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Advances in Materials Technology: MONITOR

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METAL-MATRIX COMPOSITES

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Dear Reader,

This is number 17 of UNIDO's state-of-the-art series in the field of materials entitled "Advances in Materials Technology: Monitor".

In each issue of this series, a selected material or group of materials is featured and an expert assessment made on the technological trends in those fields. In addition, other relevant information of interest to developing countries is provided. In this manner, over a cycle of several issues, materials relevant to developing countries could be covered and a state-of-the-art assessment made.

As metals now reach the limit of their potential in the more demanding aerospace and automotive applications, researchers are turning their attention to advanced composites. The question of how one of the most important composites, the Metal-matrix Composites, is being developed is of great importance to many scientists. This issue of our Monitor is therefore devoted to Metal-matrix Composites.

The main article has been written for us by two professors, Pradeep Rohatgi and Samuel C. Weaver, of the University of Wisconsin, Milwaukee, Wisconsin, USA.

Our appreciation to all our readers who share with us their knowledge and experience. We are always grateful for offers to write articles for our Monitor and welcome your ideas and suggestions on possible subjects for forthcoming issues.

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Industrial Technology Development
Division

1. METAL-MATRIX COMPOSITES

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1. INTRODUCTION

Metal matrix composites (MMC) are engineered combinations of two or more materials (one of which is a metal) where tailored properties are achieved by systematic combinations of different constituents. Conventional monolithic materials have limitations in respect of achievable combinations of strength, stiffness and density. Engineered metal-matrix composites consisting of continuous or discontinuous fibers, whiskers, or particles in a metal result in combinations of very high specific strength and specific modulus to be achieved (Tables 1A, 1B; Fig. 1A). Structurally, metal-matrix composites consist of continuous or discontinuous fibers, whiskers, or particles in an alloy matrix which reinforce the matrix or provide it with requisite properties not achievable in monolithic alloys. Furthermore, systematic design and synthesis procedures allow unique combinations of engineering properties like high elevated temperature strengths, fatigue strength, damping properties, electrical conductivity, thermal conductivity and expansion coefficient. In a broader sense, cast composites, where the volume and shape of phases is governed by phase diagrams, i.e., cast iron and aluminum-silicon alloys, have been produced by foundries for a long time. The modern composites differ in the sense that any selected volume, shape and size of reinforcement can be introduced in the matrix. The modern composites are nonequilibrium mixtures of metals and ceramics where there are no thermodynamic restrictions on the relative volume percentages, shapes and sizes of ceramic phases.

By carefully controlling the relative amounts and distribution of the ingredients constituting a composite, as well as by controlling the processing conditions, MMCs can be imparted with a tailored set of useful engineering

TABLE 1A

Mechanical Properties of Some Metal Matrix Composites

Material	Vol. Fr. Fiber (%)	Specific Strength (N • m/kg)	Specific Modulus (N • m/kg)
Al_2O_3 (FP)/Al-Li			
0°	60	20000	7.59×10^7
90°	60	4986 - 6000	4.406×10^7
SiC/Ti-6 Al-4V			
0°	35	45337	7.77×10^7
90°	35	10622	-
C/Mg (Thornd)	38	28333	-
C/Al	30	28163	6.53×10^7
6061 Al	-	11481	2.53×10^7
2014 Al	-	17143	2.59×10^7
$SiC_{(f)}$	100	78431	1.557×10^8
$SiC_{(w)}$	100	6.67×10^5	2.19×10^8
$Al_2O_{3(f)}$	100	50000	1.175×10^8
$B_{(f)}$	100	1.538×10^5	1.62×10^8
$C_{(f)}$	100	1.618×10^5	1.35×10^8
$Be_{(f)}$	100	59459	1.68×10^8
$W_{(f)}$	100	14974	1.79×10^7
B/Al 0°	50	56604	7.92×10^7
90°	50	5283	5.66×10^7
SiC/Al 0°	50	8803	1.092×10^8
90°	50	3697	-

TABLE 1B

Mechanical Properties of Cast Metal Matrix Composites

Type of MMC	V_f	Elastic Modules (GN/m^2)
Al Matrix	0	3.79
Continuous SiC Fiber (Al-4.5 Cu Matrix)	0.35	10.85
Continuous SiC Fiber (Al-11.6 Si Matrix)	0.35	10.50
Continuous SiC Fiber (Al 4.8 Mg)	0.35	10.25
Discontinuous SiC Fiber (Al Matrix)	0.44	11.6

properties which can not be realized with conventional monolithic materials (Figs. 1A, 1B).

Composite materials are attractive since they offer the possibility of attaining property combinations which are not obtained in monolithic materials and which can result in a number of service benefits. These could include increased strength, decreased weight, higher service temperature, improved wear resistance, higher elastic modulus, controlled coefficients of thermal expansion and improved fatigue properties. The quest for improved performance has resulted in a number of developments in the area of metal matrix composites. These include the preparation of the reinforcing phases and development of fabrication techniques.

Reinforcement phases for metal-matrix composites fall into three important categories -continuous or discontinuous filament, whiskers and particulate. The greatest improvements in mechanical properties are obtained from filaments in the direction of filament alignment, with whiskers and particulate offering descending strength, but greater isotropy, in that order.

A number of composite fabrication techniques have been developed that can be placed into four broad categories: those involving liquid metallurgy; those involving powder metallurgical techniques; those involving diffusion bonding of foils; and those involving vapor phase infiltration. The liquid metallurgy techniques would include unidirectional solidification to produce directionally aligned metal-matrix composites, suspension of reinforcements in melts followed by solidification, compocasting and pressure infiltration. The liquid metallurgy techniques are least expensive and the multi step diffusion bonding techniques are most expensive.

From a technological standpoint of property performance relationship, the interface between the matrix and the reinforcing phase (fiber or particle) is of central importance. Processing of metal matrix composites sometimes allows tailoring of the interface between the matrix and the fiber in order to suit specific property performance requirements. The cost of producing cast metal matrix composites has come down rapidly, especially with the use of low cost particulate reinforcements like graphite and silicon carbide. Low cost composites like metal silicon carbide particle and metal graphite particle are now commercially available. In recent years considerable activity has taken place in the area of metal matrix composites, and Table 2 shows the different fibers and matrices combined to date, the fabrication techniques and the potential fields of application. Table 3 gives more recent data of the same type for cast composites, most of which are particulate.

2. STRENGTHENING CONSIDERATIONS

Composite materials technology offers unique opportunities to tailor the properties of metals and metal alloys. Under ideal conditions the composite exhibits mechanical and physical properties defined by the rule of mixture. That is:

$$P_c = P_m F_m + P_r F_r \qquad (1)$$

where:

P_c = the properties of the composite material
P_m = the properties of the matrix phase
P_r = the properties of the reinforcement phase
F_m = the volume fraction of the matrix phase
$F_r = 1 - F_m$ the volume fraction of the reinforcement phase.

By combining matrix and reinforcement phases exhibiting the appropriate properties, dramatic changes can be made in strength, elastic modulus,

TABLE 2

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
SiC coated B	Al	Powder metallurgy; the composite article is clad with a sheet of Ti by diffusion bonding	Turbine blades
C (graphite, amorphous carbon)	Ni/Co aluminide	Coating C fibers with Ni or Co; mixing with Ni-Co Al powder; hot pressing	
C coated with boride of Ti, Zr, Hf	Al or Al alloys, Mg, Pb, Sn, Cu, Zn	Melt impregnation	
	Al alloy containing carbideforming metal, e.g., Ti and Zr	Melt impregnation	
SiC with W core	Al-Cu alloy	Coating the filaments with Cu; passing the Cu coated filaments through an Al melt	
C	Mg or Mg alloy	Melt impregnation; the molten Mg matrix contains small amounts of magnesium nitride to enhance wetting of the fibers	Turbine fan blades, pressure vessels, armor-plates
SiC	Be or alloys with Ca, W, Mo, Fe, Co, Ni, Cr, Si, Cu, Mg, and Zr	Vacuum impregnation; with molten Be or plasma spraying fibers with Be and consolidation by metallurgical process	Aerospace and nuclear industries
B + stainless steel; Borsic + Mo fibers	Al, Ti	Impregnation, spraying combination of high-strength ductile and brittle fibers	Aerospace industry

TABLE 2 (continued)

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
SiC	Ti or alloy Ti 3 Al-2.5V	Hot pressing of inter layers of fibers and matrix sheets; SiC fibers are previously coated with Zr diffusion barrier layer	Compressor blades, air foil surfaces
Carbides of Nb, Ta, and V	Ni Co and Fe Cr alloys	Unidirectional solidification	Aircraft industry
SiC containing 0.01 20% free carbon	Cr based alloys	Powder metallurgy; the free carbon reacts with the Cr to form carbides, thus improving bonding	High strength, heat resistant material, e.g., vanes and blades for turbine, rocket nozzles
SiC containing 0.01 30% free carbon	Co or Co based alloys	Powder metallurgy or melt impregnation: carbide formation between the fibers and the Co matrix	High strength, heat-resistant material, e.g., vanes and blades for turbines, rocket nozzles
SiC containing 0.01 20% free carbon	Mo based alloys	Powder metallurgy	High strength, heat resistant material, e.g., vanes and blades for turbines, rocket nozzles
C coated with carbides	Ni or Ni alloys	Melt impregnation	Aeronautical industry
B	Cu Ti Sn alloy	Liquid phase sintering	Cutting tools
C	Bronze	Various processe	Bearing materials
C	Cu alloy	Powder metallurgy; the fibers are mixed with a slurry of Cu powder and 2% of a carbine forming metal powder (Ti or Cr)	High strength, electrically conductive materials

TABLE 2 (continued)

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
C coated with Ti boride	Al, Cu, Sn, Pb, Ag, Zn, and Mg	The matrix contains alloying elements of Ti and B to prevent deterioration of the TiB coating of the fibers	Aeronautical industry
C coated with Ni	Metals with melting point lower than that of Ni	Melt impregnation	
C coated with SiO_2 + SiC	Al, Mg, Ti, and Ni	Melt impregnation, powder metallurgy	
Monocarbides of Ta, Ti, and W	Al, Al-Si alloy Ag or Ag alloys, and Cu or Cu alloys	Melt impregnation	Abrasion-resistant materials
B-SiC	Ag or Ag alloys		Electrical Conductors contacts
C	Si	Powder metallurgy	Abrasive materials
SiC	Al		
C coated with TiB	Mg,Pb, Zn, Cu, and Al	Melt impregnation	

fracture toughness, density, and coefficient of expansion. The key to control of these properties depends in part on successful selection of the reinforcement phase, and the bonding between the matrix and the reinforcement. Examples of the range of some of the mechanical properties attainable in aluminum metal-matrix composites are shown in Fig. 1 as a function of reinforcement phase strength, elastic modulus, and volume loading.

The above discussion is based on the assumption that the rule-of-mixtures is followed by the composite material. In fact, this can be the case for certain properties like modulus, when continuous filament is used as the reinforcement phase, and matrix-to-reinforcement phase interfacial reactions are controlled to provide good bonding without degradation of the reinforcement phase. An example of the agreement between the strength predicted by the rule-of-mixtures and that measured in stainless steel reinforced aluminum is shown in Fig. 2A.

Based on the agreement shown in Fig. 2A between the rule-of-mixtures prediction and measured properties, it would be desirable to fabricate all metal-matrix composites using continuous filament as the reinforcement phase, if properties mainly in one direction are required. Practically speaking, however, there are significant restrictions imposed by the use of continuous reinforcement in metal-matrix composites. The preparation of continuous filament is a complex and expensive process as shown in the lay-up process for continuous filament within the metallic matrix (Fig. 2B). In addition, continuous filament reinforcement is currently limited to simple geometries such as planar or symmetric shapes as discussed previously. Consequently, continuous filament-reinforced metal matrix composites are being evaluated only for limited, high value-added applications, especially for aerospace applications.

As a result, alternative reinforcement phase morphologies are being investigated to reduce the cost of metal matrix composites while still retaining the attractive properties. These approaches typically involve the use of less expensive, discontinuous reinforcement phases and powder metallurgy or casting techniques. Unfortunately, in the quest for lower cost, a price has to be paid in generally lower levels of property enhancement.

The short-fall in mechanical properties compared with continuous fiber reinforcement results from the decreased transfer of stress from the matrix to the reinforcement phase. As shown in Fig. 3, the efficiency of stress transfer is related to the length (l) of the reinforcement phase compared with its critical length (l_c) by the relationship:

$$S_c = S_f[V_f*(1-l_c/2*l) + E_m/Ef*(1-V_f)] \qquad (2)$$

where:

S_c = composite strength

S_f = reinforcement strength

V_f = volume fraction of reinforcement phase

l_c = minimum reinforcement phase length for full load transfer from the matrix to the reinforcement

($l_c = d*S_f/S_m$) where

d = fiber diameter and

S_m = matrix strength

l = actual reinforcement phase length

E_m = elastic modulus of the matrix

E_r = elastic modulus of the reinforcement phase.

Figure 3 reveals that for fiber lengths near the critical fiber length, relatively modest increases in strength are realized. As the ratio of l/l_c

increases, however, the efficiency of load transfer from the matrix to the reinforcement increases. For example, if $l/l_c = 16$, the discontinuously reinforced composite will exhibit approximately 96 percent of the increase in strength exhibited by a continuously reinforced composite.

Despite these theoretical advantages, there are significant practical problems associated with maintaining the integrity of high-aspect-ratio discontinuous fibers during fabrication and working. Thus, there is a high level of development activity in the use of particulates as composite reinforcement materials. However, particulate material has an aspect ratio of only about one and there is a trade-off to lower properties when using particulate reinforcement as compared with high aspect ratio fibers. There are other mechanisms between the matrix and the dispersoid which contribute to an overall increase in the strength and modulus of particulate composites. Recent studies have indicated that dislocation densities are very high in the matrix near the interface which may be responsible for strength. In addition to the length, the shape of the dispersoids also has a major influence on the properties (Fig. 3B); there are indications that flakes may be more effective than particles.

3. POWDER METALLURGY-BASED METAL-MATRIX COMPOSITES

Powder metallurgy techniques offer the following advantages over liquid metallurgy techniques of fabricating metal-matrix composites.

- Lower temperatures can be used during preparation of a P/M-based composite compared with preparation of a liquid metallurgy-based composite. The result is lesser interaction between the matrix and the reinforcement when using the P/M technique. By minimizing undesirable interfacial reactions, improved mechanical properties are obtained.

In some cases P/M techniques will permit the preparation of composites that cannot be prepared by liquid metallurgy. For instance, fibers or particles of silicon carbide will dissolve in melts of several metals like titanium, and such composites will be difficult to prepare using liquid metallurgy techniques.

However, powder metallurgy techniques remain expensive compared to liquid metallurgy techniques for composites like Al-SiC particle composites. In addition only small and simple shapes can be produced by powder metallurgy techniques.

A number of P/M composite preparation methods have been studied. The conventional powder metallurgy techniques of blending metal powders and ceramic powders, followed by pressing and sintering, have been used extensively to produce composites. In certain instances sintering is done in the presence of pressures at temperatures where there is partial melting for better bonding. The powder produces composites which can be subsequently forged and rolled.

Several companies are currently involved in the development of powder metallurgy-based metal-matrix composites using either particulates or whiskers as the reinforcement phase. Three of these companies are DWA (Delowey, Webb and Associates, Chatsworth, CA), the American Composites, formerly ARCO and Silag (Greenville, SC), and Novamet, a part of INCO Mechanically Alloyed Products Company (Wyckoff, NJ). Each of these companies has a unique feature associated with their process/product that differentiates it from the other two. Brief descriptions of these processes are shown in Figs. 4 to 6. DWA uses a proprietary blending process to combine particulate with metal powder. Silag also uses a proprietary blending process to combine its composite components. The distinction between the two is that Silag uses SiC whiskers, which are manufactured from rice hulls, as the reinforcement phase rather than particulate. Novamet, similar to DWA, uses particulate as the reinforcement phase, but employs mechanical alloying techniques to combine the reinforcement and matrix constituents.

Despite the differences in reinforcement or processing methods, all of these products show similarities. All are currently intended for high value added applications, such as military or aerospace, and all are quite expensive relative to similar, noncomposite products, i.e., \$50-\$100/pound versus \$5-\$10/pound as billet. Additionally, the relation of the mechanical properties to volume fraction reinforcement is similar. As shown in Fig. 7, the measured values of elastic modulus follow closely the predicted values for continuous filament reinforcement. However, the measured strength values are lower than the values predicted by the continuous filament reinforcement model, although they are generally above the discontinuous reinforcement model predictions, at least at the lower volume loadings.

The shortfall in strength relative to the behavior of the elastic modulus is a typical problem that currently plagues all discontinuous metal-matrix composites. It is most likely a result of decohesion between the reinforcement and matrix phases. While some of the continuous reinforcement filaments have near surface chemistries that are specially tailored to enhance this interfacial bond, similar progress has not yet been made in the case of the discontinuous reinforcement phases. This aspect of composite technology must be addressed to achieve the optimum properties attainable from discontinuous reinforcement.

In the following, two novel powder processes are described.

3.1 In-Situ Composites

In this approach to metal-matrix composite fabrication, elongated reinforcement phases are created by deformation processing of the composites, which consist of samples of elemental powders. During the working process, which may be extrusion, drawing or rolling, the constituents acquire an elongated, fibrous or lamellar morphology. To accomplish this, the reinforcing phase must be ductile under the deformation processing condition used.

The strength of nickel and tungsten in-situ composite is at least as great as a similarly worked directionally solidified alloy of the same composition. The nickel Tungsten in-situ composite contains Tungsten particles which are elongated into fibers during deformation.

The in-situ composite fabrication technique is not universally applicable to all metallic systems, and some restrictions apply to the properties of the second phase, particularly if the second phase is brittle at the working temperature.

Another factor that affects the ability to fabricate in-situ composites is the disparity in the flow stress of the constituents. Reinforcing-phase (i,e., the minor constituent) particles having a much higher flow stress than the matrix phase will not elongate into fibers or platelets during working, even when very high plastic strains are imposed. An example of such a system is Cu-11.3 weight percent Mo which, at true strains of approximately 7, still retained the molybdenum particles at near their original morphology. Presumably, if the matrix phase possessed a high work hardening rate, its flow stress could have been increased during working to the point where it would have caused deformation of the molybdenum particles.

Despite the above limitations, fibrous composites made using this technique can show unexpectedly large positive deviations in strength compared with rule of mixtures as shown by the Cu-16 volume percent Fe system. Significant deviations in strength from the rule of mixtures begin as early as true strains of approximately 2; and, at a true strain of approximately 5-6, the observed strength can be as much as 50 percent above the rule-of-mixture value.

For certain composite materials applications, the approach described above may offer significant advantages such as the following:

- The metallic constituents making up the composite are inexpensive relative to nonmetallic reinforcement.
- The composite can be formed by traditional metalworking operations.
- Thermal expansion mismatch between the metallic reinforcement and matrix is minimized, compared with nonmetallic reinforcement in a metallic matrix.
- Much higher strengths than predicted by the rule-of-mixtures can be achieved.

3.2 Spray Casting

Singer and Osprey processes, involving spray casting techniques, are based on conventional gas atomization technology. In these processes, a molten metal stream is impinged by a gas stream to create particulate. Rather than allowing the particulate to solidify, as is done in the gas atomization of metal powders, a substrate is placed in the path of the particulate. The molten particles collide with the substrate and a metallic preform is built up. These techniques can be classified as either powder or casting techniques since they combine both processes.

Recently, Singer and Ozbek used a spray codeposition process to prepare particulate reinforced composites. In their study they introduced various reinforcement phases into the atomized stream of molten metal. In this way they were able to build up a spray-cast strip structure that contained the reinforcement phase in a fairly uniform dispersion with the metallic matrix.

Incorporation of the reinforcement phase into the matrix does not occur until the reinforcement phase is trapped by molten matrix particles impinging the substrate. When impingement occurs, heat extraction from the splatted matrix particles is very rapid; and the fairly high solidification rate, combined with the fact that the reinforcement phase is in contact with the molten metal for only a very short time, greatly reduces the amount of interfacial reaction that can occur. This in turn minimizes the formation of brittle interfacial phases that sometimes degrade the properties of a composite.

Full density is not achieved during spray codeposition, and subsequent hot and cold rolling need to be used to densify the material. The distribution of all the phases tried, including sand, graphite and silicon carbide, appeared to be quite uniform despite the density variations. This feature of the process results from introducing the reinforcement phase into the atomized metal stream and entrapment of the reinforcement when the two components impinge on the substrate.

4. SOLIDIFICATION PROCESSING OF METAL-MATRIX COMPOSITES

Solidification processing of metal-matrix composites represents one of the simplest methods of producing metal-matrix composites. Cast irons and aluminum-silicon alloys are in a sense phase diagram redirected metal-matrix composites. Unidirectional solidification of eutectics can produce fiber reinforced composites in a single step. However, these are phase diagram restricted.

Modern cast metal-matrix composites which are not restricted by phase diagrams are made by introducing fibers or particles in molten or partially solidified metals followed by casting of these slurries in molds. Alternately, a preform of fibers or particles is made and it is infiltrated by molten alloys, which then freeze in the interfiber spaces to form the composite. In both these processes wetting between molten alloys and dispersoids is necessary. The cast metal composites made by dispersing pretreated particles in the melts followed by solidification are given in Table 3. In addition, several short fiber and long fiber reinforced metal-matrix composites have been made by casting techniques.

Continuous fiber reinforced Gr/Mg, Gr/Al, and several other cast FRMs are valuable structural materials since they combine high specific strength and stiffness, with a near-zero coefficient of thermal expansion, and high electrical and thermal conductivities. The primary difficulty with fabricating these cast fiber-reinforced metals is the poor wetting and bonding between fibers and metals. However, compatibility and bonding between the fiber and the metal in these systems are induced by chemical vapor deposition of a thin layer of Ti and B, or oxides like silica or metals like nickel, onto the fibers to achieve wetting. The flexible coated fibers may then be wound or laid-up and held in place with a removable binder for selective reinforcement. They are then incorporated into Mg by casting near-net shape structures by pressure infiltration of Mg. Complex structural components with high volume fraction graphite fibers can be fabricated in this manner in a foundry. High strength, high-stiffness fiber FP (100% polycrystalline

TABLE 3A

Selected Potential Applications of Cast Metal-Matrix Composites

Composite	Applications	Special Features
Aluminum/graphite	Bearings	Cheaper, lighter, self-lubricating conserve Cu, Pb, Sn, Zn, etc.
Aluminum/graphite, aluminum/aAl_2O_3, aluminum/SiC-Al_2O_3	Automobile pistons, cylinder liners, piston rings, connecting rods	Reduced wear, antiseizing, cold start, lighter, conserves fuel, improved efficiency
Copper/graphite	Sliding electrical contacts	Excellent conductivity and anti-seizing properties
Aluminum/SiC	turbocharger impellers	High-temperature use
Aluminum/glass or carbon microballoons		Ultralight material
Magnesium/carbon fiber	Tubular composites for space structures	Zero thermal expansion, High temperature strength, good specific strength and specific stiffness
Aluminum/zircon, aluminum/SiC, aluminum/silica	Cutting tools, machine shrouds, impellers	Hard, abrasion-resistant materials
Aluminum/char, aluminum/clay	Low-cost, low-energy materials	

TABLE 38

Matrix Dispersoid Combinations Used to Make Cast Particulate Composites

Matrix	Dispersoids	Size	Amount
Aluminum Based	Graphite Flake	20-60 µm	0.9-0.815%
	Graphite Granules	15-100 µm	1-8%
	Carbon Microballoons	40 µm, thickness 1-2 µm	
	Shell Char	125 µm	15%
	Al_2O_3 Particles	3-200 µm	3-30%
	Al_2O_3 Discontinuous	3-6 mm long, 15 µm dia	0-23 Vol.-%
	SiC Particles	16-120 µm	3-20%
	SiC Whiskers	(5-10 µm)	10%, 0-0.5 Vol.-%
	Mica	(40-180 µm)	3-10%
	SiO_2	(5-53 µm)	5%
	Zircon	40 µm	0-30%
	Glass Particles	100-150 µm	8%
	Glass beads (spherical)	100 µm	30%
	MgO	40 µm	10%
	Sand	75-120 µm	36 Vol.-%
	Tic Particles	46 µm	15%
	Boron Nitride Particle	46 µm	8%
	Si_2N_4 Particle	40 µm	10%
	Chilled Iron	75-120 µm	36 Vol.-%
	ZrO_2	5-80 µm	4%
	TiO_2	5-80 µm	4%
	Lead		10%

TABLE 3B (continued)

Matrix-Dispersoid Combinations Used to Make Cast Particulate Composites

Matrix	Dispersoids	Size	Amount
Copper Based	Graphite		
	Al_2O_3	11 µm	Vol fraction 0.74
	ZrO_2	5 µm	2.12 Vol.-%
Steel	TiO_2	8 µm	
	CeO_2	10 µm	
	Illite Clay	753 µm	3%
	Graphite Microballoons		

α-Alumina)/Mg composites containing up to 70 vol. % fiber FP have been prepared by a pressure infiltration process.

For non-wetting metals, fiber FP is coated with the metal by vapor deposition or by electroless plating, prior to infiltration. Coatings of Ti-B also have been used for Gr/Al, fiber FP/Al and FP/Pb metal-matrix composites. However, from the standpoint of ease of fabrication and cost, modification of matrix alloy by addition of small amounts of reactive elements like Mg, Ca, Li or Na is preferred. Fiber FP reinforced Al, Cu, Pb and Zn composites as well as several particle filled metal-matrix composites have been synthesized by using reactive agents.

Continuous adherent metallic coatings (e.g., Cu and Ni) on several non-wetting particles such as graphite, shell char and mica improve the melt-particle wettability and allow high percentages of these particles to be introduced in the solidified castings. The wetting properties of ceramics by liquid metals are governed by a number of variables such as heat of formation, stoichiometry, valence electron concentration in the ceramic phase, interfacial chemical reactions, temperature and contact time.

Therefore, while metal-matrix composites are not restricted by phase-diagram considerations (viz., fixed proportions, chemistry and morphology of solidifying phases), thermodynamic free energy and kinetic barriers still exist in their processing in the form of poor wettability and rates of mixing, and they need to be addressed for synthesizing these composites.

4.1 Casting Techniques, Microstructures, and Properties

A basic requirement of foundry processing of MMCs is initial intimate contact and intimate bonding between the ceramic phase and the molten alloy. This is achieved either by premixing of the constituents or by pressure infiltration of preforms of ceramic phase. As mentioned earlier, due to poor wettability of most ceramics with molten metals, intimate contact between fiber and alloy can be promoted only by artificially inducing wettability or by using external forces to overcome the thermodynamic surface energy barrier and viscous drag. Mixing techniques generally used for introducing and homogeneously dispersing a discontinuous phase in a melt are:

1. Addition of particles to a vigorously agitated fully or partially solidified alloy. Figure 8 shows a schematic diagram of an agitation vessel using rotating impeller.
2. Injection of discontinuous phase in the melt with the help of an injection gun.
3. Dispersing pellets or briquettes, formed by compressing powders of base alloys and the ceramic phase, in a mildly agitated melt.
4. Centrifugal dispersion of particles in a melt. This has been done for carbon microballoons.
5. Spray casting of droplets of atomized molten metals along with particulates on a substrate. This technique has been described in the previous section.

In all the above techniques, external force is used to (i) transfer a non-wettable ceramic phase into a melt, and (ii) create a homogeneous suspension in the melt. The uniformity of particle dispersion in a melt prior to solidification is controlled by the dynamics of particle movement in agitated vessels.

The melt-particle slurry can be cast either by conventional foundry techniques such as gravity or pressure die casting, centrifugal casting or by novel techniques such as squeeze casting (liquid-forging) and spray codeposition, melt spinning or laser melt-particle injection. The choice of casting technique and mold configuration is of central importance to the quality (soundness, particle distribution, etc.) of a composite casting since the suspended particles experience buoyancy driven movement in the solidifying melt until they are encapsulated in the solidifying structure by crystallizing phases. Particles like graphite, mica, talc, porous alumina, and hollow microballoons are lighter than most Al alloys and they tend to segregate near the top portion of gravity castings, leaving behind a particle-impoverished region near the bottom of the casting. Similarly, heavier particles such as zircon, glass, SiC, SiO_2, TiO_2 and ZrO_2 tend to settle down and segregate near the bottom portion of the gravity castings.

The spatial arrangement of the discontinuous ceramic phase in the cast structure principally determines the properties of the cast composite. The distribution of phases depends on the quality of melt-particle slurry prior to casting and the processing variables, including the cooling rate, viscosity of solidifying melt, shape, size and volume fraction of particle, particle and melt specific gravities, and their thermal and chemical properties, interactions of freezing solid with particles and presence of any external forces during solidification. The various techniques used to solidify melt-particle slurries are discussed below.

4.1.1 Sand Castings

The slow freezing rates obtained in insulating sand molds permit considerable buoyancy-driven segregation of particles. This leads to preferential concentration of particles lighter than Al alloys (e.g., mica, graphite, porous alumina) near the top surface of sand castings and segregation of heavier particles (sand, zircon, glass, SiC, etc.) near the bottom part of castings. These high-particle-volume fraction surfaces serve as selectively reinforced surfaces, for instance, tailor-made lubricating or abrasion-resistant contacting surfaces, for various tribological applications.

4.1.2 Die Castings

The relatively rapid freezing rates in metallic molds generally give rise to more homogeneous distributions(-SOUTH-)cles in cast matrix. Figures 9 and 10 show a microstructure of a permanent mold gravity die casting of Al alloys containing dispersions of graphite and zircon particles.

4.1.3 Centrifugal Castings

Solidification in rotating molds of composite melts containing dispersions of lighter particles, like graphite, mica, and porous alumina, exhibits two distinct zones--a particle rich zone near the inner circumference for lighter particles and a particle-impoverished zone near the outer circumference. The outer zone is particle rich if the particles like zircon or silicon carbide are heavier than the melt (Fig. 11); the outer zone is abrasion resistant due to these hard particles.

Due to centrifugal acceleration in rotating molds, the lighter graphite and mica particles segregate near the axis of rotation producing high particle volume-fraction-surfaces for bearing or cylinder liner applications. The thicknesses of these particle rich zones remain adequate for machining. Up to 8% by weight mica and graphite, and up to 30% by weight zircon, particles could be incorporated in selected zones of Al alloy castings by this technique.

4.1.4 Compocasting

Particulates and discontinuous fibers of SiC, alumina, TiC, silicon nitride, graphite, mica, glass, slag, MgO and boron carbide have been incorporated into vigorously agitated partially solid aluminum alloy slurries by a 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 and appears to be time-dependent and reversible. This semi-fusion process allows near net-shape fabrication by extrusion or forging since deformation resistance is considerably reduced due to the semi-fused state of the composite slurry. Figure 12 is a scanning micrograph of a compocast composite showing a random planer arrangement of alumina fibers.

4.1.5 Pressure-Die Casting

Pressure die-casting of composites allows larger-sized, more intricately shaped components to be rapidly produced at relatively low pressures ($\leq$ 15 MPa). Pressurized gas and hydraulic ram in a die-casting machine have been employed to synthesize porosity-free fiber and particle composites. It has been reported that high pressures, short infiltration paths and columnar solidification toward the gate produced void-free composite castings. The pressure die cast particle composites exhibit lower bulk and interfacial porosities, more uniform particle distribution, and less agglomeration of particles. High concentrations (60 wt. % or more) of zircon ($ZrSiO_4$) particles can be achieved in pressure die-cast Al-Si-Mg alloys. Pressure die castings of LM 13* - 7 wt. % graphite and Al-(4-12%)Si-(0.5-10%)Mg-alumina particle composites showed considerable improvement in particle distribution, particle-matrix bonding and elimination of porosities.

4.1.6 Squeeze Casting

Squeeze casting or liquid forging of metal-matrix composites is a recent development which involves unidirectional pressure infiltration (pressures ~ 70-200 MPa) of fiber-preforms or powder-beds by alloy melts, to produce void-free, near net-shape castings of composites (Fig. 13). The Saffill fiber reinforced pistons of aluminum alloys made by Toyota have been in use for several years in heavy diesel engines. The processing variables governing evolution of microstructures in squeeze cast MMCs are:

(i) fiber and melt preheat temperature, (ii) infiltration speed and pressure, and (iii) interfiber spacing.

If the metal or fiber temperature is too low, poorly infiltrated or porous castings are produced; high temperatures promote excessive fiber/metal reaction leading to degradation of casting properties. A threshold pressure is required to initiate liquid metal flow through a fiberous preform or powder-bed to overcome the viscous friction of molten pressure moving through reinforcements and the capillary forces if there is inadequate wetting between the melt and the fibers. Several theoretical analyses to model and analyze the frictional forces have been proposed. These relate the infiltration velocity to applied pressure, capillarity, viscosity and interfiber spacing as well as fiber preform permeability, length, diameter and geometry.

Alternatively, whiskers or particles may be mixed with molten metal prior to squeeze casting. Al alloy composites containing SiC and Al_2O_3 powders, σ-Alumina (Saffil) fibers, and silicon nitride whiskers have been fabricated by the squeeze casting process.

SiC whiskers (0-10 µm dia. 5.50 mm in length) have been dispersed in cast Al-(4-5)% Cu alloy matrix by a squeeze casting technique. The wettability problem was overcome by codispersing SiC whiskers and Al alloy powder (200 µm avg. size) in an aqueous solution of isopropyl alcohol, followed by infiltration, compaction into small briquettes and vacuum degassing. These briquettes were disintegrated into a mechanically stirred base alloy melt followed by squeeze casting under a pressure of 207 MPa. The resulting strengthening effects of composites are attributable to several factors, e.g., fine grain size, elimination of bulk and interfacial porosities, increased solid solubility due to hydrostatic pressure and the presence of high-strength SiC whiskers. Figure 13 shows a schematic diagram illustrating the principle of a squeeze casting process for particle composites.

Plate and tubular composites of Al alloys containing continuous or discontinuous SiC fibers (nicalon) can be synthesized by a squeeze casting technique. The SiC yarn consisting of about 500 monofilaments (13 μm avg. dia.) is mechanically wound around a steel frame or aligned undirectionally in an Al vessel. In the case of discontinuous SiC fibers, fiber can be chopped and packed in the vessel. The vessel with fiber is preheated in air for good penetration of molten metal matrix into interfiber space. Then the vessel is put into the mold which is preheated to 500 - 700 K. The fiber volume fraction of composites is controlled by selecting the winding conditions (for continuous fiber) or packing conditions (for discontinuous fibers) before casting.

4.1.7 Vacuum Infiltration Process

Several fiber reinforced metals (FRM) are prepared by the vacuum infiltration process. In the first step the fiber yarn is made into a handleable tape with a fugitive binder in a manner similar to producing a resin matrix composite prepreg. Fiber tapes are then laid out in the desired orientation, fiber volume fraction and shape, and are then inserted into a suitable casting mold. The fugitive organic binder is burned away and the mold is infiltrated with molten matrix metal.

The liquid infiltration process used for making graphite/Al composite differs from the above process of preparing fiber FP/Al composites. Graphite fibers are first surface treated and then infiltrated with molten metal in the form of wires and these coated graphite wires are then diffusion bonded together to form larger sections.

4.1.8 Investment Casting

In investment casting of metal-matrix composites, filament winding or prepreg handling procedures developed for fiber reinforced plastics (FRPs) are used to position and orient the proper volume fraction of continuous fibers within the casting. The layers of reinforcing fibers are glued together with an appropriate plastic adhesive (fugitive binder) which burns away without contaminating either the matrix or the fiber-matrix interface. These layers are stacked in the proper sequence and orientation, and the fiber preform thus produced is either infiltrated under pressure or by creating a vacuum in the permeable preform. Continuous graphite fiber reinforced Mg has been produced by this method.

4.1.9 Microstructures

The primary solid (α-Al) grows by rejecting solute in the melt while the discontinuous ceramic phase tends to restrict diffusion and fluid flow; α-Al tends to avoid it as shown in Fig. 9. Primary silicon and the eutectic in Al-Si alloys tend to concentrate on particle or fiber surface.

The discontinuous ceramic phase also tends to modify or refine the structure, e.g., eutectic Si in Al-Si alloys gets modified whereas primary Si is refined when solidification occurs in the presence of high volume fraction of ceramic phase. At sufficiently slow cooling rates when the secondary (DAS) in the unreinforced alloy is comparable to interfiber spacing, the grain size becomes large in comparison with interfiber spacing. In this case fibers do not enhance the nucleation of the solid phase. With a further decrease in the cooling rates, the extent of microsegregation is reduced; and, at sufficiently slow cooling rates, the matrix can be rendered free of microsegregation.

4.1.10 Properties and Applications

Modern fiber-reinforced or particle-filled metal-matrix composites produced by foundry techniques find a wide variety of applications due to the low cost of their fabrication and the specificity of achievable engineering properties. Some of these properties are high longitudinal strengths at normal and elevated temperatures, near-zero coefficients of thermal expansion, good electrical and thermal conductivities, excellent antifriction, antiabrasion, damping, corrosion and machinability.

The high temperature strength of MMCs is enhanced by reinforcements such as SiC fibers or whiskers or continuous Borsic (B fibers coated with SiC) fibers. Carbon/Al MMCs combine very high stiffness with a very low thermal expansion due to almost zero expansion coefficient of C fibers in the longitudinal direction. Graphite/Mg composites also have a nearly zero expansion coefficient.

In the case of particle-filled MMCs, the mechanical properties are not significantly altered, but tribological properties show marked improvements. Soft solid lubricant particles like graphite and mica improve antiseizing properties of Al alloys whereas hard particles like SiC, alumina, WC, TiC, zircon, silica, and boron carbide greatly improve the resistance to abrasion of Al alloys. Particle additions can also give rise to better damping and conductivity of the matrix alloy. For example, the damping capacity of aluminum and copper alloys is considerably enhanced when graphite powder is dispersed in them. Hitachi, Ltd., of Japan has produced a high damping MMC of graphite/Al or Cu under the name (GRADIA) whose damping capacity is considerably more stable at high temperatures than conventional vibration insulating alloys, including cast irons. Sliding electrical contacts made from the same alloy GRADIA (Cu-20 graphite) perform better than sintered materials of the same materials generally used, since the alloy combines excellent resistance to seizure with high electrical conductivity.

Figures 14 and 15 show photographs of fan bushes, journal bearings and several other components made from cast Al-Si-graphite particle composite and cast Al-Si-silicon carbide composite. The use of graphite in automobile engine parts considerably reduces the wear of cylinder liners as well as improves fuel efficiency and engine horsepower at equivalent cost. The most promising application of cast graphitic-aluminum alloys is for bearings which would be cheaper and lighter in addition to being self lubricating compared to the bearings currently being made out of Cu, Pb, Sn and Cd containing alloys. Cast aluminum-graphite fan bushes experience considerably reduced wear as well as temperature rise during trial at 1400 rpm for 1500 hrs.

Cast aluminum-graphite alloy pistons used in single cylinder diesel engines with a cast iron bore reduce fuel consumption and frictional horse power losses. Due to its lower density, the use of aluminum graphite composite in internal combustion engines reduces the overall weight of the engine. Such an engine does not seize during cold start or failure of lubricant due to excellent antiseizing properties of graphitic-aluminum alloys.

Alloys with a dispersed ceramic phase are finding applications in impellers and other tribological systems which run at high temperatures where there is a possibility of failure of liquid lubricant. Cast Al alloys reinforced with ceramic phase are being tried out as turbocharger impellers which run at high temperatures.

5. THE CENTERS OF METAL-MATRIX COMPOSITE MATERIALS IN THE UNITED STATES AND SOME OF THE DEVELOPING COUNTRIES

The United States is one of the most actively involved countries in research in metal-matrix composites. University-based centers in the United States with substantial activity in processing metal-matrix composites include the Center for Processing and Characterization of Composite Materials at the University of Wisconsin--Milwaukee, the Massachusetts Institute of Technology, and the University of Virginia. Other university-based centers for composites include Drexel University, Carnegie Mellon University, University of Illinois, Michigan State University, Renesslaer Polytechnic, Pennsylvania State University, University of California at Santa Barbara, University of Texas, and Witchita State University. Several other universities are in the process of opening centers on composite materials with activity in metal-matrix composites.

The companies and organizations that are very active in the metal-matrix composites in the United States and Canada include the following:

- Aluminum Company of Canada, Dural Corporation, Kaiser Aluminum, Alcoa, American Matrix
- Northrup Corporation, McDonald Douglas, Allied Signal, Advanced Composite Materials Corporation, Textron Specialty Materials
- DWA Associates, MCI Corporation, Novamet
- Martin Marietta Aerospace, Oakridge National Laboratory, North American Rockwell, General Dynamics Corporation, Lockheed Aeronautical Systems
- Dupont, General Motors Corporation, Ford Motor Company, Chrysler Corporation, Boeing Aerospace Company, General Electric, Westinghouse

- Wright Patterson Air Force Base, Dayton, Ohio
- Naval Surface Warfare Center, Silver Spring, Maryland

While the United States had a lead in the use of metal-matrix composites in aerospace and defense weapon applications, Japan has taken the lead in using metal-matrix composites on a widespread basis and in large applications such as automotive. Toyota was the first company in the world to incorporate metal-matrix composite pistons in high speed diesel engines. There is intensive activity in metal-matrix composites in several other corporations and universities in Japan.

In Europe, recently a consortium on composite materials has been formed involving all European countries, with a special emphasis on metal-matrix composites. The countries which have strong activities in composites include England, France, Italy, Norway, Sweden and West Germany.

Among the developing countries, China and India have well established research activities in metal-matrix composites. China has set up a very large institute in composite materials with a heavy emphasis in metal-matrix composites. This year's international conference on composites materials, which is one of the major biannual worldwide meetings in composites, is being hosted in China. In China, work is going on in the area of casting and powder metallurgy processes for making metal-matrix composites.

India has had substantial activity in cast and powder produced metal-matrix composites. It has leadership in cast aluminum graphite composites for automotive applications, and can offer this technology to other developing countries. India has the requisite technology base in the metals industry and it can get into large-scale manufacture of metal-matrix composites, especially particulate composites. It has laboratory scale production capability for production of carbon fibers for metal-matrix composites.

List of a Few Institutes Working on Metal-Matrix Composites in a Developing Country (India)

National Physical Laboratory, CSIR, New Delhi, India
Indian Institute of Technology, New Delhi, India
Indian Institute of Technology, Kanpur, India
Regional Research Laboratory (Bhopal), CSIR, Bhopal, India
Regional Research Laboratory (Trivandrum), CSIR, Trivandrum, India
National Aeronautical Laboratory, CSIR, Bangalore, India
Vikram Sarabhai Space Center, Trivandrum, India
Indian Institute of Science, Bangalore, India
Banaras Hindu University, Varanasi, India
University of Roorkee, Roorkee, U.P., India

6. STATE OF THE ART IN METAL-MATRIX COMPOSITES AND RELEVANCE TO DEVELOPING COUNTRIES

Intensive research in metal-matrix composites started about thirty years ago to meet the increasing requirements of properties in aerospace materials to achieve higher speeds and higher temperature engines for higher efficiencies. Much of this research was concentrated on ceramic and carbon fiber reinforced metals made by processes of plasma spray and vapor disposition or diffusion bonding of foils with interspersed layers of fibers followed by hot pressing (Fig. 28). These multi-stage processes involve several steps, and combined with the cost of long expensive fibers like Boron and carbon, the cost of metal-matrix composites thirty years ago was several hundred thousand U.S. dollars per pound. Most of these metal-matrix composites were used in aerospace applications where weight savings were of paramount importance, and to some extent in selected weapons systems, where cost was no concern (Table 2).

During the last few years, several developments have occurred in metal-matrix composites which have great relevance to developing countries.

For instance, the costs of metal-matrix composites has come down enormously during this period. The costs of metal-matrix fiber reinforced composites has come down from several hundred thousand dollars per pound to order of a thousand dollars per pound at this time due to decrease in costs of continuous fibers. The continuous fiber reinforced metal-matrix composites, therefore, still remain quite expensive for wide spread use in developing countries, except for certain critical applications where enormous savings in energy or resources can be made. However, there has been a more dramatic decrease in the cost of metal-matrix discontinuous fiber composites. The costs of particulate composites like aluminum-silicon carbide have come down to the level of two to ten dollars per pound due to the feasibility of using inexpensive particulate reinforcements and the possibility of using conventional casting processes to produce these composites.

In the early part of development of metal-matrix composites, organizations had captive research and production, or contracted small scale production of small quantities of metal-matrix continuous fiber composites. For the first time in the last five years, there are some producers and suppliers of metal matrix-silicon carbide composites both by powder metallurgy processes and by castings route. For instance, one could today obtain aluminum matrix silicon carbide composites for two to five dollars per pound from Aluminum Company of Canada. In fact in the last six months, Alcan has announced putting up of two plants with a capacity to produce twenty five millions pounds of aluminum silicon carbide or aluminum alumina composites per year in Canada and USA, and it can ship ingots of composites which can be melted in conventional foundries and cast into components very much the same way as conventional aluminum alloys are cast from shipped primary ingots. Norsk Hydro in Europe also plans to become a supplier of cast aluminum-silicon carbide composites. A number of components including pistons, impellers, brake systems, and housings have been cast out of aluminum - silicon carbide composites. This type of cast composite will be the forerunner for widespread use of metal-matrix ceramic particle composites, and could make possible secondary processing and use of these composites even in the developing world. Dow Chemical can supply small samples of cast magnesium-silicon carbide or magnesium-alumina composites. Likewise DWA Associates and American Composites can supply powder metallurgy produced aluminum-ceramic particle, whisker and fiber composites. In addition, companies like Textron can supply metal-matrix composites with higher melting metals as matrices. There are also a large number of research laboratories which can supply small samples of high melting metal-matrix composites, and composites with intermetallic compounds as matrices.

In the area of applications, the first application in large scale automotive sector was by Toyota in Japan, which put out a ceramic fiber reinforced squeeze cast aluminum piston for high speed diesel engines. This has triggered a flurry of activity in making engine components out of cast metal-matrix components. There is a great deal of activity in trying to make pistons, connecting rods and other engine parts out of aluminum-ceramic fiber composites using conventional pressure casting. In fact, Dupont had done a considerable amount of work in this area several years ago involving squeeze infiltration of FP alumina fiber, and now there is intense activity in Japan. In addition to Toyota, several companies are producing squeeze cast pistons where the combustion bowl area of the pistons (which is subjected to very high temperatures) and the ring groove area (which is subjected to high wear) are reinforced by discontinuous ceramic fibers placed in the molds as preforms before casting. These low cost, large scale mass manufacturable cast metal-matrix composites represent the biggest potential for metal-matrix composite activity in developing countries. The ingredients to make these composites are available in, or can be imported into, most of these developing countries and the composite products made will be of immediate use in many developing countries. For instance, aluminum-silicon carbide composites can save considerable amounts of energy and fuel when used in transportation systems, and can free several of these developing countries from the requirements of importing critical strategic minerals and oil that are presently not available in many of these developing countries.

Another metal-matrix composite of relevance to developing countries is cast aluminum-graphite particle composites, which has been developed in India, U.S., Europe and Japan during the last fifteen years for anti-friction applications. It has been demonstrated that pistons, cylinder liners, and bearings can be made out of cast aluminum-graphite particle composites. The use of pistons and liners of aluminum-graphite particle composites has been shown to save considerable amounts of fuel in the internal combustion engines and reduction in wear of the pistons, rings, and the liners. Aluminum graphite particle composites can replace much more expensive and heavier bearings made out of bronzes and babbit metals. Many of todays bearing materials rely on dispersions of toxic metals like lead in the matrix of copper or tin alloys. The use of graphite in place of lead can eliminate the need for lead, therefore, reducing the cost, weight, and toxicity of presently used bearing alloys. While aluminum-graphite particle composites have not been produced in the U.S.A. and Europe, they will be very useful in most of the developing countries where petroleum and metals like lead, tin, and copper, are available at very high cost and have to be imported. The technology of aluminum-graphite particle composites consists of stirring pretreated graphite particles in the melts of aluminum alloys using very conventional foundry equipment, followed by casting, either in permanent molds, or centrifugal casting machines or in pressure diecasting; most of these technologies are available in most of the developing countries and therefore, such a technology can be practiced and can be productionized in the developing world without much difficulty, and the products could be immediately used in the local industry. Japan has production facilities to make aluminum-graphite and copper-graphite composites, and India and China have the requisite research base to get into production of these alloys.

In addition to the current use of metal-matrix composites in aerospace applications, weapon systems, in the last few years in the developed world, there is interest in using these components in automotive applications, in bicycles and sporting goods like tennis rackets and golf clubs. The developing world should watch the application of metal-matrix composites in these sectors, and derive lessons to use these composites in other sectors critical to raising the standards of living in respective countries instead of leisure goods. The needs of developing world are more in the area of housing, in the area of energy generation and transportation, instead of in faster cars or airplanes, or sporting goods, or aerospace or defense systems which are driving the development of metal-matrix composites in the developed world. There is a very large increase in metal-matrix composites research in some developing countries like China, India, Egypt, and some Latin American Countries like Brazil and Argentina. Exchanges of information between developing countries themselves will be of great value, since their experience would be of greater relevance to each other. The agencies concerned with International development, like U.N. and the World Bank, could greatly facilitate this exchange.

Another area of concern in developing countries in the composite materials area, is the lack of availability of reinforcements. The continuous fiber reinforcements remain very expensive, and their production cannot be set up easily in the developing world. The developing world should initially concentrate on in-situ composites made by unidirectional solidification or powder extrusion, where the reinforcements are produced in-situ during the processing itself, thus eliminating the need for expensive reinforcements. In addition, the developing world should concentrate on short fibers, or better yet on particle reinforced metal-matrix composites which are inexpensive and have large scale application possibilities. For instance, emphasis should be given on graphite particle reinforced metal-matrix composites since graphite is available either in mineral form or in manufactured form in a large number of developing countries; with the relatively easy availability of aluminum, the production of these composites can be set up very easily. Likewise attempts should be made to learn to use readily available mineral based fibers in these developing countries, for instance, attempts should be made to use naturally occurring alumino silicate fibers, or fibers that can be readily made by melt spinning of oxides. These are areas where the developing world can immediately get into the use and manufacture of metal-matrix composites. This learning experience with inexpensive particulate metal-matrix composites will also set the stage for the developing world to get into the area of high performance metal-matrix continuous fiber composites when they become common place in the developed world, and the possibility of using ultrahigh performance materials in the developing world increases, in the next few years.

7. ELEMENTS OF EDUCATION AND TRAINING IN METAL-MATRIX COMPOSITES FOR THE DEVELOPING WORLD

For the developing world to get into the position of manufacturing and using metal-matrix composites, it will be necessary to start teaching and research in design, processing, and use of composites, in selected institutions in developing countries, complimented by a United Nations sponsored International Training Institute. These would generate individuals who would be familiar with global knowledge on metal-matrix composites, and can readily learn to use these new family of materials for there own location specific problems. In the absence of such indigenous manpower, trained personnel and infrastructure, there is the danger that the developed world imperatives in metal-matrix composites will continue to drive the development of these materials, and the progress will not be of much relevance to the developing world. The per capita availability of materials in developing countries is low and is a major constraint in raising living standards. Composite materials, specially metal-matrix composites, provide an opportunity to increase the supply of required materials at prices affordable in developing countries. However, it is necessary that scientists in developing countries are trained to explore the opportunities in metal-matrix composites for the development of their respective countries.

The science of design of composites involves prediction of properties of composites as a function of chemistry and structure of its constituents and processing. For example by changing the volume percentage and orientation of graphite fibers, magnesium graphite fiber composites with negative, zero or low positive coefficients of expansion can be designed. Subsequent to design of structure of composite component, the processes to manufacture and test the composites have to be designed and simulated. Process design requires considerable data base on manufacture of similar composites. Design of tests requires considerable data base on relationships between structure properties and performance on the specific composite in question.

In addition to the information generated in the west, the developing country scientists must be trained to use local resources and facilities to design, fabricate and test metal-matrix composite materials for use in their own environments. In certain developing countries, there are large agricultural waste products like paddy husk available; conversion of these resources into high performance whiskers like silicon carbide for reinforcements in metal-matrix composites would be an important imperative for them.

The newly emerging metal-matrix composites are based on most abundant elements (for instance carbon, aluminum, silicon, nitrogen, oxygen, magnesium to make carbon reinforced aluminum, silicon carbide reinforced magnesium, silicon carbide reinforced alumina) which are available in all countries quite equitably. Therefore the development of these composite materials will free several countries from resource constraints in manufacture of advanced materials. This, however, presents a threat to some developing countries whose economies are based on export of certain minerals like copper ores. The scientists in developing countries should be trained to analyze, and react to opportunities and threats from developments in metal-matrix composites.

Once the chemistry, structures, shape, size, volume percentages of constituents is decided by structure property relationships, the next step is to design the process to synthesize the composites. Process design is as important as product design. After the process design, the next element is design of testing and inspection procedures of composites to simulate long term performance in short term testing. The process design for developing countries should be of the type which can be used for manufacture in the low technology environment which often prevails in these countries. Computer simulation of performance of composites and the process to manufacture them, could save scarce resources in developing countries in terms of materials and energy wasted in trials. These aspects of design and simulation should form essential features of training in metal-matrix composites which could be imparted through the following elements.

7.1 Elements of Training Program in Metal-Matrix Composites

1. Lectures by program coordinators and permanent staff of the training center on principles of composite materials science. A possible text used can be Composite Materials by K. K. Chawla, American Elsevier.
2. Lectures by guest faculty working on metal-matrix composites in other institutes in developed countries.
3. Lectures by guest faculty familiar with developing countries. These could be people who are either working in a developing country or are familiar with developing country environment in relation to metal-matrix composite materials.
4. Demonstration of computer applications of design of structure, processing, properties and testing of metal-matrix composite materials. This could be done using the software available through organizations listed in this report which can be operated on personal computers and other stand alone computers available in developing countries.The participants from developing countries should be encouraged to bring material on their resources and infrastructure, and typical applications that have higher priority in their countries. Development of metal-matrix composites to

meet basic human needs using local resources should have high priority. Some examples would be composites made with local resources like mined or manufactured graphite particles, sand, aluminosilicates including clay, mica, and carbonized and pyrolized plant-based resources like natural fibers, rice husk and equisetum which can yield silicon carbide whiskers for reinforcement of composites. The work done on aluminum-graphite and aluminum-shell char composites at Regional Research Laboratories of CSIR (India) at Trivandrum and Bhopal can serve as an illustrative material to stimulate similar thinking on using local resources to make metal-matrix composites.

5. Video courses on composites available from ASM International and other organizations.
6. Laboratory demonstration of basic manufacturing processes including powder processing, vapor phase consolidation, and casting techniques. The training centers could collect samples of components of composites made in different parts of the world and demonstrate their properties and performance.
7. Demonstration of instrumentation for process control and for inspections and testing of composite materials. This could be part of an overall training in the use of modern instrumentation and sensor equipment with feedback circuits and intelligent processing using expert systems, for materials design, selection and processing. Modern instrumentation including electron microscopes, microprobes, chemical analyzes with high resolution and surface analytical techniques like ESCA, AUGER, SSNMR, SIMS, and automated testing equipment should be a part of overall exposure to advanced instrumentation for design, processing and use of metal-matrix composites.

8. A long term and continuing mechanism must be established through which summary of new information base can be supplied to the scientists working on composites in developing countries. The participants should be encouraged to write back and consult with the center on the opportunities and experience on designing, manufacturing and using composites using local resources in their respective countries. This growing body of information base could be shared by all developing countries.

8. SUMMARY

Metal-matrix composites with tailored properties have the potential of becoming one of the fastest growing family of new materials which can have large impacts on developing countries. At this time the best performing and most expensive metal-matrix composites are being considered for high value-added, relatively low-volume military and aerospace applications. However, automotive and other engine and electro mechanical energy applications which require lower cost and higher part volume, are now closer to commercialization, and these are of greatest interest to developing countries. With continued development of composite manufacturing processes and improvements in alloy design, including the possible use of particulate composites, high performance and low cost will draw closer together. The developments in the near future will involve using the casting and powder processes to produce tailored interfaces, new matrix alloys which will yield higher ductility and toughness along with higher strengths in discontinuous reinforcement composites. The science of predicting properties and performance of metal-matrix particulate composites will gain considerable ground. At this time the low cost particulate composites such as cast aluminum-alumina, aluminum-silicon carbide and aluminum-graphite composites appear to be most promising for the developing world. These composites can be readily produced in the developing countries using readily available ingredients and simple techniques, and can be used in energy and materials saving applications. It will be best to begin with simple applications like bearings, pistons, cylinder liners and then move into other high performance components. The developing world should pay special attention to the possible use of metal-matrix composites in energy, housing, and transportation sectors which are of high priority including solar photovoltaics, semiconductor and superconductor industries. Developing countries such as India and China have a good research and industrial base for producing metal-matrix composites, mechanisms should be developed to expand this capability into other developing countries through expansion of education and training in metal-matrix composites and through exchange of information between developing countries themselves. Developing countries should impart suitable training in design, processing, manufacture and use of composites made from local resources using locally available manufacturing infrastructure.

9. INFORMATION RESOURCES ON METAL-MATRIX COMPOSITES

The following journals and publications have a good repository of information on metal-matrix composites:

(1) Journal of Composite Materials

(2) Composites

(3) Proceedings of the "International Conferences on Composite Materials." Six of these have been held and the seventh will be held in China.

(4) Composite Materials Handbook by ASM International

(5) Video courses on Composites from ASM International

(6) Metallurgical Transactions (Journal by ASM-AIME)

(7) Materials Science and Engineering (Journal)

(8) Journal of Materials Science (Journal form the UK)

(9) Proceedings of Composites Conferences Organized by ASM International AIME, SAMPE, American Society for Composites and the Journals brought out by these societies.

(10) Proceedings and lecture notes from a large number of short courses organized in China, Europe, India, Japan and the United States on Composite Materials.

(11) Powder Metallurgy International (Journal)

(12) Metals Abstracts

(13) Engineered Materials Abstracts

(14) Chemical Abstracts

In addition to the above open literature, a large number of reports on commercial prospects of metal-matrix composites have been written by several consulting companies in the United States and are available at a price to subscribing organizations.

Several university centers on composites including the University of Delaware's Center of Composites publishes news letter which lists activities going on in respective centers. In addition, information is available in the United States from NTIC and MMIAC which has government information banks on composites.

APPENDIX I. SELECTED BOOKS ON METAL-MATRIX COMPOSITES

1. *Advanced Composites: The Latest Developments*. Proceedings of the Second Conference on Advanced Composites, Nov. 18-20, 1986, Dearborn, Michigan, ASM International.

2. *Composite Technology*. Proceedings of the Annual Conference on Materials Technology, April 14-15, 1988. Edited by Margaret Genisio, Materials Technology Center, Southern Illinois University at Carbondale, Illinois.

3. *Testing Technology of Metal-Matrix Composites*. Ed. Peter R. Digiovanni and Norman Ray Adsit, ASTM, 1988, Philadelphia, PA 19103.

4. *Interfaces in Metal-Matrix Composites*. Proceedings of Symposium Held at Annual Tech Meeting of Metallurgical Society in New Orleans, Louisiana, March 2-6, 1986, Ed. A. K. Dhingra and S. G. Fishman, The Metallurgical Society AIME, Warrendale, PA, USA.

5. *Mechanical Behavior of Metal-Matrix Composites*. Proceedings of a Symposium of ASM held at the 111th AIME Meeting, Dallas, Texas, Feb. 16-18, 1982. E. John E. Mack and Maurice F. Amateau, The Metallurgical Society of AIME.

6 K. K. Chawla, *Composite Material Science and Engineering*. 1987, *Materials Research and Engineering*. Ed. B. Ilshner and N. J. Grant, Springer Verlag, New York, Berlin, Heidelberg London, Paris, and Tokyo.

7. *Cast Reinforced Metal Composites*," Proceedings of the International Symposium on Advances in Cast Reinforced Metal Composites. 1988, World Material Congress, Chicago Illinois, Ed. S. G. Fishman and A. K. Khingra, ASM International, Metals Park, Ohio.

8. *Engineered Materials Handbook*. Vol. 1, Composites ASM International, 1987, Metals Park, Ohio.

9. *Advanced Materials Conference Proceedings*. Dec. 2-4, 1985, Dearborn, Michigan, ASM, Metals Park, Ohio.

10. *Proceedings of the Fifth International Conference on Composite Materials*. ICCMV, July 29-30, Aug. 1, 1985, Ed. W. C. Harrigan Jr., I. Strife, A. K. Dhingra, The Metallurgical Society of AIME (Also proceedings fo the sixth and seventh ICCM Conferences). The ICCM VIII will also have proceedings.

11. James G. Crorce, L. R. Dharari, and Walter F. Jones, *Crack Growth and Fracture of Continuous Fiber Metal Matrix Composites: Analysis and Experiments Metal Matrix Composites Testing Analysis and Fracture Modes*. ASTM STP 1032, W. S. Johnson, Ed. American Society for Testing and materials, Philadelphia, 1989.

APPENDIX II. SELECTED PAPERS ON METAL-MATRIX COMPOSITES

1. Rack, M.J., "Fabrication of High Performance Powder - Metallurgy Aluminum Matrix Composites," Advanced Materials and Manufacturing Processes, Vol. 3, No. 3, 1988, p. 327.

2. Prasad, S.V. and Rohatgi, P.K., "Tribological Properties of Al Alloy Particle Composites," Journal of Metals, Nov. 1987, p. 22.

3. Rohatgi, P.K., Asthana, R., and Das, S., International Metals Reviews, Vol. 31, No. 3, 1986, p. 115.

4. Rohatgi, P.K., "Cast Metal-Matrix Composites," ASM Metals Handbook," Vol. 15, 9th ed., Metals Park, Ohio, p. 840.

5. Cornie, J.A., Chiang, Y.M., Uhlmann, D.R., Mortensen, A., and Collins, J.M., Ceramic Bulletin, Vol. 65, 1986, p. 293.

6. Rohatgi, P.K., "Performance of an AlSi - Graphite Particle Composite Piston in Diesel Engine," Wear, Vol. 60, 1980, pp. 205-215.

7. McDaniels, D.L. and Hoffman, C.A., "Microstructure and Orientation Effects on Properties of Discontinuous Silicon Carbide/Aluminum Composites," NASA Tech. Paper 2302, July 1984.

8. Nair, S.V., Tein, J.K., and Batep, R.C., "SiC-Reinforced Aluminum Matrix Composites," International Metals Reviews, Vol. 30, No. 6, 1985, p. 275.

9. Servais, R.A., Lee, C.W. and Browning, C.E., "Intelligent Processing of Composite Materials," SAMPE Journal, Sept., Oct. 1986.

10. Rohatgi, P.K., Ranganathan, N., and Shetty, H.R., "The Use of Metal Coated Refractory Powders to make Particulate Composites by Infiltration," Composites, July 1978, p. 153.

11. Vogelsang, M, Arsenault, R.J. and Fisher, R.M., "In-situ HVEM Study of Dislocation Generation as Al/SiC Interfaces in Metal-Matrix Composites," Metallurgical Transactions, Vol. 17A, March 1986, p. 399.

12. Ghosh, P.K. and Ray, S., "Effect of Porosity and Alumina Coating on the High Temperature Mechanical Properties of Compocast Aluminum Alloy-Alumina Particulate Composites," Journal of Materials Science, Vol. 22, 1987, pp. 4077-4086.

13. Stefaneseu, D.M., Dhindaw, B.K. Kacar, S.A. and Moitra, A., "Behavior of Ceramic Particles at the Solid-Liquid Metal Interface in Metal Matrix Composites," Metallurgical Transactions, Vol. 19A, 1988, p. 2839.

14. Dhindaw, B.K., Moitra, A., Stefaneseu, D.M. and Curreri, P.A., "Directional Solidification of Al-Ni/SiC Composites During Parabolic Trajections," Metallurgical Transactions, Vol. 19A, Aug. 1988, p. 1899.

15. Girot, F.A., Quenisset, J.M. and Mastein, R., "Discontinuously Reinforced Aluminum Matrix Composites." *Composite Science and Technology*, Vol. 30, 1987, pp. 155-184.

16. Nakata, E. Kagawa, Y. and Terao, M., "Fabrication Method of SiC Fiber Reinforced Aluminum and Aluminum Alloy Composites," *Report of the Casting Research Laboratory*, Waseda University, No. 34, 1983.

17. Rack, M.J., "P/M Al. Metal Matrix Composites," *Dispersion Strengthened Al Alloys*, Ed. Y-W Kim, TMS, 1988.

18. Volker, A. and Klaus, K., "Dispal-Al Alloys with Non-Metallic Dispersoids," Report from Sinter Metal Work Krebsoge GMBM, 1988.

19. White, J., Willis, T.C., Hughes, I.R., and Jordan, R.M., "Metal Matrix Composites Produced by Spray Deposition," Alcan International Ltd., 1988.

20. "Coating of Graphite Fibers with Tungsten Carbide Using Solid and Liquid Copper as a Transfer Medium," *Metallurgical Transactions*, Vol. 19A, pp. 1988-2109.

21. Friend, C.M., "The Effect of Temperature on the Tensile Strength of Short S-Alumina Fiber/Aluminum Alloy Metal Matrix Composites," *Scripta Metallurgica*, Vol. 23, 1989, p. 33.

22. Guild, F.J., et al., "A Predictive Model for Particulate Filled Composite Materials," *Journal of Material Science*, 1989, pp. 298-307.

23. Maeda, M., et al., "Oxidation of Silicon Carbide in a Wet Atmosphere," *Journal of Material Science*, Vol. 23, 1988, pp. 3933-3939.

24. Mortensen, A., et al., "Solidification Processing of Metal-Matrix Composites," *Journal of Metals*, Feb. 1988, pp. 12-20.

25. Porink, G.L., et al., "Interfaces in Nickel Aluminide-Alumina Fiber Composites," *Journal of Material Science*, Vol. 23, 1988, pp. 3945-3951.

26. Suchida, K.T., et al., "Superconductivity of Nb3Al - Au Composites," *Journal of Material Science Letters*, Vol. 7, No. 12, p. 1269.

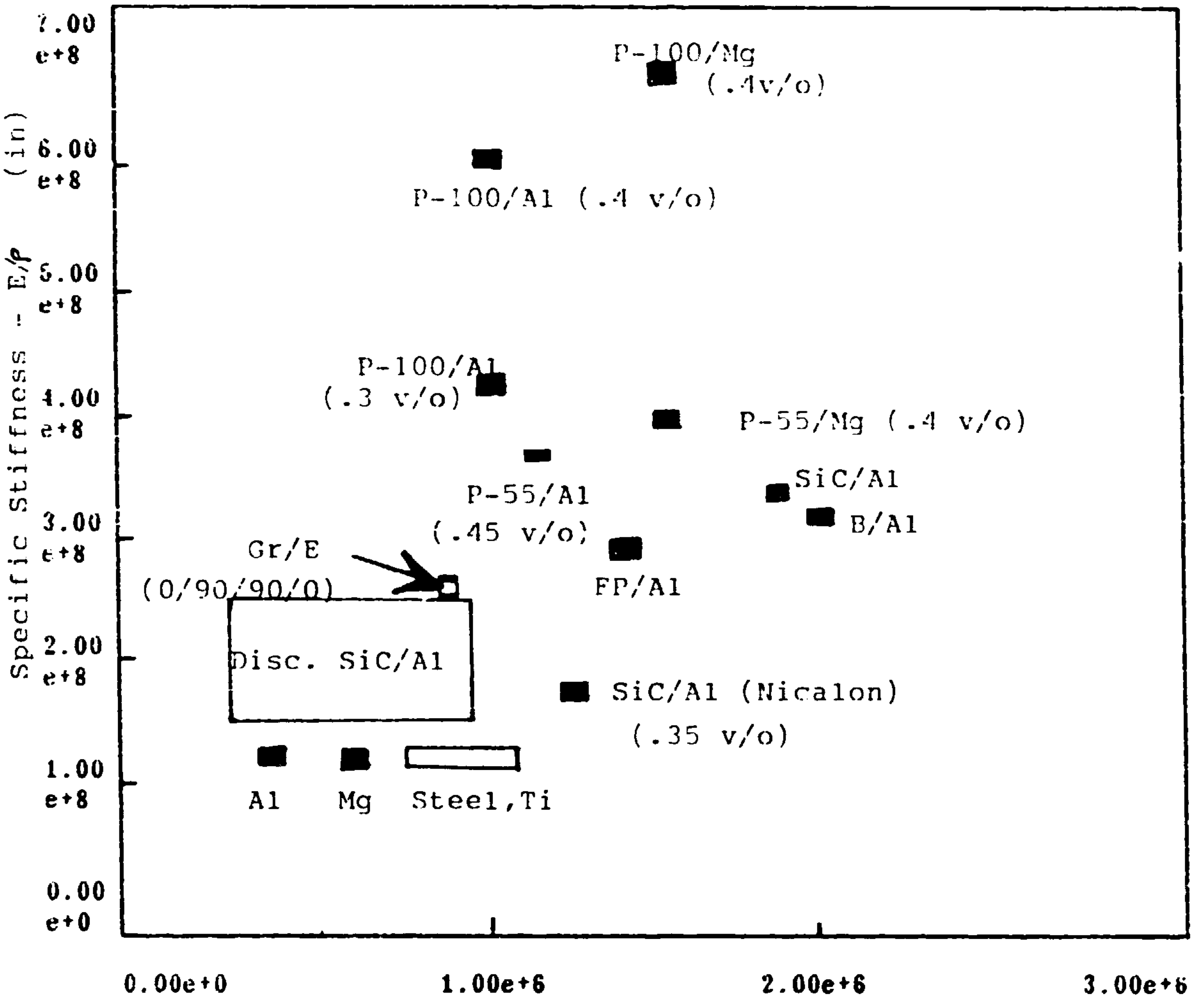
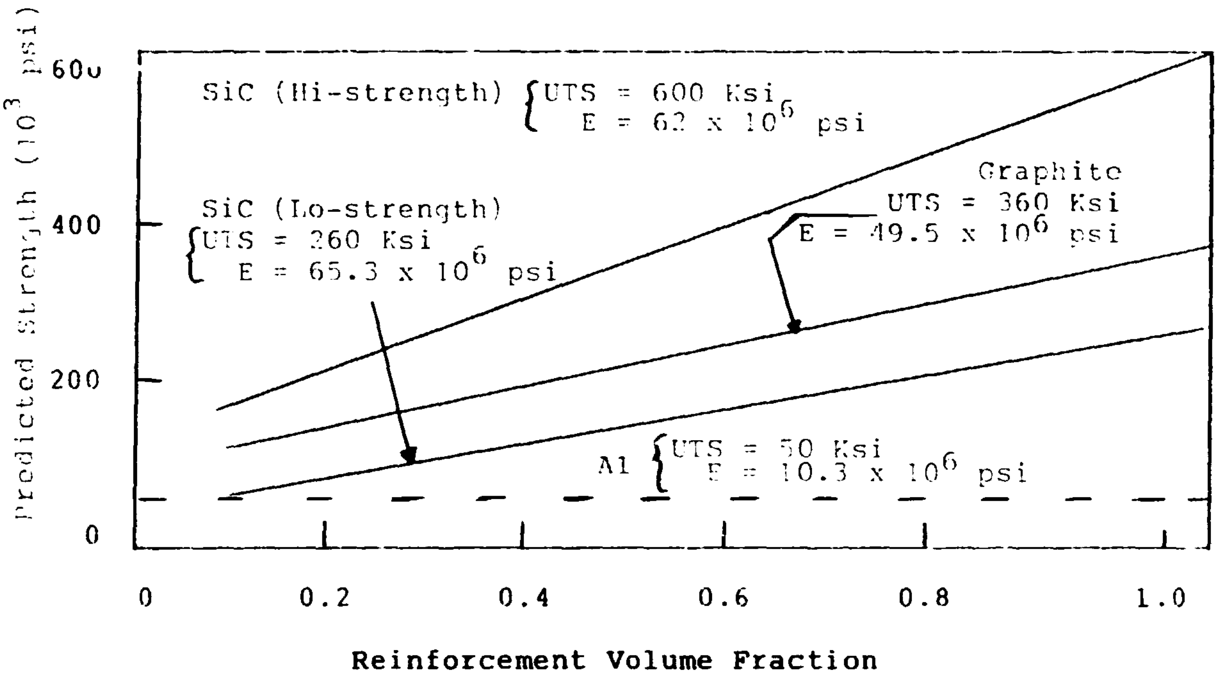


Figure 1A. Specific properties of aluminum and magnesium-matrix composite materials, compared to unreinforced alloys. Properties of continuous fiber-reinforced materials are calculated parallel to the fibers.



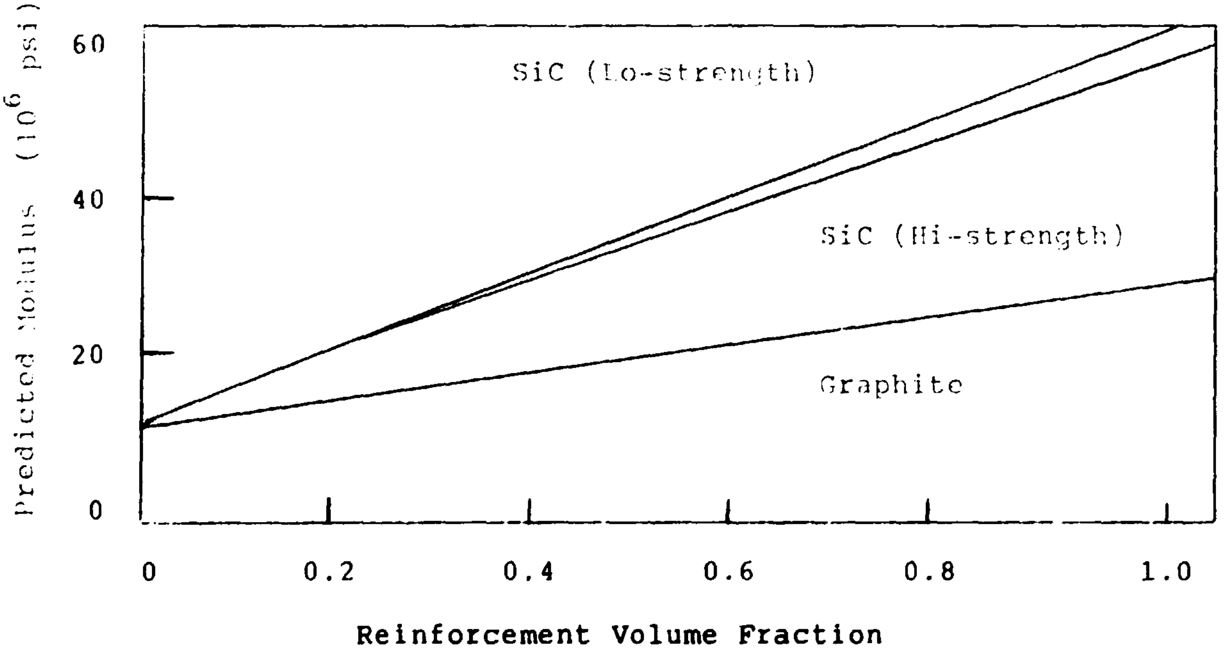


Figure 1E. Predicted values of ultimate tensile strength and elastic modulus for various aluminum matrix continuous filament reinforced composites.

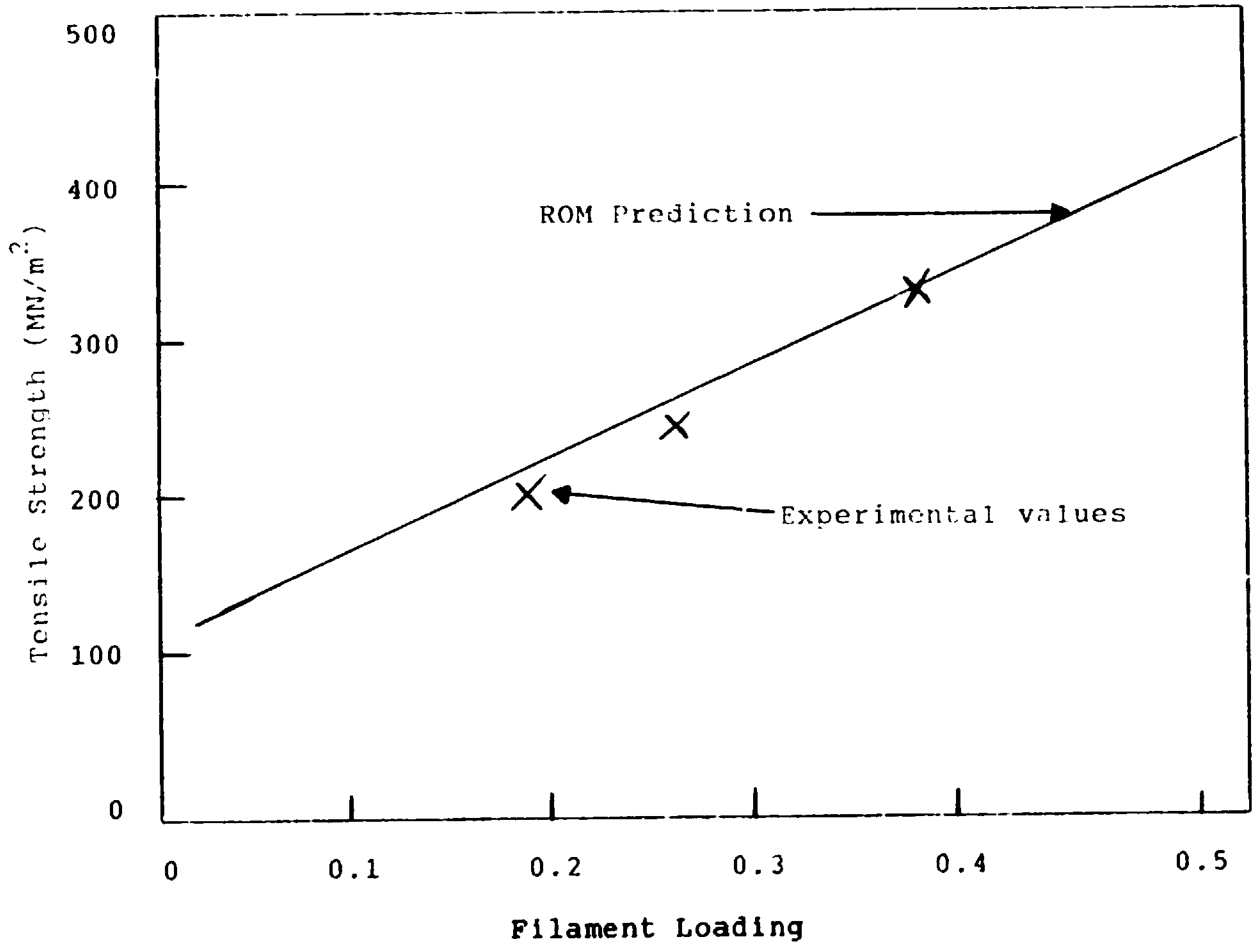


Figure 2A. Comparison of the rule-of-mixtures prediction and the observed ultimate tensile strength for an aluminum-stainless steel continuous-filament reinforced composite material.

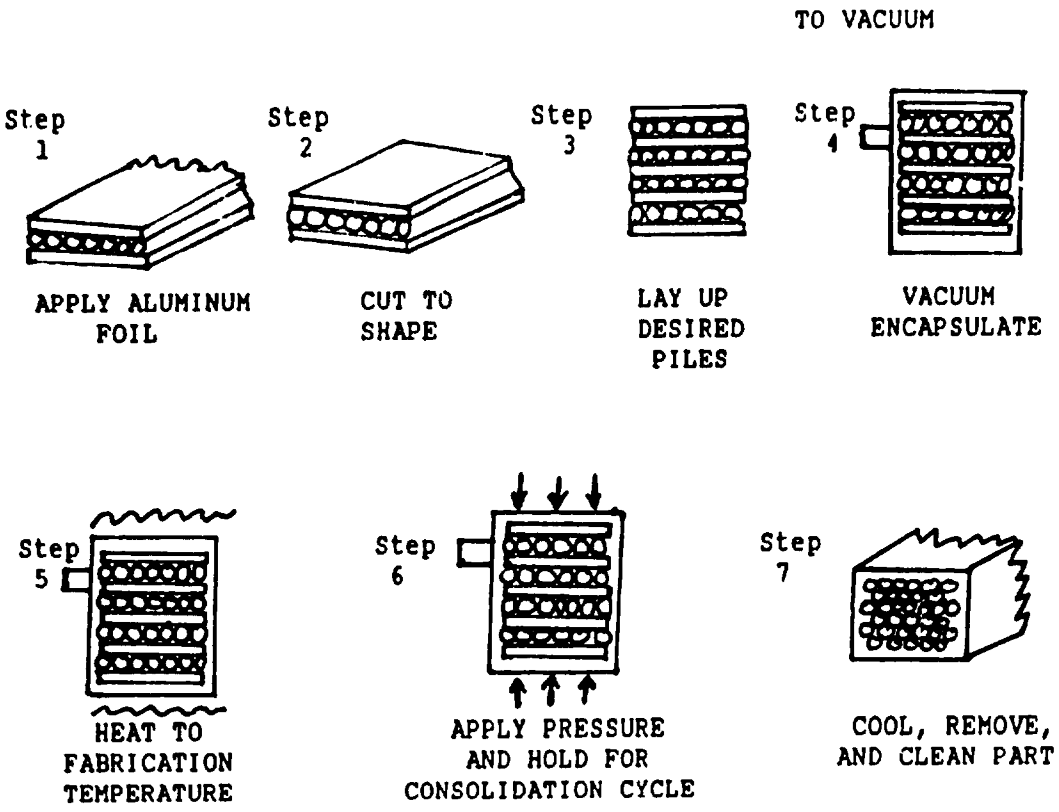


Figure 2B: Diffusion Bonding Process of Making Fiber Reinforced Metal Matrix Composites

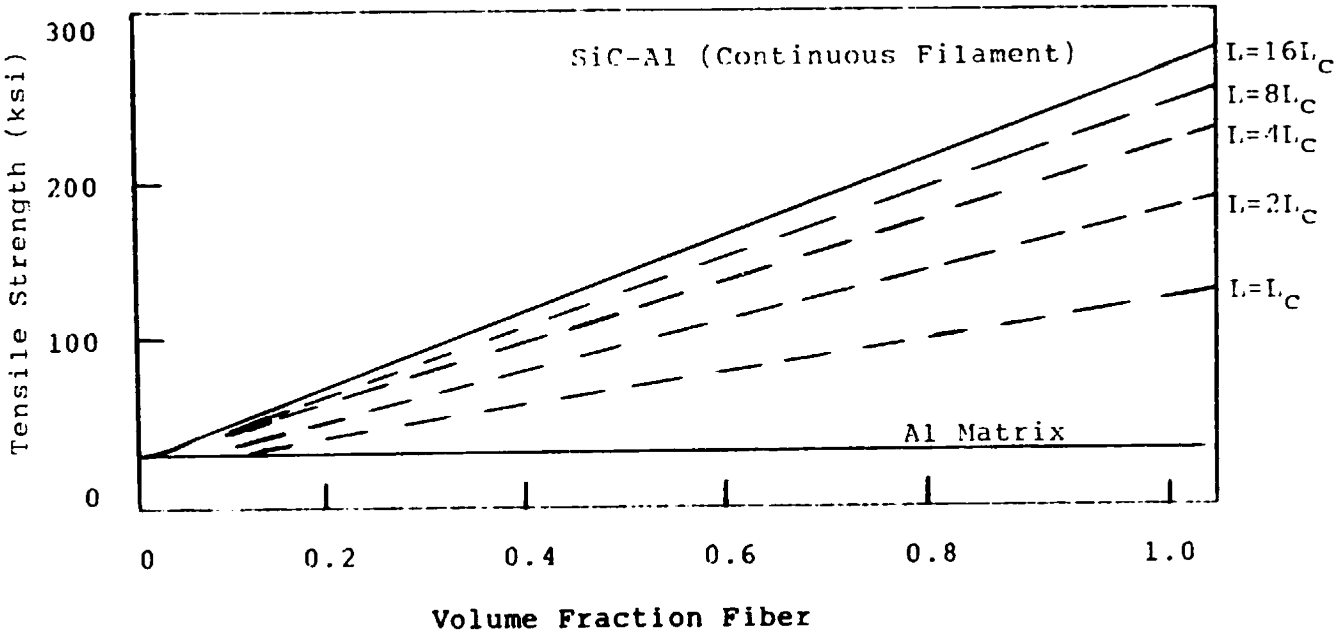


Figure 3A. Composite strength as affected by whisker length and volume loading.

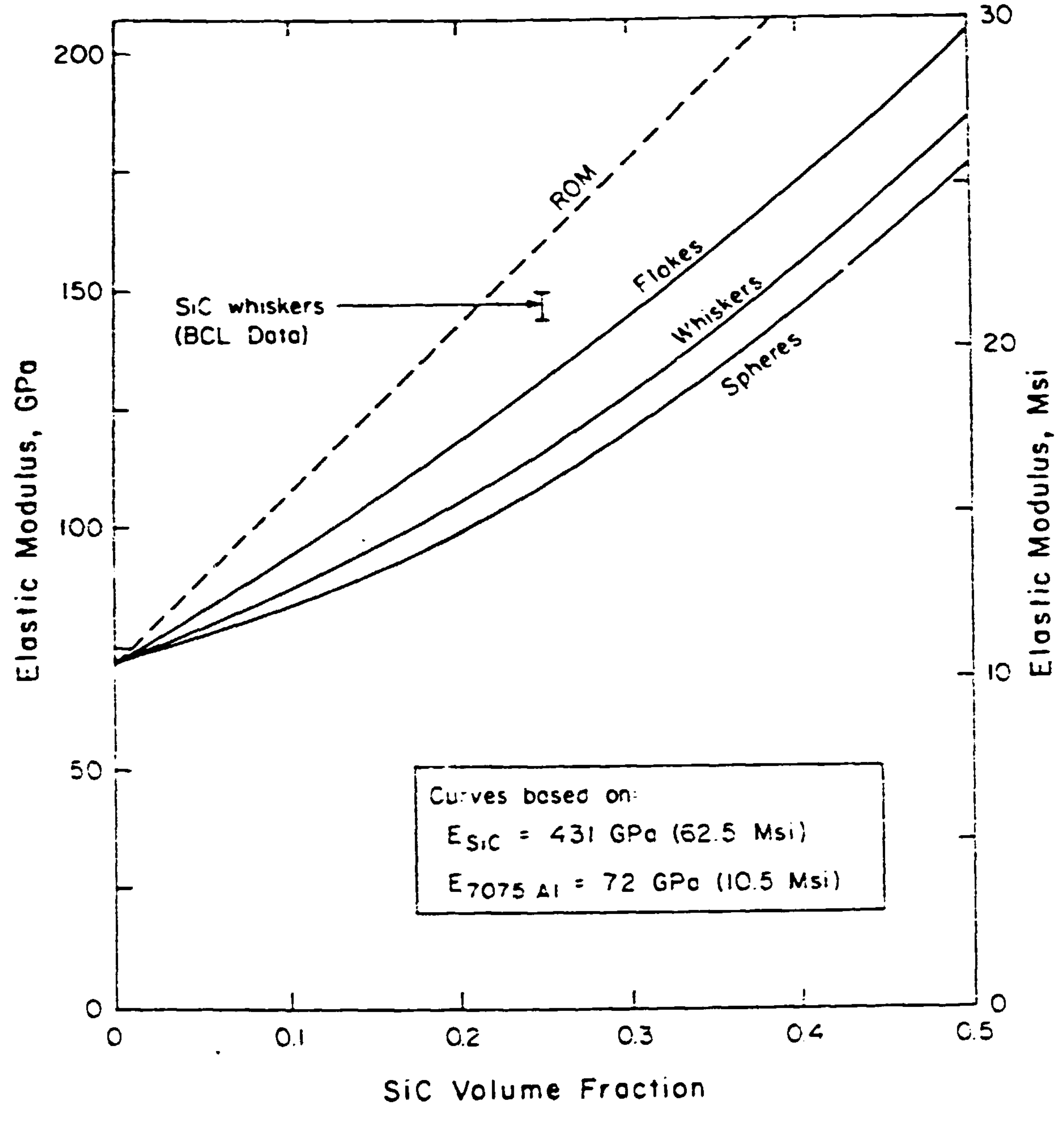


Figure 3B. Elastic Modulus of SiC Reinforced Aluminum Alloys.

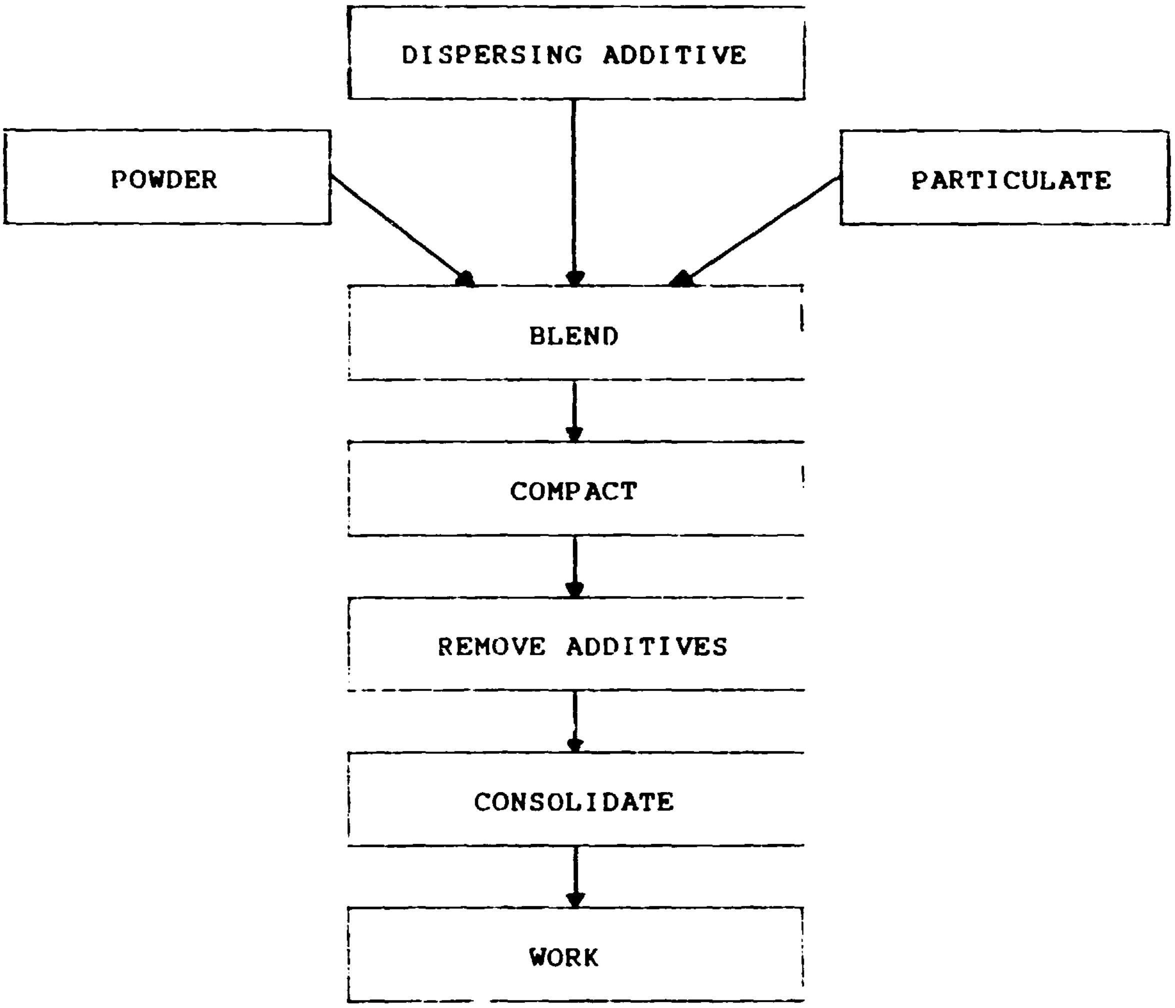


Figure 4. Schematic of the DWA Composite Process.

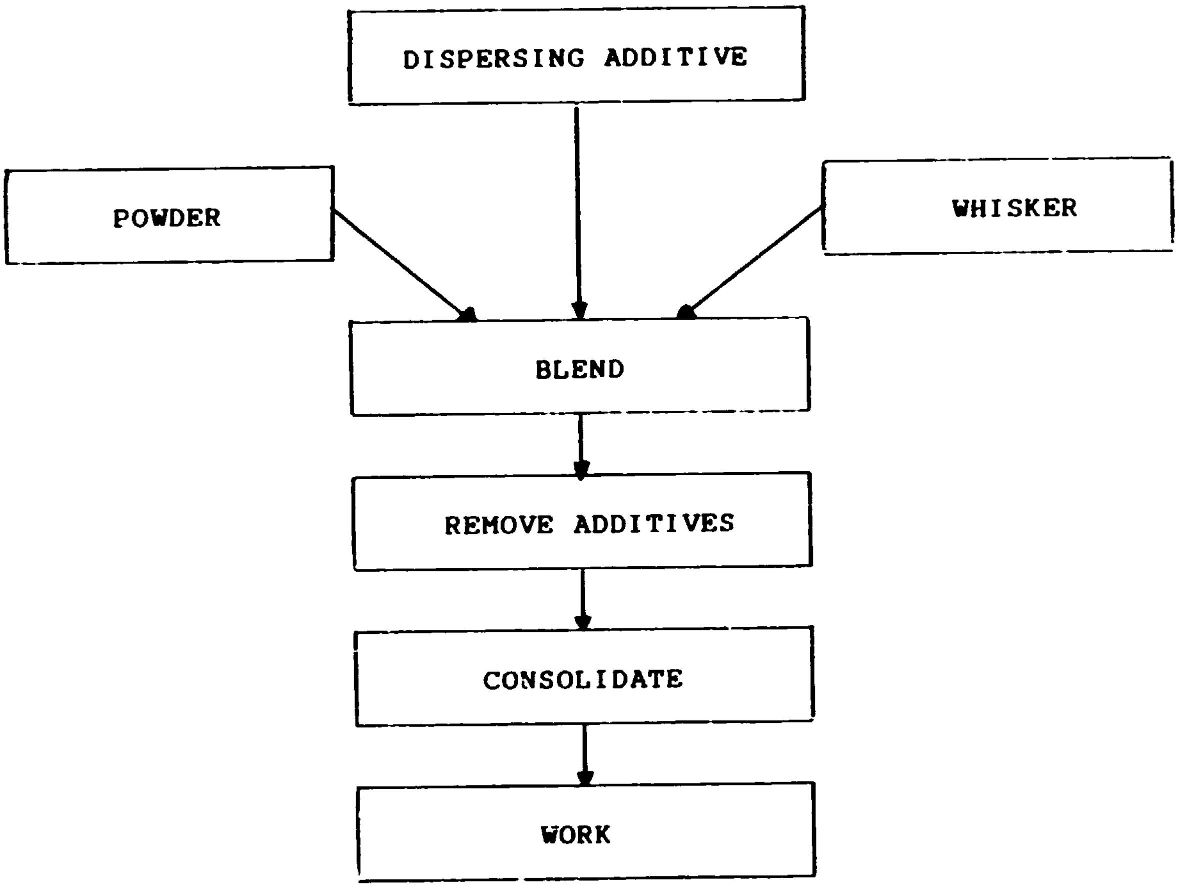


Figure 5. Schematic of the Silag (Advanced Materials Division Arco Chemical Company) Composite Preparation Process.

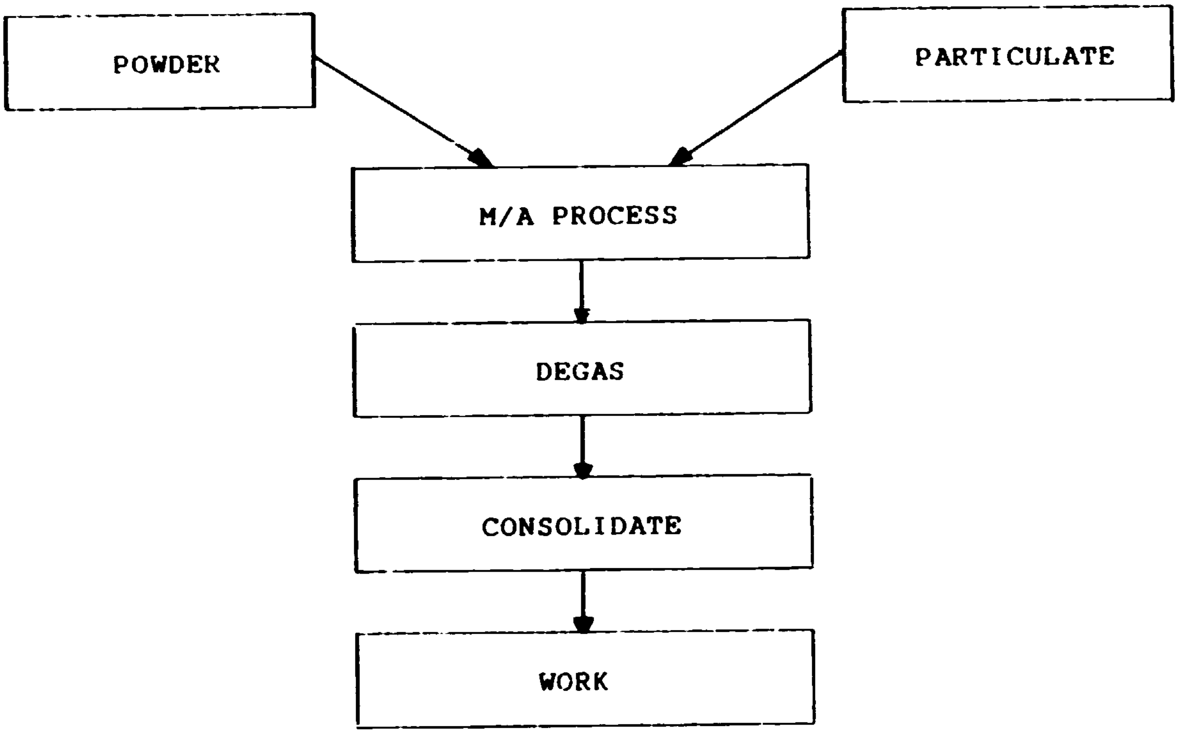


Figure 6. Schematic of the Novamet (Inco Mechanically Alloyed Products) Composite Preparation Process.

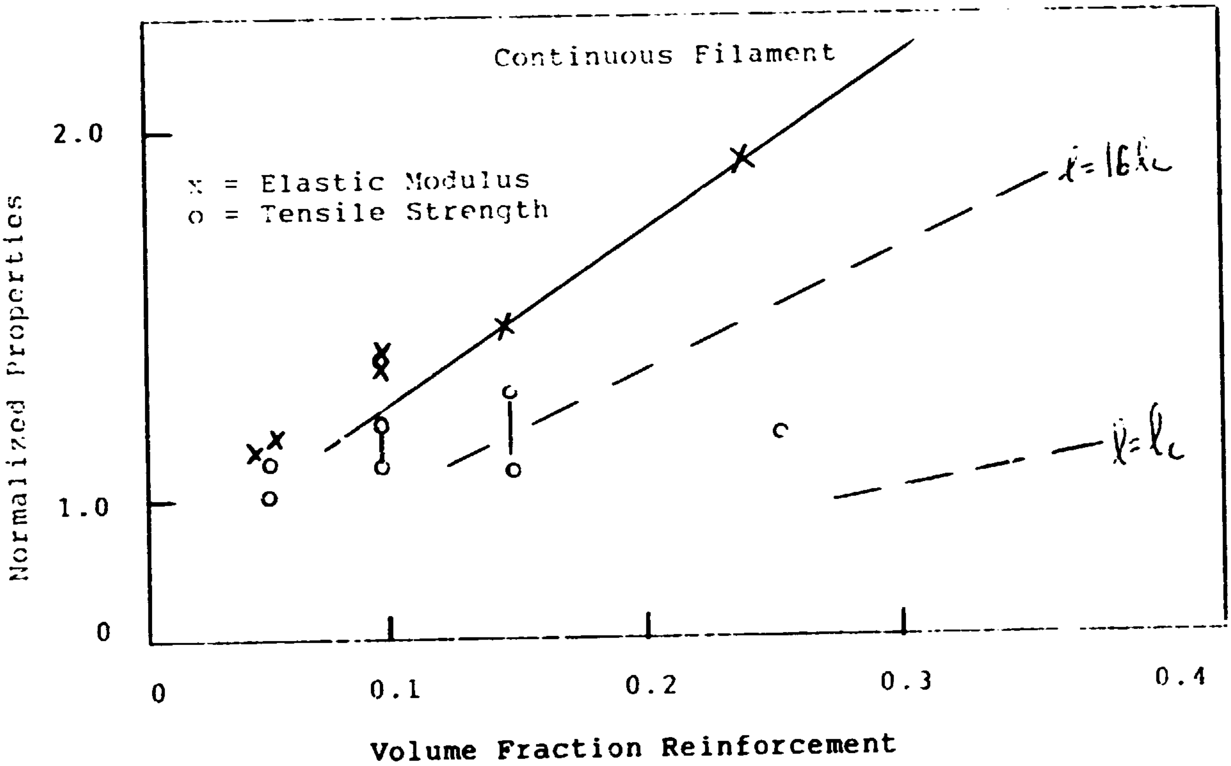


Figure 7. Comparison of normalized values of elastic modulus and ultimate tensile strength versus volume fraction reinforcement in SiC-Al alloys. Predicted values for continuous and discontinuous reinforcement are also shown.

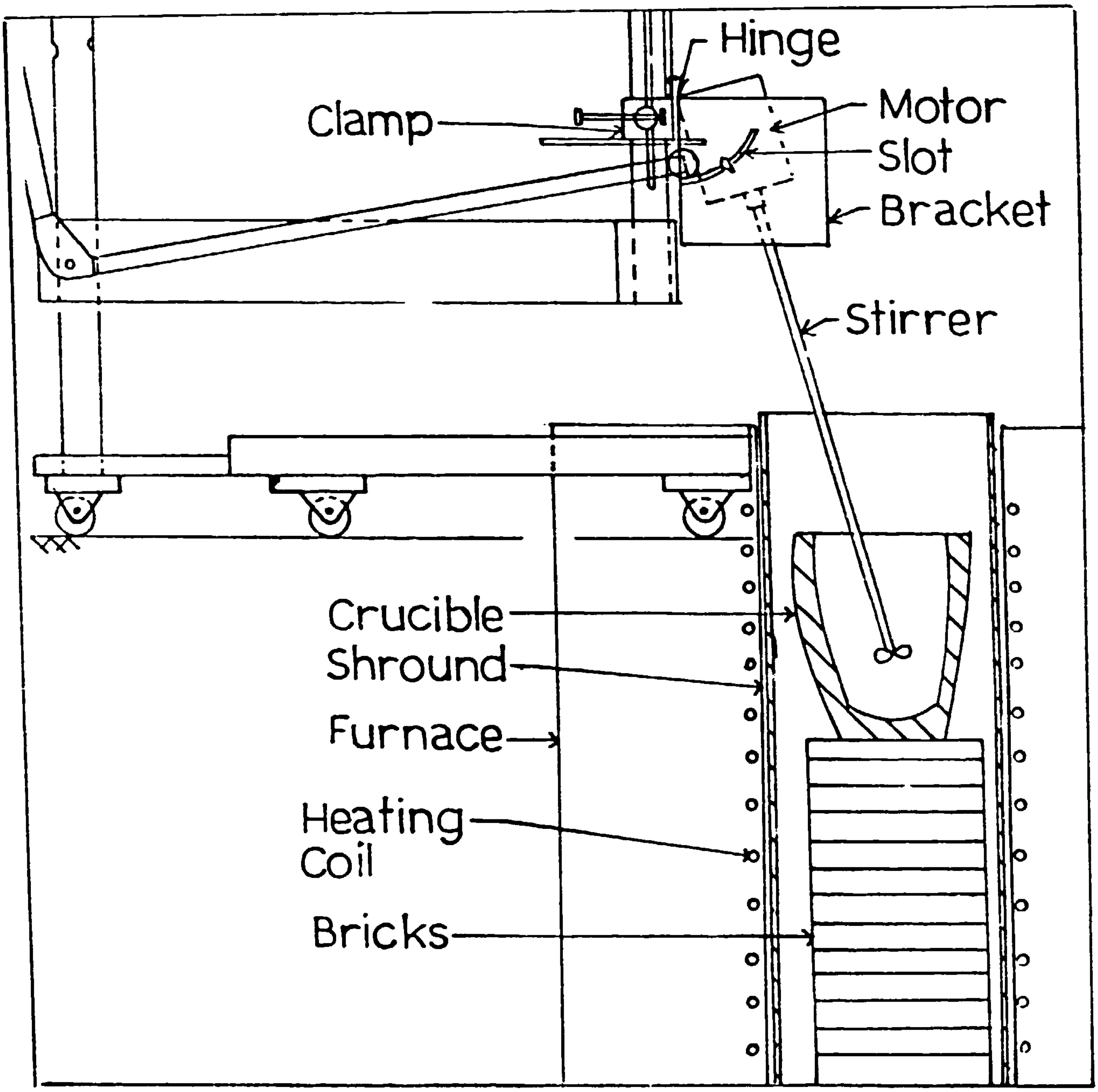


Figure 8 Schematic of experimental set-up to make cast particulate composites.

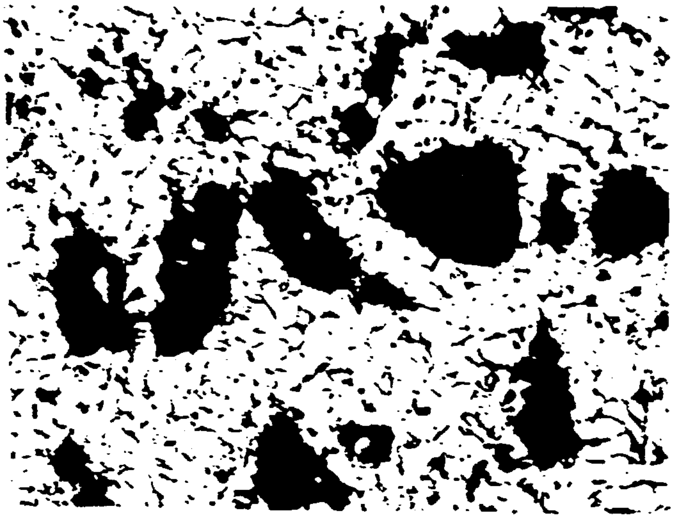


Figure 9. Optical micrograph showing distribution of graphite particles in the matrix of an aluminum alloy.

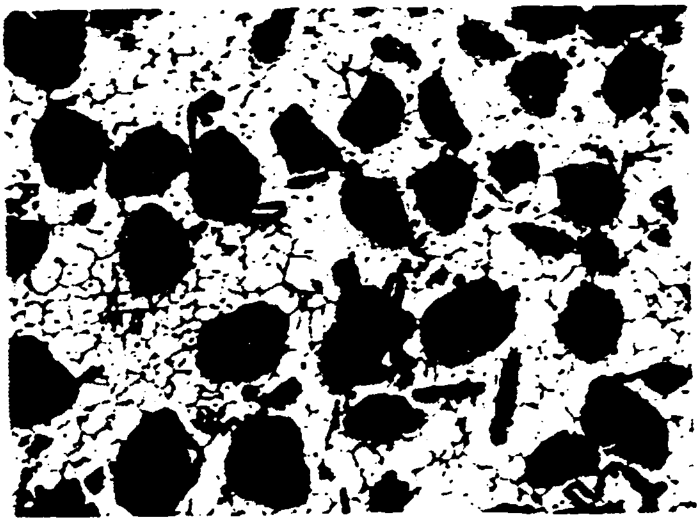


Figure 10. Microstructure of a die cast Al alloy-zircon particle composite.

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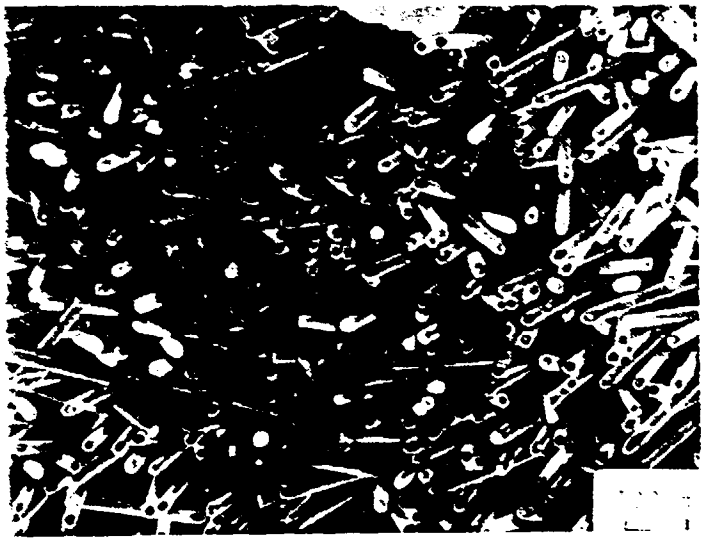

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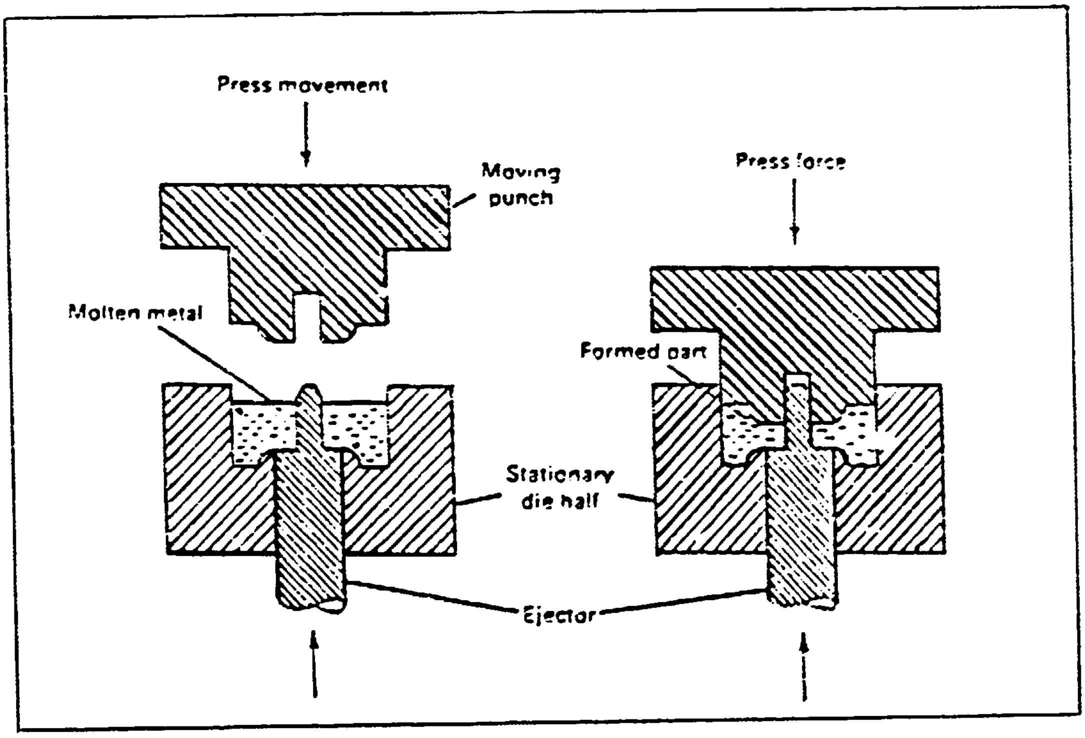
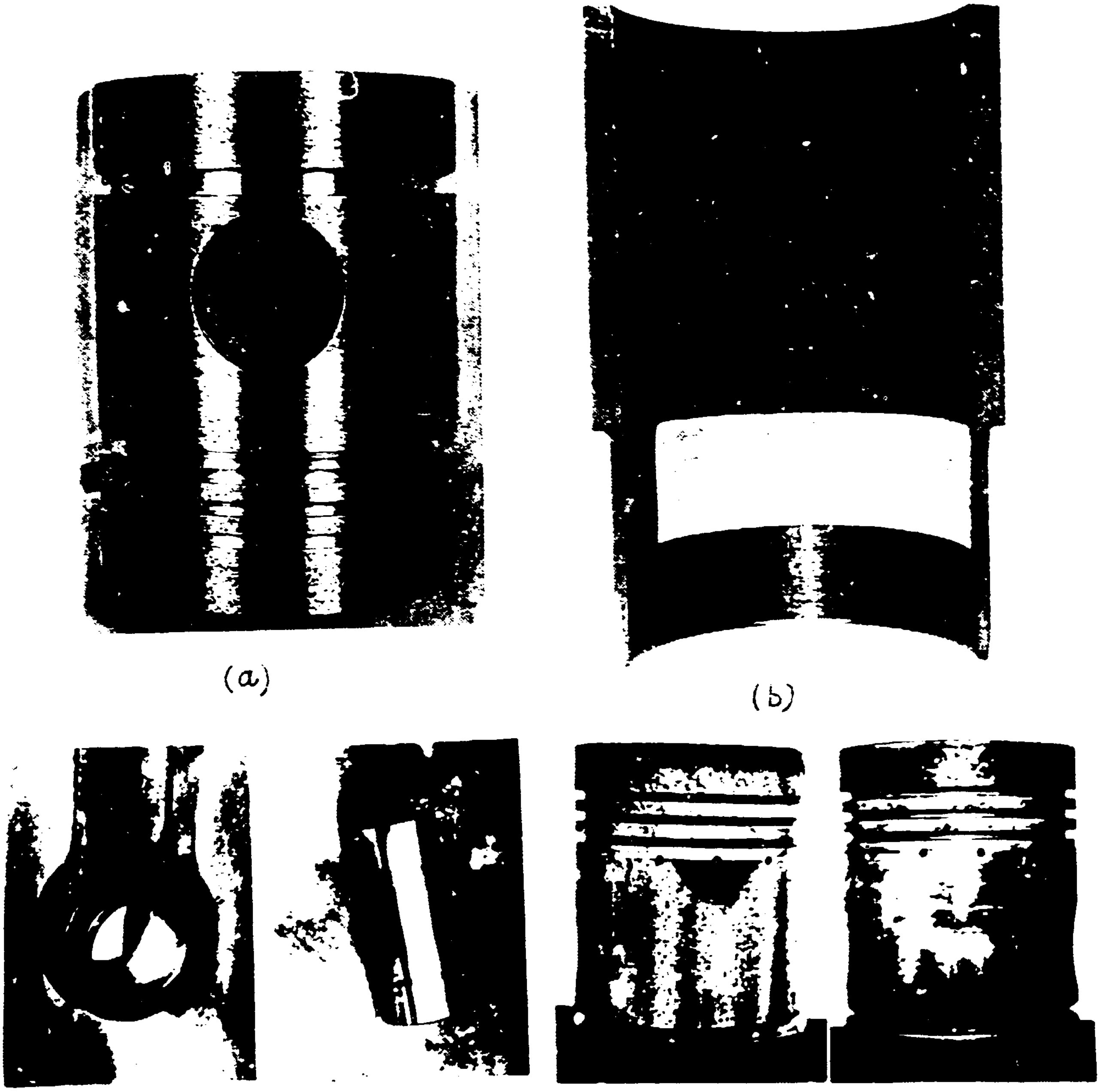


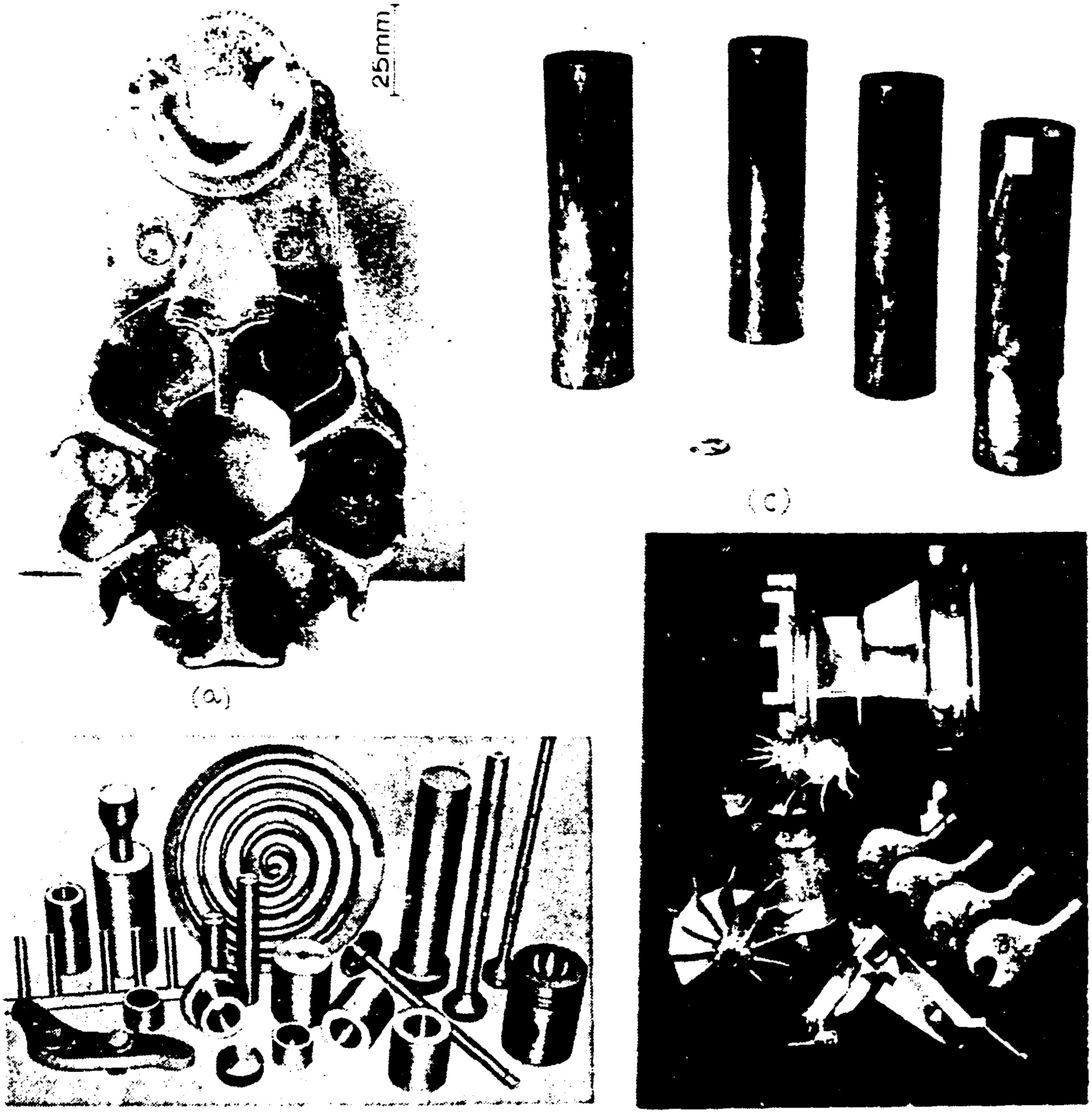
Figure 13. Squeeze casting technique of composite fabrication.


(a) (b)

(c) (d)

Figure 14. Photographs of various engineering components of cast metal matrix particulate composites.

a) An Al alloy-graphite particle composite piston.
b) Surface of an Al alloy-graphite composite cylinder liner after an endurance test. (Courtesy of AE Borgo, Italy).
c) Connecting rod fitted with bearing of an Al-Cu-graphite composite. Also shown is the corresponding pin after 100 hour test showing no evidence of surface scoring.
d) Photos comparing the surfaces of a standard graphite free alloy piston after 30 hour test and an Al-graphite piston after 60 hour run.



(a)

(b)

(c)

(d)

Figure 15. Photographs of some engineering components made from cast metal matrix composites.

a) Pressure die cast bushing spring guide of Al alloy-graphite particle composite.
b) Impeller and several other components of cast aluminum-graphite composites.
c) Graphite fiber/Mg composite for space structure applications. (Courtesy of Martin-Marietta Co.)
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a) An Al alloy graphite particle composite piston.
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c) Connecting rod fitted with bearing of an Al Cu graphite composite. Also shown is the corresponding pin after 100 hour test showing no evidence of surface scoring.
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Figure 15. Photographs of some engineering components made from cast metal matrix composites.

a) Pressure die cast bushing spring guide of Al alloy-graphite particle composite.
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2. A NEW INFILTRATION PROCESS FOR THE FABRICATION OF METAL MATRIX COMPOSITES

Abstract

A novel liquid metal infiltration technique for the production of metal-matrix composites containing various reinforcements is described. The technique is unique in that by proper control of the process conditions, infiltration occurs spontaneously, without the aid of pressure or vacuum. The required process conditions are described and the effects of the process variables are determined using a model system comprising an aluminium alloy matrix reinforced with Al_2O_3 particles.

1. Introduction

Aluminium matrix composites have been produced by various liquid phase processes, including the mixing of molten metal and ceramic particles followed by casting (i.e., compocasting), and the infiltration of molten metals into compacts of reinforcing material via the use of a pressure or vacuum assist. Similarly, solid state processes, such as the mixing of metal and ceramic powders, followed by hot pressing, and the lamination of metal foils and ceramic fibres via diffusion bonding, have been utilized to produce such materials. The liquid phase processes are potentially more economical; however, the solid state processes have been the most successful to date, with the liquid phase processes limited by the non-wetting nature of most ceramics and molten aluminium.

This article describes a novel liquid metal infiltration technique for the fabrication of aluminium matrix composites. By proper control of the process conditions excellent wetting is obtained, thus allowing the infiltration to occur spontaneously, without the application of pressure. With no pressure or vacuum apparatus required, this technique provides cost effective processing, and, due to the favourable wetting, pore-free composites with high structural integrity can be produced. Enhanced wetting typically results in an increased strength at the metal-ceramic interface, thus enhancing the mechanical properties of the composite.

2. Experiment

The experimental lay-up employed in this work consisted of an aluminium alloy ingot, measuring about 50 x 25 x 12 mm, placed on top of a permeable mass of ceramic reinforcing material that was contained within a refractory vessel (a 99.9 per cent sintered Al_2O_3 tray measuring about 100 x 45 x 20 mm). In each case there was sufficient alloy to infiltrate all of the reinforcing material.

The alloy-ceramic assembly was heated to the process temperature in a controlled atmosphere furnace in the presence of a flowing nitrogen-containing gas. To inhibit unwanted gases from entering the furnace, the exit gas was bubbled through a column of oil measuring 25 to 50 mm. After cooling, the extent to which infiltration had occurred was noted and the samples were sectioned and examined microstructurally. The lay-up is shown schematically in figure 1A, and a typical product is shown in figure 1B.

During the infiltration process, aluminium nitride may form due to reaction of the molten Al with the nitrogen-containing atmosphere. The quantity of nitride that formed in the samples was determined by measuring the unit weight gain (change in weight of the sample divided by the original alloy weight). For comparison, the weight gain obtained when pure aluminium totally coverts to AlN is 52 per cent.

3. Results and discussion

Initial experimentation identified that there exist two requirements for the spontaneous infiltration to occur, namely (i) that the aluminium alloy contain Mg and (ii) that the atmosphere contain nitrogen and be nominally oxygen-free. However, meeting these two requirements does not ensure infiltration. The correct combination of the various process variables, such as the alloy composition, the process temperature, the process time, and the nitrogen content of the atmosphere must be employed.

To determine the effect of the Mg content in the alloy on infiltration, alloys with Mg contents ranging from 1 to 10 weight per cent were placed atop beds of 220 grit fused Al_2O_3 particles (38 Alundum, Norton Co.) and were brought to temperatures ranging from 700°C to 1,000°C for ten hours in a 96 per cent $N_2/4\%H_2$ atmosphere.

The data, shown in table 1, demonstrate that higher alloyed amounts of Mg result in infiltration at lower temperatures, and that under a given set of process conditions there is a critical level of Mg required to induce infiltration. For instance, at 900°C under the current process conditions no infiltration occurred with 3 weight per cent Mg and full infiltration occurred with 5 weight per cent Mg.

Additionally, the data show that process temperature affects the infiltration kinetics. Under otherwise constant process conditions, full infiltration occurred with alloy Al-5Si-10Mg at 800°C, whereas only partial infiltration occurred at 700°C. No infiltration has been obtained with alloys containing no Mg.

The effect of the nitrogen content of the atmosphere on the infiltration process was determined by fabricating samples in atmospheres ranging from 100 per cent N_2 to 100 per cent Ar. Using alloy 520.0 (nominally Al-10Mg) a 220 grit fused Al_2O_3 bed and process conditions of a four hour soak at 800°C, no infiltration occurred in 100 per cent Ar, only partial infiltration occurred in 10 per cent N_2/90 per cent Ar and full infiltration occurred when the N_2 content equalled or exceeded 25 per cent.

In addition to affecting the process kinetics (i.e., only partial infiltration occurred with an atmosphere of 10 per cent N_2/90 per cent Ar), the atmosphere affected the quantity of nitride that formed within the product. Figure 2 plots the unit weight gain versus the per cent nitrogen in the atmosphere for all of the samples where full infiltration occurred. At high percentages of N_2, where infiltration was rapid, little nitride formed, whereas in dilute atmospheres, where infiltration was slow, observable levels of AlN formed.

In a similar fashion, the process temperature significantly affects the quantity of nitride that forms within the aluminium alloy matrix. Figure 3 plots unit weight gain versus process temperature for samples fabricated using alloy Al-5Si-3Mg-3Fe, a 220 grit fused Al_2O_3 bed and process conditions of a 5 hour dwell at temperature in 96 per cent N_2-4 per cent H_2. The results demonstrate that increased process temperatures result in increased quantities of nitride formation, and that the increase is nearly linear from 900 to 1000°C.

Thus, the AlN content of the resultant Al alloy matrix can be tailored by selecting the appropriate atmosphere and process temperature. In turn, this allows the resultant properties of the composite to be tailored without changing the alloy chemistry or the filler loading. For instance, increases in the AlN content of the aluminium alloy matrix will decrease the coefficient of thermal expansion and increase the stiffness of the composite.

Also evident from Figure 4 is that infiltration occurred into the fused Al_2O_3 at 900°C with alloy Al-5Si-3Mg-3Fe. At the same process temperature alloy Al-5Si-3Mg did not infiltrate the Al_2O_3 (table 1) demonstrating that Fe can promote infiltration at lower temperatures.

The spontaneous infiltration technique is applicable to the production of composites containing a wide range of reinforcement types.

Similarly, the spontaneous infiltration process is applicable to many filler chemistries. Examples of reinforcement materials that have been utilized include SiC, TiB_2, MgO, SiC-coated (chemical vapour deposition) graphite, and AlN.

4. Summary

A novel process for the production of metal matrix composites containing either continuous or discontinuous reinforcement is reported. The process involves the infiltration of molten aluminium alloys into loose beds or compacts of reinforcing material without the aid of pressure or vacuum (i.e., spontaneously) by proper control of the process conditions.

Using the model system of Al_2O_3 particle reinforced aluminium, the effects of the process variables on infiltration were examined. It was shown that there exist two requirements for wetting to occur, namely (i) that the alloy contain Mg and (ii) that the atmosphere be nitrogenous.

The required process temperature for infiltration to occur was shown to be strongly affected by the Mg content of the alloy, with alloys containing low levels of Mg requiring higher process temperatures. AlN precipitates were found to occur within the aluminium alloy matrix, particularly in atmospheres with low contents of nitrogen and at high process temperatures. Although the effect of filler chemistry was not quantified, the process is applicable to a wide range of filler materials. (Source: Article written by M. K. Aghajanian, J. T. Burke, D. R. White, and A. S. Nagelberg, Lanxide Corporation, Newark, Delaware 19714-6077) for the 34th International SAMPE Symposium (Society for the Advancement of Material and Process Eng., Covina, California), 8-11 May 1989.

Table 1

Effect of Mg content on temperature required for infiltration

	Infiltration (yes/no/partial)			
	700°C	800°C	900°C	1000°C
Al-5Si-1Mg	-	No	No	Partial
Al-5Si-3Mg	-	No	No	Yes
Al-5Si-5Mg	-	No	Yes	Yes
Al-5Si-10Mg	partial	Yes	Yes	-

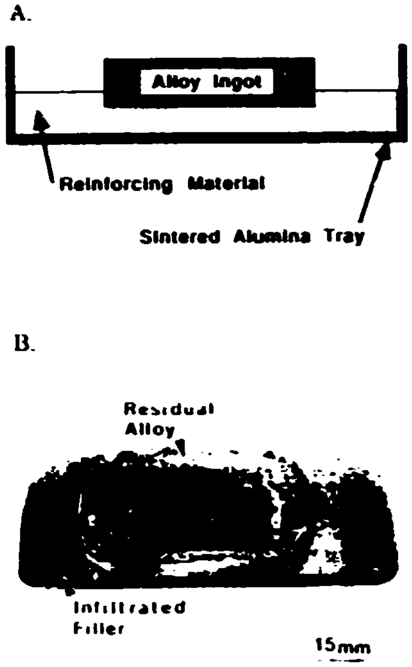


Figure 1. Experimental arrangement employed in infiltration experiments: (A) schematic and (B) sample after processing, removed from the Al_2O_3 tray

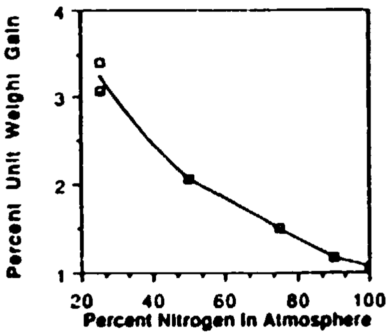


Figure 2. Dependence of unit weight gain (measure of nitride formation) on per cent N_2 in a N_2/Ar atmosphere

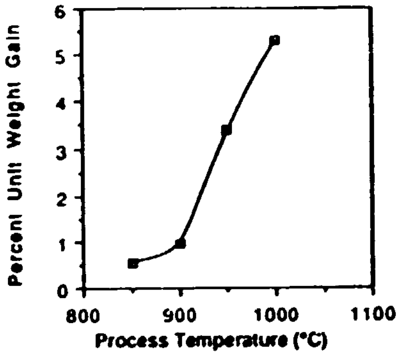


Figure 3. Relationship between process temperature and nitride formation (unit weight gain) in Al alloy matrix

In the judgement of the present authors, the science and technology of metal matrix composites are more advanced than those of ceramic composites. Work on the processing of metal matrix composites seems, however, to be more restricted in scope than that on the processing of ceramic matrix composites. For both types, the great challenge of the coming decade will be the development of novel or improved processing techniques that will form composites at or close to net shape in a cost-effective manner. The wide scale introduction of metal and ceramic composites will thus depend on improvements in processing technology.

Solidification processing of metal matrix composites

We will concern ourselves here with the case of solidification processing of preforms of multifilament tows of ceramic or carbon fibres by infiltration with molten metals or alloys and subsequent solidification. Discontinuously reinforced metal matrix composites processed by semisolid slurry solidication processing are the subject of a forthcoming review. We are restricting this review to solidification processing because there presently exists no other technique to economically manufacture ceramic yarn reinforced metals. The established vacuum hot press diffusion bonding technologies cannot be applied to < 20 µm diameter fibres unless the tows have been (1) previously infiltrated into "wires", (2) spread and coated or plated with the matrix to the desired volume fraction, or (3) infiltrated with a fine powder slurry of the matrix and binder. Such processes are intricate and expressive. In addition, advantages of pressure infiltration processing include the ability to produce net shapes with little or no requirement for subsequent forming or machining.

A number of the reinforcements being investigated for solidification processing of metal matrix composites are shown in table 1. Any improvement of composite properties must first be accompanied by an improvement in the properties of the reinforcement since mechanical properties can usually be approximated by a law of mixtures calculation.

Fundamental considerations

Solidification processing of metal matrix composites can be broken down into four fundamental categories: capillarity, fluid flow into the preform, fibre matrix interactions, and the solidification process.

Capillarity effects

Fibres can, in general, be surface treated so that they can be wet by a resin matrix. In most cases, this procedure will not happen with molten metals. It is especially difficult to wet most ceramic or carbon fibres with molten Al or Al alloys because of the omnipresent layer of Al_2O_3 at the liquid-vapour interface. Ignoring the effect of oxides on the melt surface, the pressure difference at the liquid metal front resulting from capillarity effects has been evaluated using various assumptions. The equations given in the literature are all different versions of Kelvin's equation:

$$P = \frac{4 \cos\theta}{r} \sigma_{la} \qquad (1)$$

where θ is the wetting angle of the liquid metal on the fibre in the infiltration atmosphere, r is curvature at the molten metal front, and σ_{la} is the surface energy at the liquid-vapour interface. Different assumptions lead to various forms of r as a function of fibre volume. Often, θ is assumed to equal 180° for simplicity. Making such an assumption the minimum infiltration pressures into a variety of preforms can be calculated utilizing literature values for the surface energy of the Al alloy.

Note that the Kelvin equation makes sense only if θ exists. More complex approaches were adopted by Rohatgi and co-workers for particulate-reinforced composites. Wetting is often associated with some degree of interfacial reaction that degrades the fibre properties. The liquid metal usually does not wet the fibres and energy in the form of hydrostatic pressure must be supplied for the metal to penetrate the fibre bundle.

Generally, the infiltration pressure relative to most forging processes is low. even for tightly packed preforms. However, one should consider the clamping forces on large moulds as a limitation to pressure infiltration. For example, a wing box for a large commercial aircraft might have a mould section of 20 m^2. If a pressure of 7 mPa (1000 psi) is required to infiltrate a fibre preform preset into a mould, the total clamping pressure would be 21 Kg (47 x 10^6 lbs). Thus, the reduction of the required pressure by a factor of two would decrease the clamping load by a factor of two. This difference might be crucial in terms of the economics of capital facilities.

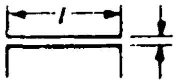
Fluid flow into the preform

Frictional forces resulting from the viscosity of the liquid metal can impede the progress of the metal through the narrow interfibre channels. An additional amount of pressure must thus be applied. The pressure incremental is dependent on the rate of infiltration.

Frictional forces have been modelled (1) with the Washburn equation for wetting systems where the metal is driven by capillarity forces into the fibre bundle and (2) with the Blake-Kozeny equation or another modification of D'Arcy's law using the Hagen-Poiseuille equation for a plane infiltration front in systems where the metal is forced into a non wetting fibre bundle. For a circular front, another more complex equation was used. The use of D'Arcy's law is permissible because the channels between fibres are fine enough for the metal flow to remain in the laminar regime at normal velocities of infiltration. Comparison with experimentally measured permeabilities was good, provided a correction was made for temperature effects (to be discussed) and a factor of 32 was used in the Blake-Kozeny equation.

For a planar front, using the Washburn equation:

$$dl/dt = \frac{(P_a + P_c)d^2}{32\eta l} \qquad (2)$$



where dl/dt is the infiltration velocity, l the pore length, d the pore, diameter, P_a the applied pressure, P_c the capillary pressure and η the viscosity of the fluid. The viscosity term is perhaps the most important consideration to the economics of pressure infiltration of metal matrix composites as compared to equivalent resin or glass transfer moulding. Figure 1 is a comparison of the viscosities of molten metals to various resins and glasses. Metals have about the same viscosity as water at $\approx 10^{-3}$ Pa·s^{-1}. Epoxies, on the other hand, have a viscosity greater than two orders of magnitude higher, and glasses are five to six orders of magnitude higher. Thus for equivalent infiltration rates (production rates) and for the same preform geometry, a pressure two orders of magnitude higher is required for epoxy and six orders of magnitude higher for glass transfer moulding.

Another phenomenon that requires consideration is analogous to fluidity in unreinforced castings, i.e., freeze choking during infiltration. The most important parameters, in addition to pressure, are mould preheat and melt superheat temperatures. Some investigators have addressed the problem of fluidity for pure metal matrices. Both experimental and modelling work have shown that the most crucial of the two is the fibre temperature. Temperatures below the melting point of the metal are permissible only insofar as they allow only a limited amount of the metal to solidify. Beyond that point, the solidified metal "chokes" the advancing liquid, and infiltration cannot be completed. Nagata and Matsuda measured a "critical preheating temperature" below which particles could not be infiltrated by a given pure metal. This temperature was independent of melt superheat. The volume fraction of solid formed was obtained by a simple heat balance equation. From this, a critical volume fraction of solid formed was deduced. Fukunaga and Goda postulated that a solid layer initially forms around the fibres. Their calculations assumed instant heat transfer between the fibres and the metal (a reasonable assumption given the dimensions of the fibres and interfibre spaces) and the solidification onto the fibres of a metal layer thick enough to bring the fibres to the melting point of the metal through evolution of latent heat. This modifies the effective fibre diameter and volume fraction and thus the permeability coefficient given by the Blake Kozeny equation. Correlation with their experiments was good.

Fukunaga and Goda also assumed that infiltration ceases when the infiltration velocity reaches a value low enough for the fibres ahead of the infiltration front to extract enough heat to solidify the metal. This assumption correlated well with their measured infiltration lengths. This also explains the observation that metal superheat has no influence on the infiltration length since the metal at the infiltration front is rapidly brought to its melting point by the cold fibres.

The above models are also in line with the following observations: (1) Magnesium alloys with a low latent heat of fusion are more difficult to cast into a cold fibre bundle. (2) Casting under conditions that preclude the formation of the solidified layer in Al SiC composites led to decreased mechanical properties of both the composite and leached fibres. This is thought to be due to a reduced reactivity of the fibres with the solid aluminium layer formed around the fibres under adequate casting conditions. The solid layer thus protects the fibres, which indeed had an improved appearance under the SEM.

One last aspect of the process of pressure infiltration complicates its modelling. The fibre preform can get compressed under high infiltration pressures. The volume fraction of the fibres may thus vary during the process.

Fibres and interfacial reactions. (Al alloy matrices with C and SiC fibres)

The fibre that reinforces the metal can, in itself, be a composite of structures. The Avco SCS 2 fibre serves well as an example of a designed fibre. Its structure is complex as is shown schematically in Figure 2. Of direct interest to the foundryman is the surface structure, which grades through an amorphous zone from crystalline SiC to nearly pure carbon. This zone tends to heal the defect structure associated with the <111> oriented SiC whiskerlike grains as they terminate at the surface normal to the fibre axis. The bulk of the ≈1 µm thick SCS coating is carbon doped with Si at the surface to promote bonding. This layer is sacrificial and may be reacted extensively with the matrix without degrading the performance of the fibre. Chemically, the SCS layer behaves like a carbon fibre surface.

The reactivity of carbon fibres to molten aluminium has been the subject of several recent studies. It has been shown that above 500°C, carbon and aluminium react to form aluminium carbide, Al_4C_3. This product first forms on the surface of the fibre then grows into the matrix and somewhat into the fibre as large hexagonal plates. When the reaction reaches this phase, the fibre strength is degraded with concomitant loss of strength in the longitudinal direction of the composite. A slight amount of reaction at the interface was reported to increase the transverse strength of the composite. Since Al_4C_3 is hygroscopic, its presence also affects the corrosion behaviour of the composite. In spite of their interreactivity, wetting of carbon by aluminium is poor below 1000°C.

The effect of alloying additions to the aluminium matrix has been investigated, both regarding wettability and fibre reactivity. A common but not general observation is that the presence of some silicon reduces the amount of reaction at the interface and hence fibre degradation.

Aluminium oxide, in addition to TiB_2, was also found on various graphite fibre-reinforced aluminium matrix composites fabricated by the Ti B coating infiltration technique. Matrices where alloys 201 and 6061. This oxide was also found on fibres coated by ion vapour deposition of Al 4 per cent Mg. The origin of the oxide layer was not determined. A similar observation was made on uncoated graphite fibre squeeze cast composites with various aluminium base matrices. Both oxides and excess carbon were found on the matrix side of the interface. This oxide was believed to be present because of oxygen adsorbed on the fibre surface prior to infiltration.

SiC fibres are not reported to be wet by Al or Al alloys below 900 to 1000°C. Most interfacial studies on SiC fibres in aluminium have been done with Nicalon fibres. The Nicalon* fibre is amorphous or fine grained SiC with free carbon and silica being incorporated in the manufacturing process. The reaction that is expected to take place at the interface from a thermodynamic point of view is:

$$3\,SiC + 4Al \rightarrow Al_4C_3 + 3(Si) \qquad (3)$$

provided the activity of Si is somewhat less than one. This reaction occurs in practice and ensuing

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* Nicalon, Nippon Carbon Co., Tokyo, Japan.

fibre degradation was reported for exposures to molten aluminium above 700 °C. The presence of Si in the matrix was found to decrease the amount of reaction taking place on individually coated fibres. It was also found using differential thermal analysis that on reheating reacted fibres, the reaction proceeded at a much slower rate. This was attributed to the limited supply of free carbon in the fibre and the presence of SiO_2 at the surface from oxidation. Also, in contradiction with Kohara, these researchers demonstrated a decrease in fibre and composite strength with increasing Si and Mg contents in the alloy. Some diffusion of Al into the SiC fibre was also reported to occur in whiskers by Arsenault and Pande.

The behaviour of the AVCO SCS-2 fibre is intermediate between that of SiC and carbon fibres. In the absence of the final silicon enhancement at the outer layer of the fibre, rapid formation of Al_4C_3 was noted similar to that observed with carbon fibres. The Si rich outer layer inhibits the reaction and the fibres can withstand ≃1h in contact with molten Al at 700°C without any significant interfacial reaction taking place. Longer exposure times or higher temperatures cause crack formation in the Si rich outer layer allowing the underlying carbon to react and form Al_4C_3.

Matrix microstructure

Porosity is the first and most critical microstructural feature present in the matrix. Voids have been repeatedly noted and proven to be deleterious to the properties of cast metal-matrix composites. Assuming the infiltration process is properly performed, the main source of porosity is the shrinkage most metals experience during solidification. A high volume fraction of reinforcement may impede the flow of interdendritic liquid and preclude any bulk movement of the metal in the semisolid state. Feeding porosity is therefore expected to be a somewhat more difficult problem to solve for metal-matrix composites. Few authors have addressed the problem.

On the subject of the matrix microstructure proper, published research is relatively scarce as well. In what follows, observations made in various studies are given by alloy system.

Al Si alloys are frequently used because of their good fluidity and compatibility with various fibres. Since the second phase (Si) is readily visible on unetched polished micrographs the number of photographs available in the literature is increased. In all cases, the large eutectic regions in proeutectic alloys were found surrounding the fibres. Silicon plates tend to nucleate on several reinforcements ranging from carbon to SiO_2 and Al_2O_3 particles for low volume fraction composites and the eutectic is thus somewhat modified. It was also observed in hypereutectic alloys that the primary phase (Si) grew from the fibres into the interfibre spaces.

Al Mg alloys, which are more difficult to etch, were reported to display a fine grain size with saffil alumina fibres. It is not clear from the micrographs that the different growth elements are not within the same grain. The second phase was predominantly on the fibres. In other studies, the second phase is again located on the fibre surfaces and along boundaries that run between the fibres.

Al Li alloys used with fibre FP* alumina fibres displayed "surprisingly small amounts of LiAl intermetallic phases present in the matrix". This was attributed to the interfacial reaction. The latter was shown to be 0.5 to 1 µm thick and consists of $LiAl_5O_8$. This hypothesis is reasonable for 60 Vol % fibres.

Nickel Based Superalloys show small dendrites barely perturbed by the comparatively large fibres.

Commercially Pure Al Alloys 6061, 220 and Al 7% Si displayed very large grain sizes and coarse continuous grain boundary networks of brittle second phase. The eutectic regions are seen to coincide with the fibre location. These fibres were coated, however, and the alloy composition is complex. Similar observations were made by Harrigan who showed that the solute content in 6061 carbon fibre composites increased close to the fibres.

Cu Ge Sn polluted by a TiB_2 coating on carbon fibres displayed unperturbed dendrites in larger interfibre regions of infiltrated tows.

Ti Cu alloys were infiltrated into carbon fibre bundles. A heavy reaction layer resulted, but the matrix displays clearly the eutectoid regions in the centre of the interfibre spaces. This corresponds to solidification of the primary Ti rich phase, which is clearly seen to have avoided the Cu rejecting interface during growth.

Al Cu alloys solidified in the same fashion with the primary phase avoiding the fibres. The eutectic is thus precipitated onto the fibres or between individual dendrite arms. Appropriate etching and microprobe scans displayed equi concentrates parallel to the fibre surfaces with the concentration minimum in the centre of the interfibre regions. Fukunaga *et al.* also observed that increasing the pressure during squeeze casting reduced the amount of eutectic present. They explained the structures they observed with a solidification mechanism whereby the alpha phase first nucleates and grows on the cold fibres. The Cu rich liquid is thus rejected to the centre of the interfibre regions. To explain these microstructural features, they postulate that a film of liquid seeps between the fibres and the primary phase as a result of shrinkage of the latter toward the end of solidification. They interpret the role of pressure with rapid solidification effects due to enhanced contact of the metal on the cold fibres. As Cu rich liquid may have been exuded out of the reinforced regions during solidification under high pressures, their interpretation is speculative at best.

Mg Al alloys with SiC fibres display similar features: the eutectic is at the fibre matrix interface and along "bridges" between the fibres.

Commercial Mg ZE 41 has been used to infiltrate fibre FP* alumina fibres. The matrix displays large grains, but as the alloy was not replenished in zirconium before infiltrating the fibres, the cause for that observation is not clear.

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* E. I. du Pont de Nemours & Co., Wilmington, DE., USA.

Al-9Si-4Cu was used to infiltrate carbon fibre bundles. The fibres are surrounded by Al_2Cu as in Al-Cu alloys. The Al_2Cu phase was the last to solidify.

Al-Ni alloys formed by assimilation into the matrix of a nickel coating were seen to display primary Al_3Ni dendrites or platelets growing from the graphite reinforcements.

In conclusion, three types of microstructures are encountered:

(1) A fine network of dendrites when the latter are much smaller than the fibres;

(2) Dendrites nucleating on the fibres and growing into the interfibre spaces (hyper-eutectic Al-Si alloys, Al_3Si alloys, Al_3Ni);

(3) A primary phase that avoided the fibres during growth. The second phase is found on the fibres or between dendrite arms. This represents the majority of cases.

After the composite is cast, it must cool to room temperature. Since the thermal expansion coefficient of the metal is generally higher than that of the fibre, tensile stresses can build up in the matrix. This may influence the microstructure of the matrix. In particular, the dislocation density was found to be increased. This increase in defect density was shown to be responsible for an increase in the aging response of 6061 alloys with B_4C or SiC fibres.

The mechanical properties of the matrix have a considerable influence on the properties of the composite, especially in the off-axis directions. The need for good control of the matrix structure is therefore obvious. The nature and properties of the interface are also of paramount importance in determining the quality of the composite. Both depend to a large extent on the matrix alloy and its processing. Studies concerning the fabrication, evaluation, interface behaviour, and mechanical properties of composites abound. Few, however, address the solidification of the alloy in any depth.

Another general feature of the composite microstructure solidification processed by most vendors and researchers is fibre distribution. Although wrapped woven preforms are designed to keep the fibre in place, local movements take place during solidification. Since the fibres are at best poorly wetted, they tend to bunch into high volume fraction clumps or clusters by the surface tension forces and momentum of the in-flowing liquid during infiltration. This problem is most severe with carbon fibres in Al matrices because of the low cohesive strengths between the matrix and interface. Thus, when two fibres touch, we can say that a defect exists of the order of two fibre diameters. This, in part, explains the low transverse properties of carbon fibre/Al alloy composites.

Future needs and directions

It is now an axiom of materials science that there is a relation between materials microstructure, materials properties, and the way the materials were made, i.e, processing. These taken together define materials performance. It is only with a thorough understanding of these relations that we will be able to predict performance. We have many more opportunities for materials design with composite materials. This opportunity is in many ways a curse in that a large data base will be difficult to obtain, given the large number of possible combinations. Thus, it is mandatory that we develop the models for both the behaviour and for the processing of this new class of materials.

In solidification processing of metal matrix composites, we have very little information on the relations between processing and metal microstructure and even less information on the effects of the metal microstructure on the mechanical properties. This work should first be performed on model systems and then be generalized to commercial systems.

We have the opportunity to design a metal matrix composite from the inside out. The review of the Avco SCS-2 fibre presented here is an example of an early attempt to design a filament utilizing fracture mechanics as a guide. This approach needs to be made more sophisticated and extended to other systems. There is not sufficient research being applied to understanding multifilament tow materials.

While we are designing the fibre, we should also turn our attention to the matrix. Most matrix alloys were developed for other purposes. However, we have shown that a significantly different microstructure can be produced by controlling the solidification rate. The low microsegregation effects noted with longer solidification times could be exploited by developing more concentrated alloys. It is also possible to affect the wettability of fibres and fibre matrix compatibility through alloying. There is need for comprehensive alloy development studies to optimize these systems for a number of generic applications.

While fundamental studies are extremely important, the manufacturing technology for solidification processed composites is retarded compared to diffusion bonding and powder metallurgical approaches. The emphasis of most DOD related programmes has been for demonstration articles. Casting techology involves expensive tooling and fixturing that may not be cost effective for producing a few parts. Thus, this technology has seriously lagged. This can be corrected by favouring technology oriented programmes over component demonstration programmes. (Extracted from Ceramic Bulletin, Vol. 65, No. 2 (1986), article was written by James A. Cornie, Yet-Ming Chiang, Donald R. Uhlmann, Andreas Mortensen, and Joseph M. Collins, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, and kindly provided to us by Professor P. Rohatgi)

Table 1

Fibre reinforcement for liquid-metal infiltration

Fiber	Strength (ksi)	Strength (MPa)	Modulus (ksi 10^3)	Modulus (MPa 10^3)	Density (lb/in³)	Density (g/cc)	ε%	Diameter (μm)
Al_2O_3 (Saffil)	290	2000	43	300	0.119	3.3	0.67	3
Al_2O_3 (FP)	200	1380	55	379	0.141	3.9	0.36	20
Continuous SiC (Nicalon)	400	2760	29	200	0.093	2.55	1.5	10–15
SCS-2	500	3450	61	407	0.11	3.05	0.8	140
Carbon								
P – 55	300	2068	55	380	0.081	2.25	0.5	10
P – 75	300	2068	75	517	0.081	2.25	0.42	10
P – 100	325	2240	100	690	0.081	2.25	0.5	10

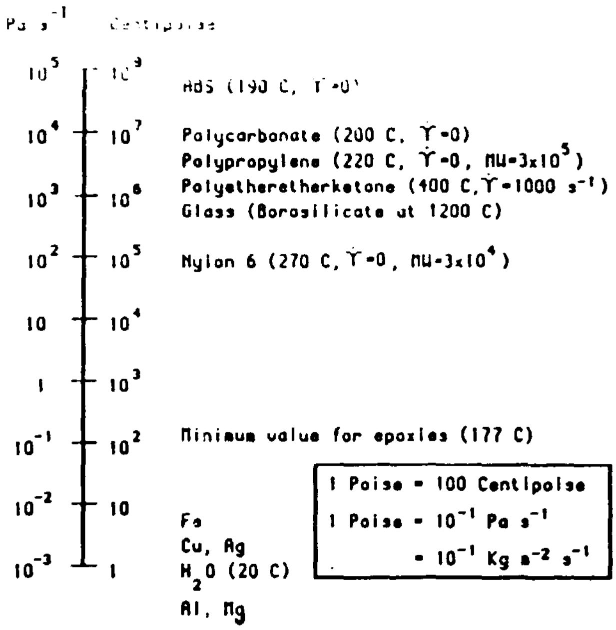


Figure 1. Viscosity of selected molten metals polymers and glasses

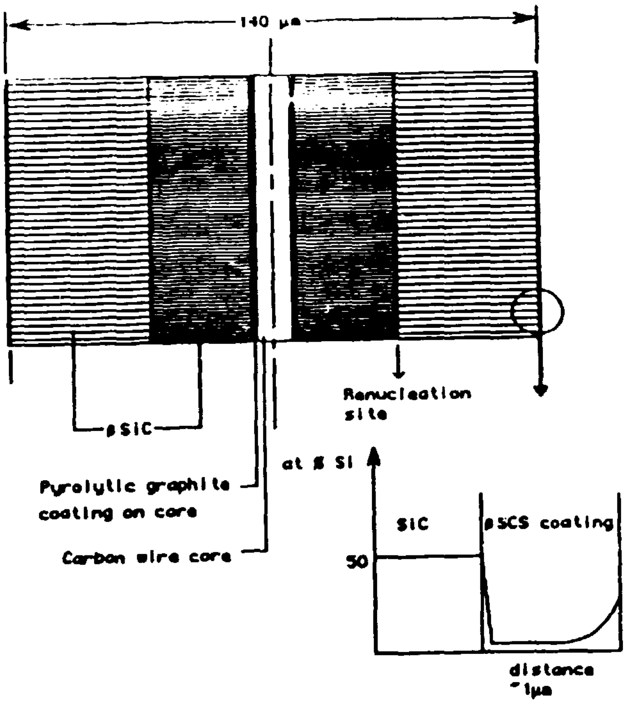


Figure 2. Schematic section of SCS-2 fibre

4. CHARACTERIZATION OF PHYSICAL, MECHANICAL, AND TRIBOLOGICAL PROPERTIES OF METAL-MATRIX COMPOSITES

Written by P.K. Rohatgi, R. Asthana and S. Das

Since there are very few generalized models available for predicting the properties of metal-matrix-particulate composites, several studies have been made to characterize the individual physical, mechanical and tribological properties of metal-ceramic particle composites. The densities of both pressure die cast and gravity die cast Al alloy-zircon composites increased with progressive additions of zircon particles, whereas graphite and Al_2O_3 (hollow particles) dispersed alloys showed a decrease (figure 1). The thermal expansion generally decreased monotonically with increasing additions of ceramic particles (figure 2), and this is a distinct advantage in applications such as automobile pistons. The thermal conductivity of Al alloys decreased with graphite additions, while the electrical resistivity of mica-dispersed Al alloys increased with increasing additions of mica. Work carried out at Hitachi has shown that graphite-dispersed Cu alloys perform better as current collectors than the sintered base alloy, since they combine the excellent conductivity of the matrix with the wear resistance of graphite.

Several workers have shown that dispersions of graphite and mica particles in several Al alloys improved their damping capacities. Similar results were reported for Cu-graphite composites. In addition, the graphite-containing alloys were found to retain their damping properties until very high temperatures, unlike the other alloys. Effects of microstructural parameters on ultrasonic velocities and elastic constants of Al-Al_2O_3 composites have been reported by Madhava _et al_.

Hardness values of Al alloys containing soft particles such as graphite, mica and coconut shell char decreased whereas those containing hard particles such as alumina, zircon, glass particles and SiC whiskers showed increase in hardness.

The elastic modulus of Al alloys containing dispersions of alumina particles, short alumina fibres, and zircon particles increased with additions of these particles. Much higher increases in modulus were reported when SiC whiskers were dispersed in squeeze cast Al alloys.

The mechanical behaviour of several Al alloys containing dispersed ceramic particles has been extensively studied. In general, the tensile strength of Al alloys in the as-cast condition decreased with addition of graphite, mica and shell char. The tensile strength of many of the cast composites followed a two thirds power law with volume fraction of dispersed particles (figure 3). Work carried out at Hitachi has also shown that the tensile strength of both Cu- and Al-base alloys decreased together with the elongation as a result of graphite additions. However, the tensile properties of cast metal-ceramic composites remained adequate for a variety of applications as has been demonstrated by actual life tests of bearings, pistons and current collectors. In a limited number of cases, especially where the matrix was pure ductile aluminium, improvements in tensile strength have also been reported to result from ceramic additions. Dispersion of alumina particles, short alumina fibres, zircon particles and SiC whiskers in solidifying Al alloys with or without pressure led to improvement in strength. Many cast composites, prepared by the compocasting technique and which were subsequently extruded showed tensile strengths comparable with that of the matrix alloy. In some cases improvements in strength were noted. Rohatgi and co workers have reported that considerable improvements in strength, ductility and hardness of Al-graphite composites could be obtained after heat treatment, hot extrusion, rolling and forging. They reported deformation of graphite particles into stringers with aspect ratio as high as 20 after hot working. Heat treatment of cast composites leads to considerable increase in their strength and ductility. It is clear that judicious selection of the matrix material and the dispersoid, and thermomechanical treatment can lead to strengthening effects in cast metal-ceramic particle composites. Heat treatment leads to stress relaxation, sometimes improved bonding, and spheroidizing of the second-phase particles, resulting in improved ductility and mechanical properties. Deformation of the composites results in stringering, fibring, fragmentation and alignment of the dispersoid. New ceramic-metal interfaces are generated during deformation, in addition to the interfaces formed during solidification; there is substructure and texture strengthening of the matrix; and there is decrease in porosity, all resulting in improvement in the properties of the composite.

The length of chips produced during the machining of Al alloys is decreased considerably by dispersions of graphite or mica particles. The decrease in chip size will be of advantage in automated, fast machining operations where long chips get wrapped around the tool.

The fracture toughness of Al alloys to which glass and fly ash particles were added did not change significantly as a result of particle dispersion. In several Al-Al_2O_3 (MgO-coated) composites fracture surfaces showed considerable plastic deformation of the matrix.

The adhesive wear rates of Al, Al-11·8Si and Al-16Si alloy castings decrease with the addition of Al_2O_3 particles 100 μm in size (figure 4). Pure Al exhibits much higher wear than the other two alloys. Large (142 μm) alumina particles provide maximum wear resistance. With a 5 per cent dispersion of alumina, the wear rate of composites is comparable with that of Al-11.8Si and Al-16Si alloys. Also, the abrasive wear rate of Al-5 per cent Al_2O_3 is lower than that of eutectic and hypereutectic Al-Si alloys. The mechanism of abrasive wear in these composites appears to be material displacement by ploughing in pure Al, and chipping for eutectic and hypereutectic Al-Si alloys containing 5 per cent Al_2O_3. The abundantly available, inexpensive Al_2O_3 can form a suitable substitute for expensive Si to achieve improved wear properties. Further, a combination of high strength and abrasion resistance can be achieved in Al-matrix composites by random planar orientation of Al_2O_3 fibres.

Several studies have demonstrated superior wear resistance of graphite dispersed alloys. Graphitic Al-Si alloys have superior wear resistance to pure Al, Al-Si and Al-Si-Ni alloys when mated with a rotating steel disc. The high wear resistance of graphite Al alloys is primarily a result of the presence of graphite particles which act as a solid lubricant. Those alloys with over 2 per cent graphite when rubbing against a rotating steel disc only at pressures in excess of 320 kPa require only an initial 1 min of run in with lubricant. The seizure resistance of these composites increases with graphite percentage. Above 2 per cent graphite, these alloys can run under conditions of boundary lubrication without seizure. In fact, the test had to be stopped because of heating of the system, and no seizure occurred even though the temperature at the interface was high enough for hot deformation. Work at Hitachi has shown that dry wear of Al- or Cu-graphite composites decreased with increasing graphite content. The reason for the excellent tribological properties of graphitic Al alloys is that the Al alloy matrix yields at low stresses and deforms extensively which enhances the deformation and fragmentation of the surface and subsurface graphite particles, even after a short running-in period. This provides a continuous film of graphite on the mating surface which prevents metal-to-metal contact, and hence prevents seizure.

Graphite additions also reduce the coefficient of friction at the mating interface and reduce the temperature rise in wear pins. Actual bearing tests have shown that the stabilization temperature of an Al-graphite-particles composite bearing is lower that that of conventional bronze bearings under identical conditions. Moreover, the oil spreadability of graphite-containing alloys was superior to that of the parent alloys. It must be noted, however, that at high volume per cent of graphite (8 per cent) in composites made by compocasting followed by squeeze casting, graphite so weakens the alloy that yielding occurs and a severe rate of wear is maintained.

Figure 5 shows the temperatures of some Al-Si-Ni alloy-graphite composites as a function of time at a pressure of 365 kPa with continuous lubrication and when the supply of lubricant was discontinued after running for 1 min. For alloys with 2 and 6.2 per cent graphite the temperature reached a constant value after about 5 min. For other alloys with 0-1 per cent graphite, the temperature rise was steep when lubrication was cut off and experiments were discontinued.

The minimum bearing parameter reached by graphitic Al alloys based on Al-12Si alloy for two types of graphite of various sizes fall within a narrow band when plotted as a function of graphite content (figure 6). This relative independence of the size and shape of the graphite particles is apparently a result of the extensive deformation of graphite during wear.

The wear rate of Al Cu alloys containing dispersions of mica particles increased with mica content as well as with bearing pressure, possibly because of loss of loosely bonded mica particles. The Al-Cu-mica composite alloy bearing can run under boundary lubrication, semi-dry, and dry conditions whereas the mica-free base alloy seizes. This is because the loose mica particles released by bearing pressure at the mating interface diminish metal-to-metal contact and act as a solid lubricant in the absence of any liquid lubricant film at the interface.

Wear rates and the coefficient of friction of Al-11.8Si alloys containing up to 8 per cent shell char particles under dry conditions of sliding decrease with increasing amount of char particles at the low sliding speed of 0.56 ,s^{-1} (figure 7). At higher speeds (5.38 ms^{-1}) the wear rate increased with vol.-% shell char particles. The adhesion of fragmented bits of shell char particles on the bearing surface reduced wear rate and the coefficient of friction. Journal bearings made from this composite alloy could run successfully under conditions of boundary lubrication without seizing.

Banerjee et al. have shown that the abrasive wear resistance of Al alloys containing zircon particles decreased, possibly because of blunting of the alumina particles of the abrasive cloth by dispersed zircon. The wear rate of Al-25 per cent zircon after ten passes was very similar to that of brass and steel (figure 8). Similarly, additions of SiC, Al_2O_3, TiC, Si_3N_4, glass and silica particles to Al alloys led to considerable improvements in wear resistance. Under low-stress abrasive wear, the wear resistance of cast Al alloy-zircon composite was equal to that of steel. (Extracted from International Metals Review, 1986, Vol. 31, No. 3. The article was kindly provided to us by Prof. Pradeep Rohatgi)

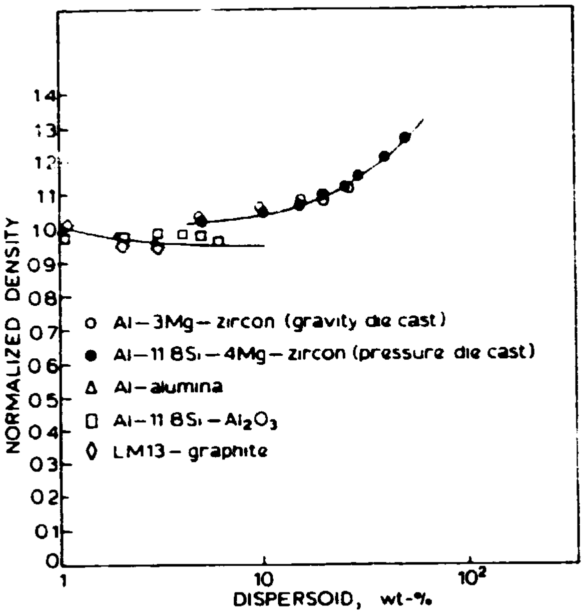


Figure 1. Density v. weight per cent dispersoids for Al-zircon, Al-alumina, and Al-graphite composites

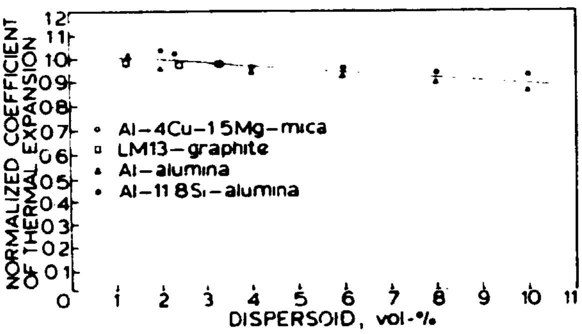


Figure 2. Coefficient of thermal expansion v. volume per cent dispersoids fo· Al-mica, Al-graphite, and Al-alumina composites

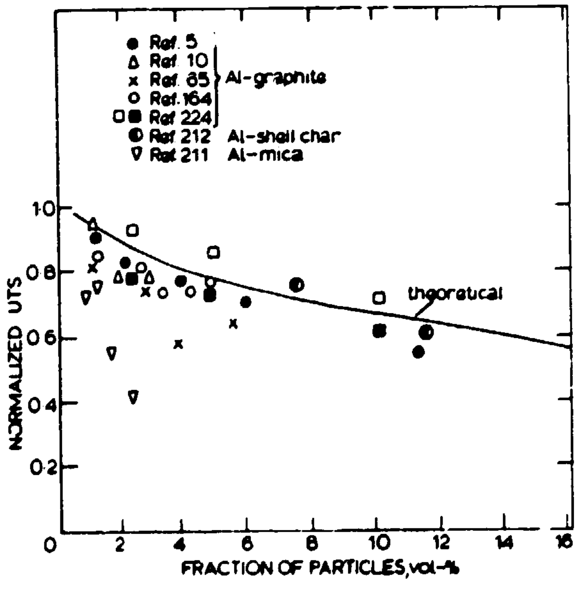


Figure 3. Strength v. volume fraction particles for Al-graphite, Al-shell char, and Al-mica composites

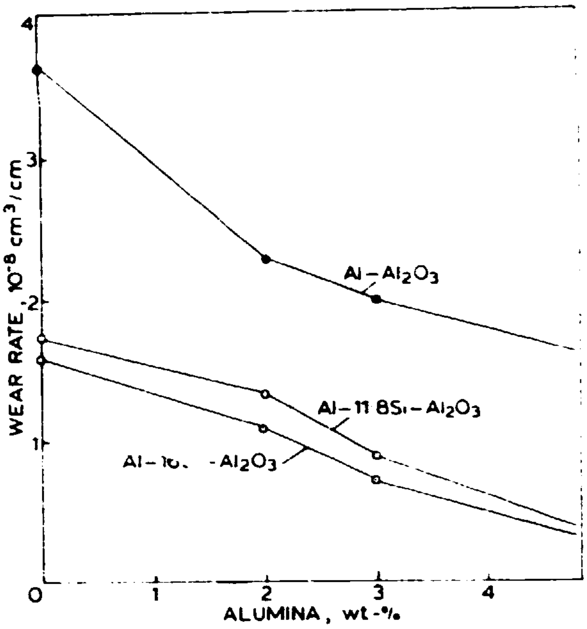


Figure 4. Wear rates of Al, Al-11.8Si and Al-16Si alloys containing different amounts of alumina (200 μm in size); load 2 kg, sliding distance 2545 m, sliding velocity 5.48 ms^{-1}

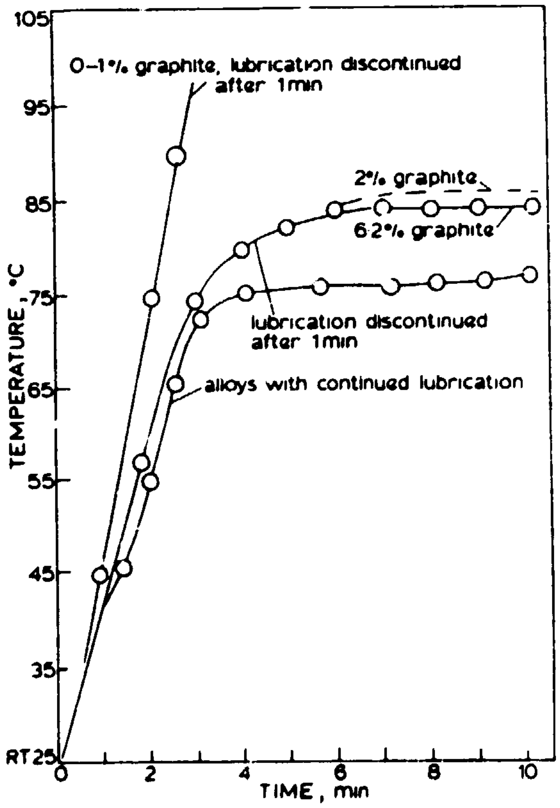


Figure 5. Typical curves of temperature change with time for graphite-Al alloys with continuous lubrication and lubrication discontinued after 1 min

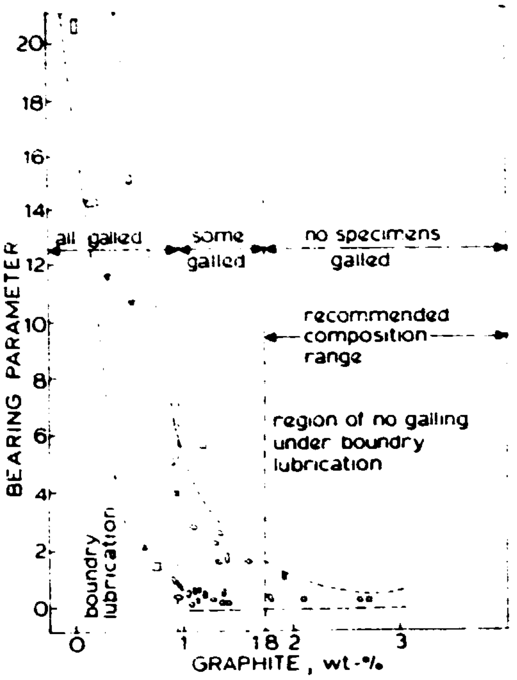


Figure 6. Galling behaviour of graphite-Al alloys as function of graphite content for size range 20-400 µm

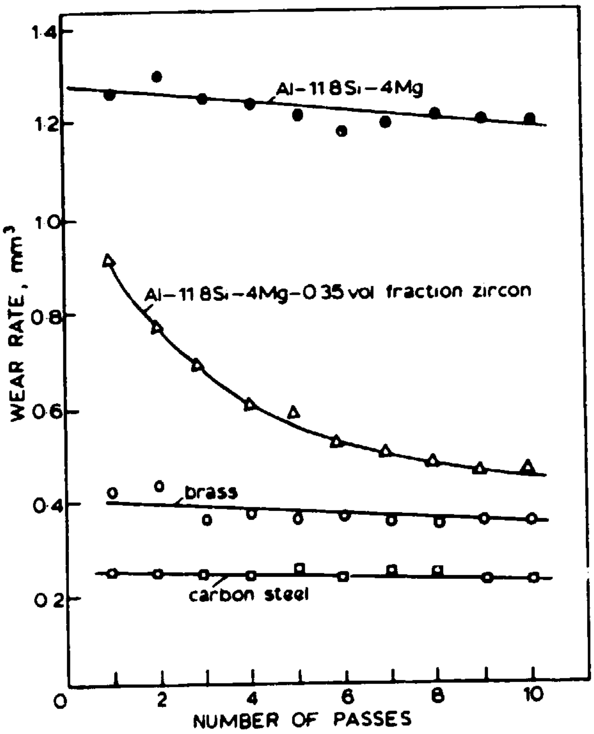
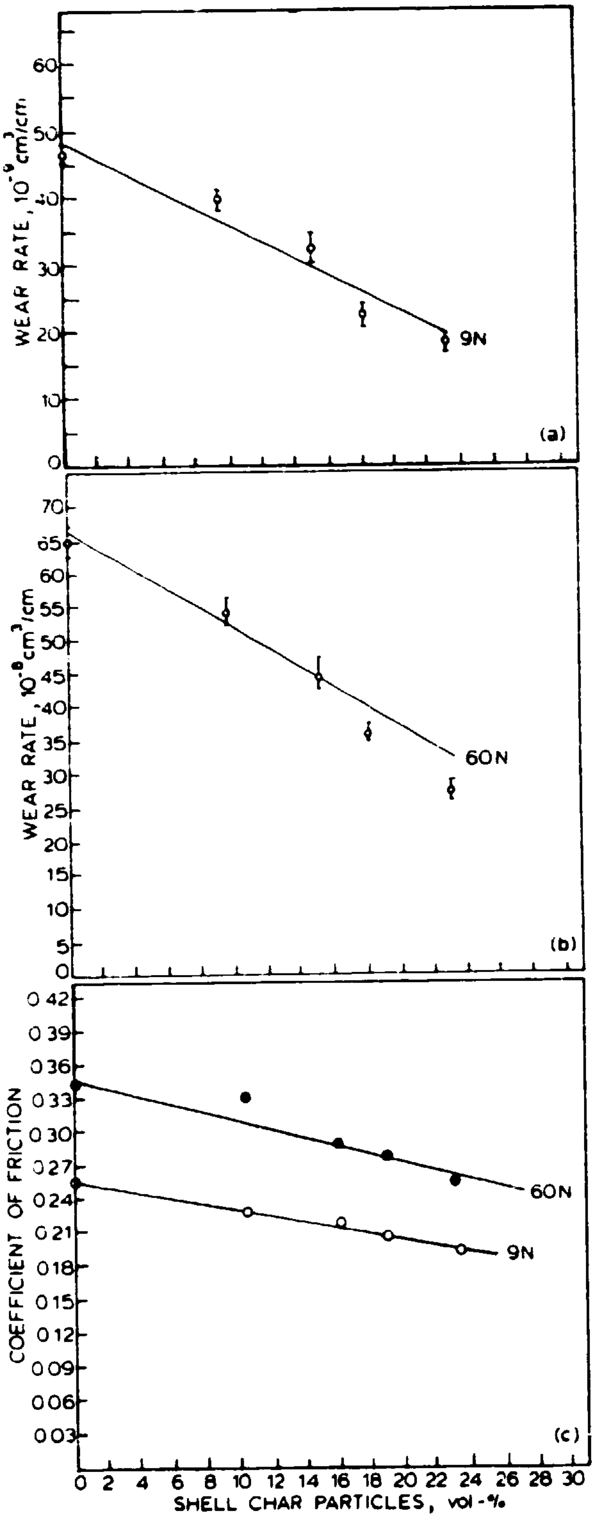


Figure 8. Wear rates of different materials as function of number of passes; load 5 N



a, b wear rate; *c* coefficient of friction

Figure 7. Effects of amount of shell char particles content on wear and friction of Al-Si alloys; speed 0.56 ms^{-1}

5. FABRICATION OF HIGH PERFORMANCE POWDER-METALLURGY ALUMINIUM MATRIX COMPOSITES

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Abstract

Recent years have seen the development of a wide range of high-performance discontinuously reinforced aluminium powder metallurgy composites. These materials have combined both standard wrought, e.g., 6061 and 2124, and specialty matrix compositions, e.g., Al-Cu-Mg-Li and Al-Fe-Ce, with a wide variety of discontinuous reinforcements, e.g., Al_2O_3, B_4C, SiC_p and SiC_w. This paper discusses the manufacturing procedures utilized to fabricate these light-weight powder-metallurgy composites. Emphasis is given to developing a generalized framework for understanding the interrelationship existing between thermo-mechanical treatment and the mechanical behaviour of these composite systems.

Introduction

Modern design procedures continually strive to increase structural efficiencies through reductions in either absolute weight or increases in the strength-to-weight ratio. Figure 1 illustrates how, for a cargo-bomber aircraft application, reductions in material density, or increases in modulus (stiffness), yield strength and/or ultimate tensile strength, can be directly translated to reductions in structural weight. For example, a 10 per cent reduction in alloy density, which can be achieved through substitution of Al-Li alloys for 2000 series aluminium alloys, will result in a 10 per cent reduction in structural weight. Alternatively, a 50 per cent increase in modulus, which can be achieved through substitution of a discontinuous silicon carbide (SiC) reinforced alloy for an unreinforced wrought aluminium alloy, will also result in a 10 per cent reduction in structural weight. Indeed, it is possible to envision combining these effects through the development of a reinforced Al-Li alloy.

System trade-studies, such as outlined above, have been the primary motivating factor in the renewed interest shown in metal-matrix composites. Initially, these investigations focused on continuous fibre reinforced metal-matrix composites. Wide spread industrial application of these composites has however been limited by the high costs of the reinforcement fibre, e.g., $300/lb for B, and the metal-matrix component fabrication process. Most recent attention has therefore been directed towards commercialization of discontinuously reinforced metal-matrix composites, notably silicon carbide particulate and whisker reinforced aluminium alloys, where low fibre costs, $2-20/lb, can be combined with standard or near-standard metal working practices. This paper discusses the manufacturing procedures used to fabricate discontinuously reinforced aluminium metal-matrix composites. It further considers how alloy chemistry and processing modifications are being utilized to enhance their mechanical performance.

Billet fabrication

Two principal methods are currently being employed to fabricate discontinuously reinforced powder metallurgy metal matrix composite billets. A generalized flow chart illustrating the first of these is presented in figure 2.

The initial step in the manufacturing sequence depicted in figure 2 involves proper selection of the discontinuous ceramic reinforcement and the matrix alloy. Selection criteria for the ceramic reinforcement include:

- Elastic modulus
- Tensile strength
- Density
- Melting temperature
- Thermal stability
- Compatibility with matrix
- Thermal coefficient of expansion
- Size and shape
- Cost

Powder-metallurgy aluminium matrix composites

Table 1 summarizes selected properties for a wide range of possible discontinuous ceramic reinforcements. Unfortunately much of the available information is for a rather narrow temperature range. This is of major importance if the composite system is to operate at elevated temperature.

Elastic moduli, tensile strengths and densities are of particular interest in establishing the eventual structural efficiencies of the discontinuously reinforced metal-matrix composites. Chemical stability of the ceramic reinforcement, including its compatibility with a suggested matrix, is of importance for both end-use and composite fabrication. For example, the matrix composition of continuous fibre FP Al_2O_3 reinforced Al must be adjusted to enhance fibre wettability since Al does not wet Al_2O_3. This is conventionally done through the addition of Li to the Al alloy matrix. However, this reaction must be limited, i.e., enough to wet the fibre to promote bonding, without reinforcement degradation either during composite fabrication or utilization.

A consideration of the thermal mismatch between the proposed reinforcement and matrix is essential if the composite will be subject to thermal cycling, for example, as might occur in an internal combustion engine. The strain, ε, developed at the interface of a discontinuously reinforced metal-matrix composite due to a single thermal cycle is:

$$\varepsilon = \Delta\alpha \Delta T$$

where $\Delta\alpha$ is the difference between the thermal coefficients of expansion for the reinforcement and the matrix, and ΔT is the range of temperature experienced during a thermal excursion. In order to minimize strain accumulation, differences in expansion coefficients between reinforcement and matrix should be minimized. It is also important to recognize that relaxation of these strains, by the formation of a dislocation network, will alter the response of a discontinuously reinforced metal-matrix composite to thermo mechanical processing from that experienced by an unreinforced alloy.

SiC whiskers may be β (BCC) or a mixture of β and α (HCP) phases. Furthermore, the whiskers generally have a faulted internal structure and an irregular surface, for the AMC SiC whisker. Finally, initial whisker lengths may range between 5 and 40 μm, figure 3, and normally contain SiC and/or SiO_2 particulates as contaminants, table 2.

A wide range of SiC particulate sizes and shapes are also available. Again, both α and β SiC crystal structures have been examined as possible reinforcements. Figure 4 shows a typical particle size distribution for α SiC particulate. The importance of selecting the appropriate SiC size to powder size ratio has recently been demonstrated by ALCOA investigators. These investigators showed that maximum toughness in SiC_p reinforced MB78, a 7000 series aluminium alloy, was associated with a distinct SiC/Al powder size ratio, figure 5.

Table 3 presents the chemical compositions of several aluminium alloys that have been, or are being examined, as possible matrix alloys. Initially, standard wrought alloy compositions, e.g., 6061 and 2124 were utilized. These were prepared as either elemental or pre-alloyed air/helium inert gas atomized powders.

Recent investigations have shown that that minor alloying elements commonly included in wrought alloys as grain refiners, e.g., Mn and Cr, are unnecessary in discontinuously reinforced metal matrix composites. Indeed, they may form large intermetallic compounds during consolidation and subsequent processing, these compounds being detrimental to the composites' tensile ductility. In addition, microstructural-mechanical behaviour examinations of these alloys has shown that leaner alloy compositions, that is alloys whose composition limits lie on the lower end of the standard wrought alloy specification limit, develop a better combination of strength, ductility and toughness. Newer compositions have therefore eliminated Mn and/or Cr, and have rebalanced (leaner) compositional limits.

Other matrix compositions that have been investigated include 7090, 7091, Al-Fe-Ce, Al-Cu-Mg-Li. These alloys take full benefit of rapid solidification. However, they do require modification of the consolidation and processing procedures described below.

A dry or wet blending operation typically follows selection of the reinforcement and matrix powder. If whiskers or short fibres are to be included in the composite this blending step must be preceeded by deagglomeration of the reinforcement. C.J. Skowronek _et. al_. have shown that this deagglomeration can be accomplished through ultrasonic agitation of alcohol fibre suspensions. While the difference between the aluminium powder and reinforcement can be specified and controlled in particulate reinforced metal matrix composites by suitable selection of powder and particulate, the same approach cannot be utilized in short fibre/whisker metal-matrix composites. In the latter, the whisker/fibre diameters are fixed within a rather narrow size range. In these composites improved mechanical working procedures offer the only potential for minimizing the detrimental effects of dissimilar powder and reinforcement diameters, that is hot/cold deformation enhances reinforcement matrix mixing.

Final billet fabrication involves cold compaction, outgassing and hot isostactic or vacuum hot pressing, figure 6. Cold compaction densities should be controlled to maintain open, interconnecting porosity. The latter is extremely important during the outgassing stage of the pressing operation. While the details of the reinforcement powder blend outgassing procedures are generally considered proprietary by the composite manufacturer, they normally involve removal of adsorbed or chemically bound water and other volatile species through the combined action of heat, vacuum and inert gas flushing. For example, outgassing of SiC reinforced aluminium metal-matrix composites involves removal of adsorbed water from both SiC and aluminium, as well as chemically bound water from the aluminium alloy. The principal reactions occurring during this outgassing process are given in table 4, where H_2 and H_2O are the primary gaseous reaction products and Al_2O_3 is the primary solid product.

The extent of these reactions during outgassing of SiC_p and SiC_w reinforced 6061 Al blends is shown in figure 7. These results suggest that the outgassing reactions are a function of the reinforcement surface chemistry. Other investigators have also shown that the details of the reactions listed in table 4 are sensitive to the Al alloy chemistry.

Once the desired isothermal temperature is reached, final consolidation is accomplished by pressure application. Selection of the consolidation temperature is typically based on the need to minimize the pressures necessary for complete consolidation without degrading the powder matrix. Preliminary data also suggest that dynamic compaction may be an attractive alternative when dealing with highly unstable rapidly solidified aluminium alloys. Furthermore, while both solid state and mushy zone consolidation temperatures have been employed, growing evidence suggests that higher tensile ductilities can be achieved following solid state pressing.

The second metal matrix billet manufacturing procedure currently being developed by ALCAN involves direct incorporation of the ceramic reinforcement in the matrix alloy as an integral part of the Osprey process, figure 8. While details of this process are still under development, 6 in. diameter SiC_p reinforced Ac-Cu-Mg-Li alloys have been produced. These billets have contained SiC having a mean diameter of 13 μm and size range 5-20 μm.

After consolidation metal-matrix composite billets are homogenized, scalped and inspected. Typical inspection criteria assure 98 per cent theoretical density prior to subsequent processing.

Primary processing

Consolidated billets, typically 98+ per cent theoretical density, can be fabricated into a wide variety of shapes utilizing standard metal working equipment. Primary working operations involving rolling, extrusion and forging have all been demonstrated.

Measurements of whisker orientation also suggest that only moderate extrusion ratio's are required for essentially complete alignment of SiC whiskers, figure 9. While this alignment can be beneficial, for example, near rule of mixture elastic moduli can be attained in properly processed extruded whisker reinforced aluminium alloys, figure 10, its presence does result in a highly anisotropic fracture behaviour.

The attainment of maximum useful work, as defined above, is a necessary but not sufficient condition for establishing optimum deformation parameters. For example, Gegel et. al. have shown that this maxima in 2124 reinforced with 20 volume per cent SiC whiskers, is associated with nearly complete dynamic recovery, higher temperatures and rates leading to incipient melting, lower temperatures and rates to dislocation accumulation. In contrast, it is now well known however that maximum toughness in wrought aluminium alloys is generally associated with an unrecrystallized grain structure. For example, further experimental examination of the microstructural conditions associated with processing of SiC reinforced 2124 has resulted in the deformation temperature being lowered to 400°C.

Secondary processing

Secondary processing procedures have included shear spinning, superplastic forming and joining. Figure 11 illustrates that elongations in excess of 300 per cent can be achieved in SiC reinforced 2124 through proper selection of temperature and strain rate. Of particular interest are the rather high strain stress associated with superplasticity in reinforced aluminium alloys when compared to other structural materials.

Finally, reinforced aluminium composites may be welded using a variety of processes, providing that the composite is initially given a vacuum heat treatment to minimize entrapped gases.

Summary

This paper has reviewed the two primary powder-metallurgy based fabrication methods currently under development for discontinuously reinforced aluminium metal-matrix composites. These procedures have a wide range of flexibility with each stage of the manufacturing process ultimately having an effect on mechanical, physical and environmental properties. While many of these effects are not completely understood current knowledge does exist for fabrication of billets up to 500 lbs. Future advancements in manufacturing technology should allow this size to increase as the demands of the market increase. (This article was kindly provided by Prof. Pradeep Rohatgi)

Table 1

Properties of selected ceramic reinforcements

Ceramic	Coefficient of Expansion ($10^{-6}/°F$)	Strength (ksi)	Elastic Modulus (mpsi)
BeO	4.1	3.5(2000°F)	27.5(2000°F)
MgO	6.45	6.0(2000°F)	22.0(2000°F)
ThO_2	5.3	28.0(2000°F)	29.0(2000°F)
UO_2	5.3	-	25.0(2000°F)
ZrO_2	6.67	12.0(2000°F)	19.2(2000°F)
CeO_2	6.9	85.4(75°F)	26.8(75°F)
Al_2O_3	4.4	32.0(2000°F)	55.0(2000°F)
$TaSi_2$	6.0	-	49.0(2300°F)
$MoSi_2$	4.85	40.0(2000°F)	40.0(2300°F)
WSi_2	5.0	-	36.0(2000°F)
TiB_2	4.6	-	60.0(2000°F)
ZrB_2	4.5	-	73.0(75 o F)
TiC	4.22	8.0(2000°F)	39.0(75°F)
ZrC	3.7	13.0(2000°F)	52.0(75°F)
HfC	3.7	-	46.0(75°F)
VC	3.98	-	63.0(75°F)
NbC	3.8	-	49.0(75°F)
TaC	3.59	-	53.0(75°F)
Mo_2C	3.33	-	33.0(75°F)
WC	2.83	-	97.0(75°F)
B_4C	3.38	400.0(75°F)	65.0(75°F)
SiC	3.00	1210.0(75°F)	47.0(2000°F)
AlN	2.69	300.0(75°F)	45.0(2000°F)

Table 2

Chemical composition for ACMC SiC whiskers

		Grade	
		SC-9	SC-10
Whisker content, %		80-90	70-80
Particle content, %		10-20	20-30
Element(ppm)			
	Ca	3700	
	Mn	2400	
	Al	1300	
	Mg	800	
	Fe	500	
	Cr	<50	
	Ni	<50	
	K	<50	
	Na	<50	
	Cu	<25	
	B	<10	
	Li	<10	
	Ti	<10	

Table 3

Chemical compositions of aluminium powders

Element

	Cu	Mg	Zn	Si	Mn	Cr	Fe	Other
Al-Cu								
2219	6.74	-	-	-	0.4	-	0.05	0.12V
Al-Cu-Mg								
2124	4.65	1.60	0.01	0.04	0.9	-	0.3	-
2124HP	4.65	1.5	0.02	-	-	-	0.1	-
2048	3.73	1.77	-	-	-	-	0.03	-
ACM1	2.95	1.37	-	-	-	-	-	-
ACM2	3.26	1.25	-	-	-	-	-	0.1 Zr
ACM3	3.67	1.84	-	0.14	0.2	-	0.2	0.6 Zr
Al-Mg-Si								
6061	0.35	1.19	0.02	0.77	-	0.22	0.32	-
6013	0.75	1.15	-	0.94	0.22	-	0.1	-
Al-Zn-Mg-Cu								
7075	1.5	2.5	5.5	-	-	0.30	-	-
7090	1.2	2.5	7.8	0.05	-	-	-	1.4 Co
7091	1.6	2.4	5.65	0.02	0.01	-	0.27	0.44 Co
SXA 60	1.33	2.35	9.7	0.1	-	-	0.06	-
SXA 90	1.31	2.49	7.8	-	0.02	-	0.03	-
AZMC1	-	0.79	3.56	-	-	-	-	-
AZMC2	0.68	0.95	4.18	-	-	-	-	-
MB78	2.0	2.0.	7.0	-	-	-	-	0.14 Zr
Al-Li								
AL1	-	-	-	-	-	-	-	1.0
AL2	-	-	-	-	-	-	-	2.0
AL3	-	-	-	-	-	-	-	3.0
Al-Mg								
5082	-	4.5	-	-	0.7	-	-	-
Al-Cu-Mg-Li								
ACML1	0.91	0.85	-	-	-	-	-	1.66 Li
ACML2	0.63	0.68	-	-	-	-	-	1.0 Li
ACML3	1.5	1.0	-	-	-	-	-	2.8 Li
ACML4	3.0	1.0	-	-	-	-	-	1.6 Li
Other								
Al-Fe-Ce	-	-	-	-	-	-	7.7	4.2 Ce
	-	-	-	-	-	-	5.6	4.6 Ce, 0.3 W
Al-Fe-Mo	-	-	-	-	-	-	6.1	1.5 Mo
Al-Fe-X	-	-	-	-	-	1.5	4.5	4.5 Ni
Al-Cr-X	-	-	-	-	0.8	3.8	-	1.3 Zr

Table 4

Chemical reactions occurring during heating of aluminium powders

$$Al_2O_3 \cdot 3H_2O \xrightarrow{> 100°C} Al_2O_3 \cdot H_2O + H_2O(g)$$

$$Al_2O_3 \cdot H_2O \xrightarrow{> 400°C} Al_2O_3 + H_2O(g)$$

$$2Al + 3H_2O \xrightarrow{> 200°C} Al_2O_3 + 3H_2(g)$$

$$2Al + 6H_2O \longrightarrow Al_2O_3 \cdot 3H_2O + 3H_2(g)$$

Table 5

Whisker aspect ratio as a function of processing

Material	L/D
Powder/whisker blend	19.8
36:1 Extrusion Ratio Round-to-Round Through Streamline Flow Die	18.0

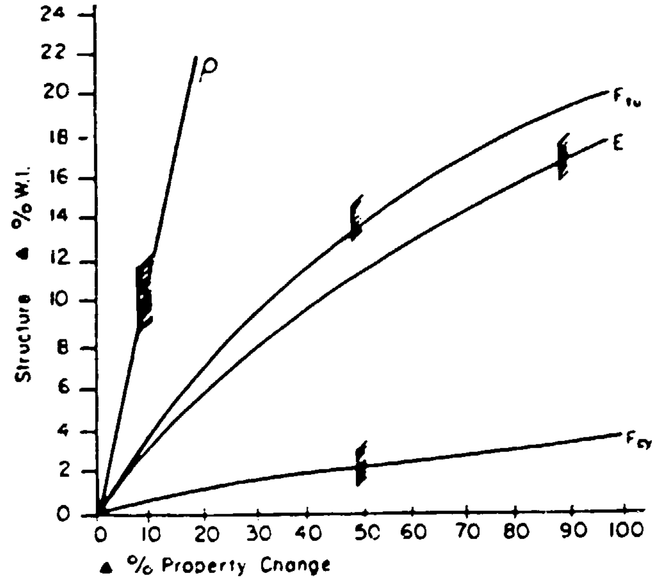


Figure 1. Performance enhancement related structural weight reductions in cargo bomber aircraft applications

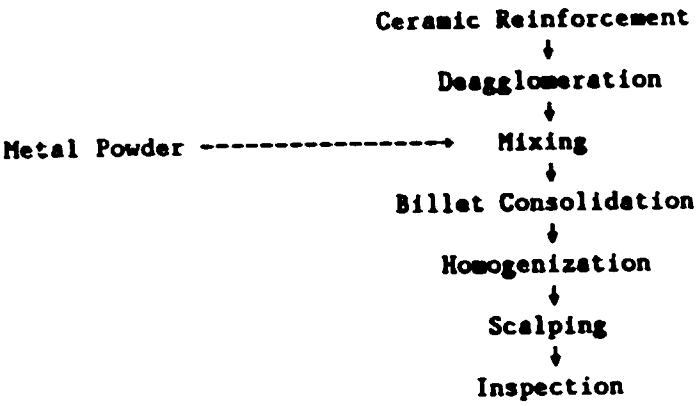


Figure 2. Powder-ceramic reinforcement blending sequence for discontinuously reinforced metal matrix composites

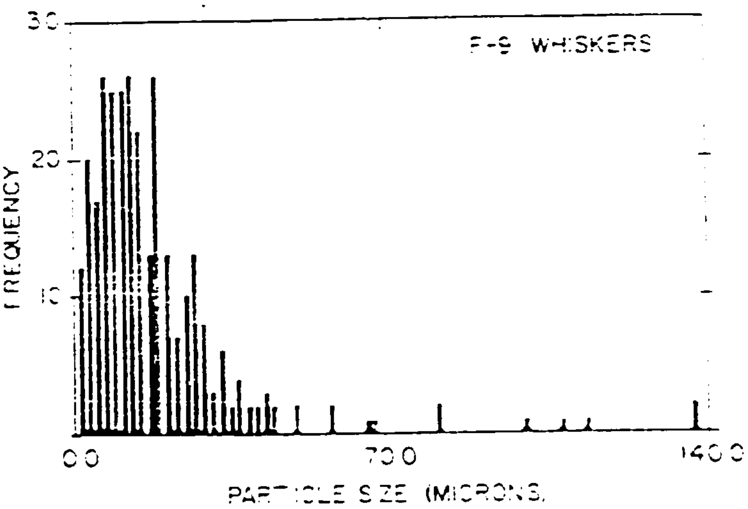


Figure 3. ACME SiC whisker size distribution

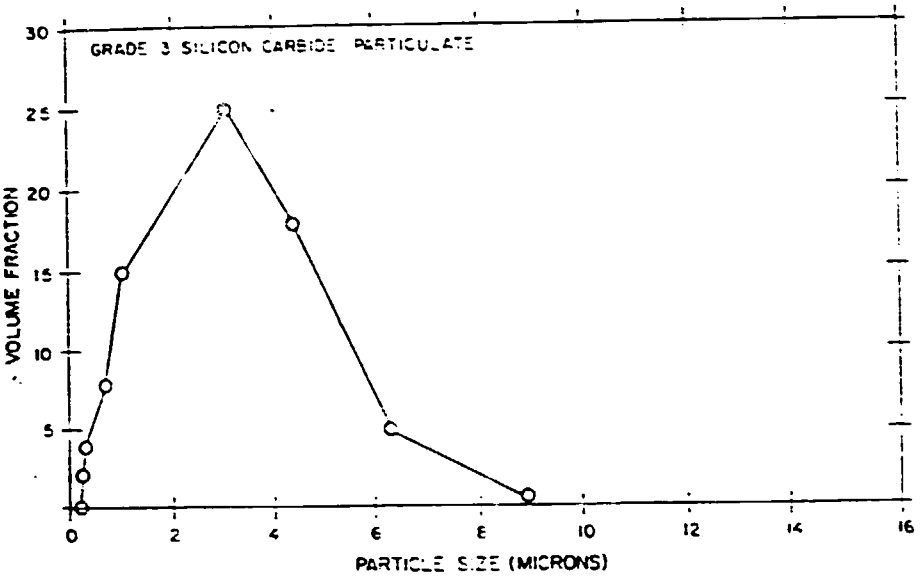


Figure 4. SiC particulate size distribution

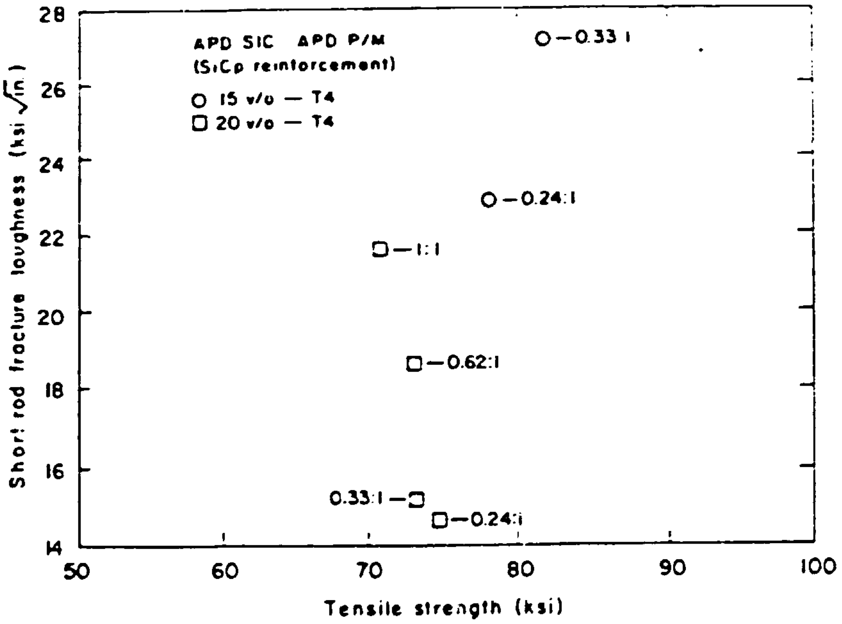
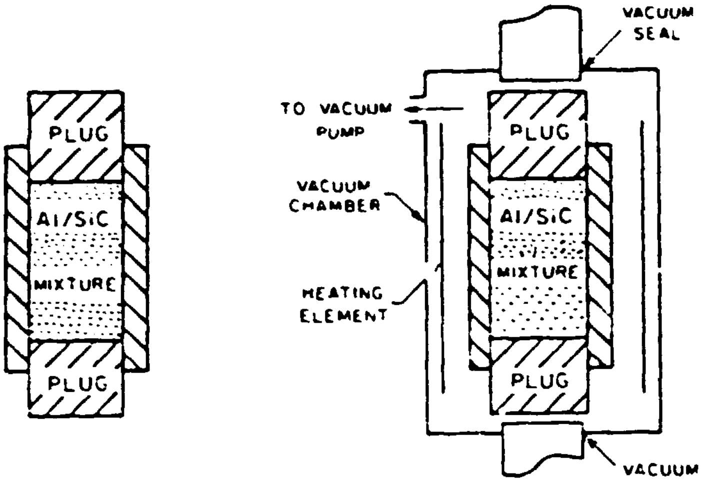
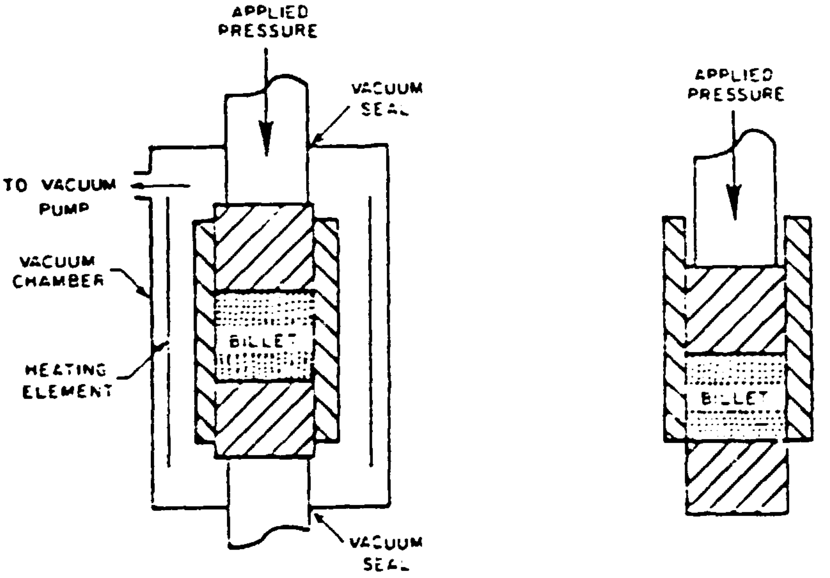


Figure 5. Influence of SiCp/Al size ratio on fracture toughness of MB78. APD: Average particle diameter



(a) LOAD POWDER INTO VHP DIE AND ASSEMBLE

(b) HEAT MIXTURE/DIE IN VACUUM, OUTGAS



(c) COMPACT INTO BILLET

(d) STRIP BILLET FROM DIE

Figure 6. Schematic representation of vacuum hot pressing

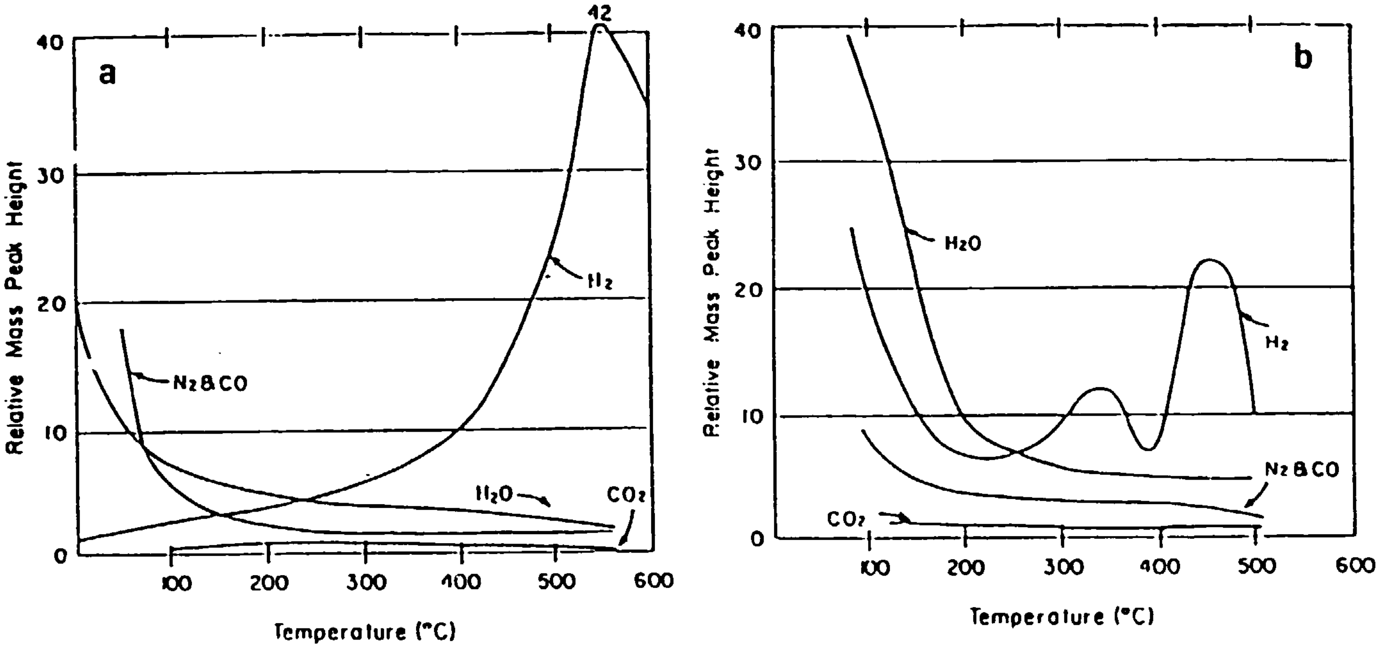


Figure 7. Residual gas analysis of outgassing reactions in (a) SiCp and (b) SiC_w reinforced 6061 aluminium

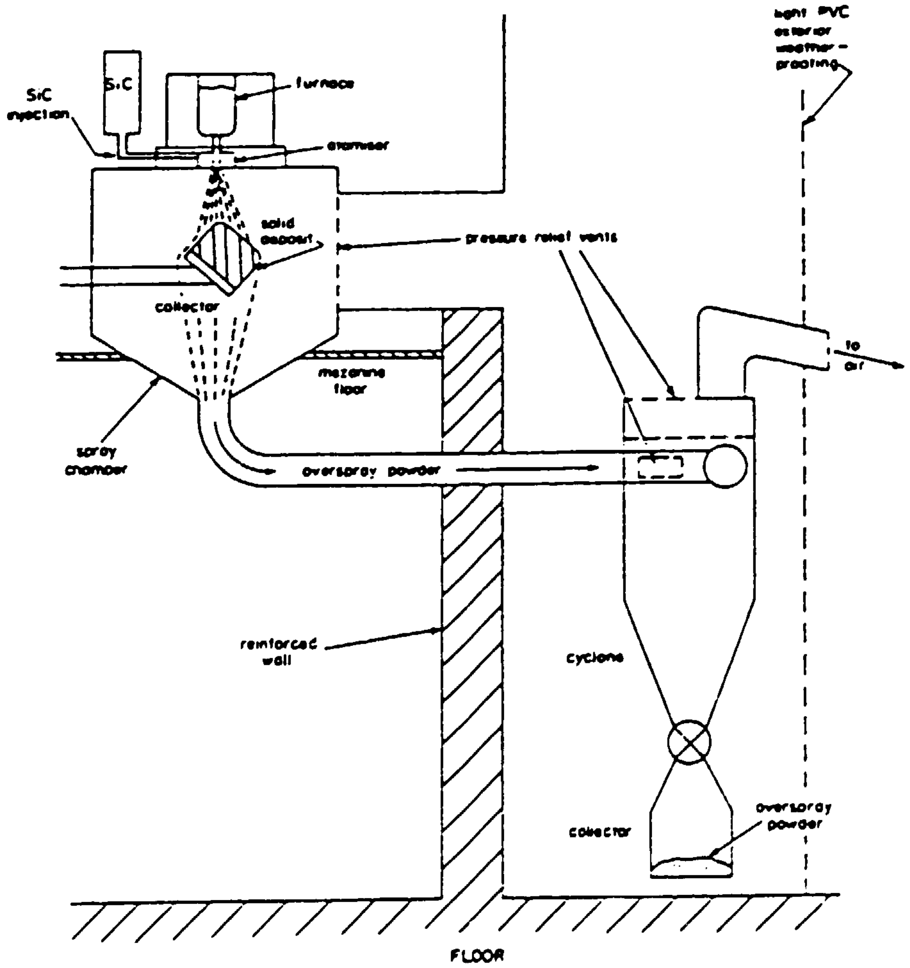


Figure 8. Schematic representation of Osprey process

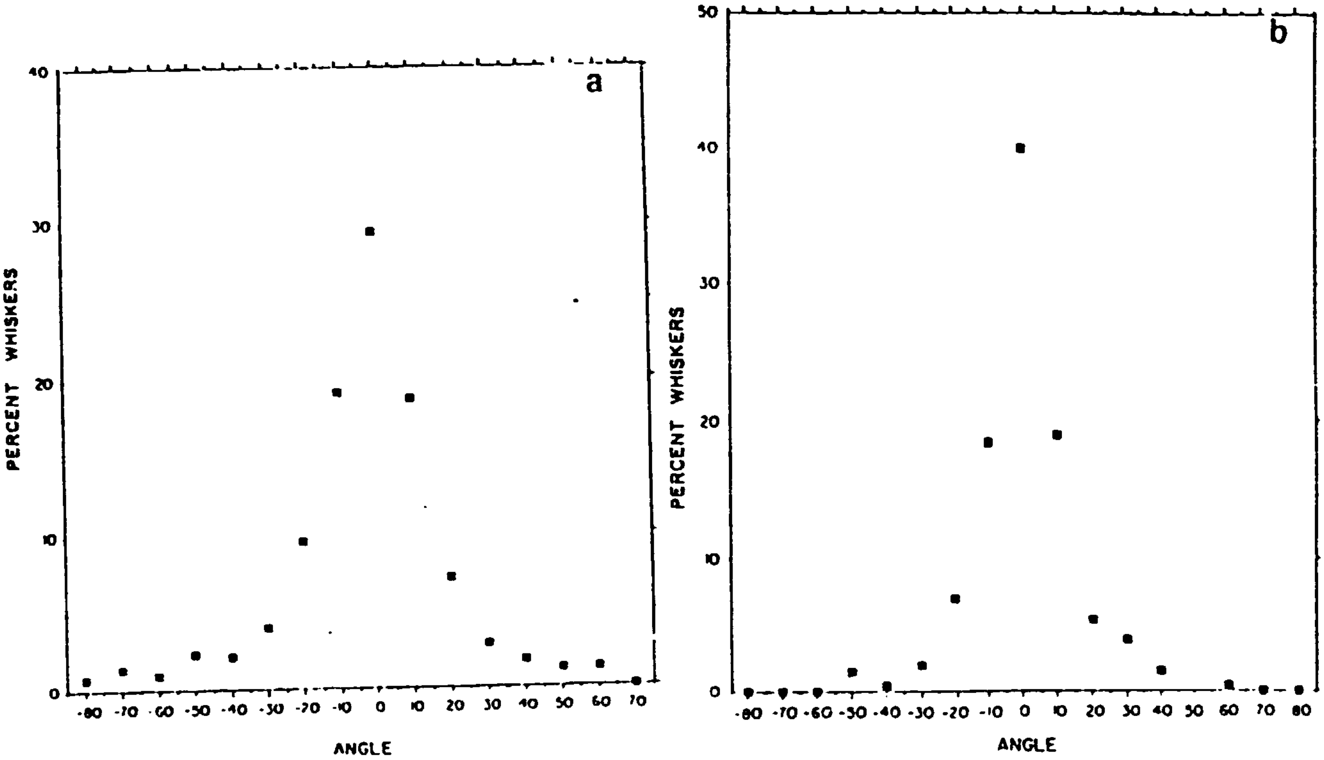


Figure 9. SiC whisker distribution in extruded 2124 reinforced with 20 volume per cent SiC whiskers (a) surface orientation plane and (b) through thickness orientation plane. Extrusion ratio 11:5:1

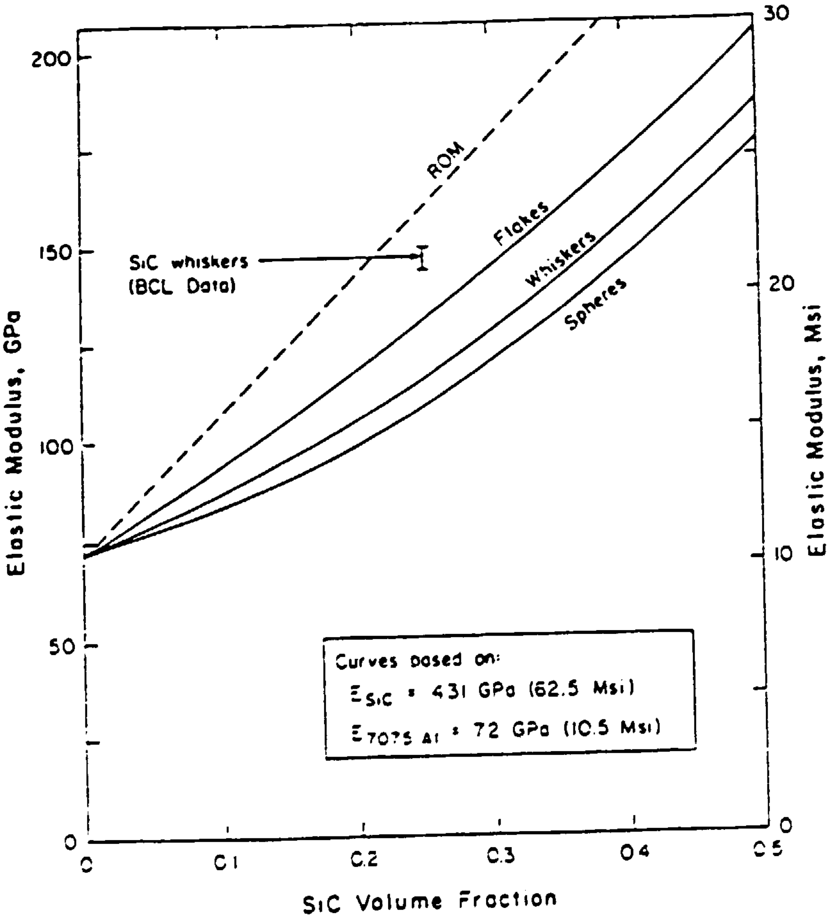
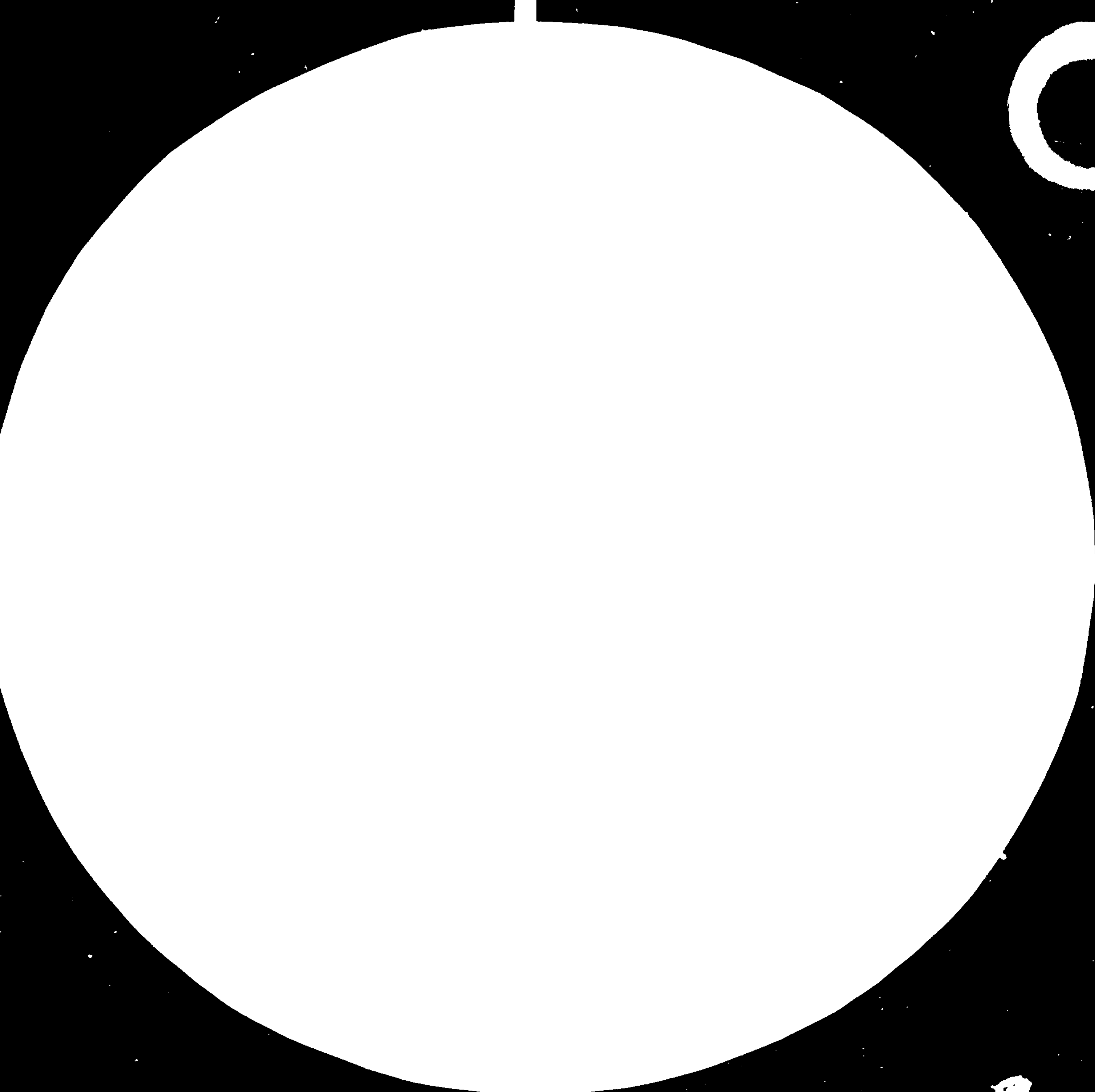
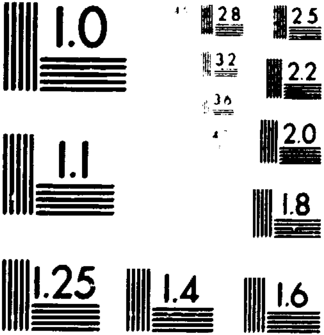


Figure 10. Elastic modulus of SiC reinforced aluminium alloys




1.0
4.5
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

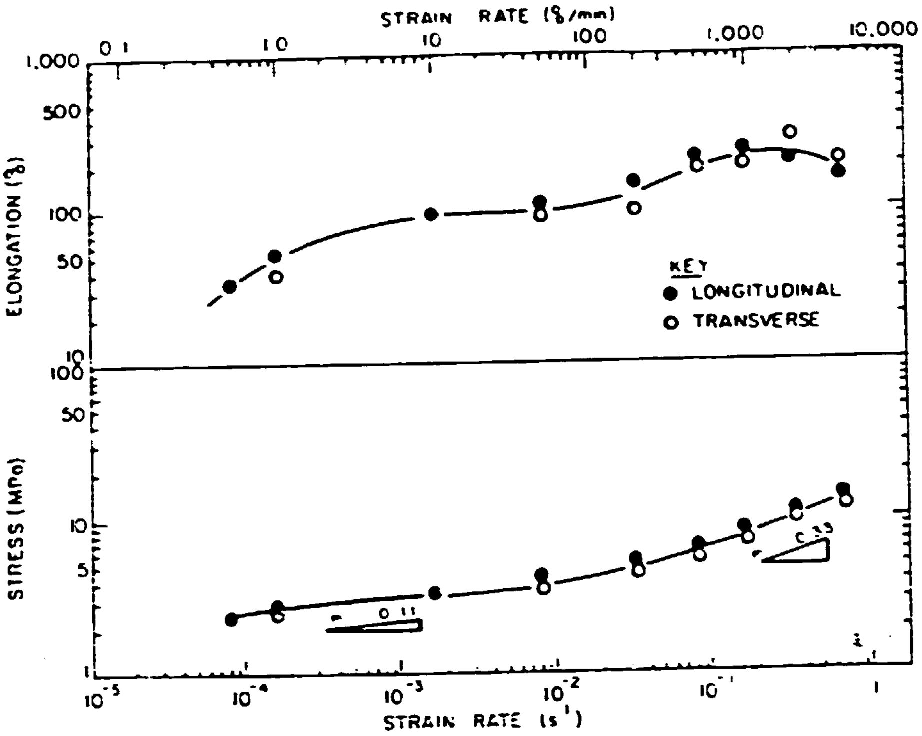


Figure 11. Elongation and flow stress as a function of strain rate for 2124 reinforced with 20 volume per cent SiC whiskers

6. MULTI FILAMENT, CONTINUOUS SiC FIBRE "NICALON" REINFORCED ALUMINIUM COMPOSITE WIRES

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Abstract

Multi-filament, continuous silicon carbide fibre NICALON produced from polycarbosilane, an organosilicon compound, possesses outstanding characteristics, such as high strength, high stiffness and high temperature stability.

NICALON is expected to be one of the best reinforcements for metal matrix composites (MMC). Now, under the MITI's project of Basic Technology for Future Industries, we have furthered research and development of a NICALON and aluminium composite wire, which can itself be fabricated into a metal-matrix composite, or can be used as the preform material for fabrication of metal-matrix composites by hot pressing, rolling and casting.

At the present, an approximately 100 metre long preform wire with a tensile strength of 1.5 GPa at room temperature and 1.35 GPa at high temperature (723 K) for pure aluminium matrix and 1.65 GPa both at room temperature and at 723 K for Al-5.7 wt% Ni eutectic alloy matrix, is available from a pilot plant.

On top of this, we have realized that this preform wire has other outstanding properties.

Therefore these result to exceed the project's targets of tensile strength 1.47 GPa at room temperature, and a heat resistant temperature of 723 K.

1. Introduction

The main commercial products of NICALON are supplied in the form of continuous yarn of 250 or 500 filaments by Nippon Carbon Co., Ltd.

Some typical properties of NICALON are shown in table 1. The single filament is very fine and flexible, which enables it to be made into cloth and other secondary products. It is also possible for it to be used for a composite material of various complicated forms. These characteristics of NICALON cannot be found in large diameter filaments made by chemical vapour deposition (CVD) such as boron and silicon carbide fibres. Different to SiC whiskers, NICALON is a continuous fibre, therefore, when used in composites, its strengthening efficiency is very high. And also, NICALON is said to be comparatively well compatible with aluminium. So it is expected to be one of the best reinforcing fibres for MMC and now being widely researched. But indeed though much expectation has been placed on fibre reinforced MMC materials the realistic progress on their development has hardly been satisfactory. This development faces many problems: in particular, the difficulty in developing an effective fabricating method of MMC with multi-filament continuous fibre.

In order to solve this problem, in Japan a national project has been carrying out development of the fabricating method for MMC under the management of the Research and Development Institute of Metals and Composites for Future Industries sponsored by the Agency of Industrial Science and Technology, MITI. The organization for MMC in the composite project is shown in figure 1. The targets for MMC, as shown in table 2 and figure 2, are tensile strength and high temperature resistance. In the MITI's project the fabricating method was characteristically divided into two parts: "composite-made process" and "forming process". Thus, in the former, a composite-made technology has been developed to produce the composite-made wire, called a Preform Wire, because a wire is regarded as the most basic material form. And in the latter, using this Preform Wire, a wide range of forming technology were incorporated to produce different forms of MMC products.

Concretely, one of the aims of the MITI's project was to develop the wire of an aluminium matrix composite using NICALON as a reinforcement.

The targets of the wire are a tensile strength of over 1.47 GPa at room temperature, and over 1.32 GPa at 723 K.

At the present, the targets have virtually been reached by Nippon Carbon Co. Ltd.

2. Experimental procedure

NICALON was used as the reinforcement, while either pure aluminium or an aluminium alloy was used as the matrix. The composition of the alloy was Al rich - Ni which is a unidirectionally solidified eutectic alloy, called "in-situ composite". The composite wires were continuously made by the liquid metal infiltration method. As can be seen from table 1, NICALON has a small filament diameter and there are 250 or 500 filaments in one yarn.

Therefore, when making a composite wire, it is necessary but hard to infiltrate the many fine gaps between the filaments with molten aluminium matrix. The manufacturing process, in short, involves treatment where the sizing agent of the fibre is removed; sufficient spacing between the filaments is made; the gaps are completely infiltrated with the molten matrix; then a yarn is pulled out continuously through a nozzle with a small hole; and finally, a yarn, that is already composite-made wire, is wound onto a drum.

Mechanical properties of the composite wires and the SiC fibres before and after the composite-made process were measured by tensile testing.

The microstructure of the wires and the exteriors of the extracted fibres were undertaken by scanning electron microscopy (SEM). Also the fracture surfaces and cross sections analysis of the wires were done by SEM.

Al - Al_3Ni eutectic phases in Al-5.7 wt% Ni matrix, was observed by SEM after etching.

Fibre volume fractions (Vf) of the wires were calculated by measuring the weight of the extracted fibres after the matrix was dissolved out. The tensile strength of the wires at high temperature were undertaken by means of the tensile tester equipped with an infrared quick heating furnace. Each test specimen was measured after being maintained in air for five minutes at the set temperature.

3. Results and discussions

3.1 Composite made state

Even though crowding of fibres is quite high, infiltration of the matrix into the gaps between the fibres is sufficient enough that no infiltrated parts between the fibres can be observed. Dendrite like voids, which are formed when the matrix solidifies and shrinks, were not detected.

The whole fracture surface was extremely irregular, and the pullout length of the fibres from the matrix was appropriately short.

This shows the high compatibility and moderate adhesive properties in the interfaces between the fibre and matrix.

The fracture aspects of the matrix showed large dimple patterns. On the other hand, the fracture aspects of fibres showed radial like sharp irregularities seen often in high strength MMC. As for an exterior observation of the extracted fibres, no visible change of fibre outside was shown before and after making the composite wires.

3.2 Tensile strength

For the production of a wire which showed improved tensile strength in the high Vf area, a straight fibre ([illegible] yarn) resulted in a higher ROM ratio.

Typical properties of the wire are shown in table 3. With Vf of about 50 per cent and a wire diameter of approximately 0.3 mmϕ, the wire had a tensile strength of 1.50 GPa and the ROM ratio was high about 0.9. Figure 5, the Weibull distribution, shows the reliability of this material.

Comparing with other typical structural materials, as is shown in table 4, the composite wires are lighter in density and superior in specific strength and specific modulus.

Concerning high temperature properties, as is shown in figure 6, even at 723 K decreases in strength due to high temperatures were slight, with a high strength of 1.35 GPa.

The values attained in the above results exceeded the original targets for MMC set up in the MITI's project.

3.3 High temperature tensile strength (at 723 K)

The composite wires with pure Al showed about 10 per cent decrease in strength at high temperature 723 K.

In order to clear up this decrease, the wires had undergone similar heat histories to those used in the high temperature tensile test (in other words, 723 K maintained for 5 minutes), and then the tensile strength was measured at room temperature. As can be seen in figure 7, there was no degradation in strength and the original strength was maintained.

Compared with the fracture surface of the wires which had undergone tensile tests at room temperature (A), the pull out of fibres from the matrix was much longer in the fracture surface of the wire tested at high temperature (B).

On the other hand, that wire which had the same heat history as (B), but had been returned to room temperature before tensile tests were carried out (C), had a very similar fracture surface to (A). It also maintained a similar strength to that of the wire at room temperature. By the way, the exterior features and strength of the extracted fibres did not differ in these fibres before and after heat treatment.

From the above, it could be deduced that the decrease in strength of the wire at high temperatures is not due to a decrease of the fibre strength caused by interface reactions between fibres and metal matrix at high temperature but due to a decrease in the stress propagation ability of fibre matrix interface caused by the softening of the metal matrix at high temperature.

Therefore, in order to increase the heat resistance of the matrix, a unidirectionally solidified eutectic alloy, Al-Al_3Ni type was chosen as the matrix. The results of this are shown in figure 8. At 723 K, no decrease in strength could be seen, meaning that the resulting NICALON-Al based composite wire has excellent heat resistance.

4. Conclusion

(1) Using the fine, continuous silicon carbide fibre NICALON as a reinforcing fibre, a composite material in the form of a wire could be continuously produced with a pure aluminium as a matrix by means of the liquid metal infiltration method. The composite-made state was very proper, and with an increase in the Vf, tensile strength also increased along with ROM. The wire length is over 100 m with a diameter of either 0.3 mmϕ or 0.5 mmϕ.

(2) This wire had a high strength of 1.50 GPa at Vf 50%, and the Weibull coefficient was highly 27. And it maintained 1.35 GPa even at 723 K. These results exceed the target values set up in the MMC development of MITI's project.

(3) Decreases in strength at high temperatures were interpreted to be due not to changes and degradations in the fibres themselves, but to the softening behaviour of the matrix at high temperatures. In order to increase the stability of heat resistance of the matrix, an *in situ* unidirectionally solidified eutectic alloy was used. The result provided a composite wire which showed no decreases in strength at high temperature 723 K.

That is, the tensile strength for Al-5.7 wt% Ni matrix, Vf 50% was 1.65 GPa both at room temperature and at 723 K. The structure of this type of matrix showed extremely fine fibrous forms of eutectic phases.

After all, the following conclusion could be made: The NICALON aluminium based composite wire has properties making it highly feasible as a preform material in forming high performance MMC. (Extracted from [illegible] International SAMPE (Society for the Advancement of Material and Process Engineering), [illegible], California, Technical Conference, [illegible] September 1988)

Table 1

Typical properties of silicon carbide continuous fibre Nicalon^R

PROPERTY	VALUE
FILAMENT DIAMETER	12, 15μmφ
CROSS SECTION	ROUND
FILAMENTS / YARN	250, 500
TEX	70, 200g/1,000m
DENSITY	2.55 g/cm³
TENSILE STRENGTH	2,500 ~ 3,000 MPa
TENSILE MODULUS	180 ~ 200 GPa
MAX USEABLE TEMPERATURE	1,250 °C
COEFFICIENT OF THERMAL EXPANSION	3.1×10^{-6}/°C

Table 2

Target for FRM (MMC)

(1) HEAT RESISTANT TEMPERATURE
723 K (450°C)
(2) TENSILE STRENGTH*
1.47 GPa (150kgf/mm²)

*[illegible]

Table 3

Properties of Nicalon^R-aluminium composite wire

PROPERTY	VALUE	
CROSS SECTION	ROUND	ROUND
DIAMETER	0.5mm	0.3mm
TEX COUNT	550g/1,000m	170g/1,000m
TENSILE STRENGTH	1,200MPa	1,500MPa
TENSILE MODULUS E_1 TENSILE MODULUS E_2	130GPa 80GPa	140GPa 85GPa
FIBER VOLUME FRACTION	45Vol%	50Vol%
MINIMUM LOOP DIAMETER	30mm	20mm

(MATRIX: PURE ALUMINUM)

Table 4

Characteristics of Nicalon composite wire and typical structural materials

MATERIALS	DENSITY g/cm³	TENSILE MODULUS GPa	TENSILE STRENGTH MPa	SPECIFIC STRENGTH 10⁶cm	SPECIFIC MODULUS 10⁸cm
AISI 4340	8.0	200	1760	2.2	2.5
Al 7475	2.7	70	570	2.1	2.6
Ti-6Al-4V	4.4	110	1290	2.9	2.5
INCO 718	8.2	210	1430	1.8	2.5
17-7 PH	[illegible]	200	1340	1.7	2.5
NICALON® AL Vf50%	2.6	140	1500	5.7	5.[illegible]
COMPOSITE WIRE Vf45%	2.6	130	1200	4.6	5.0

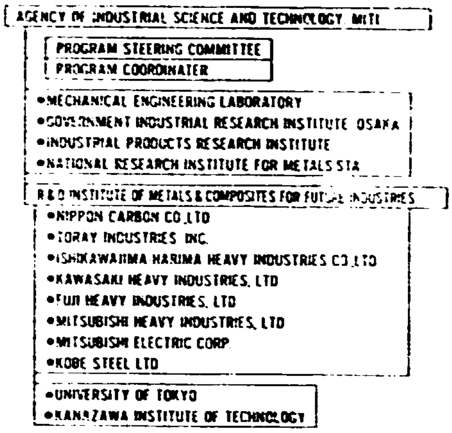

Figure 1. Joint FRM (MMC) basic industrial technology R&D team

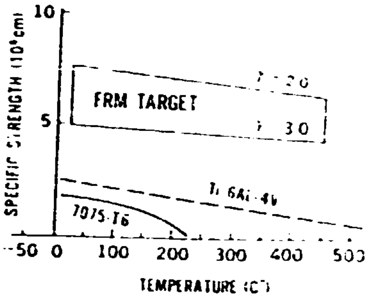

Figure 2. Target area on specific tensile strength versus temperature diagram

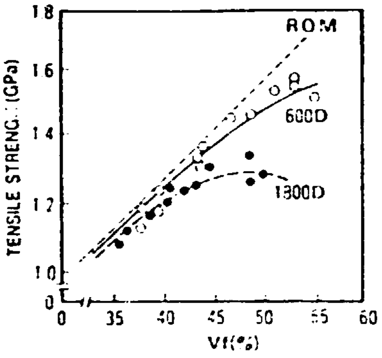

Figure 3. Wire tensile strength versus fibre volume fraction (600 D yarn is more straight than 1800 D)

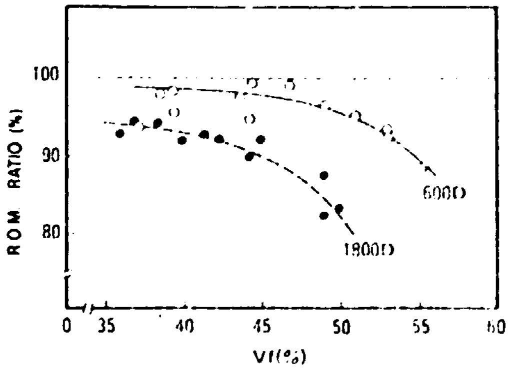

Figure 4. ROM ratio versus fibre volume fraction (600 D yarn is more straight than 1800 D)

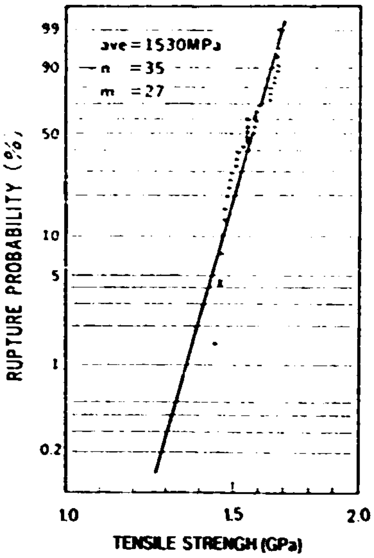

Figure 5. Weibull distribution of the tensile strength of Nicalon-aluminium composite wire

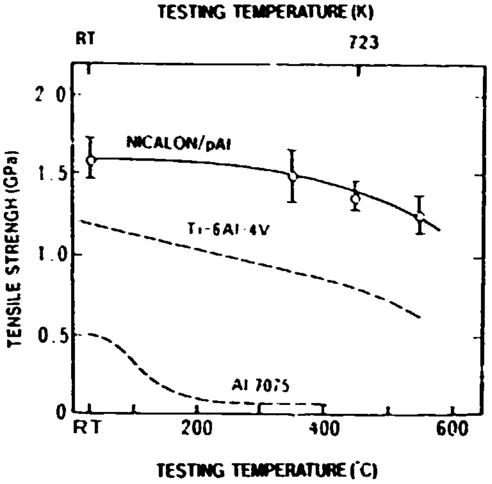

Figure 6. High temperature tensile strength of Nicalon-aluminium composite wire

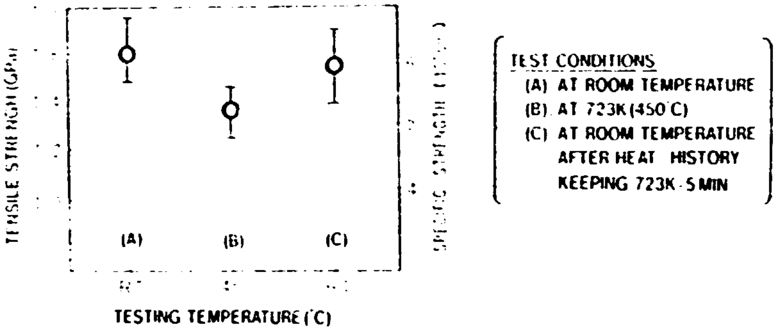

Figure 7. Tensile strength of Nicalon-aluminium composite wire at changed testing conditions

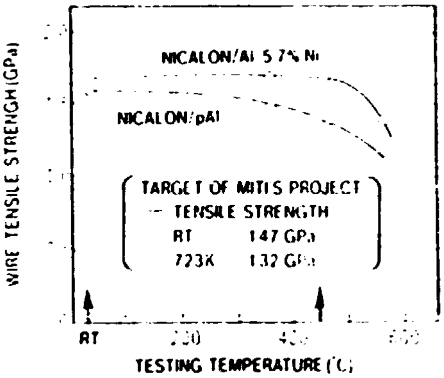

Figure 8. High temperature tensile strength of Nicalon-aluminium composite wire

7. COMPOCASTING AND SHAPE FORMING OF METAL MATRIX COMPOSITES

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Abstract

The influence of processing variables on the structure and porosity of rheocast and squeeze cast Al-4.5Cu alloy reinforced and unreinforced has been investigated experimentally. Two rheocast conditions have been considered: continuous cooling and isothermal stirring. Processing variables were varied as follows: stirring speed from 250 to 900 rpm, stirring temperature between liquidus and 640°C, isothermal stirring time from 0 to 40 min, and volume fraction of fibres from 0 to 20 per cent. The porosity content increases with increasing the stirring speed or the stirring time, but decreases with increasing the temperature.

The viscosity of these materials has been investigated using a rotational viscometer, and correlated with the processing parameters. The viscosity of the alloys and the composites increases with increasing the volume fraction of the solid phase or the fibre volume fraction, but decreases with increasing the shear rate.

An additional forming operation, e.g., squeeze casting, was used to solidify under pressure the alloys and the composites in order to decrease the porosity content. The microstructure of these materials showed the beneficial effect of the pressure on the structural refinement and homogeneity of the squeeze cast parts.

1. Introduction

The technique of rheocasting has been developed during the past few years, and published work is available providing basic fundamental and possibilities of application.

The rheocasting process consists of vigorously agitating a semi-solid alloy before casting so that the primary phase is non-dendritic giving a slurry with thixotropic properties and leading to a globular microstructure in the solidified alloy. During the stirring, fibres can be added to and retained by the melt regardless of wetting and without phenomena such as flocculation as it occurs when the alloy is completely liquid.

Combining fibre incorporation and rheocasting enhances the difficulties related to each of these two operations. The most important problem is the incorporation of gases within the semi-solid metal which lowers the mechanical performance of such materials. Furthermore, the relatively high viscosity of these slurries does not allow the use of conventional casting processes.

The aim of the present contribution is to determine the effect of the processing parameters during rheocasting on the porosity content in order to optimize the processing conditions. Viscosity measurements will allow us to determine when the different slurry are castable and how we can increase their fluidity. Finally, the squeeze casting technique is used to solidify and form under pressure the materials.

2. Porosity

Industrial processes for the manufacturing of metallic products are usually conducted in environments containing sources of hydrogen which can contaminate susceptible metals by gas absorption. The entrapped gases, even in trace quantities, usually generate unsound castings with mechanical weaknesses. For example, the presence of 1 per cent porosity in an Al-4.5Cu alloy leads to a 20 per cent decrease of its UTS. During the usual rheocasting procedure, the vortex which is generated by the stirrer facilitates the entrapment of gases in the slurry. This gas absorption is all the more important as fibres are added to the melt at the same time. So, an adequate control of the contamination (a porosity content below 0.75 per cent is necessary to obtain sound Al-4.5Cu castings) is of particular importance for the successful manufacturing operation.

Aluminium alloys which are cast by a conventional or rheocasting route retain all the dissolved hydrogen they may contain. But because the solubility of hydrogen is less in the solid than in the liquid aluminium, during solidification a part of the gases is expelled from the growing solid and is trapped in the adjacent liquid, generating two different types of porosities: matrix porosity and interdendritic porosity.

Porosity measurements have been carried out by using an image analysis technique on different specimens (reinforced and unreinforced) processed by rheocasting for different stirring speed, stirring time, temperature, and fibre volume fraction.

Figure 1 shows the evolution of the porosity content as a function of the stirring speed at different temperatures for the unreinforced alloy, in continuously cooling experiments. It appears that the higher the stirring speed the higher the porosity content, particularly above 500 rpm. Indeed, at high stirring speed, the vortex which is produced by the stirrer is so strong that it generates a turbulent flow leading to the entrapment of more and more gases. This effect is all the more important when the temperature of the slurry is low. In that case, the viscosity of the slurry is so high and the flow so turbulent that porosity content in the material increases exponentially.

In the case of isothermal steady state experiments, the results point out that the stirring time does not affect the porosity level for low stirring speeds (figure 2). However, when speed increases, the porosity content becomes strongly time dependent.

For aluminium alloy-alumina compounds, the porosity depends strongly on the volume fraction of reinforcement (figure 3): the higher the fibre content the more viscous the slurry favouring the entrapment of gases.

This effect becomes stronger at high speed because of a more severe vortex and a turbulent flow.

These different results clearly show that it will be difficult to stir the slurry at a sufficient speed (and shear rate) which allows the incorporation and the dispersion of the fibres without any important increase of the porosity.

Only compounds with low volume fraction processed at high temperature (645-650°C) will exhibit a good integrity after casting and solidification (porosity level below 0.75 per cent).

3. Viscosity

The rheocasting device previously described was used in this study to measure the apparent viscosity of the alloy with or without fibres.

The viscous torque T applied on the stirrer during continuous cooling was determined by measuring the current to the motor necessary to maintain its speed (and the shear rate).

Only continuously cooled experiments were carried out, leading to the following general observations.

The viscosity increases rapidly below the liquidus temperature of the alloy (650°C) according to different works reported in the literature. At the liquidus temperature, the apparent viscosity of the slurry is very low similar to the viscosity at casting temperature (some centipoise), as illustrated on figure 4.

As the temperature decreases and liquid alloy solidifies, the apparent viscosity increases slowly at first and exponentially as the volume fraction of solid becomes significant (above 0.20). Figure 5 also shows that at a given cooling rate, the viscosity decreases with increasing the shear rate or stirring speed.

At low solid volume fraction, the apparent viscosity is well described by the two first terms of the above equation while for solid volume fraction greater than 0.25-0.3 the last term becomes the major contributor to the apparent viscosity.

Figures 6 and 7 show that the presence of fibres within the aluminium alloy increases significantly the apparent viscosity of the compound whatever the temperature. It must be noted that the fibres were dispersed within the matrix and that the phenomenon of flocculation did not occur. Furthermore, increasing the shear rate leads to a same decrease of the apparent viscosity as for the unreinforced alloy. But in the case of reinforced alloys, this decrease occurs whatever the temperature, even above the liquidus point.

4. Forming

After stirring, the slurry is reheated when its temperature is too low and cast into the die cavity of a squeeze casting device. The punch is then lowered, it forms the part as it descends into the die cavity and finally holds the metal under high pressure until solidification is complete. The component is then removed from the die and the tooling is cleaned.

The structural refinement and homogeneity of the squeeze cast materials (solidified under a 60 MPa pressure) is evident and increases with the fibre content.

As in the case of compocast materials, the fibres are located in the interglobular spaces. During pressing fibres are oriented, and the resulting texture is transverse isotropic: fibres are randomly oriented in the planes perpendicular to the pressing direction, with no fibres in the pressing direction.

Furthermore, the quality of the materials are definitely improved since pressure closes the different porosities leading to sound materials.

5. Conclusions

The porosity of rheocast materials depends greatly on the stirring speed, the temperature of the slurry, the stirring time and the fibre content. It means that the manufacturing of aluminium matrix composites with a high volume fraction of fibres will lead to materials exhibiting a high porosity content. Furthermore, it has been shown that the viscosity of such compounds is very high but can be decreased by reducing the fibre aspect ratio or increasing the compound temperature just before casting. However, it is necessary to use a complementary technique such as squeeze casting to form the composite. This additional technique presents the advantage of decreasing the porosity content, leading to high integrity, close tolerance parts with a very fine microstructure. (Extracted from 33rd International SAMPE Symposium [Society for the Advancement of Material and Process Engineering, Covina, California], 7-10 March 1988)

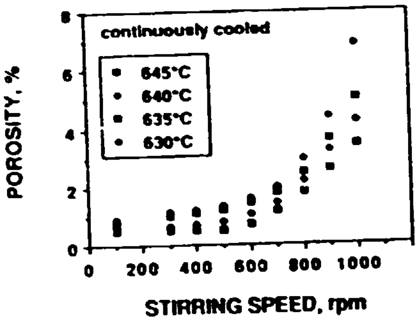


Figure 1. Effect of stirring speed and temperature on porosity content

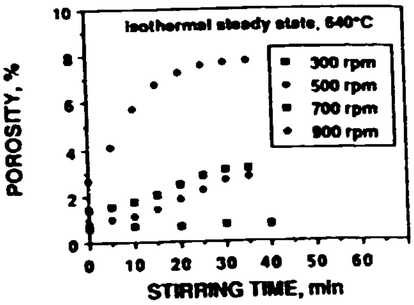


Figure 2. Effect of stirring time and speed on the porosity content

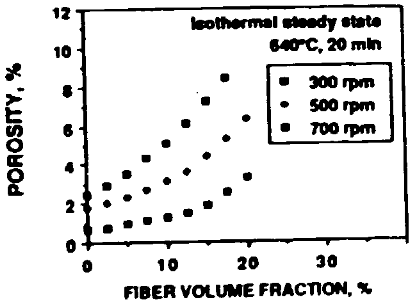


Figure 3. Effect of fibre volume fraction and stirring speed on porosity content

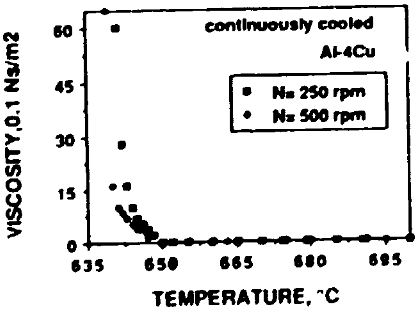


Figure 4. Effect of temperature and stirring speed on the apparent viscosity of Al-4.5Cu

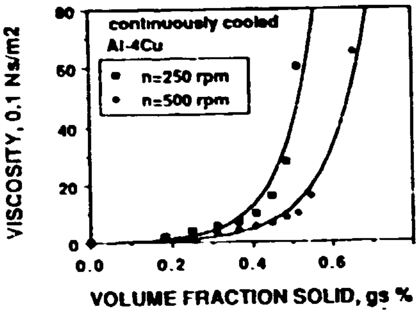


Figure 5. Effect of the volume fraction solid and the shear rate on the apparent viscosity of Al-4.5Cu

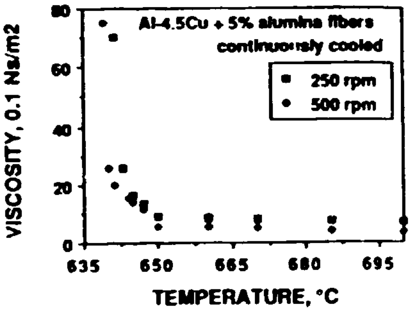


Figure 6. Effect of temperature and shear rate on the apparent viscosity of Al-4.5Cu + 5 per cent alumina fibres, L/d=500

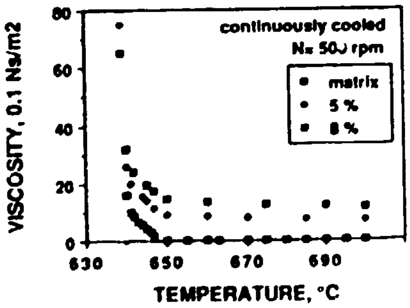


Figure 7. Effect of temperature and fibre volume fraction on the viscosity of Al-4.5Cu base composite, L/d=500

Recent advances in materials, designs and production technology bear evidence that the metallurgical R&D community has been busy lately.

Honeycomb and other sandwich composite structures are the highest strength to weight and stiffness to weight materials systems available today. These highly efficient composites, or laminates, consist of a core or in the case of honeycomb, a core structure bonded to outer skins. Typically, these materials are in the race to be selected for lightweight, basically two dimensional, structural applications.

On the other hand, metal matrix composites offer not only high strength to weight and stiffness to weight ratios, but also extremely good high temperature properties. These materials will be competitive for an impressive array of applications, ranging from airframe structures to internal combustion engine pistons.

Stronger aluminium honeycomb

Aluminium is a popular honeycomb core material. It provides a high strength to weight ratio and bonds readily to most skin materials. Unfortunately, when graphite is used in the skin material, as in graphite fibre reinforced composite skins, aluminium becomes susceptible to galvanic corrosion. Under prolonged exposure to heat and humidity, the aluminium core degrades (in 15 days or less) and fails at the skin core interface, unless the aluminium receives an anti corrosion coating.

A new technique, however, is to anodize the aluminium in phosphoric acid before coating it with the corrosion resistant primer. Offered as a new product by American Cyanamid, PAA Core honeycomb is said to be completely resistant to corrosion damage, but in addition, the pre treatment significantly strengthens the adhesive bonding of the core and between the core and skin. The interface bond is more than triple that of the bond between untreated aluminium. And the bond does not fail after three months' exposure to heat and humidity, since the coating and treatment protect the aluminium from galvanic damage from electrolyte fluids that are created between the metal and the graphite in the composite skin.

A third ingredient in many honeycomb systems is filler a foamed polymer or glass fibre reinforced polymer in the cells. Hydrophobic polyimide foams are now used to help reduce corrosion, since these materials discourage water build up within the cells. A typical material, Hexcel's Airlite 600 closed cell polyimide, provides less than 3 per cent moisture pickup by weight at 60°C (140°F) and 98 per cent relative humidity. Polyimide foam also is specified because it is non flammable, generates little smoke, and can withstand up to 260°C (500°F) continuous service. Polyimides also provide good thermal insulation.

Glass fibre reinforced resins for filler material are now being used for sound absorption, especially important for honeycomb used in paneling applications such as aircraft. Aramid foam is used to reduce smoke generation and to reduce thermal conductivity.

Unique honeycomb applications

In addition to the obvious and well documented structural applications for laminates and honeycomb, a number of unusual applications, based on secondary characteristics or properties, have emerged. For example, cores are filled with fibreglass or a batting material and the resulting composite can be used to deaden sound or vibration. In one application, the skin on one side of a panel contains small holes through which sound enters and is absorbed by the batting in honeycomb cells. These panels are used to reduce noise in aircraft and around engines.

Metal composites also are being used to provide electromagnetic and radio frequency interference (EMI, RFI) shielding of large enclosures and even buildings. Cells can be "tuned" by adjusting their size and length to attenuate a specific wave energy level. For example, in a hexagonal honeycomb, if the cell width (measured across the hexagon) equals the cell length (measured between the inner surfaces of the skins), attenuation is 40 db. For a cell four times as long as its width, attenuation is nearly 110 db. A housing for computers or sensitive controls that requires some load bearing capabilities as well would be an ideal application for these materials. Metallic laminates and honeycomb conduct heat, and thereby can be used in applications where insulation is not desired. Cellular cores contain air, so heat conduction can be by radiation and convection as well as conduction through the metal in the core. In applications where stability and resistance to buckling must be maintained in the presence of temperature differentials, metallic panels made of these materials will attain thermal equilibrium on both skins and they will not bend or deform from varying amounts of thermal expansion. In addition, these materials can be specified in applications where heat transmission is required.

On the other hand, polymer laminates and honeycomb can be used for the opposite application: insulation. With cells filled with insulating batting, an aramid reinforced honeycomb panel offers thermal conductivity as low as 0.056 W m.K (0.4 Btu in. hr ft^2 °F.

Structural laminates

Aramid Aluminium Laminates, or ARALL, represent a new family of hybrid structural composite systems that provide a combination of extremely light weight with high fatigue and fracture resistance far better fatigue resistance than solid aluminium. Under commercialization by Alcoa, the composite basically consists of thin sheets of aluminium bonded with adhesive impregnated aramid fibres.

While many varieties of the composite are possible, the first generation version consists of three sheets of 0.3 mm thick (0.012 in) 7075 T6 aluminium alternating with two layers of unidirectional aramid fibres mixed with epoxy adhesive in a 50:50 ratio by weight. The fibres are oriented in the rolling direction of the aluminium sheet. With an overall thickness of 1.3 mm (0.051 in.) the material has a density of 2.29 g cm^3 (0.083 lb in.^{3}), 18 per cent lower than an equivalent solid sheet of 7075 T6 aluminium.

The aramid fibres are credited for many of the laminate's appealing properties. Fracture strength is high, for instance, because stresses at the tips of cracks that initiated in the metal as a result of fatigue (cyclic loading) are transferred from the metal to the stronger fibres where they are arrested. Alcoa is working with laminates of tougher aluminium grades such as 2024 T3 and 7475 T6 to obtain higher fracture strengths. In addition, versions with cross ply fibre orientations have been proposed to improve impact energy absorption.

In many ways, this hybrid material behaves like fibre-reinforced polymer matrix composites. Many of the properties are directional, based on fibre orientation. Tensile strength, for example, is very directional, ranging from about 760 MPa (110,000 psi) in the longitudinal direction to 380 MPa (55,000 psi) in the transverse direction for ultimate tensile strength and 650 MPa (94,000 psi) longitudinal and 324 MPa (47,000 psi) transverse for yield strength. Compressive yield strength, however, is around 370 MPa (54,000 psi) regardless of direction.

These properties can be compared with 572 MPa (83,000 psi) ultimate, 510 MPa (74,000 psi) tensile, and 503 MPa (73,000 psi) compressive strength for solid 7075-T6. The properties of the laminate are said to remain stable over a temperature range of -34 to +82°C (-30 to +180°F) under a variety of conditions such as high humidity, salt spray, and thermal cycling. Weight gain due to moisture is negligible.

Tested in the fibre direction, the ARALL composites offer fatigue strength nearly 30 per cent above that of solid 7075 T6 aluminium. In the transverse direction, stresses are comparable but the lifetime for the composites is shorter, since the fibres provide little or no reinforcement in this direction. Compressive residual stresses can be added to the material by prestraining, thereby increasing the stresses required for crack initiation and further improvement of fatigue strength.

And they work like metals

These laminates are in the same league with carbon-fibre and similar advanced high-strength, lightweight composites. However, with metal as a major constituency, ARALL laminates offer a number of advantages. For example, they can be inspected by traditional techniques, since many forms of damage would be revealed in the form of plastic deformation of the outer plastic layers.

Thanks to their metal content, the laminates can be formed at any time during their life cycle, unlike thermoset-polymer matrix materials that are rigid after curing. Therefore, they can be fabricated by most metalworking techniques, including stamping and machining. They can be assembled with fasteners. The outer metal surfaces provide typical metallic properties such as electrical conductivity, lightning protection, reflectivity, and moisture resistance. The laminates significantly outperform conventional carbon fibre/epoxy composites in impact resistance.

The laminates also offer good sound and vibration damping, exceeding that of solid metal by a factor of two to three. Damping is about one third less across fibres than longitudinally.

Cast metal-matrix composites

A trend in metal matrix composites (MMCs) has been to develop short, whisker reinforced composites and particulate-reinforced composites in part because these materials are easier (and therefore cheaper) to process than composites containing continuous or long fibres. Two production techniques are receiving most attention today: casting and powder metallurgy. The latter, PM, is the simplest way to ensure good distribution of reinforcement within the matrix. Casting, on the other hand, is lower in cost, although at a sacrifice of some properties due to uneven dispersion of reinforcement caused by gravity and other factors during solidification. Consequently, much research is being devoted to improving properties of cast MMCs.

One interesting study at the Regional Research Laboratory, Trivandrum, India, revealed that a simple remelting and stirring of the material after initial casting significantly improves distribution of the whiskers or particulates. The phenomenon has been credited to improved wettability of the dispersoids during remelting.

This finding could have strong implications. For example, it may be possible to prepare composite ingots, much as we now do for monolithic master metals and alloys, to be provided to "foundries" for casting to final shape. Researchers also report that this concept could be extended to preparing composites highly concentrated with reinforcement to be "diluted" at the foundry before casting. Stirring, however, is critical. Blade shape, mixing time, atmosphere, and mixing speed are all important variables.

The remelting technique has been studied with aluminium matrices reinforced with graphite (up to 6 wt per cent), zirconia (up to 10 wt per cent), glass (2-10 wt per cent), and forms of coconut shell (up to 8 wt per cent) and fly ash (2.5 to 10 wt per cent). These materials have been permanent mould cast, centrifugally cast, pressure die cast, and rheocast after remelting and stirring with significant improvement in distribution of the dispersoids. Aluminium (Al-12.5Si) reinforced with 3 per cent graphite particulate bearings prepared by this technique are now in service, proving to be far more wear resistant than monolithic alloys.

Particulate glass reinforced Al-3Mg, remelted, pressure cast, and subsequently hot rolled, hot forged, or hot extruded, showed strength improvements of over 300 per cent without loss of ductility. The glass (15 wt per cent, 20-40 μm) served as a lubricant during hot working. Tensile strength of particulate fly ash reinforced hot extruded parts (5 wt per cent fly ash in 7075 Al matrix) also can be improved by hot working at some loss of ductility. Both of these MMCs are reported to have high potential for structural applications.

Long fibre reinforced MMCs also are the object of investigation. One Du Pont study is aimed at developing cast Al Li and magnesium alloys reinforced with the company's alumina long "Fibre FP". Materials and manufacturing techniques were investigated with an eye towards producing automotive engine connecting rods. Rods were cast by vacuum infiltration into a mould containing a fibre preform that placed the fibres in proper orientation. In some instances, the fibres were filament wound using wax as binder. In the mould, the molten metal is directionally solidified. For aluminium matrix composites, lithium at 1.8 to 2.2 wt per cent was found to provide best fibre wetting. Magnesium naturally wets the fibre and is another ideal material for this process.

The researchers developed a kinematic model based on finite element stress analysis for the design of connecting rods made from these materials. Prototype aluminium MMC rods containing 50 to 55 per cent Fibre FP have survived over 10 million simulated cycles. They weigh half as much as forged steel rods, with greater modulus in the longitudinal, or fibre, direction.

PM metal matrix composites

The powder metallurgy route to producing parts made from MMCs can be used to create materials with highly useful characteristics. One study, jointly by Hindustan Aeronautics Ltd., India and Laval University, Quebec, has produced a superplastic aluminium matrix composite. The Zr refined matrix alloy is Al [illegible] [illegible] reinforced with either [illegible] 15 vol per cent [illegible] particulate [illegible]. The material is hot pressed, then given a thermomechanical treatment to produce a fine grained structure.

At high [illegible] rates [illegible] 10^{-4} per [illegible] elongation to fracture exceeds 200 per cent, compared to [illegible] per cent for a conventionally formed alloy. Specific strength and modulus of the MMC are comparable to those of [illegible] unreinforced alloys. The researchers anticipate that after further development, these MMC's will be applicable for intricately shaped parts requiring high strength and stiffness and, where necessary, good wear resistance, thanks to the presence of SiC.

Ceramic reinforced MMC's have always presented machining problems. While much research is devoted to eliminate this step by perfecting near net shape production techniques, for example, the machine tool industry is trying to develop methods to improve machinability. Cleveland Twist Drill, Div. Acme Cleveland, has compiled guidelines that can produce high production rates with conventional machine tools.

Working with aluminium matrix alumina fibre reinforced composites, the machine tool manufacturer recommends drilling at 305 surface m/min ([illegible] sfm) at 0.3 mm/rev (0.012 in./rev) with solid carbide helix drills, which outperform more expensive diamond tool materials. Turning and milling should be with C-2 carbide, or ceramic coated carbide inserts at the highest feed rate possible that produces an acceptable finish. Tools should be ground with large nose radii or should be round inserts for improved surface finish. Oil coolant is not recommended; chips should be blown away with air.

Sandwich basics

Structural sandwiches or laminates consist of a core of either a solid material or a corrugated structure bonded between thin skins. The corrugated core is frequently filled with another lightweight material for added strength.

Two basic corrugated structures include the sinusoidal core and the "hat" core. In some cases, layers of core material are stacked and bonded together to form more complex cellular structures such as honeycomb. Adhesive bonding is most common, although some metal cores are welded or brazed. In producing structures from flat sheet, adhesive is applied to adjoining surfaces in strips, and then the stack of laminates is stretched into an open cellular structure by pulling the plies apart.

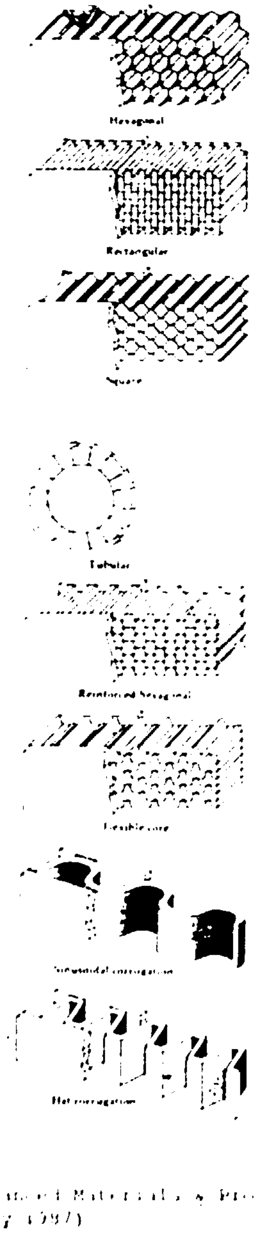
Cell structures vary, the most common being the "true" hexagonal honeycomb. For these, cells typically range from 1.5 to 25.5 mm across (0.06 to 1.00 in.).

The basic honeycomb structure is difficult to form into complex shapes or contours. However, over expanding the plies to stretch the hexagonal cells into rectangles produces a variation on the honeycomb core that is more easily formed, but at the sacrifice of some shear properties. Other variations include the reinforced hexagonal core, in which a flat sheet is inserted in the structure for added strength, but with an added weight penalty; the square cell structure, usually produced by welding; and the tube structure, produced from a corrugated sheet bonded to a flat sheet and wrapped around a mandrel. A number of proprietary variations have been introduced, including the flexible core design from Hexcel that is said to be extremely flexible and capable of being formed into compound curvatures and tight corners without buckling.

Just about any material can be used for laminated composites. Metals commonly used include stainless steel, titanium, nickel alloys, and aluminium. The most common and lowest cost materials are made from [illegible] series aluminium alloys. The [illegible] series aluminium is also common, used [illegible] in naval structures, while [illegible] is used in more critical aerospace applications. [illegible] is a higher strength version of [illegible]. For strength at high temperature service, [illegible] is specified.

Reinforced plastics are also used, particularly for honeycomb. Aramid reinforced epoxy, phenolic, and polyimide cores are being introduced. These materials offer low coefficient of thermal expansion and good electrical and thermal insulation. Glass fibre reinforced phenolics are now specified for heat resistance, while some carbon fibre reinforced resins match the strength of metal core honeycomb.

Density varies with material selection, of course, ranging typically from 16 to 880 kg/m^3 (1 to 55 lb/ft^3).



(Source: Advanced Materials & Processes inc. Metal Progress, July 1987)

9. STRUCTURE MODELLING AND THE NON DESTRUCTIVE EVALUATION OF METAL MATRIX COMPOSITES

By W. [illegible] and [illegible]*

Introduction

Experimental modelling has long been an integral part of non destructive evaluation (NDE) technology. In the earliest applications, drilled holes were used to model void like defects. Even today, this approach is often used to create standards for test system calibration. More recently, attention has focused on modelling defect type, size, and orientation in an attempt to establish more quantitative inspection capabilities. Despite successes to date, defect modelling alone cannot address all the aspects associated with the development of a rational inspection procedure. An area of particular concern is the potential impact of material structure on inspection performance. Any good NDE procedure must be able to distinguish between relevant and non-relevant indications. If the signal to noise ratio (SNR) for a particular combination of material and inspection is too small, an alternate test must be developed. In the past, coarse grain materials and "as cast" structures, in particular, presented SNR problems for conventional inspection procedures. Today, nearly all advanced composite materials present similar problems.

The very concept that makes composite materials attractive for engineering applications poses a significant limitation to the creation of rational inspection procedures. The combination of two or more materials with distinctly different physical properties (ceramics in metals, inorganics in organics, etc.) almost always provide poor SNR performance in an NDE assessment. This observation, combined with the fact that well established, defect sensitivity rules do not exist for composite materials, complicates the development of inspection methods necessary to ensure serviceability.

An empirical yet rational approach to the development of inspection capabilities for composite materials involves the adaptation of the defect modelling concept as widely applied to monolithic materials. However, because of the large number of structure variables associated with a given composite system, the number of test samples required can be exorbitant. Unlike most monolithic-material systems, very subtle changes in composite composition and processing can have a significant impact on both material properties and inspection results. Consequently, the selection and qualification of material samples for use in assessing inspectability becomes a major effort. An alternate approach, which offers a cost advantage, involves experimental modelling of the material structure.

This paper describes a number of experimental structure modelling techniques designed to expedite the assessment of a variety of non destructive evaluation methods as they apply to the SiC reinforced aluminium metal matrix composite system. Powder metallurgy and liquid mercury models are discussed.

Modelling Strategy

Many [illegible] and [illegible] interact to [illegible] the [illegible] metal matrix composites. Matrix [illegible], reinforcement type [illegible], size, [illegible] distribution, interface [illegible], [illegible] of powder metallurgy, and [illegible] are only some of the variables that must be considered. In the work reported here, the target system is SiC reinforced aluminium manufactured with [illegible] powders and powder metallurgy techniques [illegible] pressing, sintering and extrusion. A limited amount of work [illegible] to explore the feasibility of structure modelling techniques for cast composites is also included.

Within the realm of powder metal processing of composite fabrication, all of the above variables, plus others such as blending, particle coating, density, lubricants, etc., must be considered for structure modelling. In addition, a critical parameter that must be addressed is the inspection point. Before modelling, decisions must be made as to whether the modelling is intended to represent final product, projected service life conditions, or some reasonable in process point of inspection. Finally, structure modelling options must consider the applicable inspection methods. For example, liquid metal models cannot be used effectively for ultrasonic testing because the liquids cannot support the shear waves that would exist in a solid.

Consideration of processing variables, inspection points, and potential inspection methods were involved in the creation of the structure modelling strategy developed for this programme. Figure 1 illustrates the overall scope of the programme and the specific variables under consideration. Note that the programme was designed to include a number of inspection points, starting with the characterization of raw materials and proceeding through to extruded plate. The majority of NDE was conducted with eddy current methods, but both ultrasonic and radiographic techniques were explored. The compositional and processing variables investigated were selected to represent rational options for the fabrication of commercial material.

Powder models

Figure 2 illustrates the simple powder material model used in this programme. Aluminium, SiC, and selected mixtures of aluminium and SiC powders were placed in glass vials and evaluated in the dry powder, tap density condition. As shown in Figure 2, both an encircling coil and surface riding pancake coil eddy current test were used to characterize the powder samples. Eddy current data were gathered through the glass vials and the results evaluated against powder condition and composition. The specific variables examined with the dry powder model included aluminium alloy composition, SiC particle size, particle type (fibre vs. particulate), and various mixtures of aluminium plus SiC. The powder model tests were limited to eddy current evaluations. All data were collected using conventional eddy current flaw detection instrumentation (NORTEC NDT 25) and test probes. In essentially all cases, the instrumentation was balanced to reflect variations in response as

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changes in signal amplitude (horizontal amplitude). Instrument gain, test frequency, and probe size were the primary test variables.

Figure 3 shows the variation in eddy current signature associated with different prealloyed aluminium powders of essentially the same average particle size (17μm) and tap density. Note the significant variation in eddy current response with alloy type. The signal differential was the same for both the encircling and pancake probes; however, less instrument gain was required with the encircling probe.

Figure 4 shows the eddy current response for SiC powder as a function of average particle size. Note that the eddy current response, although of relatively low magnitude, does illustrate a positive correlation with increasing average particle size. These data were generated at 1 MHz under tap density conditions with an encircling coil.

Figure 5 illustrates the impact of powder-mixing on the eddy current response. In this case, SiC particles were blended with pure aluminium powder to create a model representing various degrees of reinforcement loading. Note that as the volume fraction of SiC increases, the eddy current response decreases. These data were generated at 5 MHz, with the eddy current response from 100 per cent SiC powder set at zero. Note that the inverse correlation between eddy current response and reinforcement loading is essentially linear.

Pressed powder models

A pressed-powder sample was manufactured in the form of a three-dimensional rectangular plate to expand the modelling capabilities with powder metallurgy techniques. Specifically, pressing (and sintering) the powder models permits the assessment of the role of density on NDE response. In addition, increasing the density above the 50 per cent typical of tap conditions makes it convenient to implement ultrasonic test procedures. Tests with the dry-powder models were limited to eddy current procedures, but the pressed-powder models were examined with ultrasonic and X radiographic tests as well. The ultrasonic tests were conducted with conventional flaw-detection instrumentation (Panametrics Model 5052/Tektronics Model R5403 system) and special dry-coupled transducers (Ultran KD25-2X). The dry-coupled probes do not require a liquid couplant and, therefore, eliminate problems in cases where a couplant can be absorbed into porous test material. Ultrasonic velocity measurements were used to characterize the pressed powder models.

Figure 6 shows the variation in ultrasonic velocity for 2024 aluminium powder compacts pressed to different densities (expressed as per cent of theoretical density - 2.77 g/cm^3). Note the direct correlation between velocity and per cent theoretical density. Figure 7 presents eddy current data (signal amplitude in volts) generated with the same 2024 aluminium compacts. Again, an excellent correlation exists between NDE response and powder-model density.

Figure 8 shows the variation in ultrasonic velocity as a function of SiC volume fraction in 2024 aluminium samples pressed to 87 per cent of theoretical density. Clearly, as the volume fraction of SiC increases, the ultrasonic velocity in the green compact decreases.

Figure 9 presents the eddy current test results generated with the various volume-fraction samples. Note that the eddy current results show an abrupt decrease in signal amplitude between 10 and 15 per cent loading and a plateau response up to 40 per cent SiC. When SiC whiskers (1-3 by 30-50μm) are blended with the aluminium powder in place of the SiC particles, the eddy current response is altered as shown in figure 10. The eddy current response plateau has shifted from 15 to 25 per cent loading. At volume fractions above the plateau, the whisker-reinforced models exhibit a higher eddy current response than do the particulate-reinforced models. Radiographic examination of the pressed-powder samples showed that the X-ray film density (measured with a densitometer) correlated with the compact density. However, the per cent SiC loading (whiskers or particles) could not be revealed by the radiographic results. This behaviour is not unexpected because both aluminium and SiC have about the same X-ray absorption properties.

Liquid mercury models

Figure 11 illustrates the liquid mercury model used to replicate particulate-reinforced metal-matrix composites. This modelling procedure was developed to address concerns for the assessment of matrix-to-reinforcement interfaces. More specifically, this model was created to expedite the eddy current characterization of composites prepared with molten-metal techniques (infiltration, compocasting, etc.). Figure 12 presents the results of a number of experiments in which brass and glass spheres were placed in a liquid mercury pool and eddy current measurements made as shown in figure 11. Although the spheres float on mercury, loading in a plastic container produces a uniform surface of close-packed spheres with liquid mercury filling all void spaces. Consequently, the model represents a conducting-matrix system with either conducting or nonconducting reinforcement particles. To expand the modelling capabilities, the brass spheres were used with and without an insulating plastic coating. This option permitted the evaluation of particle-to-matrix continuity. Figure 12 clearly shows a significant variation in eddy current response (signal amplitude) as a function of model configuration. Note that, because of frequency, probe size, and penetration interactions, the mercury model in figure 11 represents a realistic composite microstructure at a test frequency of 8 kHz. Further description of the mercury model and its capabilities as an experimental approach to eddy current analysis is presented elsewhere. Note that, by altering the sphere material and size as well as coating options, a nearly infinite number of composite-material structures can be modelled. Other conducting liquids and reinforcement structures can be used to change the conductivity and permeability of the matrix model.

Discussion

The simple models created and examined in this investigation clearly demonstrate the significant impact that subtle changes in structure can have on the NDE response of metal-matrix composites. In addition, this work has shown that, under controlled conditions, existing NDE techniques can be used to characterize the composite structure itself. Consequently, experimental modelling can be used to identify important parameters that can affect inspectability and, at the same time, provide guidelines for selecting and improving inspection procedures.

The dry powder, tap density models, although not truly representative of final products, can be used to establish trends for eddy current testing. The variation in baseline eddy current response with aluminium alloy (figure 3) is an important observation that represents behaviour encountered in wrought aluminium products. Specifically, different aluminium alloys exhibit different eddy current signatures. The fact that blended powder samples (aluminium plus SiC) produce eddy current results that correlate with the blend ratio is an important discovery with quality control possibilities. The variation in eddy current response with SiC particle size is an interesting observation that has not yet been traced to final product response. However, it is reasonable to expect that particle size will influence eddy current response in pressed powder composites. The limited powder-modelling work conducted in this programme shows that matrix composition, reinforcement loading, and particle size can have an important influence on the baseline eddy current response of SiC-reinforced aluminium composites. These results reflect behaviour that provides guidelines for inspectability concerns, but the most valuable aspect of the raw-powder modelling is the demonstrated potential for in-process NDE as a tool for manufacturing control. The data generated here show that conventional eddy current inspection procedures can be used to characterize and qualify important powder-material parameters. The ultimate correlation of powder parameters with final-product performance will provide the basis for eddy current acceptance criteria that can be implemented at the raw powder selection and blending stages of manufacture. Rational process control at these early stages of fabrication can have a tremendous positive impact on product yield as compared to typical final-product inspection.

Pressed-powder modelling techniques are directly representative of some of the processes used to create commercially available metal-matrix composites. Consequently, this modelling option is particularly valuable for the creation of NDE guidelines for our target system - SiC reinforced aluminium prepared with powder-processing techniques. The fact that both ultrasonic velocity and eddy current signal amplitude correlate with increasing density (figures 6 and 7) implies that either test is a rational option for the assessment of this important parameter. However, when we examine the volume fraction of SiC as a function of both ultrasonic velocity and eddy current amplitude (figures 8 and 9), we find significant differences in response. The ultrasonic velocity decreases in proportion to the per cent volume fraction of SiC (figure 8), whereas the eddy current response exhibits a plateau between 15 and 40 per cent SiC. Assessment of this observation with whisker instead of particle reinforcement confirms the existence of a plateau in the eddy current data.

Although the basic phenomenon responsible for the eddy current response remains to be identified, it is important to note that the eddy current and ultrasonic tests reflect different parameters. This distinction is critical to the selection and qualification of NDE procedures for structure characterization. For example, consider the potential complications of trying to access both density and volume per cent reinforcement with ultrasonic velocity. Because the same target velocity can be achieved by different combinations of density and reinforcement loading, it is impossible to qualify the material on the basis of ultrasonic velocity alone. (Note that 87 per cent density 2024 Al-SiC with about 13 per cent reinforcement has a velocity equivalent to pure 2024 Al at 80 per cent density.) An ultrasonic velocity test (combined with an eddy current or X-ray test) could provide a more definitive assessment of the parameters of concern. If an X-ray examination was used to confirm compact density, ultrasonic velocity would be a direct reflection of reinforcement fraction.

The experiments conducted in this effort were designed specifically to demonstrate the capabilities of various NDE options. However, there has been no attempt to qualify a given material parameter against expected service performance. For example, if the optimum SiC reinforced 2024 aluminium conditions were targeted at 25 per cent volume fraction SiC and 90 per cent density, the selection of inspection technique might be different from that selected for other conditions. The target parameters, of course, must be identified on the basis of expected service performance and qualification testing. At the present time, the rational approach to the selection of inspection criteria for the prediction of material performance must be based on NDE signatures developed from successful composite configurations. This empirical approach can then be used to guide the modelling for fine-tuning the assessment capabilities. Once the desirable structural parameters have been identified and correlated with inspection options, the NDE considerations can be directed at defect sensitivity concerns. Again, empirical correlations between NDE response and performance testing will provide the guidelines for more adequate defect sensitivity analysis. Clearly, the most defensible approach to the creation of practical NDE qualification criteria for advanced composite materials is to include NDE assessment considerations in the earliest stages of material design and performance testing.

Consideration of defect sensitivity for metal-matrix composites is a complicated aspect of structural reliability for these materials. The definition of a defect in itself remains a problem. Data in the literature identify a multitude of potential defects in composites that are not adequately characterized by the crack or voidlike discontinuities encountered in conventional monolithic materials. It has been reported that cracks in reinforcement particles and poor bonds between reinforcement particles and the matrix, as well as both reinforcement-rich and reinforcement-lean areas of a metal matrix composite, can be considered important defects. Once identified as potential problems, the immediate question becomes "Can we detect and size these defects?" In an attempt to model these potential flaws to assess detectability, the liquid mercury model shown in figure 11 was created. Although limited to eddy current testing, the model, relative to machining or other methods of simulation, can expedite the replication of defects. The very preliminary data reflected in figure 12 clearly demonstrate the fact that eddy current inspection procedures can characterize important variations in the condition of the reinforcement to matrix interface. These data imply that, at least for the modelling conditions, the interface integrity is reflected by electrical conductivity performance. It is easy to envision a situation where the formation of a nonconducting intermetallic compound at the reinforcement to matrix interface can reduce the eddy current response. This is encouraging from a signal-discrimination point of view, but it is important to note that interface condition is yet another variable that can have a significant impact on the NDE signature of composite materials. Clearly, the challenge becomes the problem of identifying and prioritizing the structure parameters that ultimately impact material performance and then creating inspection capabilities that can characterize and qualify the material.

In the modelling work conducted to date, we have shown that existing NDE capabilities can characterize isolated variations in composite microstructure. However, it is not yet possible to discriminate between different variables that may occur at the same time. In addition, none of the modelling has included crack or voidlike discontinuities that will have a pronounced effect on structural performance. To pursue these considerations in a more effective manner, it will be necessary to focus the modelling activities on a particular system where details of the final product have been specified through performance testing. This activity will constitute the next phase of the Westinghouse programme. The powder, pressed powder, and liquid-metal modelling capabilities described in this paper will be directed at a candidate SiC-reinforced aluminium system that offers properties designed to meet specific operating requirements.

Conclusions

The pertinent observations and conclusions associated with this programme are summarized below.

(1) Powder metallurgy and liquid metal modelling techniques can be used to replicate metal matrix composite structures for the assessment of inspection considerations.

(2) Conventional eddy current inspection instrumentation and techniques can be used to characterize SiC and aluminium alloy powders and blends used to create composite structures.

(3) The ultrasonic and eddy current response of SiC-Al composites is dependent upon material density and the volume fraction of reinforcement. For the case of green compacts, both ultrasonic velocity and eddy current signal amplitude increase with increasing density and decrease with increasing reinforcement.

(4) X-radiography can reflect the density of SiC Al composites but not the reinforcement loading.

(5) Liquid mercury modelling techniques can be used to replicate the reinforcement-to-matrix interface conditions for composite structures.

(6) Source discrimination problems related to NDE response versus structure-variable interactions will require multiple inspection techniques to accurately characterize composite conditions.

(7) A structure-modelling, NDE characterization programme must be integrated with composite-formulation and performance-testing considerations to limit the number of variables that must be examined in the creation of viable inspection requirements. (Source: Materials Evaluation/47/April 1989)

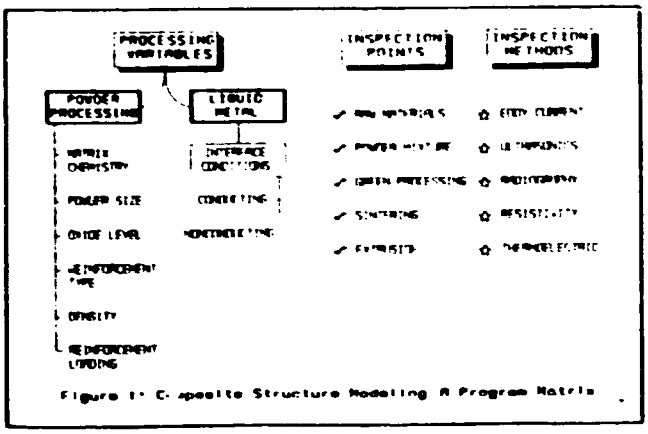

Figure 1. Composite structure modelling - a programme matrix

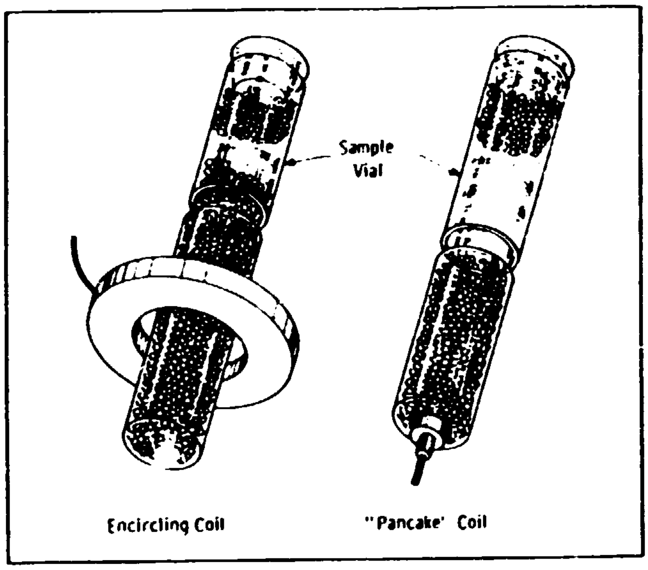

Figure 2. Dry-powder models

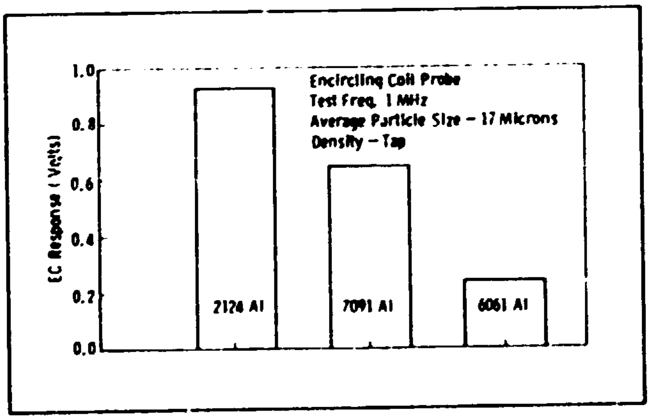

Figure 3. Eddy current response versus prealloyed aluminium powder

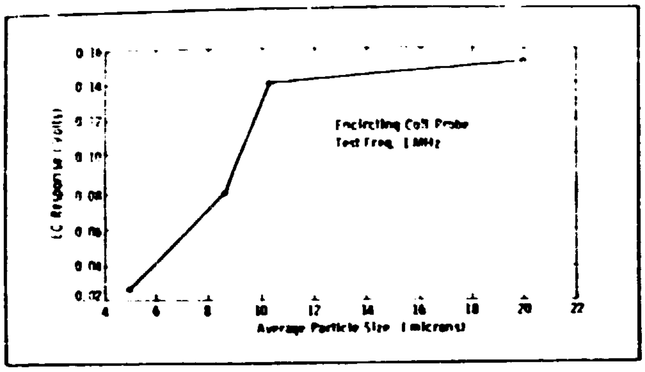

Figure 4. Eddy current response versus average particle size for SiC powders

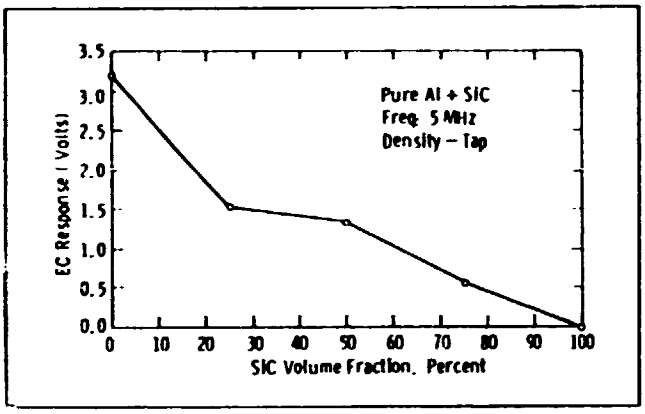

Figure 5. Eddy current response versus SiC volume fraction in Al SiC powder mixtures

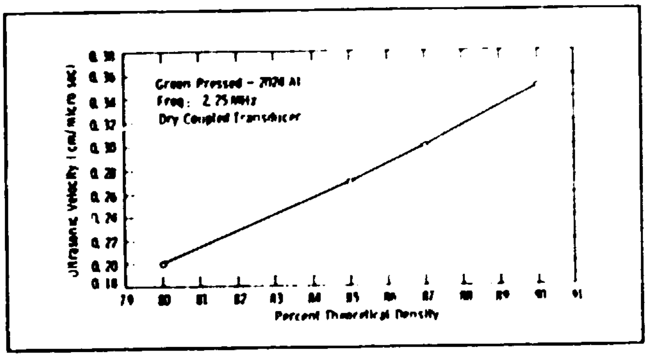

Figure 6. Ultrasonic velocity versus density of 2024 Al pressed green compacts

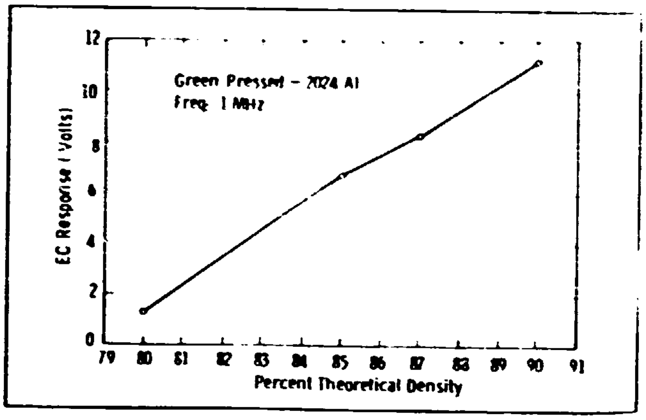

Figure 7. Eddy current response versus density of 2024 Al pressed green compacts

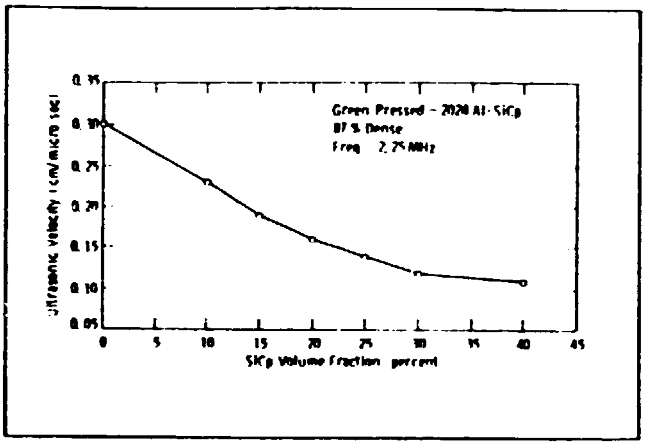

Figure 8. Ultrasonic velocity versus reinforcement volume fraction in 2024 Al SiC particulate pressed green compacts

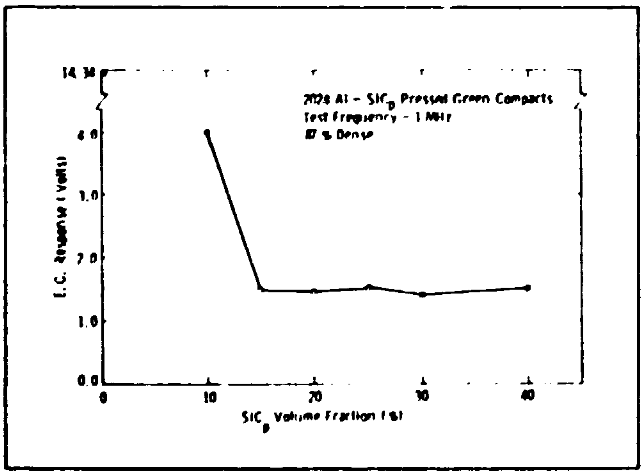

Figure 9. Effect of SiC particulate volume fraction on eddy current response

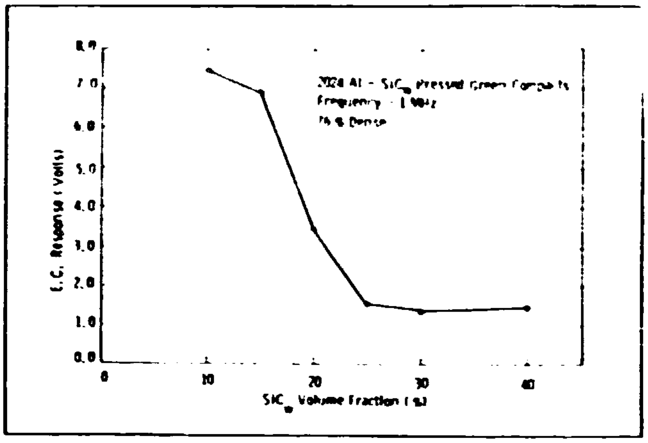

Figure 10. Effect of SiC-whisker volume fraction on eddy current response

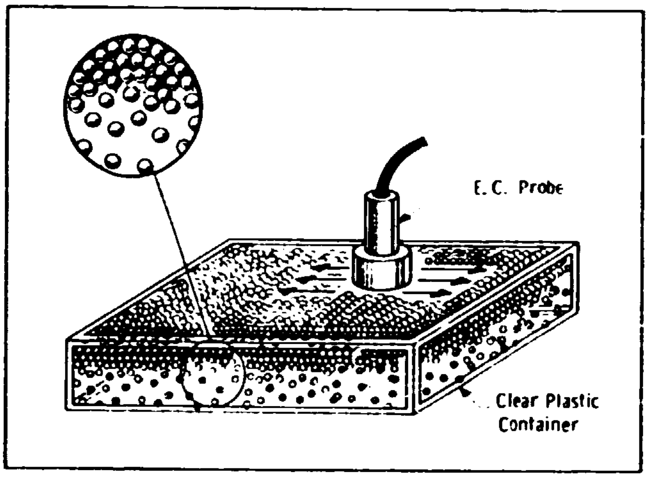

Figure 11. Liquid mercury model

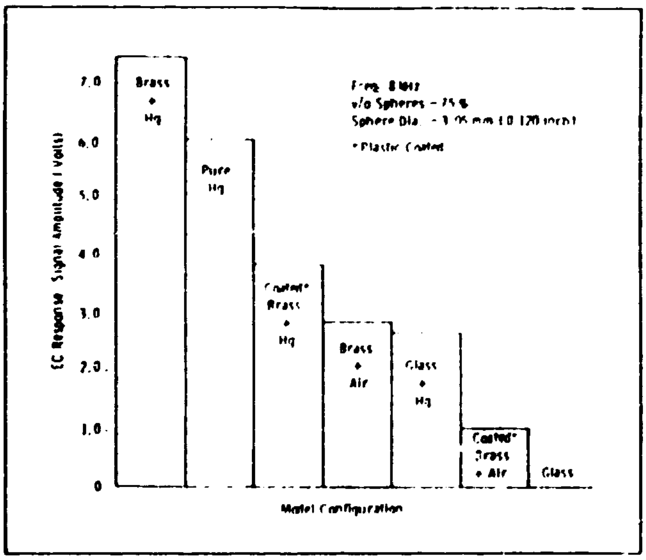

Figure 12. Preliminary mercury model results

Metal matrix composites – their time to shine.

The term composite usually means a combination of two or more constituent elements to form a modified quasi homogeneous structure that produces synergistic mechanical and physical property advantages over that of the base elements. In today's technical society, the term composite almost always brings to mind a polymer or resin matrix composite. However, metal matrix composites are starting to attract more attention. Historically, metal matrix composites (MMC's) were among the first continuous fibre reinforced composites studied. Systems, such as steel wire reinforced copper, were early model systems. Metal matrix composites available today, usually conform to one of the following three groups:

> A particulate based system formed by the addition of small granular fillers to a binder that generally results in an increase in stiffness and, perhaps, some increase in strength;
>
> A whisker flake system that realizes a greater proportion of the filler strength due to the higher aspect ratio (length diameter) of the filler and, hence, has a greater ability to transfer load;
>
> A continuous fibre system that, due to fibre continuity, realizes the full properties (strength and stiffness) of the high performance fibre.

These three composite systems are shown schematically in figure 1.

Each type of composite system has advantages and disadvantages. The particulate based system offers low cost, significant stiffness improvements, and nearly isotropic properties. However, the strength improvements are slight and the strain to failure and fracture toughness are on the low side. The whisker based composites are more costly, but do offer more strength, in general, than the particulate based composites. The continuous fibre reinforced metal matrix composites offer the best combination of strength and stiffness; however, the cost of this system is very high.

Over the past 20 years or so, the interest in metal matrix composites has fluctuated between mild interest and no interest at all. The only production continuous fibre reinforced metal matrix composite components currently in service are the tubular struts on the US space shuttles. The main disadvantage of continuous fibre reinforced metal matrix composites is the high cost of the fibres and fabrication. Cutting and drilling of some of the current systems can be very expensive compared with traditional metal shop operations. Compared with resin matrix composites, MMC may offer many attractive properties, such as better environmental tolerance to moisture and temperature, higher interlaminar strength, and better impact and lightning damage resistance. Compared with normal homogeneous structural metals, MMC offer much higher stiffness to weight and strength to weight ratios. However, in neither case could the advantages of MMC justify the additional costs.

In the early 1980s, several areas of technological advancement sparked a renewed interest in continuous fibre reinforced metal matrix composites, namely, the need for high temperature materials for aerospace structures, advanced engines, and the need for materials with a high degree of thermal dimensional stability for space antenna applications. MMC have unique properties that make these technology advancements conceivable. MMC will still be very expensive, but the applications are such that polymer matrix composites and homogeneous metals may not, based on the present state of the art technology, be able to meet the new requirements. Since there are many new MMC systems under consideration and development to meet projected needs, the future for MMC looks promising.

Space applications

Graphite reinforced metal matrix composites represent the next generation of high stiffness, low thermal expansion materials for applications on dimensionally critical spacecraft structures. Figure 2 shows the coefficient of thermal expansion (CTE) for several composite systems. The closer the CTE is to zero the better. High specific stiffness is also desirable. One such structure is the wrap rib concept space antenna. These materials offer many advantages over resin matrix composites, such as higher electrical and thermal conductivity, better radiation resistance, and no outgassing. Currently, the 6061 aluminium alloy is one of the primary metals being considered as the matrix for MMC. However, composites made with this alloy exhibit a large hysteresis during thermal cycling and residual dimension changes are induced by thermal cycling. This behaviour is unacceptable for the performance in dimensionally critical spacecraft.

Combinations of commercial high strength aluminium alloy matrixes and post fabrication processes developed at the National Aeronautics and Space Administration (NASA) Langley Research Center have resulted in MMCs that do not exhibit residual thermal strain or strain hysteresis during thermal cycling. The thermal expansion of a P100 graphite fibre reinforced 2024 aluminium alloy composite, as fabricated, after post-processing, and after 1000 thermal cycles, is shown in figure 3. The figure plots the thermal strain as the specimens were heated from room temperature to the maximum temperature, cooled to the minimum temperature, and heated again to room temperature. Notice that the expansion of the as fabricated composite (the dashed lines) is characterized by a large hysteresis and residual strain, like that of the P100 Gr 6061 Al material. After the post processing (the solid line), as well as after 1000 thermal cycles, the P100 Gr 2024 Al composite exhibits neither residual strain nor hysteresis. This behaviour was also observed for similarly processed and cycled composites made with the 201 and 7075 aluminium alloys. Thus, these metal-matrix composites, after a post fabrication process, are excellent candidate materials for dimensionally critical space structures.

The aerospace plane

Further development is required to create the lightweight, high strength materials needed so that an aerospace plane will survive the extreme temperatures and pressures it will encounter. Here enter metal matrix composites.

The temperatures that will be encountered by the aerospace plane are much too high for polymer matrix composites. Indeed, the temperatures are too high for all but a few homogeneous metals. Of these few homogeneous metals, practically none have sufficient stiffness and strength at the higher temperatures to allow the structure to survive. However, by reinforcing some of these light, high temperature alloys, that is titanium and titanium aluminides, with high strength, stiff, ceramic or graphite fibres, the resulting MMC will have the capability to survive the harsh environments of aerospace travel repeatedly.

Meeting the challenge

Metal matrix composites are unique because they combine the high stiffness and strength of fibres, but also retain the elastic plastic behaviour of the matrix material. In high temperature applications, the metal matrix may exhibit viscoelastic behaviour as well as develop significant thermal residual stresses as they are cooled down. MMC's also display unique fatigue and fracture behaviour. Experimental testing procedures for MMC are not currently very well developed or documented. Analytical material models are not currently available to handle all the particular problems, such as elastic-plastic, viscoelasticity, and thermal stresses, that need to be addressed in designing with MMC. Thus, much work remains in understanding and designing with MMC.

The high cost of MMC has kept rese[illegible]hers from being more competitive with resin mat[illegible] composites in the past. However, now the advanc[illegible] technology has progressed beyond the capabilities of resin matrix composites. The reality of hy[illegible]sonic flight hinges on the development of suitable metal matrix composites. The future of MMC looks bright because they are no longer in search of an application, but rather an important application is in search of them. (Extracted from <u>ASTM</u> <u>Standardization</u> <u>News</u>, October 1987, article written by W.S. Johnson)

<u>New approaches to microwave circuit packaging using aluminium metal matrix composites</u>, by John P. Tyler, Avantek, Incorporated Milipitas, California and Mark R. van den Bergh, DWA Composite Specialties, Inc., Chatsworth, California

1. Introduction

The design and performance of Microwave Integrated Multifunction Assemblies (MIMAs) is influenced strongly by the physical properties of the circuit and packaging materials selected. The level of complexity, integration and power density in MIMAs is rapidly increasing through advancements in microwave semiconductor technologies. The improved performance of microwave semiconductors must be accompanied by the development of packaging materials which will allow efficient operation of the devices, and thus improve the performance of the microwave circuits.

Packaging materials used in MIMAs must exhibit good thermal conductivity for efficient heat removal from power dissipating devices. Yet, the design often requires light weight materials, for reduced package density in aerospace applications. High flexural and shear strengths are also desired for a reduced cross section of structural elements. Finally, for reliability over operating temperature extremes, the thermal coefficient of expansion (TCE) of the packaging materials must be close to that of the microwave circuit elements, such as Al_2O_3, Si, and GaAs.

Aluminium metal matrix composites, consisting of an aluminium matrix alloy reinforced with 40 to 55 volume per cent silicon carbide particles, have been developed for electronic and microwave packaging applications. The electronic grade composite materials have a density similar to aluminium, while exhibiting superior flexural and shear strength properties. The composites exhibit a TCE which is less than half that of 6061 aluminium. The TCE of the composite materials is approaching that of standard microwave circuit elements. The thermal conductivity of the composites is seen to be up to ten times that of Kovar, at about one third of the density.

Thus, the bulk properties of the composite materials are very attractive to the microwave designer. There follows a description of the family of composite materials, and a comparison of their physical properties, followed by a discussion of the secondary processing of the materials into usable forms for microwave circuit packaging. Finally, current and future applications are presented.

2. Aluminium MMC materials

A. <u>Fabrication</u>: The electronic grade metal matrix composite materials discussed in this paper are part of a large family of ceramic particulate reinforced aluminium composites, produced by powder metallurgy techniques. The primary form of the material is SiC particulate Al. Electronic grade SiCp Al is distinguished from other SiCp Al forms by high reinforcement volume percentages, and by the high thermal conductivity of the matrix alloy and the SiCp reinforcement.

The SiCp Al MMC is produced first as a billet. A billet is fabricated by blending SiC particulate with aluminium powder and transferring the composite blend to a steel mould for densification. The billet is densified by vacuum hot pressing. SiCp Al billets are currently produced in weights ranging from 20 to 400 lbs. To date, electronic grade SiCp Al has been produced in weights from 20 to 65 lbs.

A P M based SiCp Al composite is rarely utilized in the "as pressed" billet form. Thermomechanical processing such as extrusion is typically performed, to optimize strength and ductility by breaking up surface aluminium oxides on the powder particles. This improves metal metal and metal SiCp bonding. Extrusion also acts to improve the distribution of the SiCp in the aluminium matrix, making it more homogeneous. Finally, extrusion allows the SiCp Al billet to be converted to a more efficient physical shape for final processing, be it rolling, forging, machining, or a combination of these processes. The primary extruded shape for electronic grade SiCp Al is a 1/2" by 5" cross section plank. Depending on the size of the billet, 5 to 15 linear feet can be produced during a single extrusion operation.

A wide range of secondary processing operations has been demonstrated with this class of composite materials. Extrusion in various forms is now a common process. Hot rolled sheets of various thickness have been produced for all available volume fraction loading materials. For production MIMA applications, SiC40 (40 v/o SiCp/Al) material has been produced in a thickness of 0.040" with a flatness of 0.0015 in./in. Smaller lots of SiC55 (55 v/o SiCp/Al) have also been produced in thicknesses ranging from 0.030" to 0.100".

Due to the abrasiveness of the SiCp reinforcement, the SiCp/Al composites are more difficult to machine than unreinforced aluminium. To minimize the secondary machining steps, the capability of forging the material to near net shape has been developed. The forging of SiCp/Al must be handled differently than with conventional aluminium. Due to its reduced strain to failure ratio, electronic grade SiCp/Al is forged at very low strain rates, and cannot be drop or hammer forged. To compensate for this, forging tools have been designed and fabricated which allow a "batch" of four components to be produced during a single forging cycle. The batch forging concept can be expanded beyond this to maximize throughput. Machining of electronic grade SiCp/Al is best accomplished using polycrystalline diamond coated tools or by EDM techniques, which will be discussed in a later section.

b. Material properties: Electronic grade SiCp/Al MMC materials have been tailored to exhibit the properties necessary for application to electronics packaging. This class of MMC is able to replace conventional metals due to its reduced thermal coefficient of expansion (TCE), high thermal conductivity, and high modulus of elasticity. The density of electronic grade SiCp/Al is only slightly higher than conventional aluminium. Thus, the application of the new composite materials will provide substantial weight savings in air-borne or space-based electronic systems.

The TCE of the electronic grade material systems are shown in comparison with aluminium in figure 4. The TCE of the composites is seen to decrease substantially with increasing volume per cent loading of the SiCp reinforcement. The SiC40 material has a TCE of 12.1 ppm/°C, approximately half that of aluminium. The TCE of the SiC55 material (8.2 ppm/°C) is nearly one third that of aluminium. Based on the TCE comparison, the SiC40 and SiC55 materials are excellent candidates for replacement of stainless steel and Kovar, respectively.

The thermal conductivity of the SiCp/Al composite ranges from 130 to > 200 W/m-°K at room temperature. This value is primarily determined by the matrix alloy composition of the material. The SiC40 material (130 W/m-°K), first developed as a replacement for beryllium in an electronic system, utilizes 6061 Al as the matrix alloy. This material system was the first SiCp/Al composite to be evaluated for microwave packaging applications.

The thermal conductivity of the SiC50 and SiC55 materials is approximately 200 W/m-°K at room temperature. Both of these material systems have been tailored for higher thermal conductivity by the selection of 6063 Al as the matrix alloy. Figure 5 shows a thermal conductivity curve for the SiC50 system and the 6063 Al matrix alloy. By extrapolation of this data, the thermal conductivity of the SiCp is about 220 W/m-°K, and thus contributes to the high thermal conductivity of the composite material.

The physical properties of the electronic grade SiCp/Al materials are compared to conventional packaging materials in figure 6. The SiCp/Al composite materials are seen to satisfy all four of the design criteria commonly used for electronic packaging materials: low density, high thermal conductivity, low TCE, and high modulus of elasticity. The TCE of electronic grade SiCp can be closely matched to alumina and other microwave circuit materials. The density of the composite material is less than one fifth that of the copper/refractory P/M materials, with a comparable thermal conductivity. The thermal conductivity of the SiC50 and SiC55 systems is significantly greater than other commonly used packaging materials. The superior thermal conductivity of the SiCp/Al system allows lower operating temperatures of semiconductor devices, thus improving operational mean time to failure figures for electronic systems.

3. Secondary material processing

The thermal and mechanical properties of the aluminium MMC's are now well known. These properties make the materials desirable to develop for electronic and microwave applications. However, the properties which make the materials attractive to the designer can also make the material very difficult to work with. The SiC particulate reinforcement can cause considerable difficulty in machining the material using standard methods and tooling. Likewise, the reinforcement can present difficulties in welding hermetic covers onto electronic packages. The difficulties in working with the material can be overcome or avoided by the use of special techniques and processes.

A. Machining: The reinforcement of the composite material makes it the most abrasive type of aluminium available. It is not often practical to machine parts using conventional carbide steel tools. However, in the drilling of small holes with high aspect ratios (width/depth), the wear of carbide bits may be sufficiently low to justify this type of tool. Typically, about a half inch of material may be drilled with a single carbide bit, in sheets less than 0.050" thick, drilling holes with an aspect ratio (width/depth) of at least 1.5:1.

The use of polycrystalline diamond or ceramic coated carbide machine tools will considerably improve these yields. For medium to large machining lots, the high tooling costs associated with coated tools is distributed over the entire lot, thus adding minimal cost to the parts. However, high speed drilling or milling equipment capable of stable machining with spindle speeds in excess of 15,000 rpm is recommended with diamond or ceramic coated tools. An RMS surface finish of 63 micro inches can be achieved by this type of machining.

In machining smaller quantities or engineering batches of parts, it is not practical to purchase diamond or ceramic coated tooling for every job. Other, more cost effective methods of processing the material must be developed.

Conventional and wire EDM machining have proven to be effective with these materials. Conventional EDM can be used to create blind cavities and through holes. Wire EDM is well suited for machining complex flat carriers for microwave circuits. Wire EDM processing of flat sheets of material can be accomplished on stacks of material up to 2" thick. For wire EDM processing, a starter hole pattern is required, which must be machined into the blank. A number of approaches has been used successfully to form the starter hole pattern: conventional EDM, conventional machining, laser drilling, and ultrasonic drilling. EDM machining produces an RMS surface finish better than 63 micro inches.

Laser machining or cutting is also proving useful in producing flat carriers. Non contact machining can alleviate some of the problems associated with traditional machining methods. Laser machining is well suited to the formation of through holes and cutouts in flat sheets of the material. However, the edge finish and profile of laser machined features in flat sheets is not as good as that associated with EDM processing.

Ultrasonic processing of the material is also a viable method. Ultrasonic energy is used in conjunction with an abrasive slurry to abrade the material in a precise and controlled manner. Ultrasonically machined sections as thin as [illegible] have been accurately produced. The surface finish of ultrasonically machined features is comparable to that of EDM. This machining seems to be ideally suited to forming blind cavities for microwave package housings. The cost of ultrasonic milling or drilling equipment is relatively low compared to laser or EDM equipment. However, ultrasonic machining requires dedicated tooling for the pattern or feature which is desired.

B. Finishing: For most electronic applications, parts fabricated from composite materials must exhibit a good surface finish ([illegible] micro inches or better), good dimensional tolerances, and excellent electrical conductivity. This requires a well controlled metallic finishing of the parts.

Microwave circuit elements may be attached to packages or carriers in two ways: by supported or unsupported resin epoxies, or by eutectic alloy brazing. In either case, the as plated surface finish of the circuit carrier is critical to the reliable attachment of the circuit elements.

In applications where GaAs or Si integrated circuits are eutectically brazed to the carriers, a high purity electroplated Au finish is required. Au bearing binary eutectic alloys used for brazing, such as Au Si or Au Sn, require a minimum of 100 micro inches of high purity of Au on the carrier for a reliable die or substrate attach operation. As a diffusion barrier, the Au generally has an underplating of 100 to 200 micro inches of nickel. The grade of nickel best suited as an underplate is a high purity nickel electroplate (no brighteners) from a sulphamate bath. When properly applied, this nickel gold finish is seen to withstand the high temperature brazing operations without discolouration, blistering or cracking.

When a composite material is to be used as a hermetic housing or sub housing, good solderability of the finish is critical to the package integrity and reliability. The soldering of hermetic feedthroughs to housings for DC and microwave I/O connections is usually done with a Sn bearing eutectic alloy, such as Sn Pb or Sn Ag. This soldering operation is best accomplished on a solderable nickel surface, rather than on gold, which tends to dissolve in the Sn rich alloy and form brittle intermetallics. An electroless nickel phosphorus finish provides good solderability, while providing excellent corrosion resistance for the housing.

For either of these two types of plating, the pre treatment of the composite materials prior to plating is similar to that for conventional aluminium. However, a heavy pre treatment of the composite material is seen to be more critical to good plating yields than with conventional materials. This includes the more common of the chemical conversion coatings used for aluminium pre treatment.

C. Welding: The ability to form high quality laser fusion weld joints between an aluminium MMC material and a high silicon aluminium cover is of great importance in applications of hermetic housings for microwave components. Microwave housings are commonly constructed from aluminium or stainless steel for laser weldability. Microwave housings constructed from MMC materials must be sealed to very low leak rates, to achieve the high reliability required of microwave components.

The SiCp reinforcement of the matrix creates great difficulty in achieving good welds of the material to itself. The addition of an intermediate aluminium to the weld is necessary to achieve good metal flow without porosity or outgassing. High silicon aluminium alloys, such as 4047 Aluminium, are good intermediate materials because of their ductility and good flow properties.

The billet forms of the composites may be extruded with up to 1/16 inch of high silicon aluminium clad on either side of the extrusion. This material may then form the weldable top surface of a microwave package. Layers of aluminium and stainless steel have been successfully clad onto the composite material using an explosive cladding process.

4. **Future Trends**

A. Applications: The MMC flat carrier forms the thermal and mechanical interface of the microwave circuitry to the rest of the system, providing savings in weight and space. The flat carrier approach represents a highly cost effective use of the material, and utilizes the desirable properties of the MMC where it is most needed: in the thermal path from the devices to the heat sink.

Progress in secondary processing abilities and near net shape forging are allowing the composite materials to be used as hermetic microwave enclosures. The ability to apply a hermetic glass to metal seal directly to the material is a critical step in the development of reliable, low cost microwave housings.

B. Advanced materials: New particulate reinforced aluminium composites are currently in development for electronic applications. One of these is synthetic diamond reinforced aluminium. Experimental billets, weighing less than 10 lbs and consisting of a 40 volume per cent loading of Type IB synthetic diamond in 6061 Al have been produced, and have been hot worked by upset forging. Preliminary TCE and thermal conductivity testing has begun, and this system has yielded the lowest TCE and the highest thermal conductivity ever measured in a particle reinforced aluminium based composite. The thermal conductivity curve for this material is shown in figure 7. Room temperature thermal conductivity is currently greater than 230 W/m °K. With the use of a higher conductivity matrix alloy, the thermal conductivity for this composite is expected to exceed 250 W/m °K. The TCE of this material system is measured to be 6.9 ppm/°C (over the range -150 to 150°C), which is within 1 ppm of alumina and GaAs. Despite these excellent thermal properties, the high cost of the diamond reinforcement may limit the widespread application of the Diamond/Al composite to electronic packaging.

5. **Conclusions**

Metal matrix composites, composed of aluminium alloys reinforced with SiC particles, have been developed for electronic packaging applications in advanced microwave systems. The materials exhibit low TCE, high thermal conductivity, and high modulus of elasticity. Electronic grade SiCp/Al also exhibits low density, which allows for significant weight savings in aerospace applications. Important manufacturing techniques have been developed, which enable cost effective processing of the material into finished components. (Source: 3rd International SAMPE [Society for the Advancement of Material and Process Engineering, Covina, California] Electronics Conference, 20-22 June 1989)

Low expansion MMCs boost avionics: metal matrix composites (MMCs) offer attractive properties for electronic packaging in aerospace applications

Electronic packaging materials are required to structurally support electronic components, protect them from hostile environmental effects, and remove excess heat generated by them. Several materials are available that effectively meet these needs, but the traditional metals used have high densities, making them unattractive in avionic applications where light weight is essential. This has led to an intensive search for alternative, low density packaging materials. Alternative packaging materials, however, also must have controlled coefficients of thermal expansion (CTEs).

Hermetic packages are needed to protect electronic circuits from moisture and other environmental hazards, and they generally have glass-to-metal seals for electrical connections and often contain semiconductor devices and or alumina circuit boards. For matched glass-to-metal seals, the thermal expansion of the housing should equal that of the glass; for compression seals, a thermal expansion moderately higher than that of the sealing glass is required. Low-expansion iron-nickel alloys such as ASTM F15 (e.g., Kovar, Carpenter Technology Corp.) or ASTM F30 (e.g., Alloy 42 or Alloy 52) are commonly used for matched-seal packages, while copper and cold-rolled steel are used for compression seals. All of these materials, however, have high densities, and iron-nickel alloys are poor thermal conductors.

Constraining-core heat sinks are used to remove heat from epoxy-glass printed wiring boards and to minimize thermal expansion mismatch between surface-mounted ceramic components, e.g., alumina leadless ceramic chip carriers and barium titanate multi-layer ceramic capacitors. Cracking of the components or fatigue failure of circuit-board/component solder joints may occur in these circuits during thermal cycling. Molybdenum and copper-clad Invar are commonly used for such heat sinks; these materials have low CTEs and high thermal conductivities, but also have high density. Beryllium also can be used for constraining-core heat sinks; it has low density and good thermal conductivity, but higher CTE than desired.

Materials meeting the requirements of light weight, controlled CTE, good thermal conductivity, and good corrosion resistance would find use in hermetic packaging, heat sinks and heat pipes. Metal matrix composites (MMCs) are well suited to such applications because they offer the ability to tailor properties of components and would allow considerable weight savings and improved thermal conductivity over materials such as Kovar and Alloy 42, now used in high reliability electronic applications. MMCs with the required properties, such as the three component Al/SiC/Si composite described in this article, meet the demand for new materials by the increasingly sophisticated military aircraft and spacecraft electronic systems market.

Tailoring MMC properties

MMCs offer unique opportunities to provide combinations of physical and mechanical properties not achievable in monolithic alloys. Discontinuously reinforced composites contain isolated particles, whiskers, or chopped fibres in a metal matrix. The most flexible method of making these composites is to use powder metallurgy processing. Conventional secondary processes such as extrusion, forging, rolling, and machining can then be used to fabricate the desired product forms.

The challenge in developing MMCs for electronic applications is to find compatible matrix reinforcement combinations that produce composites with low density and CTE, as well as high thermal conductivity and modulus. Aluminium and magnesium alloys are commonly used matrices that combine low density and reasonably high thermal conductivity, but which have CTEs much higher than those required. To reduce composite CTE while retaining low density and high thermal conductivity, reinforcements must be used that have specific combinations of properties and are compatible with the matrix material.

Carbides are covalent compounds having very high hardness and bulk modulus, and low CTE. Silicon carbide (SiC) is the most commonly used reinforcement in aluminium and magnesium MMCs. A good matrix reinforcement bond is formed in these composites during consolidation, and both particulate- and whisker-reinforced composites are finding applications as structural materials and in precision instrument and optical systems. The high hardness of SiC and boron carbide (B_4C) requires the use of diamond tools for machining composites containing them.

Nitrides. Silicon nitride (Si_3N_4) and aluminium nitride (AlN) are low CTE, relatively low density compounds. High purity AlN has a high thermal conductivity but is attacked by aqueous solutions. Si_3N_4 reacts exothermically with molten aluminium to form AlN and silicon, making it unsuitable for use in composites made by liquid-phase hot pressing unless it is protected by coatings.

Oxides. Several oxides have CTEs near zero and have been considered as reinforcements for making low-CTE MMCs. Ultralow-CTE oxides have very low bulk moduli and thermal conductivities, undesirable characteristics for making composites for electronic packaging. Silica-rich oxides react with molten aluminium to form alumina (Al_2O_3) and silicon, making them unsuitable as uncoated reinforcements in aluminium-matrix composites. In the lithium-aluminium-silicate family, petalite ($LiO_2.Al_2O_3.8SiO_2$) reacts with aluminium during hot pressing, forming a silica depleted shell around the original reinforcement particle. Spodumine ($LiO_2.Al_2O_3.4SiO_2$) reacts only slightly with aluminium during consolidation.

Other reinforcements. Other materials potentially useful as MMC reinforcements are silicon and carbon fibres. Silicon has a low CTE and high bulk modulus (primarily due to its unusually high Poisson's ratio). Silicon reinforced aluminium MMCs under the name CMSH A 40 are commercially manufactured as low CTE materials for electronic applications by Sumitomo Electric Co. High modulus pitch base carbon fibres have very high longitudinal elastic modulus and thermal conductivity, and negative longitudinal CTE. Properties are very anisotropic, however; the fibres have low transverse modulus and high transverse CTE. Aluminium, magnesium and copper matrix composites reinforced with continuous carbon fibres have been studied extensively. Very low CTE, high conductivity MMCs have been made, but they generally have highly anisotropic properties and are very expensive.

Experiments reveal good candidates

Metal-matrix composites containing different reinforcement phases were fabricated by blending atomized metal alloy powders (6061 or 2124 aluminium or ZK60A magnesium) with reinforcement particles, whiskers, or chopped fibres. Cylindrical billets 76 mm (3 in.) in diameter with greater than 98 per cent theoretical density were produced from the mixtures using degassing and vacuum hot pressing, and their physical properties were measured. Fabricabilities of those billets having attractive, physical properties were evaluated by extrusion, forging, and rolling trials on commercial equipment.

When CTE values of 6061 aluminium-alloy composites containing 30 vol per cent of various reinforcement phases from this and other studies are compared, composites reinforced with SiC or B_4C have the lowest CTE, those with AlN or silicon are about 5 to 10 per cent higher, while composites reinforced with low-expansion oxides are significantly higher. These results clearly show the importance of high reinforcement bulk modulus as predicted by mathematical models; most oxides have a much lower bulk modulus than the other phases and are less effective in constraining the matrix, resulting in relatively high composite CTE.

ZK60A magnesium alloy composites reinforced with SiC or B_4C have measured values of CTE that also are very similar, which confirms the results of aluminium-matrix composites reinforced with these materials. Reinforcement loading, however, must be about 17 per cent higher in the ZK60A-matrix composites than in the 6061-matrix composites to achieve the same low CTE value.

At high reinforcement loadings, greater additional reinforcement is needed to produce a given reduction in CTE than at low loadings, so that very high reinforcement loadings are required to produce low CTE composites. The factor that limits the minimum CTE attainable is the ability to consolidate the composites and economically fabricate them into the required product forms.

The thermal conductivity of SiC whiskers is markedly lower than that of particulate SiC 32 W.mK vs > 80 W/mK. The low conductivity of SiC whiskers relative to particulate SiC is probably due to a high density of stacking faults and microtwins and to high levels of dissolved nitrogen. Particulate SiC made by the commonly used Archeson process apparently has fewer defects and lower nitrogen levels, resulting in higher thermal conductivity. The 6061 aluminium alloy matrix has a higher thermal conductivity than 2124 alloy. The temper of the matrix alloys also has an effect on conductivity; age hardened material has a higher conductivity than solution annealed and quenched material.

Most low expansion reinforcements increase composite modulus at a similar rate from 0 to 40 vol per cent loading. The exception is silicon, which has a much lower elastic modulus than the carbides and nitrides considered. A high composite modulus is needed to control printed wiring board (PWB) expansion for constraining core heat sinks and for general dimensional stability in other packaging applications.

Three component MMC shows promise

Aluminium matrix composites can be made using virtually any reinforcement phase that does not react excessively with aluminium. Composites containing up to 45 vol per cent fine particulate (<5 µm mean particle diameter) can be vacuum hot pressed to nearly full density at moderate pressures. Above this loading level, densification becomes more difficult. Composites with up to 40 vol per cent particulate can be extruded, forged, and rolled on conventional equipment using modified practices. Above 40 vol per cent, hot workability declines rapidly. For composites containing > 50 vol per cent reinforcement, machining from a billet is generally the only practical process for fabricating parts.

To overcome the limitations and difficulties in consolidating composites containing 50 vol per cent or more reinforcement, a programme was undertaken to develop materials with CTE $< 9 \times 10^{-6}/K$ and to develop fabrication processes to manufacture sheet, plate, and forged parts. The first successful material to result from this programme is a three-component composite consisting of an aluminium-alloy matrix with SiC and elemental silicon reinforcement. Manufacturing processes have been developed that produce better than 98 per cent theoretical density vacuum hot pressed material with 55 vol per cent reinforcement using conventional production equipment. This reinforcement level results in composite CTE values of approximately $8.5 \times 10^{-6}/K$.

Prototype heat sinks, heat pipes, and micro-circuit housing packages made from the three-component composite are being evaluated by several major aerospace contractors. Fabrication processes are being developed to lower the cost and improve mechanical properties of the material. A 55 vol per cent three-component composite has been rolled to sheet 1.5 mm (0.060 in) thick using a specially developed rolling procedure, and can be close-die forged to simple shapes. Research is continuing on the Al/SiC/Si composite (patent pending) and other MMCs to develop materials with good thermal conductivity and fabricability, low density (light weight), and a low CTE attractive to the avionic industry.
(See tables and diagrams on pages 120-122.)
(Source: Advanced Materials Processes, July 1989, article written by Alan S. Geiger and Michael Jackson, Advanced Composite Materials Corp., Greer, SC, USA)

United States Air Force seeks to prove metal composites' suitability

A project being underwritten by the United States Air Force has set out to prove that metal matrix composites are suitable for mass production and can be used to construct parts of aircraft structures, including areas where stiffness and heat resistance are critical.

Currently, aircraft builders rely mainly on titanium and other metals that can withstand the rigours of high speeds and temperatures for most critical parts of an aircraft's design.

With $20 million in funding from the Air Force, Lockheed Aeronautical Systems Co. said its engineers are applying existing manufacturing technology to design and construct four generic vertical stabilizers common to high performance jet fighters using metal matrix composites.

Marietta, Ga. based Lockheed said it believes the composites contain the qualities needed in aircraft construction and that the project's findings will lead to wider use of the material for all types of aircraft.

The thrust of the whole programme is to demonstrate the production readiness of the material and establish a data base to support full production.

Metal matrix composites combine a high strength reinforcing material, such as boron, graphite or silicon carbide, with some type of holding material, or matrix. For the project, the reinforcing material is silicon carbide and the matrix is aluminium, although other metals, such as titanium, also can be used.

By demonstrating the suitability of utilizing existing manufacturing methods to produce metal-matrix composites, Lockheed said it hopes to offset partially the higher cost of the material vs. conventional materials.

While metal matrix composites cost significantly more to produce than their light metal counterparts, it is estimated that prices could stabilize at about five times more than metals if aircraft makers embrace the technology.

The big draw to metal-matrix is that it performs as well as titanium, but is far lighter - a critical requirement in tomorrow's aircraft.

Two of the stabilizers under construction by Lockheed use whisker-reinforced matrix composite skin panels, where very short silicon carbide fibres are spread throughout the matrix in a random pattern.

The other two stabilizers rely on continuous fibre-reinforced skin panels. In the second grouping, long strands of silicon carbide fibres are arranged side-by-side in the aluminium matrix.

In all four stabilizers, the skins are fastened to silicon carbide fibre, aluminium spars and silicon carbide whisker aluminium ribs.

From the outset, Lockheed engineers have approached the project as a regular production operation, following standard manufacturing procedures and using mostly standard fabrication equipment, the company said.

One deviation in the process is the use of an abrasive water-jet cutter not generally found on most aircraft production lines.

Generating 45,000 lbs. of water pressure per square inch, the device uses a thin stream of water containing powdered garnet, which acts as an abrasive to cut cleanly through the material.

Using the water jet method instead of a more conventional process saved at least 500 man hours in trimming skin panels and ribs. (Source: American Metal Market, 6 September 1989; 1989 Fairchild Publications)

Avco's specialty materials division (Lowell, MA, USA) has developed metal matrix composites that are heat resistant at 2,000° F

Avco has combined silicon carbide and titanium aluminied, a combination of titanium and aluminium, in a chemical vapour deposition process. The 0.0056" diameter silicon carbide fibres are fabricated, woven into a mat, and then sandwiched between layers of titanium foil by hot isostatic pressing. Avco's patented technology is expensive, but aerospace officials say there is a good chance Avco's material will be chosen for the National Aerospace Plane. The USAF, Navy and NASA all want the plane to fly Mach 25 orbitally and 5,000-8,000 mph in the high atmosphere. At those rates, temperatures are expected to reach 1,400° F along the fuselage to 5,260° F at the nose. (Source: American Metal Market, 18 May 1989)

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Metal matrix composite powder

Composite thermal spray coating material is produced in metal matrix powder form. The composite powder offers protection against such conditions as wear, heat, cold, and corrosion in any combination. Spheroidized powder particles have rounded TiC particles imbedded in the melted matrix imparting morphology. Product is said to have five times the wear resistance and six times lower sliding-wear rate than major comparative materials. (Alloy Technology International Inc., 169 Western Highway, West Nyack, NY 10994, USA) (Source: Machine Design, 20 July 1989)

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Novel metal matrix composites from low-cost materials

A highly abrasion resistant new class of metal-matrix composite (MMC), with controllable specific resistivity ranging from conductive to dielectric, has been invented by Robert Pond, chief scientist of Marvalaud, Inc., and a professor of metallurgy at The Johns Hopkins University. These novel materials composed of a metal-matrix reinforced with finely dispersed fly ash particulate (submicron size to 25 μm) are referred to by their inventor as composite ash metal or CAM. Although the initial work has been with aluminium, zinc, and their alloys, other metals such as copper, nickel, iron, and their alloys are also being investigated. The process, which produces fully dense MMCs containing from 5 per cent to 30 per cent by weight fly ash particulate, is believed applicable to a large number of metal-matrix materials.

Fly ash is largely composed of ca. 60 per cent silica (SiO_2), ca. 20 per cent alumina (Al_2O_3, and ca. 20 per cent ferric oxide (Fe_2O_3). Professor Pond was motivated to develop these unusual MMCs because of the low cost and abundance of this waste product. More than 80 per cent of the 60 million tons a year removed from coal-burning power plant smokestacks requires disposal.

The new composites have interesting properties including high toughness, abrasion resistance, and as mentioned above, controlled specific resistivity. The property changes in a 27 per cent aluminium zinc alloy that result from reinforcement with fly ash include: an increase in specific resistivity that is virtually linear and increases fivefold as the fly ash content varies from 0 per cent to 25 per cent (from 8 $\mu\Omega$ cm to 46 $\mu\Omega$ cm); a 30 per cent decrease in density over the same concentrations; a doubling of outer fibre tensile strength up to 15 per cent particulate concentration (4-point bend test) from 39,000 psi (269 MPa) to 78,000 psi (538 MPa); a marked increase in the modulus of elasticity also up to 15 per cent particulate concentration from ca. 2×10^6 psi (13,800 MPa) to 5.5×10^6 psi (37,950 MPa); and a decrease in friction wear of 68 per cent (as measured by weight loss after one hour abrasion in grey cast iron) from 80 mg at 0 per cent to 24 mg at 25 per cent. Comparable values have been found with other fly ash reinforced MMCs. Two as yet unexplained anomalous effects are that above 15 per cent particulate loading both the outer fibre tensile strength and the modulus of elasticity decrease.

Fly ash reinforced MMCs are formable by conventional metal forming methods such as pressing and rolling. But because they are highly abrasive, machining is difficult, so the parts have to be ground. However, a variety of shapes and dimensions are possible, and the inventor believes that this material lends itself to near net shape fabrication.

Compared with most MMCs, which are quite costly, CAM is a relatively inexpensive composite. Its potential applications are, for example, low cost dies that could be made with the Al Zn alloy matrix, which because of its abrasive qualities would have low wear; a good brake shoe material that could be made with a more thermally conductive Cu alloy matrix; and high temperature seals, e.g. for diesel engines, that could be made using a matrix with a higher melting point such as an Fe based alloy. (Robert B. Pond, Sr., Chief Scientist and Board Chairman, Marvalaud, Incorporated, P.O. Box 331, Westminster, MD 21157, USA) (Source: Materials and Processing Report, August 1987)

* * * * *

Lockheed Aeronautical Systems' Georgia unit will start assembling large vertical tail boxes made of metal-matrix composite materials in Marietta, GA, USA. The unit said the tail boxes will be fabricated from the largest metal matrix composite sheets made in the United States. Silicon carbide aluminium sheets, each 0.09" thick and measuring 70 x 220" +, have been fabricated for the demonstration project being funded by Wright Aeronautical Laboratory's Aeronautical Systems Division USAF Flight Dynamics Laboratory (Dayton, OH). The tailboxes will be mounted on "strong" back welded steel frames that would simulate a fuselage fitting. Four vertical tails will be fabricated, two having skins of silicon carbide whiskers mixed with aluminium with spars made of silicon carbide fibre mixed with aluminium, and the other two will have skins and spars made with silicon carbide fibre mixed with aluminium. Advanced Composite Materials (Greer, SC) supplied the silicon carbide whisker-aluminium material, and Avco Specialty Materials Division (Lowell, MA) the silicon carbide fibre-aluminium. (Source: MetalwNews 30 November 1987)

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Metal matrix composite tubing is competing with graphite reinforced epoxies as the advanced material of choice for structural uses in future space platforms. Metal-matrix composites have weight advantages versus customary metals and may perform at 700F versus half that for graphite epoxies. Metal-matrix tubing also could bring about improved electrical and thermal conductivity versus graphite epoxies and reportedly may better resist the space environment making it adequate for long missions. Boeing, Lockheed and Martin Marietta's Astronautics Group (Denver, CO, USA) are examining the composites. (Source: MetalwNews, 5 June 1989)

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New ceramic reinforcement preforms

Ceramic fibre or whisker reinforced metal matrix composites (MMCs) are attractive materials for automotive and aerospace applications due to their high strength to weight ratio. However, current techniques used to make ceramic fibre reinforcement preforms produce mats characterized by low density, density gradients within the mat, and planar orientation of fibres. This leads to non uniform, anisotropic MMC properties - a significant barrier to commercial use of MMCs.

This barrier may be eliminated with the development of a process for injection moulding short ceramic fibres or whiskers into complex shaped reinforcement preforms. High aspect ratio fibres or whiskers (from 20:1 to 100:1) are mixed with thermoplastic binders and surfactants to ensure complete wetting and dispersion of the reinforcements in the process, developed by Technical Ceramics Laboratories Inc., Atlanta, USA.

Preforms can be fabricated into any shape that can be injection moulded, and have completely random fibre orientation at loadings from 10 to 40 per cent. Moulding is done at low pressures, so much larger shapes than normally associated with injection moulding are possible. The metal matrix can be introduced by squeeze casting or other pressure or vacuum assisted techniques. MMCs can have the same complex shape as the preform, or the preform can be used to selectively reinforce a particular area of the part. Process compatibility has been demonstrated for silicon carbide and silicon nitride whiskers, Safil (ICI Chemicals & Polymers Group, United Kingdom) ceramic fibres, and chopped carbon fibres. Patents have been filed for the process and the preforms. (Source: Advanced Materials & Processes, September 1989)

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Carbon fibre and SiC particulate reinforced MMCs for electronic applications.

At DWA Composite Specialties several types of MMCs are under development for electronic applications. In order of increasing cost they are DWAL 20, a silicon carbide (SiC) particulate reinforced aluminium; chopped carbon fibre reinforced aluminium; and a continuous tow of high modulus, pitch based carbon fibre in aluminium or magnesium. This last composite is particularly adventageous because its coefficient of thermal expansion (CTE) can be tailored to match those of both printed wiring boards and ceramic devices such as alumina chip carriers.

The major advantages of carbon fibre MMCs are that their CTEs can be controlled and matched to those of ceramic devices; their heat dissipation can be directionally controlled by placement of the fibre layers; heat sinks are lighter and more efficient than conventional ones; they offer structural stiffening along with heat dissipation; and because of their low density their specific thermal conductivity is much higher than aluminium and copper. Specifically, the carbon fibre metal composite system has a density of ca. 0.085 lb/in.^{3} (2.4 g/cm^3) in Mg and ca. 0.098 lb/in.^{3} (2.7 g/cm^3) in Al; a high elastic modulus (55 msi, 380 GPa for uniaxial reinforcement; and 25 to 30 msi, 173 to 207 GPa for 0°/90° cross-ply fibre orientation); and "zero" CTE can be achieved by very high fibre volume loadings, or planar isotropic CTE can be achieved through cross plying approaches.

Where the application is not as demanding, the lower cost SiC particulate reinforced (25, 40, or 55 vol per cent) Al composites offer specific strength equivalent to titanium; a modulus of 16 to 22 msi (110 to 152 GPa); tailorable low CTEs matching those of steel, beryllium, and titanium; thermal conductivity equivalent to aluminium; and good abrasion resistance. The modulus of the intermediate priced chopped graphite reinforced metal composite is ca. 10 msi (69 GPa), with a CTE close to that of titanium for a 45 vol per cent chopped carbon fibre (F100) tow in aluminium (6061) at half the density of titanium. Developmental quantities of these composites are available for evaluation. (DWA Composite Specialties, Inc., 21119 Superior St., Chatsworth, CA 91311 4393, USA) (Source: Materials and Processing Report, September 1987).

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SiC-reinforced metal and ceramic composites

Nippon Carbon is the latest player in silicon carbide fibre-reinforced materials. SiC ceramics are based on lithium oxide-alumina-silica matrix, and contain 50 per cent SiC reinforcing fibres. Fracture toughness is 25 MPa-m$^{1/2}$ at 1000°C. Potential uses are in spacecraft, aircraft, and automobiles. SiC-reinforced metals contain 40 per cent fibres and 60 per cent aluminium, and have a tensile strength of 120 kg mm$_2$. The company has also developed an aluminium-coated SiC wire that can be used to make preforms. Potential uses are in aerospace and automobile engine fan blades and parts, and golf and baseball equipment. (Nippon Carbon Co., Ltd., 2-6-1, Hatchobori, Chuo-ku, Tokyo 104, Japan) (Source: High-Tech Materials Alert, August 1987; please take also note of the article "Multi-Filament Continuous SiC Fibre 'NICALON' Reinforced Aluminium Composite Wires", presented at the 20th International SAMPE Technical Conference, 27-29 September 1988, on page 92)

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Squeeze mould whisker and short-fibre preforms

A new, economical process to injection mould ceramic-whiskers and short fibres into preforms could be one of the latest success stories. That is because the lack of cheap preforms has held back further use of metal-matrix composites (MMCs) even as particulate-reinforced MMCs make market inroads. And the developer, Technical Ceramics Laboratories (TCL), wants joint ventures and applications development.

The TCL process economically produces complex shapes from such desirable reinforcements as silicon carbide and silicon nitride whiskers, ICI's Saffil alumina fibres, and chopped carbon fibre. You can make the preforms into metal-matrix composites by squeeze casting and other pressure and vacuum processes, or use them to reinforce sections of monolithic metal structures.

Injection moulding high aspect ratio (length:diameter) whiskers is no small trick, since the high aspect ratio of the whiskers usually suppresses injectability. Yet TCL has produced uniform, agglomerate free preforms from fibres and whiskers whose aspect ratio ranges from 20:1 to 100:1.

TCL does not say how it manages to inject whiskers, though it does outline the moulding process. First, the laboratory mixes whiskers or fibres with surfactants to aid wet-out and thermoplastic binders. (It can also add ceramic or metal particulates to the mixture and still maintain the random orientation of the fibres.) After moulding, the organic phase is burned off.

The resulting preforms can be made in any shape, are as strong as chalk, and require no special handling. The process lets you make larger parts at lower pressures than commonly associated with injection moulding of plastics.

Compare that to filtering ceramic fibre slurry, the way conventional ceramic whisker preforms are made. Filtering creates oriented, low-density fibre mats that contain wide variations in density that cannot uniformly reinforce anything. If you want to make a complex preform, you have to press the mats together and machine an expensive, labour-intensive process.

TCL, which has filed for a patent, has already produced some impressive preforms with the process, such as a 6-in-diameter curved, hexagonal mirror blank only 0.250-in thick.

Technical Ceramics believes it can make parts several feet long and wide and only inches thick. You can also use the preforms to make vapour-infiltrated ceramic composites. The laboratory is now looking for partners to commercialize the technology. (Technical Ceramics Laboratories, Inc., P.O. Box 385, Alpharetta, GA 30201, USA) (Source: High-Tech Materials Alert, July 1989)

* * * * *

Battelle Memorial Institute is negotiating with several firms to further develop its evaporative pattern casting (EPC) process for metal-matrix composites (MMC). Battelle's (Columbus, OH) metals processing section said the need for lightweight parts and for a new casting capability that would allow low-cost processing of certain composites are the impetus for trying to begin such a programme. An advantage of using the EPC process for MMCs is that the particulates can be moulded into the foam, providing a means to mechanically place them in the proper distribution in the mould cavity. Possible uses of MMCs using the process would mainly be engine parts including connecting rods, disc brake rotors, pistons and cylinder blocks. (Source: MetalwNews, 25 May 1987)

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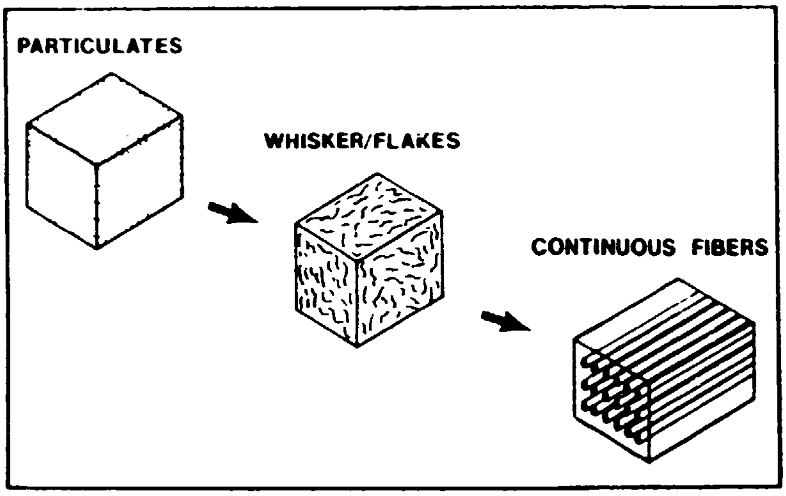


Figure 1. Metal matrix materials

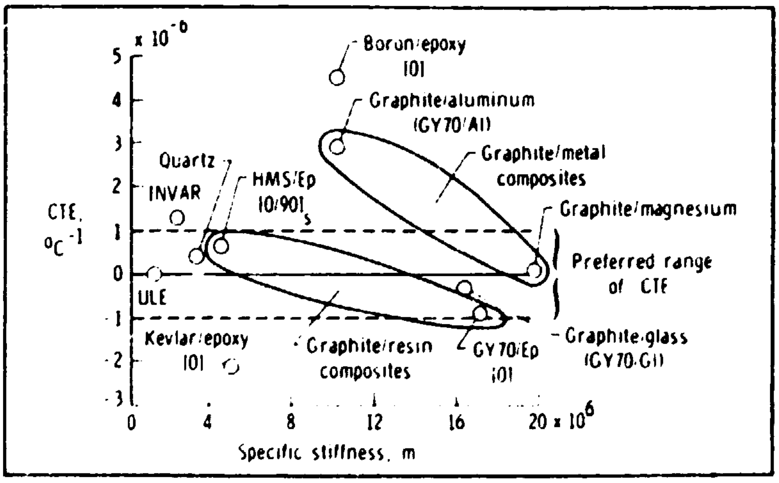


Figure 2. Stiffness and coefficient of thermal expansion (CTE) of composites for space applications

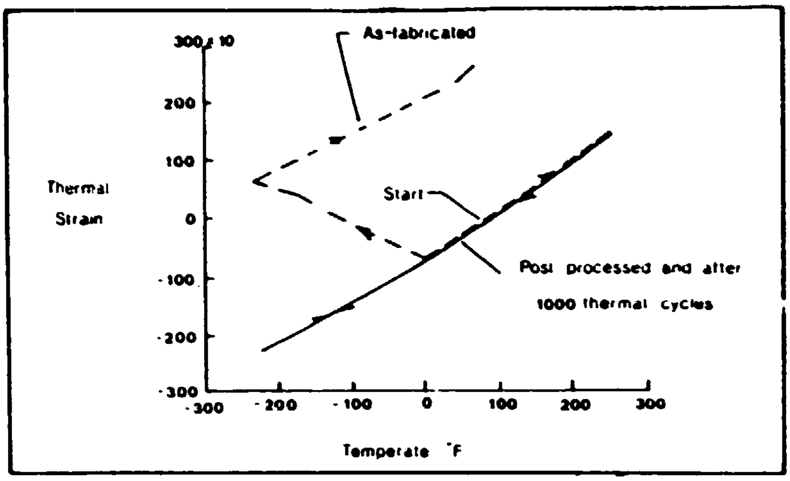


Figure 3. Thermal expansion of P100 Gr/2024 Al as-fabricated and after post processing and 1000 cycles between ± 250°F (121°C)

	TCE (ppm/°C)
Aluminum	23.5
SiC 40	12.1
SiC 50	9.4
SiC 55	8.2

Figure 4. Thermal coefficient of expansion (TCE) of electronic grade SiCp/Al

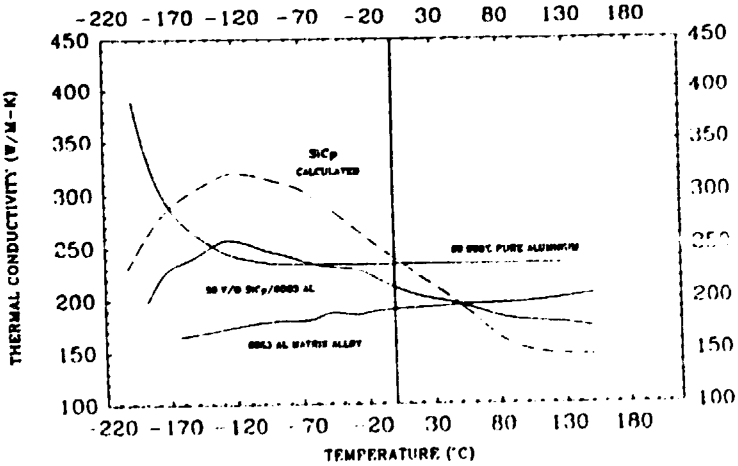


Figure 5. Thermal conductivity curves of 6063 Al and 50 v/o SiCp/6063 Al MMC. Theoretical SiCP curve is calculated by extrapolation of the 6063 Al and MMC data to 100% SiCp

	Density (g/cm³)	Thermal K (W/m/°K)	Specific Thermal K (K/ρ)	C.T.E. (ppm/°C)	Modulus (msi)
Alumina	3.2	30	9.4	7.2	50
Copper	8.8	391	44.4	17.5	17
Aluminum	2.7	221	81.9	23.5	10
Molybdenum	10.1	146	14.5	5.2	50
Kovar	8.1	17	2.1	5.4	20
Copper/Invar/Copper	8.1	131	16.2	5.4	--
Thermkon®83 (Cu-W)	14.8	190	12.8	8.3	36
Thermkon®68 (Cu-W)	16.6	167	10.1	6.5	35
SiC 40 MMC	2.9	130	44.8	12.1	20
SiC 50 MMC	2.9	200	69.0	9.6	25
SiC 55 MMC	3.0	200+	66.7+	8.2	29

Figure 6. Properties of electronic grade SiCp/Al MMC and conventional materials

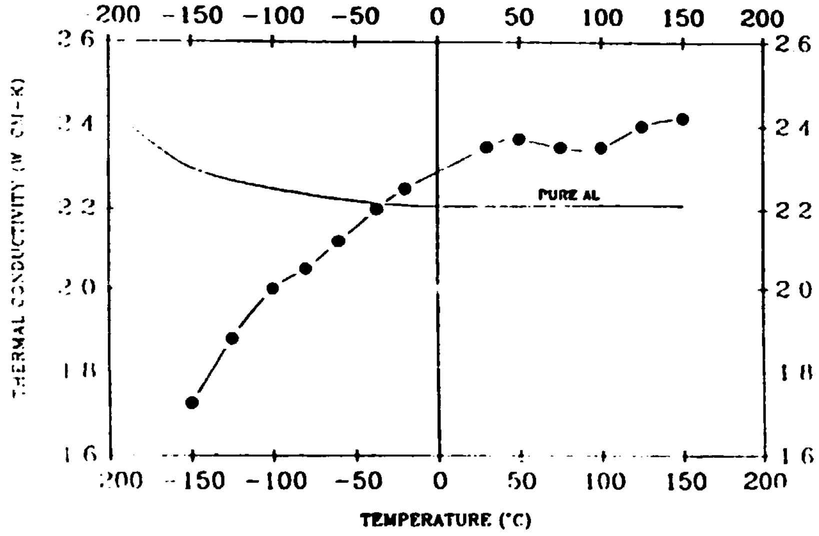
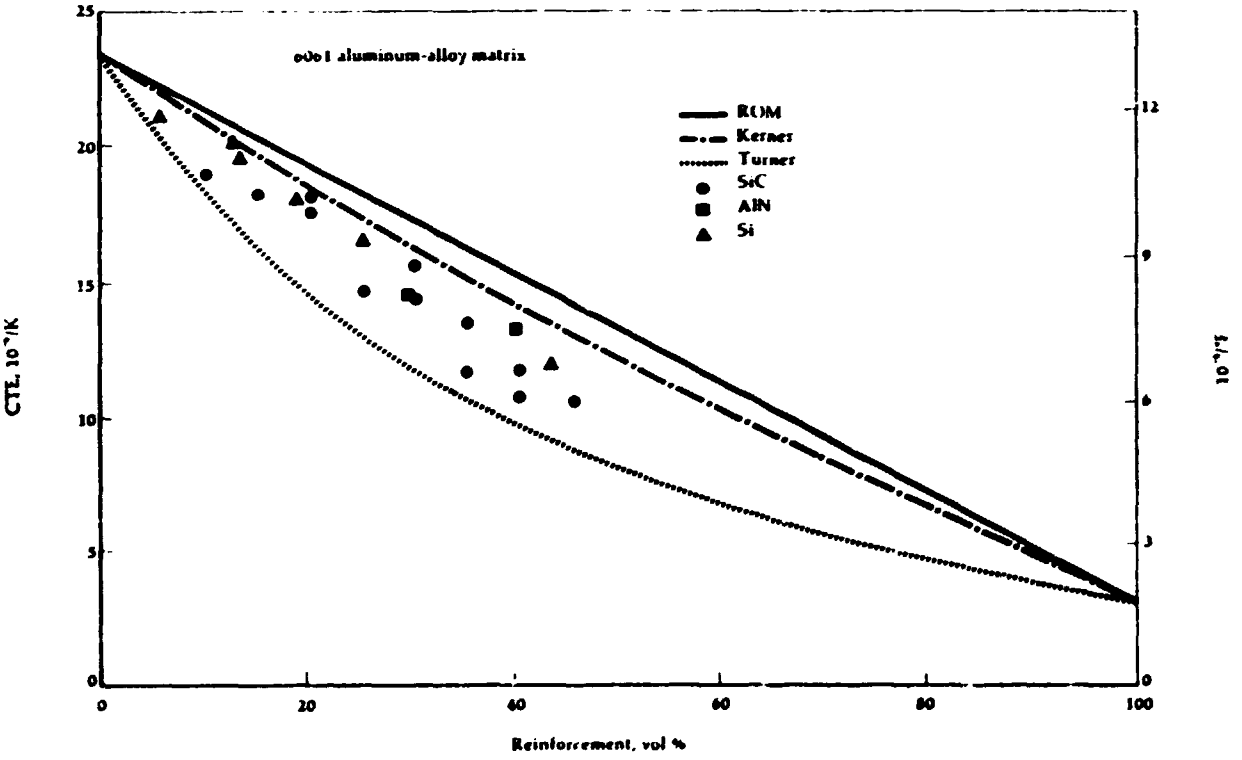


Figure 7. Thermal conductivity of 40 v/o Type IB diamond/Al MMC

Properties of selected matrix and reinforcement materials

	Young's modulus		Poission's ratio	Bulk modulus		Thermal conductivity		Coefficient of thermal expansion		Density	
	GPa	(10^6 psi)		GPa	(10^6 psi)	W/m K	(BTU/ft hr °F)	10^{-6}/K	(10^{-6}/°F)	g/cm^3	(lb/in.^{3})
Matrix Alloys											
6061 Al (T6)	70.3	(10.2)	0.34	75.2	(10.9)	171	(99)	23.4	(13.0)	2.68	(0.097)
2124 Al (T6)	72.3	(10.5)	0.34	77.7	(11.3)	152	(88)	23.0	(12.8)	2.75	(0.099)
ZK60A Mg	44.8	(6.5)	0.29	35.9	(5.2)	117	(68)	26.0	(14.4)	1.83	(0.066)
Reinforcements											
Carbides											
SiC_w	400	(58)	0.20	221	(32)	32	(18.5)	3.4	(1.9)	3.21	(0.116)
SiC_p (Grade 3)	400	(58)	0.20	221	(32)	120	(69)	3.4	(1.9)	3.21	(0.116)
B_4C	448	(65)	0.21	255	(37)	39	(22.5)	3.5	(1.9)	2.52	(0.091)
Nitrides											
AlN	345	(50)	0.25	228	(33)	150	(87)	3.3	(1.8)	3.26	(0.118)
Si_3N_4	207	(30)	0.27	152	(22)	28	(16)	1.5	(0.8)	3.18	(0.115)
Oxides											
Al_2O_3	379	(55)	0.25	255	(37)	30	(17)	7.0	(3.9)	3.98	(0.144)
SiO_2 (fused quartz)	73.1	(10.6)	0.17	36.6	(5.3)	1.4	(0.8)	<1	(<0.6)	2.66	(0.096)
$LiO_2 \cdot Al_2O_3 \cdot 4SiO_2$	67.6	(9.8)	0.19	36.6	(5.3)	1.3	(0.8)	<1	(<0.6)	2.38	(0.086)
$LiO_2 \cdot Al_2O_3 \cdot 8SiO_2$	69.0	(10.0)	0.18	35.9	(5.2)	1.3	(0.8)	<1	(<0.6)	2.39	(0.086)
$Al_2 \cdot TiO_5$	30.3	(4.4)	0.20	16.6	(2.4)	2.0	(1.2)	1.0	(0.6)	3.68	(0.133)
Others											
Si	112.4	(16.3)	0.42	235	(34)	100	(58)	3.0	(1.7)	2.33	(0.084)
C fiber (P100) (L)	690	(100)	—	—	—	400	(231)	-1.5	(-0.8)	2.18	(0.079)
C fiber (P100) (T)	—	—	—	—	—	—	—	30	(16.7)	2.18	(0.079)



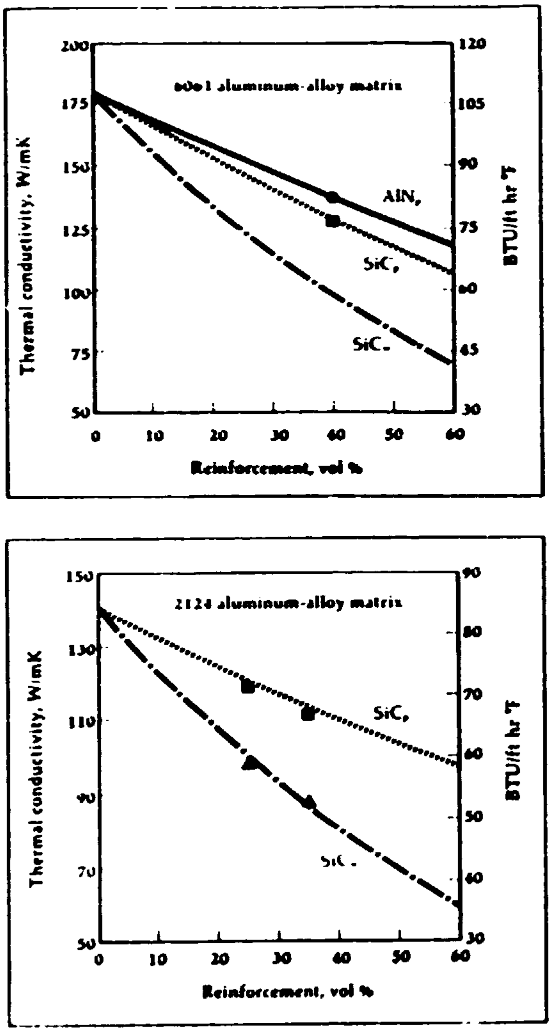
High reinforcement loadings are required in aluminium matrix composites to achieve low values of coefficient of thermal expansion (CTE). The measures CTE values for 6061 aluminium alloy reinforced with particulate AlN or silicon shown here appear to agree fairly well with the Kerner mathematical model, while the CTEs for composites reinforced with particulate SiC are closer to the Turner predictions; incorrect values used in the calculations or differences in matrix/reinforcement bonding may be responsible for this difference.

Source: Advanced Materials Processes.

Coefficient of thermal expansion for MMCs[1]

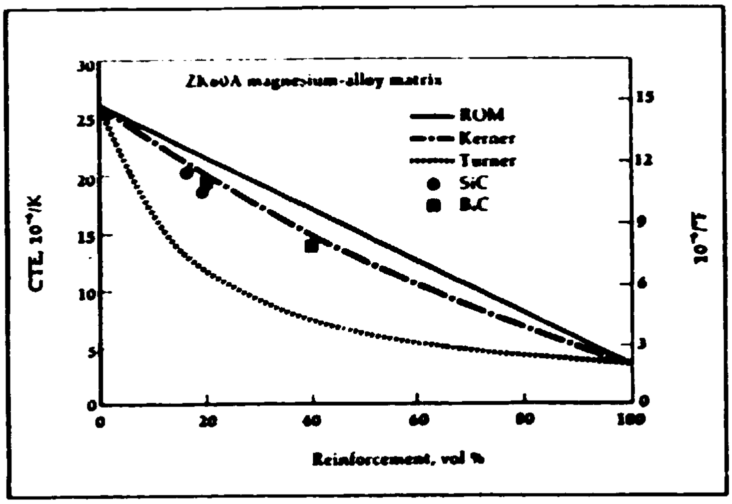
Reinforcement	Matrix alloy 6061 aluminum	 ZK60A magnesium
SiC	14.5	16.5
B_4C	14.5	16.5
AlN	15.5	—
Si	15.5	—
Al_2TiO_5	17.8	—
$LiO_2 \cdot Al_2O_3 \cdot 8SiO_2$	18.0	—

[1] *Average values for 0 to 150°C,* 10^{-6}/K of MMCs containing 30 vol % reinforcement.



The measured thermal conductivities of aluminum-matrix composites reinforced with particulate SiC are markedly higher than those of composites reinforced with SiC whiskers, but below those of composites reinforced with particulate AlN.

Prototype components made from the three-component composite are being evaluated.



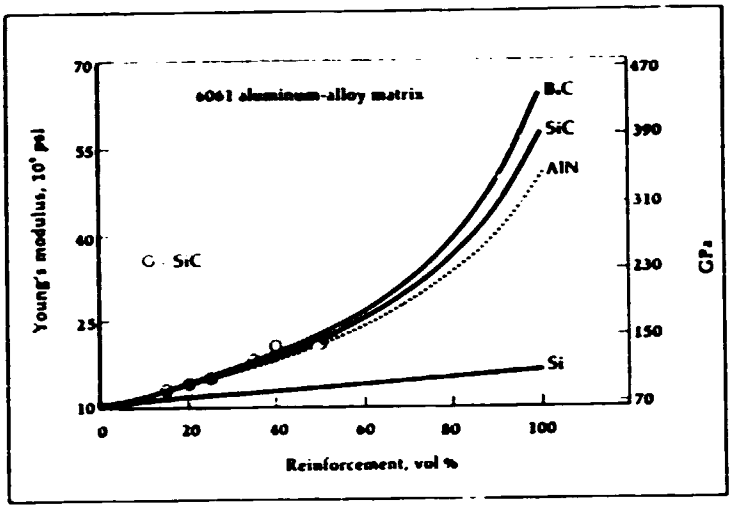
Magnesium-matrix composites show similar results to aluminum-matrix composites, except that both particulate SiC and particulate B_4C reinforcements in ZK60A magnesium alloy give measured CTEs much closer to the Kerner model than those predicted by the Turner model.

Source: Advanced Materials Processes.

Properties of some electronic grade aluminium matrix composites

	Density		Coefficient of thermal expansion[1]		Thermal Conductivity	
	g/cm^3	(lb/in.^{3})	10^{-6}/K	(10^{-6}/°F)	W/mK	(BTU/ft hr °F)
SXA A 61/40[2]	2.89	(0.105)	10.8	(6.0)	128	(74)
6061/40AlN$_p$[3]	2.92	(0.106)	13.5	(7.8)	137	(79)
Al/SiC$_p$/Si[4]	2.81	(0.102)	8.7	(4.8)	120	(70)

[1] Average values for -55 to +35°C [2] Commercial MMC with particulate SiC reinforcement registered by Advanced Composite Materials Corp [3] Experimental MMC with particulate AlN reinforcement. [4] Experimental MMC with particulate SiC and Si reinforcement, patent pending



Most low-expansion reinforcements increase the Young's modulus of aluminum-matrix composites at a similar rate from 0 to 40 vol % loading; the exception is silicon, which has a much lower effect. The measured values of Young's modulus for the SiC reinforced MMCs agree with the values predicted by the Hashin and Shtrikman model.

Source: Advanced Materials Processes.

Fibres make metals stronger

Recent developments in ceramic materials have led to a renewed interest in fibre reinforced materials, especially metal-matrix composites. Cray Advanced Materials UK, backed by Cray Electronics, was formed in 1986 to exploit the properties of this new material. The company operates under a licensing agreement from the Ministry of Defence and uses the patented Liquid Pressure Forming (LPF) process, a new technique developed for making components from fibre reinforced metals

Commercial applications of metal matrix composites presently at the feasibility demonstrator stage include components for the automotive industry, such as pistons, connecting rods, brake calipers, and wheels; as well as gas cylinders, marine propellers, armour plate, lead battery plates bicycle frames, robotic arms, train overhead electric pantographs and specialized tools.

Many other possibilities are presently being explored and although metal composite components have the reputation of being expensive, Cray believes that its unique process has significantly reduced product costs. The company strategy does not involve volume production of composite components, but rather the offering of sub licence in order to exploit fully the benefits that this remarkable material will bring to engineering.

Cray's LPF metal matrix composites have already found applications within the military, aerospace and competition racing industries. Of particular note is a four-module torpedo hull currently being produced. Cray believes that it would be extremely difficult, if not impossible, to produce this by any other method.

The LPF process is a technique for the production of ceramic fibre reinforced metal components in net shape or near net shape, with excellent dimensional tolerances and exceptional mechanical properties. Various types of ceramic fibres, such as silicon carbide, alumina, boron and carbon can be used with metals such as aluminium, magnesium, lead, zinc or copper alloys.

Fibre preform

For the process, a die is manufactured which contains a cavity in the shape of the components required. The reinforcing fibres are made into a preform, whose shape and fibre direction will enhance the performance of the component. Selective local reinforcement is also available if required. The preform may be a combination of various types of fibres as required, or a simple pre moulded shape of random short fibres.

In designing a preform, fibres are aligned to accommodate areas of high stress. When continuous fibres are used, a preform is produced by winding fibres as single tows, filaments or woven fabric into the predetermined shape. Discontinuous fibres of materials such as alumina are held in a preform by a ceramic binder.

After the preform has been placed in the heated die, the cavity is evacuated and when the condition of the metal, die and preform is correct, the molten metal is forced into the die to infiltrate the fibres and totally fill the cavity. The evacuation serves several purposes. Firstly it degasses the melt, removing any dissolved gas which could cause porosity on solidification. Secondly it removes air from the die cavity and volatile binders from the preforms, eliminating contamination by residual gases and oxidation of the molten metal. Finally it means fast and complete infiltration.

The pressure required in the LPF process is considerably lower than that used in alternative processes such as squeeze forming and diffusion bonding, with a consequent reduction in the risk of fibre damage. The following fibre forms are being successfully used to produce metal composite components:

- Silicon carbide monofilament;
- Silicon carbide cloth;
- Boron monofilament;
- Random alumina;
- Aligned alumina;
- Random carbon fibre;
- Continuous carbon fibre; and
- Steel wire.

Low die costs

The Cray LPF process can be used to produce complex shapes which vary in size from a few centimetres up to 2 x 1.5 x 1.5 m. It is essentially a single batch process that produces a net shaped reinforced component, with tolerances in the region of ± 0.2 per cent. As production times are relatively short and die costs low for volume output, component costs are lower than for other existing processes.

The advantages of producing a net shape are obvious, but if further machining is necessary or desirable this can be accomplished by conventional machining using tungsten carbide tools or electro discharge machining.

Alternatively, non reinforced areas can be designed into a component so that only the matrix alloy itself is subject to machining.

Although metal matrix composites have so far been confined to applications within the aerospace, military and competition car markets, design engineers in other civil and commercial areas should be aware of the advantages and potential of these materials. For instance, the tensile strength, compressive strength and tensile modulus of a reinforced aluminium component are two to four times greater than those of an unreinforced aluminium alloy, on a weight for weight basis.

Consider, as another example, a racing car travelling at 320 km/h (200 mph). On braking, friction generates a considerable amount of heat which increases the temperature of ordinary brake calipers dramatically, causing them to suffer a marked loss of stiffness. A caliper made from fibre reinforced aluminium would show no loss of stiffness or strength under these conditions and its lower thermal conductivity would reduce heat transfer to the hydraulic oil.

In polymer composites which are reinforced uniaxially, the tensile strength is dominated by the strength of the fibres. This is also the case in fibre reinforced metals. So when axial tensile strength at a relatively low temperature is the major design consideration, then a polymer composite may provide the lightest, cheapest option.

Transverse strength

The transverse strength, however, is generally a function of the matrix properties. In the case of a good resin it will be of the order of 40 MPa but for a fibre reinforced metal it will be much higher, around 170 Mpa. If, for example, a transverse strength of 150 MPa is required in a resin system, then a 0/90° layup of fibres must be used, which substantially reduces the overall composite properties and increases cost. In metal-matrix composites however, a simple unidirectional lay-up would suffice.

Strength in compression is related to both fibre and matrix properties and to the relationship which exists between the two. Carbon epoxy for example, has a relatively poor compressive strength (approximately 1200 MPa) compared with fibre reinforced metals. This is due to the low strength of the matrix which allows buckling of the fibres, and the low strength in compression of the carbon fibres. The strength of fibre reinforced metals is also a function of the above criteria. When the high strength of the matrix is combined with a fibre that is resistant to buckling, and then processed by the LPF technique which ensures strong interfacial bonding, the resultant compressive strength is extremely high (3000 to 4000 MPa).

But perhaps the single most important property used in the design of structures is stiffness. The modulus in the fibre direction for a good carbon epoxy uniaxial composite is comparable with that of steel (around 200 GPa). However, in the transverse direction it is extremely low (around 7 GPa). This means that the material is highly orthotropic. This aspect has in the past led to design difficulties and to the development of complex weaves to overcome the lack of off-axis stiffness. The actual design is therefore a compromise, where the very high axial stiffness cannot be readily realized.

The modulus of a composite is a function of the modulus of the fibre, the modulus of the matrix and to a lesser extent the strength of the fibre/matrix interface bond. In the case of a carbon epoxy composite for example, the modulus of the resin is relatively low (around 3 GPa) and the transverse modulus of the fibre is low. Whilst the matrix bond may be good, the overall modulus is held down by the first two characteristics.

Conversely, boron/aluminium has a relatively high modulus, because both the matrix and fibre transverse moduli are high. The transverse modulus for this system is around 138 GPa. The carbon/aluminium system is however an exception, having a low transverse modulus because carbon fibres lack transverse stiffness. Although the modulus of the matrix is relatively high, the overall transverse modulus is low, at 30 to 40 GPa.

Fibre reinforced metals are also characterized by having higher shear moduli than resin composites, by a factor of approximately 10. The combination of high axial and transverse moduli means that the very high unidirectional properties of a metal composite can be realized in practice.

Fatigue is often a design criterion of great importance. Metal composites generally have higher fatigue limits than comparable isotropic metals. The high fatigue resistance is related to the presence of the fibres which act as Griffiths crack stoppers. As a crack propagates through the matrix and approaches a fibre, the stress will be relieved by the hole in which the fibre sits, provided there is not a brittle interface bond. The crack will have to re-initiate on the opposite side of the fibre before propagation can continue. A similar situation exists for resin-based composites, although poor off-axis properties limit the full fatigue performance to certain directions only.

Fracture toughness

The fracture toughness of a metal, which is a measure of the work required to extend a crack, can be increased by using fibre reinforcement. A crack trying to cut through a bundle of fibres in a metal matrix will tend to turn along the fibre axis rather than continue in the transverse direction. The fracture toughness is dependent upon the volume fraction of fibres, the fibre orientation and diameter.

For a uniaxially reinforced boron aluminium composite with a 50 per cent volume fraction of fibres, the fracture toughness will be about 82 MPa $\sqrt{m}$ compared with 49 MPa $\sqrt{m}$ for the unreinforced alloy. Any fibre orientation other than uniaxial reduces the fracture toughness, as there will be fewer fibres in the load direction.

One of the most outstanding characteristics of fibre reinforced metals is the retention of their properties at elevated temperatures, as illustrated on the graph on page 129. Ceramics are also known to have very low coefficients of thermal expansion. For metal composites, assuming a good fibre matrix bond, the resultant coefficient is a function of the fibre and matrix coefficients, relative stiffness, fibre matrix bonding and volume fraction. The coefficient of thermal expansion will differ according to fibre direction. For example, in a silicon carbide/aluminium composite, the coefficient of thermal expansion is 6×10^{-6}/°C in the longitudinal direction, and 17×10^{-6}/°C in the transverse direction.

Carbon aluminium is a special case, since the fibre coefficient of expansion is negative in the longitudinal direction. This means that it is possible to produce a material with a zero coefficient of expansion in the fibre direction. Alumina has been used in chopped random form to produce an isotropic coefficient of 15×10^{-6}/°C at a volume fraction of 24 per cent. Carbon could also be used to produce a material with an isotropic coefficient of approximately 6×10^{-6}/°C.

The friction and wear properties of metal composites vary according to fibre type, but are generally good. Aluminium containing boron or silicon carbide as reinforcing fibres will produce characteristics similar to that of the reinforcing ceramic.
(This article was first published in Engineering Magazine, London, November 1987)

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Pilot plant for MMC precursors

Recent completion of a Navy manufacturing technology project at Cordec (Lorton, VA, USA) promises mass production of thin (0.0003 0.0008 in), pliant, metal matrix composite (MMC) tapes by vapour deposition techniques. The tapes, metal based and reinforced with graphite or ceramics fibres, are intended to serve as precursors in component fabrication, as do prepregs for the well established organic-matrix composite components.

Although the programme is focused on production of graphite-fibre-reinforced-aluminium tape, the versatility of the process has been exploited to also produce graphite/magnesium, graphite/copper and silicon carbide/titanium tape. These tapes can be wound on mandrels, or cut into plies and placed on dies for shape buildup, and then consolidated and diffusion bonded by heat and pressure.

In the continuous process at the pilot plant, tow comprised typically of thousands of fibres is drawn from a creel and the fibres spread into a monolayer. The fibres are then plasma-cleaned by argon-glow discharge, coated with metal by magnetron sputtering and the tape thus formed wound on a takeup reel.

The eight-chamber vacuum-coating system on the process-development line, which can produce tape to 2.5 in wide in lengths to 5000 ft, can be configured to deposit as many as six different sequential coatings on the fibres in a single pass. These coatings can be used to compound the matrix or serve as eutectic bonding agents, diffusion barriers, complaint layers or oxidation-resistant layers.

Besides the process-development line, two production lines can produce tapes to 6 in wide in lengths to 5000 ft. Production rates for graphite/aluminium, graphite/copper and graphite/magnesium are about 0.5 ft/min.

These are modular lines and they can be configured with a single high-rate coating module or, to increase throughput or produce multilayer coatings, additional coating modules. Coating processes include plasma-enhanced chemical vapour deposition, rf and dc magnetron sputtering, conventional and reactive ion plating, and thermal evaporation. System design is intended to facilitate converting the lines to new MMC production as user requirements change.

Also exhibited at the end-of-project demonstration at Cordec were facilities for consolidating thin-sheet MMCs by hot pressing, pultrusion and strip drawing. Sample products included panels of the graphite-reinforced metals noted earlier, seamless thin-wall graphite/magnesium tubes having a zero coefficient of thermal expansion, Nextel (alumina-boria-silica)-fibre-reinforced titanium aluminides, and graphite/columbium-nitride/copper superconducting tape. (Source: American Machinist, August 1989)

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Extremely high densities in metal-matrix composite (MMC) preforms are achieved by a process developed by Technical Ceramics Laboratories. Process works equally well with ceramic-matrix composites. The new technique gives an economical way to make complex-shaped preforms for reinforcing metal matrix and ceramic matrix composites. This will put MMCs into a much better commercial position than they have been. Using the technology, densities of at least 75 per cent vol are being achieved; in one instance, density hit 87 per cent.

The company has developed a way to injection-mould short ceramic or metal fibres and whiskers into complex shaped preforms. Matrix is introduced by a pressure or vacuum assisted process such as squeeze casting. Near-net-shape ceramic-matrix composites can be made by chemical vapour infiltration of the preform. Process can also be used to selectively reinforce a particular section of a part. To make part, shaped preform of ceramic fibres is placed in mould and molten metal is introduced. Ceramic fibre preforms are made by filtering a slurry of ceramic fibres to form a mat. (Technical Ceramics Laboratories, Inc., P.O. Box 385, Alpharetta, GA 30201, USA) (Extracted from Inside R & D, 5 July 1989)

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Infiltration process produces pore-free MMCs

A patented process for producing pore-free metal-matrix composite (MMC) components has been developed by Lanxide Corp., Newark, Del., USA. The Primax pressureless infiltration technique uses no pressure or vacuum apparatus, facilitating production of large, complex net or near-net-shape MMC components.

High reinforcement loadings and reinforcement geometries ranging from particles to continuous fibres are possible with the process, which uses either shaped loose masses or bonded preforms of ceramic reinforcing materials such as alumina (Al_2O_3) and silicon carbide. Initial experience has been with an aluminium-alloy matrix material that contains magnesium to enhance wetting of the reinforcing phase.

The first commercial product resulting from the process is NX-5101, an Al/Al_2O_3 composite. Additional aluminium-matrix materials are expected to be available soon. (Source: Advanced Materials & Processes, July 1989)

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Low cost alumina fibre for metal and polymer composites

A new, fine diameter (ca. 3 µm), semi-continuous alumina fibre, called Safimax, with high strength and modulus, which is priced at only $50/lb ($110/kg), is under development at ICI. With the present price of fibres with comparable properties such as Nicalon, Fiber FP, and Sumitomo's Alumina around $200 to $300/lb ($440 to $660/kg), the availability of Safimax should make it possible to produce cheaper aluminium and magnesium alloy metal-matrix composites (MMCs).

The polycrystalline fibre composed of 95 per cent alumina and 5 per cent silica is available in a low density (LD) and a standard density (SD) grade. The LD grade has a density of 2.0 g/cm^3, a tensile modulus of 200 GPa (29 msi), a tensile strength of 2000 MPa (290 ksi), and a maximum use temperature of 900°C (1652°F). The SD grade has a density of 3.3 g/cm^3, a tensile modulus of 300 GPa (43 msi), a tensile strength of 2000 MPA (290 ksi), and a maximum use temperature of 1600°C (2912°F). Because of its low density, the LD grade has good specific properties, as can be seen in figure 1, which compares the specific strength and modulus of Safimax alumina fibres with those of other continuous, inorganic fibres.

Similar to ICI's Saffil fibres, they have excellent resistance to molten light alloys. The stiffness properties of light alloy MMCs compare favourably with titanium and steel, and because of the low MMC density, the weight of fabricated components could be reduced by as much as 50 per cent. Anticipated initial applications are for engine support frames in aircraft and for gearbox, compressor, and fuel pump parts. And because of the fibre's low dielectric constant and good wettability and adherence to epoxy resin, Safimax fibre reinforced polymers could be useful as electronic materials. ICI also envisions future applications in ceramic composites. Developmental quantities of the fibres are now available. (ICI Chemical and Polymers Group, P.O. Box 11, The Heath, Runcorn, Cheshire, WA7 4QF, UK) (Source: Materials and Processing Report, October 1987)

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Alanx Products has started up a new 4,650 sq m ceramic/metal composites pilot plant in Newark, DE.

The plant will make parts and systems produced with new type of ceramic-metal composites for industrial uses where resistance to wear is vital. The materials feature high strength, toughness, wear resistance, less brittleness, and no densification shrinkage. A part or system made with the materials can be engineered to accommodate the needs of a certain wear-sensitive use via picking the fitting composite. Parts produced with the new composites are made at net or near-net shapes via a proprietary technology involving the oxidation of molten metal. Alanx is jointly owned by Alcan Aluminum and Lanxide. (Source: Ceramic SB, January 1989)

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Aluminium matrix composites are expected to supply better performance and efficiency in a broader variety of uses as prices fall. A majority of aluminium composites offer such benefits as light weight, good thermal conductivity, high shear strength, good abrasion resistance, high temperature capacity, non-flammability, minimal attack by such organic fluids as fuels and solvents, and capacity to be created and treated by customary techniques using present equipment. Consistently high quality products are now offered in large amounts, with major manufacturers expanding output and pledging lower prices. (Source: Material Eng., January 1989)

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A new method to produce high-quality, close-tolerance near-net-shape parts from fibre-reinforced aluminium matrix composites was unveiled at the University of Delaware's Centre for Composite Materials (Newark, DE). The centre has successfully applied compocasting, a slurry process, mixed with squeeze casting to produce shapes from an aluminium-copper alloy reinforced with short alumina fibres. The centre said advantages include the possibility of producing aluminium matrix composites with up to 60 per cent reinforcement, composites with less fibre damage vs other methods, and lower cost vs many other methods. The process also keeps the thixotropic properties of the base aluminium. (Source: MetalwNews, 26 October 1987)

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Metal composites take wing

What do you get when you combine the light weight of aluminium with the strength and stiffness of titanium? If you're Lockheed-Georgia, probably an aluminium metal-matrix composite (MMC). It works the same way as reinforced organic composites: add a strong, stiff fibre to a softer matrix to boost properties. In this case, Lockheed is experimenting with two different types of silicon carbide (SiC) ceramic stiffeners. The first is continuous 0.056 in diam SiC fibres, which are applied to 0.001-0.002 in-thick Al 6061 alloy, then covered with plasma sprayed 6061. Multiple sheets of composite are then cut, laid out, and autoclaved to produce finished parts. The fibres are made by Avco Specialty Materials Divison. The second reinforcer is single-crystal SiC whiskers (0.5-micron-diam, 20-40 microns long), made from rice hulls. They are blended (up to 25 vol per cent) with Al powder and hot compacted into cylindrical billets that can be made into sheets, plates, extrusions, or forgings. The whiskers were developed by Arco Chemical Advanced Materials Co. Lockheed will fabricate each MMC into two vertical fins with 150-in span and 40-in chord as part of the Advanced Tactical Fighter programme. (Source: Aerospace America, September 1986)

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Dural Aluminium Composites produced a 6 ft long, 7-in-dia metal-matrix composite (MMC) billet using direct-chill (DC) casting. The material was a 6061 aluminium reinforced with 10 per cent silicon carbide grinding media. The direct-chill casting technique employs a short, water-cooled metal mould. Molten metal is poured into the top of the mould and the ingot is lowered by a hydraulically operated platform as it is cast. Alcan Aluminium (Cambridge, MA), Dural's parent, built a 25 mil lb/yr ceramic-reinforced aluminium plant. Dural can produce extrusion billet, rolling slabs and foundry pig at its San Diego, CA, plant. Alcan will initially emphasize MMC extrusion billet and foundry pig, but, will produce MMC rolling slabs for sheet and plate. (Source: MetalwNews, 14 March 1988)

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New research planned for metal-metal composites

A 750,000 pounds sterling three-year investigation of processes suitable for commercial volume production of fibre-reinforced aluminium and magnesium alloys is being launched by the BNF Metals Technology Centre.

Existing production processes for these materials are discontinuous and labour intensive. BNF hopes to develop simplified semi-continuous, and possibly fully continuous, manufacturing techniques for sheet, strip and simple sections. It is now seeking support for the project from industry and hopes to share the costs between 20 or so manufacturers. Five types of company are likely to benefit from this work. BNF believes:

- Manufacturers working in light alloys who see fibre reinforcement as a natural or desirable extension of their product range;

- Companies working in heavier materials such as ferrous and copper alloys who cannot ignore light alloy composites as potential serious rivals;

- Fibre makers who wish to increase the demand for their products;

- Companies planning to enter the metal metal composites field either as manufacturers or users; and

- Existing users of these materials who are seeking improvements in material quality, reliability and design and reductions in costs.

Further information on the project is available from BNF Metals Technology Centre, Denchworth Road, Wantage, Oxfordshire OX12 9BJ. (This article was first published in Engineering Magazine, London, January 1987)

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Powder metal (p/m) alloys and metal matrix composite materials with aluminium can be welded in the laboratory, but problems are encountered with the materials in a production environment, according to Aluminium of America's laboratory (Pittsburgh, PA). Some p/m alloys and metal matrix composites tend to have a lower flow in the weld area due to large amounts of oxides found in the material. Porosity related to hydrated or moist particulates are also found within the base material itself. Weld porosity is caused by the internal hydrogen in the p/m and p/m-based metal matrix composites due to the hydrates on the oxides found on the surfaces of the small particles used in processing the material. Solid-state degassing methods have been used to cut the hydrogen in aluminium based materials and enhance the weldability with less porosity. Work has been done with an aluminium-zinc-magnesium-copper alloy that was degassed in a vacuum at 890F, which is near solution heat treating for the alloy. (Source: MetalwNews, 21 March 1988)

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Toughened complex composites

Research at Drexel University shows that the use of 3-D fibre architecture markedly improves through-the-thickness strength and damage tolerance in fibre reinforced composites. Most importantly its use eliminates failure due to delamination; a problem with conventional composites. The types of fibres processed successfully into 3-D fibre preforms include alumina, silicon carbide, pitch 100 base graphite, as well as the more conventional glass and aramid fibres. The matrix materials can be thermoset or thermoplastic polymers, alloys, ceramics, or carbon. Available 3-D fibre architectures, each with different structural toughening capabilities, include multiwarp woven fabrics, xyz structures, multiaxial-warp knit structures for complex curvatures, and 3-D braided structures for the direct formation of solid near-net shapes. Simple, and complex shapes such as I-beams, air foils, and hat stiffeners can be formed.

Metal matrix composites also have been toughened with 3-D fibre architecture. For example, in a drop weight impact test comparing the behaviour of a 3-D braid FP-Al-Li composite (17 per cent fibre volume fraction) with a unidirectional composite (35 per cent fibre volume fraction), the energy needed to initiate cracks in the 3-D braid is about four times as great as in the unidirectional composite, and a much smaller damage area was created. The 3-D braided composites also are able to absorb more energy, and should be more impact resistant at higher fibre loadings. (Source: Advanced Materials & Processes, April 1988)

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Hybrid fibres improve composite strength

A new technique that maximizes the performance of fibres in a metal matrix composite has been developed at the Toyota Central Research and Development Laboratory. In the patented process, continuous fibres are passed through a slurry containing either silicon carbide (SiC) whiskers or fine particulates, some of which adhere to the fibre surface or are homogeneously dispersed among the fibre filaments forming a hybrid fibre.

When hybridization of silicon carbide fibres are used to reinforce aluminium matrix composites made by squeeze casting, both the longitudinal and transverse strengths are increased compared with conventional fibre reinforced composites. The explanation appears to be that during the casting process the fibre preform is compacted by the rapid flow of the molten metal. This results in fibre-to-fibre contacts, which have been found to markedly decrease the strength of fibre reinforced metal matrix composites (FRMs). The presence of the whiskers or particulates on the fibre surface effectively prevents direct fibre contact, so that after metal infiltration each fibre is separated from its neighbours by the metal. A further advantage of the hybrid fibre process is that it allows some control of the FRM's fibre volume fraction.

Toyota researchers in co-operation with UBE have applied their process to UBE's continuous inorganic Si-Ti-C-O fibre, Tyranno fibre with very encouraging results. Figure 2 shows the improvement in the mechanical strength of squeeze cast pure aluminium and aluminium alloy (Al-4 per cent Cu) matrix composites reinforced with hybrid Tyranno fibres obtained by treating the fibres with SiC whiskers or β-SiC particles (<0.1 µm). For example, the longitudinal flexural strength of an unalloyed aluminium matrix composite reinforced with 71 per cent Tyranno fibre, 0.5 GPa (72.5 ksi), increases to 1.5 GPa (217.4 ksi) when the same matrix is reinforced with only 50 per cent hybrid Tyranno fibre containing 4 per cent particulates. And its transverse strength doubles from 0.15 GPa (21.7 ksi) to 0.3 GPa (43.5 ksi). UBE is interested in working with potential users on application requirements for their developmental hybrid Tyranno fibres and hybrid fibre reinforced metal matrix composites. (Tyranno Fibre Group, UBE Industries Ltd., 1978-5 Kogushi, Ube City, Yamaguchi Prefecture, 755, Japan. MMC Division, Toyota Central Research & Development Laboratories, Inc., 41-1, Yokomichi, Nagakute-cho, Aichi-gun, Aichi Prefecture, 480-11, Japan) (Source: Materials and Processing Report, October 1987)

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Osprey Metals (Neath, Wales). Osprey molten-metal spraying process has been used to make metal-matrix composite preforms by injecting ceramic particles right into the atomized matrix. Osprey Metals and Delft University (the Netherlands) have jointly extruded spray deposited aluminium-silicon-copper alloy billets.

The billets rated favourably vs a customary ingot metallurgy alloy and a similar powder metal alloy. The Osprey method has been studied at the Navy's David Taylor Research Center (Annapolis, MD), with the goal being to make pipe preforms from an Inconel 625 nickel base material. Mannesmann Demag USA (Pittsburg, PA) reports that the method now has the capacity of continuously making as-rolled quality strip and plate up to 48" wide and needs to be united with melting and finish rolling-coiling facilities to begin output in commercial amounts. (Source: MetalwNews, 12 September 1988)

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3 D metal-matrix composite weave for preforms: Researcher at University of Delaware's Centre for Composite Materials is working on 3-D woven reinforcements that can be woven into preforms with complex shapes. The metal-matrix composites (MMCs) are made to near-net shape, and there are no delamination planes.

Polycrystalline alumina are braided and woven (FP fibre) into preforms, then vacuum-infiltrated with aluminium-lithium alloy (Al-1.5Li). As fibre volume increased, so did mechanical properties. An experimental 37 vol per cent alumina-reinforced Al-Li checked in with 383 MPa tensile strength, 97 GPa Young's modulus, 0.26 failure strain, 32.3 $MPa.m^{1/2}$ fracture toughness. You will find that properties are not very different from those observed for conventional 0°uniaxial composites.

Problems researcher is working to solve include the damage caused to fibres during braiding and weaving (especially at crossover points) and infiltration as fibre content increases. Process has potential for automation. (University of Delaware, Centre for Composite Materials, Newark, DE 19716, USA) (Source: Inside R & D, 12 November 1986)

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MMCs can never be too thin

The Naval Research Laboratory has developed a way to make thinner, more consistent metal-matrix composites (MMCs) by spreading reinforcing fibres more evenly across the laminate. It is done with a pneumatic induction fibre spreader, which draws graphite fibres through a chamber where air is pumped out of nozzles on either side of the fibres. This creates a venturi effect that spreads the fibres, which are collected on a take-up spool and interleaved with aluminium foil. The fibre-foil tape is then ion plated by physical vapour deposition to form a precursor sheet that can be consolidated with other sheets into a multilayer MMC sheet. The system produces sheets down to 0.1 mm thick, one-fifth as thick as other methods, improves reinforcement consistency, and strengthens finished MMCs. It has been tested on graphite-reinforced aluminium. (Source: Aerospace America, January 1989)

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Don't say it, spray it

Do not say metal-matrix composites (MMCs) are too hard to use. Thanks to a new technology developed by Alloy Technology International, you can spray on titanium-carbide-reinforced MMCs. A typical coating might contain up to 40 per cent TiC in a nickel-chrome matrix. These new MMC coatings are slippery and have five times the wear resistance of tungsten carbide and six times that of "Stellite" cobalt-based coatings used in similar applications, according to tests run at Drexel University. But their true utility is to prevent substrate degradation under a combination of hostile conditions, such as wear, heat, cold, and corrosion. The key to this combination of excellent wear properties and low friction co-efficients is the rounded edges of the TiC particles, which slide over other materials. The coatings, trademarked ResisTic, are made by incorporating the rounded TiC particles into metals using GTE Sylvania's plasma-melt, rapid solidification system. The composite powders are then fed into a thermal spray system, which deposits them on the substrate. (Source: Aerospace America, June 1989)

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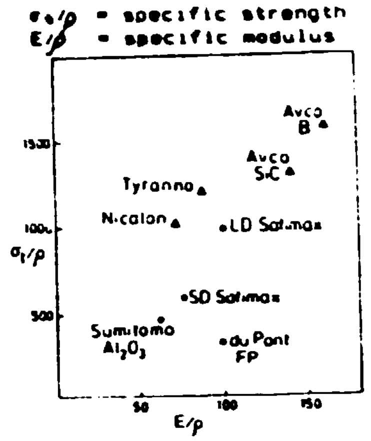


Figure 1. Specific tensile properties of some inorganic fibres)

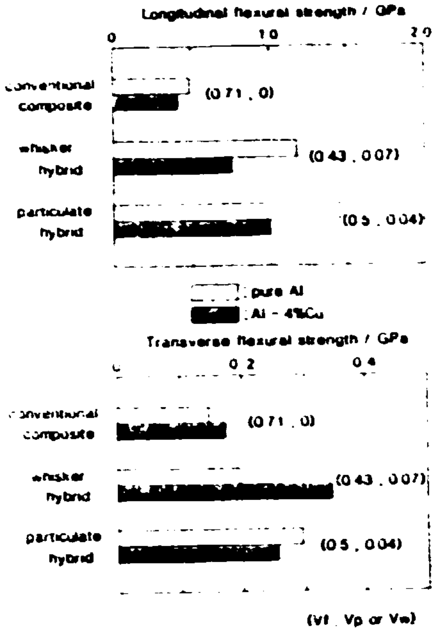
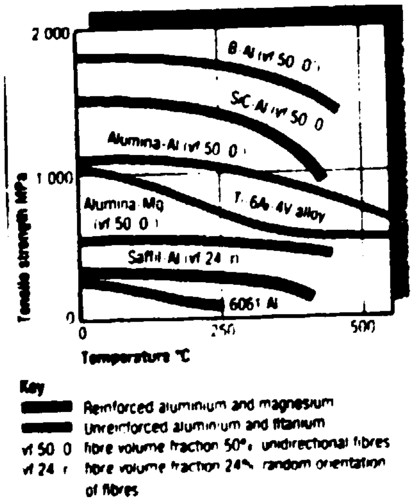


Figure 2. Strength of hybrid tyranno fibre reinforced metal matrix composites made by squeeze casting)



High-temperature tensile strengths of a range of ceramic fibre reinforced alloys

(Source: Engineering Magazine, London, November 1987)

Engineered metal matrix composite microstructures

A new generation of discontinuously reinforced metal-matrix composites, fabricated via a proprietary casting process referred to as XD$^{\text{TM}}$ technology, is under development at Martin Marietta Laboratories. With this technology, many different ceramic reinforcements (e.g., TiB_2, TiN, TiC, NbB_2, Ti_5Si_3) with morphologies ranging from particulates and platelets to high aspect ratio whiskers can be formed in situ in the melt of a wide range of alloys (e.g., TiAl, NiAl, NbAl, Cu, Al) during the casting process. The resulting metal-matrix composites have improved properties and can be cast, forged, and extruded. They can also be converted to powder using rapid solidification technology for fabricating near net shapes via powder metallurgy processes. The ability to make near-net shapes of XD$^{\text{TM}}$ titanium aluminide (TiAl) intermetallic composites is particularly advantageous because they are extremely hard and thus difficult to machine.

Most of the work that has been done to date is on the development of two-phased gamma lamellar titanium-aluminides reinforced with titanium diboride (TiB_2) particles. Analysis of the microstructure and phases of a cast ingot shows that it consists of equiaxed grains of TiAl with lamellae of Ti_3Al and TiAl. The equiaxed TiB_2 particles are found both inside the grains and at the grain boundaries.

Table 1 shows some of the improved properties at room and elevated temperatures of a Ti-45 atom per cent Al alloy reinforced with 7.5 per cent TiB_2. It has been found that heat treatment does not markedly affect the microstructure of the as-cast alloy. However, when thermomechanically processed (e.g., by hot extrusion), the matrix morphology is transformed from lamellar to equiaxed without any breakup of the TiB_2. The composite with this microstructure has better creep resistance than the unreinforced alloy, and as also shown in table 1, its room temperature elongation is also increased. Initial results of creep rate measurements at 760°C and a load of 69 MPa show steady state creep rates of 2×10^{-7} sec^{-1} compared with 9×10^{-7} sec^{-1} for the unreinforced alloy. Other properties of this composite are its fracture toughness, 12-14 MPa m$^{1/2}$, coefficient of thermal expansion, 1.0×10^{-5}/°C at 20°C increasing to 1.7×10^{-5}/°C at 800°C; and density, 3.99 g/cm^3, which makes it a lighter weight material than such high temperature alloys as Inconel 601.

The Martin Marietta researchers are also investigating XD$^{\text{TM}}$ processing of other intermetallic alloys as well as of Cu and Al alloys. In alloy systems such as Cu and Al, XD$^{\text{TM}}$ technology is expected to markedly improve superplasticity because the in situ formed particulates act to stabilize the alloy's fine grain size. Figure 1 shows the improvement in the tensile strength of an XD$^{\text{TM}}$ 6061 Al alloy reinforced with 10 vol per cent TiB_2 compared with the unreinforced alloy. Because of its thermal conductivity and superplasticity this material could prove advantageous for automotive engines.

The production of the titanium aluminide master alloy has been licensed to AMAX, which is selling the material to other Martin Marietta licensees (e.g., Howmet for investment castings), for manufacturing into various products. Martin Marietta is also interested in working with other companies to further the development of these experimental materials. (Martin Marietta Laboratories, 1450 S. Rolling Road, Baltimore, MD 21227, USA) (Source: Materials and Processing Report, April 1989)

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European developments in metal matrix composites

Metal-matrix composites with increased stiffness and strength, higher service temperatures, and controlled thermal expansion are now available with aluminium or magnesium matrices. Wrought MMC materials are reinforced with discontinuous ceramic phases, namely particles, whiskers, or short fibres. They are available in the form of billets, extrusions and forgings from the French company, Péchiney. The most immediate improvement achievable is in elastic modulus with values of 100-120 GPa (14,500-17,400 ksi) easily attainable with SiC particles in aluminium. Although obtained with a slight increase in density, the specific stiffness of these materials surpasses that of steel and titanium. In the case of SiC whisker reinforced extrusions, yield strength and tensile strength are greatly improved over those of the unreinforced matrix. Figure 2 shows high yield strengths at different temperatures for 6061 aluminium alloy with 25 per cent by volume SiC whiskers. High levels of mechanical properties have also been obtained with a 7075 aluminium-matrix.

Casting technology is also very attractive for metal-matrix composites. Casting offers the advantages of direct fabrication technology, near-net-shape technology, capability for making complex shapes, capability for using local reinforcements, and capability for using mixed reinforcements and hybrids. A casting alloy with 20 per cent by volume SiC whiskers can provide a 200°C (392°F) ultimate tensile strength, which is 200 per cent that of the unreinforced alloy. At 300°C (572°F), the composite tensile strength is 300 per cent of the strength of the unreinforced product. The use of near-net-shape castings with high loadings (up to 60 per cent) of discontinuous reinforcement also appears promising due particularly to their reduced thermal expansion. Near-net-shape technology is likely to be competitive where machining costs are critical. The use of continuous fibre preforms is also under investigation using unidirectional tapes, woven products, and filament wound systems for metal-matrix composites. (Cégédur Péchiney, BP 27, Voreppe, France) (Source: Materials and Processing Report, September 1988)

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First commercial MMC production by late '89

Hats off to Dural Aluminium Composites, which will be first to make commercial quantities of silicon carbide particulate reinforced aluminium metal-matrix composites (MMC). Dural will build a 25+ million-lb plant to produce extrusion billet and foundry pig, and, eventually, rolling slabs for sheet and plate.

The first applications will probably by superstiff tennis rackets and bicycle frame tubes. But the true target is auto applications: connecting rods, piston pins, valve guides, rocker [illegible], and later, engine blocks and cylinder heads. Dural will hire two full time salespeople to call on auto and aerospace firms.

Dural's patented direct chill (DC) process is fast and amenable to economies of scale (which is why prices will fall so fast). DC is a continuous in one end, out the other type of process. Molten metal is poured into the top of a short, water cooled mould, solidified, and removed by a hydraulic platform at the bottom of the mould. DC casting is fast enough to improve grain size and SiC particulate distribution throughout the matrix.

The resulting MMCs (10 per cent SiC 6061 Al) are 50 per cent to 60 per cent stiffer, 15 per cent to 40 per cent stronger, and an order of magnitude more wear resistant than unreinforced aluminium. Better yet, you can control their thermal expansion coefficient. (Dural Aluminium Composites Corp. 10505 Roselle Street, San Diego, CA 92121, USA) (Source: High Tech Materials Alert, April 1988)

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Industrial limits explored for metal-matrix composites

The National Institute of Standards and Technology (NIST) is inviting participation from industry, academia, and Government in a research programme to target critical areas limiting industrial use of metal and intermetallic matrix composites. Of particular interest: processing techniques to ensure a good interface between continuous fibres and aluminium alloy matrices; environmental degradation; high-speed processing; and electro-chemical techniques for the production of titanium aluminide matrix materials.
(Dr. David S. Lashmore, NIST, Bldg. 224 B166, Gaithersburg, MD 20899, USA)
(See table on page 138.)
(Source: Advanced Materials & Processes, February 1989)

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Dural Aluminium (San Diego, CA) has introduced Duralcan aluminium metal matrix composite (MMC), a ceramic particle-reinforced aluminium material. The MMC, which can be cast, extruded, forged and rolled, has excellent strength, stiffness and wear resistance although it is as light and corrosion-resistant as aluminium. The MMC was introduced for a lot of commercial and industrial uses including engine parts. Duralcan is produced via an economical casting method in which inexpensive ingot-grade aluminium and commercially offered ceramic particles are united. Dural's patented method entails a special pretreatment that eliminates undesired chemical reactions. The pretreatment minimizes dissolved gases and impurities and allows a uniform distribution of ceramic particles to be attained. This is a major factor in acquiring durable mechanical features. Dural is an Alcan Aluminium subsidiary. (Source: DieselProg, May 1989)

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Cost effective aluminium based particulate composites

Metal-matrix composites based on aluminium and aluminium lithium alloys reinforced with SiC particulates have been successfully produced by Alcan International using the Osprey spray deposition process. An advantage of spray deposition for producing composite materials over more conventional powder techniques is that no mixing of powders is required, a costly and inherently dangerous step, hence the product is relatively less expensive.

Other advantageous properties of these aluminium based SiC particulate composites are their light weight (low density), high specific strength and specific modulus (stiffness to weight ratio), and high wear resistance, plus their thermal expansion coefficients can be tailored to match other metals or for a particular product application by varying the volume per cent of SiC in the aluminium matrix. The company is targeting these composites at a bulk type market such as automotive (e.g., for cam rods, pistons, connecting rods) where lower cost alloy could be used as the base metal. The increments in strength are not as large with higher strength alloys such as Al-Li (8090) as they are with lower strength alloys.

In the adaptation of the Osprey process developed by Alcan, the reinforcing particles are incorporated into the matrix alloy as an integral part of the metal spraying process in such a way as to produce a uniform distribution throughout the finished material. The as-sprayed ingots are cylindrically shaped to minimize machining in producing extrusion billets. The composites are readily workable and can be fabricated, e.g., extruded, rolled, die cast using conventional tooling. However, some account needs to be taken of their higher abrasiveness in machining, which requires carbide tipped tools for rough machining and diamond-tipped for finishing. Alcan's spray-deposited MMCs are still developmental. However, small quantities are available to selected customers for evaluation. (Alcan International Limited, Banbury Laboratories, Banbury, Oxon OX16 7SP, UK) (Source: Materials and Processing Report, October 1987)

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Magnesium MMCs produced from melt

Magnesium metal-matrix composite (MMC) extrusions are available from The Dow Chemical Co., Midland, Mich., USA. The company's proprietary technique is said to be the only commercial process for producing cast magnesium MMCs. Other production processes rely on powder metallurgy (PM) techniques.

The reinforced materials have greater strength, modulus of elasticity, and wear resistance than unreinforced magnesium. To date, Dow has produced MMCs with silicon carbide and alumina reinforcements in a variety of alloy matrices. (Source: Advanced Materials & Processes, April 1989)

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Metal-matrix composites to grow at 20 per cent annual rate

The metal-matrix composites (MMC) market is currently $20 million, nearly all of which is research based. Although aluminium-matrix composites will continue to dominate in market share through the year 2000, growth will be led by copper and magnesium MMCs at annual rates of more than 20 per cent.

If the National Aerospace Plane programme continues to production, intermetallic MMCs (particularly titanium aluminides reinforced by carbon or titanium diboride) will approach the market position of aluminium matrix materials by 2000. Defence will consume most of the MMCs produced over the next ten years, according to a recent report by Business Communications Inc., a demand remaining as much as four times the size of the commercial market. (Source: Advanced Materials & Processes, February 1989)

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Metal-matrix composite in full production

Japan's Kobe Steel Ltd., is now using a powder metallurgical process for full-scale production of silicon-carbide whisker reinforced aluminium. The company can produce 6 x 10.5-in long (150 mm x 350 mm) billets of the composite material.

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Call for (low-cost) reinforcements

Continuous silicon carbide strands are a leading candidate for reinforcements for metal matrix composites (MMCs), but they can cost more than $300/lb. An innovative new process could cut costs by at least one and possibly two orders of magnitude, to perhaps $2-$25/lb, and still achieve high modulus and 500,000-psi tensile strength. The new process starts with cheap pitch and a commercially available source of silicon, such as metal, silicon oxide, silicon dioxide, or silicon polymers. The silicon is mixed into the pitch at high temperatures, and the mixture is then spun into fibres of the desired length. When the fibres are vacuum sintered, the silicon reacts with carbon in the pitch to form dense SiC with a diameter of 7 to 100 microns. This avoids the expensive processes (chemical vapour deposition) and raw materials (organosilicon precursors used in pyrolysis) used in conventional technology. Researchers have already learned to control the cospinning of pitch and silicon, but have not yet decided on their silicon source (or sources). Low cost SiC reinforcements could move MMCs out of exotic military applications and into more widespread use in commercial aircraft. (Source: Aerospace America, October 1986)

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World: The metal-matrix composites market is predicted at $450 million in 1998, vs $37 million in 1988, according to Kline. MMC utilization by the aerospace sector is predicted at $336 million in 1998, although this depends on such projects as the National Aerospace Plane and SDI. MMC use by automakers is predicted at $100 million+ in 1998. Autos accounted for 76 per cent or 745,000 lb of MMC in 1988, while aerospace accounted for 18 per cent. (Source: Ceram Ind, April 1989)

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Metal matrix composite producers anticipate boom

The market for metal matrix composites is still in its infancy, but producers are pouring resources into research and new capacity in order to meet an anticipated boom.

The market for the metal fibre composites will increase 70 per cent annually for the next few years, growing from about $35 million in 1987 to $475 million in 1992, according to the Freedonia Group Inc., a Cleveland market research firm.

The automotive segment will account for the greatest demand, the Freedonia report said. Auto industry demand for metal-matrix composites is negligible today but will hit about $225 million by 1992.

Players on the production side include metal and chemical industry giants, such as Alcan Aluminium Corp., Allied Signal Inc., and E.I. du Pont de Nemours & Co., as well as small start up ventures, like California Consolidated Technology Inc., and DWA Composite Specialties Inc.

Several composite manufacturers agreed with Freedonia's predictions while others disagreed, claiming the predictions were either too high or to low.

In addition to the automotive segment, the aerospace industry is expected to be a major consumer. However, the lengthy testing requirements mean the market will be some years developing.

Freedonia estimated growth in the aerospace segment from $35 million in 1987 to $85 million by 1992 and to $230 million by 2000.

Alcan's Dural Aluminium Composites Corp., is increasing capacity at its San Diego pilot plant while building a 25-million-pound operation in Jonquiere, Quebec. A third plant in the United States is under consideration.

Dural is targeting a broad range of markets, from sporting goods to missiles.

For example, the company has produced a wheel rim for a high-performance mountain bike. The rim will be produced by a French parts manufacturer and marketed through Specialized Bicycle Components, Morgan Hill, California.

On the automotive side, Dural recently cast a car-engine piston, which is targeted for the automotive aftermarket.

Also on the development side are aerospace components. At an Air Show in England, Dural displayed a composite speed brake and a hydraulic manifold, both of which were designed for fighter jets.

Typically, Dural composites use silicon carbide particulate for reinforcement. However, the company recently began adding aluminium oxide rather than silicon to the matrix.

Aluminium oxide is more readily available and promises to be less expensive than silicon carbide. The performance aspects are quite similar.

DWA Composite Specialties produces an aluminium-matrix composite it calls DWAL 20 Super Aluminium. Essentially an aluminium composite, DWA buys aluminium powder from Alcan, mixes it with reinforcement particulate and manufactures billet and other products. Like Dural, DWA tries to line up billet customers by developing prototype components and teaching fabricators how to work with the material.

The start up company fabricates a variety of products, such as automotive and aerospace components. Sizes range from small rings to 40 foot long tubes which were designed for America's Cup racer Stars and Stripes. The tubes were cut down to make two 33 foot spars for the catamaran. The use of aluminium composite material saved about 100 pounds per spar; however, the spars were not used for the actual race.

Under development is an electronic grade of material to bridge the gap between ceramic parts and metal structures.

The only commercial item in production by DWA is an inertial guidance components for missiles. The metal composite replaces beryllium in that application because of its non toxicity.

The Suppliers of Advanced Composite Materials Association will begin to "pro actively" recruit metal-matrix composite companies next year, a spokesman said.

The association is three years old and so far its major thrust has been towards polymer matrix companies. However, metal-matrix composites are in the group's by-laws as a targeted material so it 's time to reach out, the spokesman said. (Extracted from American Metal Market, 30 November 1985)

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"Squeezing" production costs from metal-ceramic composites

Ceramic-fibre reinforced metal-matrix composites (MMC) are potential materials for applications requiring good strength at high temperatures, good structural rigidity and dimensional stability, light weight, and good fabricability. The reason many MMCs have the structural capability to withstand high temperatures is because of the incorporation of ceramic fibres. Cost however, remains a barrier to adopting these composites for non critical applications. Most MMC components are made by powder-metallurgy processing, requiring hot pressing of the forging preform. The near net shape process called squeeze casting, however, offers a technique to manufacture ceramic-fibre reinforced MMC components at affordable costs.

Advantages of squeeze casting

The solidification of liquid metal under pressure - squeeze casting - helps achieve defect-free castings with improved metallurgical properties. The squeeze casting process is simple and economical, efficient in its use of raw material, and has excellent potential for automated operation at high production rates. The process yields the highest mechanical properties attainable in a cast product. In fact, the tensile properties of ferrous and non ferrous squeeze castings are comparable to those of forgings.

In addition to the densification achieved, squeeze casting produces relatively fine grains in the casting due to the intimate contact between the solidifying casting and the die, which results in a tenfold increase in heat-transfer rate over permanent-mould casting. Fine grain size also is promoted by the large number of nuclei formed due to the low casting temperature and the elevated pressure. Some wrought alloys also can be squeeze cast, because die filling in squeeze casting does not require high melt fluidity, and pressurized solidification with rapid heat transfer tends to minimize the segregation typical in wrought alloys.

The excellent mechanical properties, microstructural refinement and integrity of squeeze-cast products are used to advantage in many critical applications. Parts made recently include aluminium-alloy truck hubs, barrel heads, and hubbed flanges; brass and bronze bushings; steel missile components and differential pinion gears; and several parts made of cast iron. Other parts include aluminium domes, ductile iron mortar shells, steel bevel gears, stainless steel turbine blades, superalloy disks, aluminium automotive wheels and pistons, and gear blanks made of brass and bronze. Squeeze cast aluminium wheels are being produced commercially, and high strength aluminium pistons are expected to be commercialized soon.

The casting process

In the basic squeeze-casting process, liquid metal is metered into a preheated, lubricated die, and forged while it solidifies. The forging pressure is applied shortly after the metal begins freezing and is maintained until the entire casting has solidified.

The important squeeze-casting process variables are:

- Melt quality;
- Casting temperature;
- Tooling temperature;
- Time delay during die closing and pressure application;
- Pressure level;
- Pressure duration.

The applied pressure (typically 100 MPa, 15×10^3 psi) is high enough to suppress gas porosity; in extreme cases, standard degassing treatments are used. The shape and section thickness of the casting govern the duration of pressure necessary to ensure complete solidification. Times beyond the minimum necessary can cause wall cracking and punch retraction difficulty due to thermal contraction of the casting onto the rigid punch. The maximum duration of pressure generally is about 1 sec/mm (25 sec/in) of section thickness.

Shrinkage porosity also is limited by using minimum melt superheat during pouring. This is possible in squeeze casting because high fluidity - requiring high pouring temperatures - is not necessary to fill the die, the filling being readily achieved by the pressure applied. In heavy casting sections, which are particularly prone to shrinkage porosity, the applied pressure squirts liquid or semiliquid metal from hot spots into incipient shrinkage pores to prevent the pores from forming. Alloys with wide freezing ranges accommodate this form of melt movement very well, resulting in sound castings with minimum applied pressure.

Failure to control process variables can result in defects such as oxide inclusions, porosity, extrusion segregation, blistering, underfill, cold laps, hot tearing, sticking, case bonding, and extrusion bonding.

Adaption of the squeeze casting process to the making of composites incorporates a porous ceramic preform (fibres of different density), which is held in the die cavity by a fixture. The fibrous preform is quickly and totally infiltrated by the molten metal under pressure resulting in a sound, fully dense fibre reinforced part. Pressure levels necessary to form sound parts must be controlled to preserve the shape of the preform. Preform preheating also is important to avoid freezing of the liquid on the preform surface, which could result in incomplete infiltration in the final cast composite.

Properties of metal ceramic composites

Metal matrix composites have enhanced stiffness compared with the matrix metals alone and they retain tensile strength at elevated temperatures. For example, aluminium-alloy ceramic fibre reinforced composites can replace a high nickel cast iron insert in an aluminium-alloy diesel truck piston. The piston weight not only is reduced by 5 to 10 per cent, but also the equivalent bond strength between the reinforced area and the piston alloy is superior to that of the iron-insert aluminium alloy bond. Because the rate of heat transfer is decreased with a composite insert compared with the iron insert, the upper piston rings can be moved closer to the crown or the combustion chamber can be redesigned to operate at a higher temperature, thus providing an engine that has significantly increased fuel economy as well as reduced emissions.

In addition, ceramic fibre reinforced aluminium-alloy composites have been evaluated for combustion bowls to eliminate thermal fatigue cracking due to high thermal cyclic compressive stresses, plastic deformation, and creep. The hot-pressed composite bowls showed a 100 per cent improvement in yield strength over the bowls made from aluminium-alloy alone. Similar improvements were found in tests of other aluminium-alloy composites reinforced with fibres of two different types - high-alumina (Al_2O_3) ceramic fibres and SiC whiskers.

Both alumina and alumina silicate reinforcement in aluminium Alloy 332 composites have been found to double the ultimate tensile strength at 260°C (500°F) of a squeeze cast component. In tests of a candidate track shoe material, wear resistance of aluminium Alloy 206 squeeze cast composites reinforced with discontinuous fibres of Al_2O_3 and SiO_2 was found to be comparable to that of induction hardened AISI 1345 alloy steel, the currently used material. The test was dry sand rubber wheel abrasion (ASTM G65, procedure B). In lubricated ring wear tests of candidate materials for automotive engine pistons, aluminium Alloy 332 reinforced with Al_2O_3-SiO_2 fibres (5 to 7 per cent fibre volume) showed a 70 per cent improvement in wear resistance over high-nickel cast iron, while aluminium Alloy 242 reinforced with Al_2O_3 fibre (also 5 to 7 per cent fibre volume) showed an 80 per cent improvement.

While reinforcing with randomly oriented ceramic fibres improves the wear resistance of aluminium alloy parts, excessive localized damage can result if fibres are pulled out of the matrix during wear conditions. Interfacial properties need to be controlled to reduce the abrasiveness of pulled-out fibres. Another cause of poor mechanical properties is excessive fibre/matrix reaction. In particular, iron and silicon present in alumina fibres react with an aluminium-matrix to form a brittle phase during solidification. Control of such impurities reduces this interfacial reaction and improves mechanical properties. In all instances, however, the fracture surface shows mixed brittle (fibre) and ductile (matrix) modes during fracture.

Metallographic studies of squeeze-cast components show that other important factors for good composite properties are fibre composition, fibre volume, mechanical properties of fibres with respect to matrix, and interaction between the fibres and the alloy matrix. Squeeze casting variables can be optimized to control the interfacial reaction between fibres and the matrix.

Unfortunately, the data base of information on squeeze-cast metal ceramic composites is very limited, and to realize the full potential of composites, a comprehensive data base is needed, which could reveal many other applications where the use of these materials would be advantageous.

Preform selection

Preforms for squeeze cast composites consist of ceramic fibres (Al_2O_3 and SiO_2) bound into near-net shapes. The type and amount of fibre in a preform is selected based on the need for wear resistance, seizure resistance, yield strength, tensile strength, fatigue strength, stiffness, dimensional stability, thermal resistance, vibration and acoustical characteristics, corrosion resistance, and the operating environment of the particular part.

Preform performance is determined by ceramic-fibre volume (per cent of total part volume), chemical and physical characteristics of the fibre(s), fibre orientation in the preform, and amount of binder. These factors - as well as size, shape, and dimensional tolerance - affect preform cost and final product costs.

In order to minimize costs, preforms are designed to provide the needed performance at the lowest fibre concentrations. For example, for high-temperature fatigue resistance, cost-effective fibre volumes may be as high as 27 per cent; however, when only improved wear resistance is required, a fibre volume of less than 10 per cent is generally used. Preferred fibre orientation is not essential for improved wear resistance in an aluminium part; the fibres can either be normal or parallel to the surface being enhanced. Ceramic preforms with a variety of compositions are available.
(See tables, pages 139 and 140.)
(Source: Advanced Materials & Processes inc. Metal Progress 5/88, article written by Suresh K. Verma and John L. Dorcic, IIT Research Institute, Chicago, Ill.)

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Trimming the cost of MMCs

Innovative powder metallurgy technology takes the high cost out of manufacturing these highly specialized materials

Powder metallurgy (PM) technology offers a method to manufacture complex near-net-shape parts made of conventional and exotic alloys and alloys that cannot be produced by conventional methods, as well as metal-matrix composites (MMCs). However, PM manufacturing techniques are limited in some instances by economical and technical factors. For example, prealloyed powders (used in conventional isostatic pressing) are very expensive, and because they generally are spherical, they are not cold compactable. To overcome this limitation, these powders are compacted by hot isostatic pressing (HIP) in expensive "canning" containers. Furthermore, these containers must be removed after hot pressing, and a new container must be fabricated for each part to be manufactured. On the other hand, mechanical cold pressing of blended elemental powders is possible and economical, but properties of the powder compact are not uniform because compressive forces are essentially uniaxial resulting in anisotropy. Both methods also are limited with respect to part complexity and size. By comparison, the CHIP (from the combination of Cold and Hot Isostatic Pressing) process is an attractive economical and practicable method to fabricate titanium alloy and titanium alloy MMC parts to near net shape.

(CHIP)ing away at high manufacturing costs

CHIP is a PM technique comprising cold isostatic pressing (CIP) of blended elemental powders in a reusable elastomeric mould, followed by vacuum sintering and hot isostatic pressing (HIP) without the need for additional expensive tooling. The method incorporates elemental cold-compactable titanium powder, which is available at a relatively low cost (compared with spherical prealloyed powders) in both standard and extra low chloride (ELCI) grades. In the elemental powder blend technique, the proper proportion of master-alloy and base elemental powders are blended to obtain a uniform distribution of the required chemical composition.

The CHIP process is competitive with forging or casting in many instances. While forging refines the microstructure of wrought stock that already has a significant amount of value added, a near net-shape part seldom is feasible. Thus, machining costs are high and the buy to fly ratio (the ratio of the weight of material purchased to make a particular aircraft aerospace component to the weight of the finished component) usually is high. On the other hand, while casting may be cost competitive for some part configurations, the mechanical properties obtained usually are inferior to those of the PM CHIP process.

Cold isostatic pressing typically produces a density in the green preshaped compact of 80 to 85 per cent of theoretical. The density is uniform because the applied hydrostatic pressure is the same in all directions. Complex parts containing undercuts, reverse tapers, and closures and multiple flanges can be fabricated. Furthermore, the process is not limited to parts with small aspect ratios (ratio of height to width). Therefore, the process can be used to manufacture parts such as shafts and hollow bar and tapered tubing.

By controlling the size and other specific features of the starting powders and by properly designing the elastomeric tooling, dimensions can be closely controlled, thereby maximizing the raw material utilization and minimizing finish machining costs. This is important economically because raw-material costs account for a high proportion of production costs, and the scrap material generated by machining has little value compared with the value of the finished part.

Cold isostatic pressing of elemental blended powder produces a high yield of crack-free preforms. Such preforms are typically densified to about 95 per cent of theoretical density by vacuum sintering. Full density (100 per cent) is achieved by the subsequent hot isostatic pressing. Canning prior to hot pressing is not necessary because the porosity of the as-sintered preform is closed, i.e., closed to the outside atmosphere.

The ability to achieve properties that meet and often exceed the specifications of cast and wrought products have been demonstrated. This is valid whether comparing specifications for strength and ductility or fatigue resistance. Fatigue properties of CHIP processed ELCI Ti-6Al-4V are equivalent to those of wrought annealed material. Subsequent heat treatment of this alloy further improves fatigue resistance to a level surpassing wrought annealed Ti-6Al-4V. The CHIP technique is now a production process wherein significant cost savings are achieved in critical components.

New titanium MMC technology

Materials engineers, having recognized that monolithic alloys have inherent performance limitations, are searching for approaches to develop materials independent of equilibrium or metastable structures. One approach led to the development of MMCs, where a metal or alloy is combined with a non-equilibrium dispersed phase - generally, but not always, non-metallic. Sintered cemented carbides were some of the earliest and most successful MMCs, consisting of tungsten carbide, or other carbide particles, dispersed in a ductile metal matrix.

Continually increasing materials-performance requirements in the aerospace industry led to the development of fibre-reinforced metals (typically, an aluminium-alloy matrix), in which properties are highly directional (non-uniform). Fabrication of these composites is quite complex and expensive, and fibre-reinforced MMCs are excluded from consideration in many practical component configurations due to their geometrical and or cost constraints.

The CHIP technique is the basis on which Dynamet Technology Inc., developed a proprietary process to manufacture a new family of titanium macro- and micro-composite materials to near-net shape parts.

Commercially known as CermeTi (the subject of US and foreign patents assigned to Dynamet), the new materials are processed essentially in the same manner as monolithic alloys, except that a substantial amount of titanium-carbide particles is blended with the elemental metal powders used to make up the matrix alloy.

CermeTi materials have been characterized with respect to particle size, composition, CHIP process variables, and mechanical properties. Prototype parts made thus far include domed rocket cases, missile fins, and aircraft engine component preforms.

The stiffness (Young's modulus) of CermeTi-10 (Ti-6Al-4V matrix with 10 per cent TiC) micro-composite material is dramatically improved from room temperature to 650°C (1,200°F). In addition, the room-temperature yield and tensile strengths are retained to the upper temperature. Ductility is impaired, but reasonable ductility is retained throughout the temperature range; the ductilities of the composite and of the monolithic titanium alloy do not differ significantly at 650°C (1,200°F).

Creep and stress-rupture test results from CermeTi-15 (Ti-6Al-4V with 15 per cent TiC) and forged matrix-alloy specimens show that CermeTi materials typically have an order of magnitude increase in time to rupture compared with the unreinforced titanium alloy at temperatures to 540°C (1,000°F).

Overall, CermeTi composites provide higher modulus and better high temperature performance than monolithic titanium alloys without compromising the weight advantage of titanium. For example, the modulus improvement in CermeTi 10 is about 15 per cent at room temperature, and this advantage is maintained to 650°C (1,200°F). The strength and modulus levels increase by an additional 10 per cent in CermeTi 20.

The improvement in high temperature strength and stiffness increases the use temperature limit of Ti-6Al-4V by approximately 110°C (200°F). In addition, the composite alloy, even with limited room-temperature ductility (1 per cent) has a satisfactory level of fracture toughness. The value of $\underline{K}_{Ic}$ for CermeTi-10 (estimated from 4-point bend testing of notched test bars) is about 28 $\mathrm{MPa}\cdot\mathrm{mm}^{1/2}$ (26 $\mathrm{ksi}\cdot\mathrm{in.}^{1/2}$), which is comparable to the widely used aerospace aluminium alloy 2014-T6.

Fatigue properties of the composite are comparable to HIPed monolithic Ti-6Al-4V alloy castings. In addition, the properties can be tailored to meet specific applications by increasing or decreasing the level of reinforcement.

As with monolithic alloys, CermeTi preforms can subsequently be extruded or forged. Preshapes containing up to 20 per cent TiC have been successfully extruded, and CermeTi forging blocks weighing up to 5.5 kg (12 lb) have demonstrated good forging characteristics.

Continuing materials development is aimed at selecting alternative reinforcing particles, selecting other metal matrices including aluminium, and optimizing properties by changing processing variables.

The technology incorporated to manufacture CermeTi particulate-reinforced titanium alloy products can be extended to other matrices, other reinforcements, and other classes of high-performance materials such as titanium-aluminide intermetallic compounds.

Another feature of these new materials along with improved bulk properties is their ability to be diffusion bonded to a monolithic alloy of the same composition, because the microcomposite matrix alloy is the continuous phase. This approach yields a common matrix micro-macrocomposite structure designated CM^3C.

The CM^3C material-design approach offers an additional dimension in flexibility. Not only can matrix and reinforcing particles be selected, but also the resulting microcomposites can be bonded to monolithic alloys in a variety of ways. A more sophisticated application of the CM^3C material-design approach leads to multilayer micro-macrocomposites. Materials having up to eight alternating micro-macrocomposite layers have been fabricated.

Typical applications for these dual-property (hardness, ductility, fracture toughness, and modulus) macrocomposites include:

- Wear parts, such as gears, bearings and shafts having an abrasion-resistance surface layer and a tough, load-bearing body;
- Erosion-corrosion resistant tubing for chemical service;
- Creep fatigue-resistant engine components for elevated-temperature service.

Specifically, CM^3C can be used for any structural component where the properties of the macrocomposite would be beneficial, but where the component also would benefit from having a ductile monolithic alloy cladding or containment construction.
(See diagrammes and table on pages 140 and 141.)
(Source: Advanced Materials & Processes, July 1989. Article written by S. Abkowitz and P. Weihrauch. Dynamet Technology Inc. Burlington, Mass.)

* * * * *

Table 1

Properties of Ti-45Al-7.5% TiB_2

	20°C			800°C		
	Yield Strength (MPa)	Ultimate Strength (MPa)	% Elong (Plastic)	Yield Strength (MPa)	Ultimate Strength (MPa)	% Elong (Plastic)
As extruded	-	793	0	448	710	11
As extruded and heat treated	793	862	0.5	427	600	20

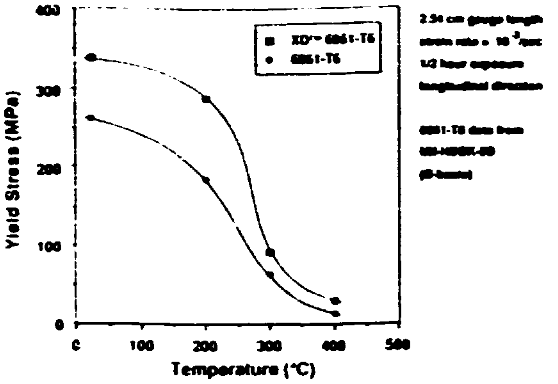


Figure 1. XD^{TM} 6061-10 vol% of TiB_2: yield stress versus temperature

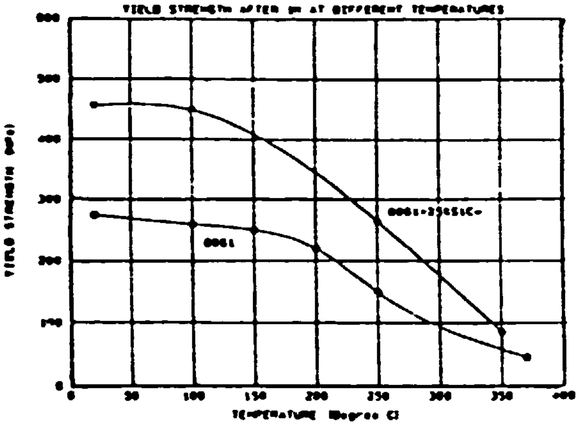


Figure 2. Yield strength of 6061 aluminium alloy with 25% SiC whiskers

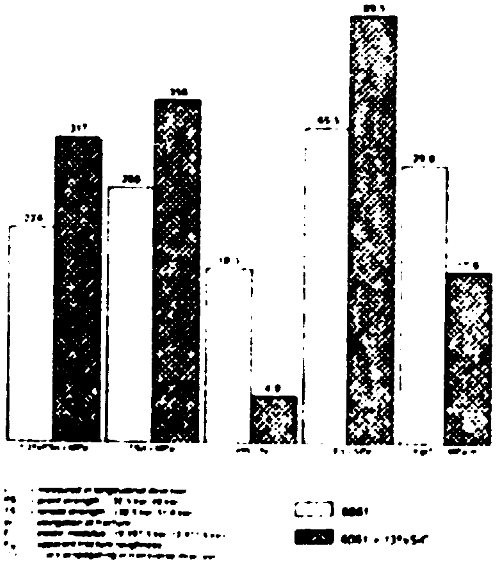


Figure 3. Comparison of Mechanical Properties with Base Alloy (6061 - Extrusion)

Metal-matrix composites market value[1]

MMC type	Year 1988	 1993	 2000	1988-2000, AAGR%[2]
Aluminum	12.0	27.4	61.4	14.6%
Magnesium	2.0	7.0	14.2	17.7%
Titanium	1.0	2.0	10.0	21.2%
Copper	1.4	4.3	20.1	24.9%
Intermetallic				
w/NASP[3]	1.6	5.5	33.7	28.9%
w/o NASP	1.6	5.5	16.3	21.3%
In Situ	1.6	5.1	18.2	22.5%
Other	0.4	2.6	5.0	23.4%
Totals				
Commercial	3.1	11.9	34.3	22.2%
Defense				
w/NASP	16.9	42.0	128.3	18.4%
w/o NASP	16.9	42.0	110.9	17.0%
All				
w/NASP	20.0	53.9	162.6	19.1%
w/o NASP	20.0	53.9	145.2	18.0%

[1] *millions, 1988 dollars* [2] *Avg. annual growth rate* [3] *National Aerospace Plane* *Source:* BCC

(Source: Advanced Materials and Processes, February 1989)

Representative MMC materials

Matrix	Fibre	Potential applications
Aluminium	Graphite	Satellite and helicopter structures
Magnesium		Space and satellite structures
Lead		Storage battery plates
Copper		Electrical contacts and bearings
Aluminium	Boron	Compressor blades and structural supports
Magnesium		Antenna structures
Titanium		Jet engine fan blades
Aluminium	Borsic	Jet-engine fan blades
Titanium		High-temperature structures and fan blades
Aluminium	Alumina	Superconductor restraints in fusion power reactors
Lead		Storage battery plates
Magnesium		Helicopter transmission structures
Aluminium	Silicon carbide	High-temperature structures
Titanium		High-temperature structures
Superalloy[1]		High-temperature engine components
Superalloy	Molybdenum	High-temperature engine components
Superalloy	Tungsten	High-temperature engine components

[1] Cobalt base.

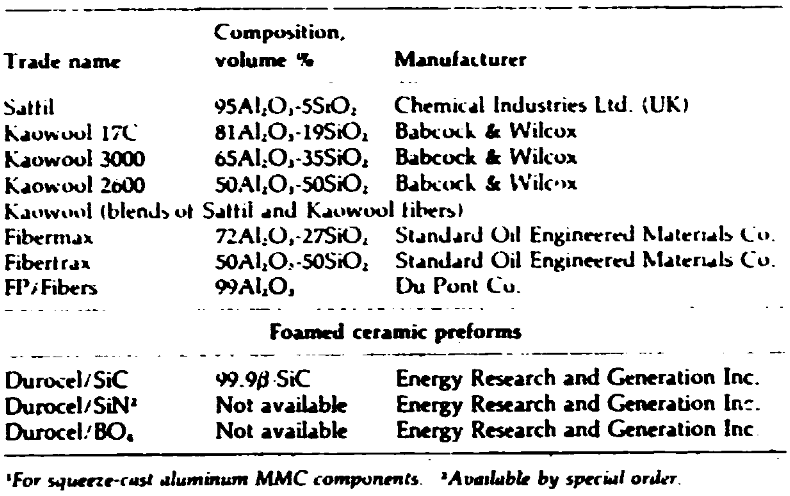
Effect of fabrication process on properties

Alloy	Fabrication process	Tensile strength, MPa	Tensile strength, ($\times 10^3$psi)	Yield strength, MPa	Yield strength, ($\times 10^3$psi)	Elongation, %
356 T6 aluminum	Squeeze casting	309	(44.8)	265	(38.5)	3
	Permanent mold	262	(38.0)	186	(27.0)	5
	Sand casting	172	(25.0)	138	(20.0)	2
6061 T6 aluminum	Squeeze casting	292	(42.3)	208	(38.8)	10
	Forging	262	(38.0)	241	(35.0)	10
CDA 377 forging brass	Squeeze casting	379	(55.0)	193	(28.0)	32.0
	Extrusion	379	(55.0)	145	(21.0)	48.0
CDA 624 aluminum bronze	Squeeze casting	783	(113.5)	365	(53.0)	13.5
	Forging	703	(102.0)	345	(50.0)	15.0
CDA 925 leaded tin bronze	Squeeze casting	382	(55.4)	245	(35.6)	19.2
	Sand casting	306	(44.4)	182	(26.4)	16.5
Type 357 stainless steel[1]	Squeeze casting	614	(89.0)	303	(44.0)	46
	Sand casting	400	(58.0)	241	(35.0)	20
	Extrusion	621	(90.0)	241	(35.0)	50
Type 321 stainless steel[2]	Squeeze casting	1063	(154.2)	889	(129.0)	15
	Forging	1077	(156.2)	783	(113.6)	7

[1] *Annealed* [2] *Heat treated*

(Source: Advanced Materials & Processes inc. Metal Progress May/88)

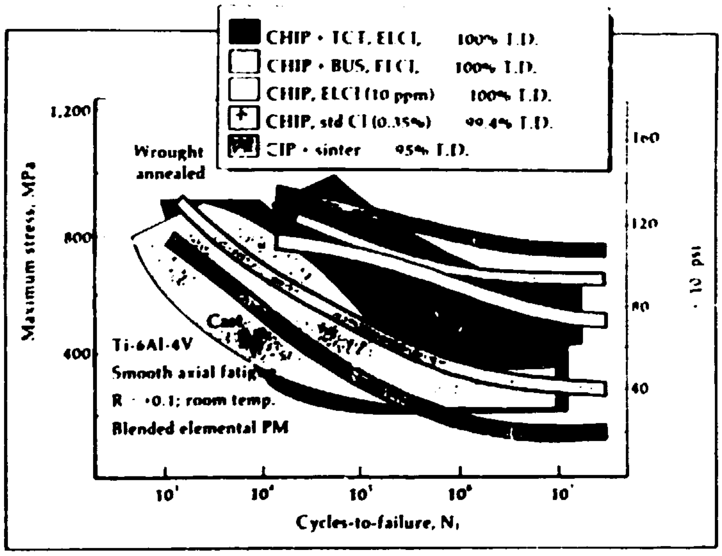
Ceramic fibres available as preforms[1]



Trade name	Composition, volume %	Manufacturer
Sattil	95Al$_2$O$_3$-5SiO$_2$	Chemical Industries Ltd. (UK)
Kaowool 17C	81Al$_2$O$_3$-19SiO$_2$	Babcock & Wilcox
Kaowool 3000	65Al$_2$O$_3$-35SiO$_2$	Babcock & Wilcox
Kaowool 2600	50Al$_2$O$_3$-50SiO$_2$	Babcock & Wilcox
Kaowool (blends of Sattil and Kaowool fibers)		
Fibermax	72Al$_2$O$_3$-27SiO$_2$	Standard Oil Engineered Materials Co.
Fibertrax	50Al$_2$O$_3$-50SiO$_2$	Standard Oil Engineered Materials Co.
FP/Fibers	99Al$_2$O$_3$	Du Pont Co.
	Foamed ceramic preforms	
Durocel/SiC	99.9β-SiC	Energy Research and Generation Inc.
Durocel/SiN[2]	Not available	Energy Research and Generation Inc.
Durocel/BO$_4$	Not available	Energy Research and Generation Inc.

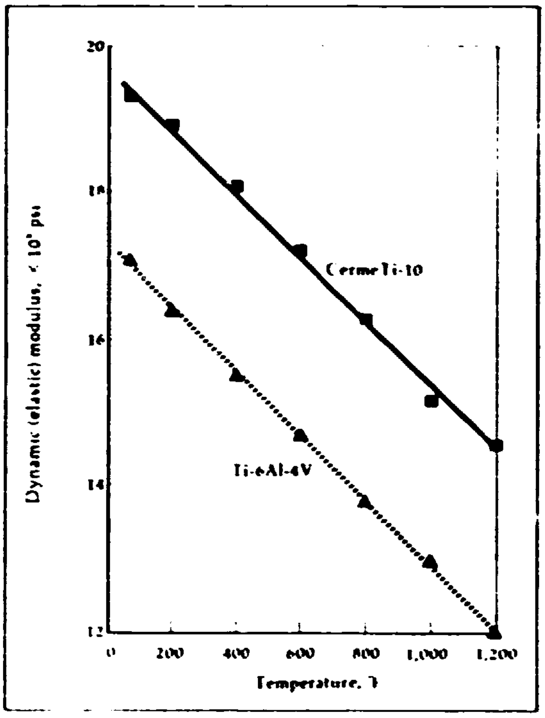
[1]For squeeze-cast aluminum MMC components. [2]Available by special order.

(Source: Advanced Materials & Processes inc. Metal Progress May/88)



Continual improvement of powder quality (including extralow chloride) and processing technology has led to the capability of producing titanium-alloy PM parts having fatigue properties comparable to wrought material.

(Source: Advanced Materials & Processes, July 1989)



The improvement in high temperature strength and stiffness of titanium-matrix microcomposites amounts to approximately a 110°C enhancement of the use temperature limit of Ti-6Al-4V. The CermeTi-10 points represent three test samples with nearly identical modulus values.

Comparative tensile properties

Material	Test temperature, °F	Ultimate tensile strength, × 10^3 psi	Yield strength, × 10^3 psi	Strain-to-failure, %
CermeTi-10	70	116-117	115-116	1.12-1.14
(Ti-6Al-4V with 10% TiC)	800	75-77	68-69	1.63-1.80
	1,000	65-67	59-61	2.15-2.66
	1,200	44-47	38-40	2.90
Ti-6Al-4V	800	73-75	55-58	11.1-12.1
	1,000	63-65	51-52	7.6-9.4
	1,200	44-45	30-33	3.9-4.5

Creep and stress rupture tests have been performed on CermeTi-15 (Ti-6Al-4V with 15% TiC). Comparisons with properties of the forged matrix alloy have demonstrated significant improvements for CermeTi materials, typically an order of magnitude increase in time to rupture measured at temperatures up to 1,000°F.

(Source: Advanced Materials & Processes, July 1989)

13. RECENT PUBLICATIONS

(Books and articles)

Testing of metal matrix composites

ASTM, Philadelphia, PA, USA, has made available Testing Technology of Metal-Matrix Composites (STP 964), ed. Di Giovanni and Adsit, containing 28 peer-reviewed papers covering material systems from the continuous silicon carbon titanium system to the particulate reinforced aluminium system. Material forms included range from precast block to braided pieces. Published in September 1988, the collection (472 pp) focuses on the need to obtain accurate and reliable test data. Current testing methodologies are defined and described, including elevated temperature tests, dynamic modulus tests, coefficient of expansion tests, and compression and buckling tests. The book is intended for composites researchers and designers, aerospace engineers, and materials scientists.

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Composites Manufacturing, an international quarterly journal from Butterworth Scientific Ltd., Guildford, Surrey, United Kingdom, is a sister journal to Composites. Scheduled for publication in early 1990, the journal will feature peer-reviewed papers on advances in the design, processing, fabrication, and production of resin-matrix, metal matrix, ceramic-matrix, and ceramic composites. It will also include news, book reviews, conference reports, a literature survey, and patent abstract sections. Readership is expected to come world-wide from engineers and scientists in materials development; suppliers in the automotive, aerospace, marine, consumer, and manufacturing industries; end-user organizations; and government and academic research establishments.

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The following four articles were published in Materials Science and Technology. Only abstracts have been used here.

Microstructural assessment of interaction zone in titanium aluminide/TiC metal-matrix composite

By D.G. Konitzer and M.H. Loretto

Samples of Ti-24Al-11Nb/TiC composites were heat treated at temperatures between 1,000 and 1,200°C for several hours and the extent of the reaction zone between the Ti-24Al-11Nb matrix and the TiC particulate was assessed using optical, scanning electron, and analytical transmission electron microscopy. It has been shown that there is an interaction zone surrounding each TiC particle caused by the diffusion of C from the TiC into the matrix and diffusion of Nb into the TiC. The extent of these interactions increases with increase of time and increase of temperature. The phases formed during heat treatment were shown to be $Ti_3(AlNb)C$ and $(TiNb)C$. The significance of these observations is briefly discussed in terms of recent work in which it has been shown that there is no detectable change in the matrix in similarly treated Ti-6Al-4V/TiC composites.

Mechanical property test procedures for metal matrix composites

By B. Roebuck, T.A.E. Gorley and L.N. McCartney

Test procedures for selected property measurements on metal matrix composite (MMC) materials are examined. The mechanical properties considered are associated with tensile, compressive, bend, impact, fracture toughness, fatigue, and high-temperature testing. A brief review is also included of mathematical models designed to predict the mechanical properties of MMCs from a knowledge of the properties of the constituents and their geometry.

Fatigue performance of alumina reinforced metal-matrix composites

By N.J. Hurd

The room temperature fatigue performance of two Saffil reinforced metal matrix composites manufactured by squeeze forming is assessed. For the composite with an LM 13 matrix, introduction of Saffil does not result in an increase in the ultimate tensile strength, and the fatigue performance is inferior to the unreinforced alloy. By contrast, the composite with a 6082 type matrix exhibits a markedly superior ultimate tensile strength and stiffness compared with the unreinforced equivalent and this is coupled with an improved overall fatigue performance.

Processing of Nb-Cu metal matrix composites

By D. Dew Hughes, P.G. Quincey and P.L. Upadhyay

During the development of new processing routes for Nb_3Sn superconductor, factors influencing the workability of two-phase metallic composites have been investigated. The ease with which such composites can be fabricated depends strongly on the relative hardness of the phases. Production of a regular uniform filamentary structure is promoted by low hardness ratios in the initial composite.

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Wear-resistant materials

Ceramic/metal composites are said to offer wear resistance in a variety of unique applications. The brochure explains formulation features, typical performance qualities, suggested applications, and handling considerations. Alanx Products L.P., 101 Lake Dr., Newark, DE 19702, USA.

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Report on advanced materials near

A bureau of Mines task force on advanced materials (USA) will publish a report - New Materials Society: Challenges and Opportunities that will incorporate opinions, viewpoints and policies of experts and compare the United States position in new materials with that of other countries.

The report will be different from any other report in that it will focus not only on polymers and ceramics but also will take a look at new alloys and metal composites and what the metals industry is doing to compete in the advanced materials field.

The study will be divided into two volumes, one including market forecasts, a summary of current government policy, research and funding and an overview of the significance of new materials in terms of national security and international competitiveness.

A second section will cover new developments in technology, including problems still to be solved and potential uses for advanced materials.

Members of the new materials task force include leading policy-makers and researchers from throughout the Bureau in the Department of Interior, including experts from its nine research centres in Oregon, Nevada, Missouri, Utah, Alabama, Minnesota and Idaho.

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Interfaces in metal matrix composites

Ed. A. K. Dhingra and S.G. Fishman, Metallurgical Society, AIME, 1986, D. A. Books (Aust.) Pty. Ltd.

The book is a collection of 17 papers presented at a symposium held at New Orleans, Louisiana, USA, in March 1986. The publication is divided into four sections: Mechanical behaviour, Characterization, Reactions, and Graphite-Al/Mg, and contains a mixture of papers dealing in high resolution electron microscopy, analysis, mechanical properties, novel experimental techniques and reviews.

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Residual stress in design, process and materials selection: proceedings of ASM's conference

Edited by William B. Young. Metals Park: ASM, 1987. 209pp. 620.1 87 071686 ISBN 0-87170 304-1

Contents: Measurement methods. Thermal processes heat treatment, case hardening. Thermal processes - casting, welding, metal matrix composites, ceramics. Thermal processes - surface films, coatings. Mechanical processes: shot peening, grit blasting. Mechanical processes: machining, grinding, forming.

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Ultrahard materials application technology Volume 4

This volume is the fourth in a series of technical books that are intended to provide an understanding of the practical capabilities and limitations of ultrahard tool materials, including both diamond and cubic boron nitride. Covering 101 pages, this volume contains seven articles by a panel of international authors and is edited by Chris Barrett. The subject matters covered are synthetic diamond as dosimeters in biological environments· polycrystalline diamond drill bits in mining applications; friction and wear of metals sliding on SYNDITE at low speeds; the prediction of diamond wear in the sawing of stone; transmission electron microscope study of SYNDAX3 compared with SYNDITE and AMBORITE; the hydrophobicity of diamond surfaces, and tool wear in the turning of glass fibre-reinforced plastic.

Ultrahard Materials Application Technology Volume 4 from De Beers Industrial Diamond Division (Pty.) Ltd., Charters, Sunninghill, Ascot, Berks. SL5 9PX, United Kingdom. Tel.: (0990) 23456, Telex: 848021, Fax: (0990) 28188.

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One hundred innovations for development: That is the title of a new publication bringing together bright new ideas from around the world designed to ease the lives of people in developing countries. They include such inventions as a foot operated treadle pump from Bangladesh (there are now 50,000 in operation); rock cracking devices (with the aggregate to be used for road-building); and wind driven ice machines.

The innovations come from 43 countries, winners of an International Inventors Awards competition held in Sweden.

Winning inventions were chosen for their ability "to promote economic and social development in the third world". All have practical applications and many are already in use.

One Hundred Innovations for Development, published by Intermediate Technology, Myson House, Railway Terrace, Rugby CV21 3HT, United Kingdom.

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Tomorrow's materials

By Ken Easterling

Aimed at a general readership including school leavers, students and undergraduates of all scientific and engineering disciplines, as well as individuals requiring updates on advanced materials, this book begins with an introduction to the fundamentals of materials science and investigates such new materials as aluminium-lithium alloys and fibre/polymer composites for aircraft frames and skins, rolled structural beams made by toughened concrete, new engineering polymers that may soon displace metals, advanced ceramics that promise to revolutionize the machine tool, electrical and automobile engine industries, fibre optical materials networks which will shortly span the world, new generations of transistor and a new superconducting ceramic with applications in computing, medical scanners and levitating trains.

A comprehensive glossary of words and terms used in materials science is also included, thereby making its content accesisble to non-specialists of the subject.

Contents:

Part 1 - Fundamentals: Introduction; Order versus chaos in the world of materials; Composite and cellular materials; Why metal bends, glass breaks and rubber stretches; Materials selection; Further reading.

Part 2 Applications: Structural materials; Lightweight materials; Wear and heat resisting materials; Optical materials; Electronic and magnetic materials; Further reading.

Book 414, ISBN 0 901462 40 3.

Further details available from Helen Turkdogan, Marketing Services Officer, The Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB.
Tel.: 01 839 4071, Telex: 8814813,
Fax: 01 839 2289.

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Materials matter

Materials in UK industry available from Mediascene, The Director Marketing Centre, Bowen Industrial Estate, Bargoed CF8 9EP, United Kingdom. Tel.: 0443 821877.

Materials issues in art and archeology (ed. E. V. Sayre and P. Vandiver) has been published by the Materials Research Society (MRS), Pittsburgh, PA, USA. The book (321 pp.) contains the proceedings of an MRS sponsored symposium held in April 1988 in Reno, NV, USA. Its 39 articles address topics ranging from geochemical characterization of 2500 year old marble sculpture to the soldering of gold in the fourth millennium B.C. The book is divided into presentations on three areas of research: structural and compositional analyses of ancient materials, ancient materials technology, and processes of deterioration and conservation. With more than 200 photographs, illustrations, charts, and tables, this publication reflects the growing scientific interest in developments, process technologies, and characterization methods for ancient materials.

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New NTIS catalogue describes services

The National Technical Information Service (NTIS) has published the 1989 update of its free 32-page catalogue describing specialized technical information products and services available only from NTIS.

NTIS disseminates the results of United States Government-sponsored R&D activities as reported by 350 federal agencies and by world wide sources, including Japan and western Europe. All scientific and technical fields are covered. Original information available:

- Technical R&D reports
- Conference presentations and proceedings
- Government patents (licensing opportunities)
- Manuals, guides and handbooks
- Subscriptions to publications from DOE and other government agencies
- Computer software and data files
- Translations
- Federal information processing standards (FIPS)
- Applied engineering studies
- Special bibliographies
- Environmental impact statements.

NTIS provides information in dozens of print and microform products, including 26 different weekly newsletters (bulletins). The newsletters summarize new reports received in each of 26 subject areas. NTIS data base is available on line through several commercial vendors.

For a free catalogue, ask for PR 827/KLC, NTIS Products and Services Catalog, NTIS, Springfield, VA 22161, USA.

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Material specialties

Volume 88-11 devotes 16 pages to coverage of high-temperature materials such as machinable ceramics, epoxies, adhesives, high-temperature tapes, ceramic cloths, and conductive materials. Brief descriptions are given for other products, such as ceramic board, liquid ceramic foam, high density castable alumina, heat sink compound, safety products, and gasket-forming compounds. Cotronics Corp., 3379 Shore Parkway, Brooklyn, NY 11235, USA.

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Directory to Indian technology available

A directory to India's technology areas, including fertilizers and chemicals, oil and gas, and energy industries is contained in a special India High Tech issue of Indo American Business Times. Intended as a resource for firms seeking to promote technology transfer between India and the United Staates, it contains business contacts (names, addresses, phone, telex, and fax numbers of hundreds of firms in India), a resource guide, and other data on India's technology areas. The issue is available from Indo American Business Times, P.O. Box 33364, Farragut Station, Washington, D.C. 20033, USA.

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Looking ahead for materials and processes

Edited by Jacques De Bossu, Guy Briens and Pierre Lissac. NY: Elsevier, 1987. 496 pp. (Materials Science Monographs: Vol. 41)
620.1'1 TA401.3 87 9059 ISBN 0 444 42803 8

Aeronautical applications. Diversified applications. Adhesives. Naval applications. Materials and space. Composites behaviour. Thermoplastics and ceramics.

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Dictionary of Scientific and Technical Terms

Fourth edition. S. P. Parker, Editor in chief, McGraw Hill Book Co., 11 W. 19th St., New York, NY 10011, USA, 1989, 2,137 pp., $95.

Although not strictly related to materials science and engineering, this volume rates mention solely for its exhaustive approach to defining the language of science and technology. The latest edition includes definitions of 100,100 terms, an increase of 7,600 from the third edition. Listings are divided among 102 separate disciplines, including crystallography, design engineering, electronics, engineering, industrial engineering, materials, metallurgy, mineralogy, mining engineering, solid state physics and spectroscopy. The definitions, written in language designed to be understandable to the non specialist, are checked for accuracy, clarity and completeness by 28 consulting editors. The volume contains more than 3,000 photographs, drawings and tables, as well as appendices that include SI English conversions, the periodic table of the elements, schematic electronic symbols, listings of scientific and technical organizations, and mathematical signs, symbols and notations.

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Japanese R&D trend analysis: advanced materials is an ambitious project to provide western technology companies insight into Japan's growing materials technology base and opportunities for strategic alliances. It is published by KRI International, a smaller (40 professionals) Japanese version of SRI International. (The two companies are affiliated and KRI's international advisory council chairman is Charles Anderson, the former president of SRI.) It has already completed reports on conductive polymers, polymer alloy and blends, and photoresists. Future reports will focus on metals and alloys, gallium arsenide and other advanced semiconductors, carbon fibre reinforced plastics, liquid crystals, ceramic composites, and structure ceramics. (Takako Kawakami, Director, KRI USA, 150 W. Santa Clara St., San Jose, CA 95113, USA)

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Information on 1,100 laboratories is given in the 1989 ASTM Directory of Testing Laboratories, which is now available. Covering 400 more laboratories than the 1988 edition, it contains laboratory names, phone numbers, testing capabilities and key contacts. The directory is indexed to allow search by location, laboratory name, fields of testing, materials or products. Copies may be purchased from ASTM Customer Service (American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA).

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Photovoltaic power generation: proceedings of the second contractors' meeting held in Hamburg, 16-18 September 1987

Edited by R. Van Overstraeten and G. Caratti, Boston, USA: Kluwer Academic, 1988. 311 pp. (Solar Energy Development - Third Programme; Vol. 3) 621.31'244 TK2960 87-36102 ISBN 90-277-2691-4

Photovoltaic power generation R&D programme. A-Si solar cells prepared by the glow discharge technique. Evaluation of promising alternative A-Si deposition methods. High efficiency crystalline silicon thin film solar cells. Thin film solar cells based on II VI and ternary chalcopyrite semiconductor materials. III-V compound semiconductors for use in thin-film cells or in monolithic multilayer cells.

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It is good to see that the Institute of Metals recently organized a major conference on the role of new materials in the renewable energy field. For example in relation to windturbines, solar power and tidal barrages. Details of the "Materials in Modern Energy Systems" conference, held at the University of Bristol on 27-29 September 1989 can no doubt be obtained from the Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB, United Kingdom.

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Solar energy applications to buildings and solar radiation data: proceedings

Edited by T. C. Steemers, Boston, USA: Kluwer Academic, 1988. 185 pp. (Solar Energy Development Third Programme; Vol. 4) 697'.78 TH7413 88-2759 ISBN 90-277-2715-5

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Tool materials for high-speed machining: proceedings of 1987 conference

Edited by J. A. Swartley Loush. Metals Park: ASM, 1987. 137 pp. 620.1 TJ1186 87-070938 ISBN 0-87170-297-5

Trends in high speed machining. Cermets, CBN, diamonds. Coating-ion implantation. Ceramics. Tool monitoring.

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Piezoresistive sensors

Solid state piezoresistive pressure sensors, transducers, and transmitters in several models are the subject of this eight page review. Discussion summarizes possible applications for various products. Quick reference selection charts show each model and provide useful data on operating features, pressure ranges, performance characteristics, outputs, electrical connections, and operating conditions. Cutaway drawing shows vital construction features of pressure sensors with best fit straight line performance specifications. Foxboro ICT Inc., 199 River Oaks Parkway, San Jose, CA 95134, USA.

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Solid-state sensors

Updated handbook includes information on solid-state pressure sensors and accelerometers. The 250-page reference guide reviews custom design options and devotes 100 pages to specific application details. Pressure sensors, transmitters, and transducers for pressure ranges from 0 to 1 psi through 1 to 5,000 psi are listed with extensive engineering data. Circuit design basics, precalibrated breadboards and fully signal-conditioned sensors are highlighted. Sensym Inc., 1255 Reamwood Ave., Sunnyvale, CA 94098, USA.

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Automotive sensors

Eight-page brochure explains how automotive sensors can be used to measure speed, motion, torque, and position in braking, suspension, powertrain and steering systems. The colour bulletin discusses sensor design and manufacturing product capabilities, and recommended applications. Research, development and customer service are highlighted. Spectrol Electronics, 17070 E. Gale Ave., City of Industry, CA 91745, USA.

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Pressure sensor advantages

The abilities of pressure sensors to protect instrumentation from the process line are explored in this 12-page brochure. Discussion focuses on design that eliminates instrument plugging and fouling by isolating instrument from the line and giving a 360 per cent reading. Accurate readings, various applications and sensor construction are detailed. Red Valve Co., 700 N. Bell Ave., Carnegie, PA 15106, USA.

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"Inductive and Capacitive Proximity Sensors" devotes 28 pages to the subject of how proximity sensors work, selection considerations and operating ranges. Miniature sensors, wide temperature range models and specialty designs are presented with extensive performance data. Wiring diagrams, mounting options, circuitry, sensitivity adjustment, terminology and dimensions also are covered. Rechner Electronics Industries Inc., 8651 Buffalo Ave., Niagara Falls, NY 14304, USA.

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Superconductivity

New materials and ceramics fabrication, behaviour and composition of the new materials, ceramic superconductor structure, and the likelihood of room temperature superconductors, are dealt with in "Introduction to superconductivity", available, priced 35 pounds sterling, from IBC, Canada Road, Byfleet, Surrey KT14 7JL, United Kingdom.

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Chemistry of high-temperature superconductors

Eds. D. L. Nelson, M. S. Whittingham and T. F. George. Washington: American Chemical Society 1987. pp. xi + 329. ISBN 0 8412 1431 X.

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Chemistry of high-temperature superconductors II

Eds. D. L. Nelson and T. F. George. Washington: American Chemical Society 1988. pp. xi + 338. ISBN 0 8412 1541 3.

The recent discovery of higher temperature superconductivity in a number of copper oxide compounds has made these materials the focus of intense research work by many scientists around the world. The goal of all this effort is a better understanding of high-temperature superconductors, which will allow the improvement of their properties and push this new class of materials into practical commercial applications.

"Chemistry of high temperature superconductors", volumes I and II, is based on the results of some of this research. Volume I comprises seven sections which discuss the theory of superconductivity, materials preparation and characterization, structure-property relationships, surfaces and interfaces, processing and fabrication, applications, and research needs and opportunities. Volume II is divided into four sections which report on the rapid progress that has been made in the following areas of physical chemistry: theory, new materials, surfaces and interfaces, and processing.

Both books provide data of invaluable help to chemists, physicists and materials scientists working in the whole spectrum of superconductivity. They make good reading for enlightenment on the race which is now on for applications and extrapolation of the phenomenon to more normal temperatures.

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Ceramics

World report on advanced ceramics (WRAC) is the ninth in a series of intelligence services provided by Technical Insights, Inc., Englewood, NJ, USA. Published monthly since November 1988, WRAC monitors major developments world-wide in the advanced ceramics industry. The publication tracks and analyses technically and commercially significant research efforts, patent grants, partnerships, and licence arrangements.

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Structural ceramics

John P. Wachtman, Jr., Editor, Academic Press, 1250 Sixth Ave., San Diego, CA 92101, USA, 1989, 388 pp., $75.

This book, Volume 29 of Academic's Treaties on materials Science and Technology series, is a useful introduction to the science and technology of advanced ceramics for engineers who may not be experts in the field. Coverage begins with a survey of potential application areas for high-performance structural ceramics. The role of structural ceramics as "enabling" materials for technologies such as advanced heat engines is discussed. This is followed by a chapter on designing with structural ceramics, including information on key material characteristics and an example design problem. Three chapters then cover the most common classes of advanced ceramics - silicon carbide, silicon nitride and sialons, and transformation toughened materials in terms of properties and processing methods. Chapters on ceramic matrix composites and tribological properties of advanced ceramics complete the book. Numerous references are presented at the end of each chapter for those seeking further reading.

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Chem. Systems Inc., Tarrytown, NY., USA, has issued a report titled "Advanced ceramic processing technology", a comprehensive survey of materials and processes employed in making advanced ceramics.

The report is divided into nine sections: raw materials, size separation, particle size reduction processes, granulation, batching and mixing processes, forming processes, drying, thermal densification, and hot forming and pressure sintering.

In the report, the processing steps and their critical variables are discussed in detail. Emphasis is placed on the effect of a powder's characteristics on an unstructured microstructure.

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Silicone materials

A new brochure from Silicone Products Div., General Electric Co., Waterford, NY, USA, details uses of silicone materials in electrical/electronic applications. Information on silicone technology for junction and die coatings, moulding compounds for packaging systems, conformal coatings and gel encapsulants, and high-temperature adhesives is included.

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International Encyclopedia of Composites

This new six volume encyclopaedia will cover all areas of composite materials and related process technology.

For more information on this and other VCH titles please contact your local bookseller or in case of difficulty:

VCH, P.O. Box 101161, D-6940 Weinheim
VCH, Hardstrasse 10, P.O. box, CH-4020 Basel
VCH, 8 Wellington Court, Cambridge CB1 1HW, UK
VCH, Suite 909, 230 East 23rd Street, New York,
NY 10010-4606, USA.

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Advanced composite mould making is a resource on the manufacture of moulds used to form or bond advanced composite parts and assemblies. The 431 pp volume, by John J. Morena, provides detailed instruction on how to use each kind of mould making material and execute each mould making process. Procedures for solving mould and tool design problems are presented. Tabular data assists in the design of advanced composite parts for such industries as aircraft, aerospace, marine, transportation, leisure and sport. Information is given on how to select and use materials.
Van Nostrand Reinhold, 115 Fifth Ave., New York, NY 10003, USA.

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The use of composites for positioning and other applications is the focus of two product brochures. The first covers composite production and polymer composite material characteristics such as vibration damping. Second brochure explains how to achieve long travels in a limited work environment with composite positioning tables using linear dc motors. Two piece construction also is featured. Anorad Corp., 110 Oser Ave., Hauppauge, NY 11788, USA.

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Advanced composites on rising curve

The fast-increasing use of composites in the aerospace industry is likely to continue, with aircraft manufacturers currently looking at such techniques as carbon, glass or aramid fibre filament winding used with prepregs for very large structures such as fuselages, engine nacelles, tail cones and windmill blades.

This is one of the conclusions emerging from a study carried out by IAL Consultants for its subscribers. The 200-page report, entitled "The market for advanced composites in the European aerospace and defense industries", brings together the views of over one hundred experts in the polymer supply, fabrication and end-use sectors. Potential applications of composites in aerospace and defence are reviewed in detail, and the report concludes with an optimistic appraisal of the market up to 1992. IAL Consultants Ltd., 14 Buckingham Palace Road, London SW1W 0QP, United Kingdom.

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Advanced composite materials, a book which aims to fill the need for a comprehensive textbook on advanced composites, is to be published by the Design Council in the United Kingdom. It is edited by Leslie Phillips, a leading consultant in polymer technology, one of original patentees of high-strength carbon fibres produced from poly acrylonitrile, and a past head of plastics technology at the Royal Aircraft Establishment, Farnborough, United Kingdom.

The book is aimed at those concerned with fibres or resin matrices, practising engineers and metallurgists who have little or no experience of composite materials, and at industrialists and academics who have an interest in the opportunities presented by these materials. It should also be suitable for students of engineering and materials science.

As well as contributions from Leslie Phillips, outlining the history, fabrication methods and applications of composites, Advanced Composite Materials contains chapters by experts specializing in:

- Properties of thermoset composites and design of pultrusions;

  Joining and finishing of composites;

  Quality control and non destructive testing;

  Design, analysis and prototype testing; and also

  Fracture and failure mechanisms.

A glossary of terms and a bibliography will also be included. Further details on the book can be obtained from Design Council Books, 28 Haymarket, London SW1Y 4SU, United Kingdom.

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Seventy-three composites papers are contained in "Proceedings of the American Society for Composites - Third Technical Conference" held in September 1988. The papers cover processing and manufacturing science, internal interfaces, materials engineering, impact and damage tolerance, reinforcement, stresses, design and characterization, durability and non-destructive testing, structure design and analysis, and fatigue and fracture. 734 pp. Order from Technomic Publishing Co., Inc., 851 New Holland Ave., P.O. Box 3535, Lancaster, PA 17604, USA.

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Plastics

Polymer publication

Magazine-format publication "Novus" includes several articles on the features and developments of polymers. Application story details polymer use in experimental aircraft Voyager. Other sections focus on product applications in lockers, bottling, batteries, flanges, and grinder pump housings. Quality, chemical resistance and design flexibility are highlighted. Geon Vinyl Div., B.F. Goodrich, Box 228011, Cleveland, OH 44122, USA.

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Luminescence techniques in solid state polymer research

Ed. L. Zlatkevich. New York: Marcel Dekker 1989, pp. i + 318. ISBN 0 8247 8045 0

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Plastics materials

Fifth edition. J. A. Brydson. Guildford: Butterworth Scientific 1989. pp. i + 839. ISBN 0 408 00721 4

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Plastics publications 1989, a new catalogue from Technomic Publishing Co. Inc., Lancaster, PA, USA, describes 81 books, journals and software packages on various aspects of plastics technology. Topic areas listed include alloys and blends, composites/reinforced plastics, computer-aided design and manufacturing (CAD/CAM), foamed plastics, interpenetrating polymer networks, non-destructive evaluation, plastic films, structure and properties, and thermoforming.

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Plastics joining

A 180 page introductory text on plastics joining is being marketed by Edison Welding Institute. Joining Plastics in Production is designed to help engineers and managers understand several of the most common methods for joining plastics and composites, including friction, ultrasonic, vibration, hot plate, hot gas, and high frequency welding. Adhesive bonding also is addressed. For ordering information, contact EWI Bookstore, 1100 Kinnear Rd., Columbus, Ohio 43212, USA.

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Epoxy structural adhesives

Bulletin DS10 3045 provides detailed selection data on several structural adhesives suited for bonding with rubber, plastics, SMC, metals and other materials. Bond strength and performance, cure times, temperatures, preparation and applications are charted for quick review. Environmental resistance and many special applications are detailed. Industrial Adhesives Div., Lord Corp., Box 10038, Erie, PA 16514, USA.

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Thermoplastic polymer additives: theory and practice

Ed. J. T. Lutz, Jr. New York: Marcel Dekker 1989. pp. xi + 523. ISBN 0 8247 7901 0

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Telechelic polymers: synthesis and applications

E. J. Goethals. Florida: CRC Press 1989. pp. i + 402. ISBN 0 8493 6764 6

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Engineering thermoplastics

A 24-page guide to designing with engineering thermoplastic materials as replacements for metals has been published by Plastics and Rubber Div., Mobay Corp., Pittsburgh, USA. The booklet discusses metals applications with potential for replacement by thermoplastics, the differences between plastics and metals, selection of thermoplastic materials, processing methods, and designing with thermoplastics.

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Styrenic polymer studies

"Stabilization of Styrenic Polymers" reviews UV and thermal stabilization of impact polystyrene, ABS, polybutadiene, SAN, crystal polystyrene, and other materials. Studies on the effects of heat and UV exposure on physical properties, performance after multiple extrusion, discolouration and other aspects are featured. Quick reference listings are included. Additives Div., Ciba-Geigy Corp., 3 Skyline Dr., Hawthorne, NY 10532, USA.

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Engineering science of polymeric materials

Z. H. Stachurski, Royal Australian Chemical Institute, Australian Polymer Science Series, 1988.

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Polymeric materials: chemistry for the future.

By Joseph Alper and Gordon L. Nelson. Paper. 110 pages. American Chemical Society, 1155 Sixteenth Street, N.W., Washington, DC 20036, USA.

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Metals

Volume 16: Machining of the Metals Handbook® provides machinists and engineers with practical information on the most recent developments in machining technology, covering: traditional and non-traditional machining processes; cutting tool materials; cutting fluids; grinding, honing and lapping; machining of specific metals and alloys; machine controls and computer applications in machining; and high productivity machining. 944 pp; order No. 6022P. Contact: ASM International, Member Customer Service Center, Metals Park, OH 44073, USA.

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Specialty alloy selection

Ten heat-resistant alloys, seven corrosion-resistant types, and two wear-resistant alloys in bar, sheet, plate, electrodes, fittings and other forms are the focus of a four-page brochure. Drawings show availability in various styles. Text describes alloy performance characteristics and ordering guidelines. High Performance Alloys Inc., Box 40, Tipton, IN 46072, USA.

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"Inspection standards for commercial quality castings" is a pocket-sized 32-page handbook on quality standards for precision investment castings. Aspects such as linearity, straightness, hole tolerances, contours and positioning are discussed. Illustrations and text also explore metallurgical and quality-control standards, metal properties, chemical changes and other factors. VSX Div., GTE Valenite Corp., Box 3950, Troy, MI 48007, USA.

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A definitive assessment of trends in the major metals, such as Al, Sn, Cu and Pb, over the next decade, is available from the Institution of Mining and Metallurgy, 44 Portland Place, London W1N 4BR, United Kingdom.

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International Metallic Materials Cross-reference

3rd edition. Genium Publishing Corporation, Room 212, 1145 Catalyn Street, Schenectady, NY 12303-1836, USA.

This new edition lists more than 45,000 metals and alloys produced around the world, giving each country's designations for "nominally equivalent" materials.

The key feature of the reference is its organization of material designations in alphanumerical order rather than by chemical composition. Each country's alphanumeric designation is followed by the material's composition, listing the percentage of its various alloying elements.

The third edition is the work of editors John G. Gensure and Daniel L. Potts, both materials engineers.

Listings contain materials produced in 34 nations, including the People's Republic of China. Fifty-nine standards organizations are represented, including four international societies (AECMA, EURONORM, COPANT and ISO), the United States Federal Government, and numerous United States technical standards groups. Thirty-four materials categories are presented.

Report on the Sixth International and Second European Conference on Composite Materials

The Imperial College of Science and Technology in London was the site of the combined ICCM-VI/ECCM-2 conferences and exhibition attended by close to 850 delegates from 31 countries. The over 250 papers and posters presented indicate the increasing interest worldwide in composites. Surprisingly, there were far more papers on metal-matrix (36) than on ceramic-matrix (6) composites. This may be more indicative of an increase in commercial competitiveness, and thus unwillingness to impart too much information, than of a decrease in interest in CMCs. Three MMCs that attracted a great deal of attention at the exhibition were Toyota's squeeze cast aluminium-matrix composite reinforced with a hybrid form of Ube's Tyranno fibre, Alcan's cost-effective aluminium reinforced with silicon carbide particulates, and Cray Advanced Materials' pressure infiltrated ceramic fibre reinforced aluminium and magnesium.

The conference featured plenary lectures preceding each of the morning and afternoon sessions. Their emphasis was largely on polymer-matrix composites. Among the lecture topics covered were the use of composites in the automotive industry, where cost is a factor; the present state of development of fibre reinforced composites for load-bearing applications above 150°C; engineering approaches to predicting the lifetime of materials and components; the history, present status and future of fibre reinforcements; the non-destructive evaluation of continuous fibre reinforced polymeric-matrix composites; and the future of advanced polymeric composites in aircraft.

It is to the credit of all those responsible that the proceedings edited by F. L. Matthews, N. C. R. Buskell and J. M. Hodgkinson of Imperial College and J. Morton of Virginia Polytechnic Institute, which were included in the registration fee, were available at the conference. The Seventh International Conference on Composite Materials was held in Beijing, China, on 25-28 August 1989, and the Third European Conference on Composite Materials was held in April 1989 in Bordeaux, France.

To obtain the ICCM and ECCM proceedings: In the United States and Canada, the Metallurgical Society, Book Order Dept., 420 Commonwealth Dr., Warrendale, PA 15086. Phone: (412) 776-9000, telex: 9103809397. Also Elsevier Applied Science Publishers Ltd., Crown House, Linton Road, Barking, Essex IG11 8JU, United Kingdom. Phone: (44) 01-594-7272, telex: 896950.

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Metal-matrix composites: property optimization and applications. 8-9 November 1989, City Conference Centre, London, United Kingdom. Organized by The Institute of Metals.

Scope

This conference was the second in a series which began with the meeting on Structure and Property Assessment in London on 23-24 November 1987. Since that time, the development of metal-matrix composites has accelerated considerably. A number of companies in the United Kingdom and world-wide are now in, or on the brink of, production of metal-matrix composites of various matrices and reinforcements.

The conference was intended to allow an opportunity for the most up-to-date information in this rapidly expanding field to be discussed. In view of the imminent production of some metal matrix composites, it was hoped that the subjects would cover the spectrum from fundamental matrix-reinforcement interactions to case studies on actual or potential applications.

The subjects covered focused on the optimization of the structure and properties of metal-matrix composites for industrial applications. Sessions included: matrix-reinforcement interactions; design and property optimization; manufacturing and processing; and applications/case studies. A wide variety of industrial applications were included to highlight the future potential of metal matrix composites.

(Conference Department (C922), The Institute of Metals, 1 Carlton House Terrace, London, SW1Y 5DB, Tel.: 01-839 4071; telex: 8814813; Fax: 01-839 2289)

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Issue No. 16 - MATERIALS DEVELOPMENTS IN SELECTED COUNTRIES

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300,
A-1400 Vienna, Austria

Advances in Materials Technology: Monitor
Reader Survey

The Advances in Materials Technology: Monitor has now been published since 1983. Although its mailing list is continuously updated as new requests for inclusion are received and changes of address are made as soon as notifications of such changes are received, I would be grateful if readers could reconfirm their interest in receiving this newsletter. Kindly, therefore, answer the questions below and mail this form to: The Editor, Advances in Materials Technology: Monitor, UNIDO Technology Programme at the above address.

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Readers' comments

We should appreciate it if readers could take the time to tell us in this space what they think of the 17th issue of Advances in Materials Technology: Monitor. Comments on the usefulness of the information and the way it has been organized will help us in preparing future issues of the Monitor. We thank you for your co-operation and look forward to hearing from you.