AFFORDABLE METAL-MATRIX COMPOSITES FOR HIGH PERFORMANCE APPLICATIONS

Edited by: Awadh B. Pandey, Kevin L. Kendig and Thomas J. Watson

SESSION I:
AEROSPACE, SPACE AND LAND VEHICLE APPLICATIONS

Metal Matrix Composites for Space Systems: Current Uses and Future Opportunities

D.B. Miracle

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184 Thorn Hill Road
Warrendale, PA 15086-7514
(724) 776-9000

METAL MATRIX COMPOSITES FOR SPACE SYSTEMS: CURRENT USES AND FUTURE OPPORTUNITIES

Daniel B. Miracle

AF Materials and Manufacturing Directorate
AFRL/MLLMD
Wright-Patterson AFB, OH 45433

Abstract

Metal matrix composites (MMC's) have fulfilled important space systems requirements for over 20 years. Current applications include structural members in the space shuttle cargo bay, a multi-functional antenna mast/signal waveguide in the Hubble Space Telescope, and electronic packaging for communication satellites in low earth orbit. The continued maturation of MMC technology, along with the expansion of new space systems concepts, now provides an unusual range of opportunities for the use of MMC's in spacecraft. Enabling capabilities in liquid rocket propulsion are also being pursued. Both particulate- and fiber-reinforced MMC's are being developed and evaluated for pump motor housings of liquid fuel rocket engines. Other liquid rocket engine components which are being pursued as a result of very attractive trade studies include inducers and impellers, cryogen ducts, lines and flanges, and the combustion chamber structural jacket. A novel approach for the manufacture of continuously-reinforced Al MMC's is being developed to produce cryogen tankage. The suite of material characteristics that make MMC's attractive for launch and on-orbit applications include very good specific strength and stiffness, high thermal and electrical conductivity, low-to-moderate thermal expansion, excellent resistance to UV radiation and good resistance to atomic oxygen. This balance of properties, and the fact that many of these properties are fully tailorable, offer unique opportunities for multi-functional use. Finally, the cost of MMC components, especially particulate-reinforced metals, can offer significant cost advantages over competing monolithic metals and organic composites. This manuscript will provide the results of a recent technology assessment of the space industry. The MMC systems offering the highest payoffs will be presented, and the impact on space systems will be described. Technical challenges to be overcome will be listed and a teaming strategy for materials development and insertion will be provided.

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Introduction

Metal matrix composites (MMC's) have matured in the past decade as an economically and industrially important class of materials. In 1999, the annual world production of MMC's amounted to over 2500 metric tons, valued at over $100B US dollars [1]. Principle markets included ground transportation, thermal management, aerospace and recreation. MMC material is commercially produced by casting and powder metallurgy, and a wide range of secondary processes are established.

Metal matrix composites (MMC's) consist of a continuous metal or intermetallic matrix phase and either continuous or discontinuous reinforcements. Continuously reinforced MMC's offer the highest levels of strength and stiffness, but the transverse properties must be managed through either adjustments in the composite architecture or through selection of components with primarily uniaxial imposed stresses. Early space applications emphasized continuously-reinforced MMC's due to the outstanding specific strength and stiffness along the fiber direction. While discontinuously reinforced MMC's have emerged over the past decade as a pervasive material solution with a wide range of applications in other industries, the use of these materials in space systems has been slow to materialize. However, the strong current investment in a range of next-generation space systems now offers many opportunities for the development, demonstration and certification of MMC's. This manuscript will describe the characteristics of MMC's that make them attractive for a wide range of space applications. While a great deal of research and development has been conducted on very many MMC systems, this manuscript will emphasize MMC's that are well-qualified and generally available on a commercial basis. The current uses of MMC's in space systems will be outlined and applications that are being considered for MMC's will be discussed. A brief description of the research and development required to achieve the properties goals needed for these applications will be provided, and this manuscript will close with comments regarding a proposed teaming strategy to expand the impact and to share the cost and risk of development and insertion.

Characteristics of MMC's

It is important to differentiate between MMC's with continuous reinforcements, and those with discontinuous reinforcements. While these two classes of materials share common features at a fundamental level (for example, matrix/reinforcement compatibility, interfacial properties), at a practical level there are dramatic differences. Failure to explicitly consider the appropriate reinforcement morphology can result in inaccurate assessments. The general characteristics of these different classes of MMC's will be briefly discussed in the following sections, followed by a more detailed discussion of properties that are most relevant to the application of MMC's in space systems. Additional information is available in recent publications [2–5].

General characteristics of continuously reinforced MMC's

Continuously-reinforced MMC's are comprised of a metal or intermetallic matrix, most often an alloy of Al, Ti or Cu, reinforced with a continuous reinforcement. These reinforcements are typically fiber tows of either carbon (C_f) or alumina ($Al_2O_{3\ f}$), or monofilaments of B or SiC. Ceramic tow reinforcements are generally less expensive and easier to handle during processing, but possess lower strength than the more expensive large-diameter (100–150 μm) B or SiC monofilaments. Continuous reinforcements are very sensitive to chemical attack by the matrix, since even a small amount of interaction can significantly decrease the reinforcement strength. Thus, care must be taken to specify a matrix/reinforcement pair that is chemically compatible, or a protective fiber coating must be used. A range of processing approaches have been successfully applied, including solid state diffusion bonding, melt infiltration, vapor deposition of the matrix alloy onto the fiber, and powder processes. Secondary processing techniques are problematic, since damage to the reinforcement is difficult to avoid, and so a near net shape approach is used, similar to the methodology employed for fiber reinforced organic matrix composites (OMC's).

Continuously reinforced MMC's offer the highest values of strength and stiffness along the axis of the reinforcements, but the transverse properties of these materials are much poorer, similar to the behavior of OMC's. Due to the small diameter of the reinforcing fibers used in OMC's and the moderate interfacial bond strength, a range of cross-ply architectures can be produced to provide an attractive level of properties within the plane of the plies. Techniques for obtaining high quality cross-plied architectures have not been established for tow-based MMC's, but cross-plied composites have been produced for titanium matrix composites (TMC's) reinforced with SiC monofilaments However, the strength of the interfacial region is sufficiently weak so that most cross-plied TMC's possess in-plane properties that are no better than the unreinforced matrix [6]. Thus, potential applications of fiber-reinforced TMC's are limited to components that are subjected to a largely uniaxial stress. Continuously-reinforced Al- and Cu-based MMC's can have much higher interfacial strengths than TMC's, and so a different conclusion might be drawn for these materials.

General characteristics of discontinuously reinforced MMC's

Discontinuously reinforced MMC's consist of a continuous metal or intermetallic matrix, typically an alloy of Al, Ti or Cu, and a discontinuous reinforcing phase. The reinforcements are most often SiC, Al_2O_3, B_4C or TiB, although many other ceramic materials have been used. The reinforcement morphology may be plate-like, whisker or particulate, but particulates (aspect ratio ~1–2) are most often used as a result of their widespread availability and lower cost. The mechanical properties of discontinuously reinforced MMC's are far less sensitive to chemical interaction between the fiber and the matrix than continuous MMC's. Primary processing techniques for discontinuous MMC's include powder metallurgy (P/M), stir casting, infiltration casting and reaction casting. Primary and secondary processing techniques share much in common with conventional metals, so that discontinuous MMC's typically utilize existing infrastructure for primary production, metal forming, joining, repair and assembly. This, coupled with the much lower cost of the constituent materials, makes discontinuous MMC's much more affordable and supportable than continuously reinforced MMC's. Discontinuous MMC's are now commercially available in a wide range of product forms (castings, forgings, sheet, extruded forms).

The physical and mechanical properties of discontinuously reinforced MMC's are largely isotropic, owing to the aspect ratio near unity of the reinforcements. The isotropic nature of discontinuously reinforced MMC's opens a far wider range of potential applications than exists for continuously reinforced MMC's. In addition, the properties are tailorable over a wide range as a result of the flexibility in specifying the size, volume fraction, composition and morphology of the reinforcement, and by varying the matrix alloy composition and heat treatment. A range of typical microstructures are shown in Fig. 1. Extruded discontinuously reinforced Al (DRA) produced by P/M is shown in Figs. 1(a) and (b), with a volume fraction of 15% and 25%, respectively. Figs. 1(c) and (d) show DRA produced by liquid metal infiltration, containing 60% and 70% of SiC particles, respectively. Unimodal SiC particles are shown in Fig. 1(c), while a bimodal distribution was used to produce the material in Fig. 1 (d). Control of the volume fraction and particle size of reinforcements provides direct control of the modulus, strength, fracture properties and coefficient of thermal expansion (CTE). The Aerospace Materials Specification (AMS) format is used in this manuscript, where an MMC is designated by the notation Matrix Alloy Designation/Reinforcement Type/Volume Fraction$_x$, where the subscript *x* denotes fiber (f), whisker (w) or particulate (p).

The suite of properties offered by discontinuously reinforced MMC's include very good specific strength and stiffness, excellent wear resistance, moderate and controllable CTE and good electrical conductivity. These properties are isotropic and tailorable over a wide range, as discussed in the previous paragraph. These characteristics give rise to applications for structural components, wear applications, thermal management and also favor precision devices that must resist deflections from thermal and/or mechanical loads. These characteristics will be discussed in more detail in the following subsections. The existing and future applications resulting from this suite of properties will be described in the next section.

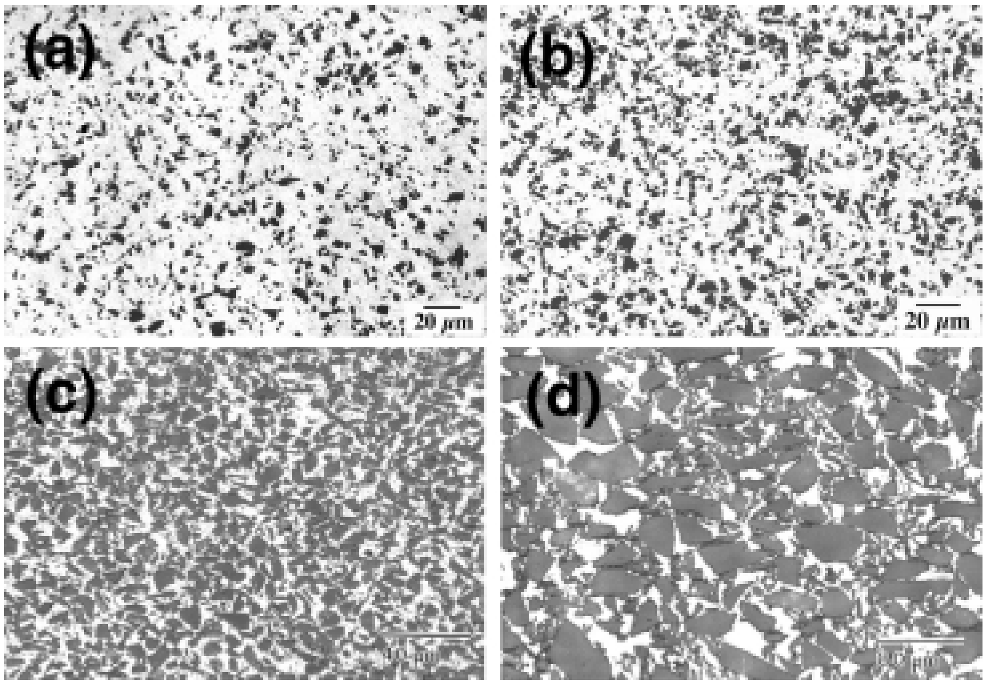

Figure 1 Extruded (a) 7091/SiC/15p and (b) 7091/SiC/25p, and liquid metal infiltrated (c) A356/SiC/60p and (d) A356/SiC/70p.

<u>Properties for structural efficiency (specific stiffness and specific strength)</u>

Stiffness is the primary design factor in most structural applications. Stiffness controls the magnitude of elastic deflection and the onset of instabilities such as buckling or crippling, thus defining the size and spacing of structural members. A higher stiffness enables smaller members or more widely spaced support structure, leading to a reduction in mass and fewer parts (hence lower assembly cost). In addition, material stiffness is a critical factor in defining the vibrational frequencies of components and structures, and the fatigue life of a material often scales directly with the material stiffness. Strength is also a primary design parameter that controls the size and spacing of support structure. The density-normalized, or specific, stiffness and strength (E/ρ and σ/ρ, respectively) are particularly important for dynamic parts and for systems that move. An increase in specific stiffness or strength provides equivalent resistance to elastic or plastic deformation *at reduced mass*. In dynamic parts, a reduction in mass translates to lower loads, providing cascading benefits in system mass. For stationary components that are part of a moving system, reduced component mass translates to reduced system mass, and hence improved efficiency. This is particularly important for space systems, where the payload for geosynchronous earth orbit (GEO) is typically only 1% of the total launch mass. Thus, small decreases in system launch mass can provide a significant increase in the payload to orbit.

The specific stiffness of conventional structural metals falls within a narrow range, as illustrated in Fig. 2. Aerospace alloys of Al, Mg, Ti, Ni and steel possess E/ρ which range from about 25–32 GPa/(Mg/m^3). Discontinuously reinforced MMC's possess significant improvements in specific stiffness owing to the high elastic modulus and low density of the ceramic reinforcements. Thus, values of 30–60 GPa/(Mg/m^3) have been obtained in commercially available DRA, with values of 35–40 GPa/(Mg/m^3) being typical for qualified structural materials. These values are not only much higher than the Al alloys upon which DRA is based, but these values are also competitive with the specific stiffness of cross-plied graphite/epoxy OMC's typically used for aerospace skin structures. Thus, DRA can compete with aerospace OMC's such as graphite/epoxy on a performance basis for sheet applications, and also have the potential benefit of significant cost savings.

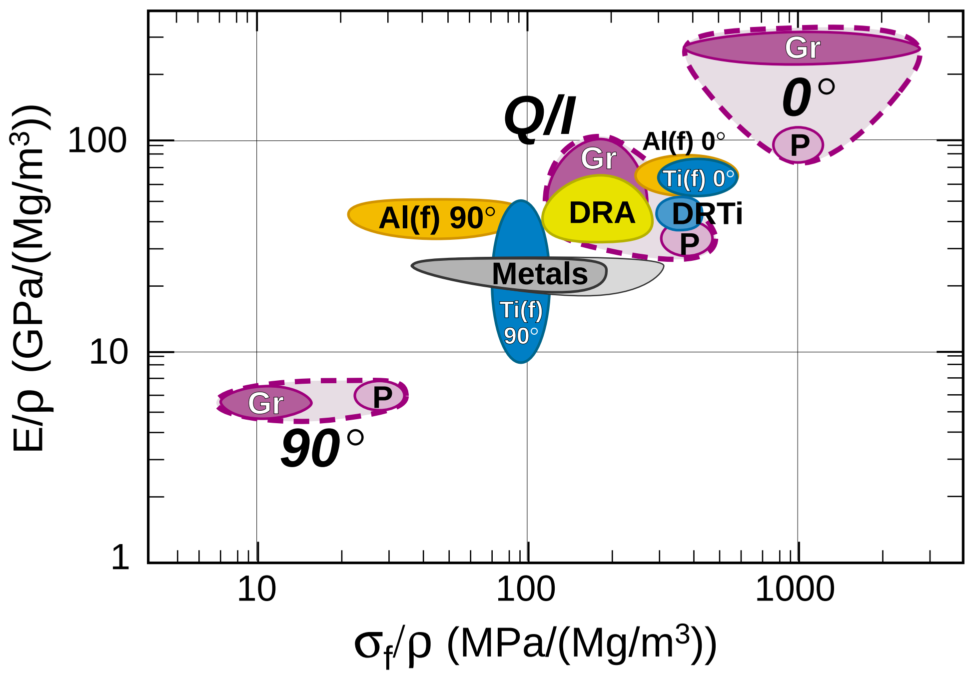

Figure 2 Specific stiffness vs. specific strength for structural materials. Aerospace organic matrix composites are shown as graphite/epoxy (Gr) or PAN/epoxy (P) in the longitudinal (0°), transverse (90°), and quasi-isotropic (Q/I) configurations. The longitudinal and transverse properties for fiber-reinforced Al (Al(f)) and Ti (Ti(f)) are also shown. Conventional aerospace metals (Metals), including Al, Mg, Ti, Ni and steel alloys, are shown, and the dashed extension indicates a few specialty metals such as β-Ti and ultra high strength steels.

The specific strength of aerospace structural metals covers a broad range owing to the sensitivity of strength to metal alloy composition and microstructure. Particle reinforcement offers an important increase in specific strength over the matrix. For example, peak-aged Al6061 has a specific ultimate strength of 115 MPa/(Mg/m^3), while DRA based on a similar 6000-series Al possesses specific strengths from 180–200 MPa/(Mg/m^3). As a result, discontinuous MMC's possess specific strengths equivalent to cross-plied graphite/epoxy.

Unidirectionally reinforced graphite/epoxy possesses a superior balance of specific stiffness and specific strength. Continuously reinforced Ti ($Ti/SiC/35_f$) and Al ($Al/Al_2O_3/50_f$) are beginning to approach the lower bounds of these materials, but graphite/epoxy is more affordable than the TMC composites, and is more established and commercially available than either MMC. However, composite structures often impose requirements in addition to excellent specific stiffness and strength in one principle direction. These requirement can include high bearing strength for attachments, resistance to cryogenic fluids (tankage), resistance to outgassing, good through-thickness thermal conductivity, high dimensional stability, resistance to burning and high temperature application. Continuously reinforced MMC's may have advantages in such applications, and efforts to employ these materials should focus on these additional requirements.

Affordability

Affordability has traditionally been a primary concern in high-volume commercial markets, but it is only recently that affordability has become a principle factor in the military aerospace industry. It is very likely that affordability will continue to grow in importance as a criteria for material selection and design in defense applications. Unfortunately, affordability is a difficult parameter to quantify. While affordability is often equated to material cost, the raw material is typically overwhelmed by costs associated with secondary processing, machining, assembly, operation and support. In the end, life cycle costs are the most rational metric, but this is not yet widely accepted as an approach for material selection. This situation is likely to persist as long as the budget decisions of the organizational unit that is responsible for design and acquisition remains separate from that which pays for operation and support.

Fig. 3 illustrates trends related to material costs. The costs shown are representative of high volume purchases for primary product forms (ingots or billets for metals, prepreg for OMC's). Material utilization, ease of secondary processing and machining, and costs associated with operation and support are not explicitly represented in Fig. 3. Within each data set for metallic materials, the lower range of cost represents cast material, while the upper bound represents wrought or P/M billet. The cost of OMC prepreg varies by a factor of four, and depends upon the complexity of the organic compound, the cost of the fiber and the amount of material ordered. In general, aerospace materials tend toward the upper limit of cost. The cost of DRA material competes directly with aerospace Ti alloys, while providing much higher specific stiffness. DRA matches the specific stiffness of graphite/epoxy cross-plied material at a cost that is lower by nearly a factor of ten. Be alloys, B and diamond also possess a very attractive balance of properties (Fig. 2). However, exceptionally high cost (and health hazards for Be materials) has limited applications to those that place an unusual premium on performance. The primary product cost for B and diamond are in the range of thousands of dollars per pound, and are off the scale for this chart. Further, none of these latter three materials are available in a range of product forms and in sufficient quantity to warrant extensive commercial interest.

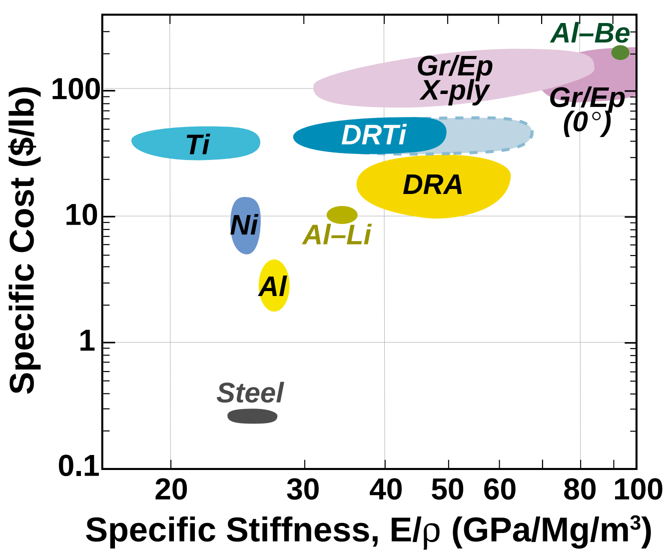

Figure 3 Representative specific costs for primary product forms (metal billet or organic matrix composite prepreg) of structural materials.

Although difficult to quantify, machining costs of DRA are generally similar to (or less than) those associated with machining Ti alloys. Stripping, painting and damage repair are far easier and less costly to accomplish in DRA than in OMC's, offering the potential for significant cost and time savings which add to the savings realized through acquisition.

Properties for resistance to thermal and mechanical distortion

Many applications require resistance to distortion from thermal or mechanical loads. Examples include optical benches and assemblies, antennae (see the discussion on the Hubble Space Telescope antenna waveguide mast), guidance systems for missiles and satellites and turbomachinery components. Resistance to mechanical deflections depends upon material characteristics such as stiffness (E) and density (ρ) as well as component geometry and the loading mode. Many precision components are well approximated as a beam under self-loaded mechanical bending, and for this arrangement materials with higher values of $E^{1/2}/\rho$ possess higher resistance to elastic deflections for a given mass. Thermal expansion produces not only intrinsic displacement, but also generates thermal stresses which can cause distortion. A large thermal conductivity (λ) reduces thermal gradients and hence thermally induced stresses. Thus, increasing the figure of merit, λ/α, decreases the magnitude of thermally-induced distortion.

Fig. 4 compares different materials classes against these two figures of merit [7,8]. Lower density is more important than increasing stiffness for mechanical stability, so materials with lower density generally perform better against this criteria. DRA materials are an exception, since the large increase in stiffness prevails over the modest increase in density. The addition of ceramic particles to a metal alloy produces only a modest decrease in thermal conductivity, but provides a significant decrease in the CTE. Thus, the figure of merit for thermal distortion, λ/α, is increased over the behavior of the unreinforced matrix alloy. As a general rule, the addition of ceramic particulates produces improvements in resistance to distortion from both thermal and mechanical loads over unreinforced matrix alloys. As a class of materials, DRA exceeds all of the common structural metals in resistance to both thermal and mechanical distortion. In addition, DRA is equivalent to graphite/epoxy with respect to mechanical distortion, but has a resistance to thermal distortion that is two orders of magnitude higher.

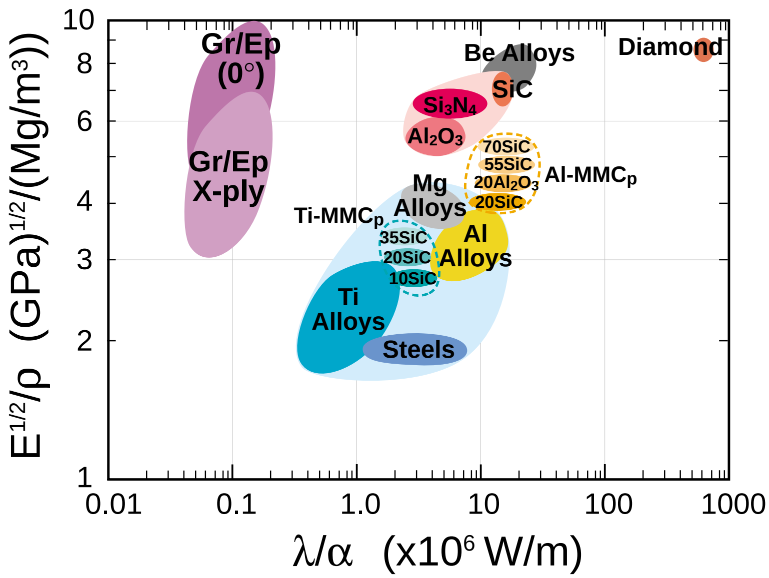

Figure 4 Materials selection chart for resistance to mechanical (vertical axis) and thermal (horizontal axis) distortions required for precision devices. Vibrational frequencies are well below the natural frequency of the device. Data taken from [7,8].

Properties for thermal management

Thermal management is important in a wide range of space-based applications, including packaging for microwave devices used in telecommunications, radiator panels, and substrates for processor chips and power semiconductor devices. A high thermal conductivity, λ, is required, and specific thermal conductivity λ/ρ is the appropriate figure of merit for components that are part of a moving system [5], particularly for spacecraft applications which must be boosted into earth orbit. CTE is the second important property for thermal management. Candidate electronic packaging materials must match the CTE of semiconductor materials and ceramic substrates, thereby avoiding buildup of residual stresses in this critical region. A CTE between 4–7x10^{-6}/K is required to match the CTE of common semiconductor and ceramic substrate materials. Thus, thermal management materials that perform best are those that possess a CTE from 4–7x10^{-6}/K, and which have the highest value of λ/ρ.

Fig. 5 shows the performance of the most commonly-used thermal management materials [5,7]. Kovar (an iron-nickel-cobalt alloy) is often used as a result of its acceptable CTE, but its high density and marginal λ makes it undesirable for spacecraft applications. Although the specific thermal conductivity of Al is higher than any other metallic material, the CTE is too high to be of value. Ceramic additions decrease the CTE, and at volume fractions ≥55%, the CTE of DRA provides a good match with semiconductor materials and ceramic substrates. The performance of DRA as a thermal management material is exceeded only by Be/BeO, and health hazards and the cost of Be/BeO limit its acceptance. DRA has been used as a thermal management material in several spacecraft subsystems for many years, as described in a following section.

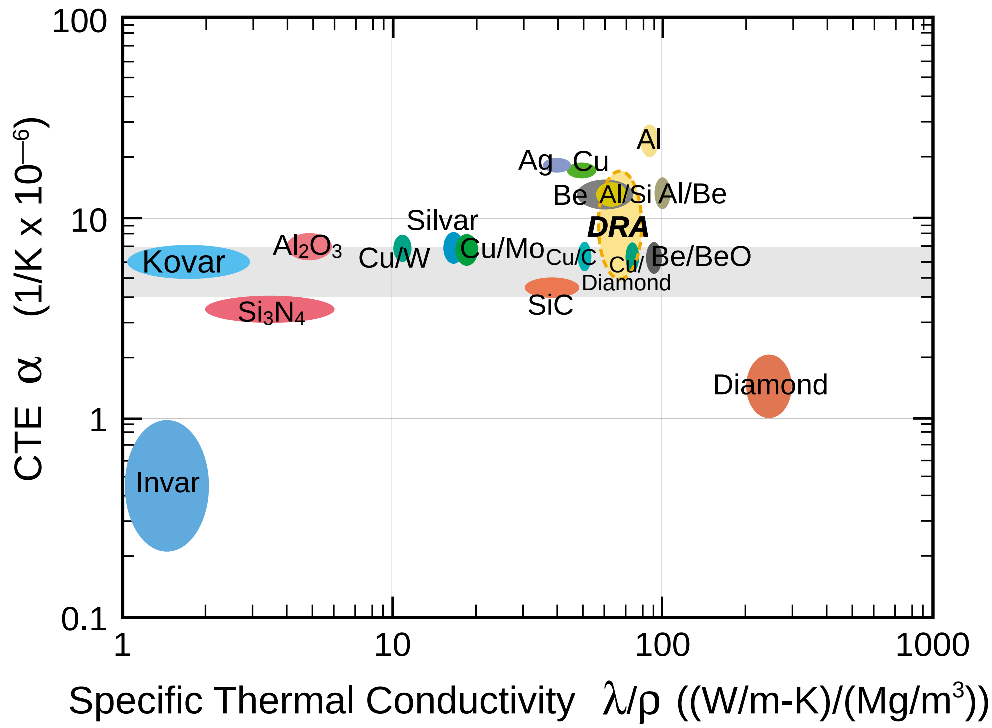

Figure 5 Materials selection chart for thermal management applications (data from [5,7]).

Summary

Discontinuous MMC's have a balance of isotropic specific stiffness and strength that is better than any other metallic structural material, and directly competitive with cross-plied graphite/epoxy. The affordability of these MMC's is also very good, owing to the low or moderate cost of constituent materials and to the commonality with the existing metals infrastructure of primary and secondary processing, machining, joining and finishing processes. Discontinuous MMC's are available in a range of wrought shapes, and near net shape P/M and cast techniques are also established. While not discussed here, discontinuous MMC's also offer significant advantages in wear, and provide true multifunctionality in a high performance material (see the discussion on the Hubble Space Telescope antenna waveguide mast).

Continuously reinforced MMC's are approaching the structural performance of axially-reinforced OMC's, but OMC's continue to be preferred over continuously reinforced MMC's where outstanding uniaxial structural properties at ambient temperature are the only requirement. However, MMC's may be preferred if other properties are required. These additional requirements can include high dimensional stability, resistance to cryogenic fluids, absence of outgassing, high temperature application, resistance to burning, good through-thickness thermal conductivity and good bearing strength. A careful analysis of requirements and benefits is needed to firmly establish the desirability of selecting continuous MMC's for candidate applications.

Current Applications of MMC's

Current applications of continuous MMC's

There are several notable space-based applications of continuously-reinforced MMC's. One major example are structural tubes for the space shuttle orbiters. Each space shuttle orbiter contains 243 MMC tubes in the mid-fuselage main frame and rib truss members, frame stabilizing struts, and in the nose landing gear and drag brace support. The material is 6061Al with 50% B monofilaments (6061/B/50_f), produced by a diffusion-bonded foil-fiber-foil technique. The tubes vary from 4 to 14 plies, are 25 to 92 mm in diameter, and are 0.6 to 2.3 m long. The struts saved 145 kg over the initial design of Al tubes due to the higher specific strength and stiffness of the MMC. An image showing some of the tubes during assembly of the mid-fuselage main frame is shown in Fig. 6.

Figure 6 Space shuttle orbiter mid-fuselage main frame showing 6061/B/50_f MMC tubes.

A second major application of a continuously-reinforced MMC is the antenna waveguide mast on the Hubble Space Telescope (HST). The mast is made by infiltrating a preform containing 40% P-100 carbon fibers with 6061 Al (6061/C/40_f) to form a rectangular boom that is 43 mm x 86 mm x 2 m long (about the size of a standard pine 2"x4" used in housing construction). The Al-MMC was selected for its high dimensional stability under both mechanical and thermal loads. This results from the combination of excellent specific strength and stiffness, and from the excellent thermal conductivity and near zero thermal expansion. The

Al-MMC antenna waveguide mast does not outgas like many OMC's, thereby avoiding possible contamination of the antenna dish and the optical components of the telescope mirrors. This material also provides excellent oxidation resistance (important for the low earth orbit of the HST). Finally, the antenna waveguide mast is truly multi-functional, providing both structural support for the antenna, and a high quality electrical path for transmitting radio signals between the spacecraft and the antenna. While the initial components were produced from the 6061/C/40_f material described above, fully satisfactory performance has been established for DRA material. Spares have now been produced from DRA due to the lower cost of production. Two views of the HST antenna waveguide mast are shown in Fig. 7.

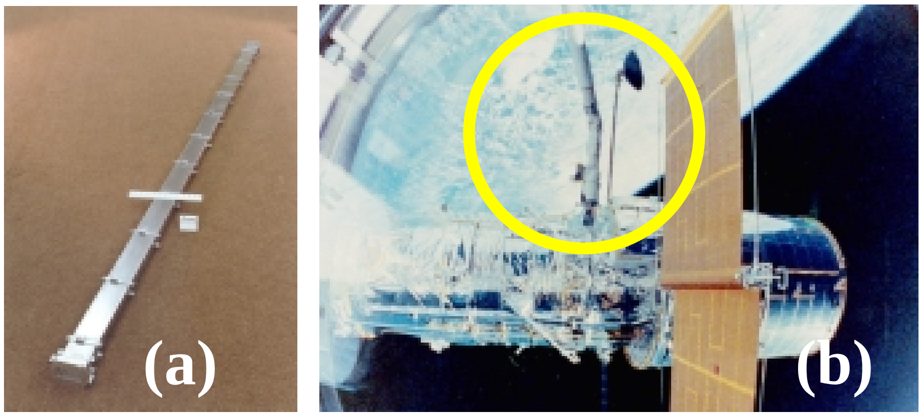

Figure 7 (a) HST antenna waveguide mast before integration, and (b) on the HST.

The Clementine spacecraft also uses a carbon fiber reinforced Al MMC. In this case, the material is used as a thermal radiator panel. Both the Al matrix and the carbon fibers provide excellent thermal conductivity within the sheet of the panel, and the Al provides excellent through thickness thermal transport.

<u>Current applications of discontinuous MMC's</u>

Discontinuously reinforced metal matrix composites have emerged as a pervasive metals technology in the past decade. A wide range of applications exist in space, automotive, aeropropulsion, aerostructural, recreation, and thermal management industries. The current domestic production capacity for powder metallurgy (P/M) DRA alone is about $91x10^3$ kg (100 tons) per year. Significant production capability also exists for discontinuously reinforced metals in the United Kingdom, Canada and Japan. A partial list of discontinuously reinforced MMC components that are currently in service is given in Table I. The expanding acceptance in these other markets and the attractive balance of properties suggest that many additional space-based applications for these materials can be pursued. Selected current applications of discontinuous MMC's in space systems are shown in Table I and will be presented below.

Discontinuous MMC's are currently used in spacecraft applications for structural (carbon/epoxy truss strut nodes, honeycomb panel face sheets, experimental solar array hinges, Hubble Space Telescope antenna waveguide mast spare), thermal (electronic packaging, power semiconductor base plates, printed circuit board heat sinks) and electrical (Hubble Space Telescope antenna waveguide mast spare) functions. Thermal management applications represent the widest range of current applications in space systems. A representative thermal management application of DRA (or AlSiC, as the material is commonly called in the thermal management industry) is in rf packaging for microwave transmitters. Fig. 8 shows a commonly-used AlSiC microwave thermal package that is representative of the component used in commercial low earth orbit (LEO) communication satellites (comsats). This component is not only significantly lighter than components produced from competing materials, but it is much more affordable as well. The part is cast to near net shape, enabling integral production of the electrical feedthrough connectors and bonding to the ceramic baseplate. Discontinuous MMC's of Be/BeO are also used as thermal management materials for electronic packaging in the same commercial LEO comsats.

Table I Partial List of Existing Applications of Discontinuously Reinforced Metals

	COMPONENT	**SYSTEM**
SPACE	Antenna Waveguide Mast Microwave Thermal Packaging Power Semiconductor Base	Hubble Space Telescope Commercial LEO satellites Commercial GEO comsats
AUTOMOTIVE	Driveshaft Exhaust Valves Engine Block Cylinder Liner Brake Rotor	Chevy Corvette, Pickup Toyota Altezza (Asian market) Honda Prelude Plymouth Prowler
AERO-PROPULSION	Fan Exit Guide Vane	Pratt & Whitney 4XXX engines
AERO-STRUCTURES	Ventral Fin Fuel Access Door Covers Rotor Blade Sleeve	F-16 F-16 Eurocopter EC-120, N-4
THERMAL MANAGEMENT	Power Semiconductor Baseplate	Motorola Power Chip
RECREATION	Bicycle Frame Brake Fins	Specialized Stump-Jumper Disney Thunder Mtn Thrill Ride

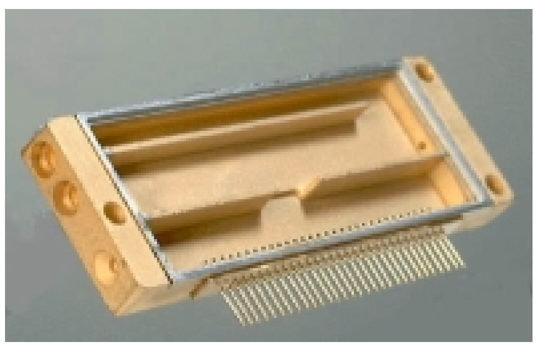

Figure 8 AlSiC microwave rf packaging used in commercial LEO communication satellites (photo courtesy GE).

AlSiC is also commonly used for thermal management of power semiconductor modules. These components can be quite sizeable (up to 150 mm x 150 mm x 6 mm in electric automobiles), and must handle large heat loads. These modules are currently used on electric motor controllers, for power conversion in cell phone ground station transmitting towers (hundreds of thousands of parts produced annually), and in spacecraft. AlSiC has replaced a commonly used Cu/W MMC for thermal management of power semiconductors in geosynchronous earth orbit (GEO) comsats. While Cu has a very high thermal conductivity, its CTE is too high to provide the required match with semiconductor materials and ceramic substrates (see Fig. 5), and so tungsten is added to decrease the CTE. However, the tungsten also decreases the thermal conductivity of the material and dramatically increases the density. The AlSiC material provided a weight savings of over 80% compared to the baseline Cu/W MMC in this commercial GEO comsat application.

DRA has also recently been used as an auxiliary mounting panel for payloads in the space shuttle orbiter. This mounting panel is a structural transition between a bridge structure in the main bay of the space shuttle orbiter and the payload. This mounting hardware supports a payload of up to 90 kg during the launch forces (11 “g’s”). The panel is constructed of a sheet of DRA bonded to a honeycomb core using a cyanate ester film adhesive.

There are two notable multifunctional applications currently in service. DRA has been certified as the material of construction for HST antenna waveguide mast spares, as described earlier. This application takes advantage of the high structural efficiency and dimensional stability under both mechanical and thermal loads, and also uses the high electrical conductivity of the DRA to transmit electrical signals between the spacecraft and the antenna. A DRA panel is also being used as a heat sink between two printed circuit board (PCB’s). Not only does this part provide thermal management, but its high specific stiffness also provides protection against flexure and vibration of the PCB’s, that could otherwise lead to early failure of the components in the PCB.

Future Applications of MMC’s

Launch applications for MMC’s

A dramatic improvement in the access to space is the major objective of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Initiative conducted by the DoD, NASA and industry. Principle goals include dramatically reduced hardware and support costs, improved reliability, expanded reusability and improved thrust-to-weight. Improved materials are absolutely essential to achieving these goals. A good overview of materials requirements and system/cycle configurations for liquid rocket propulsion systems can be found in [9]. Materials are subjected to chemically reactive oxidizers and embrittling interstitial gases. Thermal shock and large thermal expansion/contractions are standard issues that must be accounted for in material selection and component design. The operating conditions of liquid rocket engines are very aggressive. The components must contain gases at pressures from 0.1 MPa to 50 MPa, and gas temperatures from–252°C to over 3600°C. Turbopumps, injectors and combustion chambers typically experience many of these environments simultaneously.

Many opportunities exist for the application of MMC’s in launch systems. The largest payoffs for the use of MMC’s in liquid rocket engines exist in the propellant management device (PMD) subsystems and in combustion and energy conversion device (C&ECD) subsystems. PMD subsystems include cryogen lines, ducts, bellows, valves and pumps. C&ECD subsystems include the injector, thrust chamber and nozzle. Although higher risk, opportunities also exist in the area of cryogenic tankage.

Propellant Management Devices (PMD) The highest payoffs for the use of MMC’s exist in the turbopump (Fig. 9). The inlet housing and main housing are typically made from IN718 or a similar nickel-based alloy for high strength and resistance to hydrogen, while the turbine housing is often made of Waspalloy or a similar high temperature superalloy. These are complex, heavy parts that are either cast, or assembled from separate forged parts. In the space shuttle main engine (SSME), the turbopump housings alone account for nearly 15% of the total turbomachinery weight. While the turbine housing may see operating temperatures as high as 300°C (expander engine cycle) or 850°C (staged combustion engine cycle), the inlet and main housings operate between room temperature and liquid hydrogen temperature (–252°C). The primary requirements for these two housings are high specific strength, compatibility with liquid hydrogen and the ability to manufacture complex near net shape components affordably. Al-based materials possess excellent hydrogen resistance. A DRA material with a yield strength of 410 MPa (60 ksi) possesses a specific yield strength that is 30% higher than the specific yield strength of cast IN718, providing a weight reduction (without component redesign) on the order of 30%. Using a material with these properties for components such as the pump housings, lines, ducts and attachment hardware in the space shuttle main engine would reduce the engine weight by over 380 kg, and would increase the thrust-to-weight by nearly 15%. Redesign of the component to take full advantage of the properties provided by these improved materials, and by using concurrent design techniques that simultaneously account for hydrodynamics, rotor dynamics and component stresses is expected to provide even higher weight savings. While a castable DRA with a yield strength of 410 MPa does not currently exist with the required fracture properties, only a moderate risk is expected to achieve these goals.

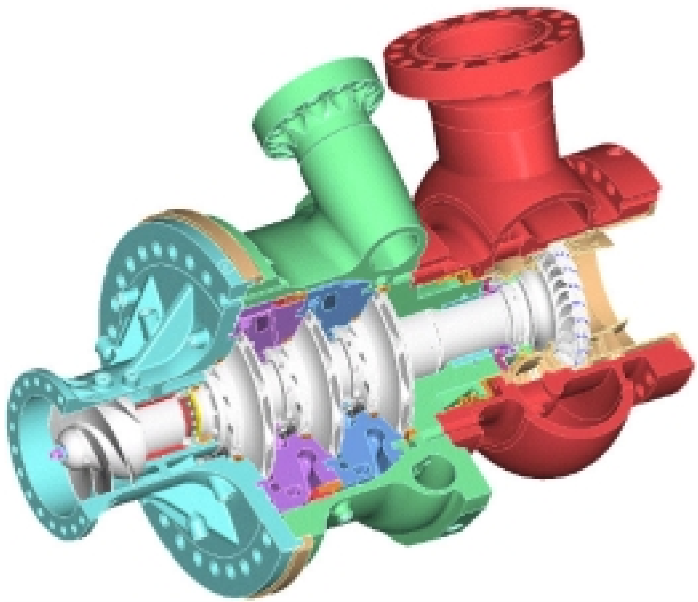

Figure 9 Advanced design for a candidate liquid hydrogen turbopump.

The principle requirements for the rotating components (inducer, impeller, turbine rotor) are the same as for the inlet and main pump housings. However, a much stricter emphasis is placed on high specific strength, since these parts are principally self-loading. The inducer and impeller are typically made from Ti-5Al-2.5Sn ELI (extra low interstitial) as a result of its high specific strength and good retention of toughness and ductility at cryogenic temperature. Ni-based superalloys are typically used in the turbine for high temperature capability and good resistance to hydrogen embrittlement. These materials are currently used at their limits, and so significant increases in rotational speed will require materials with improved specific strength. A higher rotational speed will allow a smaller diameter pump or fewer pump stages to produce the same thrust as a larger pump, thus significantly increasing the engine thrust-to-weight ratio. The complex shape of the rotating components make the use of continuous reinforcements difficult. Approaches to producing Al-based composites with very high specific strength are now being pursued, and will be discussed in the next major section below.

Significant engine weight reductions may also be achieved by using MMC's in other PMD components, such as flanges, lines, ducts and bellows. Stainless steel or nickel alloys are often used in these parts, so a large weight savings can be realized. In addition to resistance to cryogenic fluids, high specific strength is required for lines, ducts and bellows, and high specific stiffness is required for flanges. A typical line section may be 100 mm in diameter with a wall thickness of 6 mm, and can have a complex shape, as illustrated in Fig. 10.

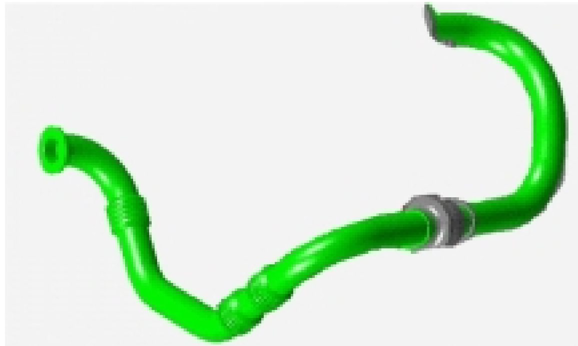

Figure 10 Representative length of cryogen line with attachment flanges and bellows.

Combustion and Energy Conversion Devices (C&ECD) The principle component currently being considered for use with an MMC is the thrust chamber structural jacket. The thrust chamber is fundamentally a pressure vessel that must contain the hot combustion gases. The chamber is lined with a relatively weak copper-based alloy that is cooled with cryogen fluid. This liner must be supported by a structural jacket to contain the high pressure combustion gases. Stainless steel or electroformed Ni are currently used. The principle requirements are a good match with the CTE of the copper alloy and good stiffness. The maximum temperature for the structural jacket is about 150°C at the bond line with the copper alloy liner. DRA is a good candidate for this application, since the specific stiffness is high and the CTE is a reasonable match with copper alloys. The strength requirements are less than 200 MPa, so that a low risk is anticipated for this application. Processing the required complex shape and bonding to the liner constitutes the major challenge, as with existing materials.

Propellant Tankage Applications Propellant tanks are currently produced from aluminum alloys as a result of their good specific strength, compatibility with cryogenic fluids and excellent formability. Significant weight reductions can be achieved with increased specific strength, but these gains must be balanced with the ability to produce large components. A novel manufacturing method is now being developed that will allow large tanks to be produced from Al monotape reinforced with a continuous tow of alumina fibers. This process uses a laser brazing technique to bond the monotape to itself as it is wound on a large diameter mandrel. This process is still in an early stage of development, but has the potential to offer significantly higher specific strength and stiffness in a metallic cryotank material.

Spacecraft applications for MMC's

Significant opportunities exist for expanded use of both continuous and discontinuous MMC's in spacecraft. The potential applications include structural, thermal management and electronic packaging functions for satellite subsystems. The properties that make MMC's attractive are very high structural efficiency (high specific stiffness and strength), outstanding thermal properties and excellent electrical conductivity (required for high quality grounding planes and transmission of electrical signals). MMC's offer the potential for improved performance, lower weight and true multifunctionality.

Thermal Management and Electronic Packaging Applications Many low-risk opportunities exist for the expanded use of MMC's in spacecraft thermal management and electronic packaging. Potential thermal management applications include radiator panels and battery sleeves. Either continuous or discontinuous MMC's can provide attractive benefits. Potential electronic packaging uses include expanded application as microwave modules, power semiconductor packages, and printed circuit board heat sinks, and use as enclosures for black boxes. Dramatic benefits can be achieved simply by specifying existing materials and technologies in new spacecraft systems. For example, a currently flying defense satellite uses over 23 kg of Kovar for microwave packaging. Substituting AlSiC would result in a weight saving on the order of 13 kg, or about 60%. The near net shape capability of AlSiC would provide a cost saving as well, as described earlier. While currently available MMC materials have properties that are sufficient to displace other thermal management materials, MMC's with improved thermal and electrical properties would provide more significant benefits in performance, weight and cost. Approaches for achieving these improved properties will be discussed in the following section.

Satellite Subsystem Applications MMC's have seen limited applications in subsystems, in spite of their excellent structural properties, the broad industrial experience in the structural application of discontinuous MMC's in other market sectors, and the established technology infrastructure. Thus, the application of MMC's in spacecraft subsystems can provide a low–risk path to important systems benefits. Potential subsystem structural applications include brackets and braces, struts, semimonocoque plates and cylinders, sandwich plates and cylinders, fittings for OMC components, and honeycomb panel faceplates and core materials. Potential applications in mechanical subsystems include hinges, gimbals, inertial wheel housings and electro-optical subsystems. In many cases, DRA could replace steel, providing significant weight savings. In addition to excellent specific stiffness and strength, the low-to-moderate CTE of MMC's is important when mating with other materials, such as steel pins for hinges.

Other Applications A high degree of structural efficiency is required in the design of satellite bus structures. These are often constructed as truss structures, or as boxes made of honeycomb panels. While truss structures have been produced completely from MMC's, the very high specific properties of uniaxial OMC's make them the preferred material for truss tubes. However, very high multiaxial stresses exist at the truss nodes, and OMC's are inefficient and difficult to produce in the complex node geometries. Al and Mg MMC nodes have been produced by infiltration casting, and Al MMC nodes have been used in service for lightly loaded trusses. However, Al or Mg MMC's have inadequate strength for heavily loaded trusses, and so titanium alloys are currently used. Discontinuously reinforced titanium alloys are now produced commercially both in the US and in Japan, and these materials could make an attractive alternative to cast titanium alloys because of the higher specific strength and stiffness offered by the MMC.

Research and Development for MMC's

The previous section illustrates the pervasive opportunities for using MMC's in space applications. Technical activity is required to develop MMC's with higher specific strength and stiffness and improved thermal properties. Technology programs aimed at expanded processing and manufacturing capability and improved design methodologies are also needed. Component demonstration programs provide an effective means of integrating material development and component design, and also provide a direct path toward material and component certification, a vital link in technology transition. The technical objectives and approaches required to continue the trend of increasing MMC usage in space systems is outlined below.

Technical objectives and approaches

Improved Structural Properties High specific strength and stiffness are primary requirements for a wide range of applications. Components that drive this requirement include pump housings and rotating components, cryogen lines, ducts, bellows and flanges, cryogen tankage, spacecraft mechanical subsystem components and truss nodes. While MMC's offer the ability to tailor strength and stiffness over a wide range, the high cost associated with certifying a new material for use is a practical barrier to the development of a single optimum material for each individual application. A reasonable strategy for developing MMC's is thus to define groupings of materials properties goals so that each material developed satisfies the requirements of several components, thereby developing one material to do many tasks. This increases the payoff for the development of a particular material, and spreads the risk and cost associated with the development of a new material.

A suggested grouping of materials is shown in Table II. In each of the three groups, a current state-of-the-art material is listed, along with a set of goal properties which represent a 30% increase in specific properties over the baseline. Specific strength is the primary requirement for each of the materials, but this must be accompanied by ductility in excess of 3–6% to ensure that point loading and stress concentrations do not lead to fracture. Ductility above this level may be unnecessary, while ductility below this level would require material to be added in regions of stress concentration, reducing the weight benefit predicted from a simple density-normalized approach. The properties listed are for tensile loading at 20°C, and are given for broad comparison only. A more rigorous comparison with candidate materials must consider properties over the full range of operating temperatures.

Table II Properties of Materials with High Structural Efficiency

	Specific Modulus *(GPa/Mg/m³)*	**Specific Yield Strength** *(MPa/Mg/m³)*	**Specific Ultimate Strength** *(MPa/Mg/m³)*	**Tensile Ductility** *(%)*
Pump Housing Materials (T_{oper} = –252°C, T_{max} = 20°C)				
INCO 718 (Cast)	25	92	122	6
Goal §	33	120	159	3–6
Pump Rotor and Cryogen Line Materials (T_{oper} = –252°C, T_{max} = 20°C)				
Ti-5Al-2.5Sn ELI	24	139	154	16–19
Goal §	31	181	200	3–6
Turbine Materials (T_{oper} = T_{max} > 300°C)				
INCO 718 (Forge)	26	126	150	11
Goal §	34	164	195	3–6
Existing Representative MMC Materials				
2219/SiC/40p (Cast)	N/A	92	115	0.8
6092/SiC/17.5p (Wrought)	38	160	182	6
Al/Al_2O_3/55_f				
(longitudinal)	71	N/A	470	<0.2
(transverse)	38	N/A	35	<0.2

(§ 30% increase over current alloy)

Pump Housing Materials   Pump housing materials have a maximum operating temperature of 20°C, and typically operate at –252°C. In addition to specific strength and ductility, the material must possess good compatibility with liquid hydrogen. Casting is preferred to produce the complex part geometries affordably. Pressure infiltration casting is the primary process being considered for MMC pump housings. A stable ceramic preform requires a volume fraction of reinforcements in excess of 30%, with ≥40% being typical. Matrices of both aluminum and copper alloys are being pursued, and discontinuous and continuous architectures have been produced, as well as hybrid continuous/discontinuous materials. SiC and alumina particulates have been used, and alumina fiber tows. The fiber tows allow the option of selective reinforcement in regions of high directional stresses. Issues include maintaining adequate fracture properties and balancing interfacial wetting to obtain adequate infiltration yet avoiding excessive chemical interaction. Higher strength matrix alloys must be developed for discontinuous MMC's, while matrix alloys with good bonding and high ductility are needed for continuous MMC's.

<u>Pump Rotor and Cryogen Line Materials</u> Pump rotor and cryogen line materials require the highest levels of specific strength while still maintaining a minimum of 3–6% ductility. At the operating temperature of –252°C, Ti-5Al-2.5Sn has a specific strength of almost 300 ($MPa/Mg/m^3$). As with pump housings, the operating temperature ranges from 20°C to –252°C, and compatibility with liquid hydrogen is required. Current rotors are machined from a solid block of wrought material. Candidate processes that take advantage of rapid prototyping techniques could significantly decrease the expense associated with the production of this component. Cryogen ducts could be extruded. The primary technical challenge is to define and develop a class of materials with the required level of specific strength while maintaining adequate fracture properties.

<u>Turbine Materials</u> Turbine materials are required to operate at the highest temperatures. In the split expander engine cycle, the maximum operating temperature of 300°C allows an Al-based material to be considered. While promising approaches to achieving the goal of high specific strength up to 300°C have been defined and are being pursued, this is considered a high risk/high payoff material development effort. The higher operating temperature of the turbine pump housing in the staged combustion engine cycle (up to 850°C) eliminates Al MMC's from consideration, but copper-based MMC's are candidates. Continuous alumina reinforcements would provide the strength required. These materials must be resistant to high pressure hydrogen in the fuel turbine, and must be burn resistant in the presence of high pressure oxygen. Very few materials resist burning in high pressure oxygen, and alloys of nickel and copper are prime candidates.

<u>Other Structural Materials</u> Cryogen tankage represent a unique opportunity for MMC's, as discussed earlier. The principle technical challenge lies in producing large tanks from the MMC tape material. Currently available DRA materials can now be used for spacecraft mechanical subsystem components, with a significant payoff over currently specified materials. However, materials successfully developed for either pump motor housings or pump rotors could also be used in spacecraft subsystems with even larger benefits.

<u>Approaches for High Specific Strength</u> Ceramic particles offer improvement in specific strength, and especially specific stiffness. Four distinct approaches have been identified for achieving high specific strength in Al MMC's. Continuous ceramic reinforcements are being pursued in both aluminum and copper MMC's. This approach offers exceptionally high specific strength in the fiber direction, but typically poor transverse properties. As a selective reinforcement this is a promising approach. The remaining three approaches rely on other strengthening mechanisms in addition to the improvement offered by discontinuous ceramic reinforcements. The first of these uses coherent precipitates of a thermodynamically stable phase. A number of precipitates have been considered in the past, but Al_3Sc appears to be the most potent strengthener. Recent work has shown Al-Mg-Sc alloys to have very attractive

values of high specific strength [10]. Efforts are now underway to develop a class of Al-Mg-Sc alloys as a suitable matrix for discontinuous MMC's. The second approach relies on a high volume fraction of incoherent intermetallic precipitates produced in alloys with transition metals (especially nickel) and rare earth elements (such as cerium or yttrium). Recent work has shown these materials to have exceptional specific strength with some plasticity [11]. These materials are solidified in an amorphous state. Subsequent thermal processing crystallizes the material, and provides a means for controlling the microstructure. The final approach uses a cryomilling process for producing a nanophase aluminum material with a distribution strengthening ceramic particles.

The approach for copper MMC's is currently emphasizing continuous alumina reinforcements. Alloying to balance burn and oxidation resistance, wettability with the reinforcement and strength and ductility are now underway. Discontinuously reinforced titanium MMC's is being pursued to obtain very high specific strength. A P/M approach is being pursued, where TiB_2 particulates are reacted with the titanium alloy matrix to produce a distribution of equilibrium TiB reinforcing needles. In-situ eutectic alloys with boron or silicon are also being developed as an affordable cast discontinuous titanium MMC.

Alloy development, including determination of the relationships between composition, microstructure and properties, is the principle effort in the Al-Mg-Sc and Al-Ni-(Y or Ce) alloys, as well as the discontinuous titanium MMC's. Supporting this effort are fundamental studies to establish quantitative relationships between particulate distribution and MMC properties. This understanding is expected to be a vital in the ability to obtain the required fracture properties in highly strengthened MMC's. Processing studies are of primary importance for continuous MMC development and for the nanophase aluminum effort. The ability to control matrix composition and the distribution of reinforcing phases while producing complex shaped components is a difficult challenge.

<u>Improved Thermal Properties</u> As discussed above, currently available DRA materials provide a superior balance of properties for thermal management and electronic packaging, and a large market already exists for DRA in this industry. However, significant improvements in thermal conductivity are yet possible, providing stronger incentive for applying these materials in the space industry. Approaches for improving thermal conductivity include use of reinforcements with higher thermal conductivity. Current SiC particles were developed for abrasive applications, but thermal conductivities in excess of 400 W/m–K have been measured in single crystal SiC particles [5]. Other potential reinforcements include pyrolytic graphite, diamond and diamond-like particles (currently used as heat spreaders and in electronic packaging), aluminum nitride and cubic boron nitride. While the specific thermal conductivity of copper is not as high as for aluminum, some potential may exist for this material. Little effort in these areas are evident in the literature, and this may be a valuable area for development.

<u>Manufacturing and Demonstration Programs</u> Processing and manufacturing work is required to reduce the cost of MMC materials and components. Near net shape processes area primary approach. Improved techniques for producing ceramic preforms for infiltration casting are required. The ability to reliably produce stable ceramic preforms with a volume fraction of reinforcing particles below 30% is a critical path technology to achieving goals for ductility and toughness. Further integration of ceramic substrates, electrical feedthroughs and lids into infiltration cast electronic packages has the potential to significantly reduce component cost in this industry. Techniques for infiltration casting of new high strength alloys need to be developed. The areas of attachments and joining, machining and plating each require attention. In the area of wrought processing, the ability to produce thin gage DRA sheet (~125 μm) will open the path to affordable DRA honeycomb applications.

It is essential that a clear link exists between efforts to develop MMC's for the applications above, and demonstration programs that require advanced materials. This approach is most effective when designers are given a 'clean sheet.' This allows candidate components to be designed to take full advantage of the properties of MMC's, rather than being constrained by design compromises and solutions that were optimized for the previously used material. This link also provides a direct path to certification of the material and component, easing the path to full transition.

Teaming strategy

Even with projected expansion in the access to space, the domestic material production capacity required to support the space industry will remain quite small. From the perspective of a material supplier, the total payoff for implementing new materials technologies is rather limited, so that the incentive for tackling the cost and risk associated with the development and certification of a new material for the space industry alone will continue to be small. A strategy for overcoming this difficulty exists in identifying materials requirements that are common with other aerospace systems. The primary material requirements for the components associated with the liquid hydrogen turbopump and cryogen lines and ducts are high specific strength, damage tolerance and resistance to cryogenic fluids. The maximum use temperature is typically room temperature, but a use temperature up to 300°C is also required for some advanced applications. The aeronautical propulsion and aerostructures industries share the requirements for high specific strength and good damage tolerance, and also require high specific stiffness and a prolonged maximum use temperature of 200–300°C. Thus, a material that satisfies the requirements of good strength and ductility at –252°C as well as high specific strength and stiffness up to 200–300°C will have a much broader market and a much higher impact. Further, the costs and risk associated with development and transition can be shared among the different industry sectors. The rocket propulsion, aeropropulsion and aerostructures industries do not often compete directly, and so a high degree of cooperation can be expected.

Concluding Remarks

MMC's have filled important needs for space systems in the past, and have a large range of opportunities for dramatic improvements in advanced space systems. The properties offered by MMC's include high specific strength and stiffness, excellent thermal and electrical properties, tailorable coefficient of thermal expansion, compatibility with cryogenic fluids and affordable processing via an established manufacturing infrastructure. Efforts are already underway in discontinuous and continuous MMC's in Al- and Cu-based systems for spacecraft and launch systems. The largest payoffs are in propellant management devices in advanced liquid rocket propulsion systems, but many opportunities exist in combustion and energy conversion devices, spacecraft thermal and mechanical subsystems and in cryogenic tankage. Interdisciplinary technical effort is required in the areas of material development, processing and manufacturing and technology demonstrations. A strategy that integrates the materials requirements in advanced space systems with similar requirements in aeropropulsion and aerostructural systems is being pursued to spread the risk and cost associated with material development and certification, and to expand the impact and payoff of successful material development.

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