ALUMINUM METAL MATRIX COMPOSITES

Metal matrix composites have been applied in areas that can cost-effectively capitalize on improvements in specific stiffness, specific strength, fatigue resistance, wear resistance, and coefficient of thermal expansion.

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Fig. 1 — The U.S. Air Force F-16 jet fighter includes silicon carbide particulate-reinforced aluminum MMCs in the ventral fin and the fuel access door covers. The arrow indicates the aluminum composite ventral fin.

Metal matrix composites 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, including aluminum, beryllium, magnesium, titanium, iron, nickel, cobalt, and silver. However, aluminum is by far the most preferred.

For reinforcements, the materials are typically ceramics, which provide a very beneficial 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, metallic materials such as tungsten and steel fibers have been considered.

The morphology of the reinforcement material is another variable of importance in metal matrix composites. The three major classes are continuous fiber, chopped fiber or whisker, and particulate. Typically, the selection of the reinforcement morphology is determined by the required 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.

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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 a very wide range of material combinations and resultant properties is available. This article describes the primary properties of aluminum composites, and highlights applications in aerospace, automotive, electronics, and commercial/industrial.

Primary properties

Metal matrix composites possess sets of properties that are of interest to designers for both structural and non-structural applications. These include specific stiffness, specific strength, fatigue resistance, wear resistance, and coefficient of thermal expansion (CTE).

• *Specific stiffness:* The addition of high-modulus metallic or ceramic reinforcement materials to the metal matrix results in an increase in elastic modulus. In the case of lightweight metals such as aluminum, titanium, and magnesium, the increases can be very significant at even moderate levels of reinforcement. Since the typical ceramic reinforcements are similar in density to the lightweight metal matrices, the overall density of the composite is not significantly affected. The increased specific stiffness (i.e. elastic modulus divided by material density) is one of the primary benefits of this class of materials.

• *Specific strength:* In addition to the higher elastic modulus of reinforcement materials, many possess

Fig. 2 —Forged 2009/SiC/15p helicopter blade sleeves are used in the Eurocopter.

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high strength as well. Gaining advantage from the strength of the reinforcement material strongly depends on its mechanical and physical properties, its morphology, and the way it bonds to the metal matrix, including its reactivity at the reinforcement / matrix interface.

Well-processed continuous-fiber reinforced composites can exhibit high specific strength in the direction of the fiber orientation. Chopped fiber and whisker reinforced materials can also exhibit increased specific strength, with the magnitude of the increase dependent on the reinforcement composition, structure, and orientation, as well as processing. Particulate-reinforced composites can exhibit specific strength increases ranging from none to a doubling over the metal matrix, depending on the matrix alloy, reinforcement type, and volume fraction.

Generally, as the aspect ratio of the reinforcement decreases, the magnitude of the increase in specific strength is lower when loaded in the same direction as the long dimension of the reinforcement.

• *Fatigue resistance:* Another property that can be enhanced in metal matrix composites relative to the unreinforced matrix is fatigue resistance. The mechanisms of enhancement differ depending on the morphology of the reinforcement and the reinforcement / matrix interface. From an applications standpoint, the important point can be understood by realizing that the incorporation of the reinforcement can influence both fatigue crack initiation and propagation. This may enable substitution of MMCs into fatigue-limited applications that the unreinforced metal matrix is unable to satisfy.

• *Wear resistance:* The increased hardness of the typical ceramic reinforcement material can also affect the tribological properties of the metal matrix composite relative to the unreinforced matrix. Particularly for the light metals, a comparative lack of wear resistance has limited their application in areas where weight could be potentially saved. For this reason, higher density materials such as steel or cast iron are most frequently selected for current wear-resistant applications. However, where particulate-reinforced MMCs have been applied, orders of magnitude improvement in wear resistance have been reported.

The improved wear resistance of MMCs is a double-edged sword. While enabling application of lightweight metallic materials, the hard ceramic reinforcement also complicates machining and other manufacturing processes. In addition, the potential abrasiveness of the MMC can cause wear in other parts of the component assembly unless a total systems approach to wear is taken.

• *Coefficient of thermal expansion:* The typical ceramic reinforcements for MMCs have significantly smaller values of the coefficient of thermal expansion (CTE) than the metal matrices into which they are incorporated. Thus, addition of ceramic reinforcements to the high-expansion metals such as aluminum, magnesium, copper, and titanium, can result in substantial reductions in the CTE.

The ability to tailor CTE through the selection of the specific reinforcement type and volume fraction can be useful in a range of applications. In structural components, matching the CTE of a lightweight alloy MMC with another structural material such as steel, nickel, titanium, or beryllium can be advantageous, especially in applications in which the operating temperature range could induce stresses from differential expansion between parts. In electronics, the ability to tailor the CTE to match typical electronic materials and ceramic substrates has opened up a market for aluminum MMCs not previously accessible to unreinforced aluminum alloys.

Aerospace composites

Many of the aircraft structure applications for MMCs seek to capitalize on increased specific stiffness. Aircraft structural applications actually require a combination of properties, including adequate strength, damage tolerance (including ductility, fracture toughness, and fatigue resistance), and corrosion resistance. MMCs typically have lower damage tolerance properties than their unreinforced counterparts, and hence the extent of application in primary structures has been limited.

More extensive application depends on the development of cost-effective large-scale MMC production processes that result in materials with improved combinations of properties over currently available materials. However, MMCs have been selected for some aircraft structures, and the following are some examples.

Silicon carbide particulate-reinforced aluminum MMC has been used in the U. S. Air Force F-16 aircraft. One application is in the ventral fins for the aircraft, which provide lateral stability during high angle of attack maneuvers (Fig. 1). A 6092 / SiC / 17.5p MMC sheet material replaced the unreinforced aluminum skins in the honeycomb structure of the fin, and, due to the increased specific stiffness and erosion resistance of the MMC material, increased service life significantly. The same material is used in the fuel access door covers for the F-16. Unreinforced aluminum access covers were experiencing cracking due to overload, and again the increased specific stiffness property of the MMC allowed this material to be successfully substituted.

Replacement of a carbon-fiber reinforced polymer tube by a SiC particulate reinforced aluminum extruded tube for a floor support strut for Airbus has also been reported. The driving force is improved damage tolerance and reduced cost.

The Eurocopter rotor sleeve shown in Fig. 2 is made of a forged SiC particulate-reinforced aluminum 2009 alloy having good stiffness and damage tolerance. The aluminum MMC replaced titanium, reducing both weight and production cost.

Automotive parts

In the automotive market, properties of interest to the automotive engineer include specific stiffness, wear resistance, and high-cycle fatigue resistance. While weight savings is also important in automotive applications, the need for achieving performance improvements with much lower cost premiums than tolerated by aerospace applications drives attention toward low-cost materials and processes. MMCs have been successfully introduced where the combination of properties and cost satisfied a particular need.

• *Engine:* Replacement for steel and cast iron in engine applications relies on the increased specific stiffness, improved wear resistance, and in some cases, on the increased high cycle fatigue resistance provided by MMCs. A watershed application for aluminum MMC was the Toyota piston for diesel engines. The part consists of selective reinforcement of the aluminum alloy by a chopped fiber preform in the ring groove area that provides improved wear and thermal fatigue resistance. These pistons were placed into commercial production in Japan.

Another component with selective reinforcement is in the Honda Prelude 2.3-liter engine. In this case, hybrid preforms consisting of carbon and alumina fibers were infiltrated by molten aluminum to form the cylinder liners during the medium-pressure squeeze casting process for the engine block.

• *Brake system:* Aluminum-based MMCs offer a very useful combination of properties for brake system applications in replacement of cast iron. High wear resistance and high thermal conductivity of aluminum MMCs enable substitution in disk brake rotors and brake drums with an attendant weight savings on the order of 50 to 60%. Since the weight reduction is in unsprung weight, it also reduces inertial forces and provides additional benefit. Also, lightweight MMC rotors enable increased acceleration and reduced braking distance. It is reported that, based on brake dynamometer testing, MMC rotors reduce brake noise and wear, and have more uniform friction over the entire testing sequence compared to cast iron rotors.

• *Driveshaft:* Aluminum MMCs in the driveshaft take advantage of the increased specific stiffness in these materials. Current driveshafts, whether aluminum or steel, are constrained by the speed at which the shaft becomes dynamically unstable. The critical speed of the driveshaft is a function of the length, inner and outer radius, and specific stiffness. In vehicles with packaging constraints that do not allow increased driveshaft diameter, MMCs offer a potential solution. Aluminum MMCs enable longer driveshafts at a given diameter, or smaller-diameter shafts at a given length. As a result of these benefits, driveshafts have been made of Al 6061 / Al_2O_3 materials produced by stir casting and subsequent extrusion into tube, such as the one illustrated in Fig. 3.

Commercial/industrial products

Fig. 3 — An Al-Al_2O_3 extruded driveshaft reduces weight and enables higher critical speeds.

A number of interesting applications have been either prototyped or produced in the general sector of commercial and industrial products.

• *Nuclear shielding:* B_4C reinforced aluminum has promise in nuclear shielding applications because the isotope B10 present in B_4C naturally absorbs neutron radiation. As a result, this type of MMC is being considered for storage casks that will contain spent fuel rods from nuclear reactors.

• *Precision parts:* Aluminum MMC in an industrial application requiring a lower weight material for improved precision has been reported. Specifically, a six-meter long MMC needle replaced a steel needle in a carpet weaving machine.

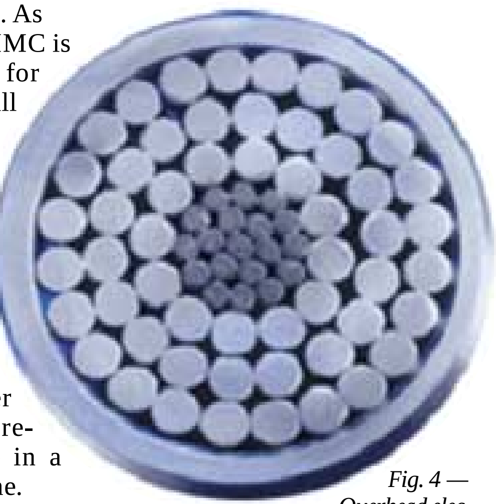

Fig. 4 — Overhead electrical conductors featuring aluminum MMC wire cores improve current carrying ability by 1.5 to 3 times compared with steel-reinforced aluminum.

• *Electrical conductors:* An innovative yet specialized application of continuous fiber reinforced aluminum is for overhead electrical conductors (Fig. 4). By infiltrating Nextel 610 continuous-fiber reinforcement with aluminum, the resulting composite wire can replace the conventional steel-reinforced wires. The performance of this product significantly improves the ampacity, or current-carrying ability, by 1.5 to 3 times compared with the steel-reinforced aluminum construction. In addition, because of the higher strength-to-weight ratio of the composite conductor, existing infrastructure such as transmission towers can remain, and longer spans between towers are possible. This advanced concept is being tested in field trials.

Electronic packaging/thermal management

A very important market area for aluminum matrix MMCs is in their application in electronic packaging and thermal management. The primary property capabilities of MMCs that are of interest in this market are the ability to tailor the coefficient of thermal expansion while retaining good thermal conductivity, and in some cases electrical conductivity, along with light weight. These components are typically high value-added.

• *AlSiC:* The key material of commercial importance has been coined "AlSiC" by the industry. While not representing any specific formulation, in general AlSiC covers particle-reinforced aluminum MMCs in which the SiC volume fraction ranges from 20% to over 70% by volume, depending on the specific needs of the application.

thermal conductivity over the baseline material.

Fig. 5 — Power module base plates for electronics applications are made of both AlSiC and aluminum-graphite MMCs.

• *Microprocessor lids:* The application of AlSiC in microprocessor lids, specifically in flip chip packages, is driven by the need for a lightweight and potentially lower-cost replacement for copper. The appropriate coefficient of thermal expansion in the MMC can be tailored to match the adjoining package by controlling the reinforcement volume fraction.

• *Other applications:* Printed wiring board cores are also being made of AlSiC materials, as replacements for conventional copper or aluminum cores. In addition to the CTE matching property, the higher specific stiffness reduces thermal cycling and vibration-induced fatigue. Yet another application in which the thermophysical properties of AlSiC are important is in carriers for hybrid circuits for power amplifiers in cellular phone base stations.

Superior thermal conductivity and light weight in a CTE-matched material are also exploited in power module base plates, which are made of both AlSiC and aluminum-graphite MMCs (Fig. 5). ■

• *Microwave packaging:* An early application of a 40 vol.% reinforced aluminum MMC was in replacement of Kovar, a heavier Ni-Co-Fe alloy, in a microwave packaging application. The major drivers here were weight savings in this part, with a 65% reduction realized, along with improved thermal conductivity over the baseline material.

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