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Synthesis and Processing of Cast Metal-Matrix Composites and Their Applications

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METAL-MATRIX COMPOSITES (MMCs) are an important class of engineered materials that are increasingly replacing a number of conventional materials in the automotive, aerospace, and sports industries, driven by the demand for lightweight and higher-strength components (Ref 1–6). MMCs are engineered combinations of two or more materials (one of which is a metal or alloy) in which tailored properties, not achievable in monolithic metals or alloys, are achieved by systematic combinations of different constituents. MMCs, in general, consist of continuous or discontinuous fibers, whiskers, or particles dispersed in a metallic alloy matrix. MMCs can be synthesized by vapor phase, liquid phase, or solid phase processes. In this article, the discussion emphasizes the liquid-phase processing where solid reinforcements are incorporated in the molten metal or alloy melt, which are then allowed to solidify to form a composite.

Cast MMCs are not new to the industry. Although traditionally not called a composite, the aluminum-silicon eutectic alloy (Fig. 1a) is composed of silicon needles embedded in an aluminum matrix. Such a microstructure may be called an in situ composite. Another example of an in situ composite commonly produced by foundries is ductile cast iron (Fig. 1b), in which graphite nodules are dispersed in a ferrite matrix. A limitation of composites such as the aluminum-silicon eutectic alloy and ductile cast iron is that the volume percentages of the two phases are restricted to narrow ranges predicted by their phase diagrams. Additionally, the morphology and spatial arrangement of reinforcements cannot be varied as freely as in synthetically produced composites, which are synthesized by physically mixing a reinforcement phase in a metallic melt. Therefore, in situ composites are excluded from the discussion in this article in order to focus on synthetic composites.

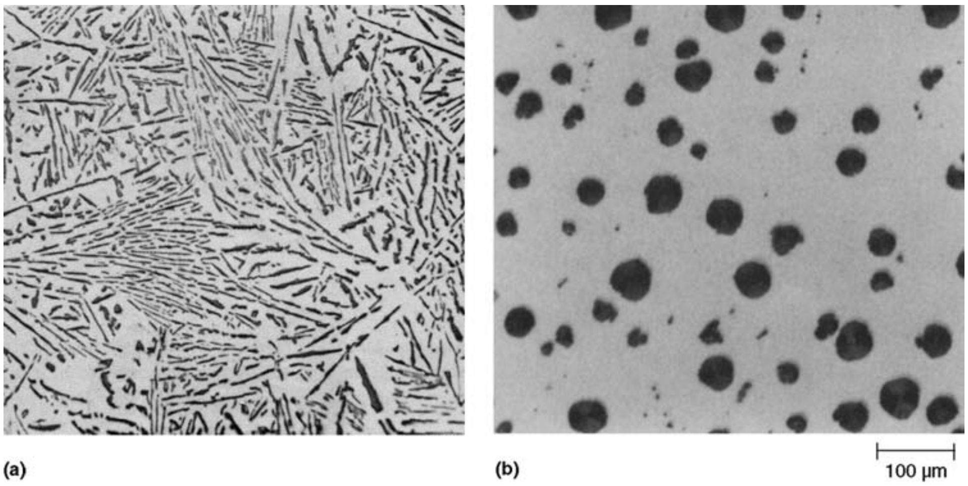
In synthetic composites, one can change, almost at will, the chemistry, shape, volume percentage, and distribution of the second phase (reinforcement). The restrictions, if any, are rheology and flow of metal between the reinforcements. Given the large number of metals and alloys used in synthesizing composite materials, it is not possible to cover all types of composites in this short discussion. Therefore, major issues pertaining to processing of cast MMCs are discussed by means of examples related to aluminum-matrix composites.

Classification of MMCs

MMCs are classified into three broad categories depending on the aspect ratio of the reinforcing phase. These categories are defined as:

- Continuous fiber-reinforced composites
- Discontinuous or short fiber-reinforced composites
- Particle-reinforced composites

The structures of the three types of MMCs are schematically shown in Fig. 2. A unidirectionally aligned continuous fiber-reinforced composite is illustrated in Fig. 2(a). The fiber material can be carbon or a ceramic such as silicon carbide (SiC), and the matrix can be a metal such as titanium, copper, or aluminum. Extensive literature is available on mechanical and thermal properties, such as modulus and thermal conductivity, of fiber-reinforced MMCs. Generally, mechanical properties, including strength and stiffness, are higher in the longitudinal direction than in the transverse direction to the fibers. Figure 2(b) illustrates a short fiber-reinforced composite. The short



(a) (b)

Fig. 1 Phase-diagram-restricted metal-matrix composites. (a) Aluminum-silicon alloy. (b) Ductile cast iron

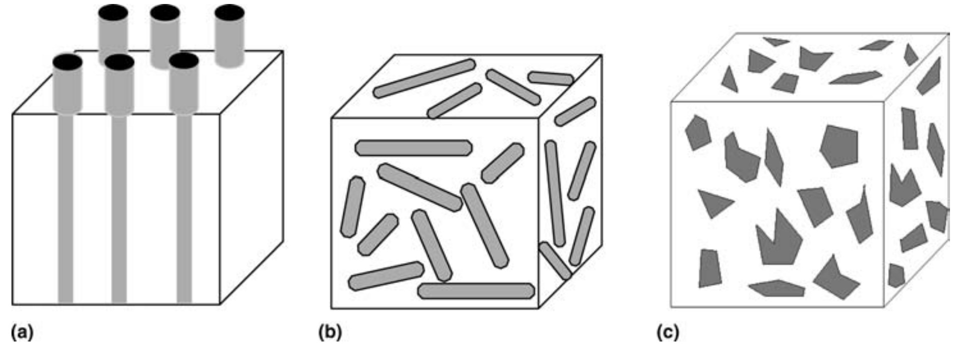


Fig. 2 Classification of metal-matrix composites. (a) Aligned continuous fiber-reinforced composite. (b) Short fiber-reinforced composite. (c) Particulate composite

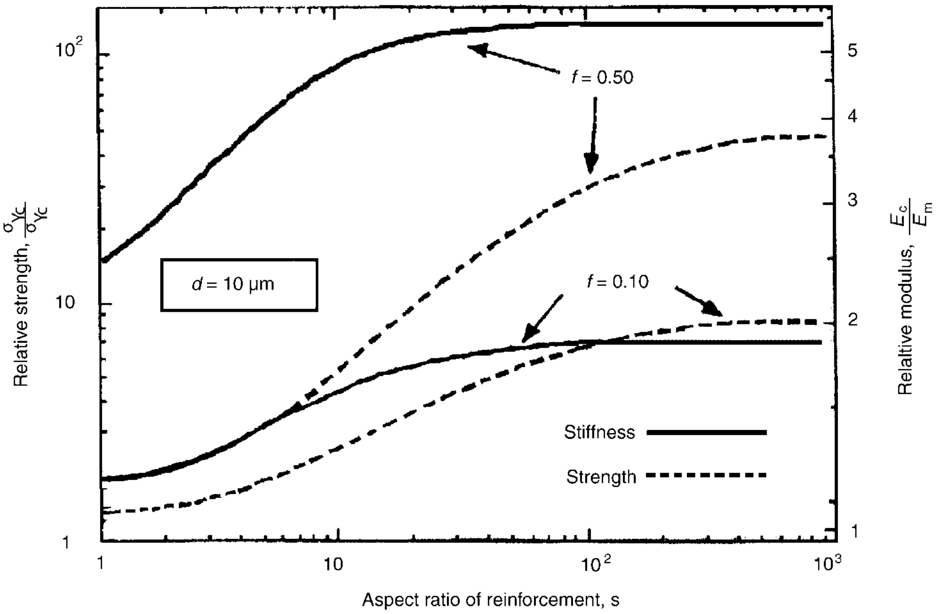


Fig. 3 Magnitude of stiffening and strengthening of composites relative to the matrix as a function of reinforcement aspect ratio and volume fraction, *f*

Fig. 4 Injection of nickel-coated graphite particles in molten aluminum alloys in an initial experiment on casting aluminum-graphite particle composites at Merica Laboratory, International Nickel Company, 1965

fibers can be either aligned or randomly oriented in the matrix material. Figure 2(c) demonstrates a particle-reinforced composite in which irregularly shaped particles of a second phase are dispersed in a metallic matrix. The particles or whiskers incorporated in these composites can be made of graphite or ceramics, such as SiC, alumina silica, and the matrix can be a metal, such as aluminum, copper, titanium, or magnesium.

Fiber-reinforced composites are used in applications where higher specific strength and specific modulus are required. Particulate composites normally provide significant improvement in wear properties of composites but only a marginal improvement in mechanical properties compared to the matrix alloy. Unlike fiber-reinforced MMCs, the particle-reinforced MMCs are generally isotropic and more amenable to secondary processing practices, such as rolling, extrusion, and forging after casting. Figure 3 schematically illustrates the magnitude and range of stiffening and strengthening of composites in relation to the matrix as a function of reinforcement aspect ratio (ratio of length to diameter) and volume fraction (*f*). Particle-reinforced MMCs differ from dispersion-hardened materials, in which the particle size varies between 0.001 and 1 μm (0.039 and 39 μin.) and the volume fraction of particles is below 0.10. Dispersion-hardened alloys are excluded from this discussion on synthetic composites.

Solidification Processing of MMCs and Possible Effects of Reinforcement on Solidification

The initial discovery of the synthesis of cast MMCs was made in 1965 at the Merica Laboratory of the International Nickel Company (Fig. 4) (Ref 7). The initial work confirmed that nickel-coated graphite particles could be either introduced to molten aluminum through an inert gas stream (Fig. 4) or stir mixed in the melt using an impeller rotating in the melt to form cast aluminum-graphite composites. Tests showed that cast aluminum-graphite composites could be run against aluminum alloys without seizing or galling, even under conditions of boundary lubrication. The initial work also included incorporation of SiC and alumina in the matrix of cast aluminum alloys.

The initial work on small-sized engines at the Associated Engineering Company demonstrated that aluminum-graphite liners were able to run against aluminum pistons without seizing in the Alpha Romeo and the Ferrari automobiles used in Formula One races. Figure 5 shows a centrifugally cast aluminum-graphite composite cylinder block of a motorcycle engine, where the graphite particles were concentrated near the inner periphery of the cylinder due to the centrifugal force during casting. The aluminum-graphite cylinder liner shown in Fig. 5 was fitted to demonstrate that one could run aluminum cylinders against aluminum pistons without seizing, as a result of solid lubrication provided by the graphite particles incorporated in the castings.

Since this initial work, considerable progress has been made in the field of cast MMCs. Table 1 shows the wide variety of combinations of metal and alloy matrices and the reinforcements that have been used to synthesize composite materials. This table is by no means comprehensive but illustrates the MMC development activities.

In solidification processing of composites, the reinforcement phase is incorporated in the

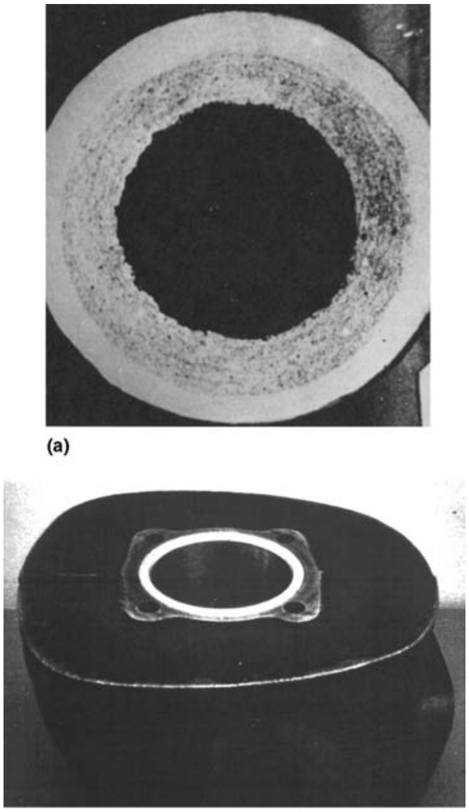


Fig. 5 (a) Centrifugally cast aluminum-graphite composite. (b) Cast iron cylinder block of a motorcycle engine fitted with an aluminum-silicon graphite liner

Table 1 Selected matrix-reinforcement combinations used to make cast metal-matrix composites

Matrix	Dispersoid	Size, μm	Amount(a)
Aluminum base	Graphite flake	20–60	0.9–0.815
	Graphite granular	15–500	1–8
	Carbon microballoons	40, thickness 1–2	...
	Shell char	125	15
	Al_2O_3 particles	3–200	3–30
	Al_2O_3 discontinuous	3–6 mm long, 15–25 μm diam	0–23 vol%
	SiC particles	9–12	3–60
	SiC whiskers	5–10	10, 0–0.5 vol%
	Mica	40–180	3–10
	SiO_2	5–53	5
	Zircon	40	0–30
	Glass particles	100–150	8
	Glass beads (spherical)	100	30
	MgO (spherical)	40	10
	Sand	75–120	36 vol%
	TiC particles	46	15
	Boron nitride particle	46	8
	Si_3N_4 particle	40	10
	Chilled iron	75–120	36 vol%
	ZrO_2	5–80	4
	TiO_2	5–80	4
	Lead	...	10
Copper base	Graphite	...	...
	Al_2O_3	11	74 vol%
	ZrO_2	5	2.12 vol%
Steel	TiO_2	8	...
	CeO_2	10	...
	Illite clay	753	3
	Graphite microballoons	...	...
Tin-base Babbit metal	Graphite particle	...	...
	Al_2O_3	...	...
Tin base	Zinc	...	...
Magnesium base	Graphite fibers	...	40–60 vol%
Zinc base	Nickel-coated graphite	...	...
	Lead	...	7

(a) In wt% unless otherwise indicated

liquid metal, which is then solidified in a mold. The possible effects of reinforcements on solidification microstructure, the property motivation for using MMCs, and present applications are discussed next. The solidification processing of composites can be divided into two main classes: stir casting and melt infiltration.

Stir Casting

In stir casting, molten metal is stirred with the help of either a mechanical stirrer (Ref 8) or high-intensity ultrasonic treatment (Ref 9–11) while the particles are added to the melt. This action disperses the reinforcing phase to create a composite melt, containing a suspension of reinforcements. Figure 6 shows a schematic view of the stir-mixing process using an impeller submerged in the melt (Ref 1). Processing of MMCs by stir mixing and casting requires special precautions, including temperature control and design of pouring and gating systems. The stir-mixed suspension of reinforcement in melts can be cast into desired shapes using a variety of conventional casting processes.

The thermodynamics and kinetics of transfer of reinforcements from the gas phase to the liquid phase through the oxide film and finally from the liquid to the solid phase is known, facilitating the development of processes to synthesize different cast MMCs (Ref 12). In several instances, coatings of wettable metals are deposited on reinforcements to facilitate their transfer into melts. For example, nickel or copper coatings are used on graphite particles that are incorporated in aluminum melts. In other cases, wetting agents, including magnesium and lithium, are added to the melts to promote wetting between the melts and reinforcements.

Stir mixing and casting are now used for large-scale production of particulate MMCs, and companies such as ALCAN market ingots of select composites including Al-SiC, which can be remelted and cast in a variety of shapes (Ref 8). Various metals, such as aluminum, magnesium, nickel, and copper, have been used as the matrix, and a wide variety of materials, such as graphite, SiC, SiO_2, Al_2O_3, Si_3N_4, and $ZrSiO_4$, have been used as reinforcements. The study of cast composites has significantly contributed to the understanding of the solidification of conventional monolithic castings, especially to the issues related to the effects of inclusions on the fluidity, viscosity, nucleation, growth, particle settling, and particle pushing.

Sand and Permanent Mold Casting. Metallic melts containing suspended ceramic particles can be cast in sand as well as permanent molds. The slow solidification rates obtained in insulating sand molds permit buoyancy-driven segregation of particles. Depending on the intrinsic hardness and density of the dispersed particles, high volume fractions of reinforcements can be concentrated at the top or bottom of a component cast by this method, to serve as selectively reinforced surfaces. Tailor-made lubricating or abrasion-resistant contact surfaces for various tribological applications have been made by this technique. Use of smaller-sized particles, thin sections of sand cast composites, and the codispersion of two types of ceramic particles, as in the case of hybrid composites, can reduce the segregation of reinforcements.

Centrifugal casting of composite melts containing particle dispersions results in the formation of two distinct zones in the solidified material: a particle-rich zone and a particle-free zone. If the particles are less dense than the melt (for example, graphite, mica, or fly ash hollow spheres in aluminum), then the particle-rich zone forms at the inner circumference. The outer zone is particle rich if the particles are denser than the melt (for example, zircon or SiC in aluminum). Centrifugal casting has been used to produce cylindrical bearings of aluminum- and copper-base composites. In these composites, the solid lubricants such as graphite are segregated at the inner periphery where they are needed for

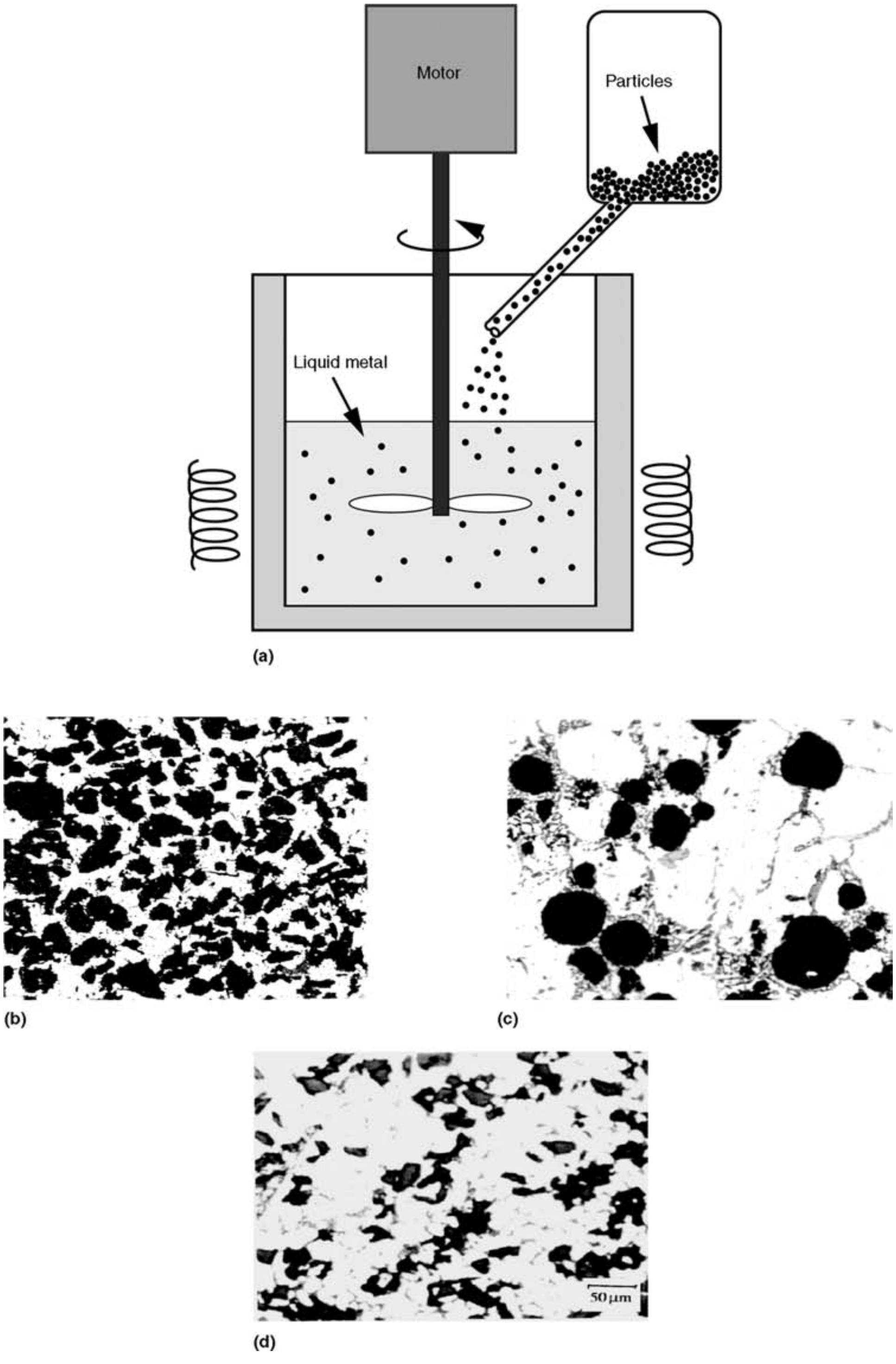


Fig. 6 (a) Schematic view of stir-casting process. Courtesy of N. Chawla. Microstructures of typical particulate cast metal-matrix composites made by stir casting: (b) Al-Si/20 vol% Gr_p, (c) Al-Si/20 vol% spherical Al_2O_{3p}, made by Comalco Australia, and (d) $Al\text{-}SiC_p$, made by Duralcan Corporation

lubrication. This technique is being used to produce selectively reinforced brake rotors, where the hard SiC reinforcement particles segregate on the outer surface of the component, improving the wear resistance.

Compocasting. Particles and discontinuous fibers of silicon carbide, titanium carbide, alumina, silicon nitride, graphite, mica, glass, slag, magnesium oxide, and boron carbide have been incorporated into vigorously agitated, partially solidified aluminum alloy slurries by the compocasting technique. The discontinuous ceramic phase is mechanically entrapped between the proeutectic phase present in the alloy slurry, which is held between its liquidus and solidus temperatures. Under mechanical agitation, such an alloy slurry exhibits thixotropy in that the viscosity decreases with increasing shear rate. This effect appears to be time-dependent and reversible. Increasing the particle residence time in the slurry promotes wetting and bond formation due to chemical reactions at the interface. This semifusion process reduces deformation resistance and allows near-net shape fabrication by extrusion or forging.

Infiltration Processes

In the infiltration technique, liquid metal is infiltrated through the narrow crevices between the fibers or particulate reinforcements, which are arranged in a preform to fix them in space (Ref 13, 14). Unlike the stir-mixing process where the reinforcements are free to float or settle in the melt, the reinforcements do not have freedom to move in the infiltration processes. As the liquid metal enters between the fibers or particles during infiltration, it cools and then solidifies, producing a composite. In general, the infiltration technique is divided into three distinct operations: the preform preparation (the reinforcement elements are assembled together into a porous body), the infiltration process (the liquid metal infiltrates the preform), and the solidification of liquid metal. In this method, a transient layer of solidified metal can form as soon as the liquid metal comes in contact with the cold fiber. Melt infiltration can be achieved with the help of mechanical pressure (Ref 15), inert gas pressure, or vacuum (Ref 16, 17). Techniques of pressureless infiltration have also been developed (Ref 18, 19), along with electromagnetic and centrifugal infiltration.

The fundamental phenomena involved in infiltration processes are surface thermodynamics, surface chemistry, fluid dynamics, and heat and solute transport. The processing variables governing the evolution of microstructures are:

- Fiber preheat temperature
- Metal superheat temperature
- Interfiber spacing
- Infiltration pressure
- Infiltration speed

If the melt or fiber temperature is too low, poorly infiltrated or porous castings will be produced. If the temperatures are too high, excessive fiber/metal reaction will degrade casting properties. Finally, if the plunger speed is too fast, the preform can be deformed on infiltration. A threshold pressure is required to initiate melt flow through a fibrous preform or powder bed. This pressure begins in the thermodynamic surface energy barrier because of nonwetting. The threshold pressure increases with increasing infiltration rates because wetting is a function of time.

Pressure Infiltration Casting. Various pressure infiltration techniques have been used to manufacture cast composites. In pressure infiltration casting, the mold and the preforms are kept at a temperature close to the melting point of the metal; this gives the metal time to flow and fill the mold without choking (Fig. 7). Once the metal has filled major voids in the mold and preform, the pressure can be increased rapidly. After this, a uniform pressure can be maintained through the mold, and the remaining voids can be infiltrated isostatically. This makes it possible to use relatively thin-walled molds and to infiltrate very fragile preforms with little damage. Even though the mold and preform start out at a high temperature, use of thin mold walls allows the mold to be cooled rapidly to minimize matrix-reinforcement interfacial reaction.

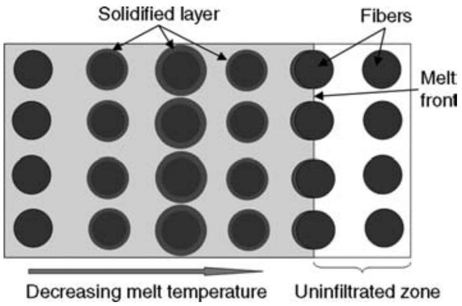


Fig. 7 Formation of composite during nonisothermal infiltration of a fiber preform by liquid metal

Squeeze Casting. In the pressure infiltration process, the liquid metal is initially under hydrodynamic pressure, which changes to hydrostatic pressure at the conclusion of preform infiltration but prior to solidification. On the other hand, during squeeze casting a premixed suspension of chopped fibers, whiskers, or particles in the matrix melt is solidified under a large hydrostatic pressure with virtually no movement of the liquid (Fig. 8) (Ref 1). Recently, squeeze casting was developed to involve unidirectional pressure infiltration of fiber preforms or particle beds in order to produce void-free, near-net shape castings of composites. Aluminosilicate fiber-reinforced aluminum alloy pistons for use in heavy diesel engines have been produced using squeeze casting. A considerable amount of work has been done on the squeeze casting of ceramic particle and fiber-reinforced MMCs for industrial applications. The fibers or particles exert a considerable influence on grain size, coarsening kinetics, and microsegregation in the matrix alloy. Squeeze casting promotes a fine, equiaxed grain structure because of large undercoolings and rapid heat extraction.

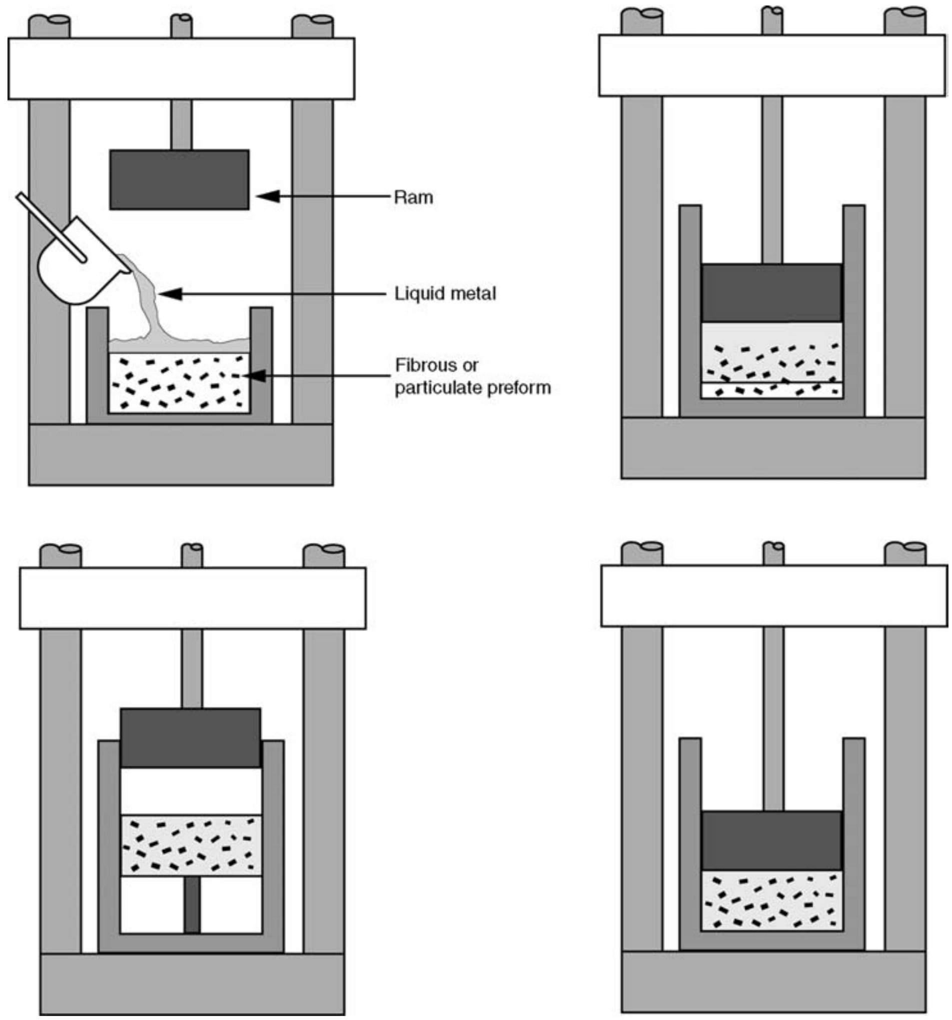


Fig. 8 Schematic representation of squeeze casting process. Courtesy of N. Chawla

Vacuum infiltration is effected by creating a negative pressure differential between the preform and the surroundings, which drives the liquid through preform interstices against the forces of surface tension, gravity, and viscous drag. Vacuum infiltration is usually done in conjunction with chemical methods of wettability enhancement, for example, fiber surface modification or addition of wetting-enhancing elements to the matrix alloy. Vacuum infiltration has been used by AVCO Specialty Materials (Textron) to infiltrate silicon-coated SiC monofilaments with aluminum, and by DuPont to infiltrate alumina fiber preforms with an aluminum-lithium alloy.

Electromagnetic Infiltration. The use of electromagnetic forces to infiltrate liquid metal into nonwetting preforms can dispense with the need for application of inert gas pressure and mechanically driven rams (Ref 20). Alumina fiber/aluminum composites have been fabricated using the electromagnetic infiltration technique. In this technique, the metal is subjected to a high-frequency electromagnetic field that interacts with the eddy currents produced within the metal. The interaction results in infiltrating the metal into the preform when the preform is suitably oriented with respect to the direction of the force. In a typical experimental design, a fiber preform is immersed in liquid metal contained in a ceramic crucible. A battery of capacitors is used to produce intense bursts of high-frequency axial magnetic field. A flux concentrator intensifies the magnetic field around the crucible. The entire assembly is configured such that body forces produced within the metal are oriented radially inward to enable melt ingress into the preform. Porosity, preform deformation, and fiber breakage are absent in the castings at the completion of infiltration and solidification. Aluminum-matrix composites reinforced with up to 25 vol% alumina fiber (Saffil, Saffil Ltd.) have been successfully produced using this technique.

Centrifugal Infiltration. Infiltration can be achieved using centrifugal force to fabricate MMCs. High rotational speeds are able to generate enough centrifugal force to overcome the capillary forces for melt penetration and viscous forces for metal flow in the preform. Aluminum-matrix composites containing fly ash and carbon microballoons were successfully fabricated by using centrifugal infiltration (Ref 21). The microballoons were packed in an alumina tube, which acts as a crucible for the molten metal poured onto the powder bed. The infiltration and dispersion of powders were carried out at rotational speeds of up to 4000 rpm, and the rotation was continued until the solidification was completed. During rotation, the centrifugal force pressurizes the molten metal into the interstices of the particle bed. As the rotation is continued through the solidification process, the particles are "frozen-in" at their final position in the casting.

Pressureless Spontaneous Infiltration. Spontaneous infiltration of preforms or permeable bodies of reinforcements by metals can be effected if the compositions of the melt and preform, temperatures, and gas atmosphere are controlled such that good wetting conditions are achieved. A cost-effective pressureless infiltration process to fabricate void-free, net-shape MMCs having high structural integrity has been developed by Lanxide Corporation, USA. The technique permits fabrication of composite components containing a wide range of reinforcements. Near-net shape SiC-reinforced aluminum-matrix composite components for electronic applications such as heat sinks have been synthesized by using pressureless infiltration of preforms. In the directed-metal oxidation process (a form of the Lanxide process), an ingot of aluminum alloy containing magnesium is placed on top of a permeable body of reinforcement or preform contained within a refractory vessel. The entire assembly is heated to a suitable temperature in an atmosphere of a free-flowing, nitrogen-bearing gas mixture. Spontaneous infiltration of the permeable reinforcement is assisted by the presence of magnesium in the alloy and an oxygen-free atmosphere. In a modified pressureless metal infiltration process (called PRIMEX, M Cubed Technologies, Inc.), magnesium in the matrix alloy volatilizes and reacts with nitrogen in the atmosphere to form a thin Mg_3N_2 coating on the reinforcement surface that makes the reinforcement system wettable. During infiltration, Mg_3N_2 reacts with aluminum to form aluminum nitride (AlN) and magnesium, which is released in the alloy. The AlN could be formed through direct reaction of nitrogen in the atmosphere with liquid aluminum. The A1N phase is present mainly as small precipitates in the composite, although thin films of this compound are also found as coating on the reinforcement surface. The spontaneous infiltration step can be followed by a mixing step prior to casting.

Advanced Pressure Infiltration Casting. MMCs containing hard reinforcements such as SiC are difficult to machine. Therefore, development of near-net shape components of MMCs is desirable. Generally, pressure infiltration technology is directed to producing near-net shape components. Special preforms can be prepared for these MMCs. These preforms have fine interstices through which the liquid metal is infiltrated. The preforms are encapsulated in a graphite mold and placed in a furnace. Liquid metal is poured and pressure is applied, causing the melt to pass through the mold and infiltrate the preform. Figure 9 shows alumina preforms of piston connecting rods developed by MMCC, Inc. and Fig. 10 schematically shows the advanced pressure

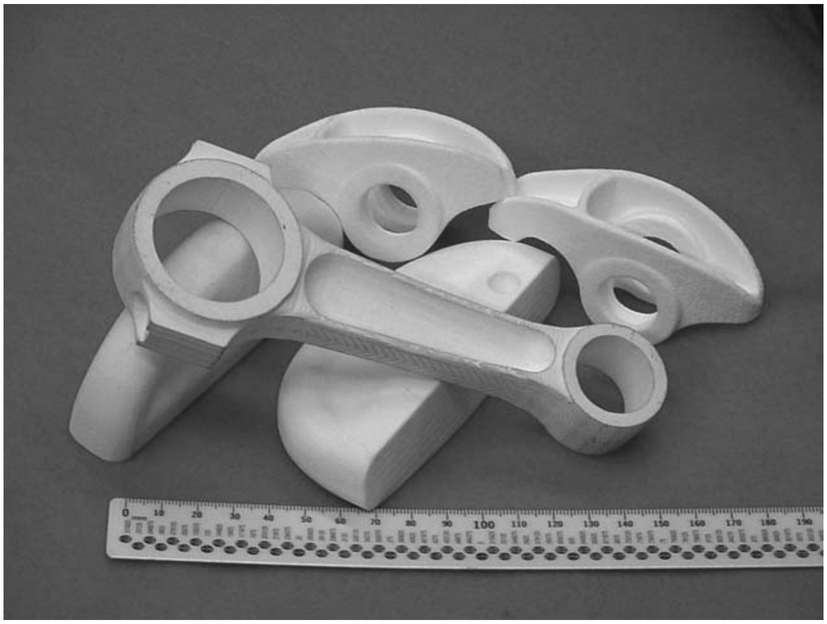


Fig. 9 Alumina preforms printed at MMCC, Inc.

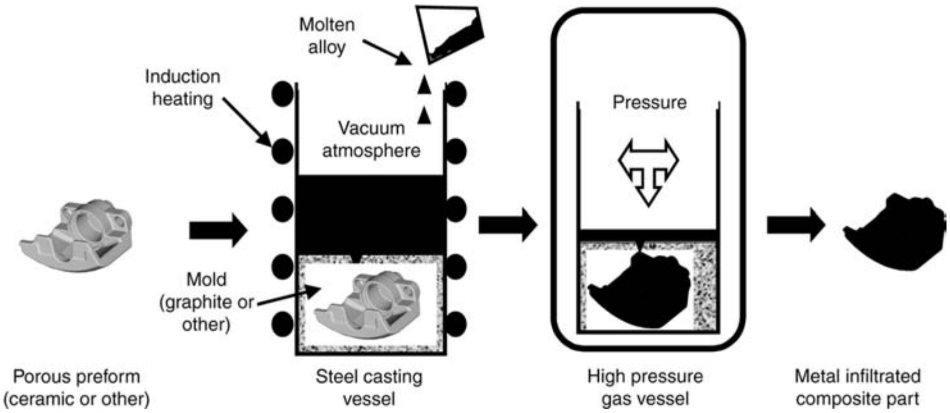


Fig. 10 Schematic of the advanced pressure infiltration casting (APIC, MMCC, Inc.) process

infiltration casting (APIC, MMCC, Inc.) process that can use such preforms (Ref 5). The main feature of this process is that the melting of the matrix metal and the preheating of the preform take place outside of the autoclave. This technique is now available to produce near-net shape pressure-infiltrated parts of MMCs.

Effects of Reinforcement Present in the Liquid Alloy on Solidification

The solidification microstructure of the matrix alloy is affected by the presence of reinforcement phase. The reinforcement can:

- Act as a solute and diffusion barrier within the melt
- Catalyze heterogeneous nucleation in the melt
- Influence the conductivity of the liquid
- Influence the viscosity and fluidity of the melt and impart thixotropic properties
- Restrict fluid convection due to restriction of liquid in narrow interstices between fibers or particles
- Settle or float due to density differences
- Influence morphological instabilities, including planer-to-dendritic solidification
- Be pushed or entrapped ahead of the solidifying interface
- Influence dendrite arm coarsening
- Influence grain size
- Reduce the amount of latent heat to be extracted out of the casting

The aforementioned effects have been discussed in several studies. Particles have been shown to settle or float in the melt and are frequently pushed in the last freezing interdendritic liquid by the growing solid-liquid interface (Ref 22–24). The effect of reinforcements on solidification processes, more specifically, on

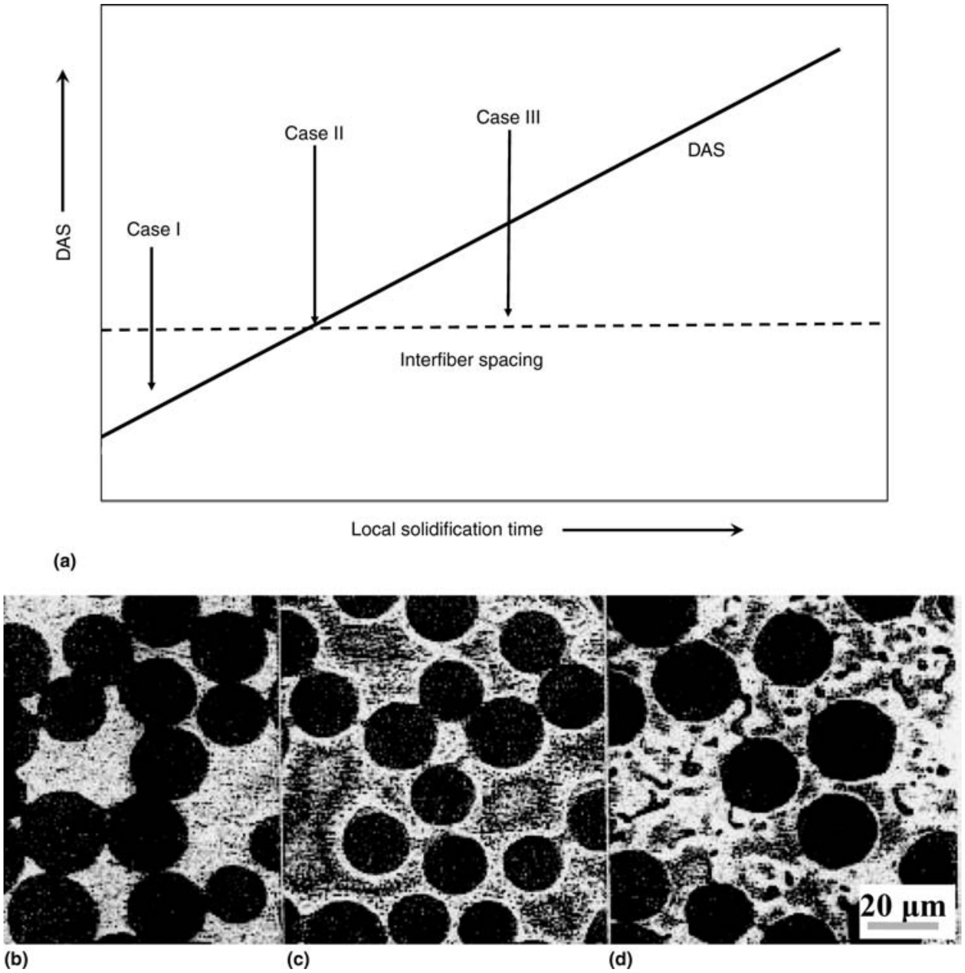


Fig. 11 (a) Graph of dendrite arm spacing (DAS) versus solidification time. (b), (c), to (d) Microstructural formation in the interfiber regions of an Al-4.5Cu-alumina fiber composite. The solidification times will vary with material.

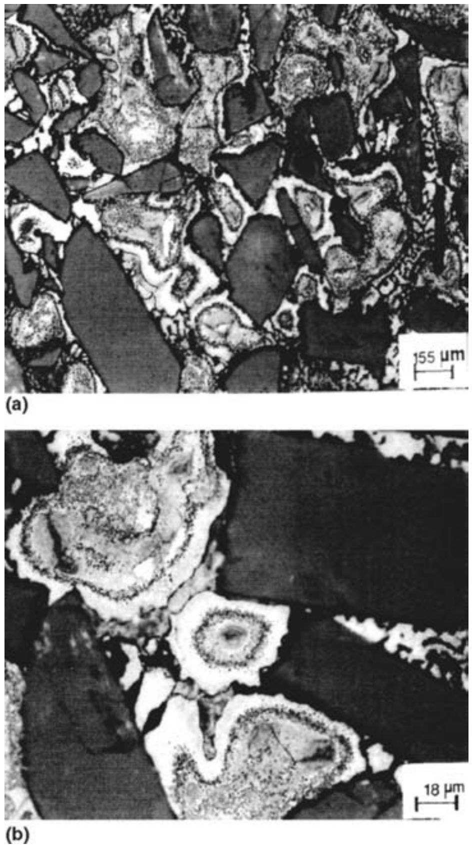


Fig. 12 Solidification microstructure of discontinuously reinforced Al-SiC alloy composites showing the influence of spacing between SiC platelets on the microsegregation pattern in aluminum-copper alloys

dendrite formation and microsegregation, is discussed in some detail.

Figure 11 shows the effect of alumina fiber spacing on the microstructure of Al-4.5% Cu alloy (Ref 25). The primary phase morphology and distribution of second phases depend on the relative magnitudes of dendrite arm spacing (DAS) and the interfiber spacing. Figure 11 shows that when the DAS is less than the interfiber spacing, a normal solidification microstructure is observed, and the fiber does not alter the microstructure. When the DAS is equal to the interfiber spacing, the second phase, that is, Al-$CuAl_2$ eutectic, segregates onto the fiber surface. Finally, when the DAS is more than the interfiber spacing, the dendritic morphology is ill-defined, and there is less precipitation of secondary phase. In this case, the fibers act as barriers to solute precipitation, and, as a result, the concentration of solute in aluminum will be more than the equilibrium value. This is important because it is possible to create microstructures with no dendrites and reduce microsegregation, resulting in decreasing homogenization time during heat treatment.

Figure 12 shows the microstructure of SiC platelets incorporated in the matrix of an aluminum-copper alloy by pressure infiltration. It shows frequent enrichment of Al-$CuAl_2$ eutectic at the SiC platelet-matrix interface as a result of nucleation of the α-phase away from the platelets (Ref 26). Figure 12 also shows significant effects of platelet spacing on microsegregration.

It is clear from Fig. 11 and 12 that reinforcements alter the solidification microstructure of alloys to a great extent, due to the restriction of spaces between which the liquid solidifies. This can be exploited to create improved microstructures in composites.

Property Motivation for Using MMCs

In MMCs, the second phases (fibers, whiskers, particles) are incorporated in metals or alloys to achieve properties that are not obtainable in conventional monolithic materials. Desired improvements in mechanical, tribological, electrical, and thermal properties can be achieved by intelligently selecting the reinforcement materials and their size, shape, and volume fraction. Table 1 shows the selected reinforcements and metallic matrices commonly used for synthesis of MMCs.

Figure 13 shows a plot of specific modulus versus specific strength for a number of materials (Ref 27). Ideally, one would like a material to be near the upper right-hand corner of the graph, where one can obtain a combination of high specific strength and high specific modulus to minimize the weight of a component. It is clear that MMCs provide a better combination of specific strength and modulus compared to monolithic alloys of aluminum, magnesium, copper, nickel, and iron. Only a few materials are better than reinforced-aluminum composites. These include graphite-epoxy composites (along the fiber direction), pure ceramics, and diamond, although they are more expensive and some of them are brittle. Figure 14 shows that the specific cost of organic composites is much higher than MMCs for similar specific stiffness (Ref 27).

In many applications, the resistance to distortion from thermal or mechanical loads is important, especially in precision devices. The higher the stiffness and thermal conductivity of the composite and the lower the coefficient of thermal expansion (CTE), the higher will be its resistance to mechanical and thermal distortion.

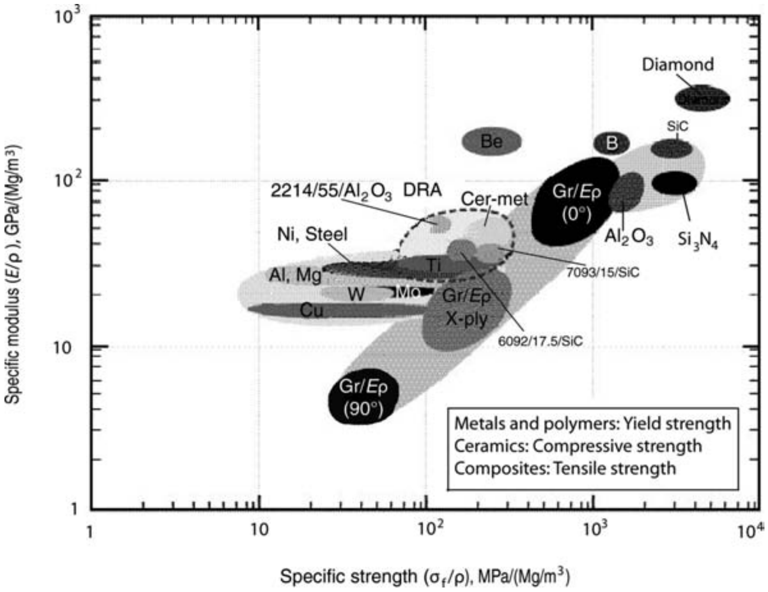


Fig. 13 Specific modulus and specific strength of various structural materials

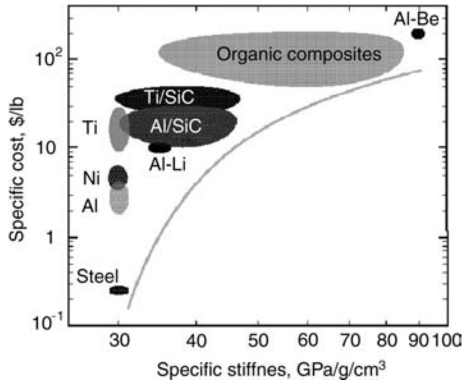


Fig. 14 Specific cost of various structural materials in primary product forms

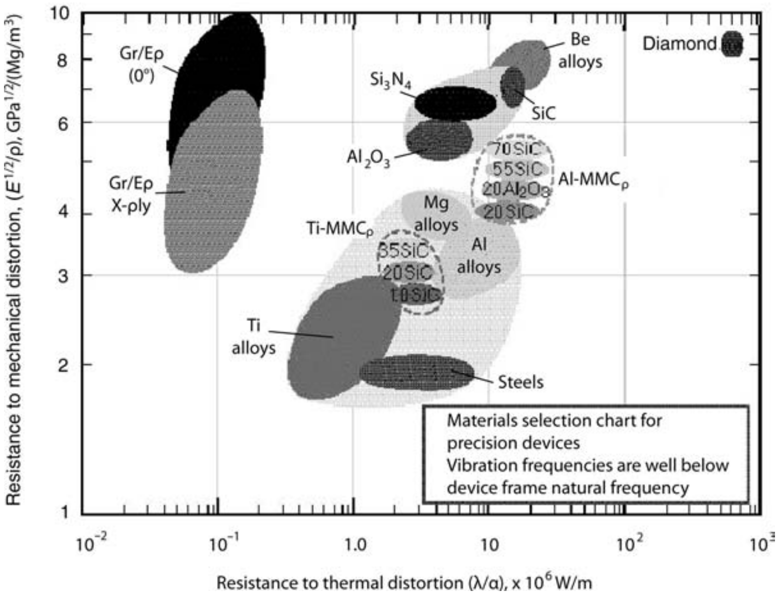


Fig. 15 Materials selection chart for resistance to mechanical and thermal distortions

Figure 15 shows the materials selection chart for resistance to mechanical and thermal distortions (Ref 27). It is observed that the closer a material is to the top right-hand corner of the chart, the higher will be its resistance to thermal and mechanical distortion. This figure shows that MMCs have one of the highest resistances to mechanical and thermal distortion, with the exceptions of beryllium and diamond.

MMCs are also becoming very popular for thermal management applications (Ref 28). For such applications, the CTE, thermal conductivity, and density are the important properties. Figure 16 shows a plot of CTE versus specific thermal conductivity. It is desired that for a given CTE value, the thermal conductivity should be as high as possible. This figure shows that for the allowable range of thermal expansion for thermal management in electronic packaging, MMCs have one of the highest specific thermal conductivities, making them a desirable choice. In fact, only beryllium-containing materials and diamond are better than MMCs. Therefore, an increasing role of MMCs in thermal management applications is expected.

The hardness of MMCs is significantly higher than that of the unreinforced-matrix alloys. Hardness increases with increasing volume fraction of reinforcement and is affected by processing variables. Also, the addition of ceramic phase in metallic matrices improves the friction and wear behavior. Figure 17 shows the wear resistance of A356 alloy and A356-SiC composite against 4140 steel. The wear loss of the composite is approximately 10 times less than that of the matrix alloy. The wear resistance of aluminum-matrix composites is better than that of cast irons, which are much heavier. Further improvement in the wear resistance of alloys can be achieved by developing hybrid composites reinforced with hard phases and soft-phase lubrication (Ref 29). For example, the transition from mild to severe wear occurred in the range of 225 to 230 °C (435 to 445 °F) for A356 alloys (Ref 30, 31). With the addition of 20 vol% SiC to the A356 alloy, the transition temperature increased to 400 to 450 °C (750 to 840 °F). A hybrid A356-matrix composite containing 20 vol% SiC and 10 vol% graphite remained in a mild wear regime even at the test temperature of 460 °C (860 °F).

Components of MMCs Currently in Use

MMCs, in view of their excellent combination of properties such as high levels of strength and stiffness, improved thermal stability, low CTE, and improved wear and seizure resistance, have already found several applications.

It is estimated that in the year 1999, the worldwide composite use was approximately 2.5 million kg (2750 ton) and increased to approximately 3.5 million kg (3850 ton) in the year 2004 (Ref 32, 33). The annual growth rate of MMCs has been approximately 6% in recent years (Ref 34). One of the reasons for limited use of MMCs is their cost. The higher cost of MMCs compared to the corresponding base alloy is due to the higher cost of fiber, more rigorous processing methods, and the difficulty in machining. However, in recent times, decreasing cost of fibers, modification of conventional metal-processing methods for processing composites, and the development of net or near-net shape components are contributing to the decrease in the cost of MMC components.

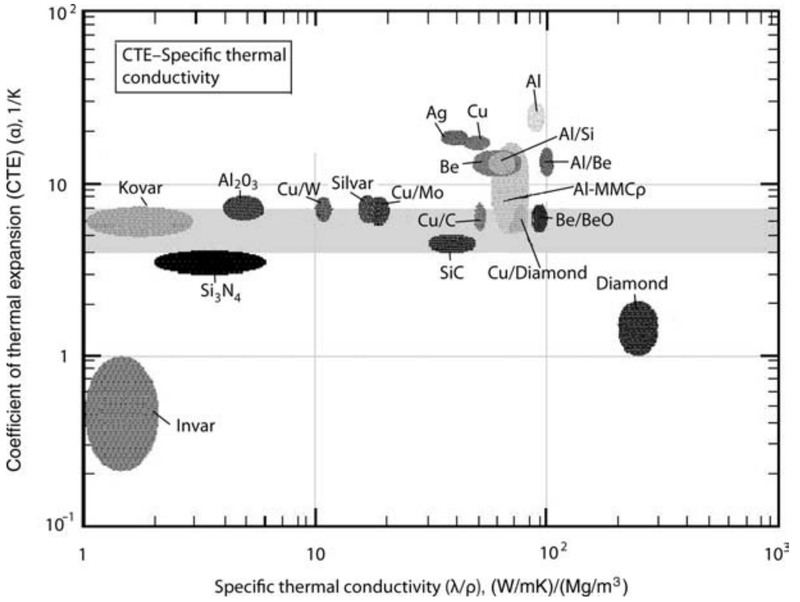


Fig. 16 Materials selection chart for thermal management applications

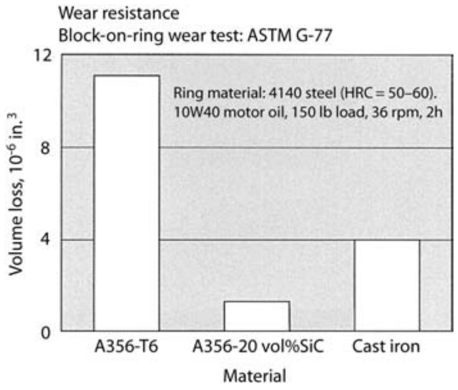


Fig. 17 Volume loss of aluminum alloy, aluminum composite, and cast iron during sliding wear

Fig. 18 An Al-SiC$_p$ composite brake rotor developed for the Chrysler Prowler

Table 2 Use of metal-matrix composites (MMCs) in automotive applications

Year	Company	Composite and component
1980	Toyota	First commercially produced MMC diesel piston by squeeze infiltration in ceramic preform
1990	Honda	Four-cylinder 2.2 L MMC engine block selectively reinforced with mixture of Saffil, alumina, and graphite fibers
1992	Toyota	Selectively reinforced low Coefficient of thermal expansion fiber engine pulley
1996	Toyota	Alumina-boria whisker-reinforced piston
1997	Toyota	Al/SiC$_p$ front brake rotors for an electric vehicle (RAV4-EV)
1997	Toyota	Heat-spreader plates of an electronic cooling device (Prius hybrid vehicle)
1997	Porsche	Porsche Boxter selectively reinforced cylinder bores
1997	GM	Al-SiC$_p$ MMC engine cradle
1997	GM	Extruded aluminum MMC propshaft on the Corvette
1997	GM	Al-SiC$_p$ driveshaft for extended S/T trucks
1998	Honda	Produced selectively reinforced bore V6 engine for Acura NSX
1998	GM	Used several MMC components (rear brake drum, electronic cooling package) for GM electric vehicle (GM-EVI)
1998	Chrysler	Used Al-SiC$_p$ brake rotors for its Prowler model
1999	Mazda	Produced fiber/particle MMC piston
1999	Lotus	Released Al-SiC$_p$ MMC brake rotors in Elise
1999	Volkswagen	Low-fuel 3 L version of the Lupo model with rear-wheel Al-SiC$_p$ brake drums
2000	Honda	Bore-reinforced in-line four-cylinder engine for its S2000 roadster
2000	Toyota	In-line four-cylinder engine for high-performance Celica with MMC bores

Source: Ref 35

There has been a dramatic decrease in the cost of particle-reinforced MMCs primarily due to the low cost of stir-mixing and casting processes and the use of inexpensive particles.

MMCs in Automotive Industries

A number of automotive components, including pistons, cylinder liners, brake rotors, and connecting rods, have been made of aluminum-matrix composites. Table 2 shows some significant early developments of composite automotive components (Ref 35).

Properties of interest to the automotive engineer include increased specific stiffness, wear resistance, and improved high-cycle fatigue resistance. While weight-savings is also important in automotive applications, the need to achieve performance improvements with much lower cost premiums than tolerated by aerospace applications drives attention toward low-cost materials and processes. The raw material cost of cast iron or steel is less than \$0.82/kg (\$0.37/lb), and discontinuously reinforced cast aluminum ingot currently costs approximately \$4.0 to 5.0/kg (\$1.8 to 2.3/lb) for large-scale production, so the raw material cost of MMCs is higher than that of the material typically replaced. However, the MMC component would typically weigh 60% less than steel, significantly improving the cost comparison. Examples of MMCs in successful automotive applications, in which the combination of properties and cost satisfied particular needs, are discussed as follows.

The first commercially made automotive MMC component was a diesel engine piston produced by Toyota, Japan, in the early 1980s (Ref 6). The piston was produced by squeeze casting technology, in which liquid aluminum was infiltrated in alumina-silica short fibers. The ceramic preform was selectively placed in the ring portion of the piston. Later on, this technology was refined by blending nickel powder into an alumina fiber preform. In this method, nickel powder reacted with aluminum and formed $NiAl_3$, which improved the adhesive wear resistance of the ring (Ref 6). Selectively reinforced aluminum composite diesel engine pistons have now become very popular throughout the world. In fact, this has triggered a flurry of activities in making other engine components from cast composites. Further, Toyota developed another MMC piston in which the preform was made of alumina-boria whisker and was selectively reinforced in the lip of the combustion bowl of the piston. In 1999, Mazda began producing pistons of fiber/particle-reinforced MMCs.

Another major use of Al-SiC$_p$ composite is for brake rotor applications. Testing has shown that composite brake rotors are as effective as cast iron rotors in braking applications, while having a higher capacity for heat dissipation and 50 to 60% lower weight. Figure 18 shows an Al-SiC$_p$ composite brake rotor used in the Chrysler Prowler. Toyota has also used A359/20 vol% SiC$_p$ composite brake rotors in their electric vehicle (RAV4-EV), as shown in Fig. 19 (Ref 36). The Lotus Elise was also released with

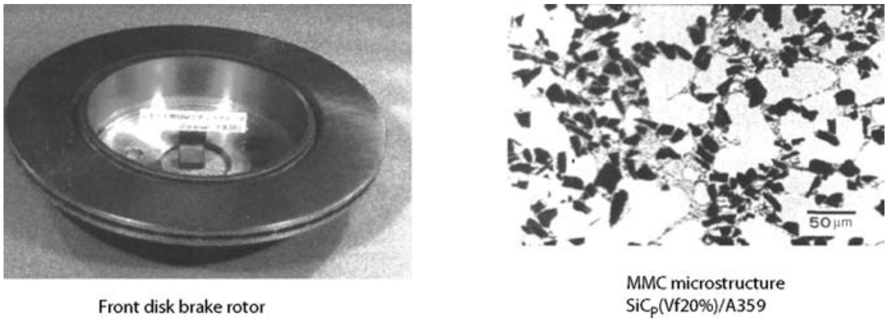


Fig. 19 An A359/20 vol% SiC_p composite brake rotor for a Toyota electric vehicle

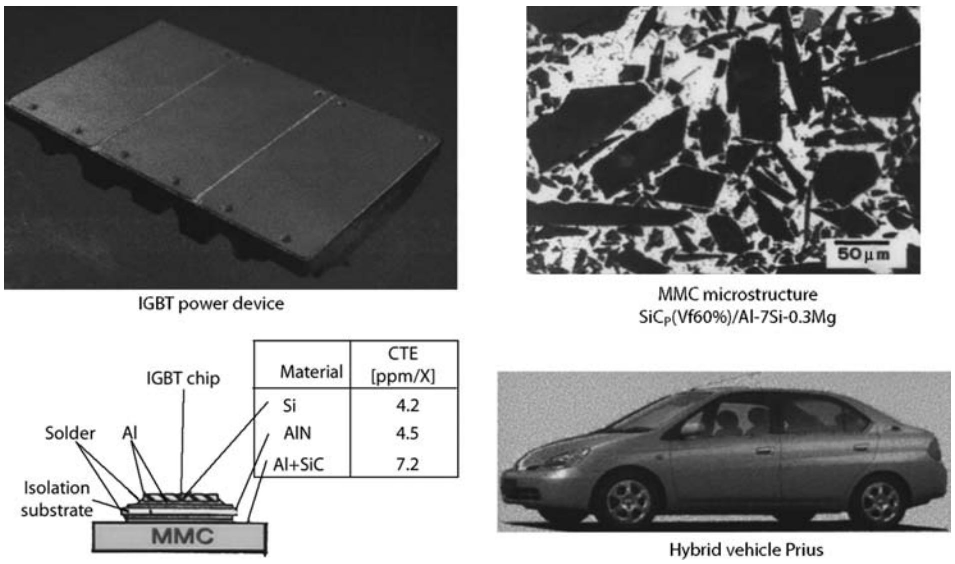


Fig. 20 Aluminum-SiC composites as heat-spreader plates of an electronic cooling device for the world's first hybrid vehicle, the Prius

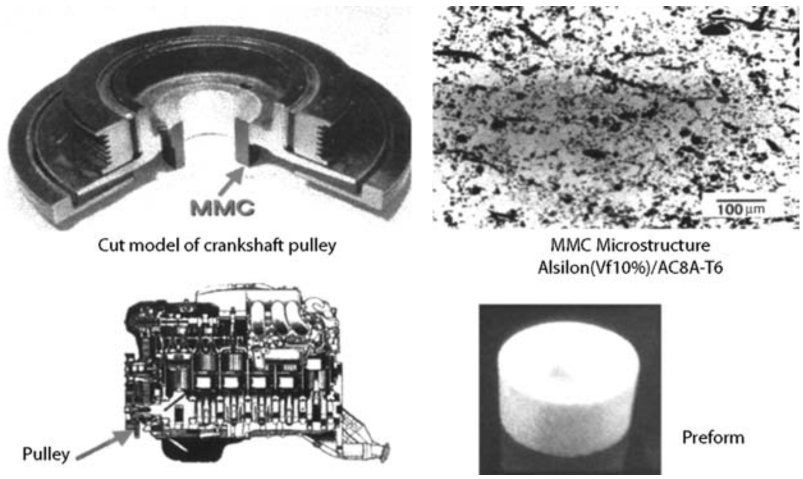


Fig. 21 Metal-matrix composite (MMC) crankshaft pulley made by infiltration of SIALON preform with aluminum

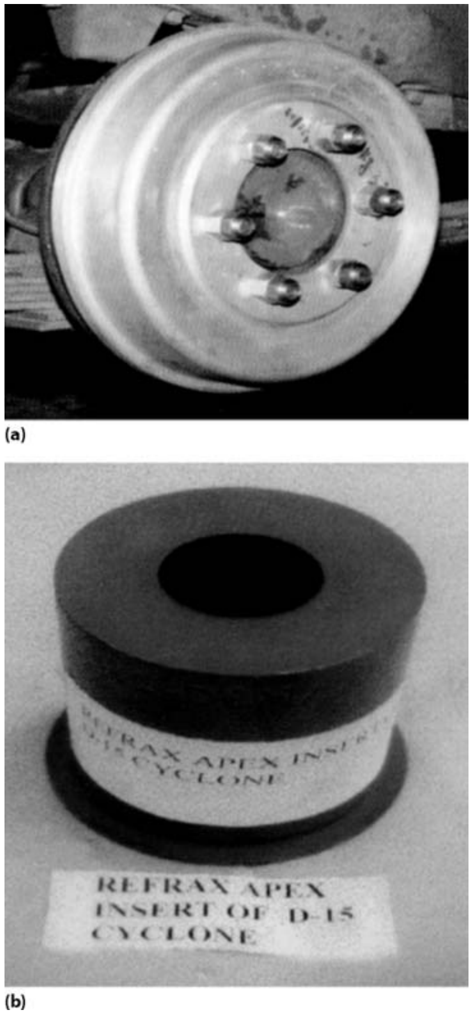


Fig. 22 Aluminum-SiC composite components. (a) Automobile brake drum. (b) Apex insert for cyclone

Al-SiC_p composite brake rotors. The Volkswagen low-fuel version of the Lupo model also had Al-SiC_p composite brake rotors in the rear wheels.

Aluminum-SiC composites were found to be very effective as heat-spreader plates of an electronic cooling device for the world's first hybrid vehicle, the Prius (Fig. 20) (Ref 36). Toyota has also developed a cylinder block with MMC bores for a high-performance spark ignition engine. The ceramic preform was made from alumina-silica short fibers filled with mullite particles. The MMC bore was made by a laminar flow die casting process. This cylinder block, with MMC cylinder bore, was introduced in the 2000 model Celica sports car.

Toyota developed an MMC crankshaft pulley that has a low CTE and does not expand away from the shaft during thermal cycling (Fig. 21). In this application, a ceramic preform was made of SIALON (Si-Al-O-N) and was infiltrated with aluminum.

Figure 22 shows prototypes of an automobile brake drum and a refrax apex insert made of Al-SiC_p composites produced at the laboratories of Council of Scientific and Industrial Research in Bhopal, India. There is a large market for cast composites in Asia, where the energy costs are very high, and replacing energy-intensive materials such as aluminum

Fig. 23 Boron-aluminum composite tubular struts used as the frame and ribs in space shuttle Orbiter. Struts are not cast but represent a category of metal-matrix composite applications.

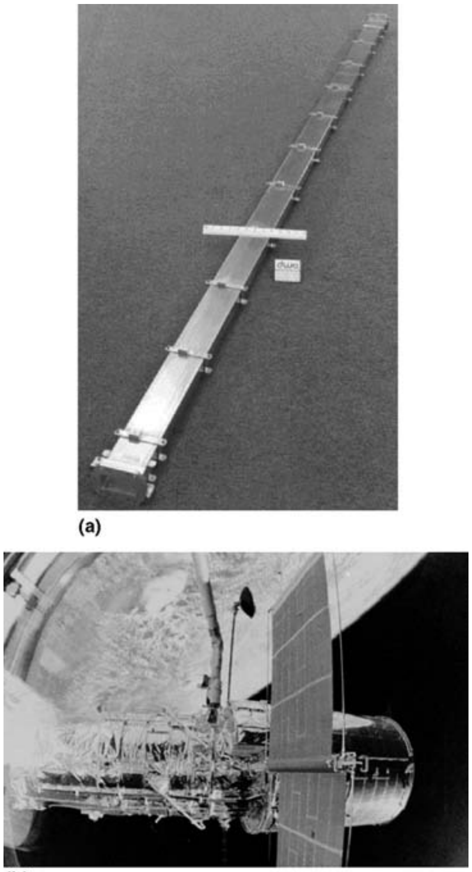


Fig. 24 The P-100/6061 aluminum high-gain antenna wave guides/boom for the Hubble Space Telescope (HST). (a) Before integration in the HST. (The ruler is 12 cm, or 5 in., long.) (b) On the HST as it is deployed in low-Earth orbit from the space shuttle Orbiter

with particulate reinforcements can result in considerable energy-savings (Ref 4).

MMCs for Space Applications

The extreme environment in space presents both a challenge and an opportunity for material scientists. In the near-Earth orbit, typical spacecrafts encounter naturally occurring phenomena such as vacuum, thermal radiation, atomic oxygen, ionizing radiation, and plasma, along with factors such as micrometeoroids and human-made debris. Therefore, aerospace applications were the original driving force for the development of MMCs. This development was due to the quest for dimensionally stable structures and weight reduction for improved performance and payload capability. The primary motivation for the insertion of MMCs into aerospace applications is the excellent balance of specific strength and stiffness offered by MMCs relative to competing structural materials.

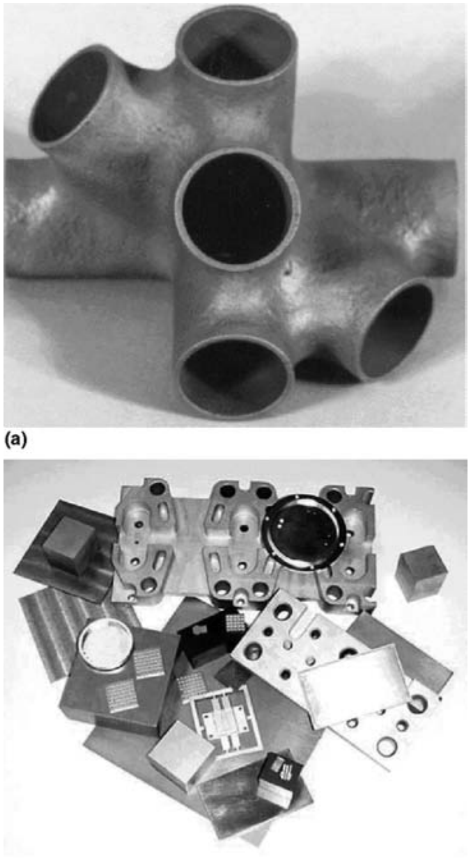


Fig. 25 Discontinuously reinforced aluminum metal-matrix composites. (a) Multi-inlet SiC_p-Al truss node. (b) Gr_p-Al composite components for electronic packaging applications

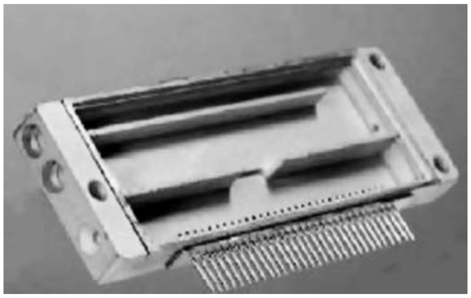


Fig. 26 Aluminum-SiC microwave radio frequency packaging for communication satellites

The SiC particle-reinforced MMCs are used in the Lockheed F-16 fighter aircraft. For instance, the use of MMCs reduces the maximum deflection of the leading-edge tip of the ventral fin in an F-l6 aircraft by over 50%, reducing the aerodynamic loads and increasing the service life from 400 to 8000 h. Aluminum alloy skins used in the honeycomb structure of the fin were replaced by 6092 Al-17.5 vol% SiC_p composite sheet material. The service life of the skins was significantly increased because of the increased specific stiffness of the aluminum-matrix composite material (Ref 37).

Although not produced by casting, one of the major space-based applications of continuous fiber-reinforced MMCs is structural tubes for space shuttles. Figure 23 shows space shuttle Orbiter's midfuselage main frame MMC tubes (Ref 38). These tubes were made of 50 vol% B fiber-reinforced aluminum-6061 alloy composites, produced by the diffusion-bonding technique. There are 243 MMC tubes of 25 to 92 mm (1 to 3.6 in.) diameter and 0.6 to 2.4 m (2 to 8 ft) length. The MMC tubes saved approximately 145 kg (320 lb) over the initial design of aluminum tubes. Another major development is the application of MMCs in an antenna wave-guide mast on the Hubble Space Telescope (Fig. 24) (Ref 38). The mast is made by infiltration technology using a preform containing 40% P-100 carbon fibers. Aluminum alloy 6061 was used as the matrix material. The mast is rectangular and has dimensions of 43 by 86 by 2000 mm (1.7 by 3.4 by 79 in.) (Ref 38). Cast Al-SiC_p and Al-SiC_w composites have also found applications as multi-inlet truss nodes and electronic packaging (Fig. 25) (Ref 38). General Electric Company designed an advanced-composite optical system gimbal, using 6061–40 vol% SiC_p composite in selected areas, requiring low expansion and high wear resistance.

MMCs for Electronic Packaging Applications

MMCs are also finding applications in spacecraft thermal management systems. Cast MMCs are very suitable for thermal management applications due to their high conductivity and low CTE. Figure 26 shows a typical radio frequency packaging for microwave transmitters used in commercial low-Earth orbit communication satellites (Ref 27). This Al-SiC composite part is cast to near-net shape. Aluminum-SiC is not only lighter than the existing materials, but it is much more affordable. The PRIMEX pressureless melt infiltration process is used to produce high-volume-fraction SiC-reinforced aluminum composites for such applications.

MMCs consisting of carbon fibers having high conductivity are also being employed in packaging and thermal management applications. There are relatively few applications to date of MMCs reinforced with continuous fibers, because they are relatively expensive. However, recent developments in fabrication methods have resulted in significant cost reductions for discontinuous-fiber MMCs, and these materials are now entering production lines.

Development of Select Cast MMCs

Aluminum-Graphite Composite

Cast aluminum-graphite particulate composites have been used in several applications, such as pistons, engine cylinder liners, and connecting rods, as shown in Fig. 27. These are the forerunners of aluminum-graphite engines being developed for antiseizing applications (Ref 12).

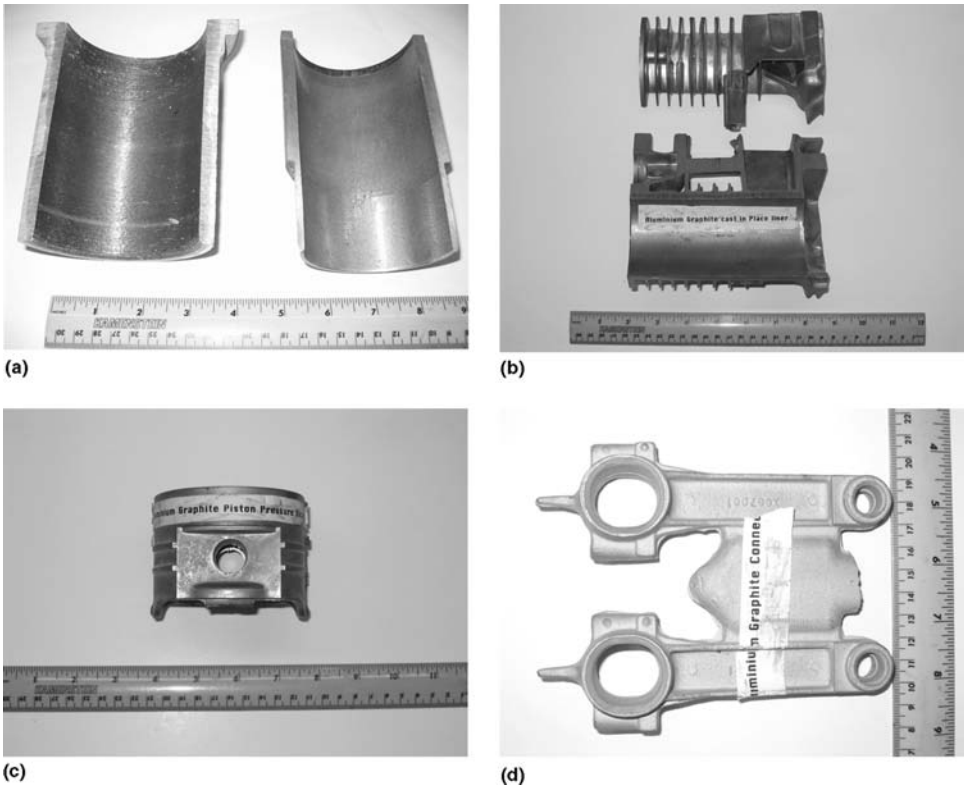


Fig. 27 Components made of aluminum-graphite composites. (a) Cylinder. (b) Cylinder liner. (c) Piston. (d) Connecting rods

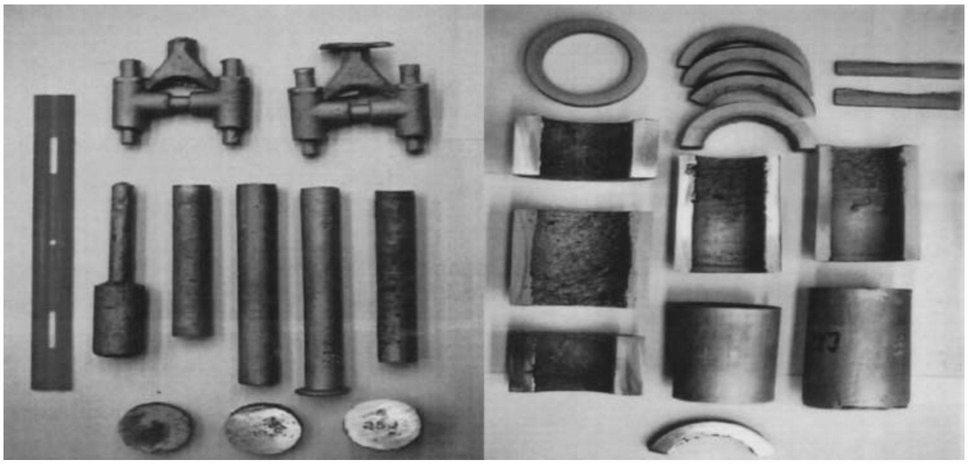


Fig. 28 Montage of lead-free copper-graphite composite castings

Lead-Free Copper Alloy/Graphite Composites

Since lead is banned in a number of copper alloys for bearing and plumbing applications, lead-free copper-graphite composites have been developed as a substitute. Graphite particles have been shown to impart machinability and lubrication characteristics similar to lead at much lower costs and without the associated toxicity. Graphite is also much cheaper and abundantly available compared to bismuth and selenium, which are being proposed as alternatives to lead. Figure 28 shows a collection of plumbing fixtures and bearings cast in copper-graphite composites at the University of Wisconsin-Milwaukee. By centrifugally casting copper alloy/graphite composite, the graphite particles can be concentrated on the inner periphery, where they selectively reinforce and provide solid lubrication for bearing applications. Figure 29 shows the microstructure from the cylinder graphite-rich zone near the inner periphery, which shows dendrites of copper and graphite particles present in the interdendritic regions (Ref 39). A comparison of wear losses of copper-graphite and lead-copper against 1040 steel reveals that the copper-graphite composite shows much less wear than the lead-copper alloy, demonstrating its suitability for bearing applications (Ref 39).

Hybrid Composites

Figure 30(a) shows hybrid composites containing both small SiC particles, which are hard, and large graphite particles, which are soft, in the matrix of a cast aluminum alloy. The production process is simplified by the simultaneous presence of two types of particles (the lighter graphite and heavier SiC). Together, they result in a buoyancy-neutral mixture where SiC is unable to settle down (due to the graphite, which is lighter and is trying to float up), and the graphite particles are unable to float up (due to the hindering effect of the SiC, which is trying to settle down). Tests at International Nickel Company and other

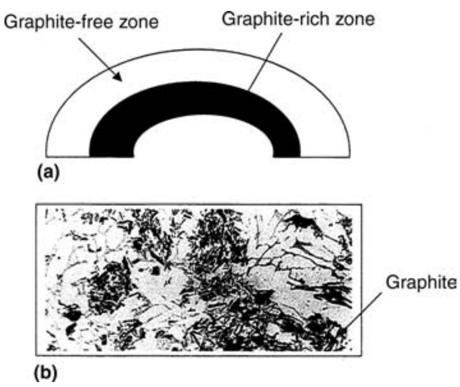


Fig. 29 (a) Schematic view of centrifugally cast copper-graphite alloy. (b) Microstructure of the graphite-rich zone

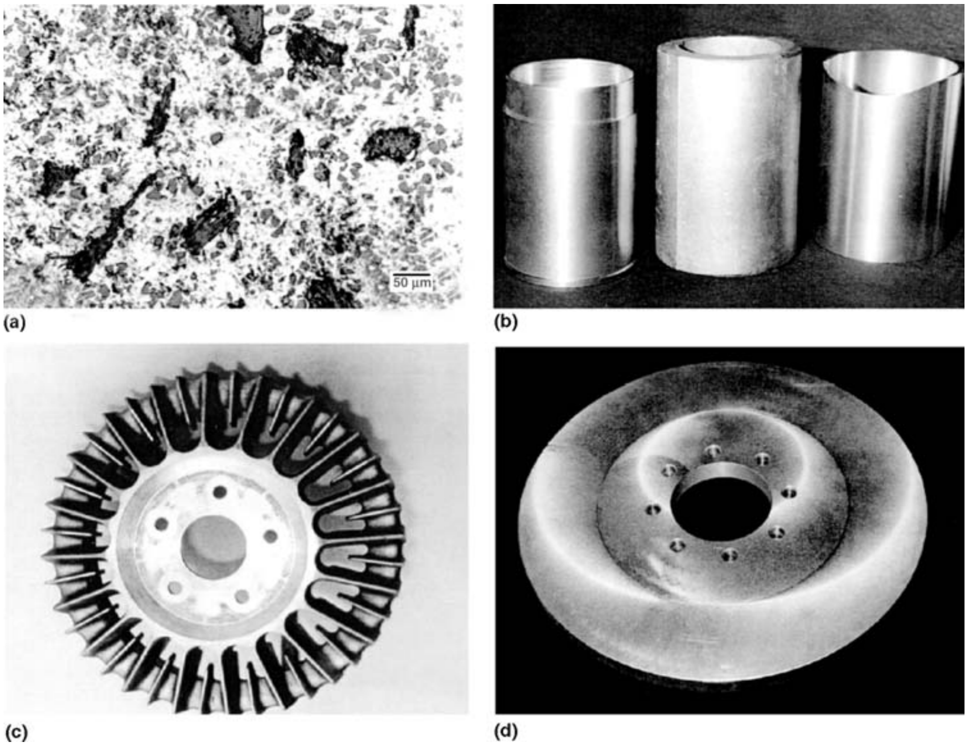


Fig. 30 (a) Microstructure of Al-SiC-graphite hybrid composite. (b) Cylinder liners made out of hybrid composites. (c) Hybrid composite disc brake. (d) Hybrid composite brake rotor

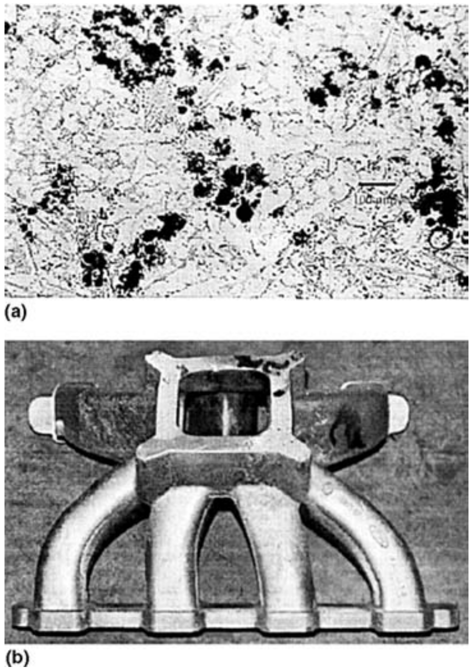


Fig. 32 (a) Microstructure of A356–10 vol% fly ash composite. (b) Intake manifold made of such a composite

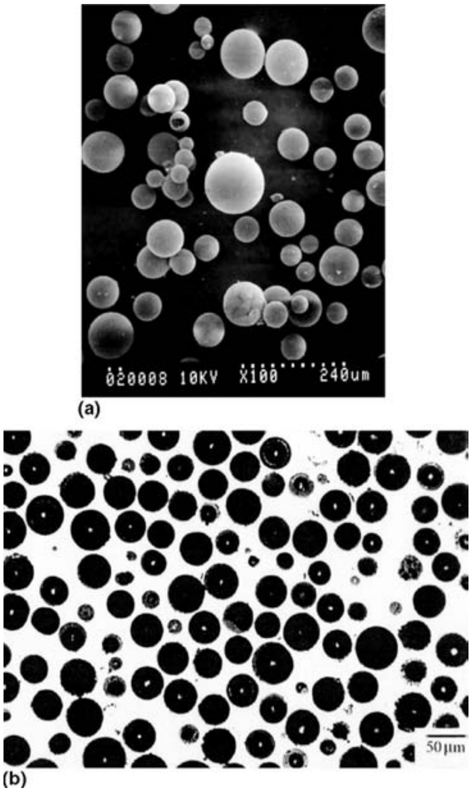


Fig. 31 (a) Fly ash cenospheres. (b) Fly ash cenospheres in α-aluminum matrix

organizations have shown that the wear resistance of these hybrid Al-SiC-graphite composites is greater than that of cast iron, and they are much easier to machine compared to Al-SiC composites. Figure 30(b–d) show cylinder liners, a brake rotor, and a disc brake, all made from aluminum-hybrid composites that are being tested as a replacement material for much heavier cast iron components (Ref 40). Several other hybrid composites, including Al-aluminum-graphite, have been developed, and their applications are being explored.

Fly-Ash-Filled Syntactic Foams

In recent years, techniques have been developed to introduce and disperse fly ash into molten metal, resulting in castings with reduced weight, cost, and CTE and higher abrasion resistance than the matrix alloy. Such composites containing hollow particles in their structure are called syntactic foams. Fly ash is a readily available waste by-product of coal combustion, and its use as a filler can result in cost reduction of MMCs because it replaces the more expensive matrix alloy in the composite. Fly ash is already used as an additive to cement, but most of it is still disposed of in landfills.

Syntactic foams can be made by pressure infiltration (Ref 41). Figure 31(a) shows cenospheres (hollow particles of fly ash), which are packed loosely in a tube and infiltrated by aluminum alloy to create aluminum/fly ash syntactic foam. Figure 31(b) shows the microstructure of cenospheric fly ash dispersed in a cast aluminum matrix. The density of this cast aluminum-base foam is 1400 kg/m^3 (87 lb/ft^3) (approximately half the density of the matrix alloy), which demonstrates the potential of reducing the weight of aluminum by the incorporation of cenospheres. This opens up the possibility of also producing syntactic foams with other types of hollow particles, not just fly ash, in foundries. These foam materials are likely to have very high damping capacity and energy-absorption characteristics of interest to automotive industries.

Figure 32(a) shows fly ash particles dispersed in a matrix of aluminum-silicon alloy produced by stir mixing and casting from a 180 kg (400 lb) melt. From such melts, it has been possible to make a variety of prototype castings, including the sand cast intake manifold shown in Fig. 32(b). This intake manifold is made of aluminum-10% fly ash and is lighter and cheaper than the conventional aluminum alloy manifolds. Figure 33 shows other sand castings, pressure die castings, and squeeze castings made from aluminum/fly ash melts, demonstrating the castability of such melts using a variety of casting processes (Ref 4). Fly ash has been filled in a variety of other matrices, including lead and magnesium, to synthesize lightweight composites.

Cast Metallic Foams

The problem of stabilization of gas bubbles by the reinforcement phase in composite melts can be converted into an opportunity to create new materials (Ref 42). Figure 34 shows a gas

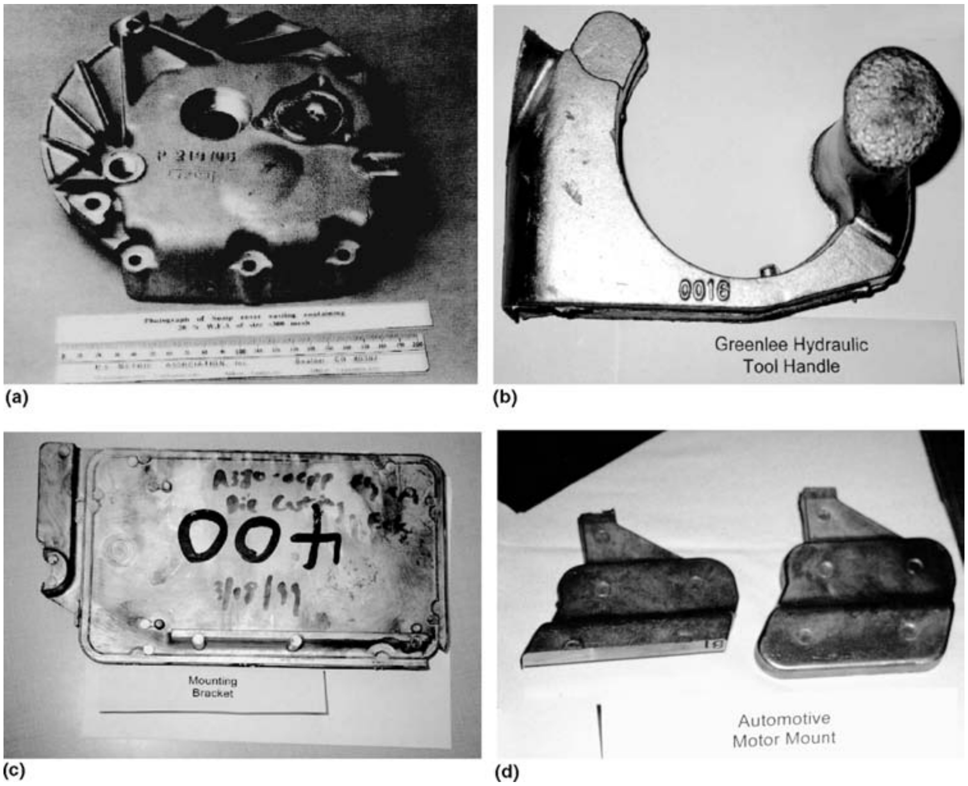


Fig. 33 Sand casting, pressure die casting, and squeeze casting of aluminum/fly ash composite. (a) Sump pump cover. (b) Greenlee hydraulic tool handle cast at Eck Industries. (c) Mounting bracket die cast at Eck Industries. (d) Motor mounts cast at Thompson Aluminum

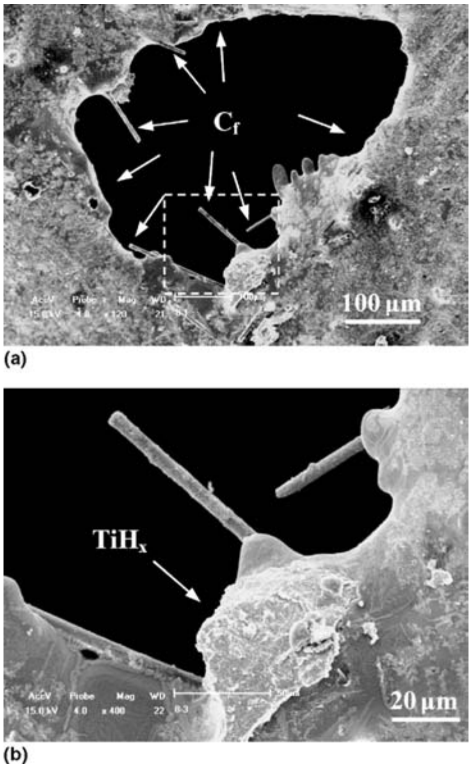


Fig. 34 Gas bubble stabilized in aluminum alloy melt by the presence of copper-coated carbon fibers

bubble stabilized by copper-coated carbon fibers in an aluminum melt (Ref 43). The copper-coated carbon fibers have stabilized the gas bubble in the melt, creating porosity, which results in making a stable foam structure. A similar phenomenon is observed in Al-SiC_p melts, which helped in synthesizing composite foams (Ref 44, 45). The structure of an Al-SiC composite foam is shown in Fig. 35 (Ref 45). These types of foams from melts of MMCs have potential uses in energy-absorbing applications in automotive and aerospace structures.

Research Imperatives

There are still many research challenges in the area of cast MMCs. To date, researchers have incorporated fibers or particles mainly in conventional monolithic alloy matrices, but have not been able to obtain the best advantage of cast MMCs. It is necessary to develop special alloys to serve as matrix materials in cast MMCs. These alloys can be specially tailored to bond to the reinforcement by having favorable thermodynamics and kinetics for desired interfacial reactions. There is a need to develop special particulate reinforcements, including surface-treated particles, for cast MMCs. There has been a significant amount of work on developing special fibers as reinforcements, but comparatively very little work has been done to develop particles specially suited for cast MMCs. For the most part, SiC that was developed for grinding applications is being incorporated in aluminum matrices to make cast MMCs.

Fig. 35 Foam material created by introducing gas in an Al-SiC melt

There is a need to develop techniques for rapid infiltration of preforms, including techniques for rapid pressureless infiltration. Current pressureless infiltration processes take a long time, while costly tooling is required for pressure infiltration. There is further need to decrease the cost of synthesis of cast MMCs to the point where their life-cycle cost, as well as their initial cost, is lower than the existing materials. Attempts should be made to develop the use of low-cost reinforcements such as fly ash in cast MMCs to bring the cost of cast MMCs below monolithic alloys. Applications of such lightweight composites in the transportation industry can result in the conservation of significant amounts of energy.

There is also a need to enhance the ductility and fracture toughness of cast MMCs through the use of special matrices, reinforcements, and processing techniques. Basic research is needed to promote nucleation of the primary phase on reinforcements so that the particles or fibers will be encapsulated within the grain or dendrite and can act as grain refiners. Research is needed to promote engulfment of particles by growing dendrites to obtain a more uniform distribution of particles in the microstructure of cast MMCs. This is likely to increase ductility and fracture toughness of cast MMCs. Techniques to cast thin-sectioned MMC components need to be developed for electronics packaging.

Low-cost techniques for machining cast MMCs, especially for drilling and tapping, also need to be developed. Techniques for near-net shape production of components are needed. Nondestructive techniques must be developed to characterize the percentage of reinforcements and porosity in cast MMC components for facilitating quality control and ensuring uniformity in successive components. Techniques for degassing and grain refining composite melts as well as technologies for recycling of cast MMCs are needed to either recover the matrix alloy or reuse the composite itself. Techniques to improve the distribution and bonding of reinforcements and the matrix are required. In addition, it is necessary to ensure that similar distribution and bonding is achieved in successive components during bulk manufacture.

Porous and cellular materials are receiving a great deal of attention, both in automotive and space applications, and can be produced using MMCs. Polymer-matrix cellular composites have been developed as functionally graded materials, nanocomposites, smart composites, and biomedical implants. Similar microstructures can also be developed in MMCs, which can have additional advantages related to the matrix metals.

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