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Original research article

Ultra-thin carbon fiber mirrors: nickel plated, optical fabrication and thermal deformation test

Liang Xu*, Yongjie Xie, Yongjie Wang, Jiaoteng Ding, Zhen Ma, Xuewu Fan

Xi'an Institute of Optics & Precision Mechanics, Chinese Academy of Sciences, Xi'an, 710068, China

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ABSTRACT

The aperture of space remote sensing camera is increasing, and the demand for lighter weight is getting higher and higher. With the advancement of active optics, the thickness of optical components has gradually grown to light and thin. It is extremely difficult to develop ultrathin mirrors using brittle materials such as traditional optical glass and silicon carbide. Due to advantages such as low density, high specific stiffness, low thermal expansion coefficient, toughness, and additive rapid manufacturing properties, carbon fiber reinforced plastic (CFRP) is one of potential applications for large-diameter ultra-thin mirrors. However, the carbon fiber composite material is a two-phase material that cannot be used as optical surface and must be surface-modified. In this paper, the surface modification of CFRP substrate was carried out by chemical nickel plating and nickel electroplating. The modified nickel layer covers all surfaces of CFRP substrate, and nickel layers satisfying the thickness, bonding force, and internal stress requirements. A Φ100 mm aperture ultra-thin carbon fiber mirror developed, after optical fabricating, its surface accuracy RMS is better than λ/15. Thermal deformation analysis and test show that the thermal deformation of ultra-thin carbon fiber mirrors is mainly manifested by the change of radius of curvature, which is caused by the thickness error of the nickel layer on the front and rear faces. In addition, although thermal deformation caused by the lamination angle error of CFRP substrate is relatively small in value, it should still be given enough attention, because the astigmatic error produced is hard to eliminate.

1. Introduction

Increasingly demanding science goals from the astrophysics, astronomy, and earth sciences communities necessitate the development of large aperture telescopes. Such as ATLAST (Advanced Technology Large Aperture Space Telescope) concept [1], the aperture of primary mirror reaches 16.5 m, and is made up of several sub-mirrors with 1 m aperture. With such a large diameter, using traditional rigid or semi-rigid mirrors, the weight is unacceptable, and the level of light weighting must be further reduced.

Active optical technology based on ultra-thin mirrors is considered a possible technical approach for future large-aperture space remote sensing cameras. Unlike thin-film mirrors, ultra-thin mirrors are on the order of millimeters in thickness and have a certain amount of surface self-sustaining capability. The precise shape of the ultra-thin mirror can be adjusted by the actuator and can be corrected in real time.

Using conventional brittle optical element materials (optical glass, silicon carbide, etc.) to develop such millimeter-level ultra-thin mirrors is extremely difficult, costly, Time-consuming, and easy to crack. With the characteristics of low density, high specific

* Corresponding author.
E-mail address: liangx@opt.ac.cn (L. Xu).

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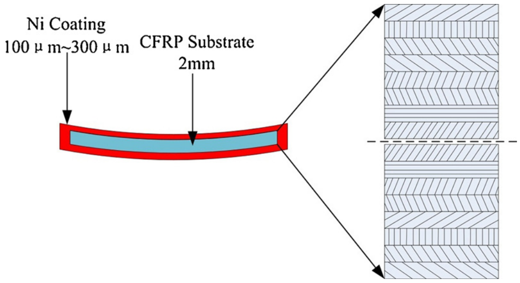

Fig. 1. Schematic structure of ultra-thin carbon fiber mirror blank.

stiffness, low coefficient of thermal expansion, etc. CFRP material is one of the ideal materials for the space optical element. At present, many research institutes have conducted technical studies on the application of visible-band carbon fiber mirrors [2–6]. Also with high toughness and additive manufacturing properties, CFRP material is suitable for the development of future large-aperture ultra-thin mirrors.

CFRP is a one of two-phase structural material, including a carbon fiber reinforced body and a polymer matrix, so it cannot be used as a reflective surface material and must be surface-modified. At present, surface modification processes of CFRP mirrors common used include two processes: 1) faces of substrate are completely covered with nickel plating, and the nickel layer can also be used as a hygroscopic barrier layer, to prevent the effect of moisture on the dimensional stability of the polymer resin. UCL [7,8] (University College London) uses surface nickel plating process for surface modification of ultra-thin carbon fiber mirrors; 2) optical replication process, by adding a thin layer of resin to the front face of the CFRP substrate as an optical reflective surface. Directly copying the high-precision surface of optical mold, and eliminating subsequent time-consuming optical processing. The drawback of optical replication is that the composite substrate and the modified resin layer are exposed to the air environment and there is dimensional instability under the influence of moisture. Both CMA [9] (Composite Mirror Applications, Inc.) and JAXA [10] (Japan Aerospace Exploration Agency) use optical replication processes to modify the surface of carbon fiber mirrors.

In this paper, nickel-plating process is used to modify the surface of ultra-thin carbon fiber mirrors. Nickel plating process is studied in terms of nickel layer thickness, improving bonding force and reducing internal stress. After finishing the nickel-plated surface modification, optical fabricating and thermal deformation testing were performed.

2. Ultra-thin carbon fiber mirror blank structure

Ultra-thin carbon fiber mirror blank structure is schematically shown in Fig. 1. It mainly includes a CFRP substrate layer and a nickel-plated modified layer completely covering the surface of the substrate. The thickness of the CFRP substrate layer is only 2 mm thick, and unidirectional prepregs are laid according to the optimized lamination sequence [11]. The T300/epoxy composite system was selected. The material parameters are shown in Table 1. The thickness of single-layer prepreg is 0.125 mm, and the optimized layup sequence is $[22.5/90/\text{-}45/\text{-}22.5/67.5/\text{-}67.5/0/45]_s$. The nickel-plated modified layer covers all the faces of CFRP substrate, and the thickness is 0.1 ~ 0.3 mm, which requires that the nickel layer material be dense and uniform in thickness. The material parameters of the nickel layer are shown in Table 2.

The main process steps of nickel-plated modified ultra-thin carbon fiber mirrors include: 1) Hot pressing curing of CFRP substrate, and the initial surface accuracy is as high as possible; 2) nickel-plated surface modification, to meet the requirements of a certain thickness, but also to meet the binding force, low stress; 3) The front surface is optically fabricated to achieve high-precision surface, including grinding and polishing processes; 4) In order to further improve the reflectivity, the reflective film can be vapor-deposited.

3. Nickel plated used for surface modification

The nickel plating process is suitable for the wide substrate, dense coating and strong bonding with the substrate, uniform and deep plating ability, easy to change the composition and mass fraction of the coating, and has unique advantages in the technology of metallization on the surface of the material.

Commonly used nickel plating processes include chemical plating and electroplating. The electroconductivity of CFRP material is not so good, and direct electroplating will inevitably result in the leakage plating. With chemical plating, there is a limit to the thickness of the nickel plating layer. Therefore, it is difficult to achieve the purpose using chemical plating or electroplating alone. For this reason, the surface modification of the ultra-thin carbon fiber mirror is realized by the Combination of chemical plating and

Table 1
Material parameters of CFRP unilateral plate.

E_{11}(GPa)	E_{22}(GPa)	λ_{12}	G_{12}(GPa)	$\alpha_{11}(10^{-6}/°C)$	$\alpha_{22}(10^{-6}/°C)$
134	8.9	0.285	4.7	−0.46	52.3