UNIDIRECTIONAL CARBON/CARBON FOR ION ENGINE OPTICS

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INTRODUCTION

Ion engines are a very promising technology for space exploration. This promise has yet to be realized because of limited lifespan of these engines. The limiting factor for lifespan of these engines is the life of the optics. Ion engines currently employ optics consisting of two or three molybdenum grids, which extract and focus the ions exiting the engine. The engines used by JPL employ three grids, they are the screen grid, the accelerator grid, and the decelerator grid. The grids JPL uses can be either 15 or 30cm diameter, depending on the type of engine being evaluated. Because of the small gap between grids (0.02cm), the surface of the grids must be accurate to +/- 0.0025cm over their entire surface, and they must be very stiff to resist the attraction between them from the accelerating voltage.

Molybdenum grids have two problems associated with them, 1) that they have a positive coefficient of thermal expansion (CTE), and 2) that they have a relatively high sputter yield from the xenon propellant. The positive CTE causes the grids to distort as they heat up to operating temperature, lowering engine efficiency, and the high sputter yield causes the grids to wear out, limiting engine life. The substitution of carbon/carbon (c/c) for molybdenum offers significant improvement in both areas. One significant weakness of c/c compared to molybdenum is its relatively low flexural modulus. This limits both the diameter of the optics and the accelerating voltage which can be used, limiting engine efficiency. This was one of the primary issues addressed by this work, and, in addressing this issue, a c/c material was developed having an equivalent flexural stiffness to that of molybdenum.

EXPERIMENTAL

The grids currently used by JPL have circular holes in an hexagonal pattern, covering 67% of the surface area of the grid. This high open area fraction makes the volume of continuous material running between the holes very small. This led to the experimental use of slots running the length of the grids in the 0^{o} direction in order to increase the volume of continuous material without lowering the open area fraction. The hexagonal hole pattern was a major factor in the decision to use unidirectional tape, rather than fabric, for the preforms. This allowed for a $[0^{o}/+60^{o}/-60^{o}]_S$ layup, which puts some continuous material between the holes in all three directions. This layup was changed to $[0^{o}/0^{o}/90^{o}]_S$ for the slotted grids, in order to achieve maximum flexural stiffness in the slot direction. Two sets of 30cm grids were built. They used the $[0^{o}/+60^{o}/-60^{o}]_S$ layup, as they are to have an hexagonal hole pattern. These grids were made spherical, having a 2 meter radius of curvature, with flat rims. The "dished" shape was used in order to provide additional rigidity because of the larger diameter of the grids.

The processing of the material consisted of a carbonization to $815^{o}C$, followed by a $3000^{o}C$ heat treatment, a 125 hour chemical vapor infiltration (CVI), then a second $3000^{o}C$ heat treatment, and a final 125 hour CVI. The very high heat treatment temperature was used in order to obtain the highest possible modulus by graphitization of both fiber and the matrix sheath. All furnace runs were performed with the panels between graphite fixtures in order to maintain surface tolerance.

After processing the materials were tested for mechanical properties. Mechanical testing consisted of tension and four point bend (flexural) tests. The $[0^{o}/+60^{o}/-60^{o}]_S$ material was tested in the 0^{o} direction in tension, and in the 0^{o} and 90^{o} directions in bending. The $[0^{o}/0^{o}/90^{o}]_S$ material was tested in both the 0^{o} and the 90^{o} directions in both tension and bending.

RESULTS AND DISCUSSION

There were no unexpected problems encountered in processing of these materials. The panels which were not completely flat after cure appeared to be flat when checked against a surface table after the first graphitization cycle. All of the flat panels maintained their flatness throughout the remainder of their processing. The 30cm panels all maintained their conformance to the tooling throughout their processing. The $[0^{o}/+60^{o}/-60^{o}]_{S}$ panels achieved a density of 1.83 g/cc after processing, with an estimated fiber volume of 57%, and the $[0^{o}/0^{o}/90^{o}]_{S}$ panels reached a density of 1.89 g/cc, with an estimated fiber volume of 50%.

The mechanical testing yielded better than expected results, particularly in tensile strength. The $[0^{o}/+60^{o}/-60^{o}]_{S}$ had an average tensile strength of 486MPa (71KSI), and a tensile modulus of 146GPa (21MSI). The $[0^{o}/0^{o}/90^{o}]_{S}$ material had a tensile strength of 755MPa (110KSI) in the 0^{o} direction, and 414MPa (60KSI) in the 90^{o} direction, with a tensile modulus of 230GPa (33MSI) in the 0^{o} direction and 120GPa (18MSI) in the 90^{o} direction. Single filament testing of heat treated E55 showed the fiber to have an heat treated tensile strength of 3,374MPa (489KSI), and an heat treated modulus of 897GPa (130MSI). Based on the calculated fiber volume, this indicates that fiber utilization was approximately 70% to 80% in strength and 80% to 90% in modulus.

The flexural testing yielded lower strengths and higher moduli than the tensile testing. This result is fortuitous, since the primary mechanical driver for this application is flexural stiffness. The flexural strength of the $[0^{o}/+60^{o}/-60^{o}]_{S}$ material was measured at 206MPa (30KSI) in the 0^{o} direction and 117MPa (17KSI) in the 90^{o} direction. Flexural modulus of this material was 276GPa (40MSI) in the 0^{o} direction and 61GPa (9MSI) in the 90^{o} direction. This significant degree of anisotropy was expected, since the layup could not be made flexurally balanced and still meet the thickness requirements of the grids. The $[0^{o}/0^{o}/90^{o}]_{S}$ material had a flexural strength of 289MPa (42KSI) in the 0^{o} direction and 50MPa (7KSI) in the 90^{o} direction. Flexural modulus of this material was 341GPa (49MSI) in the 0^{o} direction and 21GPa (3MSI) in the 90^{o} direction. The very large anisotropy of this material was intentional, since the machined grids made from this material will only have continuous material in the 0^{o} direction, and this construction was able to achieve a flexural modulus equivalent to that of molybdenum in that direction.

SUMMARY OF MECHANICAL TEST RESULTS

Tensile Properties:

Material	Direction	Strength MPa(KSI)	Modulus GPa(MSI)
Quasi Isotropic	0^{o}	486 (70.5)	146 (21.1)
Bi-directional	0^{o}	755 (109.5)	230 (33.3)
	90^{o}	414 (60.1)	120 (17.5)

Flexural Properties:

Material	Direction	Strength MPa(KSI)	Modulus GPa(MSI)
Quasi Isotropic	0^{o}	206 (29.8)	276 (40.0)
	90^{o}	117 (17.0)	61 (8.8)
Bi-directional	0^{o}	289 (41.9)	341 (49.4)
	90^{o}	50 (7.3)	21 (3.1)