Science Press

Trans. Nonferrous Met. Soc. China 17(2007) s1160−s1164

Transactions of Nonferrous Metals Society of China

www.csu.edu.cn/ysxb/

Effects of light-mass structural forms on silicon carbide mirror

HAN Jie-cai(韩杰才), HAN Yuan-yuan(韩媛媛), ZHANG Yu-min(张宇民), ZHANG Jian-han(张剑寒), YAO Wang(姚　旺), ZHOU Yu-feng(周玉锋)

Center for Composite Materials, Harbin Institute of Technology, Harbin 150080, China

Received 15 July 2007; accepted 10 September 2007

Abstract: To reduce the mass of the mirror, silicon carbide was used as the material and four light-mass structures were designed. The properties of SiC mirror open back structure with triangular cell, open back structure with hexagonal cell, sandwich structure with triangular cell, sandwich structure with hexagonal cell, were analyzed by using finite element method. The results of the static, dynamic, and thermal properties of the four kinds of SiC mirror indicate that the surface figures of the SiC mirrors are all satisfactory with the design requirements. The properties of the mirrors with sandwich structure are better than those with open back structure, except the high cost. And the mirror with triangular cell has better combination properties than the mirror with hexagonal cell. Considering the overall performance and the cost, open back structure with triangular cell is the most suitable for the SiC mirror.

Key words: silicon carbide; mirror; light-mass; structural form; finite element

1 Introduction

In keeping with the launch capability and cost, the space optics should be compact and light. Especially large mirrors should be stiff and stable, and the mass should be kept to a minimum[1−2]. Reducing the mass of the mirror can have a major impact on reducing not only the self deflection of the mirror but also the mass and cost of the entire system as well as the cost in lab testing[3−4]. Consequently many design schemes have been developed in the effort to develop light-mass mirrors for space optics over the last thirty years[5−7]. Approaches included using light-mass materials, mechanical means, fusion casting, welding means, etc[8−9]. However, there is no quantitative calculation in the traditional mirror design. In this paper, silicon carbide (SiC), the neotype light-mass material for optics, was chosen as the material of a certain primary mirror. The effects of light-mass structural forms on the SiC mirror were quantitative calculation by finite element method, which will improve the design of the mirror.

2 Selection of materials

Under the certain working condition, it is necessary to consider the physical, mechanical, optical, crystallographic and machining abilities of the material in order to choose the most ideal material of the primary mirrors in optical system[10]. The traditional optical materials include: beryllium (Be), fused silica, zerodur, aluminum (Al), etc, while SiC is a kind of neotype light-mass optical material. Two classical features in evaluating the properties of the optical materials are specific rigidity (E/ρ) and thermal distortion ratio (λ/α). The specific rigidity is proportional to the light-mass capability of the material. The thermal distortion coefficient is proportional to the thermal deformation in the presence of heat flow and is indicator of the material's reaction to thermal excursions. The relationship between specific stiffness and thermal stability of the optical materials is shown in Fig.1.

From Fig.1 we can see that SiC has better specific stiffness and the best thermal stability. In addition, SiC has other features and advantages, such as low-cost machining, short manufacturing times, no poison, etc.

Corresponding author: HAN Yuan-yuan; Tel: +86-451-86412432; E-mail: yyhan@hit.edu.cn

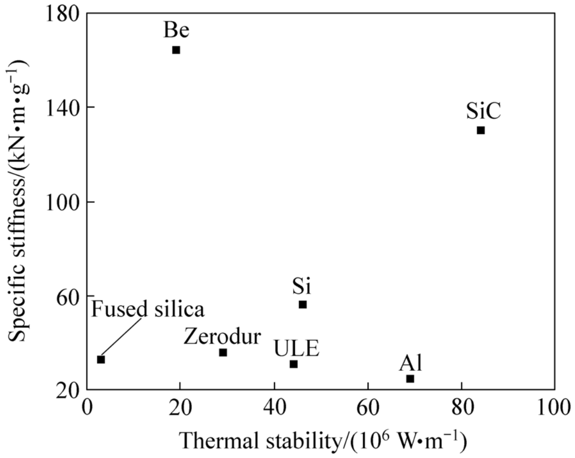

Fig.1 Specific stiffness vs thermal stability

Therefore SiC is the best choice for the mirrors and is chosen as the material of the primary mirror in a Cassegrain system in this study. The properties of SiC material are listed in Table 1.

Table 1 Properties of SiC material

Density/(kg·m^{-3})	Elastic modulus/GPa	Poisson ratio
3080	350	0.17
CTE/(10^{-6}·K^{-1})	Thermal conductivity/(W·m^{-1}·K^{-1})	
2.5	161	

3 Light-mass structural forms

The SiC primary mirror was designed according to the following specifications: diameter of 256 mm with a central hole of 77 mm in diameter with circular shape; plano-concave with parabolic surface; three-point support on the back; wavefront error (WFE) of the mirror $<\lambda/5(p-v)$ ($\lambda=632.8$ nm).

The methods to lighten the mirrors include thinning the mirror thickness, using foam structure or honeycomb structure, etc. The light-mass result of the honeycomb structure is the best, which can be made by machining or using near net shaped method. Honeycomb structure has two categories, open back structure and sandwich structure[11]. Open back structure consists of light-mass core with a front face sheet, while the sandwich structure has two face sheets to stiffen the structure as shown in Fig.2. The front sheet will be polished by conventional or advanced techniques. The light-mass core is designed to reduce mass while providing adequate support for the front plate during both polishing and mirror operation. The back sheet gives the blank further mechanical rigidity and often is used for mount attachments[12]. Manufacturing design parameters of light-mass mirror blanks are core cell pattern, cell size that is usually described by the size of an inscribed circle (b), thickness of the cell wall (t_w), height of the cell structure (h_c), and thickness of the face sheets (t_f).

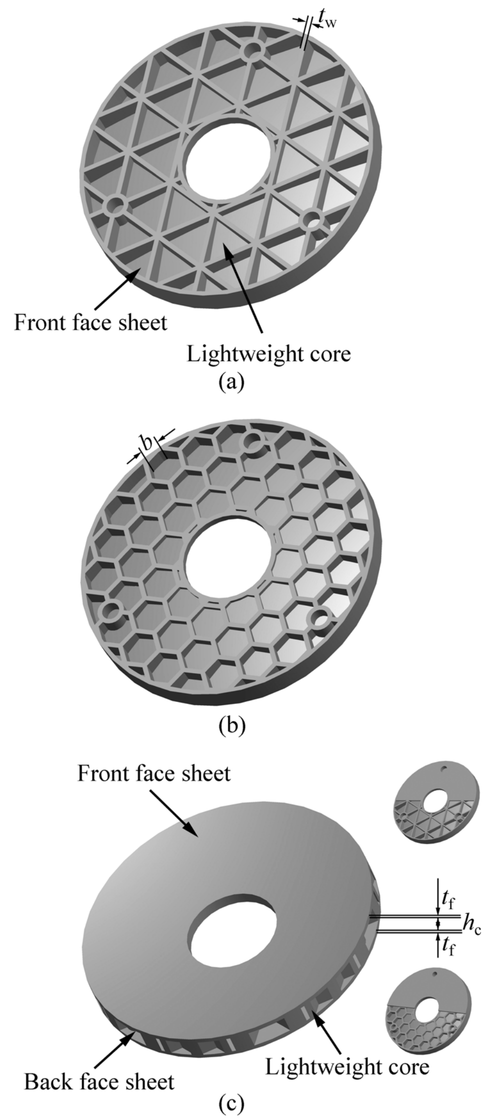

Fig.2 Light-mass mirrors with honeycomb structures: (a) Open back structure with triangular cell; (b) Open back structure with hexagonal cell; (c) Sandwich structure

Theoretically, the core cell patterns include not only the basic geometry such as triangular and square, but also the closed high-order curves, even the combination of various shapes. However, the more complex the cell is, the higher the machining cost is. Considering the locating, the square cell is usually not used for the circlemirror. Since the light-mass ratio of the circle cell that has good processability is very low, it is seldom to be used in the practical project. In this study, the open back structure with triangular and the hexagonal cell schemes, and the sandwich structure with triangular cell and hexagonal cell are compared under the condition of the same main structure parameters, b is 26.5 mm, t_w is 4 mm, t_f is 6 mm and 3 mm for open structure and sandwich structure respectively, h_c is 17 mm.

4 Finite element analysis of the mirror

4.1 Analysis of Gravity field and natural frequency

There are two cases when analyzing the effects of the gravity field on the mirror. One is the gravity direction that is vertical to the thickness direction of the mirror (x or y direction), the other is parallel to the thickness direction of the mirror (z direction), which has greater effect on the mirror surface. When laying the mirror horizontally, the maximum displacement of the circle mirror along the axial direction is given by[13]

$$\delta = C_s \frac{\gamma d^4}{Eh^2} \tag{1}$$

where C_s is the coefficient of the supporting condition, γ and E are the specific density and elastic modulus of the mirror material, respectively; d and h are the diameter and thickness of the mirror, respectively. It is shown that the diameter of the mirror is the main factor that affects the deformation of the mirror surface, which decreases with the thickness of the mirror increasing.

A measure of structural stiffness is flexural rigidity, which can be described as[14]

$$D = \frac{Eh_B^3}{12(1-v^2)} \tag{2}$$

where h_B is the equivalent thickness, ρ, E and v are density, elastic modulus and Poisson's ratio of the material, respectively. With h_B increases, the flexural rigidity of the mirror increases, which make the deformation of the mirror decrease.

Natural frequency is one of the structural vibration performances, which is given by[15]

$$f = (C/2\pi)\sqrt{g/\delta_{\max}} \tag{3}$$

where f is the fundamental natural frequency, C is the correction factor, g is acceleration due to gravity, $\delta_{\max}$ is the maximum static deformation. The natural frequency of the mirror should be high enough to gain better surface figure of the mirror.

In this study, the gravity of 1g is loaded along axial direction of the mirror, and the constraint condition is to restrict all translational degrees of freedom (DOF). Since the maximum stress that the mirror receives under the working condition is much smaller than the critical stress of the mirror material, it is ignored here. The finite element models of the mirrors are shown in Fig.3, and the calculated results are listed in Table 2.

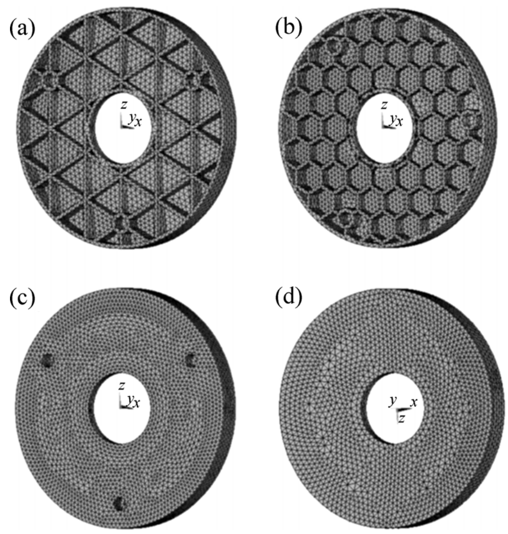

Fig.3 Finite element models of mirrors: (a) Open back structure with triangular cell; (b) Open back structure with hexagonal cell; (c) Sandwich structure with triangular cell or hexagonal cell; (d) Front of the mirror

Table 2 Properties of mirrors

Mirror	Cell	Mass/kg	Deformation/nm
Open back structure	Triangular	1.43	33.5
	Hexagonal	1.45	36.7
Sandwich structure	Triangular	1.43	19.4
	Hexagonal	1.45	19.6

First five order natural frequency/Hz				
1	2	3	4	5
3 150.7	3 284.0	3 457.1	5 760.0	7 414.1
2 974.2	3 039.3	3 295.1	5 153.4	6 888.7
3 947.6	3 959.2	4 444.9	6 943.5	9 718.0
3 973.6	3 987.0	4 399.2	6 608.1	9 495.1

From Table 2 we can see that with the same mass, the deformation of the sandwich structure is much lower than that of the open back structure, that is to say, the mirror with the sandwich structure can be made much lighter under the same surface figure. However, the cost of the sandwich structure is much higher than that of the open back structure with triangular cell. The natural frequency of the mirror with sandwich structure and triangular cell is higher than that of the mirror with open back structure and hexagonal cell, which shows that the rigidity of the mirror with triangular cell is better. The deformations of the mirrors under the gravity of 1g are shown in Fig.4.

4.2 Analysis of thermal filed

Temperature variation is another important factor that affects the surface figure of the mirror. Therefore several kinds of temperature distribution on the effects of the surface figure were analyzed. 293 K is set as the original temperature of the SiC mirror. The temperature difference is 0.1−0.5 K. First, the steady-state temperature field is calculated under different temperature levels and temperature difference in the axial and radial direction, and then the deformations of the SiC mirrors are calculated. The results of the finite element analysis are listed in Table 3.

It can be seen from Table 3 that the maximum deformation of the mirror surface is proportional to the temperature level difference. Generally the effect of the temperature level difference on the mirror surface is the most obvious, following the axial temperature field. The deformation of the mirror with sandwich structure is lower than that of the mirror with open back structure under any temperature field except that of open back structure with triangular cell under the axial temperature difference. Overall consideration, the properties of the open back structure with triangular cell is better than that of the open back structure with hexagonal cell under any temperature fields. The deformations of the mirror with open back structure with triangular cell under different temperature fields are shown in Fig.5.

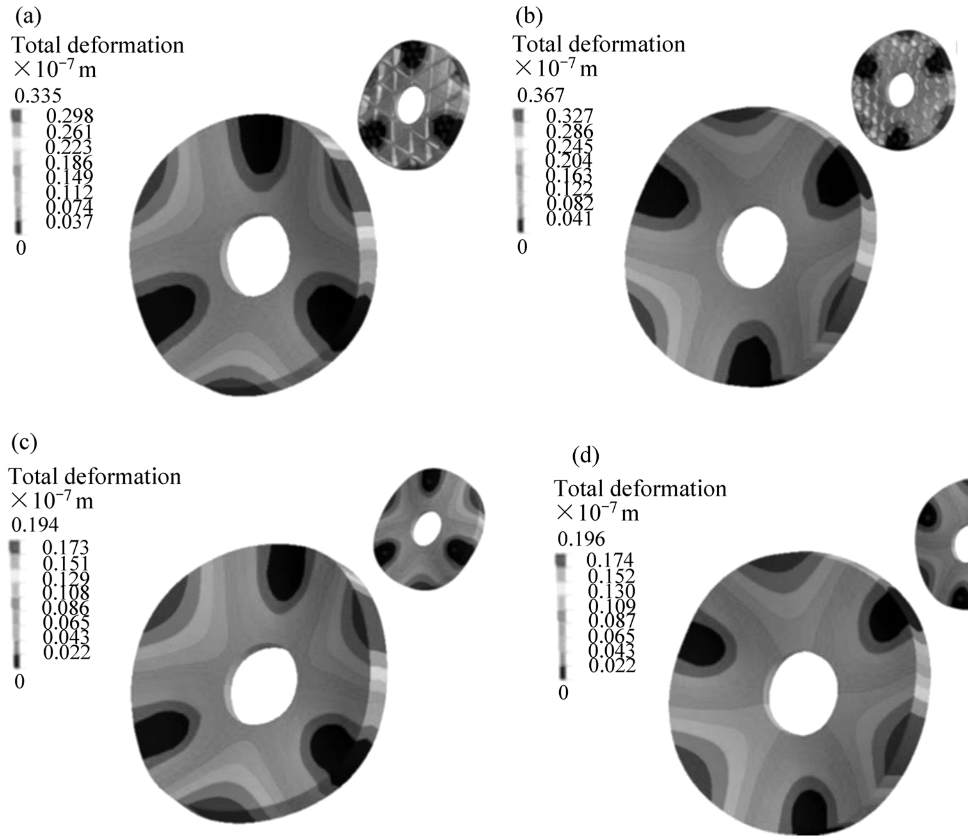

Fig.4 Deformations of mirrors under gravity of 1*g*: (a) Open back structure with triangular cell; (b) Open back structure with hexagonal cell; (c) Sandwich structure with triangular cell; (d) Sandwich structure with hexagonal cell

Table 3 Deformations of mirror surfaces under different temperatures difference

Mirror	Cell	Maximum displacement of the faceplate/nm														
		Temperature level difference/K					Radial temperature difference/K					Axial temperature difference/K				
		±0.1	±0.2	±0.3	±0.4	±0.5	±0.1	±0.2	±0.3	±0.4	±0.5	±0.1	±0.2	±0.3	±0.4	±0.5
Open back structure	Triangular	32.4	64.8	97.2	129.6	162.0	28.2	56.4	84.6	112.8	141.0	23.8	47.6	71.4	95.2	119..0
	Hexagonal	40.6	81.2	121.8	192.4	203.0	25.8	51.6	77.4	103.2	129.2	28.2	56.4	84.6	112.8	141.0
Sandwich structure	Triangular	28.4	56.8	85.2	113.6	142.0	22.0	44.0	66.0	88.0	110.0	24.8	49.6	74.4	99.2	124.0
	Hexagonal	28.8	57.6	86.4	115.2	144.0	22.6	45.2	67.8	90.4	113.0	25.2	50.4	75.6	100.8	126.0

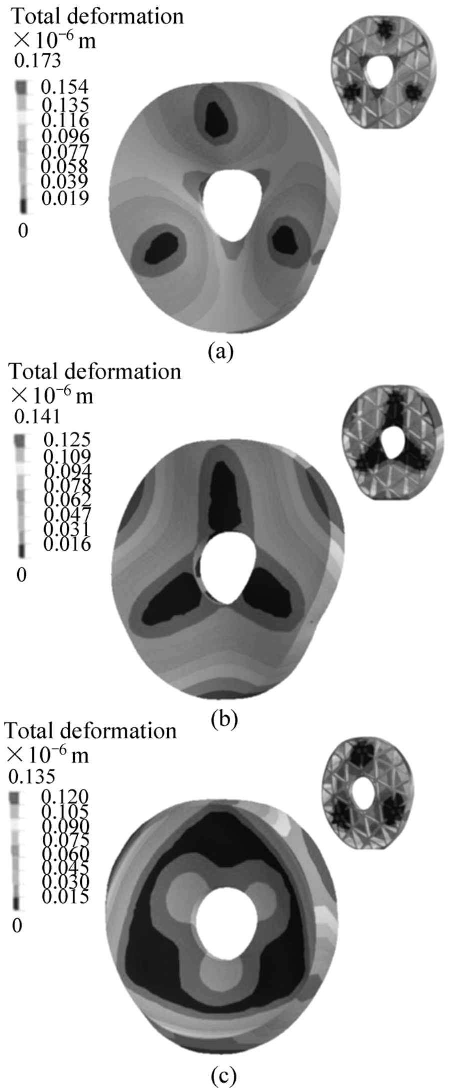

Fig.5 Deformations of mirrors with triangular cell open back structure under three temperature fields: (a) Temperature level difference with 0.5 K; (b) Radial temperature difference with 0.5 K; (c) Axial temperature difference with 0.5 K

4 Conclusions

1) The properties of the mirror with sandwich structure are better than those of the mirror with open back structure.

2) For the sandwich structure, the properties of the mirror with the triangular cell are close to those of the mirror with hexagonal cell.

3) For the open back structure, the properties of the mirror with the triangular cell are better than those of the mirror with hexagonal cell.

4) The costs of the sandwich structure and the hexagonal cell are much higher than those of the mirror with open back structure and triangular cell.

5) Overall consideration, the open back structure with triangular cell is the most suitable for the mirror in the optic system.

References

[1] BOUQOIN M, DENY P. The SiC technology is ready for the next generation of extremely large telescopes[J]. SPIE, 2004, 5494: 9−18.

[2] ROBICHAUD J, GUREGIAN J J, SCHWALM M. SiC optics for earth observing applications[J]. SPIE, 2003, 5151: 53−62.

[3] CONKEY S B, LEE C, CHAYKOVSKY S. Optimum design of a light-weight mirror using aluminum foam or honeycomb sandwich construction—a case study for the GLAS telescope[J]. SPIE, 2000, 4093: 325−332.

[4] SEIN E, TOULEMONT Y, SAFA F. A Φ3.5M SiC telescope for HERSCHEL Mission[J]. SPIE, 2003, 4850: 606−618.

[5] EBIZUKA N, DAI Y T, ETO H. Development of SiC ultra light mirror for large space telescope and for extremely huge ground based telescope[J]. SPIE, 2003, 4842: 329−334.

[6] ROBICHAUD J. SiC optics for EUV, UV, and visible space missions[J]. SPIE, 2003, 4854: 39−49.

[7] SEIN E, TOULEMONT Y, BREYSSES J. A new generation of large SiC telescopes for space applications[J]. SPIE, 2004, 5528: 83−95.

[8] JEONG I L, SEONG S C. Optical large mirror design[J]. SPIE, 2005, 5852: 60−66.

[9] BENNETT H E, SHAFFER J J, ROMEO R. Development of light-weight mirror elements for a very large astronomical adaptive optic primary mirror[J]. SPIE, 2003, 4840: 258−272.

[10] GULATI S T. Design consideration for mirror materials[J]. SPIE, 1996, 2857: 2−10.

[11] EALEY M A, WELLMAN J A. Ultralight-weight silicon carbide mirror design[J]. SPIE, 1996, 2857: 73−77.

[12] EDWARDS M J. Current fabrication techniques for ULETM and fused silica light-weight mirrors[J]. SPIE, 1998, 3356: 702−711.

[13] PEPI J W. Analytical predictions for light-weight optics in a gravitational and thermal environment[J]. SPIE, 1987, 748: 172−179.

[14] MEHTA P K. Flexural rigidity characteristics of light-massed mirrors[J]. SPIE, 1987, 748: 158−171.

[15] MYUNG K C, RALPH M R. Structural and optical properties for typical solid mirror shapes[J]. SPIE, 1990, 1303: 78−95.

(Edited by HE Xue-feng)