ANALYSIS AND TEST STUDY OF THERMAL DEFORMATION ON A GRID REINFORCED CFRP MIRROR

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ABSTRACT

Due to the low density and extremely low thermal expansion, carbon fibre reinforced plastic (CFRP) is one of potential materials applied as precise dimension components. High precise structures, such as antenna reflectors and mirrors, require very strict thermal stability. However, the CFRP laminate usually companied with large thermal deformation, because of align error, thickness error, fiber and resin uneven distribution in the preparation. Therefore, a novel grid reinforced structure was adopted to improve stiffness and resistance of thermal deformation. The validity of the design is verified by finite element method. The thermal deformation test based on the vacuum tank verifies the reliability of the finite element analysis results. For Φ150mm CFRP mirror, the test results show that the thermal deformation RMS is only 16nm when 4.5℃ raised, so thermal stability is just about 3.5nm / ℃, and satisfied the requirements in high precise structure application.

1 INTRODUCTION

Optical mirrors are mainly made of glass, silicon carbide and other materials. With the development of space optics and the widespread application of carbon fiber composites in space, it has explored the use of carbon fiber composites to fabricate lightweight spatial optical mirrors. Compared with other optical materials, carbon fiber composite material has a more balanced performance: 1) extremely low density, high specific stiffness, and low thermal expansion coefficient; 2) because of using the replication process, rapid and low-cost fabrication can achieved; 3) manufacturing equipment is relatively mature, can achieve large-diameter mirror blank, to meet the current camera diameter is growing (diameter 5 ~ 20 m), area density is getting smaller and smaller (2 ~ 10 kg / m^2) requirements. Since the beginning of the 1990s, many foreign institutions have carried out high-precision carbon fiber mirror research [1 - 5].

Nano-level high precise applications in space environment, very strict thermal stability required. In addition, the infrared telescope needs to be cooled to a low temperature environment to reduce radiated noise, so thermal stability from room temperature to low temperature is important to maintain surface accuracy. In paper [6], the thermal deformation analysis and experimental study of the carbon fiber mirror are carried out. It is considered that the laying-up error is the main reason for the out-of-plane error of the mirror blank. From [7], the thermal deformation test of all-CFRP mirror conducted. Test temperature range from 120K to 360K, the thermal stability of the mirror is about 20nm / ℃.

As we know, CFRP laminate cannot realize high thermal stability because of align error, thickness error, fibre and resin uneven distribution. Therefore, Sandwich structure usually adopted to improve stiffness and resistance of thermal deformation. In this paper, a novel grid reinforced structure was adopted to achieve highly thermal stability. Finite element analysis and thermal deformation test results verified the validity of the structure.

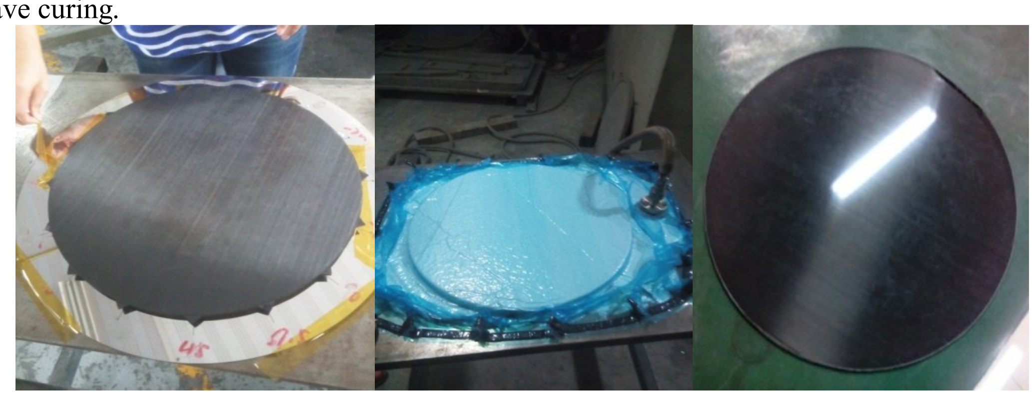
2 DESIGN AND MANUFACTURE OF LAMINATED LAYERS BASED ON THERMAL STABILIZATION

Carbon fibre composite laminates are formed by the anisotropic prepregs, and different ply designs will directly affect the in-plane and out-of-plane properties of the laminate. In addition, carbon fiber laminates under the heat load, the general appearance of "saddle-shaped" surface outside the astigmatism error. The asymmetric properties of the laminate itself are considered to be the main cause of the variation of the astigmatism, especially the anisotropy caused by the laying-up angle error [8-9].

Therefore, in order to improve the accuracy of the laminate molding surface and its thermal stability, the most direct method is to choose a lower curing temperature of the prepreg. This article selected medium temperature 120 ℃ curing M40/epoxy material system.

The authors conducted thermal deformation evaluation of carbon fiber laminates based on classical laminated plate theory and Monte Carlo method [10]. According to the minimum thermal deformation to determine the optimal design of the laying-up, while taking into account the bending stiffness uniformity, the final optimization of order is $[22.5\ 90\ -45\ -22.5\ 67.5\ -67.5\ 0\ 45]_s$.

Based on the above-mentioned optimized lamination sequence, the laying of the carbon fiber laminate is shown in Fig. 1a, where the prepregs is left with an aligned sharp corners and aligned with the slots on the tooling to achieve high accuracy angular alignment. The final molded laminate is shown in Figure 1c. For Φ300mm laminated panels, the profile accuracy is better than 0.05mm after autoclave curing.



(a)lay up (b) Hot pressing curing (c)laminate finished

Figure 1: Development of carbon fiber laminate based on optimized laying-up design.

3 STRUCTURAL DESIGN OF GRID REINFORCED CFRP MIRROR

Although the thermal stability of the carbon fiber laminate can be improved by optimizing the stacking sequence. However, due to the laying error, thickness error and non-uniformity of fiber/resin ratio, carbon fiber laminates are still accompanied by large thermal deformation. The honeycomb sandwich structure is therefore often used to improve rigidity and resistance to thermal deformation. Commonly used honeycomb core structures include aluminum honeycomb, NOMEX honeycomb, and grid reinforcement. In all honeycomb sandwich structures, the grid reinforcement structure is the best choice because the honeycomb can select the same material as the front and rear panels. Because there is no "bimetallic effect", higher thermal stability can be achieved.

The structural design of the grid-reinforced carbon fiber mirror is shown in Figure 2, including the front panel, the rear panel, and the middle grid-reinforced core structure. Front and rear panel thickness of 2mm, 16 layers of prepreg used, laying-up order is $[22.5/90/-45/-22.5/67.5/-67.5/0/45]_S$. The grid-reinforced structure is made of 1mm carbon fiber laminates with the same material system as the panels, and the laying-up order is $[0/90/45/-45]_s$.

The grid-reinforced structure of the mirror plays an important role in the stability of the mirror [11]. Considering the isotropy and the convenience of the process, the grid reinforcement structure adopts the triangular configuration. Article [12] proposed a novel grid reinforced structure design, design from the inside to outside, upward and downward cycle of the method to complete the honeycomb design. The design has the advantages of better rigidity uniformity and easy implementation of the adhesive process.

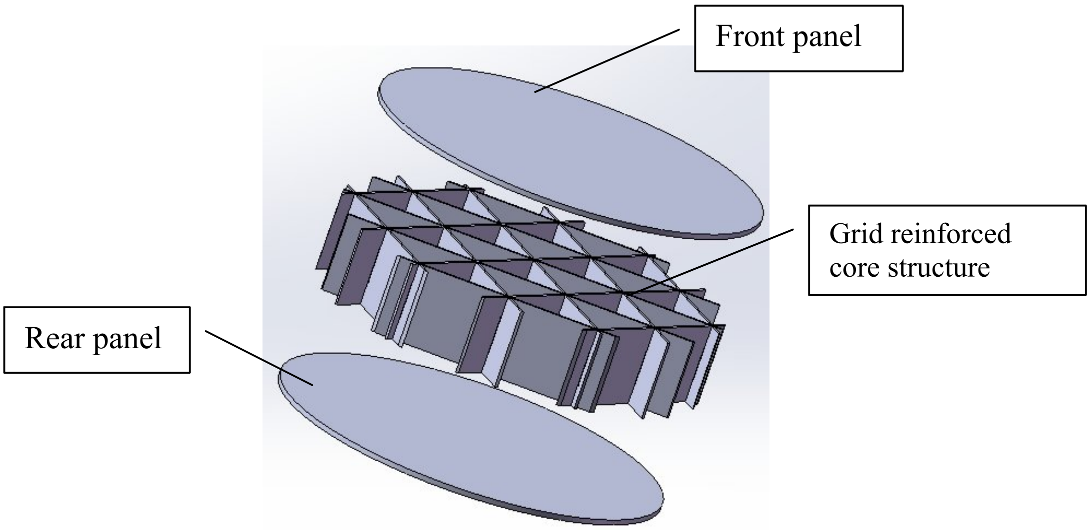


Figure 2: structural design of the grid-reinforced CFRP mirror.

Based on the above design results, the development of Φ150mm CFRP grid reinforced carbon fiber mirror was carried out. The engineering constants of the selected material system are shown in Table 1. Low shrink epoxy adhesive used to bond the plug-in panels to form grid-reinforced core, and bond the front and rear panels to the core structure. The finished Φ150mmCFRP grid reinforced carbon fiber mirror as shown in Figure 3.

Engineering constant		Magnitude
E_{11}	[GPa]	50
E_{22}	[GPa]	50
E_{33}	[GPa]	4
ν_{12}	–	0.3
ν_{23}	–	0.25
ν_{31}	–	0.02
G_{12}	[GPa]	5
G_{23}	[GPa]	2
G_{31}	[GPa]	2
α_{11}	[10^{-6}/℃]	2
α_{22}	[10^{-6}/℃]	2
α_{33}	[10^{-6}/℃]	50

Table 1: Three dimension orthotropic engineering constants of CFRP.

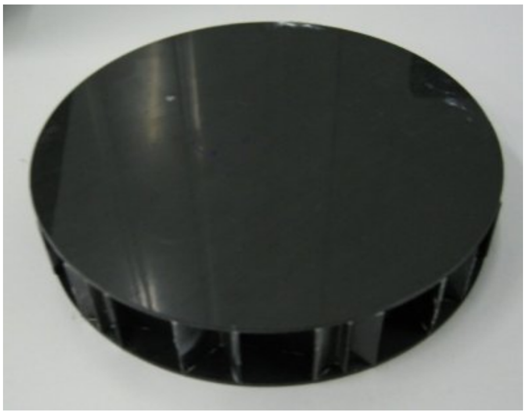
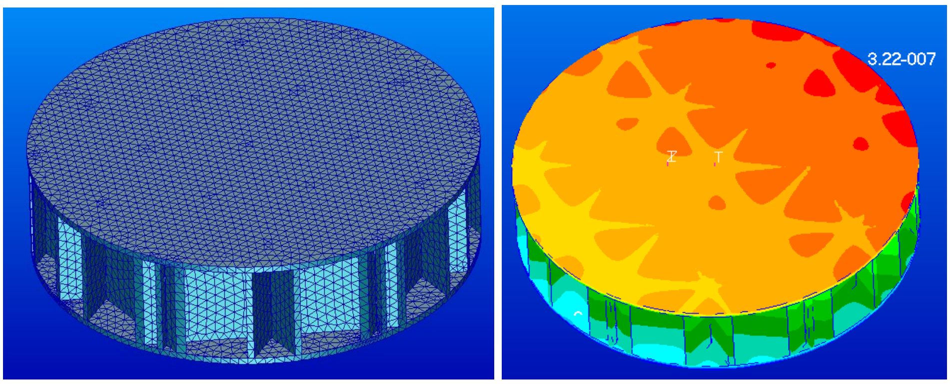


Figure 3: The Φ150mm CFRP mirror blank.

4 THERMAL DEFORMATION ANALYSIS OF THE CFRP MIRRORS

In order to consider the influence of the thermal expansion in the thickness direction of the carbon fiber laminate, the finite element model uses the solid element, and total 62967 elements as shown in Fig. 4 (a). The material model selects the three dimension orthotropic model, as shown in Table 1, without considering the laying-up angle error to bring the anisotropy of the panel and the plug-in panel. All nodes temperature increased by 1 ℃, the analysis results shown in Figure 4 (b).



(a) FEA model (b) surface change after 1℃ raised

Figure 4: FEA model and analysis result of the Φ150mm CFRP mirror.

Through the calculation, the temperature elevated 1 ℃, the out-of-plane deformation of the Φ150mm mirror: PV value 19.6nm, RMS 3.34nm. The thermal deformation is mainly manifested as the "grid effect" of the triangular grid shape, which is mainly due to the fact that the thermal expansion coefficient of the plug-in plate is much larger than its in-plane direction. Increasing the thickness of the front panel or reducing the thickness of the plug-in panels can further reduce the thermal deformation.

5 THERMAL DEFORMATION TEST OF CFRP MIRROR

After the development of the carbon fibre mirror blank is completed, the surface modification of the mirror blank is carried out by optical replication. Optical replication is a process using a thin layer of resin as the surface of the mirror and copying high precision surface profile of the mould.

As shown in Fig 5, in view of the influence of the carbon fibre composite material on the moisture absorption deformation, the thermal deformation test of the carbon fibre mirror was carried out using a vacuum tank with a temperature fluctuation of ± 0.2 °C. The dynamic interferometer used to test surface profile of the Φ150mm CFRP mirror in the tank through a quartz window.

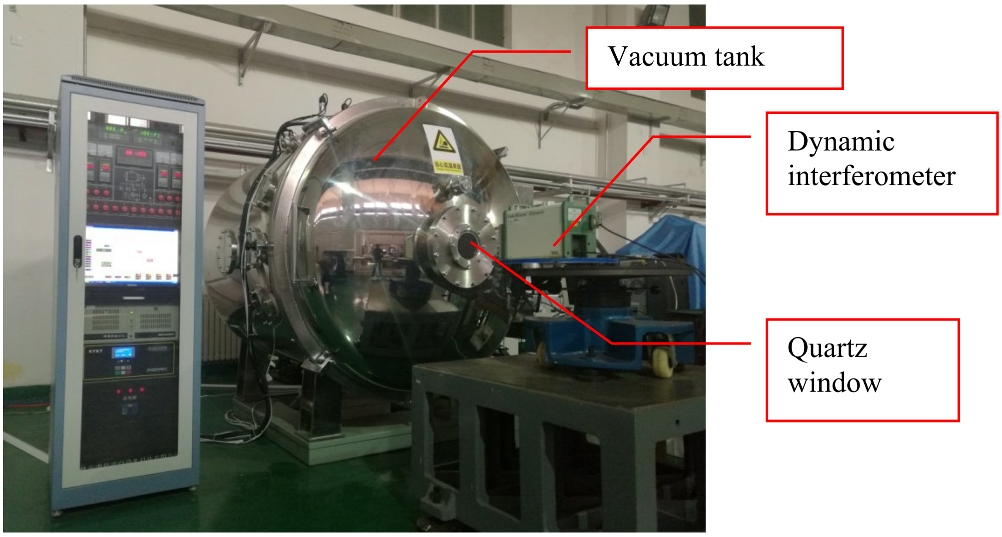


Figure 5:Thermal deformation test of the Φ150mm CFRP mirror .

When the vacuum to 10^{-4}Pa, the temperature to 21 °C, surface profile shown in Figure 6 (including the transmission wave of the quartz window). Due to the diameter limit of the interferometer, only the Φ100mm area surface of Φ150mm carbon fibre mirror was tested. And then the temperature increased to 25.5 °C, hold this temperature for 3 hours and test surface profile again, the result shown in Figure 7. So the thermal deformation result when 4.5 ℃ raised shown in Figure 8, and thermal stability is about 3.5nm/°C.

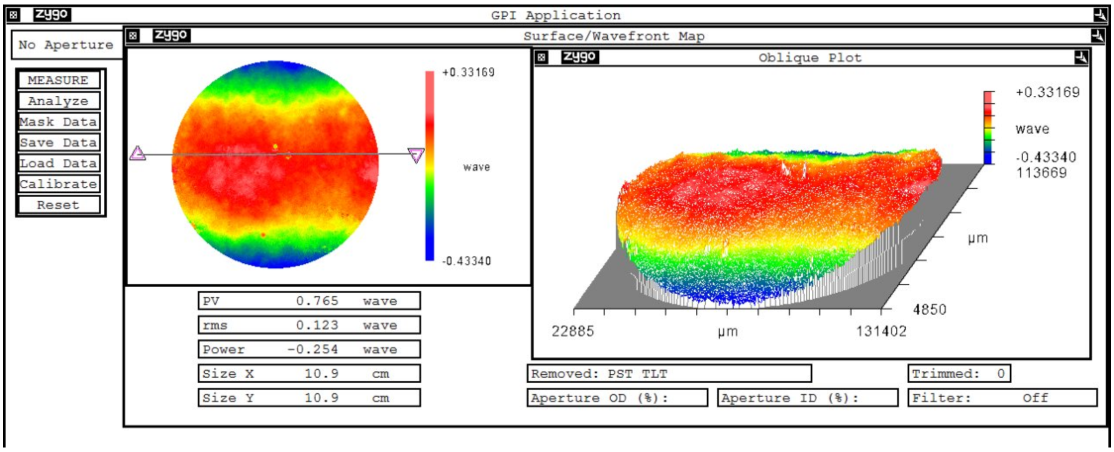


Figure 6: surface profile at 21℃ .

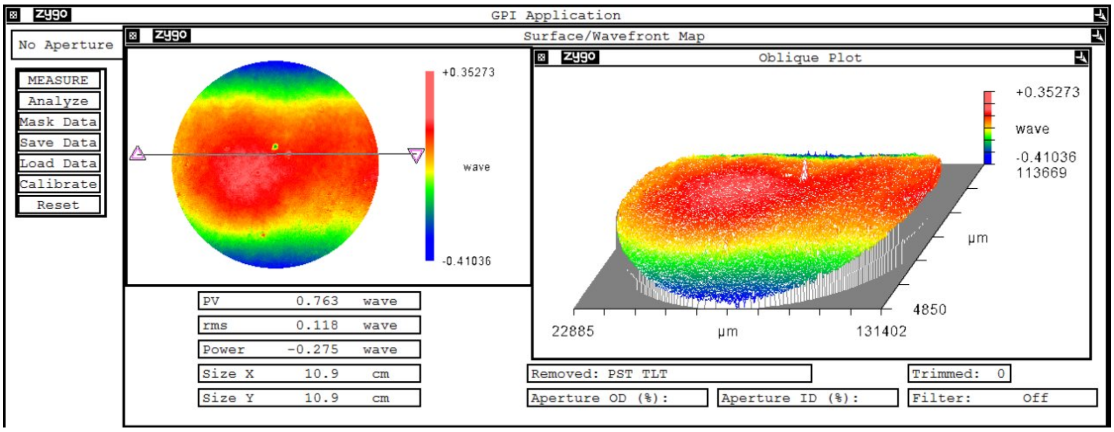


Figure 7:surface profile at 25.5℃ .

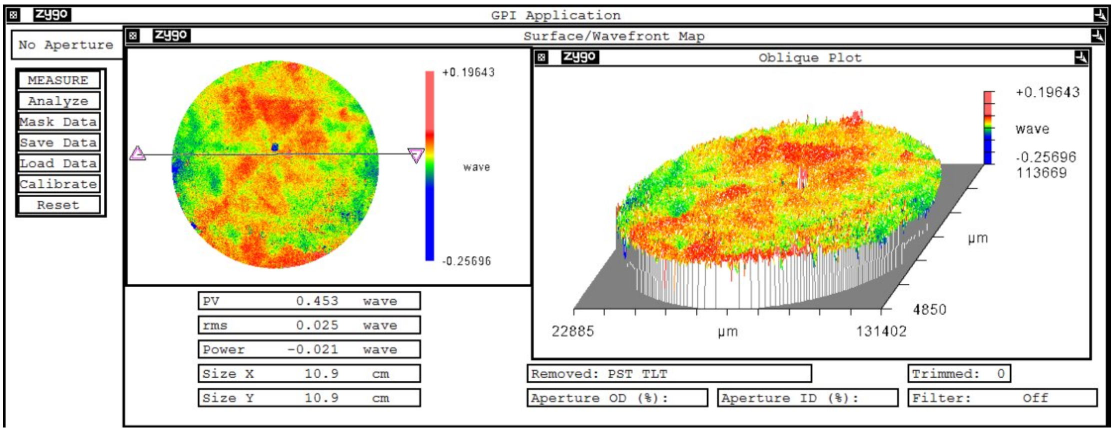


Figure 8: Thermal deformation result when 4.5℃ raised.

6 CONCLUSIONS

1) The carbon fibre panels developed with optimized ply design [22.5/90/-45/-22.5/67.5/-67.5/0/45]$_s$ have excellent thermal stability and uniform bending stiffness. ;

2) The innovative grid reinforced structure is designed to improve the thermal stability of carbon fibre mirrors, from 10nm / ℃ to 3.5nm / ℃.

3) The finite element model of 150mm carbon fibre flat mirror is established by using solid element. Through the FEA calculation, out-of-plane deformation of the Φ150mm mirror is 3.34nm (RMS) when 1 ℃ raised.

4) Thermal deformation test performed using a vacuum tank. The thermal stability of the Φ150mm mirror is 3.5nm / ℃ .The results of thermal deformation test verify the effectiveness of finite element analysis.

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