NORTH CAROLINA

A & T STATE UNIVERSITY

(NASA-CR-163008) STUDY OF COMPOSITES AS SUBSTRATE MATERIALS IN LARGE SPACE TELESCOPES Final Report (North Carolina Agricultural and Technical) 21 p HC A02/MF A01 CSCL 20F G3/74

N80-23139

Unclas 18082

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

GREENSBORO, N.C. 27411

FINAL REPORT

STUDY OF COMPOSITES AS SUBSTRATE MATERIALS IN LARGE SPACE TELESCOPES

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NSG-8045 1977-79

Prepared for

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May 1980

ACKNOWLEDGMENTS

The financial support provided for this work by the National Aeronautics and Space Administration through a Grant NSG-8045 is gratefully acknowledged. The author is grateful to Mr. Marion I. Kent (University Relations, Executive Staff) and to the technical monitors, Messrs. Charles Jones and James Stuckey of the Marshall Space Flight Center for their valuable help and assistance during the course of this investigation.

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ABSTRACT

A theoretical investigation was conducted to study the applicability of the fiber composites as possible substrate materials in the design of the primary mirror in the Space Telescope. The literature review indicates that the fiber composites appear to have potential to satisfy some of the design requirements of the primary mirror. Both the graphite/resin matrix and the graphite/metal-matrix materials may prove to be potential substrate materials. The thermal stability and the thermal expansion characteristics of these materials in a direction normal to the reflecting surface are yet to be analyzed critically. These materials in the laminate form appear to support the anticipated mechanical loads on the primary mirror. In fact, the composites show superior specific modulii as compared to many other materials, including the presently used ULE substrate. Based on the literature search and review, a set of recommendations are made to study the problem further with specific design requirements and to validate the theoretical results through testing of the scale-models.

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INTRODUCTION

With the advent of the NASA's Space Shuttle Program, a large orbitting astronomical telescope to study the distant stars is being designed and tested. This Space Telescope (ST) would be orbitting around the earth where atmospheric and other environmental disturbances are at a minimum. The design considerations of the primary mirror in such a space telescope (ST) are more severe than in a ground-based telescope. For example, a space telescope with three meter aperture is expected to have a theoretical angular resolution of 0.04 arc-seconds. Payload considerations of the space vehicle would require that the primary mirror blank (substrate) is to be light-weighted with sufficient stiffness. Moreover, it's desirable that the primary mirror surface accuracy be better than $\lambda/50$ rms, where λ is 632.8 nanometers of wavelength. The primary mirror in the ST program is being designed using Titania/Silica system as substrate material. A particular combination of this system having a trade name of ULE (ultra-low expansion) appears to satisfy many of the desirable characteristics of high-accuracy mirror blank. An ideal mirror substrate material should have [1]* dimensional stability, polishability, low thermal expansion, high thermal diffusivity, high specific modulus (elastic modulus/density ratio), homogeneity, clarity for inspection, size- and lightweight-capability. Typical mirror substrate material properties (mechanical and thermal) for various materials such as fused silica, ULE, Cer-Vit, aluminum, beryllium, etc. are tabulated in [2] and [3]. Although ULE as a substrate material is satisfactory at the present time, the search is being continued for better materials. Composites fabricated out of graphite fibers and matrix materials such as epoxy, polyimide appear to be potential candidate materials in mirror substrate design.

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*Numbers in square brackets refer to bibliography.

The present investigation was directed to the study of non-metallic composites such as graphite/epoxy system as possible substrate materials. A brief review of the possibility of using the fiber-reinforced-metal matrix composites was also conducted. The increasing use of graphite and other composites in structural designs, particularly in aerospace applications, is gaining momentum. Federal agencies such as NASA, U. S. Air Force, etc. are involved in extensive research activities [4,5] with composites in space-oriented applications. Although composites in general have high unit cost [6], the unit cost has decreased significantly since 1970 as a result of increasing demand and improved fabrication processes. The principal advantages with the use of graphite and other composites are that they can be "ordered" to fit the design requirements. With the general properties of composites in the background, the present study was concerned with exploring the possibility of using the composites as substrate materials in optical mirrors. Investigation of problems arising out of the use of composites such as grinding, polishing, adherence of reflective coatings to substrate, rigidity of substrate, hygroscopic tendency of composites, thermal and temporal stability, and other related problems was conducted.

REVIEW

Various pertinent properties applicable to the design of a ST were reviewed. The important factors that affect the performance of the ST are a) strength and stiffness, b) operating temperatures, c) laminate stacking sequence and ply-orientation, and d) environmental effects.

Modulus and Strength

In a large optical mirror requiring extreme accuracy of reflecting surface, the surface deviation is expected to be in the 1-2 nanometers rms range. Consequently, the stiffness (modulus) of the substrate material is more important than the strength. Ideally, the higher the specific stiffness (stiffness/density), the better the material. The specific stiffness of, for example, HMS graphite (Hercules, Inc.) has a value of 490×10^6 in. for unidirectional fiber orientation as compared to about 125×10^6 in. for ULE. However, the specific stiffness would degrade significantly as the stacking and fiber orientation is changed. A (0°, ±45°, 90°) laminate [7] has a specific stiffness of 180×10^6 in.

Depending on the laminate geometry and material, graphite composites have specific strengths (ultimate tensile strength/density) in the range of $(0.76 \text{ to } 4.02) \times 10^6$ in. The composite that has high specific stiffness may not necessarily possess high specific strength. Another class of aromatic polyamide fibers, commonly known as Kevlar (DuPont), was not considered. They have, relative to high modulus graphite fibers, higher specific strength but a lower specific modulus [8].

The metal-matrix composites appear to have a good potential as design alternatives to metals and advanced resin matrix composites [9-12]. These composites appear to have many of the desirable characteristics suitable for a substrate in the ST. The price of these metal-matrix composites is expected to be within reach for many applications in the next ten years. Figures 1 and 2 would support the superiority of these composites. A summary of various properties of the metal matrix composites and fibers is given in Tables 1 through 4.

Microcreep and Microyeilding

In studies [13] conducted at Perkin-Elmer (Norwalk, CT) and General Dynamics/Convair Division in related areas on small scale (6" diameter flat honeycomb disks) graphite composite specimens, deformations greater than one microinch at a stress level of 10 ksi were not observed. Solid as well as honeycomb disks were used in creep studies. Surface deformations from 75-140 microinches at stress levels of 5-20 ksi for 70 hours were noted. The honeycomb sample was observed to be tending toward complete recovery as compared to solid laminate after the removal of load. It's to be noted that these tests were conducted under applied stress. The deformations were measured using interferogram techniques. The shapes of the holographic interference patterns were the basis to test for the homogeneity of samples fabricated. Although graphite laminates are basically inhomogeneous, a pseudo-isotropic laminate can be designed through the judicious choice of fiber orientations and laminate stacking sequences.

Thermal Stability and Expansion

Graphite composites appear to have better dimensional stability [13, 14] in mirror- and optical bench component-designs as compared to other traditional candidate materials. It is known for sometime that graphite/epoxy (G/E) composites can be fabricated to develop zero coefficient of thermal expansion (CTE) or any other desired CTE. For example, CTE test results from HEAO-B and GEMS structures [15] indicate average values of $0.011 \times 10^{-6}/°F$ and $-0.026 \times 10^{-6}/°F$ where G/E laminates - GY 70/X-30 with $(0, 45, 90, 135)_{2s}$ and

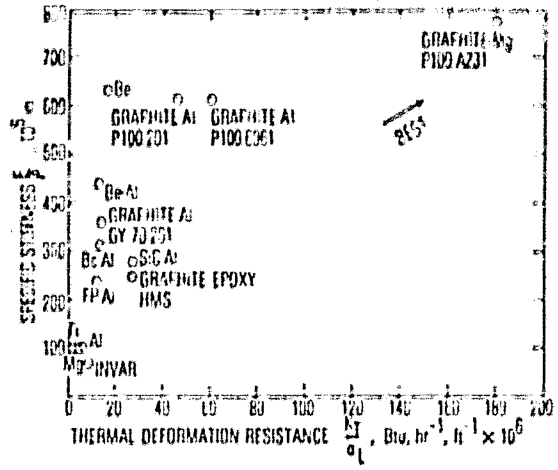

FIGURE 1. FIGURE OF MERIT FOR SATELLITE AND SPACE SYSTEM MATERIALS - Longitudinal Data (from Ref. 9).

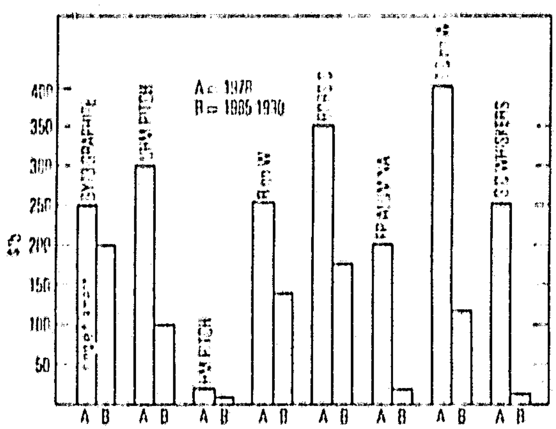

FIGURE 2. CURRENT AND PROJECTED COSTS FOR FIBERS (from Ref. 9).

Table 1. Representative Metal-Matrix Composite Materials *

Fiber	Matrix	Potential Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet engine fan blades
Borsic	Aluminum	Jet engine fan blades
	Titanium	High-temperature structures and fan blades
Alumina (FP)	Aluminum	Superconductor restraints in fusion power reactors
	Lead	Storage battery plates
	Magnesium	Helicopter transmission structures
Silicon Carbide	Aluminum	High-temperature structures
	Titanium	High-temperature structures
	Superalloy (Co-based)	High-temperature engine components
Molybdenum	Superalloy	High-temperature engine components
Tungsten	Superalloy	High-temperature engine components

* From Ref. 9

Table 2. Reinforcements for Metal-Matrix Composites *

Fiber	Tensile Strength, ksi	Modulus, msi	Density, $lb/in.^3$	Filament Diameter, μm	Remarks
B on W	525	58	0.090	100-200	Monofilament
Borsic	450	58	0.098	100-145	Monofilament
B on C	500	52	0.050	100-140	Monofilament
Graphite					
Rayon (T 50)	315	57	0.060	6	1440 fils per 2-ply yarn
PAN HTS (T 300)	340	30	0.063	8	3000 fils per yarn
PAN HM	350	55	0.067	7	10,000 fils per tow
Pitch (Type P)	200	50	0.072	5-10	2000 fils per yarn
Pitch UHM	350	100	0.074	11	2000 fils per yarn
Tungsten	458	57	0.700	380	Monofilament
FP Alumina	200-235	55	0.143	20	210 fils per yarn
Silicon Carbine on W	450	62	0.120	100-140	Monofilament
SiC on C	500	58	0.110	100	Monofilament
Glass (S, E, C)	500-600	10-12	0.09	5-10	1000 fils per strand

* From Ref. 9

Table 3. Summary of Metal-Matrix Characteristics Applicable to Satellites*

Metal Matrix Composite Property	Component Characteristic	Mission Payoff
High Specific Modulus	Structural ridigity, light weight	Accuracy in "aiming" systems and space antennas, increased reliability by component redundancy, increased mission life by greater fuel capacity, increased mission scope by additional components
High Thermal Conductivity, Low Thermal Expansion	Dimensional stability	Retains structural stability and rigidity with temperature change in orbit
No Outgassing	No contamination, Structural stability	Contamination-free optical systems without shielding
High Electrical Conductivity	Minimal electrical charging	Eliminate special conductors for space charging reduction
Thin Gauge, High Modulus	Structural integrity with minimal wall thickness	High volume and packing efficiency for shuttle transport
High-Temperature Capability, High Thermal Conductivity	Good laser hardness capability	Components resistant to laser energy with no or minimal shielding

* From Ref. 9

Table 4. Mechanical Properties of Metal-Matrix Composites[a] *

Fiber	Matrix	Reinforcement, vol%	Density, lb/in.^{3}	UTS(L), psi	E(L), $\times 10^6$ psi	UTS(T), psi	E(T), $\times 10^6$ psi	Data Source
G T 50	201 Al	30	0.086	90	24	7	5	Aerospace
G GY 70	201 Al	34	0.086	95	30	4.5	5	Lockheed[b]
G GY 70	201 Al	30	0.088	80	23	10	6	Lockheed[b]
G HM Pitch	6061 Al	41	0.088	90	47	(15)	(7)	Aerospace
G HM Pitch	AZ31 Mg	38	0.066	74	43	---	--	Lockheed[b]
B on W, 5.6-mil Fiber	6061 Al	50	0.090	200	34	20	23	GD Convair
Borsic	Ti	45	0.133	184	32.5	67	27	TRW
G T 75	Pb	41	0.270	104	29	--	--	Aerospace
G T 75	Cu	39	0.220	142	35	--	--	Aerospace
FP	201 Al	50	0.130	170	31	(20)	20	DuPont
SiC	6061 Al	50	0.106	215	33	(20)	20	DWA Composites
SiC	Ti	35	0.142	175	38	75	30	DWA Composites
SiC Whisker	Al	20	0.101	50	15	50	15	DWA Composites
B_4C on B	Ti	38	0.135	215	33	>50	>20	DWA Composites

[a]Rule-of-mixture predicted values given are in parentheses.
[b]AFML Contract No. F33615-T1-C-5190.

* From Ref. 9

Modmor I/X-30 with $(0_3, +45, -45, 90)_s$, respectively - have been used. Some of the advantages of using G/E materials in structures is the ability of the designer in maneuvering the laminate variables such as fiber and matrix selection, ply orientation, stacking sequence, fabrication techniques, etc. to serve the end use. In the above two examples, the G/E laminates have been used to maintain certain critical distances between precision components. Further, these critical distances are in the plane of the laminate. The suitability of G/E laminates to achieve dimensional control in a direction perpendicular to the laminate plane has not yet been investigated in depth. One of the difficulties encountered in this type of application is inherent in the lamina design itself, viz., the epoxy matrix bonding the unidirectional fibers itself would expand with changes in environmental conditions.

Most of the research conducted to-date is slanted towards the application of G/E composites to structural design where basic criteria are strength, stiffness, in-plane CTE control and environmental effects. However, the work by Fager [16], Goggin [17], and Freund [18] has some applicability to the present investigation leading to the dimensional variation normal to the laminate plane. Part of Fager's work shows that a surface contour of 0.002 inches RMS was achieved in the design of an 8 ft. graphite/epoxy parabolic reflector. The above RMS value appears to refer to the as-fabricated accuracy of the reflector. Goggin and Freund have conducted some experiments at Perkin-Elmer Corp. that were related to the dimensional stability of G/E substrate. This research was concerned with a) property investigations such as laminate CTE, microyield strength and microcreep behavior under different loading conditions, b) optical processing studies such as direct polishing of substrates, polishing of coated substrates, use of replication techniques, polishing of bonded glass plate to a honeycomb core, and c) the effect of environmental factors such as humidity, thermal cycling, thermal and temporal stability on the G/E substrates. The substrate materials investigated in the above studies were Thornel 75S/ELRB 4617, GY-70/X-904 and Modmor I/ELRB 4617. The ply-orientation and stacking sequence were $(0, +60, -60)_s$ and $(0, +45, -45, 90)_s$. Some of the measurements were made on glass plate/honeycomb core sandwich type specimens. Some of the thermal analysis techniques [18] such as the thermogravimetric analysis and the thermomechanical analysis can be used to find the thermal stability information and the expansion coefficients of the composites. It is claimed [19] that the graphite/epoxy system when used in light-weight mirrors and in similar applications requiring precision dimensional tolerances appears to be unsurpassed over a range of desirable overall performance characteristics such as thermal expansion, dimensional stability with thermal cycling, microyield strength, etc.

Moisture Effects

Graphite/epoxy composites are generally known to absorb moisture resulting in, besides other effects such as strength degradation, dimensional changes. This problem becomes more critical when the optical surface needed is to be very accurate. According to tests performed at Perkin-Elmer Corp., surface deviations due to humidity effects are recoverable by vacuum drying [13]. This has been observed for glass-plated mirrors of honeycomb type construction. Mirror fabricated by General Dynamics/Convair with HM-S/X-30 material performed better in humidity/vacuum cycling and thermal stability evaluations. Using linear viscoelastic models [20], the time, temperature, and moisture dependent dimensional changes in the graphite/epoxy laminates can be predicted. However, if the substrate is a graphite/metal matrix material, some of the problems such as the out-gassing and moisture absorbancy may not be that critical.

CONCLUSIONS

1. Fibers: With high modulus or ultra-high modulus (pitch based) graphite fibers [9], the axial and the transverse deformations would be relatively small. The pitch-based fibers have shown a modulus value of 100 msi. This high value in turn would result in a very high specific modulus in those composite laminates fabricated with these fibers. If the fiber volume in the composite is relatively high [21], the coefficient of thermal expansion of the composite laminate is expected to improve.
2. Matrix: Polysulphones such as P-1700, PKXA; Polyethersulphones such as 100 P, 200 P; and other thermoplastics could be screened further. Investigations conducted by Hoggatt, et. al. [22-26], Maximovich [27] , Chasin and Feltzin [28] show that these materials are (a) good structural adhesives and matrix resins, (b) relatively void free, and (c) less hygroscopic as compared to epoxy matrix. Composites fabricated out of these matrix materials can be formed or molded with small bend radii [29]. These resins are also considered to be good at higher operating temperatures as compared to epoxy matrix. With fewer voids and better resistance to moisture, laminates with the above fiber/matrix combinations are expected to develop better dimensional stability. The in-plane and normal to the plane coefficients of thermal expansion are also expected to improve.

   If metal-matrix materials such as magnesium, aluminum, etc. are used in association with the ultra-high modulus graphite fibers as reinforcements [9], not only the specific stiffness but also the resistance to thermal deformations would improve considerably. However, the deformation normal to the laminate plane is not known.

3. Faceplates: Since the dimensional changes normal to the laminate plane - this plane being the reflecting surface - is uncertain by using the fiber/matrix combination, thin ULE faceplates supported by a composite core may be used. This technique may assure better surface accuracy (provided by the ULE material) and stiffness (provided by the composite core). The thermal distortions that would result by using several different materials (ULE, composite core) have to be analyzed carefully not only in the plane of the primary reflecting surface but also in a direction normal to this plane.

RECOMMENDATIONS

Based on the theoretical review, the following recommendations are suggested:

1. Define the design criteria and constraints applicable to the development of a small-scale model of the primary reflecting surface of the Space Telescope.
2. Theoretical analyses in detail be performed leading to the development of two to three optional designs (graphite/resin matrix composite, graphite/metal-matrix composite, and faceplate/core sandwich type composite) for the primary mirror.
3. Based on the theoretical analyses, fabricate the scale model(s) and validate the predicted results experimentally.

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