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Processing, Fabrication & Application of Advanced Composites

Edited by: K. Upadhya

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Processing, Fabrication and Application of Advanced Composites

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This book is a collective effort involving hundreds of technical specialists. It brings together a wealth of information from worldwide sources to help scientists, engineers, and technicians solve current and long-range problems.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

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Preface

It is not an exaggeration to state that composite materials have become "solutions in search of problems," especially in the areas of advanced aircraft and space technology. Composites will remain the materials of choice as long as higher strength and lower weight remain prime design criteria. The aerospace industry has provided the proving ground for many composites; however, composites applications have expanded to a wide variety of markets including transportation, construction, and recreation. Composites universally have shown a weight savings of at least 20% over their metal counterparts and a much lower operational and maintenance cost. Composites will continue to find applications in the futuristic and exotic demanding systems such as advanced aircraft and space stations, but the large scale growth of the composites industry will require less costly aircraft and space stations, but the large scale growth of the composites industry will require less costly processing methods and availability of more data an predicting the service life and mode of failures in the field.

This proceedings contains invited and contribute d papers presented at the conference on Processing, Fabrication, and Applications of Advanced Composites, held in Long Beach, California, 9-11 August 1993. The prime objective of the conference, sponsored by ASM International and co-sponsored by TMS, was to provide a forum for researchers and scientists to present a state-of-the art review of novel processing and fabrication of advanced composite materials. This was achieved by including papers dealing with fundamentals of science and technology of processing composite materials, and in-depth papers related to continuing research on controlling and tailoring the fiber/matrix interface, process modeling and strengthening mechanism(s) in these materials. Papers were presented by a broad group of researchers and scientists representing universities, federal laboratories, and industries. This book contains papers on metal-matrix, intermetallic-matrix, ceramic-matrix, polymer-matrix, and C/C composites. There also is one chapter on fabrication of functionally graded materials (FGM). It is my hope that this book will be an excellent resource for engineers and scientists engaged in the selection and/or processing of composite materials.

The efforts of ASM International deserve a special thanks. I also wish to thank all authors, presenters, and participants who took part in the conference, who by their contributions made the conference a success.

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Proceedings of the 1993 Conference on Processing, Fabrication and Applications of Advanced Composites, Long Beach, CA, 9-11 August 1993

High Performance High Temperature Materials for Rocket Engines and Space Environment

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Abstract

It will not be an overstatement to say that aerospace has provided a major thrust in the research and development for ceramics and non-metallic materials. It is almost certain that the importance of these materials in spacecraft as well as in space communications will increase immensely by the end of this century. In this paper, a critical review has been presented of the applications and performance of the ceramics, composites and non-metallic materials in the futuristic spacecraft and space communications and their impact on achieving the twin goals for reduced weight and increased performance.

Introduction

During the last three decades, manned space projects have resulted in the significant advancement in the science and technology of communications, surveillance and metrological fields. Futuristic space operations will offer numerous technological challenge and benefits in other important disciplines, including medical research and materials science. The space station and Lunar/Mars initiative will provide even greater opportunity for technical breakthrough and scientific achievements.

However, one of the major roadblocks in achieving the landmark success in the futuristic hypersonic plane such as National Aerospace Plane (NASP) (X-30) will depend on the availability and performance of the high temperature materials. The NASP demonstration vehicle will be designed to operate from the conventional runway. The ascent and reentry trajectories projected for the NASP necessitate operations at speeds and altitudes at which equilibrium temperatures will be far greater than those currently encountered by the space shuttle. Figure 1 illustrates the schematic of a hypersonic plane and the temperature profile associated with this system. [1] Initial tests have indicated that, for weight and air drag reasons, the thermal protection system used on the space shuttle will not be adequate for application on the NASP. Therefore, the NASP program has accelerated the efforts into research and development of advanced materials such as Continuous Fiber Reinforced Ceramic Matrix-Composites (CFRCMC), Carbon-Carbon Composite and various intermetallic materials, especially gamma titanium-aluminum intermetallic materials for high temperature applications.

Carbon-Carbon Composites will remain a "Material of Choice" as long as higher strength and lower weight will remain the main criterion for rocket engineers. However, the use of C-C composites in missiles and launch vehicles has been thus far limited because of its extremely poor performance in an oxidizing environment, especially above 350°C. Carbon-Carbon composites possess a unique combination of desirable properties (i) high strength/weight ratio (ii) extreme thermal shock resistance (iii) very low coefficient of thermal expansion and (iv) strength retention and creep resistance over a wide temperature range. Figure 2 illustrates the strength/weight ratio with respect to temperature of C-C composite in comparison to several other materials. All the aforementioned properties of C-C composite make it highly desirable candidate for missile components. For example, 1 lb of weight-savings in the missiles' components will save 6-8 lbs of propellent which will translate into exponential return on payload fraction. Also, C-C composite nozzle will maintain constant throat diameter, which result in less propellant consumption and increase in payload fraction. Finally, high strength and durability of C-C will eliminate nozzle failures and results in increased reliability.

Rocket Engines and Missiles

Reusable rocket engines for future space missions will be required to operate for longer durations, withstand more duty cycles and perform more efficiently than current reusable rocket engines. To achieve these goals, the hot section components of this H_2/O_2 burning engine will require the much higher temperature material than the currently used superalloys.

A select group of materials which offer potential to outperform the superalloys includes ceramics, intermetallics and C-C composite. Each of these materials exhibits lower density and can operate at higher temperature than superalloys. However, amongst the three listed materials, the ceramics offer the greatest potential for the tolerance to the aggressive environment which exists in the rocket engine as seen in figure 3. However, load carrying capability of monolithic ceramics is extremely sensitive to the processing flame. As a result there is always some probability of catastrophe failure under thermal shock conditions.

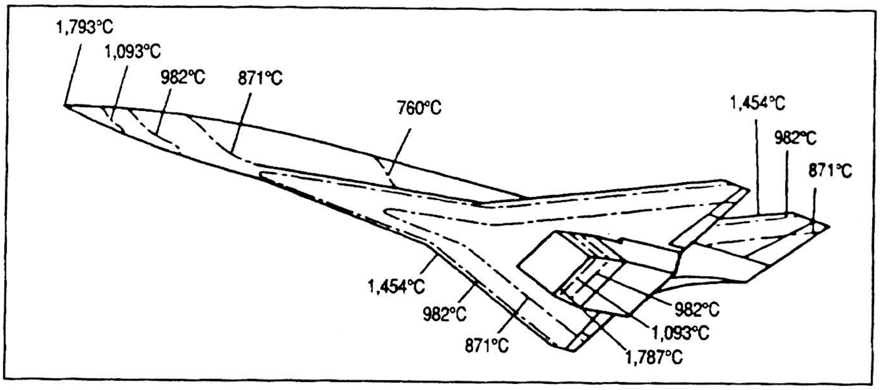

Figure 1. A schematic of a transatmospheric spacecraft and the associated maximum temperature profile.

However, recent research results indicate that reliability and durability of ceramics materials can be improved by reinforcing them with continuous ceramic fibers. Continuous fiber reinforced ceramic matrix composite (CFRCMC) appear to offer a great potential for use in rocket-engine turbine components. In fact, a recent study at General Electric, Rocketdyne and NASA Lewis have confirmed that the us of CFRCMC materials into severe thermal environment of rocket-engine turbopump hot section offers three distinct benefits namely: increased performance, improved component life and greater design flexibility. [2]

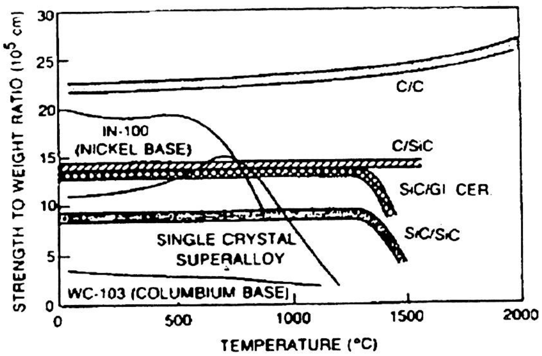

Figure 2. The relative strength-to-weight ratios of different materials.

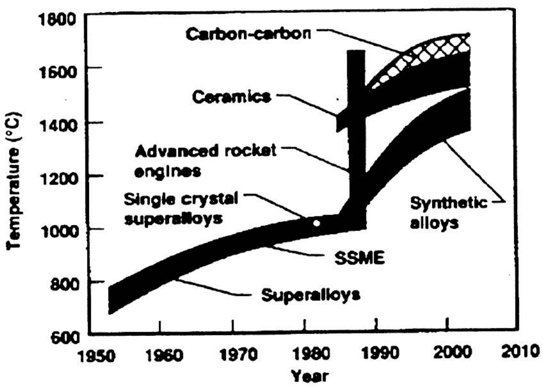

Figure 3. Rocket-engine turbine blade materials needs and capabilities.

For a rocket engine turbine, there is a direct relationship between temperature and the performance, i.e., the higher the temperature, the greater the efficiency. However, the upper temperature limit is set by the restrictions imposed by the engine system. Several CFRCMC materials have been tested for rocket engine applications and this is shown in Table 1. The test results indicated that the most promising material is carbon fiber reinforced SiC composite which exhibited the necessary combination of mechanical properties, ease of fabricating the components for rocket engine and adequate environmental resistance. Another material, which showed better environmental resistance than C/SiC but reduced load carrying capability at operating temperature was SiC/SiC CFRCMC. C-C composite, obviously was not a viable candidate because of unavailability of a suitable oxidation protective coating for this material, which it requires for use in the rocket engine highly oxidizing environment. SiC/Si_3N_4 is still very undeveloped and untested material for being a viable candidate for application in the rocket engine component. [3]

Finally, in the small H_2/O_2 rocket engine tests which generated high heating rate thermal shock, only SiC/SiC and SiC/Si_3N_4 demonstrated any ability to survive the rocket engines severe thermal shock environment as illustrated in fig 4. Based on a series of tests carried out by G.E., Rocketdyne and NASA Lewis Research Center, for performance, producibility and thermal shock resistance, there is some evidence that CFRCMC exhibit many of the properties required for rocket engines turbines, including low density, environmental durability thermal shock resistance, toughness and reliability. The use of CFRCMC offers great potential for increased performance and payload capability, improved component life, and greater design flexibility.

National Aerospace Plane

As mentioned earlier the National Aerospace Plane (NASP) also known as X-30 will take off and land on conventional runways, cruise at approximately 17,000 miles/hour and reach orbit in a single propulsion stage. The most critical factor in achieving all these multipurpose goal is the development of suitable light weight/high strength materials that will perform satisfactorily at much higher temperature than any one of today's materials and structural components made from these advanced materials. Figure 5 shows the final version of NASP X-30 which design has been accepted by all the contractors.[4]

The tasks for the materials development for the NASP, have been given to General Dynamics for the refractory composites; McDonnell Douglas for the titanium metal-matrix composites; Pratt & Whitney for the high specific creep strength materials, Rockwell for the titanium aluminide intermettallics and Rocketdyne for the high thermal conductivity composites.

Refractory composites include both C-C and ceramic matrix composites. The research effort is directed towards fabrication, joining and life predictions of these composites. Refractory composite parts will be as large as possible to minimize the weight and the number of joints and fasteners. Joining will be the key to the development of these refractory composites. Most of the fasteners will be made of either C-C or ceramic materials.

SiC fibers reinforced titanium matrix composite materials retain strength and stiffness up to 1800°F. Research effort on titanium matrix composites for NASP includes matrix development and characterization, fiber development; processing, structural fabrication and components testing. Processing methods for composites include fiber on foil, plasma spray and low pressure plasma spraying techniques. The most desirable matrix properties are the ambient temperature ductility and high temperature interfacial compatibility in the fiber coupled in the higher strength, low density and ease of fabrication.

.The prime candidates for the high specific creep strength materials are; titanium-aluminum intermetallics and silicon carbide filament reinforced titanium matrix composite. Also, the important fiber materials are titanium diboride and alumina whose coefficient of thermal expansion (CTE) value is closer than SiC fiber material. Research efforts are also directed towards developing monolithic titanium-aluminide which possesses very low density but high strength up to 1500°F without any reinforcement. This material will be used in the sheet form to fabricate both engine and airframe structural components.

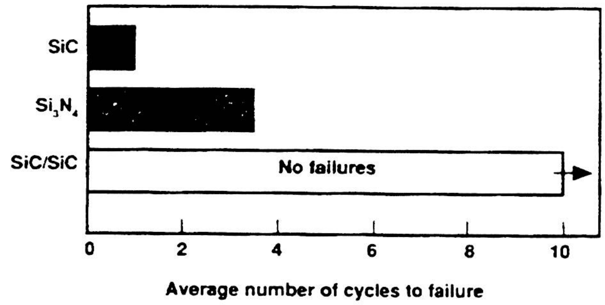

Figure 4. The results of thermal shock tests for monolithic SiC and Si_3N_4 compared to an SiC-reinforced SiC composite.

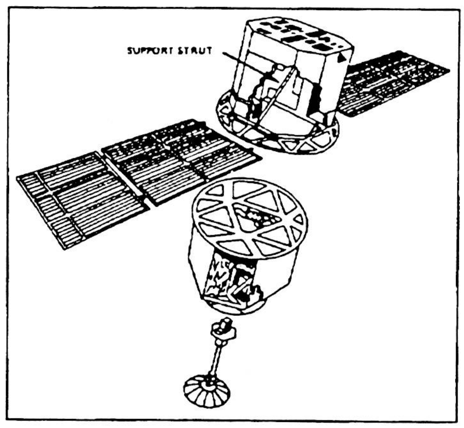

Figure 5. A schematic of the solar maximum mission satellite. Shown is the location of the composite struts.

Several materials are under development for high thermal conductivity and structural efficiency at elevated temperature. The NASP, X-30 will have numerous components such as leading edges and engine combustion chamber walls which will require extensive cooling of the surfaces. The material under development is copper matrix composite with high modulus graphite fiber for good structural and thermal properties. The research efforts are directed to infilterate graphite tows to coat individual filaments with a layer of copper and then compact the composite. Another copper composite is under development with a discontinuous second phase such as Niobium for better elevated temperature directional strengths. Beryllium combines low density, high stiffness and good thermal conductivity. The research effort is continuing on the methods to increase structural efficiency at elevated temperature up to 1400°F.

A common goal of the research projects for the development of the NASP materials is to develop a suitable coating to prevent oxidation of structural materials at the elevated temperature, especially carbon-carbon and hydrogen embrittlement of low temperature actively cooled structures, especially titanium structural components. The main function of coating is to maintain the integrity of the substrate metal when exposed to critical gases such as oxygen, hydrogen and nitrogen in the liquid slush or atomic state. Evaluating coating performance, therefore, will require measuring substrate physical and mechanical properties after exposure to the simulated NASP flight conditions. Besides, oxidation and hydrogen protection, these coatings will be required to maintain components structural integrity by radiating heat and keeping catalytic reaction to a minimum. Therefore, besides usual required coating properties these coatings will need to possess a high emissive value to radiate maximum amount of heat flux from the surface of these structural components.

The key technologies required to develop the NASP continue to mature and at this time there does not appear to be any technological obstacle to building an X-30. However, a vehicle fabrication decision is to be made in March 1993 with first flight planned for 1997 and a single stage to orbit (SSTO) demonstration flight in 1999.

Composites in Space Applications

Because of the large temperature variations in the space environment (-160°C to 93°C) and the need to maintain precise alignment of communication and sensor systems, the dimensional stability becomes a critical factor. Composites reinforced with Graphite and Kevlar fibers possess a high specific strength and modulus and low coefficient of thermal expansion, thus making them very attractive materials for space applications. Since stiffness and low thermal distortion, rather than strength, are the major considerations for spacecraft structures, the materials properties needed will differ from those used in other aircraft structures. Other important factors for spacecraft include thermal and electrical conductivity, long term stability under vacuum, space radiation and low outgassing.

As mentioned earlier, the dimensional stability of the material is a critical factor in the space environment and this factor alone greatly favors Gr-Ep and Kv-Ep because of their high stiffness and almost nothing to very low coefficient of thermal expansion. Metals in general have high CTE and even a change of a few °C can cause them to expand or contract significantly. Since Kv and Gr fibers exhibit negative CTE and epoxy exhibits normal CTE behavior, this combination of Gr or Kv fibers and Ep matrix almost totally offsets each other's CTE behavior and the resultant composite will have no thermal expansion or contraction even over a large temperature range. Also, it is worth mentioning here that strength of a material becomes secondary to stiffness because of weightlessness into space. We will clear this point by considering the use of GR-Ep "Mechanical Arm" of the space shuttle, which is 15 meters tubular boom with 38 cm in diameter. It contains "writs", "elbow" and "shoulder" joints for rotating in the yaw, pitch and roll modes. On the earth, this mechanical arm will never be able to support its own weight of 411 kg. In orbit, however, it is designed to handle a payload weighing on earth 24,500 kg.

Satellites and Communication Systems Antennas

Composites have become the chosen material for spacecraft antennas. The high gain antenna system of Voyager illustrates some of the unique factors of the composites. The 3.7 meter Gr-Ep primary reflector is one of the largest composite flight antennas ever fabricated. Another example is the optical bench developed for the High Energy Astronomical Observatory Mission B (HEAO-B) satellite which required high stiffness and low coefficient of thermal expansion. The Application Technology Satellite (ATS) uses a 4.4 meter hybrid truss to support its large parabolic antennas. The truss consists of eight circular tubes. They combine hoop and longitudinal layers of Gr-Ep tape with a single outer layer of hoop-wound SG1-Ep. The composite truss is 50% lighter than the aluminum equivalent structures. Two major antenna components for commercial advanced telecommunications have been successfully fabricated from composites and are operating in space. These consist of the antenna dish support ribs and the electronic package and radon support struts. Other types of satellite components also have been fabricated from composites (Figure 6), including support strut in the solar maximum mission satellite [5]. The struts were fabricated from GR-Ep composite and are the primary structural members supporting the satellite payload. In the camera mount for the space experiments in star photography Gl-Ep prepegs were used. Also, space telescopes have used composites in their structural components. A Gr-Ep metering cylindrical shell about 3 meters long and 1.7 meters in diameter was fabricated to hold the secondary mirror. Gr-Ep was selected primarily for its low coefficient of thermal expansion, which is critical for maintaining a stable focal length for the telescope.

The use of composites on spacecraft is growing as experience and the data on the performance of these composites are obtained. More recent satellite currently in service contains over 4000 composite parts. Major composite structures made from Gr-Ep and Gr-Kv-Ep hybrid materials include 11 antennas, antenna support truss structures and solar array. In other satellite applications, where thermal distortion or high specific stiffness was a critical factor, Gr-Al and Gr-Mg proved almost suitable composite material.

Space Shuttle

Since the shuttle is an aircraft as well as spacecraft, its center of gravity during return to earth must be far enough forward to provide proper aerodynamic trim. Since the engines and the thrust structures all are heavy components and are located behind, it was critical to reduce the aft weight in particular and overall weight in general. This is why maximum use of composite materials was achieved in the space shuttle and a weight saving of 1633 kg was achieved over the initial all metal components. The components include Gr-Ep skins and Nomex honeycomb on the orbital maneuvering system and titanium I beams and tubes reinforced with B-Ep in the aft thrust structures. Also, filament wound pressure vessels, titanium fuselage frame supports selectively reinforced with B-Ep, ceramic matrix composite ablative tiles and C-C composite nose covers. The nose cap and leading wing edges are subjected to the highest temperature of about 1480°C during the reentry of the space shuttle into earth's atmosphere. We will discuss some of the important components and materials used in the space shuttle.

Metal-Matrix Composite Struts (MMC Struts)

The space shuttle was one of the first production application of MMC. It has 242 unidirectional B-Al circular tubes which serve as main frame and rib-truss struts, frame stabilizing braces, nose-landing-gear drag-brace struts, resulting in a 44% weight saving over aluminum extrusions. The B-Al tubes which help support the fuselage frame of the space shuttle, offer weight saving of 145 kg and possess lower thermal conductivity which reduces the heat flow into equipment of the components. This is shown in Figure 7 [6].

Cargo-Bay-Doors

The shuttle cargo bay doors are the largest Gr-Ep composite structures ever built and are shown in Figure 8 [7]. These Gr-Ep doors are 18.3 meters long and were selected not only for weight saving but more so for its lower thermal expansions. This prevents warping due to the large temperature difference to which these doors are subjected to in orbit. Each door contains four expansion joints to accommodate the large difference in the CTE of EP-Gr door and its aluminum frame.

Pressure Vessels

Most space vehicles require storage of gas and fluids in tanks under high pressure and at cryogenic temperatures. The space shuttle, for example, uses about 60 of these pressure vessels, several of which have a Kv-filament overwrap with a cryoformed 301 stainless steel inner liner. These pressure vessels are 25 inches in diameter operating at 3 kips/in^2. By using composites the tanks save an estimated weight of 199 kg. Another important application of composite materials which is not very well known was in the part of a lunar surface drill carried to the Moon by astronauts during Apollo missions. 15-17 drills were connected to penetrate to a depth of 3 meters. The tubular bore stem was constructed from B-Ep and Gl-Ep hybrid composite and a tungsten carbide drill bit was used at the end of the stem. A combination of drilling and impacting actions was employed to drill through the soil and rock layers.

Space Stations

Large space platforms have been proposed for several applications such as communications satellites, megawatt power modules, large antennas, and manufacturing of medicine and single crystals of several materials in the weightless environment. These structural materials must possess such specific properties:

a) lightweight;
b) high strength and stiffness at elevated temperature;
c) minimum dimensional changes with respect to variations in the environment's temperature;
d) oxidation resistant;
e) hydrogen compatibility

The current thinking is that these space platform structural materials will be carried into orbit by the space shuttle and then assembled into zero gravity space. Operational space platforms may require Gr-Ep half column over 10 meters long. These columns would be fabricated by winding dry graphite fibers around a hot, tapered steel tube. Aluminum fittings would be placed on the end of the graphite and the winding would be inserted into a second steel tube, and finally resin will be injected into this mold set-up. The whole operation would take place in space and the space shuttle would carry about 5000 half columns into space in one trip.

Figure 6. A schematic of the space shuttle. Shown is the location of boron-reinforced aluminum supports in the fuselage.

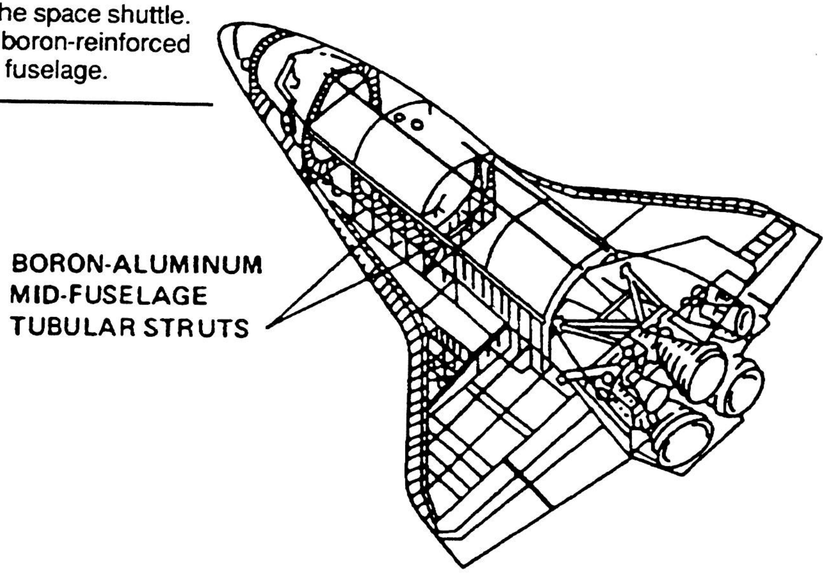

Table I. Selection Criteria for Fiber-Reinforced Ceramic-Matrix Composite Systems

Fiber/Matrix System	Screening Criteria Used
SiC/Lithium-Alumino-Silicate	Maximum operating temperature
SiC/Magnesium-Alumino-Silicate	
SiC/Calcium-Alumino-Silicate	Thermal shock resistance
SiC/Black Glass	
SiC/Borosilicate	Environmental resistance
SiC/Silica	
C/Lithium-Alumino-Silicate	Ultimate tensile strength
C/Borosilicate	
C/Silica	Fracture toughness
C/Alumina	
SiC/Silicon Nitride	Fabricability
SiC/SiC	
C/SiC	Maturity
C/C	

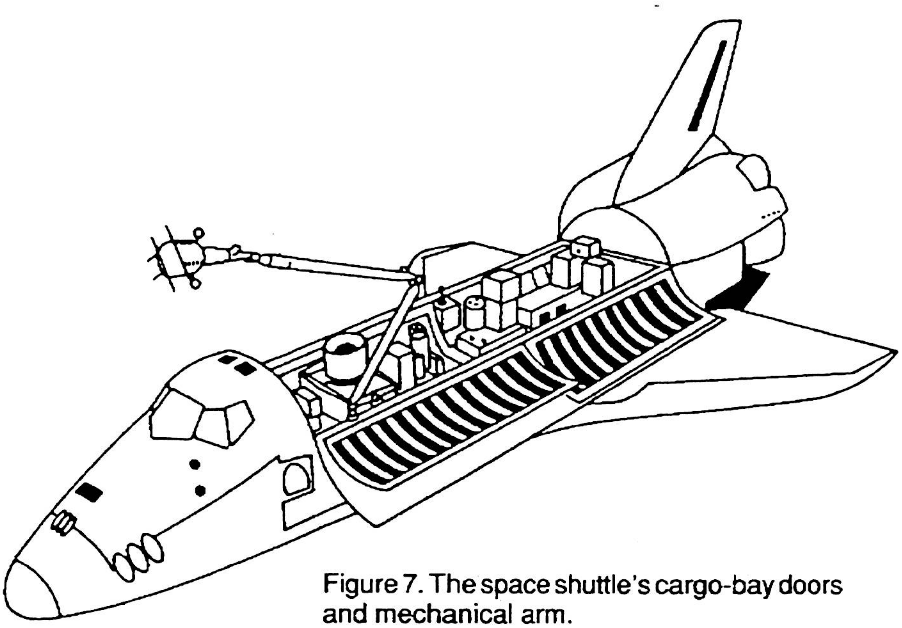

Figure 7. The space shuttle's cargo-bay doors and mechanical arm.

Another project aims at fabricating composite structural beams in the space itself. Carbon reinforced polysulfone ribbon made on earth would be delivered by the space shuttle. It would be formed into triangular beams by employing a pultrusion type process originally developed by a private company named Goldsworthy Engineering. In this scheme, three separate ribbons are heat shaped into hot dies and welded in a final heated die to form triangular corner sections. Intercoaster struts at 90° and 45° complete the beam structure. The finished beams from this process are much stronger than aluminum and possess near zero thermal coefficient of expansion, which is the prime requirement for the space station structural materials.

Concluding Remarks

Ceramics Matrix Composites and intermetallics are relatively a new class of materials. However, the processing technologies of these materials are maturing at a very fast pace as the components made are significantly lighter, retain strength and stiffness even at elevated temperature and are more durable in comparison to the equivalent metallic counterparts. As the data on the service life of these materials are becoming available it can be safely said that these materials possess excellent fatigue loading resistance, maintain dimensional integrity at elevated temperature and can easily be fabricated into structural components and repaired. These exotic materials will continue to find new applications, but the large scale growth in the market place will require less costly processing methods and availability of more data on the predicting service life and mode of failure in the field.

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