METAL MATRIX COMPOSITES - THEIR PROPERTIES AND APPLICATIONS

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Abstract: Over last two decades researchers and manufacturers, i.e., automotive and aerospace, have paid attentions and interests to metal–matrix composites (MMC) owing to their unique physical/mechanical properties and performance. MMC possess superior combinations of elevated-temperature capabilities, high thermal conductivity, high strength and stiffness, high strength-to-density ratio, and low coefficient of thermal expansion. In this paper, upon a general introduction to composite materials, the properties of reinforcement and matrix materials and the properties of MMC, in particular, are reviewed. The microstructure, design consideration, fabrication methods, strengthening mechanisms, matrix/reinforcement-based classifications and applications of MMC are addressed.

1. METAL MATRIX COMPOSITES

Metal matrix composites (MMCs) comprise a relatively wide range of materials defined by the metal matrix, reinforcement type, and reinforcement geometry. In the area of the matrix, most metallic systems have been explored for use in metal matrix composites, including Al, Be, Mg, Ti, Fe, Ni, Co, and Ag. By far the largest usage is in aluminum matrix composites. From a reinforcement perspective, the materials used are typically ceramics since they provide a very desirable combination of stiffness, strength, and relatively low density. Candidate reinforcement materials include SiC, Al_2O_3, B_4C, TiC, TiB_2, graphite, and a number of other ceramics. In addition, there has been work on metallic materials as reinforcements, notably W and steel fibers.

The morphology of the reinforcement material is another variable of importance in metal matrix composites. The three major classes of reinforcement morphology are continuous fiber, chopped fiber or whisker, and particulate. Typically, selection of the reinforcement morphology is determined by the desired property/cost combination. Generally, continuous fiber reinforced MMCs provide the highest properties in the direction of the fiber orientation but are the most expensive. Chopped fiber and whisker reinforced materials can produce significant property improvements in the plane or direction of their orientation, at somewhat lower cost. Particulates provide a comparatively more moderate but isotropic increase in properties and are typically available at the lowest cost. By adding to the three variables of metallic matrix, reinforcement material, and reinforcement morphology, the further options of reinforcement volume fraction, orientation, and matrix alloy composition and heat treatment, it is apparent that there is a very wide range of available material combinations and resultant properties. The specifics of the MMC systems, their manufacturing processes, and properties have been covered in Volume 3 of this series. This chapter will focus on how MMCs have been applied in specific application areas.

2. 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 II lists the properties of discontinuously reinforced aluminum (DRA) composites for spacecraft and commercial applications. DRA is an isotropic MMC with specific mechanical properties superior to conventional aerospace materials. For example, DWA Aluminum 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.

Table I. Material Properties of Unidrectional 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, r (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. Material Properties of Discontinuously Reinforced Aluminum-Matrix Composites

Properties	**Graphite AlGA 7-230**	**Al6092/SiC/17.5p**	**Al/SiC/63p**
Density, r (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 (m-ohm-cm)	6.89	—	

3. 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.

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

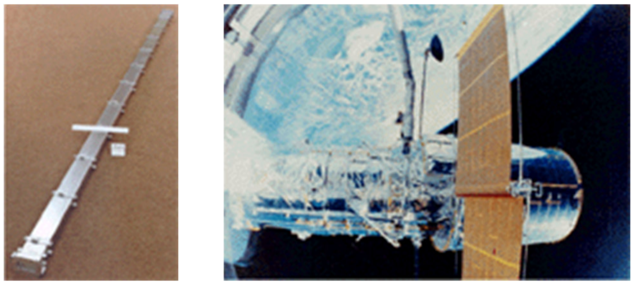


Figure 2. The P100/6061 Al high-gain antenna wave guides/ boom for the Hubble Space Telescope (HST) shown (a-left) before integration in the HST, and (b-right) on the HST as it is deployed in low-earth orbit from the space shuttle orbiter.

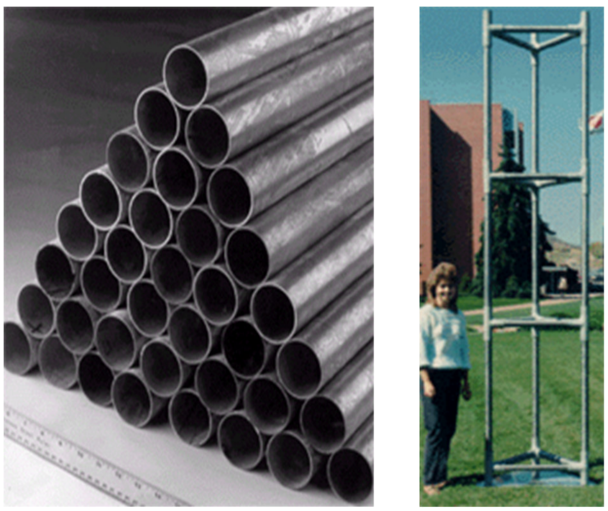


Figure 3. P100/AZ91C Gr/Mg tubes produced by the vacuum-assist casting process: (a-left) as-cast tubes, and (b-right) demonstration Gr/Mg truss structure.

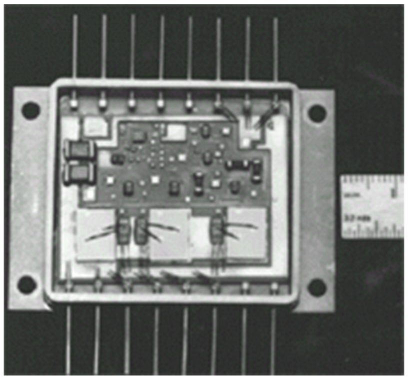
Figure 4. Cast SiC_p/Al attachment fittings: (a-top) multi-inlet fitting for a truss node, and (b-bottom) cast fitting brazed to a Gr/Al tube.

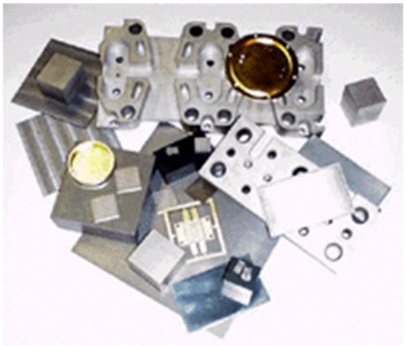
Like the Gr/Al structural boom, a few MMCs have been designed to serve multiple purposes, such as structural, electrical, and thermal-control functions. For example, prototype Gr/Al composites were developed as structural radiators to perform structural, thermal, and EMI-shielding functions. Also, Gr/Cu MMCs with high thermal conductivity were developed for high-temperature structural radiators. 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.





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. 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. DRA is also used for thermal management of spacecraft 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.

4. 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 favorable 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 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 applications have been discussed.)

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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