Introduction to Composites

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A COMPOSITE MATERIAL is a macroscopic combination of two or more distinct materials, having a recognizable interface between them. Composites are used not only for their structural properties, but also for electrical, thermal, tribological, and environmental applications. Modern composite materials are usually optimized to achieve a particular balance of properties for a given range of applications. Given the vast range of materials that may be considered as composites and the broad range of uses for which composite materials may be designed, it is difficult to agree upon a single, simple, and useful definition. However, as a common practical definition, composite materials may be restricted to emphasize those materials that contain a continuous matrix constituent that binds together and provides form to an array of a stronger, stiffer reinforcement constituent. The resulting composite material has a balance of structural properties that is superior to either constituent material alone. The improved structural properties generally result from a load-sharing mechanism. Although composites optimized for other functional properties (besides high structural efficiency) could be produced from completely different constituent combinations than fit this structural definition, it has been found that composites developed for structural applications also provide attractive performance in these other functional areas as well. As a result, this simple definition for structural composites provides a useful definition for most current functional composites.

Thus, composites typically have a fiber or particle phase that is stiffer and stronger than the continuous matrix phase. Many types of reinforcements also often have good thermal and electrical conductivity, a coefficient of thermal expansion (CTE) that is less than the matrix, and/or good wear resistance. There are, however, exceptions that may still be considered composites, such as rubber-modified polymers, where the discontinuous phase is more compliant and more ductile than the polymer, resulting in improved toughness. Similarly, steel wires have been used to reinforce gray cast iron in truck and trailer brake drums.

Composites are commonly classified at two distinct levels. The first level of classification is usually made with respect to the matrix constituent. The major composite classes include organic-matrix composites (OMCs), metal-matrix composites (MMCs), and ceramic-matrix composites (CMCs). The term "organic-matrix composite" is generally assumed to include two classes of composites: polymer-matrix composites (PMCs) and carbon-matrix composites (commonly referred to as carbon-carbon composites). Carbon-matrix composites are typically formed from PMCs by including the extra steps of carbonizing and densifying the original polymer matrix. In the research and development community, intermetallic-matrix composites (IMCs) are sometimes listed as a classification that is distinct from MMCs. However, significant commercial applications of IMCs do not yet exist, and in a practical sense these materials do not provide a radically different set of properties relative to MMCs. In each of these systems, the matrix is typically a continuous phase throughout the component.

The second level of classification refers to the reinforcement form—particulate reinforcements, whisker reinforcements, continuous fiber laminated composites, and woven composites (braided and knitted fiber architectures are included in this category), as depicted in Fig. 1 (Ref 1). In order to provide a useful increase in properties, there generally must be a substantial volume fraction (~10% or more) of the reinforcement. A reinforcement is considered to be a "particle" if all of its dimensions are roughly equal. Thus, particulate-reinforced composites include those reinforced by spheres, rods, flakes, and many other shapes of roughly equal axes. Whisker reinforcements, with an aspect ratio typically between approximately 20 to 100, are often considered together with particulates in MMCs. Together, these are classified as "discontinuous" reinforcements, because the reinforcing phase is discontinuous for the lower volume fractions typically used in MMCs. There are also materials, usually polymers, that contain particles that extend rather than reinforce the material. These are generally referred to as "filled" systems. Because filler particles are included for the purpose of cost reduction rather than reinforcement, these composites are not generally considered to be particulate composites. Nonetheless, in some cases the filler will also reinforce the matrix material. The same may be true for particles added for nonstructural purposes, such as fire resistance, control of shrinkage, and increased thermal or electrical conductivity.

Continuous fiber-reinforced composites contain reinforcements having lengths much greater than their cross-sectional dimensions. Such a composite is considered to be a discontinuous fiber or short fiber composite if its properties vary with fiber length. On the other hand, when the length of the fiber is such that any further increase in length does not, for example, further increase the elastic modulus or strength of the composite, the composite is considered to be continuous fiber reinforced. Most continuous fiber (or continuous filament) composites, in fact, contain fibers that are comparable in length to the overall dimensions of the composite part. As shown in Fig. 1, each layer or "ply" of a continuous fiber composite typically has a specific fiber orientation direction. These layers can be stacked such that each layer has a specified fiber orientation, thereby giving the entire laminated stack ("laminate") highly tailorable overall properties. Complicating the definition of a composite as having both continuous and discontinuous phases is the fact that in a laminated composite, neither of these phases may be regarded as truly continuous in three dimensions. Many applications require isotropy in a plane, and this is achieved by controlling the fiber orientation within a laminated composite. Hybrid organic-metal laminates are also used, where, for exam-

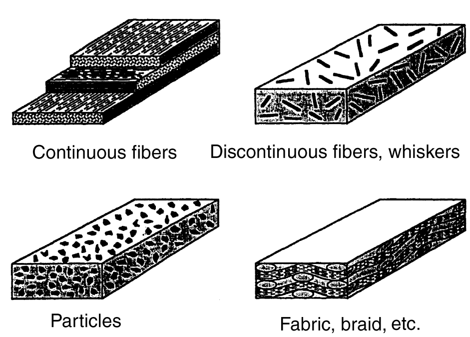

Fig. 1 Common forms of fiber reinforcement. In general, the reinforcements can be straight continuous fibers, discontinuous or chopped fibers, particles or flakes, or continuous fibers that are woven, braided, or knitted. Source: Ref 1

ple, layers of glass/epoxy are combined with aluminum alloy sheets. These laminates provide improved wear, impact and blast resistance, and fire resistance.

The final category of fiber architecture is that formed by weaving, braiding, or knitting the fiber bundles or "tows" to create interlocking fibers that often have orientations slightly or fully in an orientation orthogonal to the primary structural plane. This approach is taken for a variety of reasons, including the ability to have structural, thermal, or electrical properties in the third or "out-of-plane" dimension. Another often-cited reason for using these architectures is that the "unwetted" or dry fiber preforms (fibers before any matrix is added) are easier to handle, lower in cost, and conform to highly curved shapes more readily than the highly aligned, continuous fiber form.

In addition to these general categories, it is possible to create fiber architectures that are combinations of two or more of these categories. For example, it is possible to create laminated structures of both knitted fabric and continuous fiber layers. The design flexibility offered by composites is truly infinite!

A Brief History of Composite Materials

Organic-matrix composites, or OMCs, originated through efforts in the aerospace community during World War II to produce materials with specific strength and stiffness values that were significantly higher than existing structural materials. In addition, existing aerospace structural alloys, such as those based on aluminum, were subject to corrosion and fatigue damage, and OMCs provided an approach to overcome these issues. By the end of the war, glass-fiber-reinforced plastics had been used successfully in filament-wound rocket motors and demonstrated in various other prototype structural aircraft applications. These materials were put into broader use in the 1950s and provided important improvements in structural response and corrosion resistance. Commercial applications in consumer sporting equipment in the 1960s provided a larger market, which improved design and production capabilities, established consumer familiarity and confidence, and lowered costs.

Defense spending during the Cold War ensured sufficient resources for research and development of new, high-technology materials, and a market for their application. The significant number of new military aircraft, and the large numbers of systems ordered, provided an ideal environment for the development and insertion of high-performance OMCs. The energy crisis during the 1970s provided a significant incentive for the introduction of OMCs into commercial aircraft, and the successful experience in military aircraft was an important factor in their acceptance in the commercial industry. Dramatic improvements in structural efficiency became possible during this period, through the introduction of high-performance carbon fibers. Improved manufacturing capabilities and design methodologies provided the background for significant increases in OMC use for military and commercial aircraft and spacecraft structures.

Over the past 30 years, OMCs have won an increasing mass fraction of aircraft and spacecraft structures. This is demonstrated by the fact that the vintage 1970s application of OMCs to fighter aircraft was typically confined to tailskins and other secondary or "noncritical" flight structures. For example, only 2% of the F-15 E/F was comprised of OMCs. During the subsequent years, significant government and private investments were made toward research, development, fabrication, testing, and flight service demonstration of composite materials and structures. Parallel programs were also ongoing for the use of composites in military and civilian land and naval vehicles. For example, the development of fiberglass structures for boats and other marine applications was extremely successful and now accounts for a significant portion of composite production volume. During these years, confidence in using composite materials increased dramatically. This was also a period of great innovation in manufacturing, assembly, and repair method development.

The advantages demonstrated by composites, in addition to high stiffness, high strength, and low density, include corrosion resistance, long fatigue lives, tailorable properties (including thermal expansion, critical to satellite structures), and the ability to form complex shapes. (This advantage was demonstrated in the ability to create "low observable," or stealth, structures for military systems.) An example of recent OMC application is the next-generation U.S. tactical fighter aircraft, the F-22. Over 24% of the F-22 structure is OMCs. The B-2 bomber, shown in Fig. 2, is constructed using an even higher percentage of composites, as are current helicopter and vertical lift designs. For example, the tiltrotor V-22 Osprey is over 41% composite materials. The upper-use temperature of PMCs has also increased dramatically: early epoxies were considered useable (for extended periods) up to 121 °C (250 °F). Current generation polymers, such as bismaleimides, have increased that limit to around 204 °C (400 °F), and the use of polyimide-matrix composites has extended the range to 288 °C (550 °F).

Once considered premium materials only to be used if their high costs could be justified by increased performance, OMCs can now often "buy their way onto" new applications. This is

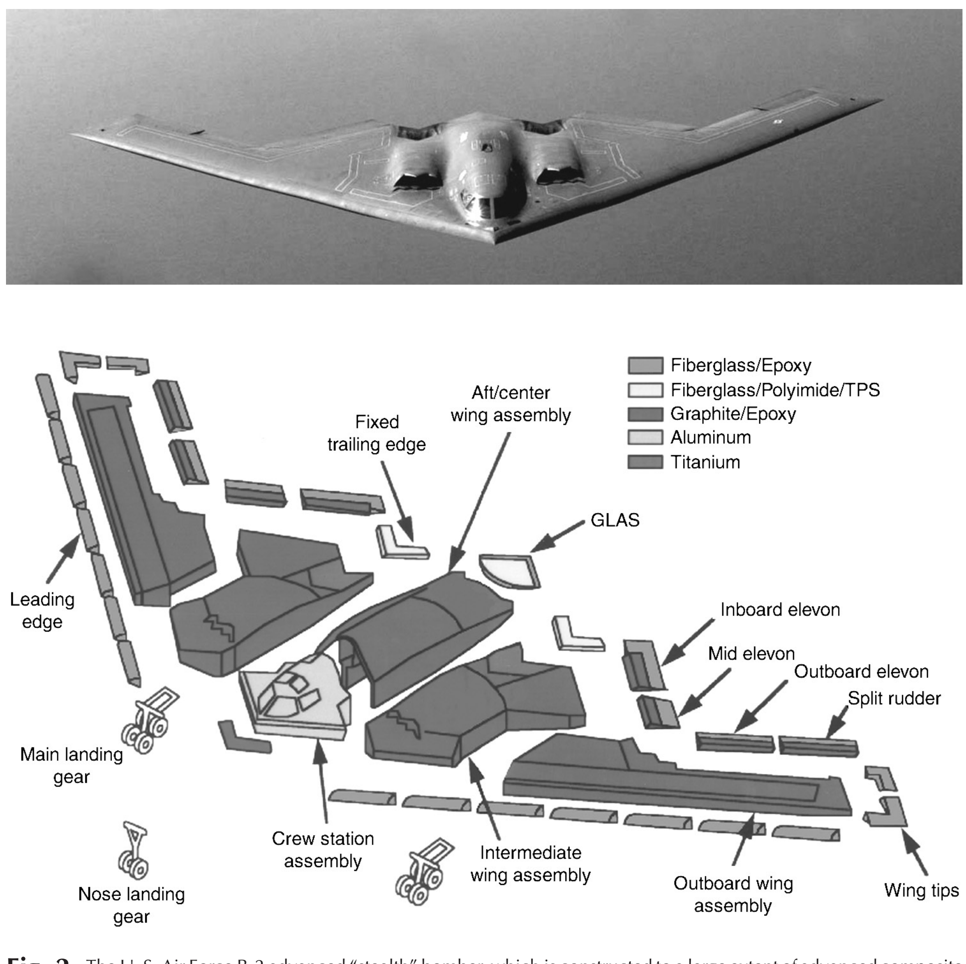

Fig. 2 The U. S. Air Force B-2 advanced "stealth" bomber, which is constructed to a large extent of advanced composite materials

due not only to a dramatic drop in materials costs, but also in advances in the ability to fabricate large, complex parts requiring far less hand labor to manually assemble. A recent example of this is the addition of large composite structures in the tail and landing gear pods on the C-17 cargo aircraft. Clearly, the applications, technology, confidence, and other considerations of high-performance OMCs have expanded dramatically since the 1980s. Perhaps the most dramatic example of this is the growing use of high-performance OMCs in the commodity market of infrastructure.

Metal-Matrix Composites. The first focused efforts to develop MMCs originated in the 1950s and early 1960s. The principal motivation was to dramatically extend the structural efficiency of metallic materials while retaining their advantages, including high chemical inertness, high shear strength, and good property retention at high temperatures. Early work on sintered aluminum powder was a precursor to discontinuously reinforced MMCs. The development of high-strength monofilaments—first boron and then silicon carbide (SiC)—enabled significant efforts on fiber-reinforced MMCs throughout the 1960s and early 1970s. Issues associated with processing, fiber damage, and fiber-matrix interactions were established and overcome to produce useful materials. Although these were very expensive and had marginal reproducibility, important applications were established, including 243 structural components on the space shuttle orbiters. Recession in the early 1970s produced significant research and development funding cuts, leading to an end of this phase of MMC discovery and development.

In the late 1970s, efforts were renewed on discontinuously reinforced MMCs using SiC whisker reinforcements. The high cost of the whiskers (Ref 2) and difficulty in avoiding whisker damage during consolidation led to the concept of particulate reinforcements (Ref 3). The resulting materials provided nearly equivalent strength and stiffness, but with much lower cost and easier processing. A renaissance in both discontinuous and fiber-reinforced MMCs continued through the 1980s. Major efforts included particle-reinforced, whisker-reinforced, and tow-based MMCs of aluminum, magnesium, iron, and copper for applications in the automotive, thermal management, tribology, and aerospace industries. In addition, monofilament-reinforced titanium MMCs were developed for high-temperature aeronautical systems, including structures for high-mach airframes and critical rotating components for advanced gas turbine engines. Significant improvements in performance and materials quality were matched by an increasing number of mostly small businesses that specialized in the production of MMC components for target markets. One by one, MMC applications entered service during this timeframe. However, these successful insertions were not often widely advertised, and so the full impact of MMC technology was not widely appreciated.

In the early 1990s, a U.S. Air Force Title III program provided a significant investment to establish an MMC technology base for the aerospace industry in the United States. This program produced several landmark military and commercial aerospace applications of discontinuously reinforced aluminum (DRA), which are described in some detail in the Section "Applications and Experience" in this Volume. In addition to these dramatic successes, new MMC insertions in the ground transportation, industrial, and thermal management/electronic packaging industries far exceeded the growth in the aerospace industry. Thus, the insertion of new materials in military and commercial aircraft has actually lagged behind the industrial sector, reversing the trend of earlier years for the insertion of new materials. The MMC market for thermal management and electronic packaging alone was five times larger than the aerospace market in 1999, and this gap is expected to increase in the coming five years, due to aggressive growth in the ground transportation and thermal management markets (Ref 4).

Ceramic-Matrix Composites. Ceramic-matrix composite development has continued to focus on achieving useful structural and environmental properties at the highest operating temperatures. The high risk associated with this task foreshadows the relatively small number of commercial products. However, development of CMCs for other uses has also been pursued, and significant commercial products now exist. These are described in the article "Applications of Ceramic-Matrix Composites" in this Volume.

General Use Considerations

General Characteristics. First and foremost, composites are engineered materials that have been designed to provide significantly higher specific stiffness and specific strength (stiffness or strength divided by material density)—that is, higher structural efficiency—relative to previously available structural materials. In composite materials, strength and stiffness are provided by the high-strength, high-modulus reinforcements. The actual magnitude in composite strength and stiffness can be controlled over a significant range by controlling the volume fraction of reinforcements and by selecting reinforcements with the desired levels of strength and stiffness. In fiber-reinforced composites, the strength and stiffness may be further controlled by specifying the fiber orientation. The highest levels of properties are achieved when all fibers are aligned along the primary loading direction within the composite. However, this simultaneously produces a material with the lowest specific properties for loads perpendicular to the fiber direction. These highly anisotropic properties must be considered in the use of the material. Of course, various laminate architectures can be produced to provide isotropy within a plane, and this is often done with OMCs.

Figure 3 shows the specific strength and specific stiffness of a wide range of engineering structural materials. The highest structural efficiency is obtained with graphite-fiber uniaxially reinforced epoxy matrix (graphite 0° in Fig. 3), and this provides part of the motivation for the widespread use of these materials. However, this material also provides the lowest structural effi-

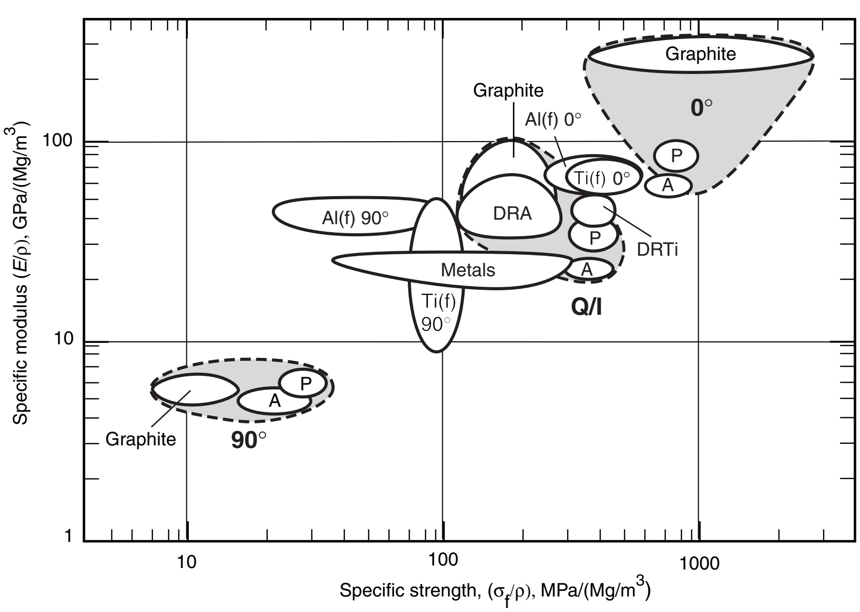

Fig. 3 Materials selection chart depicting normalized strength and stiffness characteristics for various materials systems. Note the high amount of anisotropy (or directional dependence) in composite materials, which can be exploited to create extremely lightweight structures. DRA, discontinuously reinforced aluminum; DRTi; discontinously reinforced titanium; Q/I, quasi-isotropic; P, polyacrylonitrile PAN fibers; A, aramid fibers

ciency for loads that are normal to the fiber axis (graphite 90°). There are two common approaches for dealing with the low properties in the off-axis condition. The first is to use the axially reinforced material in components with largely axial loading, so that the off-axis stresses on the composite are minimal, and the material is used most efficiently. The second approach is to cross-ply the reinforcement so that some fraction of the fibers are aligned along the off-axis loads. Both approaches are fully successful and have been used extensively, thereby overcoming the poor transverse properties of OMCs. A great deal of flexibility exists in the lay-up of a composite, so that the fraction of fibers in any given direction can be tailored in proportion to the load that must be supported. In-plane isotropy is required in some applications, so a quasi-isotropic (Q/I) graphite/epoxy laminate is produced. This is most often accomplished by orienting the laminating plies at equal numbers of 0°, 90°, +45°, and –45° plies, although there are other stacking sequences that will result in in-plane isotropy. The specific stiffness of quasi-isotropic laminated OMCs is significantly higher than structural metals. The highest specific strength of these materials is superior to all common structural metals, with the exception of a few specialty β–titanium alloys and ultrahigh-strength steels.

Fiber-reinforced metals provide axial and transverse properties that fall between the extremes of the axial and transverse graphite/epoxy OMCs. However, the technology base for fiber-reinforced MMCs is less mature. Processing difficulties currently limit the ability to form complex shapes for SiC monofilament-reinforced titanium alloys. Further, cross-plied architectures have not been successfully demonstrated in any commercial fiber-reinforced MMC. While the high cost of constituent materials dramatically limits the appeal of MMCs reinforced with monofilaments, aluminum alloys reinforced with a tow-based alumina reinforcement are commercially available and can be significantly cheaper than graphite/epoxy OMCs. As a result, these are finding applications in industries that are typically very cost-sensitive. Fiber-reinforced MMCs are now entering applications in limited areas where the metallike behavior is important, including high bearing strength, good wear resistance, high electrical conductivity, and elevated temperature operation. Some of these applications are discussed in the Section "Applications and Experience" in this Volume.

Particle-reinforced metals provide essentially isotropic properties that are in the same general range as graphite/epoxy quasi-isotropic material (Fig. 3). Discontinuously reinforced aluminum is currently by far the most widely used MMC. For reinforcement volume fractions of ≤25%, DRA has structural efficiency that overlaps that of quasi-isotropic OMCs and has good fracture toughness and ductility, so that a number of important structural applications have been established. (See the articles "Aeronautical Applications of Metal-Matrix Composites" and "Automotive Applications of Metal-Matrix Composites" in this Volume.) The fracture properties for higher volume fractions are lower, but these materials are used widely for wear-resistant applications and for thermal management and electronic packaging. The relatively low cost and ease of manufacturing makes DRA an affordable material where high structural efficiency is required. Discontinuously reinforced titanium (DRTi) is less mature than DRA, but already has several important applications established, including intake and exhaust valves in production automobile engines. (See the article "Automotive Applications of Metal-Matrix Composites" in this Volume.) Current DRTi materials have reinforcement volume fractions of ≤20%, and significant improvements are expected for higher reinforcement volume fractions. Current DRTi materials provide a balance of specific strength and specific stiffness that is superior to that of any isotropic engineering material, including quasi-isotropic OMCs.

Almost all high-strength/high-stiffness materials fail because of the propagation of flaws. A fiber of such a material is inherently stronger than the bulk form, because the size of a flaw is limited by the small diameter of the fiber. In addition, if equal volumes of fibrous and bulk material are compared, it is found that even if a flaw does produce failure in a fiber, it will not propagate to fail the entire assemblage of fibers, as would happen in the bulk material. When this material is also lightweight, there is a tremendous potential advantage in specific strength and/or specific stiffness over conventional materials. These desirable fiber properties can be converted to practical application when the fibers are embedded in a matrix that binds them together, transfers load to and between the fibers, and protects them from environments and handling. In addition, fiber-reinforced composites are ideally suited to anisotropic loading situations where weight is critical. The high strengths and moduli of these composites can be tailored to the high load direction(s), with little material wasted on needless reinforcement.

To be useful for structures, materials must offer more than just strength and stiffness. Damage tolerance, fatigue resistance, environmental resistance, and other secondary properties are also required so that the composite can perform its primary structural function. Additional functional properties for which a composite may be developed include high thermal or electrical conductivity (or conversely, electrical and/or thermal insulation), good wear resistance, controlled CTE, and/or environmental resistance. Although composites with significantly different constituents can be conceived to optimize any of these functional properties, the typical organic and metallic composite systems described previously provide a useful range of these functional properties. Specifically, in addition to high strength and stiffness, the reinforcements commonly used in OMCs and MMCs generally have low CTE, high hardness, good electrical and thermal conductivity, and good chemical inertness. As a result, the structural composites in common use can also be tailored to provide other useful functional properties with only minor alterations. The balance of properties obtained in these composites typically cannot be obtained in any other monolithic material. Examples of these functional applications are provided in the Section "Applications and Experience" in this Volume.

Materials Selection and Use. The selection of an optimal material for an intended application is a difficult and multidisciplinary task that requires careful understanding and analysis of a great many variables. The simple introductory comments given previously regarding the two primary figures of merit for structural applications provide a useful starting point for bounding this multivariable problem, but do not address the difficulty associated when trade-offs between competing characteristics must be made. The information and approaches required to help with these decisions are covered in some detail throughout this Volume, so the purpose of this brief introduction is to outline broad considerations and approaches that may help to quickly bound the problem to a tractable and well-defined set of issues.

As a starting point, the application requirements and constraints must be clearly understood. This allows definition of the primary design criteria. An approach for comparing the response across the full range of candidate materials for carefully selected relevant pairs of figures of merit to achieve these primary design criteria has recently been provided (Ref 5). To support this approach, graphical representation of a vast amount of materials properties has been undertaken and completed—these are often commonly referred to as "Ashby plots." Figure 3 provides a simple example of such a representation, because specific stiffness and specific strength are the figures of merit to resist an axial deflection or to support a given load, respectively, at minimum mass. Pairwise comparisons of figures of merit for many other design objectives provide a flexible and complete methodology for quickly bounding a difficult materials selection problem. Additional information on the use of Ashby plots is provided in the article "Material Selection Charts" in *Materials Selection and Design,* Volume 20 of *ASM Handbook.*

As explicitly engineered materials, composites in actual use integrate materials specification and component design. For example, the number and orientation of plies is typically explicitly considered during the design of components produced from OMCs. By tailoring the local architecture to the component geometry and anticipated stresses, the designer is able to take best advantage of the materials properties and to produce the component at a minimum mass. In fact, the relatively high raw material cost and high lay-up cost of OMCs has led to a highly unitized approach to design and manufacturing. This has dramatically reduced the cost of manufacture by reducing material waste and by eliminating high labor costs associated with extra manufacturing and joining steps. Fewer parts also lead to reduced inventory and overhead costs. The high structural efficiency and tailorability of OMCs has enabled this important integration in design and materials specification, and this unitized design and manufacturing approach has largely offset the high perceived costs of high-performance OMCs. While similar approaches cannot currently be achieved with fiber-reinforced MMCs, the concept of selective reinforcement in regions of high stress has been considered and is likely to find application in the near future.

Technology Overview

With some few exceptions, only "high-performance" composites are considered in this Volume. These are composites that have superior performance compared to conventional structural metals. Thus, the focus for OMCs is on continuous fiber-reinforced composites, although the principles are often applicable to other types of composites as well. Continuous fiber-reinforced composites are generally referred to as simply fiber-reinforced composites, and in some cases, as merely fiber composites or composites. Composites with organic (resin) matrices are emphasized throughout this Volume, because these OMCs are by far the most commonly used structural composites. Nonetheless, MMCs are now an established technology with strong impact and growing applications, and so MMCs are discussed explicitly throughout this Volume. Only very limited discussion of CMCs is provided in this Volume.

The following is an introduction to composite materials constituents, product forms, and fabrications processes. The purpose is to provide a simple overview that may serve as a point of departure for the nonspecialist. More detailed information is provided on each of these topics elsewhere in this Volume.

Reinforcements

The principal purpose of the reinforcement is to provide superior levels of strength and stiffness to the composite. In a continuous fiber-reinforced composite, the fibers provide virtually all of the strength and stiffness. Even in particle-reinforced composites, significant improvements are obtained. For example, the addition of 20% SiC to 6061 aluminum provides an increase in strength of over 50% and an increase in stiffness of over 40%. As mentioned earlier, typical reinforcing materials (graphite, glass, SiC, alumina) may also provide thermal and electrical conductivity, controlled thermal expansion, and wear resistance in addition to structural properties.

By far the most widely used reinforcement form in high-performance OMCs are fiber tows. These typically consist of thousands of fine filaments arranged in a single bundle. A fiber tow can be handled as a single unit and so can be wrapped or woven using commercial equipment. Fiber tows also have important applications in MMCs and CMCs. Fiber monofilaments are used in OMCs, MMCs, and CMCs; they consist of a single fiber with a diameter generally ≥100 μm (4 mils). In MMCs, particulates and chopped fibers are the most commonly used reinforcement morphology, and these are also applied in OMCs. Whiskers and platelets are used to a lesser degree in OMCs and MMCs.

Glass Fibers. Initial scientific and engineering understanding of fiber-reinforced organic-matrix composites was based on studies of glass-fiber-reinforced composites. Both continuous and discontinuous glass-fiber-reinforced composites have found extensive application, ranging from nonstructural, low-performance uses, such as panels in aircraft and appliances, to such high-performance applications as rocket motor cases and pressure vessels. The reasons for the widespread use of glass fibers in composites, both in the past and in the present, include competitive price, availability, good handleability, ease of processing, high strength, and other acceptable properties. Furthermore, the advent of highly efficient silane coupling agents, which are very compatible with either polyester or epoxy matrices, provided a strong and much-needed boost in property translation and in environmental durability.

The glass fiber most commonly used is known as E-glass, a glass fiber having a useful balance of mechanical, chemical, and electrical properties at very moderate cost. Typical strength and stiffness levels for the individual filaments are about 3450 MPa (500 ksi) tensile strength and 75.8 GPa (11×10^6 psi) Young's modulus. Higher-performance, higher-cost S-2 glass fibers have properties of 4830 MPa (700 ksi) tensile strength and a modulus of 96.5 GPa (14×10^6 psi). For specialized applications, such as ablatives, thermal barriers, antenna windows, and radomes, high-silica and quartz fibers are also used.

Boron fibers were the first high-performance monofilament reinforcement available for use in advanced composites. Developed and first marketed in the early 1960s, these high-strength, high-modulus fibers found application in composite structural components on the U.S. Air Force F-15 and the U.S. Navy F-14 aircraft. Because these aircraft are still in service and the high costs of changeover are unacceptable, boron fibers are still being used today, even though carbon fibers are now available with equivalent or better properties at a significantly lower price. Boron-epoxy composites have been used in the sporting goods industry, and boron fibers have been used in MMCs because of their excellent mechanical properties, thermal stability, and reduced reactivity with the matrix (compared to carbon fibers). Boron fibers are produced as a rather large monofilament fiber or "wire" (100 to 200 μm, or 4 to 8 mils, diameter) by chemical vapor deposition (CVD) of boron onto a tungsten or pyrolyzed carbon substrate. The resulting fibers have excellent strength (3450 MPa, or 500 ksi) and stiffness (400 GPa, or 58×10^6 psi). Because of their large fiber diameters, they form composites having extremely high compressive strengths. However, because both the precursor gases and the manufacturing process are inherently expensive, boron fibers cannot be expected to compete with carbon fibers on the basis of cost alone. The use of boron fibers has seen somewhat of a resurgence lately in the use of composite patch repairs of crack damage in aluminum aircraft structure.

Carbon Fibers. Although the search for high-performance reinforcing fibers was highly successful, the early limited demand outside the military aerospace industry did not permit the cost reductions that would have resulted from more extensive use. As a result, widespread industrial applications for the variety of new materials progressed very slowly in all but specialty applications where higher costs could be justified. Factors that changed this situation were the extensive use of carbon-fiber-reinforced composites in recreational equipment and the increased cost of energy in the early 1970s. The promise of commercial quantities of carbon-fiber materials from a number of sources at attractive prices created a resurgence of interest in advanced composites in the general aerospace industry. Currently, carbon fibers are the best known and most widely used reinforcing fibers in advanced composites. Although there are many reasons for this situation, two factors predominate. First, the manufacturing technology for carbon fibers, although complex, is more amenable to large-scale production than are those of many of the other advanced fibers. Second, carbon fibers have very useful engineering properties that, for the most part, can be readily translated into usable composite physical and mechanical properties.

Carbon fibers are available from a number of domestic and foreign manufacturers in a wide range of forms having an even wider range of mechanical properties. The earliest commercially available carbon fibers were produced by thermal decomposition of rayon precursor materials. The process involved highly controlled steps of heat treatment and tension to form the appropriately ordered carbon structure. Rayon has been largely supplanted as a precursor by polyacrylonitrile (PAN). Polyacrylonitrile precursors produce much more economical fibers because the carbon yield is higher and because PAN-based fibers do not intrinsically require a final high-temperature "graphitization" step.

Polyacrylonitrile-based fibers having intermediate-modulus values of about 240 to 310 GPa (35 to 45 $\times 10^6$ psi), combined with strengths ranging from 3515 to 6380 MPa (510 to 925 ksi), are now commercially available. Because carbon fibers display linear stress-strain behavior to failure, the increase in strength also means an increase in the elongation-to-failure. The commercial fibers thus display elongations of up to 2.2%, which means that they exceed the strain capabilities of conventional organic matrices. The diameter of carbon fibers typically ranges from 8 to 10 μm (0.3 to 0.4 mils). Polyacrylonitrile-based fibers are available in various "tow sizes," meaning the number of carbon fibers per bundle. Currently, tow sizes range from low (1000 fibers per tow) at high cost ($40 to $70 per pound) to very high tow counts (hundreds of thousands of fibers per tow) for less than $10 per pound.

Carbon fibers are also manufactured from pitch precursor for specialty applications. Pitch-fiber properties typically include high modulus and thermal conductivity, as might be required on satellite structures. Modulus values in commercially available fibers range up to 825 GPa (120×10^6 psi).

Aramid Fibers. Aramid is a generic term for a class of aromatic polyamide fibers introduced commercially during the early 1960s. These high-performance fibers are all variations of poly para-phenyleneterephthalamide. A broad range of properties are available. Kevlar 149 (DuPont), for example, has a tensile modulus of 180 GPa (26×10^6 psi) and tensile strength of 3450 MPa (500 ksi). The more commonly used Kevlar 49 (DuPont) has a tensile modulus of 131 GPa (19 $\times\ 10_6$ psi) and a tensile strength of 3620 MPa (525) ksi).

Aramid fiber is unusual in that it is technically a thermoplastic polymer (like nylon), but rather than melting when heated, it decomposes before reaching its projected melting temperature. With polymerization, it forms rigid, rodlike molecules that cannot be drawn from a melt, as textile fiber molecules can, but must instead be spun from a liquid crystalline solution in sulfuric acid. The polymerization and manufacturing processes for aramid fibers are complex and exacting and involve many aggressive chemical species.

The high strength of aramid fiber, combined with a fiber modulus considerably higher than S-glass, gave it early application in filament-wound rocket motor cases, gas pressure vessels, and lightly loaded secondary structures on fixed-wing commercial aircraft and helicopters. The fiber shows linear tensile stress-strain behavior to failure, but unlike inorganic fibers, is surprisingly damage tolerant. However, it also displays far lower strength in compression than carbon and other inorganic fibers and relatively poor adhesion to matrix resins. Moisture uptake may also need to be considered. Nevertheless, because of properties such as its high specific strength, low density, and toughness, significant markets exist.

Other Organic Fibers. Another common category of fibers are ultrahigh-molecular-weight polyethylene fibers, such as Spectra from AlliedSignal Inc. The modulus of Spectra can range up to 113 GPa (16×10^6 psi), with tensile strengths up to 3250 MPa (470 ksi). These fibers have high chemical, impact, and moisture resistance, as well as low density, good vibration damping, and low dielectric constant. Major applications include ballistic armor, radomes, boats, and other recreational products.

Silicon Carbide Monofilaments. Silicon carbide monofilaments have been developed for reinforcements in MMCs based on aluminum and titanium alloy matrices and for CMCs. Fibers that are now commercially available are all produced by CVD of fine-grained β-SiC, which is deposited on either a tungsten or a carbon filament core. Each of the fibers also uses a carbon-based coating to improve fiber strength by healing surface defects, to improve handleability, and to protect the fiber from interaction with the metal matrix during consolidation and use. The monofilaments range in diameter from 100 to 142 μm (4 to 5.6 mils). The CTE for all of the SiC monofilaments is 4.5×10^{-6}/°C, (2.5×10^{-6}/°F) and the density is 3.0 g/cm^3 (0.11 lb/in.^{3}) for fibers with a carbon core and 3.4 g/cm^3 (0.12 lb/in.^{3}) for fibers deposited on tungsten. There are currently three manufacturers of SiC monofilament.

Textron Systems markets the venerable SCS-6 monofilament, which has been used longer than any other SiC monofilament. It is deposited on a carbon core by a two-pass process, which produces a distinct change in grain size at the fiber midradius. A multilayer carbon-based coating consists of an intentional gradation in silicon content to enhance the coating effectiveness. The overall fiber diameter is 142 μm (5.6 mils). The minimum specified average properties are 3450 MPa (500 ksi) strength and 345 GPa (50×10^6 psi) stiffness. The typical average properties are 4300 MPa (625 ksi) strength and 390 GPa (56×10^6 psi) stiffness. There is a great deal of data and experience behind this fiber, which has been produced by the same process since 1983. Process improvements have led to the Textron Systems Ultra SCS fiber. While the carbon core, fiber coating, and fiber diameter are identical to the SCS-6, the SiC possesses a finer grain size that is uniform across the fiber diameter. The minimum average specified properties are 5860 MPa (850 ksi) strength and 360 GPa (52×10^6 psi) stiffness. The typical average values obtained are 6550 MPa (950 ksi) strength and 415 GPa (60×10^6 psi) stiffness.

Two SiC monofilaments are available from the Atlantic Research Corporation (Gainesville, VA). Trimarc-1 is 127 μm (5 mils) in diameter on a tungsten core, with a multilayer carbon coating 4 to 5 μm (0.16 to 0.20 mils) thick. The typical mean fiber strength is 3550 MPa (515 ksi), and the modulus is 420 GPa (61×10^6 psi). Trimarc-2 is deposited on a carbon core and is 142 μm (5.6 mils) in diameter. The typical strength is 3790 MPa (550 ksi), and the typical modulus is 400 to 414 GPa (58 to 60×10^6 psi). The Sigma SiC monofilament is produced by QinetiQ, formerly the Defence Evaluation and Research Agency (DERA), in the United Kingdom. The DERA Sigma 1140+ fiber is 100 μm (4 mils) in diameter, is produced on a tungsten core, and has a carbon coating about 5 μm (0.2 mils) thick. The typical strength is between 3400 to 3500 MPa (490 to 510 ksi), and the modulus is 380 GPa (55×10^6 psi).

Alumina-Fiber Reinforcements. A number of alumina (Al_2O_3) fibers have been developed and used for MMCs and CMCs, including ceramic tows and monofilaments. At present, production MMCs only use alumina tows. The most commonly used material is the Nextel 610 fiber produced by 3M (St. Paul, MN). This is ≥99% α–alumina and has a density of 3.96 g/cm^3. Tows are available that contain from 400 to 2550 filaments per tow. The mean filament diameter is 10 to 12 μm (0.4 to 0.5 mils). The typical fiber properties are 2930 MPa (425 ksi) strength and 373 GPa (54×10^6 psi) modulus. The CTE is 7.9×10^{-6}/°C.

Particulate reinforcements in MMCs typically use abrasive-grade ceramic grit. This provides a ready commercial source, and the high volumes associated with the abrasives industry help maintain a low cost. Silicon carbide, alumina, and boron carbide (B_4C) are most often used. Titanium carbide (TiC) is also used for iron and titanium alloy matrices. While TiB is used as a reinforcement in discontinuously reinforced titanium alloys, this reinforcement is typically obtained by in situ reaction with TiB_2. Silicon carbide offers the best strength and stiffness for aluminum matrices, but is slightly more expensive than alumina. "Green" SiC offers better strength and thermal conductivity relative to "black" SiC, and so is used where these properties are important. Typical grit sizes used are between F-600 (mean grit size between 8.3 to10.3 μm, or 0.33 to 0.41 mils) and F-1200 (mean grit size between 2.5 to 3.5 μm, or 0.11 to 0.14 mils). Alumina is slightly cheaper than SiC, and so is attractive where cost is critical, such as in the automotive sector. Alumina is slightly more dense than SiC and has a higher CTE. Alumina is chemically more stable than SiC in molten aluminum, and so is frequently used in cast DRA. Silicon carbide particulates are still used for cast MMCs, and silicon is added as an alloying addition to reduce the reactivity with the molten metal.

Matrices

The purpose of the matrix is to bind the reinforcements together by virtue of its cohesive and adhesive characteristics, to transfer load to and between reinforcements, and to protect the reinforcements from environments and handling. The matrix also provides a solid form to the composite, which aids handling during manufacture and is typically required in a finished part. This is particularly necessary in discontinuously reinforced composites, because the reinforcements are not of sufficient length to provide a handleable form. Because the reinforcements are typically stronger and stiffer, the matrix is often the "weak link" in the composite, from a structural perspective. As a continuous phase, the matrix therefore controls the transverse properties, interlaminar strength, and elevated-temperature strength of the composite. However, the matrix allows the strength of the reinforcements to be used to their full potential by providing effective load transfer from external forces to the reinforcement. The matrix holds reinforcing fibers in the proper orientation and position so that they can carry the intended loads and distributes the loads more or less evenly among the reinforcements. Further, the matrix provides a vital inelastic response so that stress concentrations are reduced dramatically and internal stresses are redistributed from broken reinforcements. In organic matrices, this inelastic response is often obtained by microcracking; in metals, plastic deformation yields the needed compliance. Debonding, often properly considered as an interfacial phenomenon, is an important mechanism that adds to load redistribution and blunting of stress concentrations. A broad overview of important matrices is provided subsequently.

Organic matrices for commercial applications include polyester and vinyl ester resins; epoxy resins are used for some "high-end" applications.

Polyester and vinyl ester resins are the most widely used of all matrix materials. They are used mainly in commercial, industrial, and transportation applications, including chemically resistant piping and reactors, truck cabs and bodies, appliances, bathtubs and showers, and automobile hoods, decks, and doors. The very large number of resin formulations, curing agents, fillers, and other components provides a tremendous range of possible properties.

The development of highly effective silane coupling agents for glass fibers allowed the fabrication of glass-fiber-reinforced polyester and vinyl ester composites that have excellent mechanical properties and acceptable environmental durability. These enhanced characteristics have been the major factors in the widespread use of these composites today.

The problems of attaining adequate adhesion to carbon and aramid fibers have discouraged the development of applications for polyester or vinyl ester composites that use these fibers. Although there are applications of high-performance fiberglass composites in military and aerospace structures, the relatively poor properties of advanced composites of polyester and vinyl ester resins when used with other fibers, combined with the comparatively large cure shrinkage of these resins, have generally restricted such composites to lower-performance applications.

Other Resins. When property requirements justify the additional costs, epoxies and other resins, as discussed subsequently, are used in commercial applications, including high-performance sporting goods (such as tennis rackets and fishing rods), piping for chemical processing plants, and printed circuit boards.

Organic matrices for aerospace applications include epoxy, bismaleimide, and polyimide resins. Various other thermoset and thermoplastic resins are in development or use for specific applications.

Epoxy resins are presently used far more than all other matrices in advanced composite materials for structural aerospace applications. Although epoxies are sensitive to moisture in both their cured and uncured states, they are generally superior to polyesters in resisting moisture and other environmental influences and offer lower cure shrinkage and better mechanical properties. Even though the elongation-to-failure of most cured epoxies is relatively low, for many applications epoxies provide an almost unbeatable combination of handling characteristics, processing flexibility, composite mechanical properties, and acceptable cost. Modified "toughened" epoxy resin formulations (typically via the addition of thermoplastic or rubber additives) have improved elongation capabilities. In addition, a substantial database exists for epoxy resins, because both the U.S. Air Force and the U.S. Navy have been flying aircraft with epoxy-matrix structural components since 1972, and the in-service experience with these components has been very satisfactory.

Moisture absorption decreases the glass transition temperature (T_g) of an epoxy resin. Because a significant loss of epoxy properties occurs at the T_g, the T_g in most cases describes the upper-use temperature limit of the composite. To avoid subjecting the resins to temperatures equal to or higher than this so-called wet T_g (the wet T_g is the T_g measured after the polymer matrix has been exposed to a specified humid environment and allowed to absorb moisture until it reaches equilibrium), epoxy resins are presently limited to a maximum service temperature of about 120 °C (250 °F) for highly loaded, long-term applications and even lower temperatures (80 to 105 °C, or 180 to 220 °F) for toughened epoxy resins. Although this limit is conservative for some applications, its imposition has generally avoided serious thermal-performance difficulties. Considerable effort continues to be expended to develop epoxy resins that will perform satisfactorily at higher temperatures when wet. However, progress in increasing the 120 °C (250 °F) limit has been slow.

Bismaleimide resins (BMI) possess many of the same desirable features as do epoxies, such as fair handleability, relative ease of processing, and excellent composite properties. They are superior to epoxies in maximum hot/wet use temperature, extending the safe in-service temperature to 177 to 230 °C (350 to 450 °F). They are available from a number of suppliers. Unfortunately, BMIs also tend to display the same deficiencies (or worse) as do epoxies: they have an even lower elongation-to-failure and are quite brittle. Damage tolerance is generally comparable to commercial aerospace epoxy resins. Progress has been made to formulate BMIs with improved toughness properties.

Polyimide resins are available with a maximum hot/wet in-service temperature of 232 °C (450 °F) and above (up to 370 °C, or 700 °F, for single use short periods). Unlike the previously mentioned resins, these cure by a condensation reaction that releases volatiles during cure. This poses a problem, because the released volatiles produce voids in the resulting composite. Substantial effort has been made to reduce this problem, and there are currently several polyimide resins in which the final cure occurs by an addition reaction that does not release volatiles. These resins will produce good-quality, low-void-content composite parts. Unfortunately, like BMIs, polyimides are quite brittle.

Other Thermosetting Resins. The attempt to produce improved thermosetting resins is ongoing, with major efforts focusing on hot/wet performance and/or impact resistance of epoxies, BMIs, and polyimides. Other resins are constantly in development, and some are in commercial use for specialized applications. Phenolic resins, for example, have been used for years in applications requiring very high heat resistance and excellent char and ablative performance. These resins also have good dielectric properties, combined with dimensional and thermal stability. Unfortunately, they also cure by a condensation reaction, giving off water as a byproduct and producing a voidy laminate. However, they also produce low smoke and less toxic by-products upon combustion and are therefore often used in such applications as aircraft interior panels where combustion requirements justify the lower properties. Cyanate esters are also used as matrix materials. Their low-moisture-absorption characteristics and superior electrical properties allow them to see applications in satellite structures, radomes, antennas, and electronic components.

Thermoplastic Resins. The dual goal of improving both hot/wet properties and impact resistance of composite matrices has led to the development, and limited use, of high-temperature thermoplastic resin matrices. These materials are very different from the commodity thermoplastics (such as polyethylene, polyvinyl chloride, and polystyrene) that are commonly used as plastic bags, plastic piping, and plastic tableware. The commodity thermoplastics exhibit very little resistance to elevated temperatures; the high-performance thermoplastics exhibit resistance that can be superior to that of epoxy.

Thermoplastic-matrix materials are tougher and offer the potential of improved hot/wet resistance and long-term room-temperature storage. Because of their high strains-to-failure, they also are the only matrices currently available that allow, at least theoretically, the new intermediate-modulus, high-strength (and strain) carbon fibers to use their full strain potential in the composite. Thermoplastics are generally considered to be *semicrystalline* (meaning the atoms in the polymer chains arrange themselves in regular arrays to some degree) or *amorphous* (meaning there is no local order to the molecular chains). These materials include such resins as polyether etherketone, polyphenylene sulfide, polyetherimide (all of which are intended to maintain thermoplastic character in the final composite), and others, such as polyamideimide, which is originally molded as a thermoplastic but is then post-cured in the final composite to produce partial thermosetting characteristics (and thus improved subsequent temperature resistance). Thermoplastic matrices do not absorb any significant amount of water, but organic solvent resistance is an area of concern for the noncrystalline thermoplastics.

Metal and Ceramic Matrices. Unlike their organic counterparts, the metal alloy matrix in MMCs provides an important contribution to the strength of the composite. This results not only from the higher strength of metal alloys relative to organic resins typically used as matrices, but also from the fact that most MMCs currently have discontinuous reinforcements and a much higher matrix volume fraction. Metal-matrix composites are currently in service using matrices based on alloys of aluminum, titanium, iron, cobalt, copper, silver, and beryllium. Copper, silver, and beryllium MMCs are mostly used for thermal management and electrical contacts; iron MMCs are used for industrial wear-resistant applications, such as rollers and tool dies; and titanium MMCs are used primarily for automotive, aerospace, and recreational products. Cobalt MMCs (cemented carbides, or cermets) are included here as an MMC, although not all agree upon this classification, while oxide-dispersion-strengthened nickel is explicitly excluded, because strengthening in these alloys occurs by a dislocation mechanism rather than a load-sharing mechanism. By far the most widely produced MMCs are based on aluminum alloy matrices, and these are in current use for automotive and rail ground transportation, thermal management and electronic packaging, aerospace, and recreational applications.

A wide range of cast and wrought aluminum alloys are used as matrices in aluminum MMCs. A standard nomenclature, American National Standards Institute (ANSI) H35.5-1997, has been established for aluminum MMCs: 2009/SiC/15p-T4. The first four digits (or three digits for cast alloys) are the Aluminum Association alloy designation, which specifies the matrix alloy composition. This is followed by the reinforcement composition and the reinforcement volume fraction (in volume percent). A single letter signifies the reinforcement morphology (“p” is particle, “w” is whisker, and “f” is fiber). The standard Aluminum Association temper designation is used at the end of the MMC designation, as appropriate.

The most widely used MMC casting alloys are based on aluminum-silicon, which are used to produce foundry ingots. The high-silicon aluminum alloys improve castability and minimize chemical interaction with the SiC reinforcements during melting. Common matrix alloy compositions are based on aluminum casting alloys such as 359, 360, and 380. The modifications generally include higher silicon and sometimes higher magnesium or manganese or lower copper (Ref 6). Infiltration casting also often uses aluminum-silicon alloys, such as A356, and this is common for materials used in thermal management. However, wrought alloy compositions, including common 2*xxx* and 6*xxx* alloys, can also be used for infiltration casting. For pressureless casting, the matrix composition is carefully controlled to provide the desired reactions and microstructures. Silicon is typically at 10% (by weight), and 1% Mg (by weight) is also critical.

Cast billets or blooms for subsequent thermomechanical processing often use wrought matrix alloys containing magnesium, such as 2024 and 6061. Billet obtained by powder metallurgy also uses conventional wrought alloy compositions, or may use modified alloys that have been optimized for use in an MMC matrix. Two examples are 6091, which is a modified 6061 alloy, and 6092, which is a modification of 6013. Often, the modification involves a small reduction in the concentration of alloy additions used for grain refinement, because the reinforcing particulates restrict grain growth. Also, a maximum level is specified for oxygen to ensure that the powder does not introduce a large fraction of oxide particles.

Metal-matrix composites of copper, beryllium, and silver are used primarily for their excellent electrical and thermal properties, and reinforcements are added for control of thermal expansion or improved wear resistance. The matrix is usually the pure element to retain the excellent thermal or electrical properties. Typical reinforcements, such as molybdenum in copper and silver, tungsten and tungsten carbide in copper, and beryllium oxide in beryllium, are insoluble in the matrix.

Titanium MMCs use conventional wrought alloy matrices when the reinforcement is continuous. For current applications, Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) is used. (See the article “Aeronautical Applications of Metal-Matrix Composites” in this Volume.) Other commercial alloys, such as Ti-6Al-4V and Timetal 21S, have been used extensively in development and component demonstrations. A number of alloys have been used in research and development of DRTi. The largest commercial application of DRTi by far is for automotive intake and exhaust valves. The intake valve uses Ti–6Al–4V as the matrix, but the exhaust valve requires a high-temperature matrix alloy. The composition used is Ti-6.5Al-4.6Sn-4.6Zr-1.0Mo-1Nb-0.3Si (Ref 7, 8).

Ceramic-matrix composites currently in use generally use SiC or inhibited carbon as the matrix. The role of the matrix is to provide the required wear and abrasion resistance, or to protect the fiber from oxidation and damage.

Material Forms

Composite materials are generally available in a range of raw product forms. These forms provide a standardized unit for cost-effective production and are a convenient input for manufacturing processes. Further, standardizing the raw product form allows better control over constituent composition and distribution. A brief discussion of the raw product forms used most often in composite manufacture is provided subsequently.

Organic-Matrix Composites. Continuous reinforcing fibers are available in many product forms, ranging from monofilaments (for fibers such as boron and SiC) to multifilament fiber bundles, and from unidirectional ribbons to single-layer fabrics and multilayer fabric mats. The organic matrices are generally mixed from the individual components if the matrix is a thermoset, or are available as sheet, powders, or pellets if the matrix is a thermoplastic. The reinforcing fibers and matrix resins may be combined into many different nonfinal material or product forms that are designed for subsequent use with specific fabrication processes. In the case of continuous fibers, these combinations of unidirectional fiber ribbons, tows, or woven fabrics with resin and formed into broad sheets are called prepregs. (In some cases, the fiber tows are impregnated with resin and wound back on spools, still as tows, to form “towpregs.”) At this stage, prepregs/towpregs are still largely uncured.

Using prepregs rather than in-line impregnation of the fibers during the final composite fabrication process can offer significant advantages. Prepregs can have very precisely controlled fiber-resin ratios, highly controlled tack and drape (in the case of thermoset matrices), controlled resin flow during the cure process, and, in some processes, better control of fiber angle and placement. Prepreg materials can be produced and stored, normally under refrigeration for thermosetting matrices, and then used in processes ranging from hand lay-up to highly automated filament winding, tape laying, or tow placement. Processes such as pultrusion and braiding can also use prepreg forms instead of in-line resin impregnation. While the latter may be lower in initial cost, it may be prohibitive for some resin systems (such as thermoplastics), and parameters such as fiber-resin ratio may not be as easily controlled, as is the case with a prepreg.

Discontinuous fiber-reinforced product forms include sheet molding compounds, bulk molding compounds, injection molding compounds, and dry preforms fabricated for use in resin infusion processes. Many other forms of reinforcement exist, primarily in fiberglass materials. Both continuous and discontinuous mats, with and without binder materials, are available. Of course, composites reinforced primarily with discontinuous fibers have lower mechanical properties than those with continuous fibers. This is because all of the loads in discontinuous fiber composites must be carried by the matrix in shear from fiber length to fiber length (shear lag). In addition, fiber volume in discontinuous fiber composites is normally quite a bit lower than is typical in continuous fiber composites.

Composite materials are very often used as facesheets and combined with core materials to form sandwich structures. Common forms for core materials are foams (open and closed cell), honeycomb (often made from fiberglass, aramid, or aluminum) whereby the longitudinal axes of the cells are perpendicular to the primary plane of the structural sandwich, and foam-filled honeycomb. Sandwich structures have extremely high structural bending stiffness, which is exploited in bending- and buckling- critical applications.

Metal-Matrix Composites. The largest supplier of MMC primary product forms is Alcan Engineered Cast Products (formerly Duralcan USA). Billet and blooms for wrought processing and foundry ingots for remelting are produced by a patented casting process. Batches of 6.8 metric tons are melted, and the ceramic particles are suspended in the melt by a high-energy mixing process. The molten MMC is then cast into bloom, billet, or ingot. These material forms are then provided to customers who apply secondary forming operations, such as extrusion, forging, rolling, or remelting and casting.

The aerospace industry relies upon MMC billet produced by a powder metallurgy process. The primary process, performed by DWA Aluminum Composites, mixes matrix and reinforcing powder in a high-shear mixer, then outgases and consolidates the powder into billet. Billet sizes over 360 kg (800 lb) are typical, and billets up to 450 kg (1000 lb) are available.

A major portion of the MMC market relies upon components produced in near-net shape processes other than recasting of foundry ingot. The most commonly used processes are infiltration casting and squeeze casting. In both cases, carefully produced porous ceramic preforms are required. Infiltration preforms of ceramic particulates are produced by either a slurry-casting approach, by powder pressing, or by injection molding. These preforms provide a uniform distribution of the reinforcement and a controlled porosity for infiltration. In addition, the preform provides adequate "green strength" to resist the pressures that are sometimes applied during infiltration. Another important near-net shape process is a proprietary in situ casting technique used by DMC^2 Electronic Components (formerly Lanxide Electronic Components). As the MMC is formed in situ during solidification, special MMC foundry ingot or preforms are not required.

Wire and tape product forms of continuously reinforced aluminum MMCs are now commercially available. The MMC has a reinforcement volume fraction of approximately 55% alumina (Nextel 610). The wire is by far the most common form. A variety of diameters is available, but 2.6 mm (0.10 in.) is the median diameter. These are produced by a patented process by 3M.

Fabrication Processes

Organic-Matrix Composites. A host of processes exist for the fabrication of OMC components. Fiber-reinforced composites used in most high-performance applications are laminated with unidirectional (or fabric) layers at discrete angles to one another (such as in plywood), thereby allowing for highly tailored directional stiffness and strength properties. A variety of fiber-placement processes are available to achieve this desired combination of orientations. Two common processes are lay-up (by hand or machine) and filament winding/tow placement. With lay-up, material that is in prepreg or dry fiber form (dry fibers contain no resin, so this form typically consists of knitted, braided, or woven layers) is cut and laid up, layer by layer, to produce a laminate of the desired number of plies and associated ply orientations. In filament winding/tow placement, a fiber bundle or ribbon is impregnated with resin and wound upon a mandrel to produce a shape: with filament winding it is often a simple geometry, such as a tube or pressure vessel; with tow placement the shapes can often be more complex. As mentioned before, filament winding/tow placement may use wet liquid resin or prepreg.

Composite fiber-placement fabrication procedures can be labor intensive, so most major composite component fabricators are developing and/or using automatic fabrication equipment. Such equipment is often used for composite components that have a relatively large area and reasonable production rate. Two methods predominate. One involves laying up the plies with tape. Large tape-laying machines are computer controlled, include gantry robot systems, and are equipped with a specially designed tape-dispensing head. Another method involves the cutout of entire plies from unidirectional broad goods using laser, waterjet, or reciprocating-knife cutters. Cutout ply patterns are transferred to a tool and laid up by hand or automatic equipment with specially designed pick-up and lay-down heads. Laser-generated guidelines can be projected onto a part to indicate the location of the next part to be placed.

If the fiber-placement process involved the use of "dry" fibers, the next step in the process is to infuse this dry fiber preform with liquid resin. One of the most basic processes to do this is called resin transfer molding (RTM). In the RTM process, the dry fiber preform is first placed in an open matched mold. The mold is closed and resin is injected into ports in the mold. Excess air is forced out other vents in the mold. In vacuum-assisted resin transfer molding, vacuum can be applied to the vent ports to assist in drawing the resin into the fiber preform and removing any trapped air. There are many variations of the resin infusion process. For example, for cost reduction, molds can contain a single-sided hard tool side, where the opposite side of the tool can just be a simple, flexible vacuum bag. Other variations contain an air gap or high permeability layers over the planform surface of the part, to allow the liquid resin to flow quickly over and "above" the surface, before the slower process of diffusing through the preform (hence, using this method, the liquid has only to diffuse through the preform thickness, not across the part width direction as in RTM). In one variation of this process (liquid compression molding), once the resin has flowed through the air gap over the preform, the tool can be further closed creating additional pressure to force the resin into the preform. Probably the oldest of all methods of resin infusion is "wet lay-up," in which the fibers, typically textiles, are dipped in the resin (or the resin squeegeed into the textile layer) and the wet layer is placed on a single-sided mold.

The fiber placement (and resin infusion, if appropriate) process is followed by some type of cure process to harden (cross link) the polymer-matrix resin. For a low-cure-temperature or two-part mix thermoset matrix, this may simply involve holding the part at room temperature until cure completion. However, for applications involving elevated-temperature service or for thermoplastics, there must be an elevated-temperature cure. Filament-wound parts may be cured at elevated temperature in an open oven; in some cases, consolidation and surface finish may be improved by applying an external female mold or vacuum bag. Lay-ups are most commonly consolidated by applying both heat and pressure in an autoclave, but they may also be molded, pressed, or vacuum bag cured. (For example, in the RTM process, the molds themselves may be heated.)

There are also special fabrication processes, such as pultrusion, that combine fiber placement, consolidation, and elevated-temperature cure in one continuous operation. The pultrusion process is a low-cost, high-volume method to produce long parts with constant (or nearly constant) cross section containing fibers aligned predominantly along the longitudinal axis of the part. The pultrusion process is a continous "line" process, whereby fiber tows are mechanically gripped and pulled from their spools, through a resin bath, then through a heated die containing the desired cross section of the part. Another common industrial process is compression molding, typically whereby flat sheets of preimpregnated fibers are placed in an open heated mold. The mold halves are subsequently closed and the resin then cured to final shape.

To select the best composite fabrication process, the designer generally chooses the process that will provide an acceptable-quality component for the lowest cost. In evaluating cost and quality, however, tooling cost, production rate, materials cost, desired part finish, and many other factors must be considered. Only after all the pertinent factors have been weighed can the fabrication method (or the material) be selected.

Metal-Matrix Composites. Nearly twice the volume of MMCs are produced by casting and other liquid routes compared to solid-state fabrication, and this gap is expected to widen in coming years. This is lead by automotive applications, such as engine block cylinder liners and brake components, and in the thermal management industry. By a great margin, aluminum MMCs are the most commonly cast materials. A wide variety of techniques are now commercially established, including pour casting, infiltration casting, and in situ processing.

Casting typically begins with a foundry ingot material, as described previously. Upon remelting, the molten composite must be well stirred to keep the reinforcements well distributed. Both SiC and alumina reinforcements have a density slightly higher than aluminum alloys, and so tend to settle. Settling is avoided with boron carbide reinforcements in aluminum alloys, because the densities are nearly identical, but the higher cost of these reinforcements has restricted their use in high-volume applications. In cast aluminum MMCs using SiC reinforcements, the liquid metal temperature must be kept below about 730 °C (1346 °F) to avoid the formation of aluminum carbide, Al_3C_4. Due to the higher viscosity of the MMC, this process is typically used for reinforcement volume fractions of ≤20%. The Alcan material has been successfully cast using a number of standard techniques, including green sand, bonded sand, permanent mold, plaster mold, investment, lost foam, and centrifugal casting (Ref 6). Small but important modifications are sometimes required for MMC casting. For example, the design of gating systems must specifically take account of the higher melt viscosity, so that air entrapment is avoided. With proper design, excellent results have been obtained.

Pressure casting of MMCs has been used commercially since the early 1980s. In this process (often called "squeeze casting"), a porous ceramic preform is introduced into a permanent mold cavity. A fixed volume of molten metal alloy is introduced and is rapidly pressed into the ceramic preform by a mechanical force. After solidification, the part is ejected from the mold, and the process is repeated. Because the process is very rapid, it is well suited for high volumes, such as those represented by the automotive industry. Another feature leading to good cost-effectiveness is the reusability of the permanent mold. A notable example of squeeze-cast components are the selectively reinforced MMC pistons introduced by Toyota Motor Manufacturing in 1983 as the first commercial MMC application in the automotive industry. Production rates of over 100,000 per month have been achieved (Ref 4).

A number of approaches are used for the production of components via infiltration casting. The primary difference between these techniques is in the amount of gas pressure applied to force the molten metal into the porous ceramic preform. Typical gas pressures range from 5.5 MPa (800 psi) to 10.3 MPa (1500 psi). The hydrostatic pressure and moderate rates of pressurization eliminate the need for high-strength tooling and minimize the possibility of damaging the preform as the molten metal is infiltrated. The mold is not permanent, but five to ten parts can typically be produced from a single mold before replacement. While excellent results can be obtained, a pressure chamber with adequate volume and heating capability is required. This process is well suited to aerospace components, where high quality and low or moderate production volumes are required, or to electronic packaging, where the small component size allows up to several hundred parts to be made in a single run.

A pressureless process is used to produce MMCs by infiltrating a porous, nonreactive ceramic preform. The aluminum alloy contains magnesium, and the infiltration is conducted in a nitrogen atmosphere. The magnesium reacts with the nitrogen gas to form Mg_3N_2, which enables spontaneous infiltration of the ceramic preform. As the molten aluminum is drawn into the preform, the Mg_3N_2 is reduced to form aluminum nitride, and the magnesium is released into solid solution (Ref 6).

The fabrication processes established for the metalworking industry, such as extrusion, forging, and rolling, are typically used for particle-reinforced MMCs with only small modifications. Extrusion of MMCs is used extensively: in the automotive industry (for example, driveshafts for trucks and the Chevrolet Corvette), for aerospace components (such as the fan exit guide vane of Pratt and Whitney 4*xxx* series gas turbine engines), and recreation products (such as bicycle frame tubing). Extrusion billet up to 51 cm (20 in.) in diameter has been commercially extruded. Some commercially produced components represent significant geometrical complexity. Excellent dimensional tolerances and surface finish can be achieved in the as-extruded product. Hard-face extrusion die coatings are often used to extend die life.

Commercial MMC components are also produced by rolling and forging. Rolled MMC product includes plate and sheet. Plate is used for applications such as clutch plates, thermal management input material, and fuel access doors in the aerospace industry. Sheet is used primarily for aerospace components, and material over 76 cm (30 in.) has been produced. Rolling preforms are produced by both casting and powder metallurgy processes. Forging of MMCs is used for fatigue-critical applications, such as helicopter rotor blade sleeves. A cylindrical extrusion preform is blocker-forged and then closed-die forged to the final shape. Excellent dimensional tolerances are maintained. Forging is being developed for automotive connecting rods. The microstructural refinement provided by the forging process improves the fatigue response, which is a critical requirement for this application.

The processes described previously are those most extensively used for existing applications. Many other fabrication processes are being used or have been established for MMCs, including spray forming, drawing, piercing, and ring rolling.

Machining and finishing operations for MMCs are similar to those used for metals. By far the greatest experience exists for aluminum MMCs. Standard mills, lathes, and computer numerical control machines can be used, as long as the cutting parameters are properly selected. Because of the strong, hard, ceramic reinforcements in MMCs, significant tool wear results when using simple high-speed steel tools and even carbide tools. However, economies of machining identical to that obtained with conventional tooling can be achieved in MMCs using polycrystalline diamond (PCD) on a unit-operation basis. Tool wear is reduced and surface quality improved for more aggressive cuts and higher speeds, improving the overall speed of machining. Experience at Alcan has shown that coarse-grained PCD (15 to 40 μm, or 0.6 to 1.6 mils) provides the best overall performance and cost-effectiveness (Ref 4). In some cases, operations in MMCs provide superior results compared to unreinforced metals.

Applications

The purpose of this brief introduction is to provide broad insights and unifying themes regarding the diverse applications of composite materials. An overview of OMC use is highlighted. The dramatic progress in the technology and application of MMCs is discussed, and the current status of CMC applications is provided. Because of their recent maturity to the point of becoming a robust commercial technology, the subsequent section on MMC applications is somewhat expanded in this introduction. Detailed information relating to the application of composite materials over a broad range of categories is provided in the Section "Applications and Experience" in this Volume.

Organic-Matrix Composite Applications

Based on their high-performance properties, reduced-cost manufacturing methods, and the higher level of confidence among users, the use of OMC materials has expanded greatly since the mid-1980s. These applications are well documented in the "Applications and Experience" Section of this Volume, as well as in other sources (Ref 7). High-performance composites were borne of the need for extremely high-performance aircraft structures during the days of the Cold War. The military aerospace markets still constitute a major user of the higher-end performance materials. For example, the B-2 bomber, F-22 fighter, Joint Strike Fighter, F-18E/F aircraft, Eurofighter, Gripen aircraft, and Rafale aircraft in production, on the books, or in prototype form are all constructed using high percentages of OMCs. Current-production helicopters are now largely composite. On the commercial side, OMCs constitute a significant portion of the new large Boeing 777 and planned Airbus jumbo A380, which reportedly will contain the first carbon fiber wing center secton in a large commercial aircraft, in addition to extensive, OMC use in tail surfaces, bulkheads, and fuselage keel and floor beams), as well as intermediate-sized transport aircraft and business jets, and they are prevalent in many small commercial and homebuilt aircraft. Space applications for OMCs have flourished, from satellite structures (where low CTE, in addition to low weight, is a major advantage of OMCs) to the use of OMCs in booster fairings, shrouds, and tanks. The maturity of high-temperature OMC structures has afforded the use of OMCs in many engine applications for both air and space vehicles.

The sports and recreation market continues to be one of the primary consumers of composite raw materials. Golf clubs, bicycles, snowboards, water skis, tennis rackets, hockey sticks, and so on— the list of consumer products now produced using OMCs is extensive and commonplace. On the marine side, the consumer use of fiberglass OMCs in low- to high-end boats is the norm. Military ships have seen several applications of OMCs, primarily topside structures and minesweepers. Carbon-fiber composites can be seen in high-performance engine-powered, sail-powered, and human-powered racing boats.

A potentially huge market exists for composite materials in the upgrading of the infrastructure needs. For example, 31% of the highway bridges in the United States are categorized as structurally deficient. To address this, many activities are underway at national, state, and local levels to use composites to repair and, in some cases, replace deficient bridges. Figure 4 shows an example of an all-fiberglass bridge being installed in Butler County, Ohio. This bridge is fully instrumented to detect structural performance loss. At the time of this writing, the bridge has almost four years of service with, almost no maintenance required. Composites have also been used for seismic enhancement of existing highways and bridges.

Land vehicles have also benefited greatly from the application of OMCs. Military armored vehicles have been demonstrated that offer ballistic protection of their occupants in addition to light weight. The demand for energy-efficient and low-maintenance vehicles has spurred composites use in advanced automobile, truck, bus, and train commercial products. Production parts include everything from small linkage assemblies to very large exterior structural panels.

Rounding out the OMC application discussion are a host of products. For example, the medical industry has applied OMCs to products ranging from implanted orthopedic devices to x-ray tables and lightweight assistance devices. (An example is shown in Fig. 5). Industrial applications include electronic housings, large rollers, tanks, robotic arms, and so on. Spoolable piping for oil wells allows deeper wells due to the increased strength and reduced "hang weight" of composite tubular products. In short, the development and use of OMCs were initially spurred by early investments based on military need, and, based on those successes, have now dramatically taken off in the private sector, based solely on their commercial merits.

Metal-Matrix Composite Applications

In 1999, the MMC world market amounted to over 2.5×10^6 kg (2500 metric tons). While this is hardly remarkable relative to production volumes of more historical structural materials, it certainly illustrates that MMCs are no longer a marginal technology and have passed the threshold into a self-sufficient materials technology. This is also clearly demonstrated by the number of functions and the wide range of applications that are satisfied by MMCs. In this subsection, instructive selected applications are briefly presented in each of the major existing markets to illustrate the breadth and impact of current applications and to highlight application trends. This introduction is by no means exhaustive, and more detailed information is provided in the Section "Applications and Experience" and in other information sources cited in this Volume. Some of the subsequent information was taken from a recent market analysis of MMCs (Ref 4).

Ground Transportation/Automotive. The ground transportation industry (automotive and rail) accounted for 62% of the total MMC world market by volume in 1999. However, the high production rates and imperative emphasis on low cost resulted in a surprisingly low total market share by value—only 7%! By far the single most prevalent composite used in this sector is DRA. The most common application strategy is to displace components made of cast iron or steel, maximizing weight reductions. However, replacement of steel based simply on reduced weight is clearly an inadequate motivation for the use of DRA; otherwise most of an automobile structure would be displaced. Therefore, components are targeted where other benefits besides simple weight reduction are possible, so that the additional cost of insertion can be justified. Selected applications that illustrate the additional benefits obtained by the use of MMCs are provided subsequently.

A selectively reinforced piston head was introduced by Toyota Motor Manufacturing in 1983. Produced by squeeze casting, this was a reasonably low-cost and high-rate production process. The reinforcements provided improved wear resistance and lower thermal conductivity, so that more of the heat generated by the combustion gases was available for producing work. Further, the MMC provided a lower CTE than unreinforced aluminum, so that tighter tolerances and hence, higher pressure and better performance were obtained. Squeeze-cast piston liners have been used in the Honda Prelude since

Fig. 4 All-composite bridge in Butler County, Ohio. Factory-constructed primarily using glass fiber, the bridge was trucked to the site and installed in less than one day.

Fig. 5 Carbon/epoxy composite crutch. This crutch is stronger than its aluminum counterpart yet weighs 50% less, is quieter, and is more aesthetically pleasing.

1990, displacing cast iron inserts (Fig. 6). In a novel manufacturing process, the engine block casting and piston liner preform infiltration are performed simultaneously, eliminating the cost of assembly associated with the cast iron inserts. More importantly, the MMC liners provided improved wear resistance, so that the overall liner thickness could be reduced. This yielded an increase in engine displacement, so that more horsepower is obtained from the same overall powerplant weight and volume. Finally, the thermal conductivity of the MMC is much higher than the cast iron liner, so that the operating temperature is decreased, resulting in extended engine life.

Automotive driveshafts represent a component application motivated primarily by structural properties. Driveshaft design is limited by rotational instability, which is controlled by the specific stiffness of the driveshaft material. The higher specific stiffness of DRA relative to steel or aluminum allows a longer driveshaft of a given diameter. This is important in trucks and large passenger cars, where two-piece metal driveshafts are often used. Replacement with DRA allows a single-piece driveshaft. Not only is significant weight saved as a result of material substitution, but elimination of the central support for the two-piece unit provides additional weight savings. Finally, MMC driveshafts require less counterweight mass compared to steel. In all, as much as 9 kg (20 lb) have been saved by this application. Metal-matrix composite driveshafts were first introduced in the Chevrolet S-10 and GMC Sonoma in 1996, and have been used in the Chevrolet Corvette beginning in 1997. In 1999, Ford Motor Company introduced MMC driveshafts in the "Police Interceptor" version of the Crown Victoria.

Other significant MMC components include automotive and rail brake components, DRA snow tire studs, and DRTi automotive intake and exhaust valves in the Toyota Altezza. Additional information is provided in the article "Automotive Applications of Metal-Matrix Composites" in this Volume.

Thermal Management and Electronic Packaging. Materials for thermal management and electronic packaging requre high thermal conductivity to dissipate large, localized heat loads, and a controlled CTE to minimize thermal stresses with semiconductor and ceramic baseplate materials. Previous preferred materials include Kovar, an Fe-Ni-Co alloy with 17% Co, and copper MMCs reinforced with molybdenum or tungsten to lower the CTE. Copper-MMCs reinforced with graphite or diamond have been developed, but are less frequently used. A beryllium/beryllium oxide MMC is sometimes used where weight is most critical, but cost and health concerns limit this application. Aluminum MMCs with 55 to 70% SiC are now widely used for thermal management applications.

Aluminum MMCs, such as DRA, provide better performance (higher thermal conductivity) relative to previous preferred materials. For example, DRA has a thermal conductivity that is nearly ten times higher than Kovar and up to 20% higher than copper-molybdenum and copper-tungsten MMCs. Discontinuously reinforced aluminum provides a dramatic weight reduction, 65 to 80% relative to copper-molybdenum and copper-tungsten, providing an important functional benefit for aerospace components and a significant commercial advantage for portable electronics, such as laptop computers and cellular telephones. Finally, processing innovations yield significant cost reductions for DRA components. Net shape processing reduces machining, which is difficult and costly for Kovar and copper MMCs reinforced with molybdenum or tungsten, and enables integration of the infiltration step with bonding to ceramic baseplate and incorporation of wire feed-throughs, resulting in fewer processing steps. Together, these provide cost savings of up to 65%.

Unlike the automotive market, MMCs for the electronic packaging sector are high value-added. Although this is the second-largest MMC market in terms of volume (26.5%), it is by far the largest in terms of value (66%) (Ref 4). Current applications of MMCs include radio frequency packaging for microwave transmitters in commercial low-earth orbit communications satellites (Fig. 7) and for power semiconductors in geosynchronous earth orbit. Metal-matrix composites are also used as power semiconductor baseplates for electric motor controllers and for power conversion in cell phone ground station transmitting towers. Finally, MMCs are being more widely used as thermal management materials for commercial flip-chip packaging of computer chips. Additional details are provided in the article "Thermal Management and Electronic Packaging Applications" in this Volume.

Aerospace. Several DRA applications emerged in the early 1990s as a result of defense investment in the United States. The ventral fin on the F-16 aircraft was experiencing a high incidence of failure as a result of unanticipated turbulence. Of the several materials and design options considered, DRA sheet was chosen as the best overall alternative. The higher specific strength and stiffness, good supportability, and affordability were considerations in the final selection of DRA. As a result of the successful experience with DRA in this application, the F-16 project office selected DRA to solve a cracking problem of the fuselage at the corners of fuel access doors. Again, the mechanical properties of DRA and retention of the same form, fit, and function led to the selection of DRA as the final solution. Discontinuously reinforced aluminum was also qualified and entered service in a commercial gas turbine application (fan exit guide vanes) as a result of this program. Discontinuously reinforced aluminum double-hollow extrusions replaced solid graphite/epoxy to resolve an issue with poor erosion and ballistic impact response. Discontinuously reinforced aluminum also resulted in a cost savings to the manufacturer of well over $100 million.

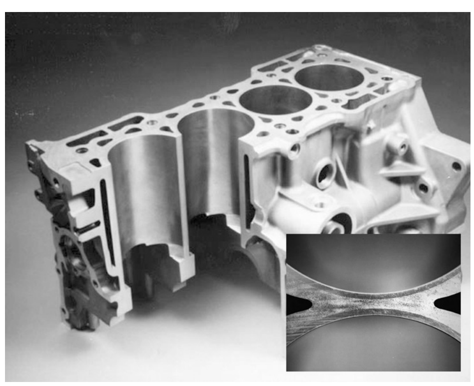

Fig. 6 Cutaway section of the Honda Prelude 2000 cc cast aluminum engine block with integral MMC piston liners. A cross section of the MMC liners is shown in the inset. These piston liners have been in production since 1990.

Continuously reinforced titanium-matrix composites (TMCs) are bill of material for nozzle actuator piston rods for the Pratt and Whitney F119 engine in the F-22. Specific strength and specific stiffness, along with good fatigue response at a maximum operating temperature of 450 °C (850 °F), are the requirements. The hollow TMC rod replaced a solid rod of precipitation-hardened stainless steel and has resulted in a direct weight savings of 3.4 kg (7.5 lb) per aircraft. This is the first aerospace application of TMC materials. Following the successful specification of TMCs for this part, TMCs are now specified for nozzle actuator links in the General Electric F110 engine for the F-16 aircraft. Additional details for each of these applications are provided in the Section "Applications and Experience" in this Volume.

Industrial, Recreational, and Infrastructure. Metal-matrix composites are used for a range of applications in these sectors, including DRA for bicycle frames and iron-based MMCs reinforced with TiC (Ferro-TiC, Alloy Technology International, Inc.) for wear-resistant tool and die coatings and industrial rollers. A continuously reinforced aluminum MMC produced by 3M is being used in high-performance automotive applications and has completed certification testing for overhead power transmission conductors (Ref 4). Steel cable is typically used as the core for "high-tension" power conductors. The steel bears the weight of the aluminum conduc-

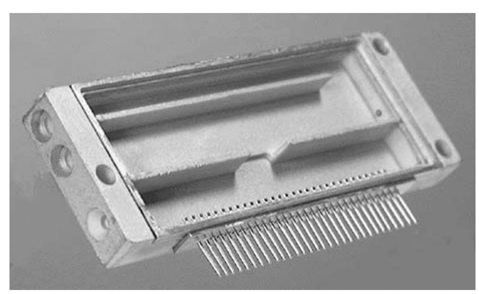

Fig. 7 An AlSiC radio frequency microwave packaging used in commercial low-earth orbit communications satellites. Courtesy of General Electric Company

tor, but carries little of the current, due to a low electrical conductivity (only one-eighth that of aluminum). Depending on the specifics of the transmission installation, the conductor can heat to temperatures in excess of 200 °C (400 °F) during peak use. In regions of the world such as Japan, the conductors can operate above 200 °C (400 °F) under continuous use and as high as 240 °C (460 °F) or more during peak loads. Sagging due to thermal expansion is an issue. The important properties for conductor cores are specific strength, electrical conductivity, CTE, high-temperature capabilities, and cost. Increased demand for electricity and the impact of deregulation requires utility companies to consider means for increasing the ampacity (i.e., the maximum current flow in the line). Higher ampacity produces higher conductor temperatures, resulting in line sagging that requires significant tower modifications to maintain needed line clearance. Tower construction is the major cost associated with new or increased power transmission and includes considerations such as purchasing right of way, satisfying environmental impacts, and design and construction costs. The ability to avoid the costs associated with tower construction provides the opportunity for new conductor materials. The aluminum MMC conductor provides the strength of steel cable at less than half the density. More importantly, the MMC conductor carries four times more current than steel and has a CTE one-half that of steel. Although the aluminum MMC conductor is more expensive than conventional conductors on a unit-length basis, the ampacity gains are significant, with projected increases of 200 to 300% with no tower modifications required. Thus, at a system level, the use of MMC conductors may provide an attractive cost savings. A cross section of a conductor with an aluminum MMC core is shown in Fig. 8.

An aluminum MMC reinforced with boron carbide particulates is now being used for nuclear waste storage casks. The casks must meet stringent requirements for both transportation and long-term storage. The MMC is used as a liner for a carbon-steel outer container. The required neutron-absorbing capabilities are provided by the B_{10} isotope in boron carbide. Each cask uses 2.3 tonnes (2.5 tons) of aluminum-boron carbide MMC, and the first cask was delivered in 2000.

Summary. A number of insights are available regarding the application of MMCs discussed previously. The initial motivation for the application of MMCs typically comes from improved performance, such as lighter weight from better specific structural properties, improved thermal conductivity, or better wear resistance. In addition, pressures imposed by legislative, economic, or environmental concerns often play an important role. Examples include legislated financial penalties for failure to comply with corporate average fuel economy requirements for lighter, more fuel-efficient automobiles, regulatory requirements for nuclear storage, and environmental impact from the construction of towers for new overhead power conductors. Of course in every case, cost is a primary selection criterion. Although MMCs are almost always more expensive on a per-pound basis relative to the material displaced, an overall cost reduction is often a result of several considerations. Novel or simplified processing reduces costs and can eliminate steps, resulting in a cheaper component. Life cycle considerations (reduced repair frequency, higher reliability, longer life) further enhance the cost comparison. Finally, system-level benefits are sometimes obtained, such as increased engine displacement for MMC cylinder liners or reduced tolerances for MMC pistons, which further extend the payoff. The multifunctionality offered by MMCs greatly aids in obtaining these additional benefits.

The first successful entry of MMCs into a system is the most difficult. This reflects the lack of designer familiarity with MMCs. However, additional applications often follow the first use, as designer familiarity and confidence grows. These follow-on applications may be within the same system or company, but can also be from a competitor. Examples include the fuel access doors, which followed the ventral fin for the F-16, and specification of DRA driveshafts in Chevrolet trucks, followed by use in the Chevrolet Corvette, and then insertion in the Ford Crown Victoria.

Unlike the paradigm during the Cold War era, the first applications of MMCs have, by and large, come from the commercial sector. Both high-volume/low-cost and low-volume/high value-added technologies have been successfully pursued for MMCs. This has provided the incentive for establishing the technology base for further expansion.

Fig. 8 Cross section of an electrical conductor for power transmission. The core consists of 19 individual wires made from a continuously reinforced aluminum MMC produced by 3M. The MMC core supports the load for the 54 aluminum wires and also carries a significant current, unlike competing steel cores. Courtesy of 3M

Ceramic-Matrix Composite Applications

Ceramic-matrix composites have successfully entered service as exhaust nozzle flaps and seals in the F414 engine, now used in the Navy F-18 E/F (Fig. 9). The exhaust temperature of the F414 is over 80 °C (145 °F) higher than for the F404 engine used in the previous version of the F-18. As a result, the metal flaps and seals were failing in tens of hours. The CMC parts consist of a Nicalon (Dow Corning Corp.) fiber with an inhibited carbon matrix. A thick SiC overcoat and glaze provide protection from oxidation. There are 12 flaps and 12 seals per engine, and the seals are attached to metal backing plates with metal rivets and a zirconia overcoat. The seals are subjected to the highest temperatures, and the flaps must support the largest mechanical loads. Further, the flaps must survive a high thermal gradient, and the CMC is subjected to rubbing with the back face of the seal. Insertion of the CMC flaps and seals has produced a weight savings of nearly 1 kg (2 lb) per engine relative to the metal parts. Because this mass is at the very back of the aircraft, additional weight savings can be obtained by removing ballast to shift the center of gravity of the aircraft. The CMC flaps have a useful life that is at least double the design requirement of 500 hours.

Ceramic-matrix composites are now also commercially available as brake rotors for automobiles. Short carbon fibers and carbon powder are pressed and sintered into a porous green compact, which is then easily machined to shape. This part is then reheated and infiltrated with molten silicon, which reacts with the carbon to form SiC. The resulting disc is 50% lighter than conventional discs, yielding a 20 kg (44 lb) weight saving in the Porsche 911 Turbo. Since the rotor weight is unsprung, improved handling also results. The wear rate is half that of con-

Fig. 9 Exhaust nozzle of an F414 engine on an F-18 E/F aircraft, showing the twelve sets of CMC flaps and seals. The white areas on the seals are a zirconia overcoat for mechanical fasteners. Over an order-of-magnitude increase in life has been obtained with the CMC flaps and seals.

ventional metal rotors, and a service life of 300,000 km (185,000 miles) is reported. The new Porsche braking system uses an MMC brake pad. Ceramic-matrix composite brake rotors have also been demonstrated for the Inter-City Express high-speed trains in Germany, where a total weight savings of 5.5 metric tons is obtained per trainset.

View of the Future

A conservative view has been taken in this Volume, which emphasizes current technologies and known applications. Growth in the volume, applications, value, and impact of composites technologies is expected as a result of the natural growth of many of the existing applications. Infrastructure applications of OMCs and both automotive and thermal management components for MMCs typify this expected growth. However, there are also many composites applications in new uses and representing new technologies that are now on the verge of certification. In addition, robust research and development over the coming years is expected to provide entirely new composite materials options, opening up entirely new markets. In the closing part of this article, the prognosis for each of these possibilities is briefly discussed.

Organic-Matrix Composites. Without a doubt, military requirements fueled investments in the development of advanced composites from the 1940s through the end of the Cold War (around 1990). Since that time, however, Department of Defense requirements for advanced composites have begun to represent only a small portion of the total amount of OMCs used by all markets combined. As discussed previously, the rise in the use of OMCs in transportation, recreation, infrastructure, and industrial applications is fully expected to continue to increase. Current active research areas provide some insight into OMC technologies that will mature to practical application in both the short and long term. These future directions can be broken down into three areas: materials and processing advances, advances in structural concepts, and progress in design and certification.

Development of polymers that can withstand sustained use in realistic service environments of both moisture and high temperatures (exceeding 370 °C, or 700 °F) is expected to allow for the increased use of PMCs in hot structural areas. Current research into nanophase reinforcements, essentially third-phase reinforcements, has already shown some progress on this front. Processing of OMCs is also evolving. For example, research into the use of electron beam curing shows promise of being able to cure large structures less expensively than by using traditional autoclaves. In terms of advanced structural concepts, the highly anisotropic nature of OMCs has only begun to be exploited. Current structures often appear similar to traditional isotropic metallic ones (for example, orthogonal rib/stringer designs), in which OMCs are used primarily for their light weight and high stiffness and strength. To fully use the high-fiber properties, unconventional three-dimensional structural architectures are being explored. In addition, research into "multifunctional" materials and structures is being pursued. Examples include structures that serve thermal management, self- or external assessment, self-repair, and self-actuation functions. (An example of this would be the use of active embedded layers for vibration damping in helicopter rotor blades.)

The current aerospace structural design process relies on a "building-block" approach. This approach has served the military well, as is evidenced by the large weight savings provided by OMCs, while the number of structural failures has been negligible. However, this approach requires, for example, large statistical databases of materials properties to be established early in the structural design cycle. This leaves little flexibility for large, real-time changes in the structure to optimize design and minimize cost. As the fidelity, validation, and integration of analytical models (micromechanical through structural) increases, ultimately it is believed that structures can be designed and "tested" almost entirely analytically. This would dramatically shorten the design cycle and allow for the exploration of vast numbers of design concepts, all at very low cost. The expensive experimental testing, although probably always required to some extent, will be dramatically reduced.

Metal-Matrix Composites. For MMCs, a conservative annual market growth rate of between 15 to 20% has been projected through 2004 (Ref 4). This will be led by the ground transportation industry (automotive and rail), and in the high value-added thermal management and electronic packaging sector. Additional applications are expected to result from increased experience and confidence in MMCs, based on prior use and on natural market growth. The growth in the automotive and rail industry is expected from increasing pressure for light weight, fuel economy, and reliability. In the thermal management and electronic packaging industry, increased MMC use will result from the dramatic growth in this industry for new networking and wireless communications installations. The largest market by far, and the largest projected growth, is for DRA, which is expected to double in production volume between 1999 and 2004 (Ref 4).

This growth is anticipated from existing technologies and applications. However, significant new applications and markets are being pursued vigorously for MMC technologies that are now on the verge of widespread acceptance. A notable example is the relatively low-cost continuously reinforced aluminum MMC produced by 3M. Significant progress has been achieved in the last two years toward the acceptance of this material for overhead power transmission conductors (high tension wires), as briefly discussed previously. This application, if successful, will represent a dramatic increase in the worldwide MMC market and may be nearly equal to the entire annual volume of the ground transportation market. The simple, flexible material form (wire and tape) is amenable to use in a wide range of other applications. The uniaxial configuration is ideal for hoop and tube or rod configurations, and it can easily be used as an insert for selective reinforcement of components. Many potential applications are currently being pursued, including flywheel containment, high-speed electric motors, and high-performance automotive components. A novel process using the tape preform is being pursued to produce large cryogen tanks for rocket propulsion, paving the way for building large structures from a simple-to-manufacture material form.

In the farther term, technology innovations leading to new and significantly improved MMC materials can be expected as a result of the robust international activity in MMC research and development. Two examples are DRA for elevated-temperature use and aerospace-grade DRTi. Titanium alloys are specified in many applications, especially aerospace, where the use temperature exceeds the current limit for aluminum alloys, about 150 °C (300 °F). The titanium is more expensive, more difficult to machine, and heavier, yet is required to support the use temperature. A modest increase in use temperature, to about 200 °C (400 °F), will provide the opportunity to replace many aerospace components currently made of titanium with an aluminum material. Discontinuously reinforced titanium shows very attractive structural properties (Fig. 3) and is currently used commercially in automotive valves for the Toyota Altezza (Ref 9). However, the approaches taken to ensure that cost goals were met are incompatible with aerospace requirements. Research and development of DRTi for aerospace applications show that this MMC has the potential of exceeding the structural efficiency of all metallic materials, and of cross-plied graphite/epoxy. While initial volumes are not expected to be large, the promise afforded by this material and other advanced MMC technologies makes the future bright for MMCs.

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