Metal-Matrix Composites for Space Applications

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ABSTRACT: From the onset of the space era, both organic-matrix and metal-matrix composites (MMCs), with high specific stiffness and near-zero coefficient of thermal expansion (CTE), have been developed for space applications. Of the organic-matrix composites, graphite/epoxy (Gr/Ep) has been used in space for truss elements, bus panels, antennas, wave guides, and parabolic reflectors in the past 30 years. MMCs possess high-temperature capability, high thermal conductivity, low CTE, and high specific stiffness and strength. Those potential benefits generated optimism for MMCs for critical space system applications in the late 1980s. The purpose of this article is to detail the history, status, and opportunities of MMCs for space applications.

INTRODUCTION

The extreme environment in space presents both a challenge and opportunity for material scientists. In the near-earth orbit, typical spacecraft encounter naturally occurring phenomena such as vacuum, thermal radiation, atomic oxygen, ionizing radiation, and plasma, along with factors such as micrometeoroids and human-made debris. For example, the International Space Station, during its 30-year life, will undergo about 175,000 thermal cycles from +125°C to –125°C as it moves in and out of the Earth's shadow. Re-entry vehicles for Earth and Mars missions may encounter temperatures that exceed 1,500°C. Critical spacecraft missions, therefore, demand lightweight space structures with high pointing accuracy and dimensional stability in the presence of dynamic and thermal disturbances. Composite materials, with their high specific stiffness and low coefficient of thermal expansion (CTE), provide the necessary characteristics to produce lightweight and dimensionally stable structures. Therefore, both organic-matrix and metal-matrix composites (MMCs) have been developed for space application.

Despite the successful production of MMCs such as continuous-fiber reinforced boron/aluminum (B/Al), graphite/ aluminum (Gr/Al), and graphite/ magnesium (Gr/Mg),the technology insertion was limited by the concerns related to ease of manufacturing and inspection, scale-up, and cost. Organic-matrix composites continued to successfully address the system-level concerns related to micro cracking during thermal cycling and radiation exposure, and electromagnetic interference (EMI) shielding; MMCs are inherently resistant to those factors. Concurrently, discontinuously reinforced MMCs such as silicon-carbide particulate (p) reinforced aluminum (SiC_p/Al) and G_p/Al composites were developed cost effectively both for aerospace applications (e.g., electronic packaging) and commercial applications. This paper describes the benefits, drawbacks, potential for the various MMCs in the U.S. space program.

HISTORICAL PERSPECTIVE

Historically, MMCs, such as steel-wire reinforced copper, were among the first continuous-fiber reinforced composites studied as a model system. Initial work in late 1960s was stimulated by the high-performance needs of the aerospace industry. In these development efforts, performance, not cost, was the primary driver. Boron filament, the first high-strength, high-modulus reinforcement, was developed both for metal- and organic- matrix composites. Because of the fiber-strength degradation and poor wettability in molten-aluminum alloys, the early carbon fibers could only be properly reinforced in organic-matrix composites. Therefore, the development of MMCs was primarily directed toward diffusion-bonding processing. At the same time, optimum (air stable) surface coatings were developed for boron and graphite fibers to facilitate wetting and inhibit reaction with aluminum or magnesium alloys during processing.

METAL-MATRIX COMPOSITE PROCESSING

Three processing methods have been primarily used to develop MMCs: high-pressure diffusion bonding, casting, and powder-metallurgy techniques. More specifically, the diffusion-bonding and casting methods have been used for continuous- fiber reinforced MMCs. Discontinuously reinforced MMCs have been produced by powder metallurgy and pressure-assist casting processes. MMCs such as B/Al, Gr/Al, Gr/Mg, and Gr/ Cu have been manufactured by diffusion bonding for prototype spacecraft components such as tubes plates and pannels.

Properties

Table I lists the typical properties of a few continuous-fiber reinforced MMCs. Generally, measured properties of as-fabricated MMCs are consistent with the analytically predicted properties of each composite. The primary advantage of MMCs over counterpart organic-matrix composites is the maximum operating temperature. For example, B/Al offers useful mechanical properties up to 510°C, whereas an equivalent B/Ep composite is limited to about 190°C. In addition, MMCs such as Gr/Al, Gr/Mg, and Gr/Cu exhibit higher thermal conductivity because of the significant contribution from the metallic matrix.

Table I. Material Properties of Uni-directional Metal-Matrix Composites for Space Applications

Properties	P100/6061 Al (0°)	P100/AZ91C Mg (0°)	Boron/Al (0°)
Volume Percent Reinforcement	42.2	43	50
Density, ρ (gm/cm^3)	2.5	1.97	2.7
Poisson Ratio n_{xy}	0.295	0.3	0.23
Specific Heat C_p (J/kg-K)	812	795	801
Longitudinal			
Young's Modulus (x) (GPa)	342.5	323.8	235
Ultimate Tensile Strength (x) (MPa)	905	710.0	1100
Thermal Conductivity K_x (W/m-K)	320.0	189	—
CTE_x (10^{-6} /K*)	-0.49	0.54	5.8
Transverse			
Young's Modulus (y) (GPa)	35.4	20.7	138
Ultimate Tensile Strength (y) (MPa)	25.0	22.0	110
Thermal Conductivity K_y (W/m-K)	72.0	32.0	—

* Slope of a line joining extreme points (at –100°C and +100°C) of the thermal strain curve (first cycle).

Table II lists the properties of discontinuously reinforced aluminium (DRA) composites for spacecraft and commercial applications. DRA is an isotropic MMC with specific mechanical properties superior to conventional aerospace materials. For example, DWA Aluminium Composites has produced MMCs using 6092 and 2009 matrix alloys for the best combination of strength, ductility, and fracture toughness, and 6063 matrix alloy to obtain high thermal conductivity. Similarly, Metal Matrix Cast Composite (MMCC) Inc. has produced graphite particulate-reinforced aluminium composites for the optimum combination of high specific thermal conductivity and CTE.

Table II. Material Properties of Discontinuously Reinforced Aluminium-Matrix Composites

Properties	Graphite Al GA 7-230	Al6092/SiC/17.5p	Al/SiC/63p
Density, ρ (gm/cm^3)	2.45	2.8	3.01
Young's Modulus (GPa)	88.7	100	220
Compressive Yield Strength (MPa)	109.6	406.5	
Tensile Ultimate Strength (MPa)	76.8	461.6	253
Compressive Ultimate Strength (MPa)	202.6	—	
CTE (x-y) (10^{-6} /K)	6.5-9.5	16.4	7.9
Thermal Conductivity (W/m-K) (x-y)	190	165	175
(z)	150		170
Electrical Resistivity (µ-ohm-cm)	6.89	—	

APPLICATIONS

While the desire for high-precision, dimensionally stable spacecraft structures has driven the development of MMCs, applications thus far have been limited by difficult fabrication processes. The first successful application of continuous-fiber reinforced MMC has been the application of B/Al tubular struts used as the frame and rib truss members in the mid-fuselage section, and as the landing gear drag link of the Space Shuttle Orbiter (Figure 1). Several hundred B/Al tube assemblies with titanium collars and end fittings were produced for each shuttle orbiter. In this application, the B/Al tubes provided 45% weight savings over the baseline aluminum design.

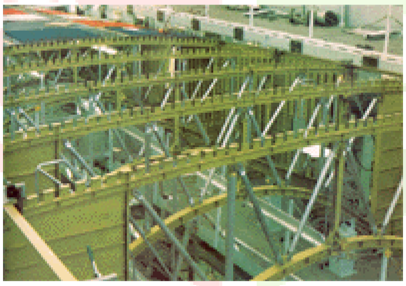


Figure 1. Mid-fuselage structure of Space Shuttle Orbiter showing boron-aluminum tubes. (Photo courtesy of U.S. Air Force/NASA).

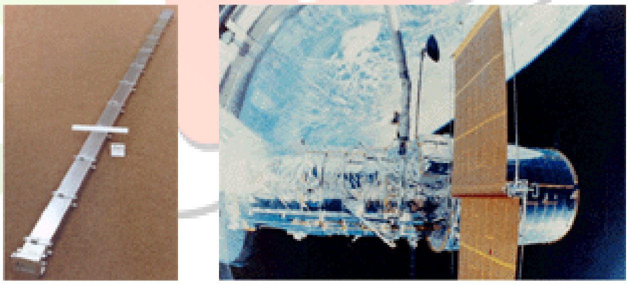


Figure 2. The P100/6061 Al high-gain antenna wave guides/ boom for the Hubble Space Telescope (HST) shown (a-left) before integration in the HST, and (b-right) on the HST as it is deployed in low-earth orbit from the space shuttle orbiter.

The major application of Gr/Al composite is a high-gain antenna boom (Figures 2a and 2b) for the Hubble Space Telescope made with diffusion-bonded sheet of P100 graphite fibers in 6061 Al. This boom (3.6 m long) offers the desired stiffness and low CTE to maintain the position of the antenna during space maneuvers. In addition, it provides the wave-guide function, with the MMC's excellent electrical conductivity enabling electrical-signal transmission between the spacecraft and the antenna dish. Also contributing to its success in this function is the MMC's high dimensional stability—the material maintains internal dimensional tolerance of ±0.15 mm along the entire length. While the part currently in service is continuously reinforced with graphite fibers, replacement structures produced with less expensive DRA have been certified.

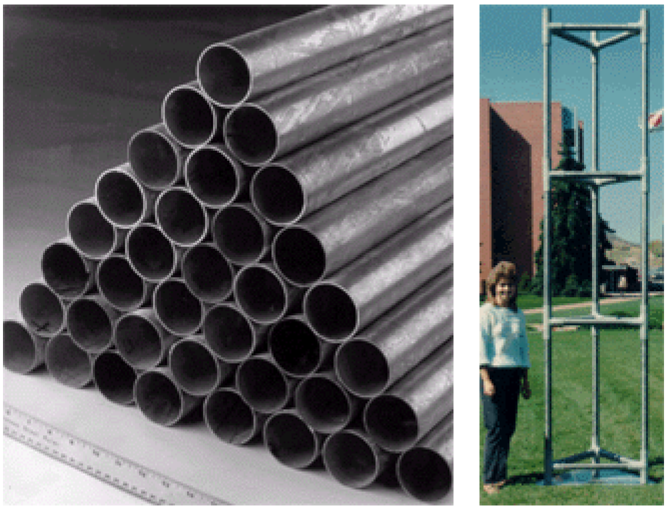


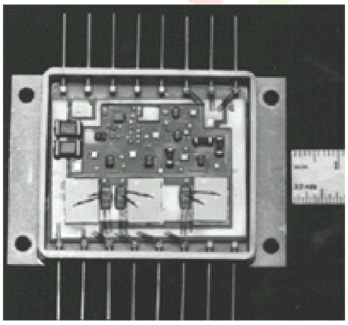
Figure 3. P100/AZ91C Gr/Mg tubes produced by the vacuum-assist casting process: (a-left) as-cast tubes, and (b-right) demonstration Gr/Mg truss structure.

Figure 4. Cast SiC_p/Al attachment fittings: (a-top) multi-inlet fitting for a truss node, and (b-bottom) cast fitting brazed to a Gr/Al tube.

Like the Gr/Al structural boom, a few MMCs have been designed to serve multiple purposes, such as structural, electrical, and thermal-control functions. For example, prototype Gr/Al composites were developed as structural radiators to perform structural, thermal, and EMI-shielding functions.[5] Also, Gr/Cu MMCs with high thermal conductivity were developed for high-temperature structural radiators.[6] A DRA panel is used as a heat sink between two printed circuit boards to provide both thermal management and protection against flexure and vibration, which could lead to premature failure of the components in the circuit board.

In technology-development programs sponsored by the U.S. Defense Advanced Research Projects Agency and the U.S. Air Force, graphite/magnesium tubes for truss-structure applications have been successfully produced (jointly by Lockheed Martin Space Systems of Colorado and Fiber Materials of Maine) by the filament-winding vacuum-assisted casting process. Figures 3a and 3b show a few of the cast Gr/Mg tubes (50 mm dia 1.2 m long) that were produced to demonstrate the reproducibility and reliability of the fabrication method.

Of the DRA composites, reinforcements of both particulate SiC_p/Al and whisker (w) SiC_w/Al were extensively characterized and evaluated during the 1980s. Potential applications included joints and attachment fittings for truss structures, longerons, electronic packages, thermal planes, mechanism housings, and bushings. Figures 4a and 4b show a multi-inlet SiC_p/Al truss node produced by a near net-shape casting process.



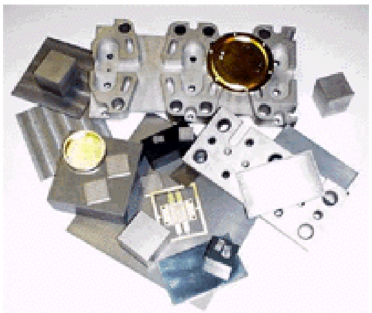


Figure 5. Discontinuously reinforced aluminum MMCs for electronic packaging applications: (a-top) SiC_p/Al electronic package for a remote power controller (photo courtesy of Lockheed Martin Corporation), and (b-bottom) cast Gr_p/Al components (photo courtesy of MMCC, Inc.).

Because of their combination of high thermal conductivity, tailorable CTE (to match the CTE of electronic materials such as gallium arsenide or alumina), and low density, DRA composites are especially advantageous for electronic packaging and thermal-management applications.[8,9] Several SiC_p/Al and Gr_p/Al (Figures 5a and 5b) electronic packages have been space-qualified and are now flown on communication satellites and Global Positioning System satellites. These components are not only significantly lighter than those produced from previous metal alloys, but they provide significant cost savings through net-shape manufacturing.[9] DRA is also used for thermal management ofspacecraft power semiconductor modules in geosynchronous earth-orbit communication satellites, displacing Cu/W alloys with a much higher density and lower thermal conductivity, while generating a weight savings of more than 80%. These modules are also used in a number of land-based systems, which accounts for an annual production near 1 million piece-parts. With these demonstrated benefits, application of DRA MMCs for electronic packages will continue to flourish for space applications.

STATUS AND FUTURE

When continuous-fiber reinforced MMCs were no longer needed for the critical strategic defense system/missions, the development of those MMCs for space applications came to an abrupt halt. Major improvements were still necessary, and manufacturing and assembly problems remained to be solved. In essence, continuous-fiber reinforced MMCs were not able to attain their full potential as an engineered material for spacecraft applications. During the same period, Gr/Ep, with its superior specific stiffness and strength in the uniaxially-aligned fiber orientation, became an established choice for tube structures in spacecraft trusses. Issues of environmental stability in the space environment have been satisfactorily resolved.

However, particle-reinforced metals provide very good specific strength and stiffness, isotropic properties, ease of manufacturing to near net shape, excellent thermal and electrical properties, and affordability, making discontinuous MMCs suitable for a wide range of space applications. The high structural efficiency and isotropic properties of discontinuously reinforced metals provide a good match with the required multiaxial loading for truss nodes, where high loads are encountered. DRA is a candidate for lightly-loaded trusses, while discontinuously reinforced Ti (DRTi) is more favourable for highly-loaded trusses. DRTi, now commercially available in both the United States and Japan, offers excellent values of absolute strength and stiffness as well as specific strength and stiffness

A wide range of additional applications exist for discontinuously reinforced metals. Opportunities for thermal management and electronic packaging include radiator panels and battery sleeves, power semiconductor packages, microwave modules, black box enclosures, and printed circuit board heat sinks. For example, the DSCS-III, a military communication satellite, uses more than 23 kg of Kovar for microwave packaging. Replacing this metal with Al/SiC_p, which is used for thermal management in land-based systems, would save more than 13 kg of weight and provide a cost savings over Kovar components. Potential satellite subsystem applications include brackets and braces currently made from metals with lower specific strength and stiffness, semimonocoque plates and cylinders, fittings for organic-matrix composite tubes, hinges, gimbals, inertial wheel housings and electro-optical subsystems.

MMCs are routinely included as candidate materials for primary and secondary structural applications. However, simply having the best engineered material with extraordinary strength, stiffness, and environmental resistance is no guarantee of insertion. The availability and affordability of continuously reinforced MMC remains a significant barrier to insertion.

Designers who often make the decision of material selection must become more familiar with the properties, commercial availability and life-cycle affordability of existing discontinuously reinforced metals. Material performance must be integrated with innovative design and affordable manufacturing methods to produce systems and subsystems that provide tangible benefits. However, in the absence of system-pull and adequate resources, it is difficult to surmount the technical and cost barriers.

Recognizing that defense- and aerospace- driven materials need to turn to the commercial market place, Carlson[10] cited four recurring principles that will shape the future of advanced materials such as organic-matrix and MMCs. These four principles included system solutions, economical manufacturing processing, diverse markets, and new technologies. In terms of system solutions, the decision regarding designs, processes and materials must be made synergistically to attain maximum benefit. No single mission or system application can sustain the cost of developing new materials and processes. Thus, the use of DRA in diverse markets such as automotive, recreational, and aircraft industries has made DRA MMC affordable for spacecraft applications such as electronic packaging. Building upon the success of DRA in electronic packaging and in structural applications in the automotive and aeronautical fields, DRA is also being evaluated for truss end fittings, mechanism housings, and longerons.

During the development of MMCs, significant advancements were made on the fundamental science and technology front, including a basic understanding of composite behavior, fiber-matrix interfaces, surface coatings, manufacturing processes, and thermal-mechanical processing of MMCs. Subsequently, the technology experience benefited the latter development of high-temperature intermetallic- matrix composites. (Research activities that will be required to support more widespread use of MMCs for space application

Lightweight, stiff, and strong Gr/Al and DRA MMCs will continue to be included in material trade studies for spacecraft components, as MMCs offer significant payoffs in terms of performance (e.g., high precision, survivable) for specific systems. For successful use in space applications, continuous MMCs must become more affordable, readily available, reliable/reproducible, and repairable, exhibiting equivalent or better properties than competing graphite/ epoxy or metallic parts. Discontinuous metals, with their broad range of functional properties including high structural efficiency and isotropic properties, offer the greatest potential for a wide range of space-system applications. A good understanding provided by years of research, and a strong industry based on applications in the automotive, recreation, aeronautical, and land-based communications markets, have established the foundation for cost-effective insertion of discontinuously reinforced metals in the space industry.

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