Chapter 4

Metal Matrix Composites

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FINDINGS

Metal matrix composites (MMCs) usually consist of a low-density metal, such as aluminum or magnesium, reinforced with particulate or fibers of a ceramic material, such as silicon carbide or graphite. Compared with unreinforced metals, MMCs offer higher specific strength and stiffness, higher operating temperature, and greater wear resistance, as well as the opportunity to tailor these properties for a particular application.

However, MMCs also have some disadvantages compared with metals. Chief among these are the higher cost of fabrication for high-performance MMCs, and lower ductility and toughness. Presently, MMCs tend to cluster around two extreme types. One consists of very high performance composites reinforced with expensive continuous fibers and requiring expensive processing methods. The other consists of relatively low-cost and low-performance composites reinforced with relatively inexpensive particulate or fibers. The cost of the first type is too high for any but military or space applications, whereas the cost/benefit advantages of the second type over unreinforced metal alloys remain in doubt.

Current Applications and Market Opportunities

Current markets for MMCs are primarily in military and aerospace applications. Experimental MMC components have been developed for use in aircraft, satellites, jet engines, missiles, and the National Aeronautics and Space Administration (NASA) space shuttle. The first production application of a particulate-reinforced MMC in the United States is a set of covers for a missile guidance system.

The most important commercial application to date is the MMC diesel engine piston made by Toyota. This composite piston offers better wear resistance and high-temperature strength than the cast iron piston it replaced. It is estimated that 300,000 such pistons are produced and sold in Japan annually. This development is very important because it demonstrates that MMCs are at least not prohibitively expensive for a very cost sensitive application. Other commercial applications include cutting tools and circuit-breaker contacts.

Longer Term Applications

Metal matrix composites with high specific stiffness and strength could be used in applications in which saving weight is an important factor. Included in this category are robots, high-speed machinery, and high-speed rotating shafts for ships or land vehicles. Good wear resistance, along with high specific strength, also favors MMC use in automotive engine and brake parts. Tailorable coefficient of thermal expansion and thermal conductivity make them good candidates for lasers, precision machinery, and electronic packaging. However, the current level of development effort appears to be inadequate to bring about commercialization of any of these in the next 5 years, with the possible exception of diesel engine pistons.

Based on information now in the public domain, the following military applications for MMCs appear attractive: high-temperature fighter aircraft engines and structures; high-temperature missile structures; and spacecraft structures. Testing of a National Aerospace Plane (NASP) prototype is scheduled for the early to mid 1990s, which might be too early to include MMCs. However, it may be possible to incorporate MMCs in the structure or engines of the production vehicle.

Research and Development Priorities

MMCs are just beginning to be used in production applications. In order to make present materials more commercially attractive, and to develop better materials, the following research and development priorities should receive attention:

- Cheaper Processes: To develop low-cost, highly reliable manufacturing processes, research should concentrate on optimizing and evaluating processes such as plasma spraying, powder metallurgy processes, modified casting techniques, liquid metal infiltration and diffusion bonding.
- ***Cheaper** Materials:* Development of lower cost fiber reinforcements is a major need. Continued development work on existing materials is important to lower costs as well.
- ***Coatings:*** Research in the area of reinforcement/matrix interface coatings is necessary. These coatings can prevent deleterious chemical reactions between matrix and reinforcement which weaken the composite, particularly at high temperature, and optimize the interracial fiber/matrix bond.

INTRODUCTION

Metal matrix composites (MMCs) generally consist of lightweight metal alloys of aluminum, magnesium, or titanium, reinforced with ceramic particulate, whiskers, or fibers.[1] The reinforcement is very important because it determines the mechanical properties, cost, and performance of a given composite.

Composites reinforced with particulate (discontinuous types of reinforcement) can have costs comparable to unreinforced metals, with significantly better hardness, and somewhat better stiffness and strength. Continuous reinforcement (long fiber or wire reinforcement) can result in dramatic improvements in MMC properties, but costs remain high. Continuously and discontinuously reinforced MMCs have very different applications, and will be treated separately throughout this chapter.

Tailorability is a key advantage of all types of composites, but is particularly so in the case of MMCs. MMCs can be designed to fulfill requirements that no other materials, including other advanced materials, can achieve. There are a number of niche applications in aerospace structures and electronics that capitalize on this advantage.

PROPERTIES OF METAL MATRIX COMPOSITES

There are considerable differences in published property data for MMCs. This is partly due to the fact that there are no industry standards for MMCs, as there are for metals. Reinforcements and composites are typically made by proprietary processes, and, as a consequence, the properties of materials having the same nominal composition can be radically different. The issue is further clouded by the fact that many reinforcements and MMCs are still in the developmental stage, and are continually being refined. Numerous test methods are used throughout the industry, and it is widely recognized that this is a major source of differences in reported properties.[2] Property data given in this chapter are therefore given as ranges rather than as single values.

Some MMC properties cannot be measured as they would be for monolithic metals. For instance, toughness is an important but hard-to-define material property. Standard fracture mechanics tests and analytical methods for metals are based on the assumption of self-similar crack extension; i.e., a crack will simply lengthen without changing shape. Composites, however, are non homogeneous materials with complex internal damage patterns. As a result, the applicability of conventional fracture mechanics to MMCs is controversial, especially for fiber-reinforced materials.

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[1] As used in this chapter, the terms "aluminum, "magnesium, " and "titanium" denote alloys of these materials used as matrix metals.

[2] Carl Zweben, "Metal Matrix Composites, " contractor report for OTA, January 1987.

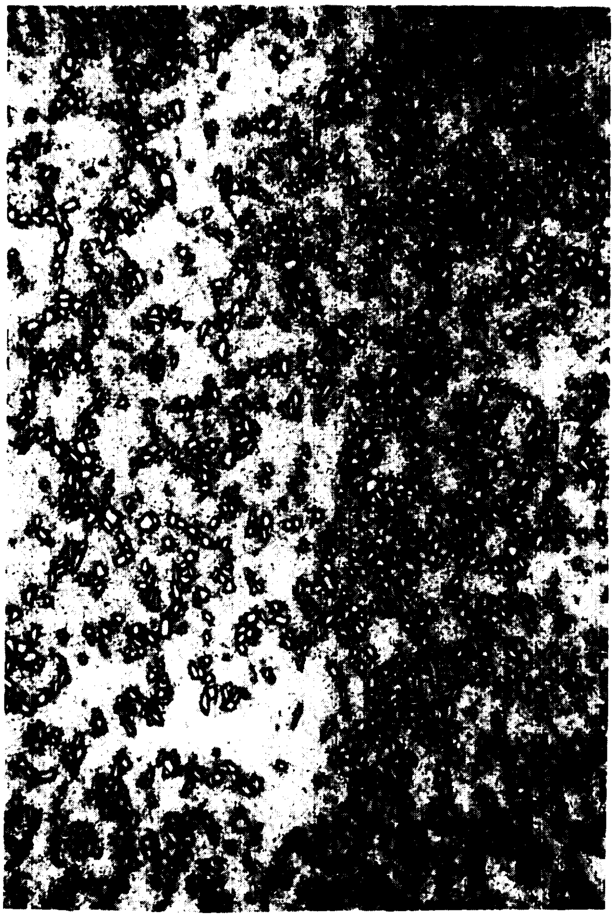

Photo credit: DWA Composite Specialties, Inc.

Micrograph (75x magnification) of 20 percent volume fraction silicon carbide particulate-reinforced 2124 aluminum.

Discontinuous Reinforcement

There are two types of discontinuous reinforcement for MMCs: particulate and whiskers. The most common types of particulate are alumina, boron carbide, silicon carbide, titanium carbide, and tungsten carbide. The most common type of whisker is silicon carbide, but whiskers of alumina and silicon nitride have also been produced. Whiskers generally cost more than particulate, as seen in table 4-1. For instance, silicon carbide whiskers cost $95 per pound, whereas silicon carbide particulate costs $3 per pound. Cost projections show that although this difference will decrease as production volumes increase, particulate will always have a cost advantage.[3]

Table 4-1.—Costs of a Representative Sample of MMC Reinforcements

Reinforcement	Price ($/pound)
Alumina-silica fiber	1
Silicon carbide particulate	3[a]
Silicon carbide whisker	95
Alumina fiber (FP)	200
Boron fiber	$262
Graphite fiber (P-100)	950[a]

Higher performance reinforcements (e.g., graphite and boron fibers) have significantly higher costs as well.

[a] Joseph Dolowy, personal communication, DWA Composite Specialties, Inc., July 1987.

SOURCE: Carl Zweben, "Metal Matrix Composites, " contractor report for OTA, January 1987.

In terms of tailorability, a very important advantage in MMC applications, particulate reinforcement offers various desirable properties. Boron carbide and silicon carbide, for instance, are widely used, inexpensive, commercial abrasives that can offer good wear resistance as well as high specific stiffness. Titanium carbide offers a high melting point and chemical inertness which are desirable properties for processing and stability in use. Tungsten carbide has high strength and hardness at high temperature.

In composites, a general rule is that mechanical properties such as strength and stiffness tend to increase as reinforcement length increases.[4] Particulate can be considered to be the limit of short fibers. Particulate-reinforced composites are isotropic, having the same mechanical properties in all directions.

In principle, whiskers should confer superior properties because of their higher aspect ratio (length divided by diameter). However, whiskers are 'brittle and tend to break up into shorter lengths during processing. This reduces their reinforcement efficiency, and makes the much higher cost of whisker reinforcement hard to justify. Development of improved processing techniques could produce whisker-reinforced MMCs with mechanical properties superior to those made from particulates.

Another disadvantage of using whisker reinforcement is that whiskers tend to become oriented by some processes, such as rolling and extrusion, producing composites with different properties in different directions (anisotropy).[5]

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[3] Ibid

[4] Ibid.

[5] See the discussion on an isotropy in ch. 3 on Polymer Matrix Composites.

Anisotropy can be a desirable property, but it is a disadvantage if it cannot be controlled precisely in the manufacture of the material. It is also more difficult to pack whiskers than particulate, and thus it is possible to obtain higher reinforcement:matrix ratios (fiber volume fraction, v/o) with particulate. Higher reinforcement percentages lead to better mechanical properties such as higher strength.

Continuous Reinforcement

In fiber reinforcement, by far the most common kind of continuous reinforcement, many types of fibers are used; most of them are carbon or ceramic. Carbon types are referred to as graphite and are based on pitch or polyacrylonitrile (PAN) precursor. Ceramic types include alumina, silica, boron, alumina-silica, alumina-boria-silica, zirconia, magnesia, mullite, boron nitride, titanium diboride, silicon carbide, and boron carbide. All of these fibers are brittle, flaw-sensitive materials. As such, they exhibit the phenomenon of size effect (see ch. 2); i.e., the strength of these fibers decreases as the length increases.

Fiber/matrix interface coatings offer another dimension of tailorability to MMCs. Coatings are very important to the behavior of MMCs to prevent undesirable reactions, improve the strength of the fibers, and tailor the bond strength between fiber and matrix. A reaction barrier is needed for some fiber/matrix combinations, particularly when the composite is exposed to high temperatures in processing or service. For example, boron fiber can be coated with boron carbide and silicon carbide reaction barriers to prevent diffusion and chemical reactions with the matrix that decrease the strength of the composite. Alumina fibers can be given a surface coating of silica to improve tensile strength.

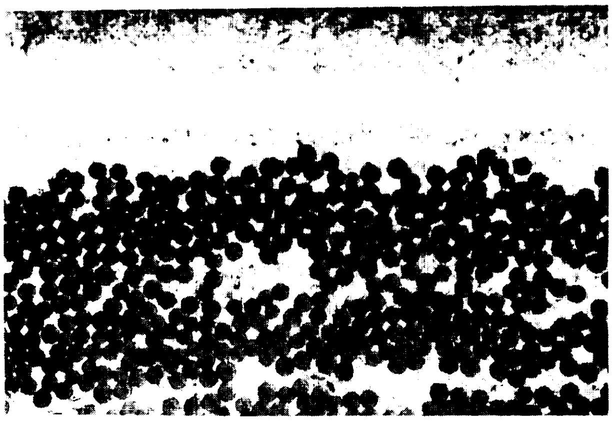

Photo credit: DWA Composite Specialties, Inc.

Cross-section of continuous graphite fiber-reinforced aluminum composite: 52 percent volume fraction fiber, uniaxially reinforced. 300x magnification

Coatings can also be used to tailor the bond strength between fiber and matrix. If adhesion between fiber and matrix is too good, cracks in the matrix propagate right through the fibers, and the composite is brittle. By reducing the bond strength, coatings can enhance crack deflection at the interface, and lead to higher energy absorption during fracture through fiber pullout mechanisms. Sometimes a coating is needed to promote wetting between the matrix and the fiber, and thereby achieve a good bond. Graphite can be coated with titanium diboride in order to promote wetting.

processing techniques, as well as coatings, can be used to control deleterious fiber/matrix interactions. The application of pressure can be used to force intimate contact between fiber and matrix and thus promote wetting; squeeze casting is one process that does this.

A less common type of continuous reinforcement is wire reinforcement. Wires are made of such metals as titanium, tungsten, molybdenum, beryllium, and stainless steel. Such wires offer some tailorability for certain niche applications; for example, tungsten wire offers good high-temperature creep resistance, which is an advantage in fighter aircraft jet engines and other aerospace applications.

MMC Properties Compared to Other Structural Materials

Table 4-2 compares the most important material properties of MMCs with those of other structural materials discussed in this assessment.

Strength and Stiffness

The stiffnesses and strengths of particulate-reinforced aluminum MMCs are significantly better than those of the aluminum matrix. For exampie, at a volume fraction of 40 percent silicon carbide particulate reinforcement, the strength is about 65 percent greater than that of the 6061 aluminum matrix, and the stiffness is doubled.[6] Particulate-reinforced MMCs, which are isotropic materials, have lower strength than the axial strength (parallel to the direction of continuous fiber reinforcement) of advanced polymer matrix composites (PMCs), see table 4-2. However, they have much better strength than the transverse strength (perpendicular to the direction of continuous fiber reinforcement) of PMCs. The stiffness of particulate MMCs can be considered to be about the same as that of PMCs.

Unlike particulate-reinforced MMCs and monolithic metals in general, fiber-reinforced MMCs can be highly an isotropic, having different strengths and stiffnesses in different directions. The highest values of strength and stiffness are achieved along the direction of fiber reinforcement. In this direction, strength and stiffness are much higher than in the unreinforced metal, as shown in table ***4-2.*** In fact, the stiffness in the axial direction can be as high as six times that of the matrix material in a graphite fiber/aluminum matrix composite: see table 4-3. However, in the transverse directions, strength values show no improvement over the matrix metal. Transverse strengths and stiffnesses of continuous fiber-reinforced MMCs compared to PMCs are very good, thereby giving MMCs an important advantage over the leading PMCs in structures subject to high transverse stresses.

High values of specific strength and specific stiffness (strength and stiffness divided by density) are desirable for high-strength, low-weight applications such as aircraft structures. Typically, particulate MMCs have somewhat better specific strength and specific stiffness than the matrix metal, and fiber-reinforced MMCs have much better specific strength and specific stiffness than the matrix metal.

Unfortunately, MMCs have a higher density than PMCs, making specific strength and specific stiffness lower than those for PMCs in the axial direction. Transverse specific strength and specific stiffness of MMCs are still better than those of PMCs.

High-Temperature Properties

MMCs offer improved elevated-temperature strength and modulus over both PMCs and metals. Reinforcements make it possible to extend the useful temperature range of low density metals such as aluminum, which have limited high-temperature capability (see table 4-2). MMCs typically have higher strength and stiffness than PMCs at **200 to 300° C (342** to ***5720*** F), although development of resins with higher temperature capabilities may be eroding this advantage. No other structural material, however, can compete with ceramics at very high temperature.

Fiber-reinforced MMCs experience matrix/reinforcement interface reactions at high tempera-

Table 4.2.—Structural Properties of Representative MMCs, Compared to Other Materials

Property	Matrix(l)* metal[a]	Particulate(2)* MMC[a]	Fiber(3)* MMC[a]	PMC[b]	Ceramic[b]
Strength (M Pa) (axial)	-290	290-480	620-1,240	820-1,680	140-3,900
Stiffness (G Pa) (axial)	-70	80-140	130-450	61-224	97-400
Specific strength (axial)	-100	100-170	250-390	630-670	51-670
Specific gravity	2.5-2.8	-2.8	2.5-3.2	1.3-2.5	2.7-5.8
Transverse strength (MPa)	-290	290-480	30-170	11-56	140-3,900
Transverse stiffness (GPa)	Same as axial	Same as axial	34-173	3-12	Same as axial
Maximum use temperature (“C)	180	300	300	260	1,200-1,600
Plane strain fracture toughness (MPa-m$^{1/2}$)	18-35	12-35	—	—	3-9

PMC IS used to denote a range of materials including graphite/epoxy, graphite/polylmlde, boron/polyimide, and S-glass/epoxy
Ceramic is used to denote a range of materials including zirconia, silicon carbide, and silicon nitride
“NOTE: (1) 6061 aluminum
(2) 6061 aluminum reinforced with 0-400/0 volume fractions of SiC particulate
(3) 6061 aluminum reinforced with 50°/0 volume fractions of fibers of graphite, boron. silicon carbide, or alumina

SOURCES [a] Carl Zweben, “Metal Matrix Composites, ” contractor report for OTA, January 1987
[b] "Guide to Selecting Engineered Materials. ” *Advanced Materials and Processes, vol. 2, No* 1, June 1987

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[6] Carl Zweben, “Metal Matrix Composites, ” contractor report fot OTA, January 1987.

Table 4-3.—Strength and Stiffness of Some Fiber. Reinforced MMCs (Fiber v/o = 50%)

Material Matrix material	Tensile strength (axial) MPa	Tensile strength (transverse) MPa	Stiffness (axial) GPa	Stiffness (transverse) GPa
Aluminum 6061-T6 ....,	290	290	70	70
Titanium Ti-6Al-4V	1170	1170	114	114
Composite				
Graphite[a]/aluminum . . .	690	30	450	34
Boron/aluminum.	1240	140	205	140
Silicon carbide[b]/ aluminum	1240	100	205	140
Silicon carbide[c]/ aluminum	**1040**	70	**130**	**99**
Alumina[d]/aluminum	**620**	170	**205**	**140**
Silicon carbide[8]/ titanium	**1720**	340	**260**	**173**
Graphite[a]/copper	**512**	31	**464**	**49**

Properly Improvements of MMCs over unreinforced metals can be significant For example, the axial stiffness of graphite fiber-reinforced aluminum is roughly 6 times greater than that of the unreinforced aluminum The axial tensile strength of silicon carbide fiber-reinforced aluminum is about 4 times greater than that of the unreinforced aluminum

aP-120

[b]AVCO monofilament

[c]"Nicalon"

[d]Fiber "FP"

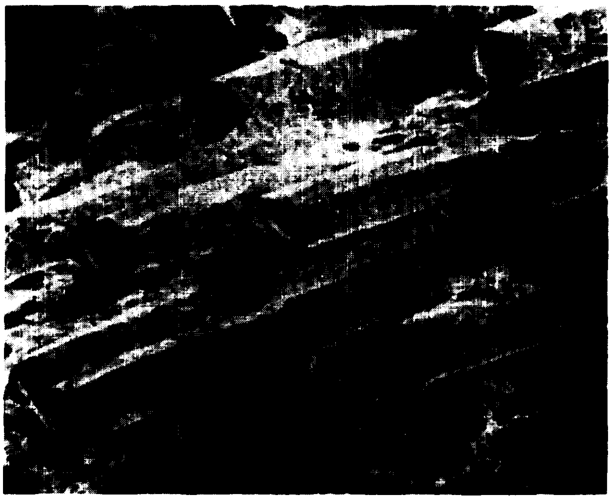
‘AVCO monofilament

SOURCES: For **all composites except graophit/copper:** Carl Zweben, “Metal Matrix Composites, ” contractor report for OTA, January 1987. For **graphite/copper only: C** Kaufmann, American Cyanamid, personal communication, Oct. 19, 1987.

tures. In addition, the transverse high-temperature strength of fiber-reinforced MMCs is only as good as that of the matrix metal, since mechanical properties in the transverse direction are dominated by the matrix and the fiber/matrix interface. For example, at 320 C (608° F), the axial tensile strength of boron fiber-reinforced aluminum is about 1.1 gigapascals (GPa) compared to only 0.07 GPa for monolithic 6061 aluminum, whereas the transverse strength is 0.08 GPa, about the same as that for the monolithic 6061.[7]

Wear Resistance

Wear resistance of MMCs is excellent compared to that of monolithic metals and PMCs, owing to the presence of the hard ceramic reinforcements. For instance, in one test, the abrasive wear of 2024 aluminum under a 1 kilogram load was shown to be 6 times greater than the wear of the same alloy containing 20 percent volume fraction of silicon carbide whiskers.[8] An alumina-silica fiber-reinforced aluminum piston used in Toyota automobiles demonstrated an 85 percent improvement in wear resistance over the cast iron piston with nickel insert used previously.[9]



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Fracture and Toughness

There is a wide variation in fracture toughness among MMCs, although it is generally lower than that of the monolithic metal. Fracture toughness can vary between 65 and 100 percent of the fracture toughness of the monolithic metal alloy.[10] Lower toughness is a trade-off for higher strength and stiffness. Particulate-reinforced MMCs have a lower ultimate tensile strain than the unreinforced metals (see table 4-4) which may be important in some applications. This brittleness can complicate the design process and make joining more difficult as well. Comparison to PMCs is difficult, because the toughness of PMCs is very temperature-dependent.

Thermal Properties

The introduction of silicon carbide particulate into aluminum results in materials having lower coefficients of thermal expansion, a desirable property for some types of applications. By choosing an appropriate composition, the coefficient

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[7] Ibid.

[8] Ibid.

[9] Ibid.

[10] Ibid.

Table 4-4.—Properties of 6061 Aluminum Reinforced With Silicon Carbide Particulate

Reinforcement	Stiffness (G Pa)	Tensile strength (M Pa)	Tensile strain
0%	10	290	16.0%
10	83		7.0
15	86	3&l	6.5
20	90	430	6.0
25	103	—	3.5
30	117	470	2.0
35	124	—	1.0
40	140	480	0.6

Note the sharp rise in stiffness in the 400/0 composite (140 GPa) compared to the unreinforced aluminum (10 GPa). Ultimate tensile strength nearly doubles and tensile strain decreases nearly a full order of magnitude.

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

of thermal expansion can be near zero in some MMCs. MMCs also tend to be good heat conductors. Using high thermal conductivity graphite fibers, aluminum-matrix or copper-matrix MMCs can have very high thermal conductivity, compared with other types of composites.

Environmental Behavior

In terms of environmental stability, MMCs have two advantages over PMCs. First, they suffer less water damage than PMCs which can absorb moisture, thereby reducing their high-temperature performance. Second, some MMCs, such as reinforced titanium, can stand high-temperature corrosive environments, unlike PMCs.

Nevertheless, some MMCs are subject to environmental degradation not found in PMCs. For instance, graphite fibers undergo a galvanic reaction with aluminum. This can be a problem when the graphite/aluminum interface is exposed to air or moisture. In addition, PMCs are resistant to attack by many chemicals (e.g., acids) that corrode aluminum, steel, and magnesium.

cost

A major disadvantage of MMCs compared to most other structural materials is that they are generally more expensive. Both constituent material costs and processing costs are higher. Costs of higher performance reinforcements (mostly fibers) are high, and lower cost reinforcements (mostly particulate) may not yield dramatic improvements in performance. Cost/benefit ratios of most MMCs dictate that they be used only in high-performance applications. However, both

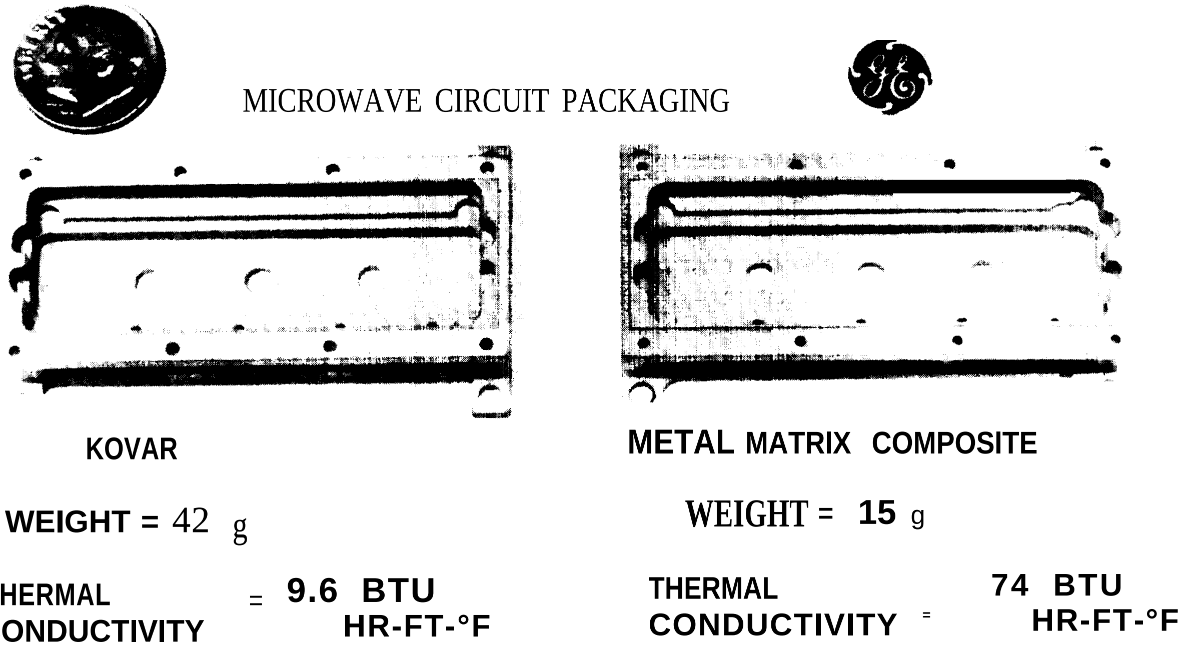

Photo credit: General Electric Co.

Silicon carbide particle-reinforced aluminum microwave package the material and production costs may drop as more experience is gained in MMC production.

Tailorability of Properties

In some applications, MMCs offer unique combinations of properties that cannot be found in other materials. Electronics packaging for aircraft requires a hard-to-achieve combination of low coefficient of thermal expansion, high thermal conductivity, and low density. Certain MMCs can meet these requirements, replacing beryllium, which is scarce and presents toxicity problems.

Several other examples can be cited to illustrate the unique advantages of MMCs in specialty applications. A large heat transfer coefficient is desirable for space-based radiators; this property is offered by graphite fiber-reinforced copper, aluminum, and titanium (although this latter fiber/matrix combination unfortunately has some interface reaction problems). The higher transverse strengths of MMCs compared to PMCs have led to several MMC space applications, such as the space shuttle orbiter struts, made of boron fiber-reinforced aluminum.

One of the most important applications of MMCs is the Toyota truck diesel engine piston, produced at a rate of about 300,000 pistons per Year.[11] This consists of aluminum selectively reinforced in the critical region of the top ring groove with a ring-shaped ceramic fiber preform. (A preform is an assemblage of reinforcements in the shape of the final product that can be infiltrated with the matrix to form a composite.)

Two types of fibers are used: alumina and alumina-silica. Both are relatively low-cost materials originally developed for furnace insulation.

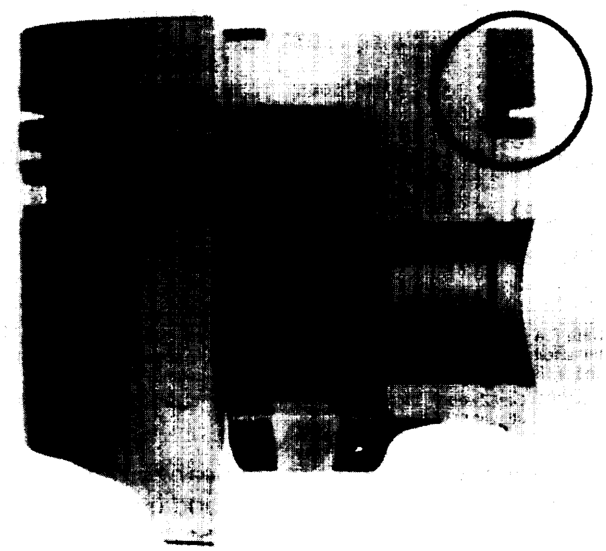

Photo credit: Toyota Motor Corp.

Aluminum diesel engine piston with local fiber reinforcement in ring groove area

Use of local reinforcement to improve wear resistance makes possible the elimination of nickel and cast iron inserts. This reduces piston weight and increases thermal conductivity, improving engine performance and reducing vibration.

This approach minimizes cost and thereby makes MMCs more competitive with cast iron. This design not only offers better wear resistance and better high-temperature strength but also eliminates one type of part failure associated with the design it replaced. It is considered by some to be a development of historic proportions because it demonstrates that MMCs can be reliably mass produced. It also shows that at least one type of aluminum matrix MMC can perform reliably in a very severe environment.

DESIGN, PROCESSING, AND TESTING

In ceramics and polymer matrix composites manufacturing, the material is formed to its final shape as the microstructure of the material is formed. MMCs can be produced in this way, or, as is traditionally done with metals, formed into billets or sheets and later machined to a final shape. Viable, inexpensive near-net-shape techniques for forming MMCs have not been successfully developed as yet, and there is still a debate about on the advantages of producing standard

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[11] Ibid.

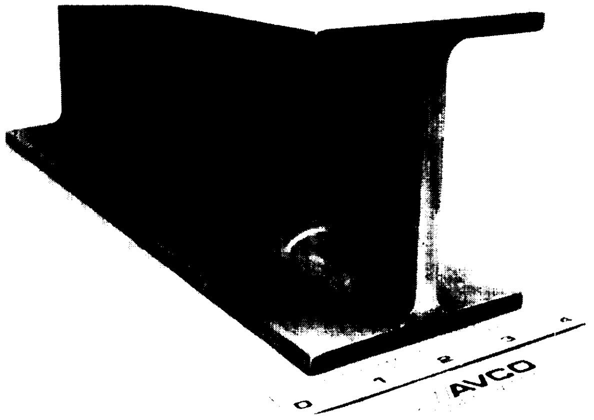

Photo credit: AVCO Corp.

Centrifugal casting of silicon carbide-reinforced aluminum.

shapes to be machined by the purchaser to final form, compared to the custom production of near-net-shape parts. Forming of net-shape MMC parts necessitates close integration of design and manufacture, where production of standard MMC structural shapes does not.

Design

The variability of metal matrix composite properties is a handicap to designing with these materials. There are currently no design aids such as property databases, performance standards, and standard test methods. In addition, most designers are much more familiar with monolithic metals. The lack of experience with MMCs increases the design and manufacturing costs associated with the development of a new product. As with ceramic structures, brittleness is a new and difficult concept to most designers. MMCs are brittle materials, and new methods of design will become important in the development of MMC applications.

Processing

Because MMC technology is hardly beyond the stage of R&D at present, costs for all methods of producing MMCs are still high. Manufacturing methods must ensure good bonding between matrix and reinforcement, and must not result in undesirable matrix/fiber interracial reactions.

MMC production processes can be divided into primary and secondary processing methods, though these categories are not as distinct as is the case with monolithic metals. Primary processes (those processes used first to form the material) can be broken down into *combining* and *consolidation* operations. Secondary processes can be either ***shaping*** or *joining* operations. Table 4-5 shows the manufacturing methods discussed here and notes which types of operations are included in each method.

As with ceramics, net-shape methods are very important manufacturing processes. The machining of MMCs is very difficult and costly in that MMCs are very abrasive, and diamond tools are needed. In addition, it is desirable to reduce the amount of scrap left from the machining process because the materials themselves are very expensive.

Continuous Reinforcement[12]

The following discussion covers the primary and secondary processes involved in the manufacture of MMCs with continuous reinforcement.

Primary Processes.– Basic methods of combining and consolidating MMCs include liquid metal infiltration, modified casting processes, and deposition methods such as plasma spraying. Hot pressing consolidates and shapes MMCs. Diffusion bonding consolidates, shapes and joins MMCs. See table 4-6 for selected MMC processing methods and their characteristics.

There is considerably more disagreement on what is the most promising method for processing fiber-reinforced MMCs than there is for processing of particulate-reinforced MMCs. The Toyota diesel engine piston has been heralded as an example of the promise of modified casting techniques for keeping costs down. Critics charge that these types of casting techniques have not proven adequate for manufacturing MMCs with desirable mechanical properties. (The Toyota piston

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[12] As examples in the following discussion of processing, two common types of particulate- and fiber-reinforced composites will be referred to as needed: silicon carbide particulate-reinforced aluminum, and boron fiber-reinforced alum inure.

Table 4-5.—MMC Manufacturing Methods

	Combines	Consolidates	Shapes	Joins
Primary methods:				
Casting **Squeeze casting,** **compocasting,** **gravity casting,** **low-pressure casting**	x	x	x	
Diffusion bonding		x	x	x
Liquid infiltration **Gravity,** inert gas pressure, vacuum infiltration	x	x		
Deposition Chemical coating, plasma spraying, chemical vapor deposition, physical vapor deposition, electrochemical plating	X	X		
Powder processing Hot pressing, ball mill mixing, vacuum pressing, extrusion, rolling	X	X	X	
Secondary methods:				
Shaping **Forging, extruding, rolling,** **bending, shearing, spinning,** **machining**		X	X	
Machining Turning, boring, drilling, milling, sawing, grinding, routing, electrical discharge machining chemical milling, electrochemical milling			x	
Forming Press brake, superplastic, **creep forming**		x	x	x
Bonding Adhesive, diffusion				X
Fastening				X
Soldering, brazing, welding				X

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

uses fiber reinforcement mostly for wear resistance and less for more universally important properties such as strength.) Some industry MMC advocates suggest that processes such as diffusion bonding and plasma spraying are more promising for achieving high performance, and that lower costs will come only with more production experience with these processes.

secondary Processes.–Machining processes for MMCs reinforced with ceramic materials, which are hard and abrasive, generally are much more expensive than for monolithic structural metals. As a rule, diamond tools are required because carbide and other tools wear out too quickly. Despite this limitation, all of the basic mechanical methods, such as drilling, sawing, milling, and turning have been proven to be effective with MMCs. Electrical discharge machining also has been shown to be effective.

Mechanical fastening methods, such as riveting and bolting have been found to work for continuously-reinforced MMCs. The same is true

Table 4-6.—Selected MMC Processing Techniques and Their Characteristics

Techniques	Characteristics
For fiber-reinforced MMCs:	
Liquid metal infiltration (low pressure)	near-net-shape parts economical high porosity oxidation of matrix and fiber not reliable as yet
Liquid metal infiltration (intert gas pressure, vacuum)	less porosity and oxidation than low pressure techniques
Low pressure casting	near-net-shape parts low cost expensive preforms required three-dimensional preforms are difficult to make
Squeeze casting	good fiber wetting lower porosity expensive molds needed large capacity presses needed
Plasma spraying	potential for lower processing costs
Diffusion bonding	lower temperatures than hot pressing reduces fiber/matrix interactions not capable of net-shape parts except simple shapes slow, expensive fiber damage can occur
Hot Pressing	heats matrix above melt temperature, which can degrade reinforcement
For particulate-reinforced MMCs:	
Powder metallurgy	high volume fractions of particulate are possible (better properties) powders are expensive not for near-net-shape parts
Liquid metal infiltration	net-shape parts can use ingots rather than powders lower volume fraction of particulate (means lower mechanical properties)
Squeeze casting	may offer cost advantage; however molds and presses may be expensive

SOURCE Carl Zweben, "Metal Matrix Composites, " contractor report for OTA, January 1987

for adhesive bonding. Boron fiber-reinforced aluminum pieces can be metallurgically joined by soldering, brazing, resistance welding and diffusion bonding.

Discontinuous Reinforcement

The following discussion covers the primary and secondary processes involved in the manufacture of MMCs with discontinuous reinforcement.

Primary Processes.–The most common methods for producing particulate- and whisker-reinforced MMCs are powder processing techniques. There has not been much success at producing near-net-shape structures as yet.[13] (See discussion in chapter 2 on the desirability of near-net-shape processing.) Other processes for discontinuously-reinforced MMCs are liquid metal infiltration and casting techniques (see table ***4-6).***

At this time, there is no one MMC manufacturing method that holds great promise for reduc-

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[13] Zweben, op. cit., January 1987

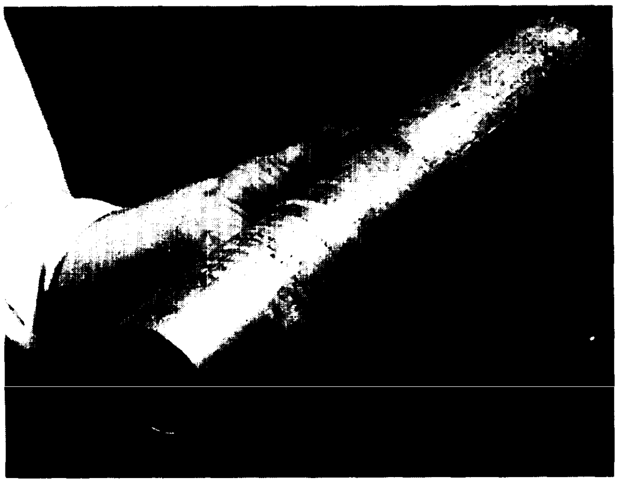

Photo credit: AVCO Specialty Materials

Centrifugal casting around braided tube of SiC fibers and yarn.

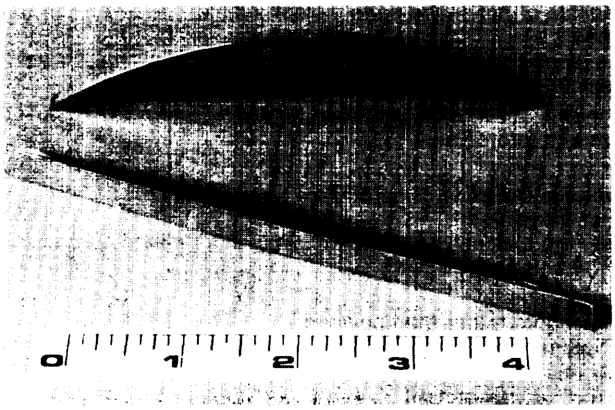

Photo credit: AVCO Specialty Materials

Diffusion bonded SiC fiber-reinforced titanium: cross section of a hollow turbine blade.

ing costs, although there seems to be some agreement that for particulate-reinforced MMCs, liquid metal infiltration and powder metallurgy techniques are likely candidates for future development.

Secondary Processes.–One of the major advantages of particulate- and whisker-reinforced MMCs is that most of the conventional metalworking processes can be used with minor modifications (see table 4-5), Methods demonstrated include forging, extruding, rolling, bending, shearing, and machining. Although they are expensive, all conventional machining methods have been found to work for these materials, including turning, milling, and grinding.

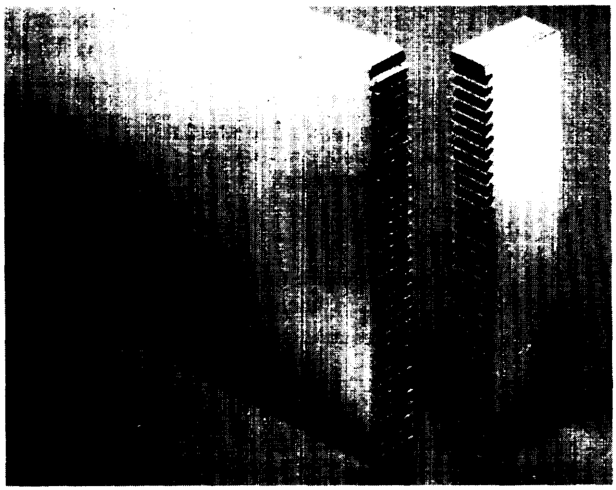

Photo credit: AVCO Specialty Materials

Silicon carbide fiber-reinforced aluminum shaped by electrical discharge machining.

A wide variety of joining methods can be used including mechanical fastening techniques, metallurgical methods employed with monolithic metals, and adhesive bonding as used for PMCs.

costs

MMC costs are currently very high, and for them to come down, there must be some standardization and a reliable compilation of materials properties (in a form such as a design database). This can be achieved only through greater production experience with MMC materials. Some experts argue that entirely new materials and processes must be found that are cheaper than the present ones. Opponents of this view hold that development of new processes and materials will delay a decrease in costs of existing materials, because it will take much longer to gain the production experience necessary.

Most present users buy preformed shapes, such as billets, plates, bars and tubes, and then machine these shapes to specification. MMCs are not currently sold in standard sizes; users can order any size, manufactured to order. This lack of standardization keeps prices for shapes high. Some users produce their own MMCs for use in-house. For example, Lockheed Georgia produces silicon carbide fiber-reinforced aluminum matrix composites for designing, manufacturing and testing fighter aircraft fins.

The cost of an MMC part depends on many factors including shape, type of matrix and reinforcement, reinforcement volume fraction, reinforcement orientation, primary and secondary fabrication methods, tooling costs, and number of parts in the production run. At present, there is little information available on production costs. The only items produced in any quantity are the Toyota engine pistons. Costs for this application are proprietary information, but the costs of these MMCs are at least not prohibitive in a very cost-sensitive product.

Costs are very volume sensitive; high costs keep volumes low, and low volumes mean high costs. Of course, some materials are inherently expensive and will never be cheap enough for widespread commercial use, regardless of volume.

With the exception of alumina-silica discontinuous reinforcement fibers, reinforcement prices are orders of magnitude higher than those of metals used in mass production items such as automobiles. Unfortunately, the stiffness of alumina-silica fibers is not substantially greater than that of aluminum. The room-temperature strength of aluminum reinforced with these fibers also shows little or no improvement over monolithic aluminum, although wear resistance and elevated-temperature strength are enhanced. The significance of this is that the fibers that provide major improvements in material properties are quite expensive, while use of low-cost alumina-silica fibers provides only modest gains in strength and stiffness.

Testing

Unlike monolithic metals, in which the main types of flaws are cracks, porosity, and inclusions, composites are complex, heterogeneous materials that are susceptible to more kinds of flaws, including delamination, fiber misalignment, and fiber fracture.

Failure in monolithic metals occurs primarily by crack propagation. The analytical tool called linear elastic fracture mechanics (LEFM) is used to predict the stress levels at which cracks in metals will propagate unstably, causing failure. Failure modes in composites, especially those reinforced with fibers or whiskers, are far more complex, and there are no verified analytical methods to predict failure stress levels associated with observed defects. As a consequence, empirical methods have to be used to evaluate how critical a given flaw is in an MMC.

Two basic methods have been established as reliable flaw-detection techniques for MMCs: radiography and ultrasonic C-scan. Radiography, useful only for thin panels, detects fiber misalignment and fractures. C-scan identifies delamination and voids. There are no existing nondestructive evaluation (N DE) methods for reinforcement degradation in MMCs.

The costs of NDE methods for MMCs should be no greater than for monolithic metals. However, the reliability of manufacturing processes for these materials has not been established and MMCs cannot be reliably or repeatably produced as yet. Because fabrication processes are not dependable at present, it is generally necessary to use NDE for MMCs in cases where testing would not be employed at all, or as extensively, for monolithic metals, This additional cost factor should decrease as experience and confidence are gained with MMCs.

HEALTH AND SAFETY

There is little documentation as yet of safe handling and machining practices for MMCs. Materials handling practices are given by materials safety data sheets, and few yet exist for MMCs. However, there is one materials safety data sheet that applies to the MMC production process of plasma spraying.[14]

Health hazards associated with MMCs are similar to those found in the production of ceramics and PMCs. As with ceramics the most serious

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[14] Robert Buffenbarger, International Association of Machinists and Aerospace Workers, personal communication, March 23, 1987.

health hazard is associated with the possible carcinogenic effects of ceramic fibers due to their size and shape. MMC reinforcement fibers falling in this category include alumina, alumina-silica, graphite, boron carbide, and alumina-boria-silica. The effects of ceramic fibers on humans are largely unknown. Until such data become available, the indications discussed in chapter 2 for ceramics also apply to the manufacture of MMCs reinforced with these fibers.

APPLICATIONS

There are very few commercial applications of MMCs at the present time. Industry observers believe that the level of development effort in the United States is not large enough to lead to significant near-term commercial use of MMCs. However, the Toyota truck diesel engine piston has spurred the major U.S. automakers to undertake preliminary activity in MMCs. Although considerable interest in these materials is being generated in the United States, it will be decades before they are likely to have an appreciable impact on production levels of competing materials.

MMCs are not competing solely with monolithic metals; they are also competing with the whole range of advanced materials, including PMCs, ceramics, and other new metal alloys. It is not yet clear whether, compared to PMCs, ceramics, and monolithic metals, MMCs will have big enough performance advantages to warrant use in a wide variety of applications. In fact, MMCs may be limited to niche applications in which the combinations of properties required cannot be satisfied by other structural materials.

The properties that make MMCs attractive are high strength and stiffness, good wear resistance, and tailorable coefficient of thermal expansion and thermal conductivity. Furthermore, development of high-temperature MMCs has been cited as a way to help reduce U.S. dependence on critical and strategic materials, such as manganese and cobalt.[15] The following sections describe the current and future applications for which these properties are of value.

Current Applications

Current MMC markets in the United States are primarily military. MMCs have potential for use in aircraft structures, aircraft engines, and naval weapons systems. Experimental MMC components were first developed for applications in aircraft, jet engines, rockets, and the space shuttle. There has been little government funding of MMCs for commercial applications in the United States, and only a small number of specialized applications have been developed by private industry.

Military/Space

The high stiffness and compression strength and low density of boron fiber-reinforced aluminum led to its use in production space shuttle orbiter struts. Its high cost has prevented wider use.

The National Aeronautics and Space Administration (NASA) Hubble Space Telescope uses two antenna masts made of aluminum reinforced with P-100 pitch-based graphite fibers. This material was selected because of its high specific stiffness and low coefficient of thermal expansion.[16] This material replaced a dimensionally stable telescope mount and an aluminum waveguide, resulting in a 70 percent weight savings.[17]

Two companies are producing silicon carbide particulate-reinforced aluminum instrument covers for a missile guidance system. This is the first production application of particulate-reinforced MMCsin the United States.

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[15] Zweben, op. cit., January 1987

[16] Ibid.

[17] William C. Riley, Research Opportunites, Inc., personal communication, October 27, 1987.

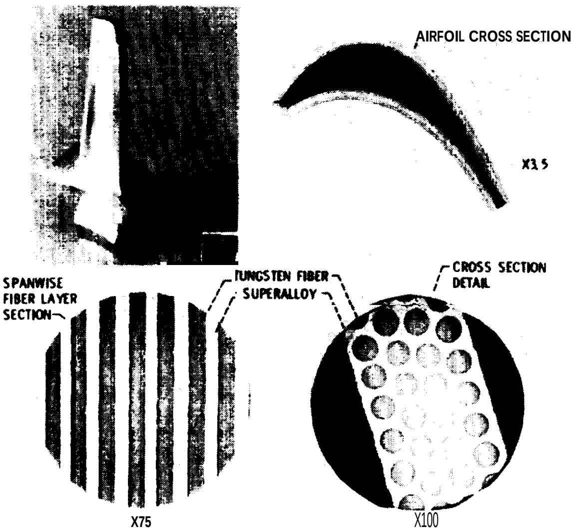


Photo credit: NASA Lewis Research Center

Tungsten wire-reinforced super alloy gas turbine engine blade

Commercial

The Toyota piston has stimulated a considerable interest in MMCs for pistons and other automotive parts on a worldwide basis. Other components now being evaluated by automakers world-wide include connecting rods, cam followers, cylinder liners, brake parts, and drive shafts.

Experimental MMC bearings have been tested on railroad cars in the United Kingdom. An experimental material for electronic applications has been developed in Japan, consisting of copper reinforced with graphite fiber, Another electrical use of MMCs is in circuit breakers. Graphite-reinforced copper used as a “compliant layer” minimizes thermal stresses in an experimental magnetohydrodynamic (MHD) generator ceramic channel in Japan. An aluminum tennis racket selectively reinforced with boron fiber was sold commercially in the United States for a brief time during the 1970s,

Future Applications

Future applications include those which could be possible in the next *5* to 15 years.

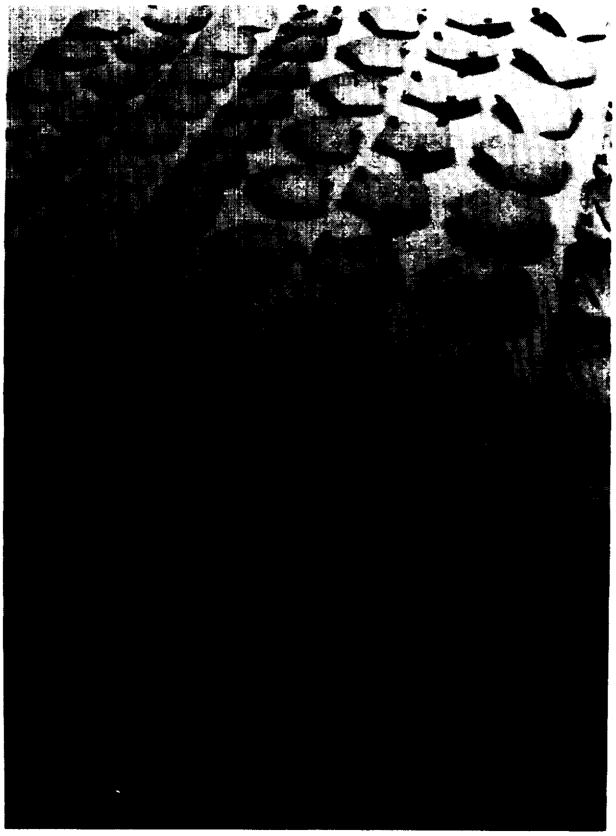


Photo credit: Advanced Composite Materials

Missile guidance system covers of silicon carbide particle-reinforced aluminum.

Military/Space

Based on information in the public domain, the following applications appear likely to be developed in the United States: high-temperature fighter aircraft engines and structures, high-temperature missile structures, spacecraft structures, high-speed mechanical systems, and electronic packaging.

Development of applications such as hypersonic aircraft, which will require efficient high-temperature structural materials, will undoubtedly lead to increasing interest in MMCs.

Commercial

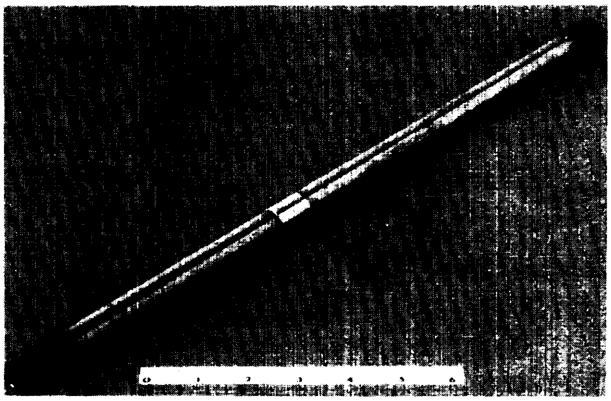
Commercial applications in the next 5 years are likely to be limited to diesel engine pistons, and perhaps sporting goods such as golf clubs, tennis rackets, skis, and fishing poles. There are a number of potential applications that are technically possible but for which the current level of development effort is inadequate to bring about commercialization in the next 5 years; these include: brake components, push rods, rocker arms, machinery and robot components, computer equipment, prosthetics, and electronic packaging.

High Specific Stiffness and Strength.–MMC materials with high specific stiffness and strength are likely to have special merit in applications in which weight will be a critical factor. Included in this category are land-based vehicles, aircraft, ships, machinery in which parts experience high accelerations and decelerations, high-speed shafts and rotating devices subject to strong centrifugal forces.

The high value of weight in aircraft makes use of MMCs a strong possibility for structural applications, as well as for engine and other mechanical system components. Mechanical properties of MMCs could be important for a number of medical applications, including replacement joints, bone splices, prosthetics, and wheelchairs.

There are numerous industrial machinery components that could benefit from the superior specific strength and stiffness of MMCs. For example, high-speed packaging machines typically have reciprocating parts. Some types of high-speed machine tools have been developed to the point where the limiting factor is the mass of the assemblies holding the cutting or grinding tools, which experience rapid accelerations and decelerations. Further productivity improvements will require materials with higher specific mechanical properties. Computer peripheral equipment, such as printers, tape drives, and magnetic disk devices commonly have components that must move rapidly. MMCs are well suited for such parts.

The excellent mechanical properties of MMCs make them prime candidates for future application in robots, in which the weight and inertia of the components have a major effect on performance and load capacity. Centrifugal forces are a major design consideration in high-speed rotating equipment, such as centrifuges, generators, and turbines. As these forces are directly proportional to the mass of the rotating components, use of materials with high specific properties - MMCs - will be a way of achieving future performance goals.



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For high-speed rotating shafts, such as automobile and truck drive shafts, a major design consideration is that the rotational speed at which the shaft starts to vibrate unstably, called the critical speed, must be higher than the operating speed. As critical speed depends on the ratio of stiffness to density, the high specific stiffness of MMCs makes them attractive candidates for this application.

Attractive Thermal Properties. -There are a number of potential future applications for which the unique combinations of physical properties of MMCs will be advantageous. For example, the special needs of electronic components present particularly attractive opportunities.

Electronic devices use many ceramic and ceramic-like materials, that are brittle and have low coefficients of thermal expansion (CTEs). Examples are ceramic substrates such as alumina and beryllia, and semiconductors such as silicon and gallium arsenide. These components frequently are housed in small, metallic packages. MMCs can help prevent fracture of the components or failure of the solder or adhesive used to mount these components, since the CTE of the package can be tailored to match that of the device.

Another desirable feature of packaging materials is high thermal conductivity to dissipate heat generated in the system, since the reliability of electronic chips decreases as operating temperature increases. Two of the more common metals now used in packaging are molybdenum and Kovar, a nickel-iron alloy. The thermal conductivity of Kovar is quite low, only about 5 percent of that of copper, and it cannot be used in applications in which large amounts of heat must be dissipated. Molybdenum, which is more expensive and difficult to machine, is normally used in such cases. MMCs (e. g., with a high thermal conductivity copper matrix) could be used instead of these two materials. Examples of potential future applications include heat sinks, power semiconductor electrodes, and microwave carriers.

The low CTE that can be achieved with some MMCs makes them attractive for use in precision machinery that undergoes significant temperature change. For example, machines that assemble precision devices are commonly aligned when cold. After the machines warm up, thermal expansion frequently causes them to go out of alignment. This results in defective parts and down time required for realignment. Laser devices, which require extremely stable cavity lengths, are another potential application for which low CTE is an advantage.

Markets

Market projections for MMCs vary widely. One market forecast by C. H. Kline is that MMCs will play no significant role in the current advanced composite markets until after 1995.[18] A second forecast (Technomic Consultants) is that U.S. nonmilitary uses of MMCs will reach $100 million per year by 1994, and world-wide commercial uses will reach $2 billion per year. [19]

There does seem to be agreement though, that in the United States, MMC materials are likely to be used primarily in military and space applications, and, to a much smaller degree, in electronic and automotive applications. Because MMC materials are currently used mainly for research purposes, the markets for them are now only a few thousand pounds per year.[20] Materials costs should decrease with time, as production volumes increase. However, the actual downward trend has been slower than most predictions, and the cost/performance benefits of MMCs have yet to be demonstrated over alternative materials in large volume applications.

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[18] Jacques Shouttens, Metal Matrix Composites Information Analysis Center (MMCIAC), personal communication, March 27, 1987.

[19] Ibid.

[20] Ibid.

RESEARCH AND DEVELOPMENT PRIORITIES

Federal funding of MMC research and development (R&D) comes mainly from the military. Combined totals for the three services plus the Defense Advanced Research Projects Agency (DARPA) for **6.1,6.2,** and 6.3A money were $29.7 million for fiscal year 1987.[21] There are a number of classified projects, and projects in other categories of funds, that also involve MMCs. Although the Department of Defense is the major government funding source, NASA also funds MMC research. NASA plans to provide $8.6 million for MMCs in fiscal year 1988, up from $5.6 million in fiscal year 1987.[22]

The following section describes R&D priorities for MMCs in three broad categories of descending priority. These categories reflect a consensus as determined by OTA of research that needs to be done in order to promote the development of these materials.

Very Important

Cheaper Processes

First in importance is the need for low-cost, highly-reliable manufacturing processes. Several industry experts advocate emphasis on modified casting processes; others suggest diffusion bonding and liquid metal infiltration as likely candidates for production of fiber-reinforced MMCs.

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[21] Jerome Persh, Department of Defense, personal communication, August 1987.

[22] Brian Quigley, National Aeronautics and Space Administration, personal communication, December 1987.

There is some agreement that plasma spraying is also a promising method. For particulate-reinforced MMCs, powder metallurgy and liquid infiltration techniques are considered most promising. To develop near-term applications, research should concentrate on optimizing and evaluating these processes, including development of low-cost preforms.

Cheaper Materials

Development of high-strength fiber reinforcements of significantly lower cost is a major need, as there are no high-performance, low-cost fibers available at present. There are two schools of thought as to the best approach to reducing costs. Some analysts believe that the range of usefulness can be expanded by the development of new fibers with better all-purpose design properties, such as higher strength, higher temperature, and lower cost; they also see new matrix alloys as important to facilitate processing and to optimize MMC performance. However, some critics charge that this search for all-purpose fibers and better matrices is likely to be unrewarding and that increased production experience with present fibers and matrices is the best route to lower costs, particularly for potential near-term applications.

Interphase

Control over the fiber/matrix interphase in MMCs is critical to both the cost and performance of these materials. For example, new fiber coatings are needed to permit a single fiber to be used with a variety of matrices. This would be cheaper than developing a new fiber for each matrix.

At high temperatures, fiber/matrix interactions can seriously degrade MMC strength. Research in the area of coatings is desirable, not only to prevent these deleterious reactions but also to promote the proper degree of wetting to form a good fiber/matrix bond. Coatings add to the material and processing costs of MMCs, so that research into cheaper coatings and processes is essential.

Important Environmental Behavior

It is critical to understand how reinforcements and matrices interact, particularly at high temperatures, both during fabrication and in service. A thorough understanding of material behavior is necessary to ensure reliable use and to provide guidelines for development of materials with improved properties. To date, study of the behavior of MMCs in deleterious environments has been much more limited than for PMCs. Research is needed in the areas of stress/temperature/deformation relations, strength, mechanical and thermal fatigue, impact, fracture, creep rupture, and wear.

Fracture

The subject of fracture behavior in MMCs deserves special attention. The applicability of traditional analytical techniques is controversial because MMCs are strongly heterogeneous materials. It seems reasonable that these traditional techniques should be valid at least for particulate-reinforced MMCs, because they do not appear to have the complex internal failure modes associated with fiber-reinforced MMCs. In view of the lack of agreement on how to characterize fracture behavior of MMCs, though, it will be necessary to rely on empirical methods until a clearer picture emerges.

Nondestructive Evaluation

Reliable NDE techniques must be developed for MMCs. They should include techniques for detecting flaws and analytical methods to evaluate the significance of these flaws. In MMCs as in PMCs, there is the possibility of many kinds of flaws, including delamination, fiber misalignment, and fracture. There are no NDE procedures presently available for measuring the extent of undesirable reinforcement/matrix interaction and resultant property degradation.

Machining

The machining of MMCs is currently a very expensive process that requires diamond tools because of the materials' very hard and abrasive ceramic reinforcements. As machining is a major cost factor, development of improved methods tailored to the unique properties of MMCs would help to make these materials more competitive.

Desirable

Modeling

Analytical modeling methods would be of value in helping to develop and optimize processes for fabricating MMCs. What are needed are design methods that take into account plasticity effects and provide for development of efficient, selectively reinforced structures and mechanical components. Research on modeling of processing behavior is necessary, together with the eventual development of databases of properties and process parameters.