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Metal-Matrix Composites

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METAL-MATRIX COMPOSITES (MMCs) are a class of materials with potential for a wide variety of structural and thermal management applications. Metal-matrix composites are capable of providing higher-temperature operating limits than their base metal counterparts, and they can be tailored to give improved strength, stiffness, thermal conductivity, abrasion resistance, creep resistance, or dimensional stability. Unlike resin-matrix composites, they are nonflammable, do not outgas in a vacuum, and suffer minimal attack by organic fluids such as fuels and solvents.

The principle of incorporating a high-performance second phase into a conventional engineering material to produce a combination with features not obtainable from the individual constituents is well known. In a MMC, the continuous, or matrix, phase is a monolithic alloy, and the reinforcement consists of high-performance carbon, metallic, or ceramic additions. Reinforced intermetallic compounds such as the aluminides of titanium, nickel, and iron are also discussed in this article (for more information on intermetallic compounds, see the article "Ordered Intermetallics" in this Volume).

Reinforcements, characterized as either continuous or discontinuous, may constitute from 10 to 60 vol% of the composite. Continuous fiber or filament reinforcements include graphite (Gr), silicon carbide (SiC), boron, aluminum oxide (Al_2O_3), and refractory metals. Discontinuous reinforcements consist mainly of SiC in whisker (w) form, particulate (p) types of SiC, Al_2O_3, or titanium diboride (TiB_2), and short or chopped fibers of Al_2O_3 or graphite. Figure 1 shows cross sections of typical continuous and discontinuous reinforcement MMCs.

The salient characteristics of metals as matrices are manifested in a variety of ways; in particular, a metal matrix imparts a metallic nature to the composite in terms of thermal and electrical conductivity, manufacturing operations, and interaction with the environment. Matrix-dominated mechanical properties, such as the transverse elastic modulus and strength of unidirectionally reinforced composites, are sufficiently high in some MMCs to permit use of the unidirectional lay-up in engineering structures.

This article will give an overview of the current status of MMCs, including information on physical and mechanical properties, processing methods, distinctive features, and the various types of continuously and discontinuously reinforced MMCs. More information on the processing and properties of MMCs is available in the Section "Metal, Carbon/Graphite, and Ceramic Matrix Composites" in *Composites*, Volume 1 of the *Engineered Materials Handbook* published by ASM INTERNATIONAL.

Property Prediction

Property predictions of MMCs can be obtained from mathematical models, which require as input a knowledge of the properties and geometry of the constituents. For metals reinforced by straight, parallel continuous fibers, three properties that are frequently of interest are the elastic modulus, the coefficient of thermal expansion, and the thermal conductivity in the fiber direction. Reasonable values can be obtained from rule-of-mixture expressions for Young's modulus (Ref 1):

$$E_c = E_f v_f + E_m v_m \qquad \text{(Eq 1)}$$

coefficient of thermal expansion (Ref 2):

$$\alpha_c = \frac{\alpha_f v_f E_f + \alpha_m v_m E_m}{E_f v_f + E_m v_m} \qquad \text{(Eq 2)}$$

and thermal conductivity (Ref 3):

$$k_c = k_f v_f + k_m v_m \qquad \text{(Eq 3)}$$

where v is volume fraction, and E, α, and k are the modulus, coefficient of thermal expansion, and thermal conductivity in the fiber direction, respectively. The subscripts c, f, and m refer to composite, fiber, and matrix, respectively.

Processing Methods

Processing methods for MMCs are divided into primary and secondary categories. Primary processing is the operation by which the composite is synthesized from its raw materials. It involves introducing the reinforcement into the matrix in the appropriate amount and location, and achieving proper bonding of the constituents. Secondary processing consists of all the additional steps needed to make the primary composite into a finished hardware component.

Many reinforcement and matrix materials are not inherently compatible, and such materials cannot be processed into a composite without tailoring the properties of an interface between them. In some composites the coupling between the reinforcing agent and the metal is poor and must be enhanced. For MMCs made from reactive constituents, the challenge is to avoid excessive chemical activity at the interface, which would degrade the properties of the material. These problems are usually resolved either by applying a surface treatment or coating to the reinforcement or by modifying the composition of the matrix alloy.

Solidification processing (Ref 4, 5), solid-state bonding, and matrix deposition techniques have been used to fabricate MMCs. Solidification processing offers a near-net-shape manufacturing capability, which is economically attractive. Developers have explored various liquid metal techniques that use multifilament yarns, chopped fibers, or particulates as the reinforcement. A castable ceramic/aluminum MMC is now commercially available (Ref 6); cast components of this composite are shown in Fig. 2. Solid-state methods use lower fabrication temperatures with potentially better control of the interface thermodynamics and kinetics. The two principal categories of solid-state fabrication are diffusion bonding of materials in thin sheet form (Ref 7) and powder metallurgy techniques (Ref 8). Matrix deposition processes, in which the matrix is deposited on the fiber, include electrochemical plating, plasma spraying, and physical vapor deposition (Ref 7). A new method, metal spray deposition, is currently being investigated (Ref 9). After deposition process-

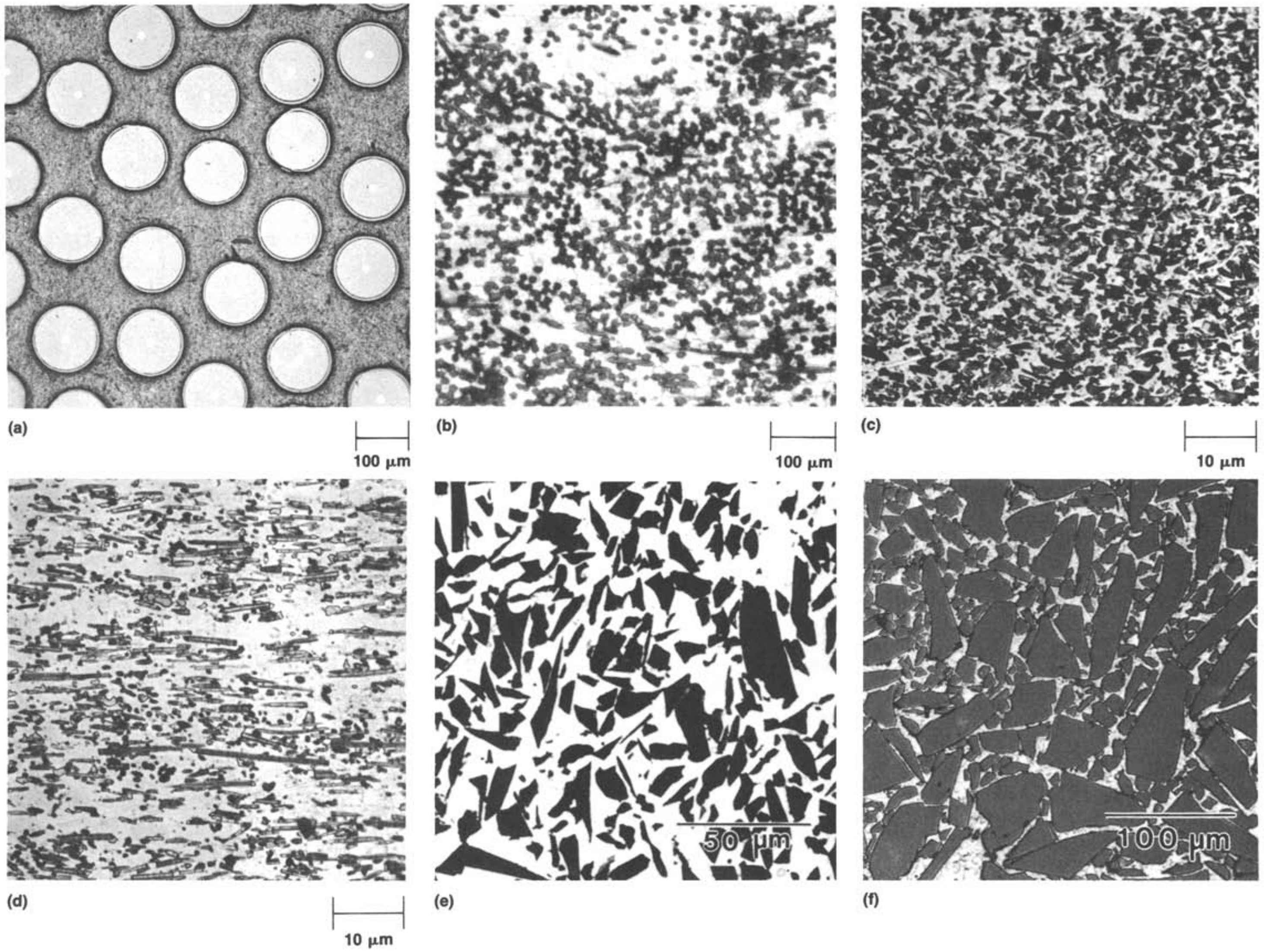

Fig. 1 Cross sections of typical fiber-reinforced MMCs. (a) Continuous-fiber-reinforced boron/aluminum composite. Shown here are 142 µm diam boron filaments coated with B_4C in a 6061 aluminum alloy matrix. (b) Discontinuous graphite/aluminum composite. Cross section shows 10 µm diam chopped graphite fibers (40 vol%) in a 2014 aluminum alloy matrix. (c) A 6061 aluminum alloy matrix reinforced with 40 vol% SiC particles. (d) Whisker-reinforced (20 vol% SiC) aluminum MMC. (e) and (f) MMCs manufactured using the PRIMEX™ pressureless metal infiltration process. (e) An Al_2O_3-reinforced (60 vol%) aluminum MMC. (f) A highly reinforced (81 vol%) MMC consisting of SiC particles in an aluminum alloy matrix. The black specks in the matrix are particles of an inorganic preform binder and do not indicate porosity. (a) and (b) Courtesy of DWA Composite Specialties, Inc. (c) and (d) Courtesy of Advanced Composite Materials Corporation. (e) and (f) Courtesy of Lanxide Corporation

ing, a secondary consolidation step such as diffusion bonding often is needed to produce a component.

Which secondary processes are appropriate for a given MMC depends largely on whether the reinforcement is continuous or discontinuous. Discontinuously reinforced MMCs are amenable to many common metal forming operations, including extrusion, forging, and rolling. Because a high percentage of the materials used to reinforce discontinuous MMCs are hard oxides or carbides, machining can be difficult, and methods such as diamond sawing, electrical discharge machining (Ref 10), and abrasive waterjet cutting (Ref 11) are sometimes utilized (see *Machining*, Volume 16 of the 9th Edition of *Metals Handbook* for more information about these machining methods).

Aluminum-Matrix Composites

Most of the commercial work on MMCs has focused on aluminum as the matrix metal. The combination of light weight, environmental resistance, and useful mechanical properties has made aluminum alloys very popular; these properties also make aluminum well suited for use as a matrix metal. The melting point of aluminum is high enough to satisfy many application requirements, yet low enough to render composite processing reasonably convenient. Also, aluminum can accommodate a variety of reinforcing agents, including continuous boron, Al_2O_3, SiC, and graphite fibers, and various particles, short fibers, and whiskers (Ref 12). The microstructures of various aluminum matrix MMCs are shown in Fig. 1.

Continuous Fiber Aluminum MMC. Boron/aluminum is a technologically mature continuous fiber MMC (Fig. 1a). Applications for this composite include tubular truss members in the midfuselage structure of the Space Shuttle orbiter and cold plates in electronic microchip carrier multilayer boards. Fabrication processes for B/Al composites are based on hot-press diffusion bonding or plasma spraying methods (Ref 13). Selected properties of a B/Al composite are given in Table 1.

Continuous SiC fibers (SiC_c) are now commercially available; these fibers are candidate replacements for boron fibers because they have similar properties and offer a potential cost advantage. One such SiC fiber is SCS, which can be manufactured with any of several surface chemistries to

Table 1 Room-temperature properties of unidirectional continuous fiber aluminum-matrix composites

Property	B/6061 Al	SCS-2/6061 Al	P100 Gr/6061 Al	FP/Al-2Li(a)
Fiber content, vol%	48	47	43.5	55
Longitudinal modulus, GPa (10^6 psi)	214 (31)	204 (29.6)	301 (43.6)	207 (30)
Transverse modulus, GPa (10^6 psi)	· · ·	118 (17.1)	48 (7.0)	144 (20.9)
Longitudinal strength, MPa (ksi)	1520 (220)	1462 (212)	543 (79)	552 (80)
Transverse strength, MPa (ksi)	· · ·	86 (12.5)	13 (2)	172 (25)

(a) FP is the proprietary designation for an alpha alumina (α-Al_2O_3) fiber developed by E.I. Du Pont de Nemours & Company, Inc. Source: Ref 14–16

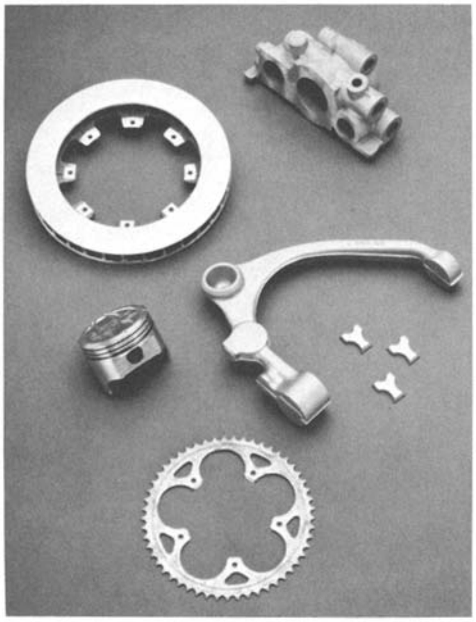

Fig. 2 Discontinuous silicon carbide/aluminum castings. Pictured are a sand cast automotive disk brake rotor and upper control arm, a permanent mold cast piston, a high-pressure die cast bicycle sprocket, an investment cast aircraft hydraulic manifold, and three investment cast engine cylinder inserts. Courtesy of Dural Aluminum Composites Corporation

enhance bonding with a particular matrix, such as aluminum or titanium (Ref 14). The SCS-2 fiber, tailored for aluminum, has a 1 μm (0.04 mil) thick carbon rich coating that increases in silicon content toward its outer surface.

Silicon carbide/aluminum MMCs exhibit increased strength and stiffness as compared with unreinforced aluminum, and with no weight penalty. Selected properties of SCS-2/Al are given in Table 1. In contrast to the base metal, the composite retains its room-temperature tensile strength at temperatures up to 260 °C (500 °F) (Fig. 3). This material is the focus of development programs for a variety of applications; an example of an advanced aerospace application for an SCS/Al MMC is shown in Fig. 4.

Graphite/aluminum (Gr/Al) MMC development was initially prompted by the commercial appearance of strong and stiff carbon fibers in the 1960s. As shown in Fig. 5, carbon fibers offer a range of properties, including an elastic modulus up to 966 GPa (140 psi × 10^6) and a negative coefficient of thermal expansion down to -1.62×10^{-6}/°C (-0.9×10^{-6}/°F). However, carbon and aluminum in combination are difficult materials to process into a composite. A deleterious reaction between carbon and aluminum, poor wetting of carbon by molten aluminum, and oxidation of the carbon are significant technical barriers to the production of these composites (Ref 19). Three processes are currently used for making commercial Gr/Al MMCs: liquid metal infiltration of fiber tows (Ref 20), vacuum vapor deposition of the matrix on spread tows (Ref 21, 22), and hot press bonding of spread tows sandwiched between sheets of aluminum (Ref 19). With both precursor wires and metal-coated fibers, secondary processing such as diffusion bonding or pultrusion is needed to make structural elements. Squeeze casting also is feasible for the fabrication of this composite (Ref 23).

Precision aerospace structures with strict tolerances on dimensional stability need stiff, lightweight materials that exhibit low thermal distortion. Graphite/aluminum MMCs have the potential to meet these requirements. Unidirectional P100 Gr/6061 Al pultruded tube (Ref 15) exhibits an elastic modulus in the fiber direction significantly greater than that of steel, and it has a density approximately one-third that of steel (Table 1). Reference 24 contains additional data for P100 Gr/Al.

In theory, Gr/Al angle-plied laminates can be designed to provide a coefficient of thermal expansion (CTE) of exactly zero by selecting the appropriate ply-stacking arrangement and fiber content. In practice, a near-zero CTE has been realized, but expansion behavior is complicated by hysteresis attributed to plastic deformation occur-

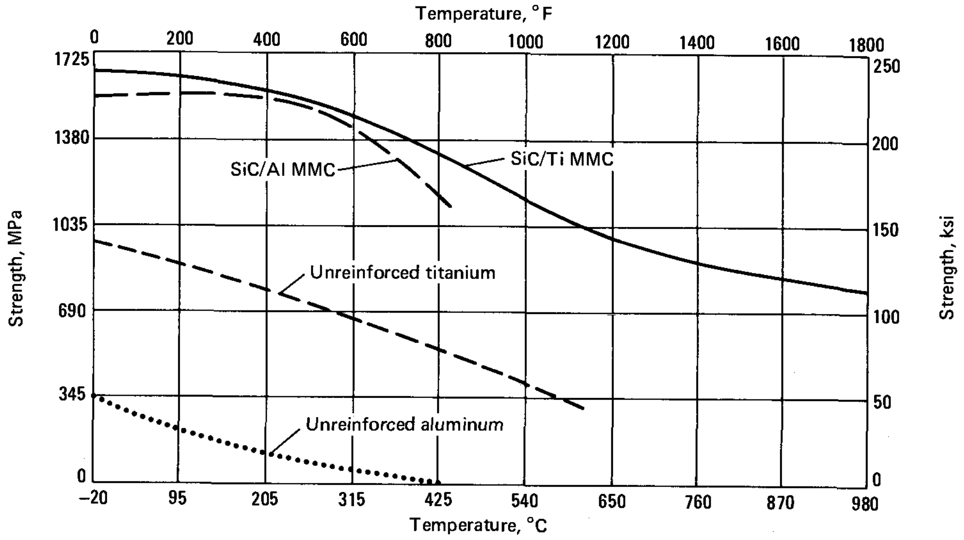

Fig. 3 Effect of temperature on tensile strength for two continuous fiber MMCs and two unreinforced metals. Source: Ref 17

Fig. 4 Advanced aircraft stabilator spar made from an SCS/Al MMC. Courtesy of Textron Specialty Materials

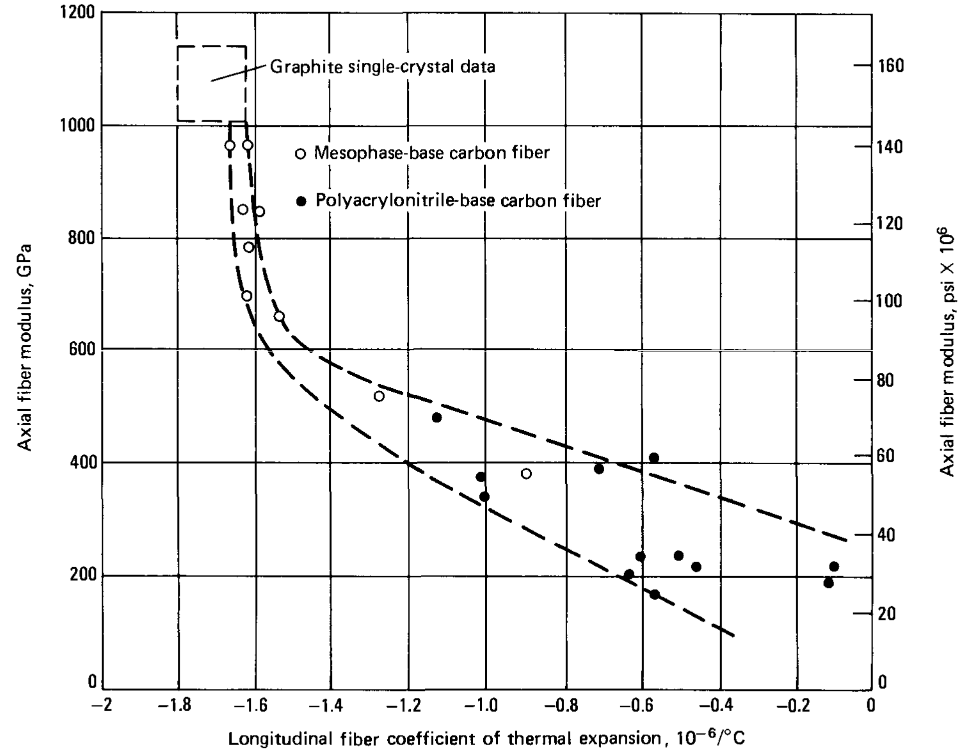

Fig. 5 Carbon fiber axial modulus versus axial coefficient of thermal expansion for mesophase (pitch-base) and polyacrylonitride-base (pan-base) graphite fibers. Source: Ref 18

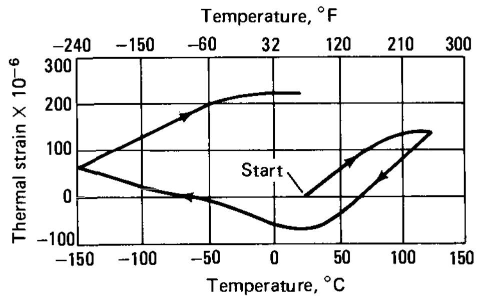

Fig. 6 Thermal expansion in the fiber direction of a P100 Gr/6061 Al single-ply unidirectional composite laminate. Source: Ref 25

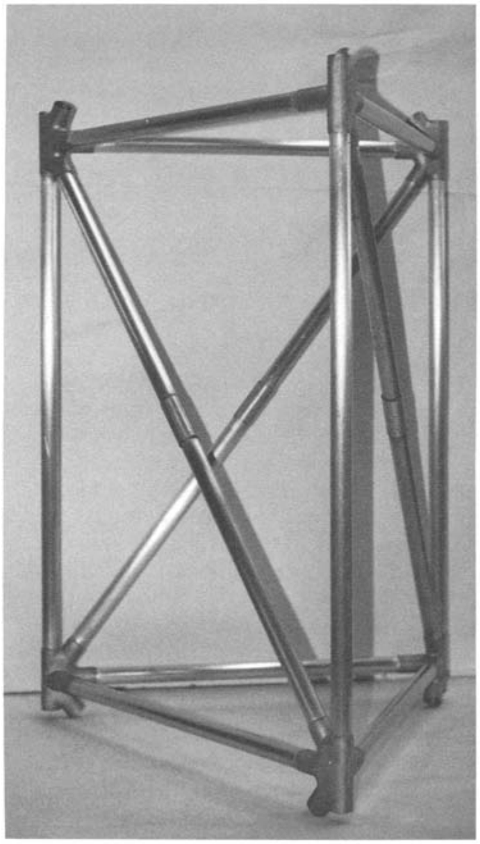

Fig. 7 Space truss made of ±12° lay-up graphite/aluminum tubes. Axial coefficient of thermal expansion is −0.072 × 10^{-6}/°C per bay. Courtesy of DWA Composite Specialties, Inc.

ring in the matrix during thermal excursions (Fig. 6). Full-scale segments of a Gr/Al space truss (Fig. 7) have been fabricated and successfully tested. The advent of pitch-based graphite fibers with three times the thermal conductivity of copper (Ref 26) suggests that a high-conductivity low-CTE version of Gr/Al can be developed for electronic heat sinks and space thermal radiators.

Aluminum oxide/aluminum (Al_2O_3/Al) MMCs can be fabricated by a number of methods, but liquid or semisolid-state processing techniques are commonly used. Certain of the oxide ceramic fibers used as reinforcements are inexpensive and provide the composite with improved properties as compared with those of unreinforced aluminum alloys. For example, the composite has an improved resistance to wear and thermal fatigue deformation and a reduced coefficient of thermal expansion. Continuous fiber Al_2O_3/Al MMCs are fabricated by arranging Al_2O_3 tapes in a desired orientation to make a preform, inserting the preform into a mold, and infiltrating the preform with molten aluminum via a vacuum assist (Ref 27). Reinforcement-to-matrix bonding is achieved by small additions of lithium to the melt. The room-temperature properties of a unidirectional Al_2O_3/Al (FP/Al-2Li) are given in Table 1; additional mechanical properties of continuous Al_2O_3/Al are given in Ref 28.

Discontinuous Aluminum MMCs. Discontinuous silicon carbide/aluminum (SiC_d/Al) is a designation that encompasses materials with SiC particles, whiskers, nodules, flakes, platelets, or short fibers in an aluminum matrix (see Fig. 1). Several companies are currently involved in the development of powder metallurgy SiC_d/Al, using either particles or whiskers as the reinforcement phase (Ref 8). A casting technology exists for this type of MMC, and melt-produced ingots can be procured in whatever form is needed—extrusion billets, ingots, or rolling blanks—for further processing (Ref 29). Arsenault and Wu (Ref 30) compared powder metallurgy and melt-produced discontinuous SiC/Al composites to determine if a correlation exists between strength and processing type. They found that if the size, volume fraction, distribution of the reinforcement, and bonding with the matrix are the same, then the strengths of the powder metallurgy and melt-produced MMCs are the same.

Whiskers in discontinuously reinforced MMCs can be oriented in processing to provide directional properties. McDanels (Ref 31) evaluated the effects of reinforcement type, matrix alloy, reinforcement content, and orientation on the tensile behavior of SiC_d/Al composites made by powder metallurgy techniques. He concluded that these composites offer a 50 to 100% increase in elastic modulus as compared with unreinforced aluminum (Fig. 8). He also found that these materials have a stiffness approximately equivalent to that of titanium but with one-third less density. Tensile and yield strengths of SiC_d/Al composites are up to 60% greater than those of the unreinforced matrix alloy. Selected properties of SiC_d/Al MMCs are given in Table 2. Studies of the elevated-temperature mechanical properties of SiC_d/Al with either 20% whisker or 25% particulate reinforcement indicate that SiC_d/Al can be used effectively for long-time exposures to temperatures of at least 200 °C (400 °F) and for short exposures at 260 °C (500 °F) (Ref 31, 33).

Discontinuous silicon carbide/aluminum MMCs are being developed by the aerospace industry for use as airplane skins, intercostal ribs, and electrical equipment

Table 2 Properties of discontinuous silicon carbide/aluminum composites

Property	SiC_p/Al-4Cu-1.5Mg(a)	SiC_w/Al-4Cu-1.5Mg(b)
Reinforcement content, vol%	20	15
Longitudinal modulus, GPa (10^6 psi)	110 (16)	108 (15.7)
Transverse modulus, GPa (10^6 psi)	105 (15)	90 (13)
Longitudinal tensile strength, MPa (ksi)	648 (94)	683 (99)
Transverse tensile strength, MPa (ksi)	641 (93)	545 (79)
Longitudinal strain to failure, %	5	4.3
Transverse strain to failure, %	5	7.4

(a) 12.7 mm (0.5 in.) plate. (b) 1.8–3.2 mm (0.070–0.125 in.) sheet. Source: Advanced Composite Materials Corporation

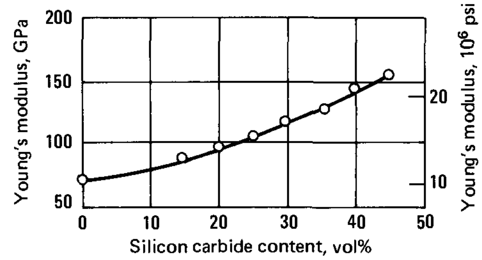

Fig. 8 Effect of reinforcement content on the Young's modulus of a particulate-reinforced SiC/2124-T6 Al MMC. Source: Ref 32

racks (Fig. 9). These composites can be tailored to exhibit dimensional stability, that is, resistance to microcreep, which is important for precision mirror optics and inertial measurement units (Fig. 10). In the electronics industry, metals such as iron-nickel alloys that are now used for packaging materials and heat sinks are candidates for replacement by SiC_d/Al. The composite has lower density, better thermal conductivity (≥160 W/m · K), and can be made to have a low coefficient of thermal expansion (Fig. 11). Hybrid electronic packages made from SiC_d/Al are shown in Fig. 12.

Most Gr/Al MMC development work has focused on using continuous fibers as reinforcement. However, various solidification processing techniques have been investigated for use in the production of cast particle Gr/Al for applications needing an inexpensive antifriction material (Ref 35).

Discontinuous Al_2O_3/Al MMCs are made using short fibers, particles, or compacted staple fiber preforms as reinforcements. The addition of chopped Al_2O_3 fibers to an agitated, partially solid aluminum alloy slurry has been used to produce a castable discontinuous MMC (Ref 36). Squeeze casting has attracted much attention because the process minimizes material and energy use, produces net shape components, and offers a selective reinforcement capability (Ref 37, 38).

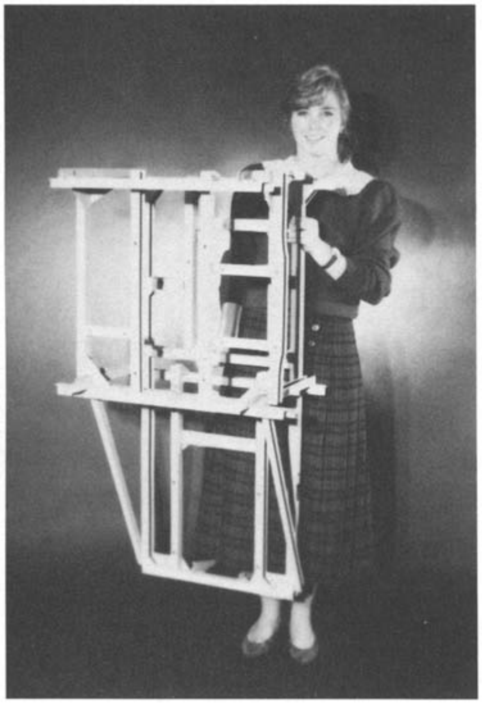

Fig. 9 Lightweight aircraft equipment racks made of particulate SiC/Al. Courtesy of DWA Composite Specialties, Inc. and Lockheed ASD

A recent development in MMC fabrication technology is the proprietary Lanxide PRIMEX™ process, which involves pressureless metal infiltration into a ceramic preform. This process has been used to produce an Al_2O_3/Al composite by the infiltration of a bed of alumina particles with a molten alloy that was exposed to an oxidizing atmosphere. The matrix material of the resultant composite is composed of a mixture of the oxidation reaction product and unreacted aluminum alloy (Ref 39). The Lanxide process offers net shape capability (Fig. 13), and the properties of composites produced by this method can be tailored to fit specific applications.

Aluminum oxide/aluminum MMCs are candidate materials for moving parts of automotive engines, such as pistons (Ref 40), connecting rods (Ref 16), piston pins, and various components in the cylinder head and valve train (Ref 41). Examples of automotive parts fabricated from MMCs are shown in Fig. 14. These components were fabricated from aluminum-base composites with reinforcements typically of silicon carbide or alumina in volume loadings ranging from 5 to 25%. A variety of processing techniques can be used to fabricate such parts. For example, production of the combustion bowl area of the diesel piston involved squeeze casting a ceramic preform with metal; the cylinder liner was sand mold cast; and the connecting rod was made using novel forming processes specifically adapted for composites. Other possible automotive applications for this class of materials include brake rotors, brake calipers, and drive shafts.

A Toyota diesel engine piston selectively reinforced with an aluminosilicate ceramic compact is currently in production (Ref 42). Selective reinforcement of the all-aluminum piston with a ceramic fiber preform provides wear resistance equal to that of a piston with an iron insert, and the thermal transport is only marginally lower than that of unreinforced aluminum. With the elimination of the iron insert, piston weight is reduced, and high-temperature strength and thermal stability are enhanced.

Magnesium-Matrix Composites

Magnesium composites are being developed to exploit essentially the same properties as those provided by aluminum MMCs: high stiffness, light weight, and low CTE. In practice, the choice between aluminum and magnesium as a matrix is usually made on the basis of weight versus corrosion resistance. Magnesium is approximately two-thirds as dense as aluminum, but it is more active in a corrosive environment. Magnesium has a lower thermal conductivity, which is sometimes a factor in its selection. Three types of magnesium MMCs are currently under development: continuous fiber Gr/Mg for space structures (Ref 43), short staple fiber Al_2O_3/Mg for automotive engine components (Ref 44), and discontinuous SiC or B_4C/Mg for engine components (Ref

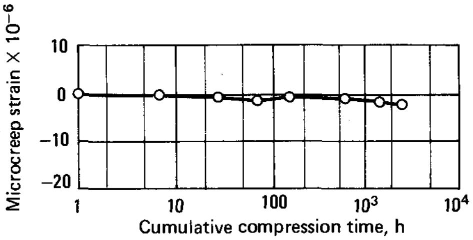

Fig. 10 Microcreep behavior of 2124-T6 aluminum reinforced with 30 vol% SiC particulate. Performance of composite indicates long-term dimensional stability. Source: Ref 32

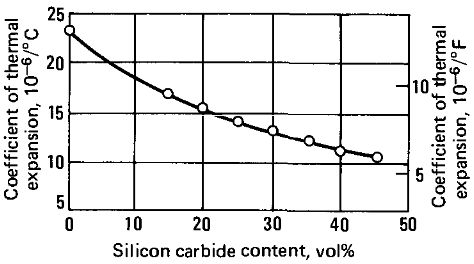

Fig. 11 Effect of reinforcement content on the room-temperature coefficient of thermal expansion for a SiC_p/2124-T6 Al MMC. Source: Ref 34

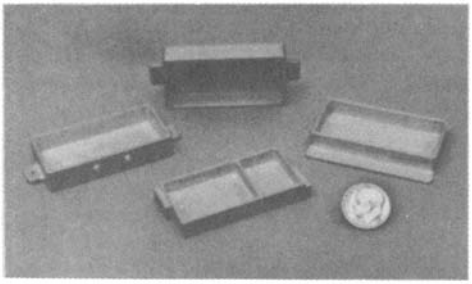

Fig. 12 Electronic packages made from SiC_d/Al (60 vol% SiC) MMCs. Courtesy of Lanxide Corporation

45) and low-expansion electronic packaging materials (Ref 46). Processing methods for all three types parallel those used for their aluminum MMC counterparts.

The production of the continuous-fiber Gr/Mg composite involves the titanium-boron coating method of making composite wires, physical vapor deposition of the matrix on fibers, or diffusion bonding of fiber-thin sheet sandwiches to make panels. A casting technology exists for Gr/Mg that involves the deposition of an air-stable silicon dioxide coating on the fibers from an organometallic precursor solution (Ref 47). Magnesium wets the coating, permitting incorporation of the matrix by near-net-shape casting procedures (Ref 48). Testing of a unidirectionally reinforced Gr/Mg MMC in the fiber direction recorded modulus values in agreement with Eq 1 and a tensile strength of 572 MPa (83 ksi) (Ref 43). A P100 Gr/AZ91C Mg unidirectional laminate was shown to have a lower CTE and smaller residual strain than those of a P100 Gr/6061 Al MMC after both composites had undergone thermal cycling between −155 °C and 120 °C (−250 and 250 °F) (Ref 25).

Titanium-Matrix Composites

Titanium was selected for use as a matrix metal because of its good specific strength at both room and moderately elevated temperatures and its excellent corrosion resistance. In comparison with aluminum, titanium retains its strength at higher temperatures; it has increasingly been used as a replacement for aluminum in aircraft and missile structures as the operating speeds of these items have increased from subsonic to supersonic. Efforts to develop titanium MMCs were hampered for years by processing problems stemming from the high reactivity of titanium with many reinforcing materials. Reference 49 is a review of titanium MMC technology. Silicon carbide is now the accepted reinforcement; the SCS-6 fiber is an example of one commercially available type. The SCS-6 fiber has a 140 μm (5.6 mil) diameter, a 33 μm (1.3 mil) carbon core, and a carbon-rich surface (Fig. 15).

Although a number of processing techniques have been evaluated for titanium MMCs, only high-temperature/short-time roll bonding, hot isostatic pressing, and vacuum hot pressing have been used to any substantial degree. Plasma spraying also is employed to deposit a titanium matrix onto the fibers (Ref 50). Properties for a representative unidirectional SiC/Ti laminate are given in Table 3. The elevated-temperature strength of the SiC/Ti composite is significantly greater than that of unreinforced titanium (Fig. 3). Potential applications for continuous titanium MMCs lie primarily in the aerospace industry and include major aircraft structural components (Ref 51) and fan and compressor blades for advanced turbine engines.

Table 3 Room-temperature properties of a unidirectional SiC_c/Ti MMC

Property	SCS-6/Ti-6A1-4V
Fiber content, vol%	37
Longitudinal modulus, GPa (10^6 psi)	221 (32)
Transverse modulus, GPa (10^6 psi)	165 (24)
Longitudinal strength, MPa (ksi)	1447 (210)
Transverse strength, MPa (ksi)	413 (60)

Source: Ref 14

Titanium MMCs with discontinuous reinforcements are in the early stages of development (Ref 52). This type of composite has a moderate stiffness and elevated-temperature strength advantage over monolithic titanium alloys. It also offers a near-net-shape manufacturing capability with the use of powder metallurgy techniques; therefore, it may be more economical to fabricate than continuous fiber titanium MMCs.

Copper-Matrix Composites

Copper appears to have potential as a matrix metal for composites that require thermal conductivity and high-temperature strength properties superior to those of aluminum MMCs. Copper MMCs with continuous and discontinuous reinforcements are being evaluated.

Continuous tungsten fiber reinforced copper composites were first fabricated in the late 1950s as research models for studying stress-strain behavior, stress-rupture and creep phenomena, and impact strength and conductivity in MMCs (Ref 53). The composites were made by liquid-phase infiltration. On the basis of their high strength at temperatures up to 925 °C (1700 °F), W/Cu MMCs are now being considered for use as

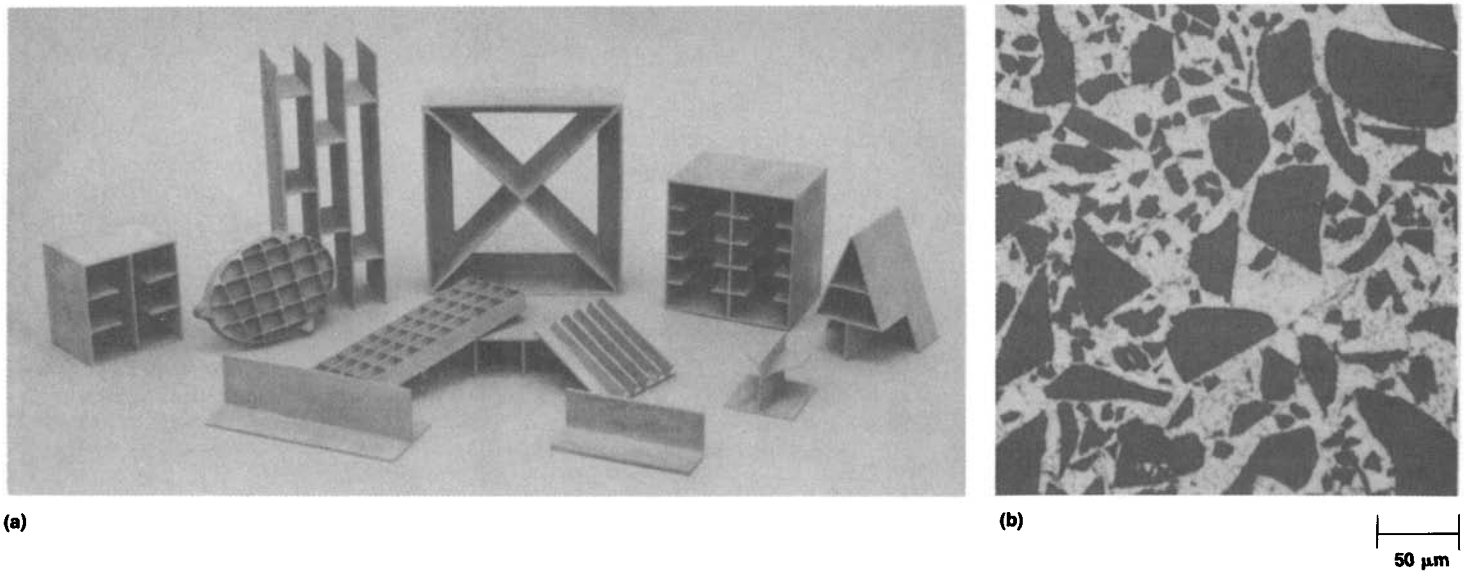

Fig. 13 Discontinuous silicon carbide/aluminum MMC (60 vol% SiC) produced by the PRIMEX™ process. (a) Near-net-shape components fabricated from the composite. (b) Composite microstructure. Courtesy of Lanxide Corporation

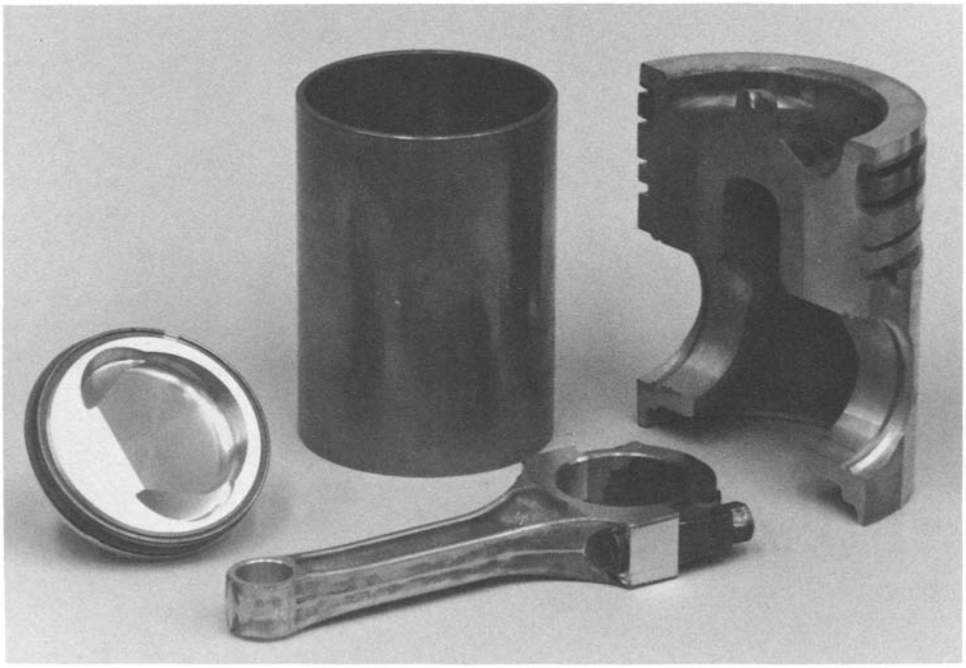

Fig. 14 Automotive components fabricated from MMCs. Clockwise from left: experimental piston for a gasoline engine, experimental cylinder liner, production piston for a heavy-duty diesel truck engine, and experimental connecting rod. Courtesy of Ford Motor Company

liner materials for the combustion chamber walls of advanced rocket engines (Ref 54).

Continuous Gr/Cu MMCs. Interest in continuous Gr/Cu MMCs gained impetus from the development of advanced graphite fibers. Copper has good thermal conductivity, but it is heavy and has poor elevated-temperature mechanical properties. Pitch-base graphite fibers have been developed that have room-temperature axial thermal conductivity properties better than those of copper (Ref 26). The addition of these fibers to copper reduces density, increases stiffness, raises the service temperature, and provides a mechanism for tailoring the coefficient of thermal expansion. One approach to the fabrication of Gr/Cu MMCs uses a plating process to envelop each graphite fiber with a pure copper coating, yielding MMC fibers flexible enough to be woven into fabric (Ref 55). The copper-coated fibers must be hot pressed to produce a consolidated component. Table 4 compares the thermal properties of aluminum and copper MMCs with those of unreinforced aluminum and copper. Graphite/copper MMCs have the potential to be used for thermal management of electronic components (Ref 55), satellite radiator panels (Ref 56), and advanced airplane structures (Ref 57).

***In situ* Composites.** Discontinuous MMCs formed by the working of mixtures of individual metal phases exhibit strengths as much as 50% higher than those predicted in theory from the strength of the individual constituents (Ref 8). These materials are called *in situ* composites because the elongated ribbon morphology of the reinforcing phase is developed in place by heavy mechanical working, which can consist of extrusion, drawing, or rolling. This approach has been applied to the fabrication of discontinuous refractory metal/copper composites, with niobium/copper serving as the prototype. Niobium/copper maintains high strength at temperatures up to 400 °C (750 °F), and it remains stronger than high-temperature copper alloys and dispersion-hardened copper up to 600 °C (1110 °F) (Ref 58). These composites are candidates for applications such as electrical contacts that require good strength plus conductivity at moderate temperatures.

Table 4 Thermal properties of unreinforced and reinforced aluminum and copper

Material	Reinforcement content, vol%	Density g/cm^3	Density lb/ft^3	Axial thermal conductivity W/m · °C	Axial thermal conductivity Btu/ft · h · °F	Axial coefficient of thermal expansion 10^{-6}/°C	Axial coefficient of thermal expansion 10^{-6}/°F
Aluminum	0	2.71	169	221	128	23.6	13.1
Copper	0	8.94	558	391	226	17.6	9.7
SiC$_p$/Al	40	2.91	182	128	74	12.6	7
P120 Gr/Al	60	2.41	150	419	242	−0.32	−0.17
P120 Gr/Cu	60	4.90	306	522	302	−0.07	−0.04

Source: Ref 34

Superalloy-Matrix Composites

Superalloys are commonly used for turbine engine hardware and, therefore, superalloy-matrix composites were among the first candidate materials considered for upgrading turbine performance by raising component operating temperatures. Superalloy MMCs were developed to their present state over a period of years, starting from the early 1960s. The following summary is drawn from the review in Ref 59.

High-temperature strength in superalloy MMCs has been achieved only through the use of refractory metal reinforcements (tungsten, molybdenum, tantalum, and niobium fibers with compositions specially modified for this purpose). The strongest fiber developed, a tungsten alloy, exhibited a strength of more than 2070 MPa (300 ksi) at 1095 °C (2000 °F), or more than six times the strength of the superalloy now used in the Space Shuttle main engine.

Much of the early work on superalloy MMCs consisted of fiber-matrix compatibility studies, which ultimately led to the use of matrix alloys that exhibit limited reaction with the fibers. Tungsten fibers, for example, are least reactive in iron-base matrices, and they can endure short exposures at temperatures up to 1195 °C (2190 °F) with no detectable reaction.

Fabrication of superalloy MMCs is accomplished via solid-phase, liquid-phase, or deposition processing. The methods include investment casting, the use of matrix metals in thin sheet form, the use of matrix metals in powder sheet form made by rolling powders with an organic binder, powder metallurgy techniques, slip casting of metal alloy powders, and arc spraying. Iron-, nickel-, and cobalt-base MMCs have been made, and a wide range of properties have been achieved with these MMCs, including elevated-temperature tensile strength, stress-rupture strength, creep resistance, low- and high-cycle fatigue strength, impact strength, oxidation resistance, and thermal conductivity (Ref 59). The feasibility of making a component with a complex shape was shown using a first-stage convection-cooled turbine blade as a model from which a W/FeCrAlY hollow composite blade was designed and fabricated. Additional information on superalloy MMCs reinforced with refractory metals can be found in the article "Refractory Metals and Alloys" in this Volume.

Intermetallic-Matrix Composites

One disadvantage of superalloy MMCs is their high density, which limits the potential minimum weight of parts made from these materials. High melting points and relatively low densities make intermetallic-matrix composites (IMCs) viable candidates for lighter turbine engine materials

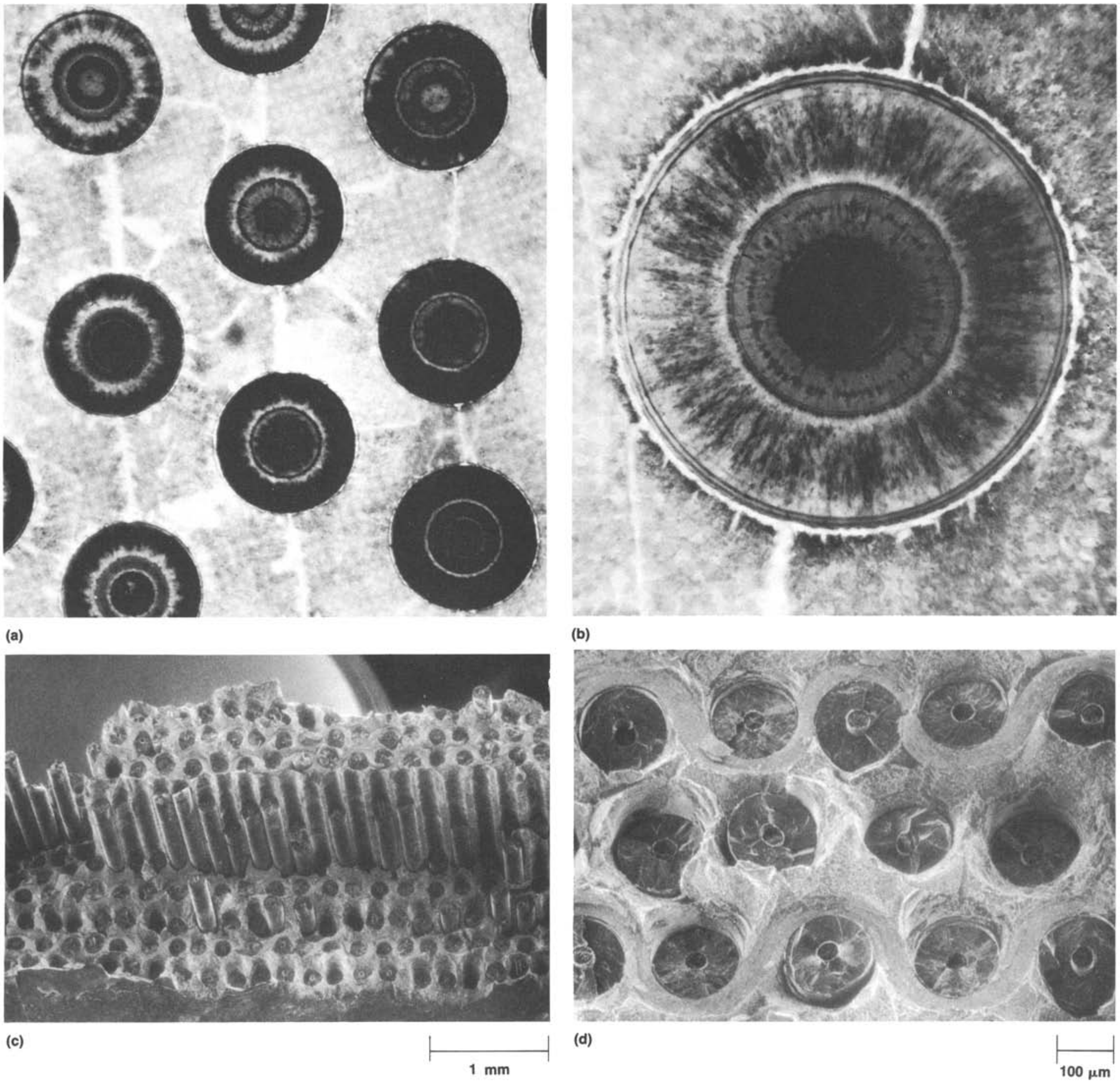

Fig. 15 Continuous-fiber-reinforced titanium-matrix MMCs. (a) Hot-pressed SiC fibers (SCS-6, 35 vol%) in a Ti-6Al-4V matrix. Fiber thickness, 140 µm; density, 3.86 g/cm^3. (b) Chemical vapor deposited SiC fiber (SCS-6) showing the central carbon monofilament substrate and the carbon-rich surface. Fiber properties: thickness, 140 µm; tensile strength, 3450 MPa (500 ksi); modulus of elasticity, 400 GPa (58 × 10^6 psi); density, 3.0 g/cm^3. (c) Fracture surface of a hot-pressed SCS-6 SiC/titanium MMC plate. (d) Close-up view of fractured SCS-6 fibers. Courtesy of Textron Specialty Materials, a subsidiary of Textron, Inc.

(Ref 60). An intermetallic compound differs from an alloy in that the former has a fixed compositional range, a long-range order to the arrangement of atoms within the lattice, and a limited number of slip systems available for plastic deformation. At present, the IMC technology is in its infancy, and many critical issues remain to be addressed.

Aluminides of nickel, titanium, and iron have received most of the early attention as potential matrices for IMCs. Work on aluminide IMCs is concerned with developing methods to fabricate reproducible specimens with useful properties; work is also being done on characterizing the interface chemical reactions of fiber/matrix combinations. Candidate reinforcements for commercially available intermetallic materials are SiC and Al_2O_3 fibers, refractory metal fibers, and particulates such as titanium carbide (TiC) and titanium diboride (TiB_2). Research is being done to find methods for growing advanced single-crystal fibers and using refractory metal aluminides and silicides as matrices (Ref 61). Key factors in selecting a reinforcement/matrix combination are chemical compatibility at the processing temperature and an approximate match of thermal expansion coefficients between the material pair to minimize residual fabrication stresses.

Reference 62 is an overview of the development of nickel aluminide IMCs, and it describes the various processing techniques used to make this composite. These techniques include hot pressing, diffusion bonding, hot extrusion, reactive sintering, and liquid infiltration. Reference 63 presents evidence that silicon carbide cannot serve as a reinforcement for nickel aluminide IMCs without the use of a diffusion barrier coating. A gas pressure liquid infiltration technique has been used to produce continuous fiber Al_2O_3/NiAl (Ref 64). Reference 65 describes a powder cloth method for the fabrication of a 40 vol% continuous fiber SiC/Ti_3Al + Nb IMC. Data on IMC properties are very limited.

The XD composites are a proprietary class of discontinuous reinforcement *in situ* composites. The XD technology uses a casting process to produce a fine, closely spaced, and uniform distribution of second-phase particles (Ref 66). The dispersoids are formed and grown *in situ* instead of being mechanically mixed as a separate additive. This approach to making ceramic-stiffened composites has been demonstrated for a number of metals as well as for titanium and nickel aluminides (Ref 67). Strength levels of greater than 690 MPa (100 ksi) were measured at 20 °C (70 °F) and at 800 °C (1470 °F) for a two-phase lamellar Ti-45 at.% Al alloy reinforced with equiaxed TiB_2 ceramic particulates (Ref 66).

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