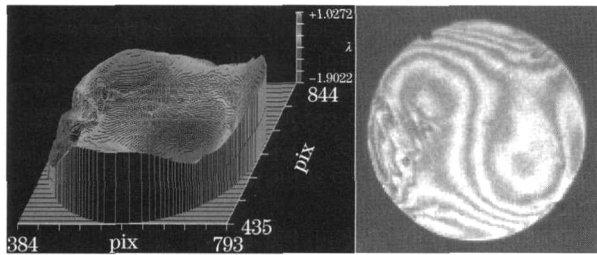

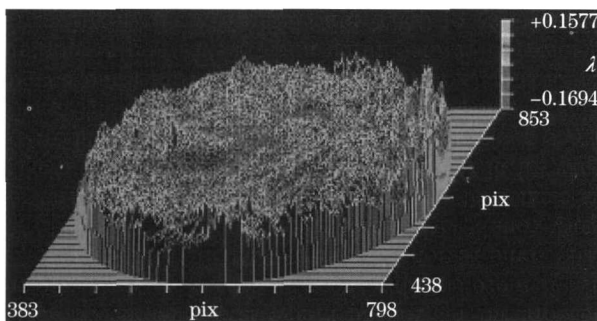Fig. 2. Surface figure after digital-controlled polishing.

Fig. 3. Final surface figure error.

where ΔW_1 is the deviation between the actual surface figure and the ideal surface figur, ΔW_2 is the deviation between the ideal surface figure and the reference wavefront which is a standard flat wavefront here, and ΔW_3 is the non-null error.

ΔW_1 is just the surface shape error we are interested in. ΔW_2 will keep constant, therefore this part can be regarded as the system error and eliminated from the direct testing result. It can be calculated by the mathematical software such as Matlab and the data can be transformed to "dat" format by a small tool within Metropro. After this "dat" file is set the "sys" error file and this item is unlocked in Metropro, ΔW_2 will be subtracted from the testing result automatically. If ΔW_3 is determined, the surface shape error can be obtained.

The non-null error ΔW_3 is caused by the test and reference rays in the interferometer following different optical paths through the system in non-null testing manner. It is difficult to perform reverse ray tracing on commercial interferometer[9−11]. Thereby a sphere mirror is tested by this non-null method to estimate the effect of non-null error. The radius of curvature of the experimental sphere is 4092.5 mm and the diameter is 10 mm. ΔW has been eliminated in testing process. The surface shape (ΔW_1) is PV 0.091λ, RMS 0.008λ by traditional testing while the results are PV 0.089λ, RMS 0.008λ through the non-null method proposed in this letter under the same

condition as Fig. 4 shows. The digital mask of sphere is shown in Fig. 5. It can be seen from the comparison of the two results that the RMS values are completely the same and the difference between the two PV values is only 0.002λ. The largest difference is 0.005λ in iterative measurements. Obviously, the non-null error has little effect on the testing result and can be ignored. The non-null error is related to the distance between the mirror and the interferometer. The more steeper the surface is, the more distinct the non-null error is. Considering the largest deviation of the sphere from flat reference is about 5λ and the largest sag increment is 1.74 λ/mm while the corresponding values of the asphere are about 3.3λ and less than 0.05 λ/mm, which are smaller than
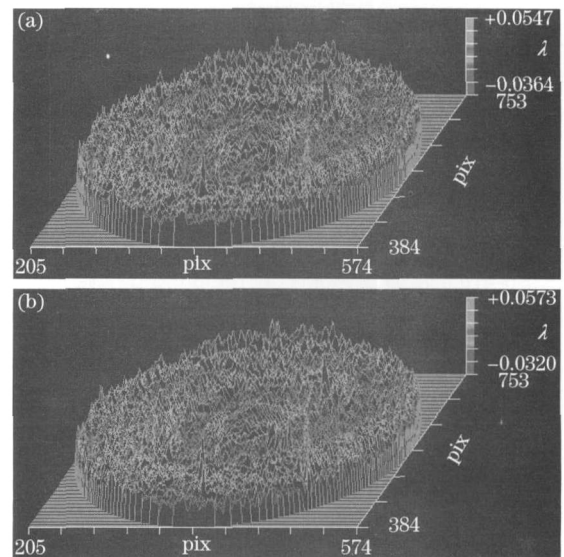

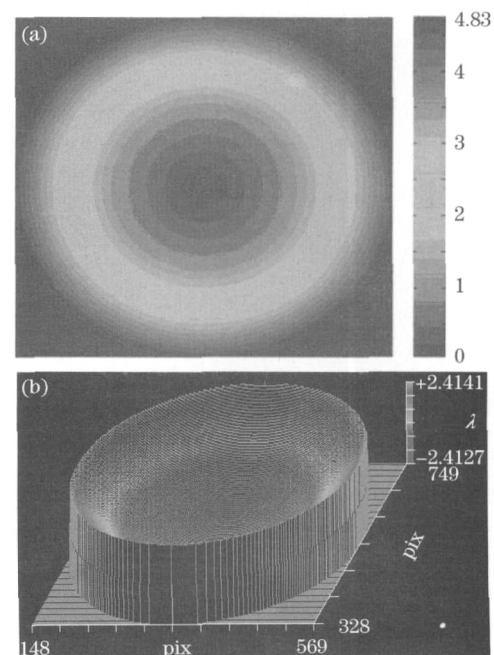Fig. 4. (a) Result of traditional testing; (b) result of non-null testing.

Fig. 5. (a) System error generated in Matlab for non-null testing of the sphere model; (b) system error shown in Metropro for non-null testing of the sphere model.
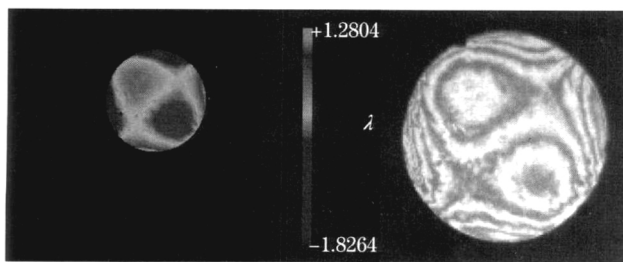
Fig. 6. Final surface figure.

the sphere mirror. Thus it can be concluded that if the testing condition of the asphere workpiece is the same as the sphere mirror, mainly the distance between the workpiece and the interferometer, the non-null error has nearly no effect on the testing result and can be neglected.

Based on the analysis above, if the deviation between the ideal surface figure and the flat plane is set to be the system error, ΔW_1 can be obtained directly by the non-null testing. The final surface figure of the asphere workpiece is shown in Fig. 6 with PV 0.327λ, RMS 0.023λ.

If the position of the workpiece in x-y plane is changed, the system error file must be recalculated because the fringe area is different. If the workpiece rotates a certain angel, then the data of system error file must rotate the same angle to keep coincide with it. It is intensively suggested to keep the rotation angle of the surface same during the whole manufacturing process. In the actual testing process, simple symbols (two thin lines) are made respectively on side face of the workpiece and the alignment stage. When the two lines match to each other, the reposition is considered to be accomplished. The repetition accuracy is about $0.2°$ which can be negligible. It is mainly because rotational direction of the surface is not very fixed and tiny deviation is regarded to be acceptable. Besides the sag difference between neighboring points is small due to the huge number of sampling points

(about 450×450) in the system error file, which provides the instinctive tolerance to the limited position error.

In conclusion, a cubic surface has been manufactured and tested. The surface shape errors are PV 0.327λ and RMS 0.023λ. A non-null method is applied to test the surface and the retrace error is proved to have little effect on the result. The future work will concentrate on the manufacturing and testing of more complex unrotational-symmetric surface. Especially, more testing methods such as computer-generated holography (CGH) and sub-aperture stitching will be adopted.

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