Materials and Design 30 (2009) 9–14

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Effect of materials and modelling on the design of the space-based lightweight mirror

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ARTICLE INFO

Article history:
Received 27 November 2007
Accepted 22 April 2008
Available online 1 May 2008

Keywords:
A. Multi-materials
B. Honeycombs
E. Mechanical

ABSTRACT

This paper focused on the application of finite element analysis in the design and validation of a space-based lightweight mirror. Reaction-bonded silicon carbide (RB SiC) and silicon carbide particle reinforced aluminum matrix composites (SiC_p/Al) were selected as candidate materials for the mirror, and the finite element model created by discretizing the mirror assembly was employed to predict the performance of the mirror. The results indicated that RB SiC offered more excellent characteristics relative to other traditional materials and was a better candidate for space application in comparison with SiC_p/Al.

1. Introduction

An on-orbit optical system could result in increased precision and stability. There are several reasons why space is an excellent place for a telescope. First and foremost, the instrument is above the Earth's atmosphere, and the atmosphere is the source of several concerns. The biggest issue is atmospheric absorption over portions of the near infrared spectrum. The atmosphere also contains the weather events like clouds, precipitation, and high winds. In addition to the weather, the atmosphere contains turbulent wind layers that degrade the image quality [1,2].

Although refractive optics is still used in many areas, reflective optics has proven advantageous in a majority of optical imaging applications, especially in the space-based optics field [3–7]. The color aberration is avoided in the reflective optical system because the mirrors reflect instead of refract the energy from the source, and mirrors can be used to form image with high brightness and precision [8]. Moreover, the use of lightweight large-scale mirror can increase the performance and efficiency of an optical system.

As components for use in space, the mirrors must satisfy strict functional and operational requirements. They must be lightweight, fit in the payload shroud of the launch vehicle, and withstand high launch accelerations [9]. Many materials such as monolithic aluminum, optical grade beryllium, ULE glass and Zerodur have been used to fabricate the space-based mirrors over the past several decades [10–12]. The materials mentioned above could be placed into one of two categories: metals and glasses/glass-ceramics. Metals have a much higher thermal conductivity than glasses/glass-ceramics, however, many glasses and glass-ceramics benefits from having a much lower coefficient of thermal expansion and elasticity. The high thermal conductivity, low coefficient of thermal expansion and elasticity are very important for the space mirror materials.

In the recent years, the silicon carbide and silicon carbide reinforced aluminum matrix composites have become attractive candidate materials for space-based lightweight mirrors due to excellent thermal and mechanical performance. Reaction-bonded silicon carbide (RB SiC) and silicon carbide particle reinforced aluminum matrix composites (SiC_p/Al) have higher thermal stability (thermal conductivity/coefficient of thermal expansion) and specific stiffness (elastic modulus/density) than fused silica, ULE and Zerodur. In comparison with beryllium, RB SiC and SiC_p/Al have disadvantage of low specific stiffness, whereas high thermal stability, innocuity and isotropic properties make RB SiC and SiC_p/Al more attractive than beryllium for space application. Thus, RB SiC and SiC_p/Al have been chosen for a prototype design of the space-based lightweight mirror in this paper. It should be noted that it is quite expensive to experimentally validate the performance of the mirror prototype, and thus finite element simulation alone can provide a valuable insight and understanding of this design and help in new prototype or product design and development [13–17]. Finite element modelling and simulation of the lightweight mirror is quite complex in nature due to the complexity of the mirror structure and the loading conditions. In the subsequent section the finite element modelling and simulation details based on finite element analysis package ANSYS are presented.

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doi:10.1016/j.matdes.2008.04.056

2. Design specifications

The mirror assembly model developed is shown in Fig. 1. Two shafts are mounted and glued in the two holes of the elliptic open-back mirror substrate, respectively. The substrate consists of a faceplate and many reinforcing ribs arranged in the hexagonal pattern. The whole component is supported by the shafts at the bearing positions, and then the displacement of the mirror assembly is constrained entirely. The structural parameter definition of the mirror substrate is shown in Fig. 2, the dimension values are listed in the Table 1.

The image quality and precision of the optical system are mainly influenced by surface figure error of the mirror. In the present study, the mirror surface error must be less than 80 nm, which is the foremost precondition of the mirror design. The strength margins and natural frequency are important factors for the safety of the mirror under launching loads. For this work, the maximum equivalent stress of the mirror under launching loads must be lower than material strength and the first mode frequency of the mirror must be more than 100 Hz in order to avoid structural failure.

3. Load cases and analysis tasks

Compared with ground-based systems, the gravitational and the thermal loading are quite different for space-based systems. The mirror is designed and fabricated in a 1-*g* (*g* is acceleration of gravity, $g = 9.8\ \mathrm{m/s^2}$) ground environment, yet must operate within microgravity conditions. Furthermore, the thermal loading can be severe in an environment outside the Earth's atmosphere; the thermal gradients across the mirror due to solar flux or other equipment on the satellite are also experienced. In addition, the high-g inertia load, the vibration and the impact in the launching phase have a big influence on the performance and the safety of the mirror.

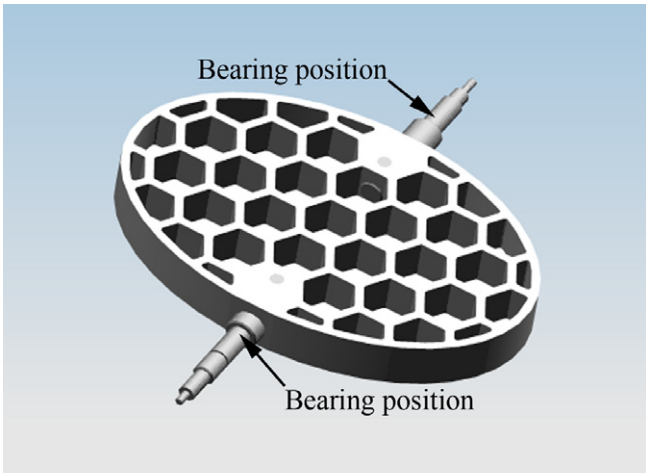

Fig. 1. 3-D model of the mirror assembly.

Table 1
Structural parameters values of the mirror prototype

Structural parameters (m)	Values
Length *L*	0.15
Width *W*	0.1
Interval *I*	0.017
Height H_1	0.0075
Height H_2	0.018
Thickness T_1	0.003
Thickness T_2	0.003
Thickness T_3	0.003
Diameter D_1	0.009
Diameter D_2	0.005

Based on the mentioned above traits of the environment in which the mirror will be operating, three load cases are determined as typical loading conditions to validate the mechanical response of the mirror prototype. The particular description of these load cases is as follows:

(1) Load case-1 is gravity offload of 1-*g* which is derived from the difference of the gravity environment between the ground and the working orbit.
(2) Load case-2 applied to the mirror consists of temperature gradient and gravity offload of 1-*g*. The temperature gradient of the mirror is variable in the working process because of the instability of ambient thermal sources. Calculation in the mirror design indicates that the temperature gradient along the dimension H_2 (see Fig. 2) is the main thermal load which must be considered in the simulation analysis, and its change range is from 0 K/m to 0.3 K/m.
(3) Load case-3 is a gravity type loading with a magnitude of 12-*g*. This selection is based on the flight limit loads of the relative launch vehicles.

To ensure the structural integrity of the mirror, it is felt that a detailed analysis must be carried out to protect against the surface

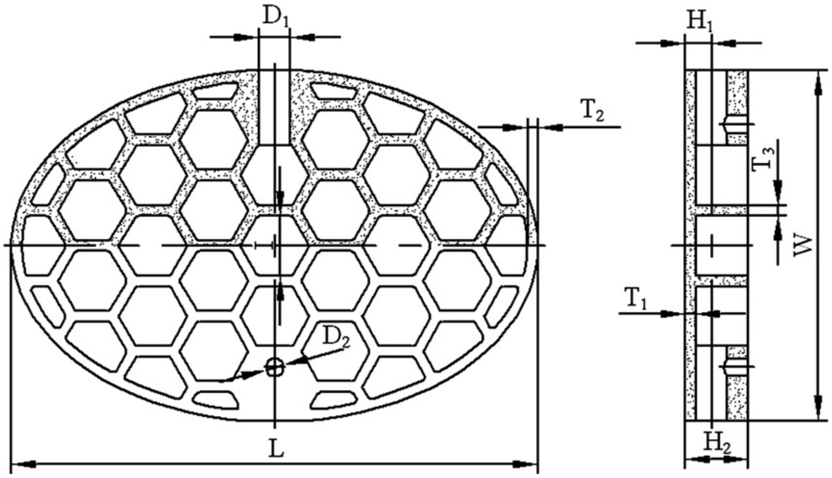

Fig. 2. Abbreviated drawing of the mirror configuration.