The Manufacturing and Testing of an Unrotational-symmetric SiC Mirror

Yan Feng[1, 2], Fan Di[1], Zhang Bin-zhi[1], Zhang Xue-jun[1]

1.Optical Technology Research Center, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033,China

Office Phone: 86-431-86708690 E-mail: greatyf@mail.nankai.edu.cn

2. Graduate School, Chinese Academy of Science, Beijing 100084, China

Abstract:

In previous work, wavefront coding technology has been applied on an off-axis three mirror anastigmatic optical system. The secondary mirror is selected as the wavefront coded element. After redesigned the surface of secondary mirror becomes an unusual unrotational-symmetric surface with cubic term, which can not be tested by traditional null testing with compensator. For preparing for manufacturing and testing this kind of elements, a simple cubic surface whose equation is $z = 3\lambda(x^3 + y^3)$(where x, y is normalized coordinate, $\lambda = 0.6328\mu m$) is polished. The final surface figure is 0.327λ (PV) and 0.023λ (RMS). The manufacture of this surface is introduced in this paper. The tilt component is subtracted to minimize the material removal. Also a non-null method is described for testing the experimental element. The deviation from a reference plane of the cubic surface is regarded as system error. In another words, the ideal cubic surface is set as the reference artificially. A special system error file for interferometer can be created so that the cubic term can be extracted during the testing process automatically. The residual error is just the departure from the ideal figure of the surface under machining by this way. The error and effective range is also presented. But the method may not be practical for the secondary mirror as wavefront coded element because the surface of that kind is convex asphere added cubic term. An improved non-null method is discussed for testing this kind of surface.

Key words:

SiC, unrotational-symmetric, digital controlling manufacturing, non-null testing, surface shape

A non-null testing method based on digital mask is proposed to test this surface and the accuracy

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of the method is testified by experiment.

1Introduction

The manufacturing and testing of rotational-symmetric surface such as sphere, conic surface has been well developed while the fabrication of unrotational-symmetric surface is still an difficult problem for most optical shop. 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. The previous work has propose a design of TMA optical system with wavefront coding technology, in which the secondary mirror is regarded as the “wavefront coding element” and its new surface equation is shown as follow:

$$z(x,y)=\frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}}+\beta(x^3+y^3) \quad (1)$$

where $\beta=\varepsilon\cdot\frac{\lambda}{2\pi}\cdot\frac{R_{stop}}{R_{EP}}\cdot\frac{1}{R_{stop}{}^3}$ ($\frac{1}{R_{stop}{}^3}$ is normalized factor, ε □ 20) (2)

It is obviously seen that the surface shape of the secondary mirror is a typical unrotational-symmetric asphere.

Silicon carbide is a kind of ceramic optics material developed in recent years which offered a series of advantages over other traditional optical substrate materials such as low density, low thermal expansion coefficient, high thermal conductivity, large special heat, large modulus of elasticity and potential cost and schedule. So SiC is an attractive candidate for making optical mirrors of space borne telescopes due to its excellent thermo-mechanical properties.

Based on these two reasons, a simple cubic surface with the equation $z=3\lambda(x^3+y^3)$ (where x, y is normalized coordinate, $\lambda=0.6328\mu m$) is polished on SiC substrate for experiment with the digital controlling manufacturing equipment FSGJ-1. Some extra handwork is also done after machining. The final surface figure is 0.327λ (PV) and 0.023λ (RMS).

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 a special system error file can be created by theoretical calculation and format transformation. After the sys-err file is activated in Metropro (the controlling software of Zygo interferometer), the deviation between the ideal cubic surface and the flat reference can be subtracted from the testing result automatically and the surface error between the actual surface and ideal surface can be obtained directly. The non-null error of this testing method is demarcated by a testing experiment of a spherical model. An improved testing method for the surface as equation (1) describes is also discussed.

2. Manufacturing of the unrotational-symmetric surface

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 about $3.8\mu m$, which is a tough job in polishing stage. It also can be realized spontaneously that if the fiducial plane could be tilted 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 kind of misalignment error and can be compensated easily by adjusting direction of surface. The surface equation can be expanded by Zernike polynomial in formula (3):

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

Where $Z_2 = x \quad Z_3 = y$

$$Z_7 = 3x^3 + 3xy^2 - 2x \quad Z_8 = 3y^3 + 3yx^2 - 2y \quad Z_{10} = x^3 - 3xy^2 \quad Z_{11} = -y^3 + 3x^2 y$$

After the tilt term is removed, the surface equation can be rewritten as follow.

$$z^* = 3\lambda(x^3 + y^3) - 1.5\lambda(x + y) \quad (4)$$

The material removal of the lowest point is about 3.27λ as fig. 1(b) shows.

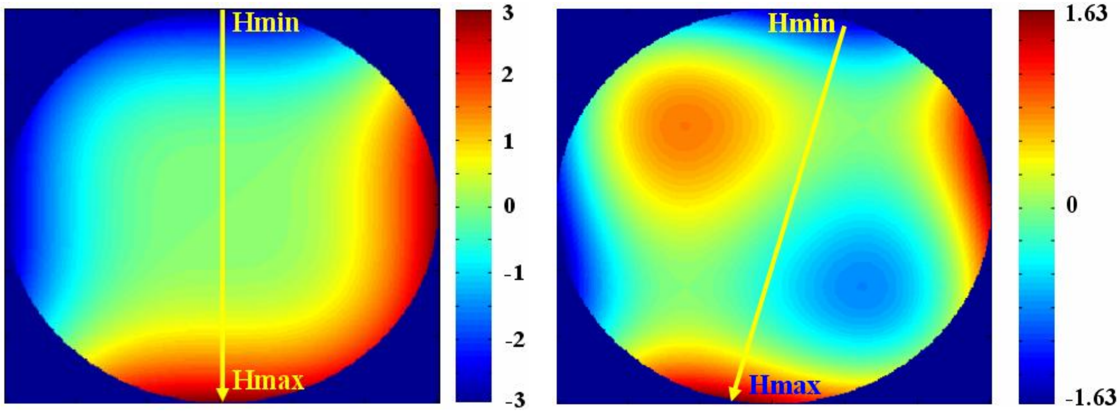

Fig.1 (a)surface figure before subtracting tilt (b) surface figure after subtracting tilt (unit, λ)

The digital controlling manufacturing machine FSGJ-1 is applied to polish the surface in the first stage. The starting point is a plane with $PV0.15\lambda$, $rms0.02\lambda$ and the abrasive is $0-0.5\mu m$ diamond slurry. After the digital-controlled polishing the surface figure is shown in fig. 2. The shape error is $PV0.982\lambda$, $rms0.09\lambda$ .The FSGJ-1 was designed for manufacturing mid-aperture mirror about $\Phi 300mm - \Phi 600mm$ and the smallest polishing pad is about 30mm. 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. The final surface shape is 0.327λ (PV) and 0.023λ (RMS) as shown in figure 3. The testing method will be presented in section 3.

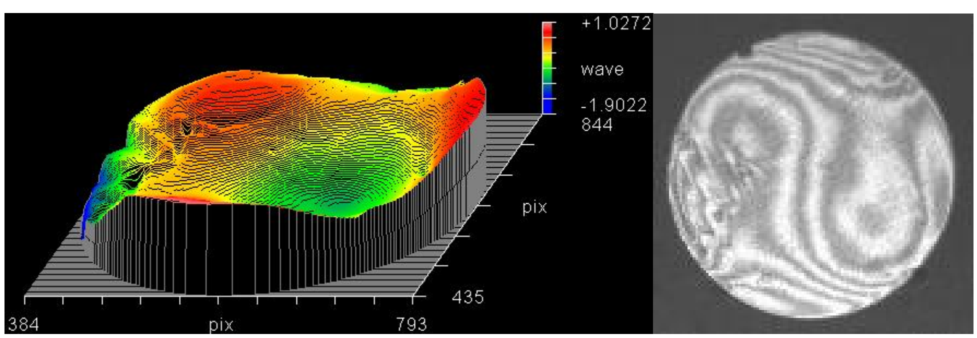

Fig.2 Surface figure after digital-controlled polishing

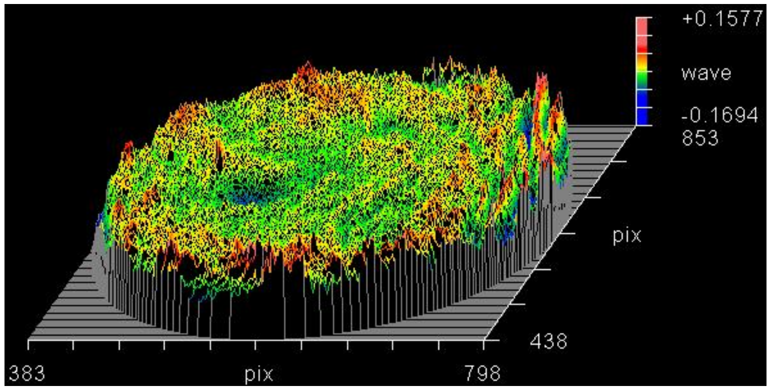

Fig.3 final surface figure error

3. Testing of the unrotational-symmetric surface

For most rotational-symmetrical conicoid (high order terms included maybe) the null testing method is most widely used, in which a group of lens is combined together to transform the perfect flat or sphere wavefront to asphere wavefront coincide 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 special asphere wavefront needed. So a non-null testing method is proposed.

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 to three parts as formula (5) shows:

$$\Delta W_{act\ to\ ref} = \Delta W_{act\ to\ ideal} + \Delta W_{ideal\ to\ ref} + \Delta W_{non-null} \quad (5)$$

The first part is the deviation between the actual surface figure and the ideal surface figure; the second part is the deviation between the ideal surface figure and the reference wavefront (a standard flat wavefront here) and the third part is the non-null error.

The first part is just the surface shape error interested in. The second part $\Delta W_{ideal\ to\ ref}$ will keep constant so that this part can be regarded as the system error and calculated by mathematical software such as Matlab。The calculating process is a little trouble some. First of all, several testing is performed to obtain the size and the position of the interferogram which is included in the testing result(in ".xyz" format) when the testing environment is steady. The size is given by the number of CCD pixels on both x and y directions of a rectangular field which involves the interferogram while the position is given by x and y coordinates of the top-left starting point of the rectangular field. The size of interferogram is proposed to set about 450pix×450pix, which is also the size of $\Delta W_{ideal\ to\ ref}$. A large interferogram contains too many sampling points, which will take a long time to calculate, while if the size is set too small, the testing result will became more sensitive to environment. Secondly, since the size and the position coordinates of the $\Delta W_{ideal\ to\ ref}$ is determined and the equation of the ideal surface is known, a n×3 matrix can be easily created in Matlab in which the first and second columns are x and y coordinates while the third column is the sag deviation between the ideal surface and the flat reference of a sampling point. Next these data can be written to a TXT file. After some necessary change to the data format, the file can be saved as ".xyz" format and then transformed to "dat" format by an additive tool within Metropro. Finally this dat file is set the "sys error file" and this item is activated in Metropro, thus the $\Delta W_{ideal\ to\ ref}$ will be subtracted from the testing result automatically. Of course in iterative measurements the size and the position of the interferogram will not keep strictly the same and fluctuate a little while the made system error file can not change along with. This problem may introduce certain error. But the fluctuation is very tiny(about 1 pix) when the testing environment is steady. Dense sampling point also helps to decrease the effect of the problem. It has been proven that the problem has little effect on testing results, which coincides with each other very well in iterative measurements.

Since $\Delta W_{ideal\ to\ ref}$ is calculated the surface shape error will be obtained so long as the third part $\Delta W_{non-null}$ is determined. The non-null error $\Delta W_{non-null}$ is caused by the testing and reference rays following different optical paths through the system in non-null testing manner. It is nearly impossible to perform exact reverse ray tracing on commercial interferometer for the optical design is unknown. 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 4092.5mm and the diameter is 100mm. But only a small area of $\Phi 10mm$ is concerned about since the fringes will be too dense because of deep deviation. The surface shape($\Delta W_{act\ to\ ideal}$) is $PV0.091\lambda$, $rms0.008\lambda$ by traditional testing as fig. 4(a) shows. In the non-null testing proposed in this paper, a special system error file is made as fig. 5 shows, which is just the ideal surface shape of the sphere model. The testing result ($\Delta W_{act\ to\ ideal} + \Delta W_{non-null}$, $\Delta W_{ideal\ to\ ref}$ has been eliminated in testing process) is $PV0.089\lambda, rms0.008\lambda$ through the non-null method under the same condition(especially the distance between the surface under test and the interferometer) as fig.4 (b) shows. 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 0.004λ in iterative measurements). Obviously the non-null error has little effect on the testing result. The non-null error is related to the distance between the surface under test and the interferometer. For the non-null testing of sphere model, different position of the sphere will induce different power error, which means different system error file should be made for different position of the surface. But in fact difference among system error files within a large range is very small, which is enough to control the power error at different position. It is shown in experiments that the difference will not exceed $\pm\frac{1}{30}\lambda$ PV in about 2-meters range. Of course if the system error file is kept constant for different position, the power error can also be eliminated by Metropro, which will also get the right result. Furthermore the asphere under test has no rotational-symmetry, which is immune to power natively. The gradient of the surface is another important factor impacting on the accuracy of the non-null testing. The steeper the surface is, the more distinct the non-null error is. Considering the largest deviation of the sphere from flat reference is about 4.8λ and the largest sag increment is $1.74\lambda / mm$ while the corresponding values of the asphere are about 3.3λ and less than $0.05\lambda / mm$, which are much smaller than the sphere mirror. Thus it can be concluded that when the distance between the asphere under test and the interferometer is not too far, the non-null error has nearly no effect on the testing result of the unrotational-symmetric asphere and can be neglected.

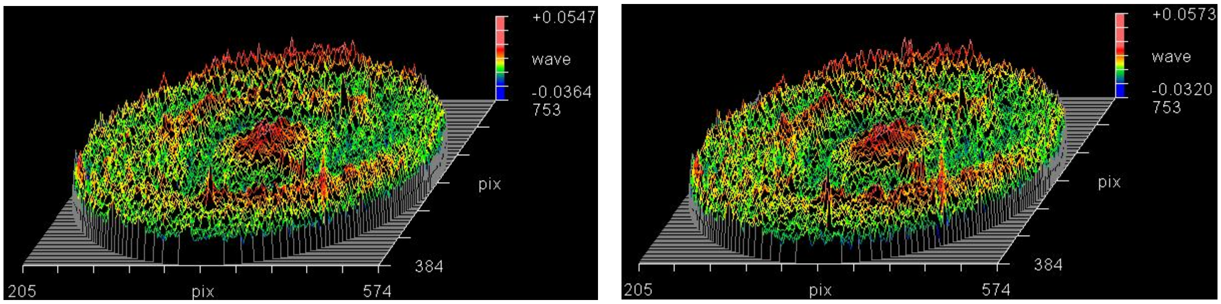

Fig.4 (a) result of traditional testing (b) result of non-null testing proposed in the paper

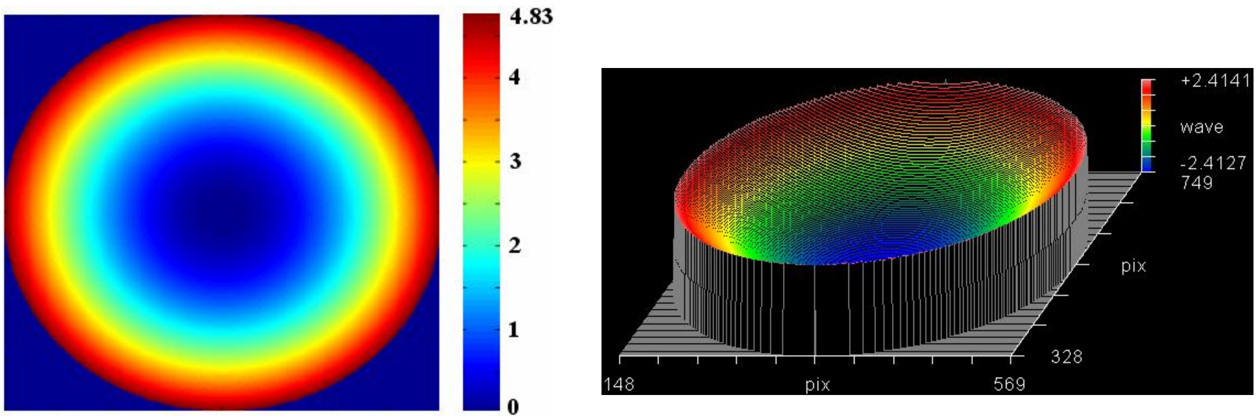

Fig.5 system error subtracted in non-null testing of the sphere model (unit, λ)

Based on the analysis above, if the deviation between the ideal surface figure and the flat plane (as fig. 1(b) shows) is set the system error, the surface shape error $\Delta W_{act\ to\ ideal}$ can be obtained directly by the non-null testing. The final surface figure of the asphere workpiece is shown in fig. 6 with $PV\ 0.327\lambda, rms\ 0.023\lambda$.

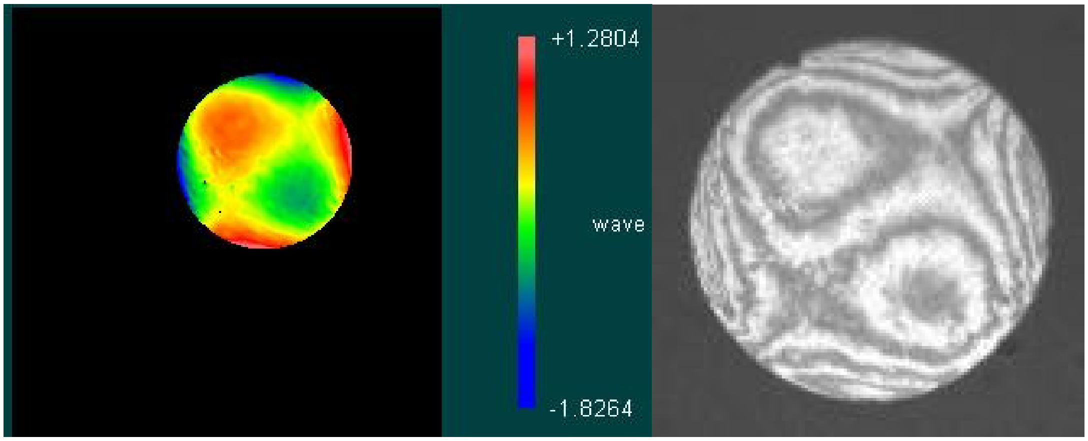

Fig.6 final surface figure (unit, λ)

Of course, 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 rotates the same angle to keep coincide with it. It is intensively suggested to keep the rotation angle of the surface the same during the whole manufacturing process.

4 Improved testing for conic asphere with cubic term

If surface shape is an asphere with cubic terms as formula (2) shows,

$$z(x,y)=\frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}}+\beta(x^3+y^3)$$ (where x, y is normalized coordinate, $\lambda = 0.6328\mu m$)

The testing method must be improved to fit that kind of surface because the non-unique error needs to be re-demarcated. An improved method is proposed.

Firstly, a best-fit-asphere is manufactured, which surface equation is the original asphere without cubic terms as formula (6) shows:

$$z(x,y)=\frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}} \quad (6)$$ (where x, y is normalized coordinate, $\lambda = 0.6328\mu m$)

The traditional testing method (with compensator or with CGH) is applied to obtain the final surface shape error which is expressed by Δw_1.

Next the non-null testing is applied in which a proper standard spherical mirror is selected to make the fringes not too dense. The testing result can be expressed by Δw_2. The Δw_2 can be regarded as comprising by two parts: one part is Δw_1, which is the actual surface error; while the other part is the non-null error, which can be expressed by $\Delta w_{non-null}$. Since Δw_1 and Δw_2 is know, then $\Delta w_{non-null}$ can be calculated. When the magnitude of cubic term (β) is not too big, the $\Delta w_{non-null}$ can be seen as the non-null error of the surface with cubic terms.

Finally, the procedure is the same as part 3 refers. The asphere is tested in the non-null manner with the same standard spherical mirror. The direct testing result can also be divided into three parts as formula (3) shows:

$\Delta W_{act\ to\ ref} = \Delta W_{act\ to\ ideal} + \Delta W_{ideal\ to\ ref} + \Delta W_{non-null}$, where $\Delta W_{act\ to\ ideal}$ is the surface shape error interested in; $\Delta W_{ideal\ to\ ref}$ is the deviation between the ideal surface shape and the spherical reference wavefront and $\Delta W_{non-null}$ is the non-null error. Since the $\Delta W_{ideal\ to\ ref}$ can be calculated and $\Delta W_{non-null}$ can be demarcated, $\Delta W_{act\ to\ ideal}$ can be obtained.

Of course there are two limitations with this testing method. One is that the additive cubic term ($\beta(x^3 + y^3)$) can not be too big otherwise the non-null error can not be replaced by that of best-fit-asphere, the other is that the whole surface shape of best-fit-asphere must be obtained by the non-null testing method. If the deviating between the best-fit-asphere and the reference wavefront is too large, the density of the fringe will exceed the Nyquist frequency of the CCD. Thus more or less data of surface sag will be lost and the non-null error distribution can not be obtained. However, in most optical design the cubic term is slight and the largest deviation is always below 2λ, the only limitation is the gradient of the best-fit-asphere. When the two conditions are both satisfied, the asphere with cubic can be tested through this testing method with good accuracy.

5 Conclusion

It is presented in this paper that a cubic surface has been manufactured and tested. The surface shape is 0.327λ (PV) and 0.023λ (RMS). A non-null method is applied to test the surface and the retrace error is proven to have little effect to the result. The future work concentrates on the manufacturing and testing of more complex unrotational-symmetric surface such as conicoid with cubic terms. Especially, more testing method such as CGH, sub-aperture stitching will be adopted.

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