Aeronautical Applications of Metal-Matrix Composites

Daniel B. Miracle, Air Force Research Laboratory

METAL-MATRIX COMPOSITES (MMCs) could claim only a few significant applications as recently as the 1980s. None of these were aeronautical applications. Since that time, however, dramatic advancements have been made in the areas of material and process development, design, manufacturing scale-up, and certification of MMCs. As a result, a number of significant MMC applications are now in service in the aeronautical field. Metal-matrix composites are used in both military and commercial aeronautical systems. Major applications exist for aerostructural components and parts in aeropropulsion systems, and a growing number of uses in aeronautical subsystems is evident. The current generation of MMC applications largely includes structural components and applications for thermal management, but important applications for wear resistance have also been considered.

The primary motivation for the insertion of MMCs into aeronautical systems is the excellent balance of specific strength and stiffness offered by MMCs relative to competing structural materials. As shown in Fig. 1, fiber-reinforced MMCs offer specific strengths and stiffnesses significantly higher than those of aerospace metal alloys. However, their properties are highly anisotropic, limiting potential applications, as discussed in more detail subsequently. Further, their specific properties are still inferior to those of organic-matrix composites, such as graphite/epoxy, in the uniaxial orientation. Discontinuously reinforced aluminum (DRA) MMCs have isotropic properties and provide specific stiffness values that are higher than those of aerospace metal alloys by as much as 100%. While the highest levels of specific stiffness are obtained by using higher volume fractions of particulate reinforcement, good fracture properties (ductility, toughness, and fatigue) can only be obtained with current technology for volume fractions of 25% or less.

Data points for the most widely used DRA aerospace materials are labeled in Fig. 1 and have volume fractions that range from 15 to 25% of SiC particles. These materials have isotropic specific stiffnesses up to 50% higher than those of metal alloys and isotropic specific strengths that are equivalent to those of the best commonly-used aerospace metal alloys, such as Ti-6Al-4V and 7075-T6 aluminum. These MMCs also provide specific stiffnesses equivalent to those of the best graphite/epoxy cross-plied material and have specific strengths in the midrange of cross-plied organic composites. The structural properties of discontinuously reinforced titanium (DRTi) are shown in Fig. 1 to illustrate the potential of this class of MMCs. Although less mature than DRA, these materials already have important applications, including intake and exhaust valves in production automobiles (see the article "Automotive Applications of Metal-Matrix Composites" in this Section). The labeled bubble illustrates the current range of specific properties of DRTi for reinforcement volume fractions to 20%, and the larger bubble outlines the projected range of properties that may be achieved with higher volume fractions.

A great deal of effort has been undertaken to develop fiber-reinforced MMCs for aerospace applications. Early success was achieved with aluminum alloys reinforced with boron monofilaments or graphite fibers, resulting in spacecraft applications (see the article "Space Applications" in this Section). However, no applications in aeronautical systems resulted from fiber-reinforced aluminum MMCs. Additional matrix alloys based on copper, magnesium, nickel, and niobium have been studied, but by far the largest effort has focused on fiber-reinforced titanium alloys. The motivation for this research and development activity was to obtain exceptional specific strength and stiffness for high-temperature applications in systems such as the National Aerospace Plane (NASP) in the United States and in advanced gas turbine engines. Candidate matrix alloys included α-titanium alloys, α + β-titanium alloys, β-titanium alloys, and titanium-aluminide alloys. Alumina was sometimes considered as a reinforcing fiber, but SiC monofilaments were most commonly used. A number of innovative processes were explored and developed. Although the required material properties goals were largely achieved in these research and development efforts, the high raw material cost associated with the SiC monofilament and difficulty in processing and machining provided critical barriers to insertion.

Significant resources have been applied to develop these materials for critical components in gas turbine compressors of advanced gas turbine engines. In one case, such efforts are still underway, and it is not certain whether a successful insertion will result. Nonetheless, fiber-reinforced titanium has been specified as bill of material in an actuator piston rod for a nozzle actuator in the F119 engine for the F-22 aircraft and for use as an actuator linkage in the F110 engine for the F-16 aircraft. These parts provide a simple component shape, easing manufacturing concerns. The loading is purely axial, which takes best advantage of material properties. Finally, the part is not fracture-critical, providing

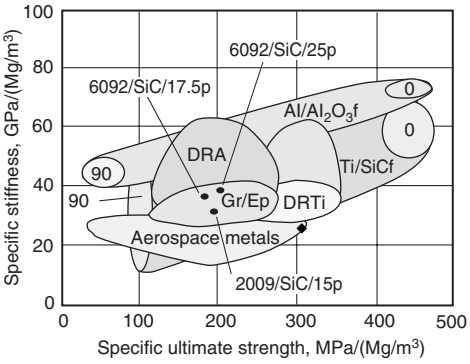


Fig. 1 Specific strength and specific stiffness of existing aerospace structural materials with isotropic properties, including metal alloys, discontinuously reinforced aluminum (DRA), discontinuously reinforced titanium (DRTi), and cross-plied graphite/epoxy (Gr/Ep). Graphite/epoxy/overlaps the lower-stiffness region of DRA. Three data points for particular aerospace-qualified DRA materials are labeled. Fiber-reinforced MMCs (Al/Al_2O_3f and Ti/SiCf, or TMC) are also shown. Data for DRTi are available only for reinforcement volume fractions of ≤20%, as represented by the labeled oval, and the larger oval suggests the potential properties that may be achieved with higher volume fractions of reinforcement. The diamond represents data for high strength specialty steel.

a low-risk component for first insertion. These components are discussed later in this article.

An equally large, though more diffuse, activity on discontinuously reinforced metals has been undertaken in the past 20 years. Many international efforts have explored MMCs based on alloys of magnesium, copper, iron, and titanium. A number of important applications have been developed for discontinuously reinforced Fe, including hard, wear-resistant parts such as industrial rollers and extrusion dies. Discontinuously reinforced titanium has been successfully developed for a few significant applications, including intake and exhaust valves in the automotive industry (Ref 1). Clearly, however, the most significant success over this time period has been the development and commercialization of DRA. Self-sustaining industries are now established in Great Britain, Canada, and the United States, satisfying demands from the automotive, aerospace, thermal management, tribology, and recreation industries. Applications of DRA range from sophisticated, high-technology components such as net shape, integrally processed multifunctional parts to simple commodities such as automotive-cylinder liners and snow tire studs. By far the widest range of applications exists in the automotive, space, thermal management, and aeronautical fields. The current aerospace powder metallurgy (P/M) market in the United States alone amounts to 50 tonnes per year, and the automotive market represents a volume over an order of magnitude larger.

The DRA materials constitute an extremely broad and flexible material system. Matrix alloys can be based on either cast or wrought compositions, and a full range of microstructural modifications from thermal and mechanical treatment is available. SiC, Al_2O_3, B_4C, and graphite are commonly used as reinforcements. Reinforcements may be particulate or whiskers and may comprise a volume fraction from 10 to 70% by volume. A significant degree of control can be exercised over the size and distribution of reinforcing particles. A number of commercial primary and secondary processes have been established for DRA, and the interested reader is referred to other articles within this Volume for a detailed description.

A convenient standardized nomenclature, ANSI H35.5-1997, has been established for aluminum MMCs and is illustrated here: 2009/SiC/15p-T4. The four-digit Aluminum Association alloy designation, which specifies the matrix alloy composition, is followed by the reinforcement composition. This is followed by the reinforcement volume fraction (in volume percent), and a single letter that signifies the morphology of the reinforcements (p = particle, w = whisker, and f = fiber). The standard Aluminum Association temper designation (T4 in the example) is used at the end of the MMC designation, as appropriate.

The following briefly describes the most significant aeronautical applications of MMCs. With only one exception (the hydraulic manifold for the V-22), the components described are now in production—the remaining component had been selected as bill of material and was awaiting certification testing at the time of publication. Each description includes discussion of the main features and requirements of the particular application, including service requirements and deficiencies of previous materials. Design considerations and trade-off studies that led to the selection of the MMC are highlighted. The MMC material and process as it applies to the specific component is then described. Finally, the benefits that have resulted from the use of MMCs are highlighted. In this article, a distinction is drawn between applications for aeronautical systems, which are covered here, and space systems, which are covered elsewhere in this Section. Many important applications of DRA are established in aeronautical systems for thermal management and electronic packaging, but these are covered elsewhere in this Section (in the article "Thermal Management and Electronic Packaging Applications"). Automotive uses of MMCs are described in the article "Automotive Applications of Metal-Matrix Composites" in this Section.

Aerostructural Applications

Ventral Fin. The F-16 aircraft has two ventral fins on the lower half of the fuselage just aft of (behind) the wings (Fig. 2). In a number of operational regimes, including those with high angles of attack, the horizontal stabilizers become less effective due to turbulence from the wings. The purpose of the ventral fins is to provide additional flight stability to the aircraft under such conditions. The ventral fins are subjected to aerodynamic loading and require high strength and stiffness. The ventral fins, however, were experiencing a higher than expected rate of failure. The failure mode was dramatic and resulted in complete destruction of the component. The cause of these failures was identified as unanticipated loading from aerodynamic turbulence (that occurred during certain flight maneuvers), such as a rapid decrease in power to the engines (a "throttle chop"). This causes a wave of highly turbulent air, originating at the front of the engine intake, to propagate along the fuselage. The ventral fins were subjected to a rolling moment and a first mode torsion, which twisted the fin along the fuselage axis. Measurements on operational aircraft during such maneuvers showed that the peak-to-peak amplitude of the ventral fin oscillation at the tip, resulting from the rolling moment, was as much as 10 cm (4 in.). These bending moments produced elongation of the bolt holes and eventual failure. While pilot and aircraft were not seriously endangered, the frequent failures led to high downtime and significant repair costs.

The original ventral fins were made of a built-up structure consisting of a 2024-T4 aluminum alloy sheet over an internal structure. This internal structure consists of a central root rib that projects normal to the fuselage skin, and a front and rear spar, which are parallel to the fuselage skin. The sheet is attached to these structures, and a honeycomb core completes the assembly. The assembly is attached to an engine access panel, which is, in turn, attached to the fuselage. Design trade studies were conducted to identify the best solution to the ventral fin failure problem described. Critical design properties included high stiffness and good high cycle fatigue strength. Preferred solutions that would provide the same form, fit, and function of the original design were sought, so that additional certification of significantly different materials or component configurations would not be required. As an example, a preferred solution would allow stripping, painting, and repair of battle damage (bullet holes) by techniques that had already been specified and standardized for the existing aluminum part. In addition, the preferred solution should be affordable. Candidate solutions included a graphite/epoxy skin over the existing spar structure, regions of increased thickness of the original 2024-T4 aluminum alloy, and a DRA sheet over the aluminum alloy spar. Graphite/epoxy was eliminated because of the difficulties of support and cost, and the modified aluminum alloy and DRA approaches underwent testing.

The DRA material selected for study was 6092/SiC/17.5p. The 6092 aluminum matrix alloy is a modified 6*xxx* age-hardenable aluminum alloy that was optimized to be used as a matrix alloy for DRA. This alloy has been approved by the Aluminum Association and is the DRA matrix analog to 6013. Design trade studies and material and process development were undertaken as a collaborative effort between Lockheed-Martin, the U.S. Air Force Air Logistics Center at

Fig. 2 An F-16 aircraft, illustrating the ventral fins, which are located on the bottom of the fuselage just aft of (behind) the wings. The ventral fins are now assembled from 6092/SiC/17.5p discontinuously-reinforced aluminum sheet material produced via a powder metallurgy process.

Ogden, UT, DWA Aluminum Composites, and the U.S. Air Force Materials and Manufacturing Directorate. Material and process development and process scale-up were conducted by DWA Aluminum Composites Specialties, Inc. under a contract with the U.S. Air Force. In this work, powder handling, mixing, outgassing, and consolidation were established. Sheet rolling of consolidated powder was also established. Initial billets 51 cm (20 in.) in diameter were extruded to 7.5 × 36 cm (3 × 14 in.) rolling stock. This was cut to 66 cm (26 in.) lengths, then cross-rolled from 36 cm to 76 cm. The material was then rotated 90° and rolled to final thickness (3.18 and 1.02 mm, or 0.125 and 0.040 in.). The material was sheared to length, heat treated, and quenched. Flatness was obtained by stretching (3.18 mm) or offset rolling (1.02 mm). The DRA sheet was then inserted into the existing repair line established for the original aluminum fins. The only modifications required were the use of polycrystalline diamond tooling and a new chemical masking agent. The standard chemical milling process established for the original aluminum component was used for surface activation required for adhesive bonding to the honeycomb core.

In addition to establishing the commercial processes required to produce the DRA material in sufficient quantity and of quality, the DRA material satisfactorily completed the rigorous testing schedule required for MIL-HDBK-5 certification testing, providing design-allowables properties for the 6092/SiC/17.5p material. Data obtained from this study are shown in Table 1. The design trade studies showed DRA to be the preferred solution. Extensive flight testing was conducted in collaboration between the U.S. Air Force, Lockheed Martin, the Royal Netherlands Air Force, and the National Aerospace Laboratory of the Netherlands (NLR). The flight testing was fully successful, and the DRA ventral fin has been established as the preferred spare.

The DRA sheet provided a 40% increase in specific stiffness over the baseline design. This increased stiffness nearly eliminated the first mode torsional loads on the fin, providing a solution to the bolt hole elongation. Instrumented flight testing showed that the peak tip deflections of the ventral fin were reduced by 50%. As a result of this effort, replacement of the original ventral fins is now in progress with the 6092/SiC/17.5p DRA ventral fins. A projected improvement in service life of 400% is expected for the new ventral fins, and flight experience over the past several years now bears this number out. The reduced maintenance, inspection, and downtime costs associated with the DRA ventral fins have resulted in a life-cycle cost savings to the Air Force of over $26 million.

Fuel Access Door Covers. During high-G maneuvers, the fuselage of the F-16 aircraft is subjected to bending stresses, which produce significant axial stresses in the skin. The upper fuselage skin is perforated by many fuel access doors (Fig. 3). In the original aircraft design, these doors did not carry any of the load in the fuselage skin, and so the corners of the door openings act as stress concentrators. As a result, the F-16 fuselage skin was cracking near the vertical tail root. As a solution to this problem, special door fasteners were designed that allowed the doors to carry some of the load, thus reducing the stress at the door openings. These new fasteners required a redesign of the doors, since the original doors were not designed to support a load. Several design options were considered, including 2024 Al doors of double thickness and 6092/SiC/17.5p DRA doors. Critical design properties for the new doors included high strength and stiffness, high bearing strength, good high-cycle fatigue resistance, and compatibility with jet fuel equivalent to aluminum alloys.

The doors are made of 6092/SiC/17.5p wrought P/M material in sheet form. The process is identical to that described for the F-16 ventral fins, with the exception that the final sheet thickness is 2.54 mm (0.10 in.) for most doors, with a few at 2.03 mm (0.08 in.). After producing the sheet, the doors are shipped to the fabricator. The final dimensions are obtained with a high-speed routing operation followed by finish machining. Holes are pre-punched and then drilled. Routing and drilling are done with diamond tooling, and the punching operation is done using standard equipment. The DRA punches much better than standard aluminum alloys do, due to the higher modulus. The punched surface is much cleaner, with no edge rollover. The door is roll-formed to the final contour and given the final aging heat treatment. Since the upper fuselage skin is a fuel-cell wall, the door material must be compatible with JP-4 jet fuel. Exposure studies established that the DRA response is equivalent to that of the unreinforced metal alloy. The part is cleaned and painted in a final operation.

In combination with the improved door fasteners, the 6092/SiC/17.5p DRA doors provided the best solution to the cracking problem because of the combination of higher specific strength and stiffness compared to that of 2024 aluminum. The DRA was also able to satisfy a higher bearing allowable, which was required by the new door fasteners. Doors of DRA have been inserted in 23 of the 26 fuel access doors on the F-16 aircraft in an active retrofitting program called Falcon Up. This is the first military retrofit application for a MMC. As a result of the new doors and fasteners, the peak skin stresses have been reduced by 38% and the average skin stresses have been lowered by 10%. This has fully eliminated the cracking previously observed in the F-16 upper fuselage skins and has extended the durability life calculation for the F-16 fuselage to over 8000 flight hours.

Helicopter Blade Sleeve. The Eurocopter France EC120 and N4 helicopters are used for civilian law enforcement and search and rescue in Europe, the United States, and in many other countries. The large centrifugal loads of each rotor blade (the N4 has five blades) are supported by a blade sleeve, which holds the rotor blade to the drive shaft (Fig. 4). This component requires an infinite fatigue life, excellent fretting fatigue resistance, high specific strength, and good fracture toughness. The blade sleeve is designated as a Class I vital critical rotating part, since component failure results in total loss of the craft and its inhabitants. Helicopter performance and durability are linked very strongly to rotating mass, and the principle motivation for consideration of DRA in this application is the reduction in rotating mass and the high cost associated with titanium alloy, which has now been replaced by DRA.

Forged 2009/SiC/15p-T4 DRA has replaced the wrought titanium alloy component originally specified. Extrusion of a 36 cm (14 in.) P/M billet, which weighs 95 kg (210 lb), provides a 95 mm (3.7 in.) diameter preform. After cutting to length, each piece is blocker forged, followed by

Table 1 Properties of 6092/SiC/17.5p and 2009/SiC/15p-T4 MMCs

Property	6092/SiC/17.5p	2009/SiC/15p-T4
Tensile yield strength, MPa (ksi)	434 (63)	343 (54)
Ultimate tensile strength ± 1 standard deviation, MPa (ksi)	490 (71)	498 ± 4.5 (72 ± 0.7)
Tensile modulus, GPa (10^6 psi)	107 (15.5)	93 (13.5)
Strain to failure, %	6	6.2
Fracture toughness, MPa $\sqrt{m}$ (ksi $\sqrt{in.}$)	Not measured	25 (23)
High cycle fatigue strength at 10^7 cycles	Not measured	270 (39)
Bearing ultimate strength (*e*/*D* 2.0), MPa (ksi)	924 (134)	Not measured
Shear strength (longitudinal), MPa (ksi)	296 (43)	Not measured
Density, g/cm^3 (lb/in.^{3})	2.80 (0.101)	2.83 (0.102)

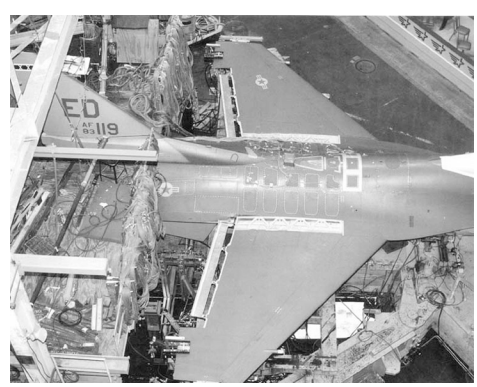


Fig. 3 An F-16 center fuselage, illustrating the size and location of fuel access door covers, which are located between the wings. Of the 26 doors on each F-16, 23 are now made from 6092/SiC/17.5p discontinuously-reinforced aluminum.

closed-die forging to a sonic inspection envelope. The sonic envelope is also the final component shape, and less than 1% of material is discarded as scrap after drilling and final machining. As a result of the criticality of this component, extensive testing and certification are conducted. Twenty-five-year traceability is provided for raw materials and finished goods via archived documentation of processing and inspection. In addition to measuring minimum mechanical properties in the transverse orientation on each billet, the electrical conductivity (as a quality check for microstructural uniformity), chemistry, reinforcement volume fraction, and density are also documented for each billet. Inspection is performed via a macroetch and ultrasonic inspection using MIL-STD 2154 Class AA (no defect ≥1.2 mm, or $^{3}/_{64}$ in., is allowed). The primary requirement is for infinite fatigue life. The 2009/SiC/15p-T4 material has a fatigue strength of 270 MPa (39 ksi) at 10^7 cycles, compared to 155 and 180 MPa (22 and 26 ksi) for 2024-T4 and 7075-T6, respectively. This excellent fatigue performance allows DRA to compete successfully with wrought titanium. The fracture toughness of this DRA material is 25 MPa $\sqrt{m}$ (23 ksi $\sqrt{in.}$), and the specific strength is comparable to the displaced titanium alloy. Other properties for the 2009/SiC/15p-T4 DRA material are provided in Table 1.

Nearly 14 kg (over 30 lb) of rotating mass have been saved by the use of 2009/SiC/15p-T4 DRA, which is a dramatic reduction for helicopter rotors. In addition to reduced weight, the DRA blade sleeves are less costly to produce, providing a saving in acquisition cost. This is the first aerospace application of DRA in a fracture-critical component.

Aeropropulsion Applications

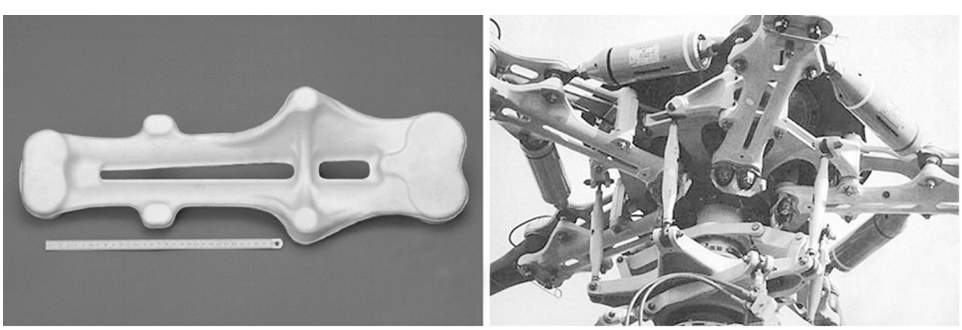
Fan Exit Guide Vane. The fan exit guide vane (FEGV) of high-bypass gas turbine engines removes the "swirl" component of bypass air, so that maximum thrust can be obtained from the redirected air flow. In commercial engines, primary design requirements include high specific stiffness, excellent erosion and ballistic response, and low acquisition and support costs. Recent engines have specified graphite/epoxy for this application. However, poor ballistic performance and susceptibility to erosion from airborne particulates and rain have led to high in-service costs and concerns regarding flight safety. An interim solution, bonding a titanium-alloy foil over the graphite/epoxy leading edge, provided improvement in the erosion response (but no improvement in ballistic performance) and increased the cost significantly.

Between 1996 and 1998, 6092/SiC/17.5p DRA has entered service in the Pratt & Whitney 4084, 4090 and 4098 engines, replacing graphite/epoxy. The DRA material is a P/M product that is consolidated into billets. A large reduction ratio during extrusion provides improved particulate distribution, which enhances the fracture properties of the material. A high-tolerance extrusion produces the net shape airfoil contour of the component, and a double-hollow internal configuration is produced to remove unnecessary mass (Fig. 5). The bridge between the two hollow cavities is both formed and joined during the extrusion process, and this bridge improves the structural performance of the airfoil. The resulting DRA component weight is equivalent to the solid graphite/epoxy unit initially specified. Extrusion of this part utilizes existing metalworking infrastructure with only minor modifications. The extrusion die is a standard tool steel die, with a Ferro-TiC die insert. (Ferro-TiC, a trademark of Alloy Technology International Inc., is a discontinuously reinforced iron alloy that uses TiC particulates as reinforcement; it is used in the tool and die industry, and for high wear applications such as industrial rollers.) Current FEGV dimensions include a chord width of 14 cm (5.5 in.) or 19 cm (7.5 in.) and a length of 61 cm (24 in.). After cutting to length, each part is coined to provide a slight camber and is then embedded in thermoplastic end fittings with an elastomeric coupling agent. Over 10,000 piece parts have been manufactured to date.

This component, used in engines that power the Boeing 777 aircraft, was the first commercial aerospace production application of DRA. The DRA components have demonstrated a sevenfold reduction in erosion rate and significant increase in resistance to ballistic damage from foreign objects, such as hailstones. A dramatic reduction in the unit acquisition cost was realized at the time of introduction. In addition, an overall increase in service life of 300% and reduced maintenance and repair costs also increase the life-cycle cost savings. The total realized savings since introduction has been well in excess of $100 million.

TMC Nozzle Actuator Piston Rod. Turbine-engine nozzle flaps increase the efficiency of gas turbine engines by controlling the velocity and, in some cases, the direction of the exhaust gas. This is accomplished by controlling the nozzle flap position via actuator and linkage devices. A pair of divergent nozzle flaps are used on each of the two Pratt & Whitney F119 engines used on the F-22 aircraft. Each divergent nozzle flap is driven by an actuator assembly consisting of a hydraulic cylinder and a metallic piston, which is connected, in turn, to a linkage mechanism. The piston must support large axial loads and must also possess high stiffness. Weight is a primary concern in the F-22 aircraft, so specific strength and stiffness are the primary selection criteria. The piston rod is subjected to fatigue loading, and the maximum operating temperature is 450 °C (850 °F). The initial material specified for the piston actuator was a solid rod of 13-8 Cr-Ni precipitation hardened stainless steel, which has now been replaced by a SiC fiber-reinforced titanium alloy MMC. This MMC is often referred to as a titanium-matrix composite (TMC), and it is inferred that the reinforcement is continuous when this acronym is used.

The TMC actuator piston rod is manufactured by a novel metal wire process. A Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) alloy is hot-drawn in a conventional wire drawing process to a diameter of 178 μm (0.007 in.). The Trimarc-1 SiC monofil-



(a) (b)

Fig. 4 EC-120 helicopter rotor application. (a) Rotor blade sleeve. The part is made of forged 2009/SiC/15p discontinuously reinforced aluminum (DRA). The scale below the part is 30 cm long. (b) Rotor assembly showing the DRA blade sleeves. Photos courtesy of DWA Aluminum Composites, Inc.

Fig. 5 Fan exit guide vane blank (top), showing the high quality of the as-extruded product and the double-hollow construction. Below is an assembled fan exit guide vane mounted in the endcap. This component is used in Pratt & Whitney 4084, 4090, and 4098 gas turbine engines. Component dimensions are provided in the text. Courtesy of DWA Aluminum Composites, Inc.

ament reinforcement is 129 μm (5.07 × 10–3 in.) in diameter, and is produced by a chemical vapor deposition process on a tungsten wire core. An outer C-based coating protects the fiber from chemical interaction with the matrix during consolidation and service. The Ti-6242 metal wire is combined with 34 vol% of the SiC monofilament by wrapping on a rotating drum. The wires are held together with an organic binder and are then cut and removed from the drum to make a preform "cloth." This cloth is wrapped around a solid titanium mandrel, so that the SiC and Ti-6242 wires are parallel to the long axis of the mandrel. A short Ti-6242 cylinder, with an outer diameter of 10 cm (4 in.) and 5 cm (2 in.) high, is placed around one end of the cloth-wrapped mandrel, from which the piston head will be formed. After hot isostatic pressing consolidation, the piston head is machined from the stocky cylinder at one end of the piston, and a threaded connection is machined from the titanium mandrel at the other end. The remainder of the mandrel is removed by gun drilling. The final component is 30.5 cm (12 in.) long, and the shaft is 3.79 cm (1.49 in.) in diameter (Fig. 6a). The excellent fiber spacing is shown in the figure inset.

The use of a TMC in the actuator piston is a landmark application and represents the first aerospace application of TMCs. In addition to providing significant improvement in the specific strength and stiffness over steel (compare steel properties, indicated by the diamond data point, with Ti/SiCf in Fig. 1), the TMC material passed fatigue properties certification by a very wide margin. Certification of the TMC actuator piston rods has resulted in a direct weight savings of 3.4 kg (7.4 lb) per aircraft. The F-22 is an extremely weight-sensitive aircraft, so this weight savings is considered significant. Further, since the weight removed is in the aft end of the aircraft, counterweights added in the fore section of the aircraft to shift the aircraft center of gravity forward can also be removed, providing additional weight savings. At the time of publication, the first orders of the TMC actuator pistons had been shipped for the initial production phase of F-22 aircraft.

TMC Nozzle Actuator Links. Based on the experience gained from the success of the TMC actuator piston rod, TMCs have now been certified as nozzle links on the General Electric F110 engine, used for F-16 aircraft. The nozzle of the F110 engine consists of 24 nozzle flaps arranged symmetrically around the exhaust periphery in a "turkey feather" configuration. Every second nozzle flap is driven by an actuator via a nozzle link, so that 12 TMC nozzle link actuators are now specified for each engine. The original link was produced from a square tube of Inconel 718, which was formed from sheet and welded along its length.

The manufacturing process begins by winding Trimarc-2 SiC monofilament, which is similar to Trimarc-1 but is produced on a carbon core, on a drum as for the piston rod. Rather than using metal wire, Ti-6242 powder is sprayed with an organic binder over the wound SiC fibers to produce a preform cloth. This cloth is then cut and removed from the drum as before, and wrapped around a mandrel. Added at each end are Ti-6242 fittings for a clevis attachment and a threaded end, and the entire assembly is consolidated via HIP. After machining the clevis and the threaded end, the mandrel is removed. A finished part is shown in Fig. 6(b).

The new TMC links have been certified for F110 engine rebuilds in the F-16. The TMC links provide a 50% increase in buckling resistance relative to the Inconel 718 component. Insertion of the TMC links have provided a direct weight savings of over 2 kg (4.5 lb) per shipset. This application provides a low-risk first insertion of TMCs for the F110 engine. From this, the end-user will gain critical field experience in the application and support of TMCs, and the manufacturer (Atlantic Research Corporation) will be able to identify and implement important process improvements anticipated to improve material quality and reduce costs.

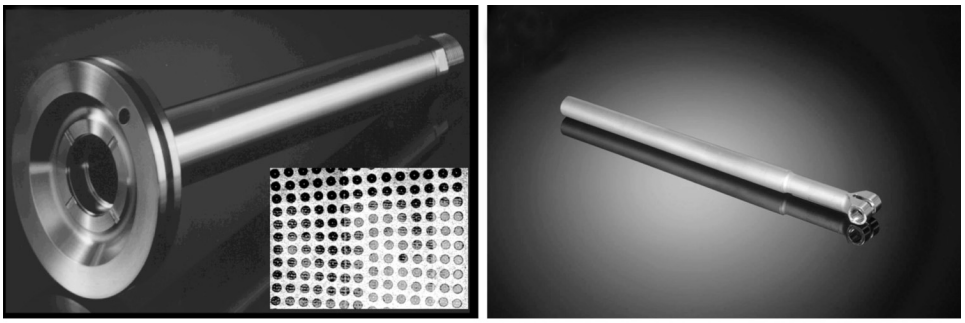
Aeronautical Subsystem Applications

T-1 Racks. The first flight application of DRA in a military aircraft occurred as avionics support racks for the Lockheed-Martin U2/TR-1 Spy Plane. The material used was 6091/SiC/25p DRA. The matrix alloy is the DRA analog to 6061. The principal requirements for the racks are isotropic stiffness, good bearing strength, and high electrical conductivity, necessary for a high-quality grounding plane for the avionics. The original structure was an aluminum alloy, but this was replaced by graphite/epoxy in order to save weight. However, the need for isotropic stiffness required a quasi-isotropic lay-up, which produced section channels that were thicker than necessary to support the primary loads. The poor bearing strength of the graphite/epoxy also added weight to the structure, since local reinforcement was required. Finally, the high-quality grounding plane was provided by bonding aluminum foil to the structure. This added both weight and cost, and introduced significant support issues when the aluminum foil was damaged as avionics racks were slid across the surface.

The rack section channels were the first successful attempt to produce precision mill shapes of DRA from multiple-holed extrusion dies. Straight tubing was produced with a minimum gage thickness. The reduced mass allowed by the minimum gage, along with the high intrinsic electrical conductivity and good bearing strength, allowed the DRA rack to save 20% in weight over the graphite/epoxy design and 34% relative to the original aluminum design. Reduced material costs improved manufacturability, and improved supportability led to reduced component cost. This part was first introduced in 1988.

Hydraulic Manifold in V-22 Osprey Tiltrotor and F-18 E/F. Materials of DRA are being used to produce hydraulic manifolds for the Navy Osprey V-22 Tiltrotor aircraft. The manifolds redistribute high-pressure hydraulic fluid (up to 70 MPa) to flight control surfaces. In addition to high mean pressures, the manifold is subjected to impulse loading during flight. The operating temperature is up to 100 °C (210 °F). Selection criteria include affordable near net shape processing, high specific strength to support the high hydraulic pressures, and good resistance to high-cycle fatigue from the impulse loading. Two manifolds are used for each V-22 aircraft.

The initial design specified 7050 aluminum, but the hydraulic manifold failed in burst tests, so a whisker-reinforced 2009/SiC/15w DRA is now being used. Components are manufactured by a P/M process, whereby a solid block is produced, and the manifold is machined from this solid block of DRA. This material satisfies the service requirements, but the material cost is high due to the whisker reinforcements used. The component cost is high due to the significant machining required.



(a) (b)

Fig. 6 Jet engine applications of titanium-matrix composites. (a) A nozzle actuator piston rod used on the Pratt & Whitney F119 engine for F-22 aircraft. The part is made of a Ti-6Al-2Sn-4Zr-2Mo alloy reinforced with SiC monofilaments that are 129 μm in diameter. The inset shows the typical distribution of the SiC reinforcements (inside diameter of the rod is to the left in this inset micrograph). (b) A nozzle actuator link from the General Electric F110 engine, made of a similar metal-matrix composite, used for F-16 aircraft. Component dimensions are provided in the text. Courtesy of Atlantic Research Corporation.

An alternate DRA material, A206/SiC/40p DRA, produced by pressure infiltration casting of a molten aluminum alloy into a particulate ceramic preform, is now being pursued. Preform manufacture is simplified by a unique castable process, providing a preform that is near net shape. Controlled reinforcement volume fractions from 30 to 70% can be achieved. A clean preform that is free of organic material is produced, and a uniform particle distribution is achieved. This process uses low-cost SiC particulates, which significantly reduces the cost of producing a manifold. The near net shape processing requires only finish machining, further reducing component cost. Full-scale components have passed proof, impulse, and burst testing. This component was awaiting certification testing by Bell Helicopter at the time of publication. An image of this component is provided in Fig. 7.

A DRA fluid manifold end gland is currently in production for the F-18 E/F. This component is part of the subsystem that controls the rudder and aileron. The end gland is 7.5 cm (3 in.) in diameter and is less than 7.5 cm (3 in.) in length. There are two fittings per aircraft. The operational conditions are similar to those described for the V-22 manifold. In addition, this component requires good wear resistance. The original component was made from an aluminum bronze. While this performed well, the high density of this material led to an excessive part weight. The DRA component is made from 2009/SiC/15p, which is machined from an extrusion. This is precisely the same material and process as described above for the helicopter blade sleeve, and so certification requirements were minimal. The DRA component provides reduced weight, and has a lower coefficient of thermal expansion, a higher wear resistance, and a fatigue limit that is twice that of the initial component. This last property is notable, since standard high-strength aluminum alloys typically possess poor fatigue response in hydraulic fluid when the pressure is greater than about 34 MPa (5 ksi). As a result, titanium is often specified for these applications. However, the DRA component performed very well in fatigue testing in high-pressure hydraulic fluid, so that DRA can now be considered a replacement for titanium alloys in similar applications.

Implementation Strategy

Critical evaluation of the case histories above provide useful guidance for future successful efforts to apply MMCs in new applications. Since technical considerations for the selection of an MMC are reviewed earlier in this article and elsewhere in this Volume, discussion here emphasizes nontechnical approaches. Experience has shown that the nontechnical factors are often at least as important as are the technical details in selecting materials to meet specific application requirements.

In every single component described above, the MMC displaced some other material that had been initially specified. This reflects the embryonic familiarity and confidence with which the design community views MMCs. This poor familiarity is manifested as a perceived high initial cost, concern about availability and depth of supply chain, lack of field experience, questions on reparability, and knowledge base and analysis tools available to design engineers that address MMCs. It is therefore essential that an internal advocate exists within the organization considering the use of an MMC. This advocacy function must be knowledgeable in MMC capabilities and limitations and should also possess some contact within the design function for the organization. Previous examples described herein also strongly support the importance of a close collaboration between the system manufacturer, the materials and component suppliers, and the end-use customer. The customer (or user) provides system requirements and constraints. When a solution to an existing problem is sought, the customer can provide information relating to causes and modes of failure; the customer establishes the value of the proposed improvement and also may provide insights into possible solutions. The manufacturer typically provides the design function. Internal testing and certification by the manufacturer is also critical, since data generated in house is often considered more relevant and reliable. Finally, the supply chain provides detailed information regarding the material capability and processing options and limitations. Such partnerships divide the risk and combine expertise to achieve an optimum solution. Many of the successes described resulted from such teamwork.

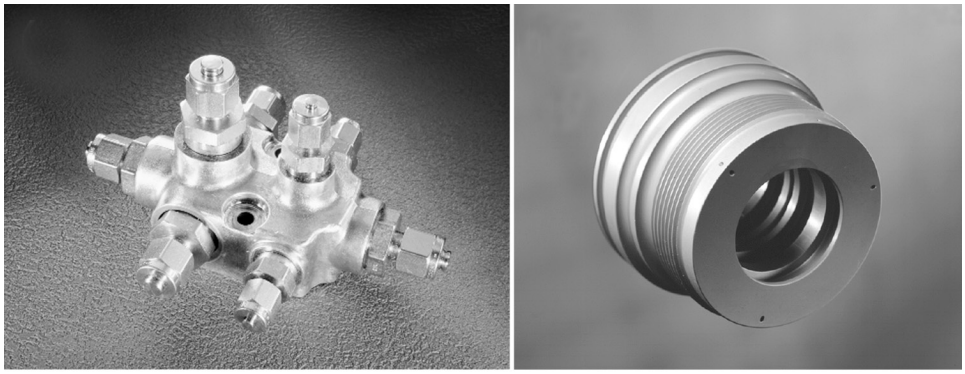
Another important point is that MMCs nearly always solved an existing operational problem or deficiency in the previous examples. Very infrequently are new materials such as MMCs selected simply because they provide a benefit over an existing system if that system is not currently deficient in some operational consideration. This follows from the high cost of certifying a new material and from the conservative design philosophy typically followed in the aeronautical industry.

The approach of developing a single MMC material that can satisfy the requirements for a range of applications is an effective strategy for reducing certification costs. Thus, certification costs for a particular material can be shared by several business units within a given company. Multiple applications provide an expanded payoff, thus providing a better return on investment for certification costs. In two cases above, a second application of an MMC within an organization followed a successful first insertion. A related approach is to form cross-industry teams (such as aeropropulsion and rocket propulsion, or aerostructures and automotive), which can share ideas and resources while minimizing issues of competition. Thus, a useful materials development strategy is to achieve a balance of properties that are acceptable for several requirements, rather than tailoring an MMC to achieve an optimum set of properties for a single application. Again, this approach shares the risk and expands the impact.

With regard to fiber-reinforced MMCs, the conservative approach of focusing on applications with simple geometric shapes and relatively low risk for failure is proposed until the technology matures and designer familiarity and confidence increases. Components with nearly axial loading are also suggested, since the technology for producing isotropy via cross-plied architectures is expected to remain difficult in the coming years.

View of the Future

While the emphasis of this Volume is as a practical guide for existing technologies, a brief



(a) (b)

Fig. 7 Manifold applications. (a) A manifold used to redistribute high-pressure hydraulic fluid to flight control surfaces in V-22 Osprey Tiltrotor aircraft. This component is made by infiltration casting of A206/SiC/40p discontinuously reinforced aluminum. Courtesy of Triton Systems, Inc. (b) A fluid manifold end gland currently used in F-18 E/F aircraft as part of the subsystem that controls the rudder and aileron. The material is a powder metallurgy discontinuously reinforced aluminum, 2009/SiC/15p. Dimensions for the end gland are provided in the text. Courtesy of DWA Aluminum Composites, Inc.

look forward may be helpful to anticipate and benefit from major advancements as they develop.

The use of DRA is almost certain to continue the current trend of increasing application. The existing stable, production-oriented supplier base has brought costs down significantly, so that cast DRA can compete on a cost basis in some applications even with steel, and P/M DRA competes very favorably with titanium alloys. Subsystem uses provide the lowest risk of insertion, but aerostructural applications are expected to provide a strong market. Cast DRA is the standard MMC material and process for the automotive industry, and steady progress in this technology, especially infiltration casting, for high-quality aerospace applications is expected to produce initial applications in coming years. This near net shape process will improve the overall affordability of this material. Efforts to produce uniform ceramic preforms at reinforcement volume fractions below 30% is important to ensure that infiltration cast DRA components retain adequate fracture properties.

A great deal of progress has been achieved in producing affordable aluminum MMCs reinforced with alumina fiber tows. This is now a commercial product, and markets include high-performance automotive and mechanical subsystems. Power transmission cables are likely to enter first service within a few years. Many aerospace applications have largely axial loading and simple component shape, and so are candidates for this material. Candidate components include cases, shrouds, struts, rods, and shafts. In many cases these have requirements that eliminate organic-matrix composites from consideration, and so significant benefit over existing metal materials are expected. The processing technology has been well established for a simple unit product shape.

Two remaining MMC technologies with significant potential in the next ten years include DRA for application at temperatures up to about 200 °C (400 °F), and DRTi. High-temperature DRA is a prime candidate for replacing many titanium components that are specified because the use temperature is just a little higher than the full-life capability of aluminum alloys (about 150 °C, or 300 °F). Examples include engine pylon structures for transport aircraft and aft fuselage structure for fighter aircraft where the engine is embedded in the fuselage. In both cases, conduction and radiation from the engine heats the surrounding structures. Titanium provides a significant cost and weight penalty, and so is an important target for these applications. The DRTi materials may provide the highest level of isotropic strength and stiffness of any common structural material and so have a very broad range of possible applications. The DRTi materials may be produced by cast, wrought, or P/M technology, providing flexible processing and forming options.

REFERENCE

1. F.H. Froes, "Fourteenth International Titanium Application Conference and Exhibition," *Light Met. Age,* Vol 57 (No. 1, 2), 1999, p 117–121