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# Metal-matrix Composites

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**ABSTRACT**

This paper reviews the world-wide upsurge in metal-matrix composite research and development activities with particular emphasis on cast metal-matrix particulate composites. Extensive applications of cast aluminium alloy MMCs in day-to-day use in transportation as well as durable good industries are expected to advance rapidly in the next decade.

The potential for extensive application of cast composites is very large in India, especially in the areas of transportation, energy and electromechanical machinery; the extensive use of composites can lead to large savings in materials and energy, and in several instances, reduce environmental pollution.

It is important that engineering education and short-term courses be organized to bring MMCs to the attention of students and engineering industry leaders. India already has excellent infrastructure for development of composites, and has a long track record of world class research in cast metal matrix particulate composites. It is now necessary to catalyze prototype and regular production of selected composite components, and get them used in different sectors, especially railways, cars, trucks, buses, scooters and other electromechanical machinery. This will require suitable policies backed up by funding to bring together the first rate talent in cast composites which already exists in India, to form viable development groups followed by setting up of production plants involving the pròcess engineering capability already available within the country. On the longer term, cast composites should be developed for use in energy generation equipment, electronic packaging aerospace systems, and smart structures.

## 1. INTRODUCTION

Metal-matrix composites (MMCs) 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 to achievable combinations of strength, stiffness and density. Engineered MMCs consisting of continuous or discontinuous fibres, whiskers, or particles in a metal achieve combinations of very high specific strength and specific modulus (Tables 1, 2, and Fig. 1). Furthermore, systematic design and synthesis procedures allow unique combinations of engineering properties in composites like high elevated temperature strength, fatigue strength, damping property, electrical and thermal conductivities, friction coefficient, wear resistance and expansion coefficient. Structurally, MMCs consist of continuous or discontinuous fibres, whiskers, or particles in an alloy matrix which reinforce the matrix or provide it with requisite properties not achievable in monolithic alloys. In a broader sense, cast composites, where the volume and shape of phase is governed by phase diagrams, for example, cast iron and aluminium-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

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Table Specific mechanical properties of some materials

| Material | Fibre (vol %) | Specific strength (N-m/kg) | Specific modulus ($10^7$ N-m/kg) |
|---|---|---|---|
| $Al_2O_3$/(FP)*Al-Li* | | | |
| 0° | 60 | 20000 | 7.59 |
| 90° | 60 | 5000 - 600( | 4.41 |
| *SiC/Ti*-6 *Al*-4V | | | |
| 0° | 35 | 45300 | 7 7: |
| 90° | 35 | 10200 | |
| *C/Mg* Thornel | 38 | 28300 | |
| *C/Al* | 30 | 28200 | 6.53 |
| 6061 *Al* | | 11500 | 2 53 |
| 2014 *Al* | | 17100 | 2.59 |
| $SiC_{(f)}$ | 100 | 78400 | 15.7 |
| $SiC_{(w)}$ | 100 | $6.67 \times 10^5$ | 21.9 |
| $Al_2O_{3(f)}$ | 100 | 50000 | 11.8 |
| $B_{(f)}$ | 100 | $1.54 \times 10^5$ | 16.2 |
| $C_{(f)}$ | 100 | $1.62 \times 10^5$ | 13.5 |
| $Be_{(f)}$ | 100 | 59500 | 16.8 |
| $W_{(f)}$ | 100 | 15000 | 1.79 |
| *B/Al* | | | |
| 0° | 50 | 56600 | 7.92 |
| 90° | 50 | 5280 | 5.66 |
| *SiC/Al* | | | |
| | | 8800 | 10.9 |
| | 50 | 3700 | |

Table 2. Typical elastic modulii of cast aluminium composites

| Metal-matrix composite | Volume fraction | Elastic modulus (GPa) |
|---|---|---|
| *Al* matrix | 0 | 68.9 |
| Continuous *SiC* fibre (*Al*-4.5 *Cu* matrix) | 0.35 | 74.7 |
| Continuous *SiC* fibre (*Al*-11.6 *Si* matrix) | 0.35 | 72.3 |
| Continuous *SiC* fibre (*Al*-4.8 *Mg*) | 0.35 | 64.4 |
| Discontinuous *SiC* fibre (*Al* matrix) | 0.44 | 79.9 |

of reinforcement can be artificially introduced in the matrix. The modern composites are nonequilibrium combinations of metals and ceramics, where there are fewer thermodynamic restrictions on the relative volume percentages, shapes and size of ceramic phases.

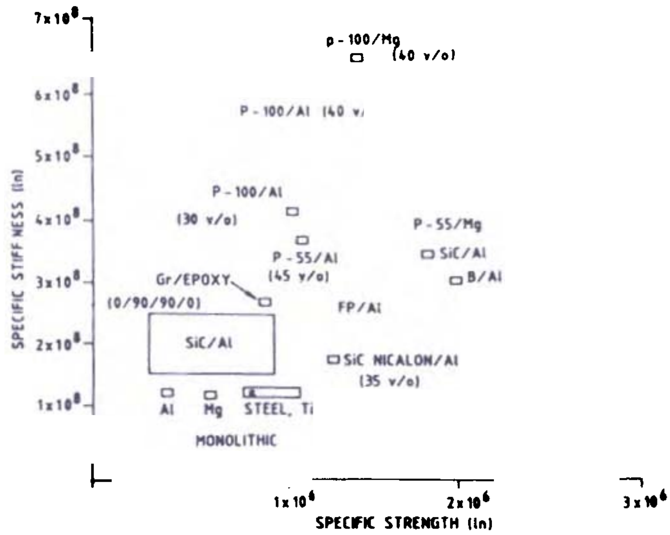



**Figure 1** Specific properites of aluminium and magnesium-matrix composite materials, compared to unreinforced alloys (Properties of continuous fibre-reinforced materials are calculated parallel to the fibres).

By carefully controlling the relative amounts and distribution of the ingredients constituting a composite as well as the processing conditions, MMCs can be imparted with a tailored set of useful engineering properties which cannot be realised with conventional monolithic materials (Fig. 1). 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 significant 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 MMC fabrication technology. These include both the preparation of the reinforcing phases and the development of fabrication techniques.

Reinforcing phase for MMCs fall into three important categories: (i) continuous and discontinuous filament, (ii) whiskers, and (iii) particulate. The important improvements in mechanical properties are obtained from filaments in the direction of their alignment, with whiskers and particulates offering lesser strength with greater isotropy.

A number of composite fabrication techniques have been developed that can be placed into four broad categories. These are: (i) liquid metallurgy, (ii) powder metallurgical techniques, (iii) diffusion bonding of filaments and foils, and (iv) vapour phase infiltration. The liquid metallurgy techniques include unidirectional solidifications to produce directionally aligned MMCs, suspension of reinforcement in melts followed by solidifi cation, compocasting, squeeze casting, spray casting, and pressure infiltration. The liquid metallurgy techniques are the least expensive of all, and the multi-step diffusion bonding techniques may be the most expensive.

From a technological standpoint of property-performance relationship, the interface between the matrix and the reinforcing phase (fibre or particle) is of primary importance. Processing of MMCs sometimes allows tailoring of the interface between the matrix and the fibre in order to meet specific property-performance requirements. The cost of producing cast MMCs has come down rapidly, especially with the use of low cost particulate reinforcement like graphite, alumina and silicon carbide. Low cost, large tonnage composites with *Sic*, $Al_2O_3$ and graphite particle are now commercially available. In recent years considerable activity has taken place in the area of MMCs, and some examples of different fibres and matrix combined to date, the fabrication techniques and the potential fields of application are shown in Table 3. Table 4 gives more recent data of same type for cast composites, most of which are particulate.

## 2. COMPOSITE MATERIAL PROPERTY DEVELOPMENT

Composite materials technology offer unique opportunities to tailor the properties of metals and metal alloys. Under ideal conditions, the composite exhibits the principal mechanical, thermal, physical and tribological properties defined by the so-called 'rule-of-mixture' as shown in Eqn (1).

$$P_c = P_m V_m + P_f V_f \quad (1)$$

where $P_c$ are the properties of the composite materials, $P_m$ are the properties of matrix phase, $P_f$ are the properties of reinforcement phase, $V_m$ is the volume fraction of the matrix phase, and $V_f$ is 1-$V_m$ is the volume fraction of the reinforcement phase.

By combining matrix and reinforcing phases exhibiting the selected properties, new materials with dramatic improvements in strength, elastic modulus, fracture toughness, density, and coefficient of expansion can be manufactured. Predicted strength and elastic modulus value of some aluminium matrix composites as a function of filament properties and volume fraction are shown in Fig. 2. The key to controlling these properties depends on both a successful selection of the reinforcing phase and an efficient bonding between the matrix and the reinforcing phase. Examples of the range of some of the specific mechanical properties attainable in aluminium and magnesium MMCs have been shown earlier in Fig. 1 as a function of reinforcing phases and volume loading.

The preceding discussion is based on the assumption that rule-of-mixtures is followed by the composite materials. In fact, this can be the case for certain properties like modulus, when continuous filament is

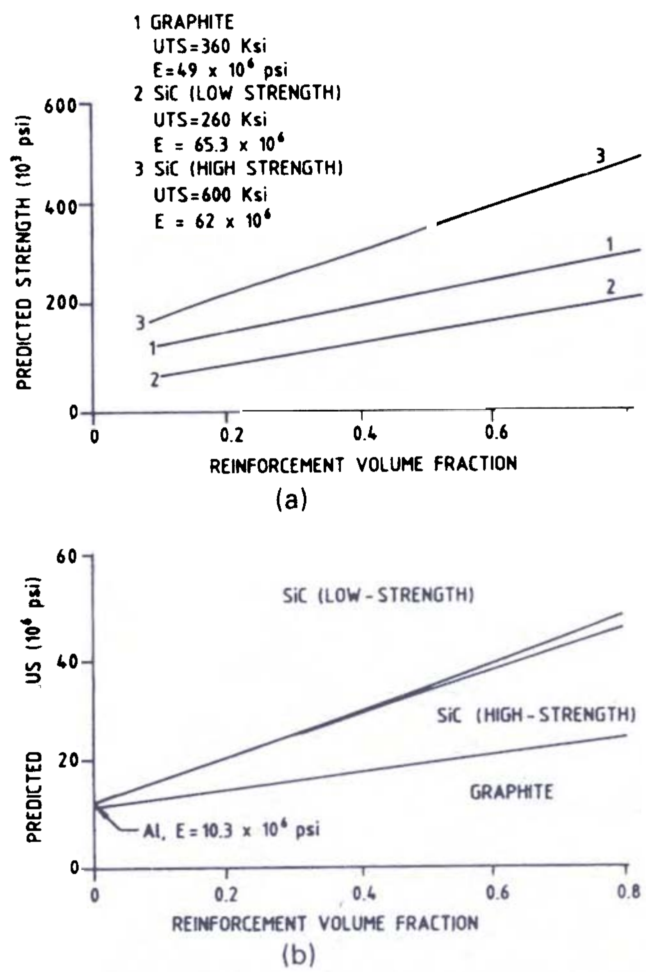



**Figure 2.** Predicted properties of aluminium matrix comopsites as a function of filament volume content (a) ultimate tensile strength, and (b) elastic modulus.

**Table 3. Fibres, matrix, fabrication techniques and fields of application of MMCs**

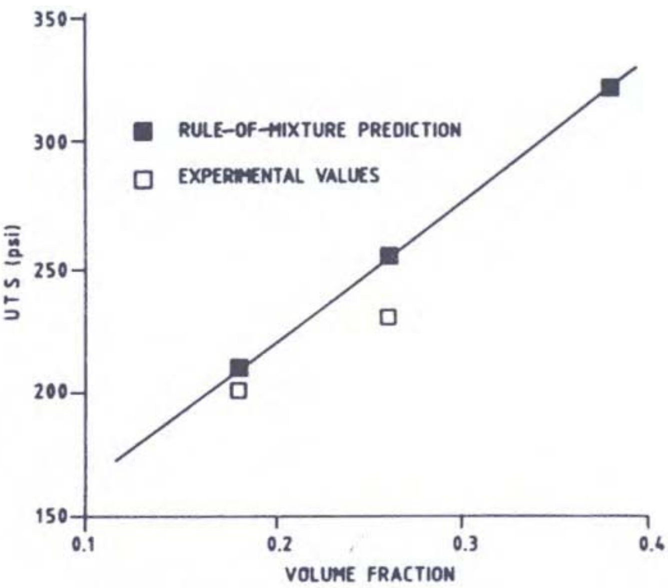
| Fibres | Matrix | Field of application |
|---|---|---|
| *Powder metallurgy route* | | |
| *SiC* coated *B* | *Al* | Turbine blades |
| *C* (graphite, amorphous carbon) | *Ni/Co* aluminide | |
| *SiC* containing 0.01-20% free carbon | *Cr* based alloys | High strength, heat resistant material, e.g., vanes and blades for turbines, rocket nozzles |
| *SiC* containing 0.01-30% free carbon | *Co* based alloy | -do- |
| *SiC* containing 0.01-30% free carbon | *Mo* based alloy | -do- |
| *C* | *Cu* alloy | High strength, electrically conductive materials, bearings and other tribological applications |
| *C* | *Si* | Abrasive materials |
| *Liquid metallurgy route* | | |
| *(a) Melt impregnation* | | |
| *C* coated with boride of *Ti*, *Zr*, *Hf* | *Al* or *Al* alloys, *Mg*, *Pb*, *Sn*, *Cu* and *Zn* | |
| *C* coated with boride of *Ti*, *Zr*, *Hf* | *Al* alloy containing carbide forming metal, e.g., *Ti* and *Zr* | |
| *C* | *Mg* or *Mg* alloy | Turbine fan blades |
| *SiC* | *Be* or alloys with *Ca*, *W*, *Mo*, *Fe*, *Co*, *Ni*, *Cr*, *Si*, *Cu*, *Mg* and *Zr* | Aerospace and nuclear industries |
| *B* + stainless steel, Borsic + *Mo* fibres | *Al*, *Ti* | Aerospace industry |
| *(b) Directional solidification* | | |
| Carbides of *Nb*, *Ta* and *W* | *Ni-Co* and *Fe-Cr* alloys | Aircraft industry |
| *(c) Casting process* | | |
| Carbon particulates, short fibres | *Al*, *Cu* | Tribological application |
| *SiC* particulates | *Al* | Wear resistant materials |
| *(d) In-situ technique* | | |
| *TiC* | *Al* | High temperature applications, wear resistant materials |
| *(e) Other processes* | | |
| *B* | *Cu-Ti-Sn* alloy (liquid phase sintering) | Cutting tools |
| *SiC* | *Ti* or alloy, *Ti*-3, *Al*-2.5 V, *H* or pressing of interlayer of fibres and matrix sheets, *SiC* fibres are previously coated with *Zr* diffusion barrier layer | Compressor blades, air foil surfaces |
| *SiC* | *Be* or alloys with *Ca*, *W*, *Mo*, *Fe*, *Co*, *Ni*, *Cr*, *Si*, *Cu*, *Mg*, and *Zr* (plasma spraying fibres with *Be* and consolidation by metallurgical processes) | Aerospace and nuclear industries |
| *B* + stainless steel, borsic + *Mo* fibres | *Al*, *Ti*, spraying combination of high strength ductile and brittle fibres | Aerospace industry |

**Table 4. Selected potential applications of cast MMCs**

| Composite | Applications | Special features |
|---|---|---|
| Aluminium/graphite | Bearings | Cheaper, lighter, self-lubricating, conserves *Cu, Pb, Sn, Zn,* etc. |
| Aluminium/graphite, Aluminium/$Al_2O_3$, Aluminium/$SiC$-$Al_2O_3$ | Automobile pistons, cylinder liners, piston rings, connecting rods | Reduced wear, antiseizing, cold start, lighter, conserves fuel, improved efficiency, tribological application |
| Copper/graphite | Sliding electrical contacts | Excellent conductivity and antiseizing properties, high machinability, tribological application |
| Aluminium/$SiC$ | Turbocharger impellers | High temperature use; tribological application |
| Aluminium/glass or carbon microballoons | | Ultralight material, antivibration material |
| Magnesium/carbon fibre | Tubular composites for space structures | Zero thermal expansion, high temperature stregnth, good specific stregnth and specific stiffness |
| Aluminium/zircon Aluminium/$SiC$, Aluminium/silica | Cutting tools, machine shrouds impellers | Hard, abrasion-resistant material, tribological application |
| Aluminium/char, Aluminium/clay | Low-cost, low-energy materials | Cheaper and lighter structural material |

used as the reinforcing phase, and matrix-to-reinforcement phase interfacial reactions are controlled to provide good bonding without degradation of the reinforcing phase. An example of a good agreement between the strength predicted by the rule-of-mixture and that measured in stainless steel filament reinforced aluminium is shown in Fig. 3.

Based on the agreement shown in Fig. 3 between the rule-of-mixture prediction and measured properties, it would seem to be desirable to fabricate all MMC composites using continuous filament as the reinforcement phase, if properties mainly in one direction are required. Practically speaking, however, there are significant restrictions imposed on the use of continuous reinforcement in MMCs. The preparation of a continuous filament reinforced component is a complex and expensive process, as shown in the lay-up process for continuous filament reinforced metallic




Fugure 3. Comparison of the rule-of-mixtures prediction and the observed ultimate tensile strength for an aluminium stainless steel continuous filament-reinforced composite material.

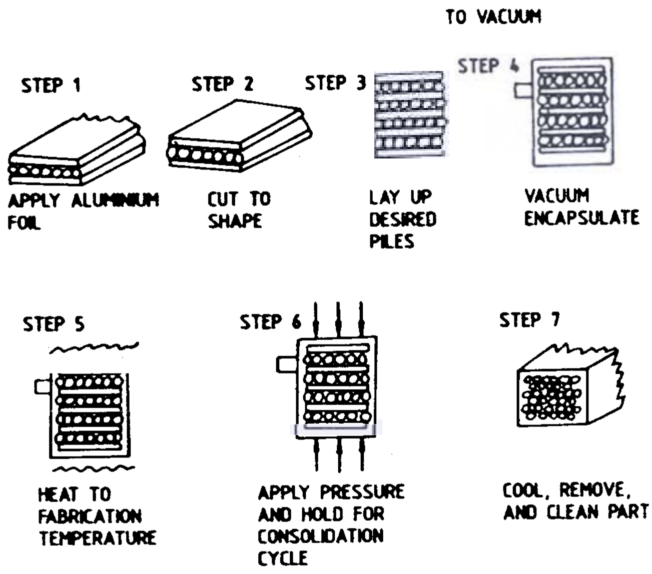



**Figure 4. Diffusion bonding process of making fibre-reinforced MMCs.**

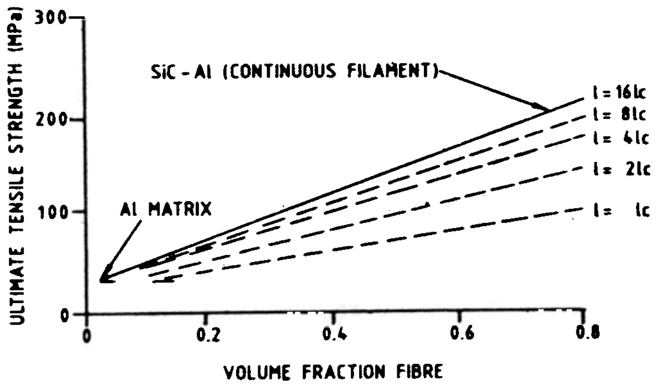



**Figure 5. Composite strength as affected by volume loading and whisker length as a multiple of minimum (critical) whisker length for full load transfer.**

matrix (Fig. 4). In addition, continuous filament reinforcement is currently limited to simple geometries such as planar or symmetric shapes. Consequently, continuous filament-reinforced MMCs are now in use in limited, high value-added applications, especially, for aerospace structures and space applications.

As a result, alternative reinforcement phase morphologies are being investigated to reduce the cost of MMCs while retaining the attractive properties. These approaches typically involve the use of less expensive, discontinuous reinforcement phase and powder metallurgy or casting techniques. Unfortunately, in the quest for lower cost, a price has to be paid in terms of lower levels of mechanical property enhacement. However, particulate composites can be lower in cost and they can import property improvements equivalent to or better than fibres, when one considers properties like damping or machinability.

The short-fall in mechanical properties compared with continuous fibre reinforcement results from the reduced ability to transfer stress from the matrix, the continuous phase, to the reinforcement, the lower volume discontinuous phase. As shown in Fig. 5, the efficiency of load transfer is related to the length ($l$) of the reinforcement phase compared with its critical length ($l_c$) by the relationship:

$$S_c = S_f \left[ V_f \left\{ \frac{l - l_c}{2.1} \right\} + \frac{E_m}{E_f} (l - V_f) \right] \quad (2)$$

where $S_c$ is the composite strength, $S_f$ is the reinforcement strength, $V_f$ is the volume fraction of reinforcing phase, $l_c$ is the minimum reinforcing phase length for full load transfer from the matrix to the reinforcement, ($l_c = dS_f/S_m$ where $d$ is the fibre diameter and $S_m$ is the matrix strength), $l$ is the actual reinforcing phase length, $E_m$ is the elastic modulus of the matrix, and $E_f$ is the elastic modulus of the reinforcing phase.

Figure 5 reveals that for fibre lengths near the critical fibre length, relatively modest increases in strength can only be realised. However, as the ratio of $l/l_c$ increases, the efficiency of load transfer from the matrix to the reinforcement increases. For example, at $l/l_c$ = 16, the discontinuously reinforced composite may exhibit approximately 96 per cent of the increase in strength exhibited by a continuously reinforced composite at equal volume loading.

Despite these theoretical advantages, there are significant practical problems associated with maintaining the integrity of high aspect ratio discontinuous fibres during fabrication and working. Thus, there is a high level of development activity in the use of particulates as composite reinforcement materials. However, particulate materials may be considered to have an aspect ratio of only about one, and one may expect somewhat lower properties when using particulate reinforcement as compared with high aspect ratio chopped fibres or whiskers. 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 also be responsible for the additional strength. In addition to the length, the shape of the dispersoids also has a major influence on the properties (Fig. 6), there are indications that flakes may be more effective than particles.

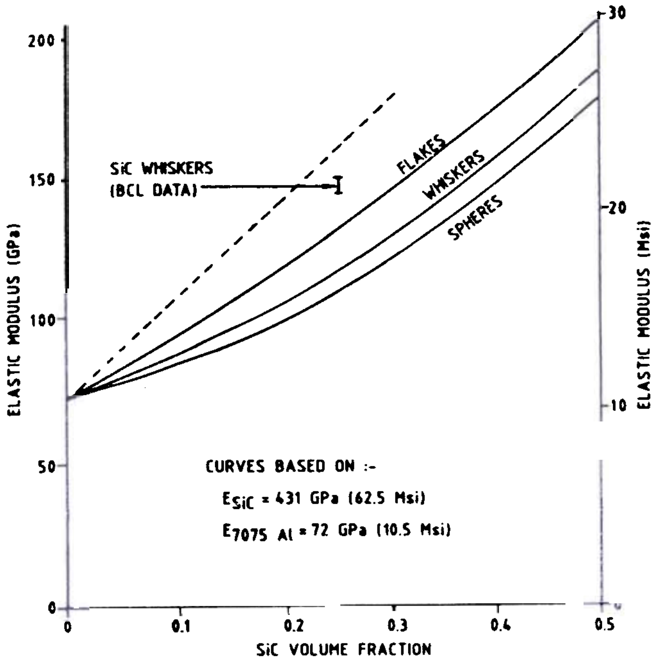



Figure 6. Elastic modulus of *SiC*-reinforced aluminium alloys.

## 3. MMC FABRICATION TECHNOLOGY

Many MMC technologies under development are competing with one another. The least expensive route uses solidification technology, i.e., molten metal casting ro... , of which several variations are possible. Other routes involve solid state processing at a relatively lower temperature which, though more expensive, in some cases offers advantage over the casting route. Some routes are specific to reinforcement phase morphology, for example: continuous filament–winding, layup and solid state processing; particulate (micron size)–solid PM route as well as casting, spray forming and other process; particulate (nano size)—gas liquid, liquid-liquid and solid-liquid in-situ displacement reactions and processing; chopped fibres and whiskers—PM or casting route followed by high tempe-ature solid state processing, for example, extrusion.

The emphasis in this review is on the development of MMCs for the widespread applications which necessitate lower costs. This means that the composites should be economical to produce and the casting route is considered to be the most applicable one, as shown in Fig. 7. A review of the PM route—a solid state

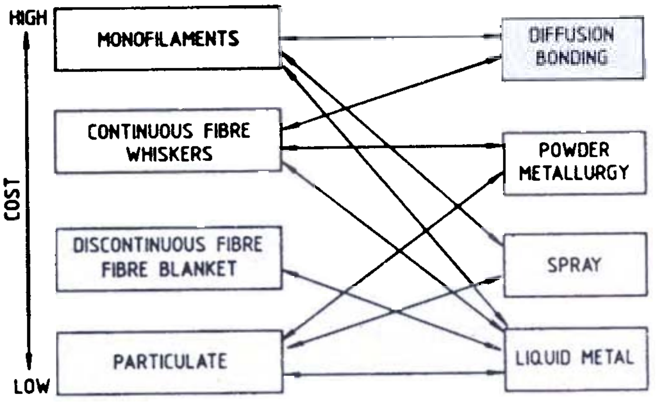



Figure 7. Reinforcement, processing and costs of MMCs for automotive applications.

processing technology is briefly described and then the various technologies of the casting route will be reviewed in some detail. Continuous filament winding and layup techniques for the manufacturing of MMCs is highly application specific, and have been described in the literature; and no effort is made in this paper to review this technology.

### 3.: Powder Metallurgy-based MMCs

Powder metallurgy techniques offer the following three advantages over liquid metallurgy techniques for fabricating MMCs.

(a) Lower temperatures can be used during preparation of a PM-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 PM technique. By minimizing undesirable interfacial reactions, improved mechanical properties are obtained.

(b) In some cases, PM techniques will permit the preparation of composites that cannot be prepared by the liquid metallurgy. For instance, fibres 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.

(c) However, PM techniques remain expensive compared to liquid metallurgy techniques for the composites like Al-SiC particle composites. In addition, only small and simple shape can be produced by PM techniques.

A number of PM composite preparation methods have been studied. The conventional PM 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 a partial melting for better bonding. The powder process composites can be subsequently forged, rolled or extruded.

Several companies are currently involved in the development of PM-based MMCs using either particulates or whiskers as the reinforcement phase. Three of these companies are Delowey, Webb and Associates (DWA), Chatsworth; 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 schematic outlines of the process steps are shown in Figs 8 and 9. DWA uses a proprietary

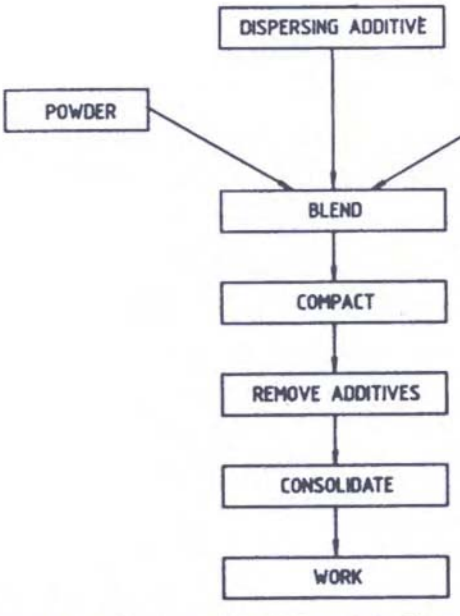



**Figure 8.** Schematic of the DWA and the Silag composite process (in the Silag process, the 'compact' step is not used).

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

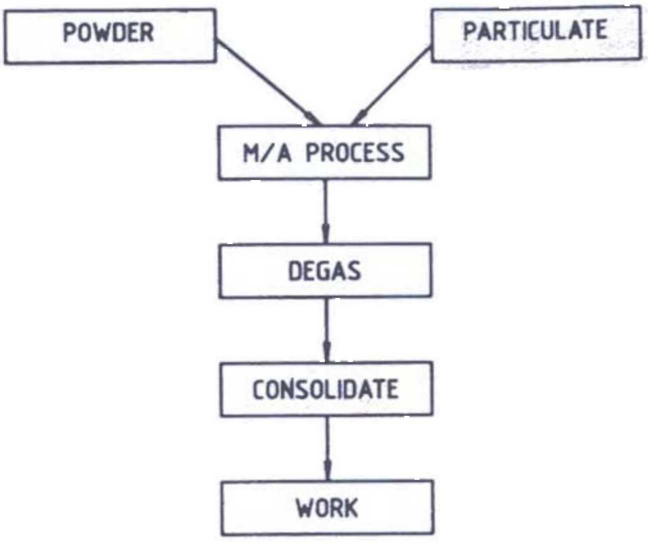



**Figure 9.** Schematic of the Novamet (Inco mechanically alloyed products) composite preperation process.

manufactured form 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., US \$50-100/lb (\$110-220/kg) versus US \$5-10/lb (\$11-22/kg), as billet. Additionally, the relationship of the mechanical properties to volume fraction reinforcement is similar. As shown in Fig. 10, the measured normalized values

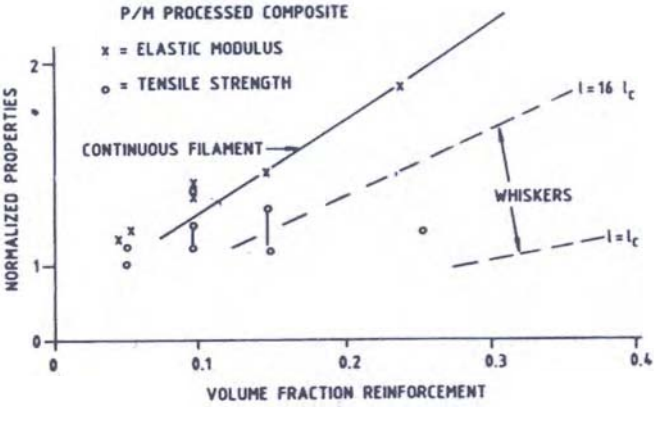



**Figure 10.** Comparison of normalised values of elastic modulus and ultimate tensile strength vs volume fraction reinforcement in *SiC-Al* alloys (predicted values for continuous and discontinous reinforcements are also shown).

of elastic modulus (normalized with respect to matrix alloy property) closely follow the predicted values for continuous filament reinforcement. However, the measured strength values are lower than the values predicted by 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 affects all discontinuous MMCs. It is most likely a result of bond weakening 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.

Using PM route, novel processing techniques can produce elongated whisker-like reinforcements *in-situ*. In this approach to MMC fabrication, elongated reinforcement phases are created by deformation processing of the composites, 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 conditions 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 fibres 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 fibres or platelets during working, even if very high deformation strains are imposed. An example of such a system is, *Cu*-11.3 weight per cent *Mo* which, at true strains of approximately seven, still retained the molybdenum particles at their near 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 prepared using this technique can show unexpectedly large positive deviations in strength compared with rule-of-mixtures as shown by the *Cu*-16 volume per cent *Fe* system. Significant deviations in strength from the rule-of-mixtures begin as early as true strains of approximately two; and at a true strain of approximately five to six, the observed strength can be as much as 50 per cent above the rule-of-mixture value.

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

(a) The metallic constituents making up the composite are inexpensive relative to the reinforcement;

(b) The composite can be formed by traditional metal-working operations;

(c) Thermal expansion mismatch between the metallic reinforcement and matrix is minimized, compared with non-metallic reinforcement in a metallic matrix; and

(d) Higher strengths than predicted by the rule-of-mixtures can be achieved.

### 3.2 Solidification Processing of MMCs

Solidification processing represents one of the simplest methods of producing MMCs. Cast irons and aluminium-silicon alloys are in a sense phase diagram dictated MMCs. Unidirectional solidification of eutectics can produce fibre reinforced composites in a single step. However, these are all phase diagram restricted.

Modern cast MMCs, not restricted by phase diagrams, are made by introducing fibres or particles in molten or partially solidified metals followed by casting of these slurries in molds. Alternately, a preform of fibres or particles is made and it is infiltrated by molten alloys, which then freeze in the inter fibre spaces to form the composite. In both these processes, adequate wetting between molten alloys and dispersoids is essential. The cast metal composites made by dispersing pretreated particles in the melts followed by

Table 5. **Matrix-dispersoid combinations used to make cast particulate composites**

| Dispersoids | Size ($\mu$m) | Amount (vol %) |
|---|---|---|
| *Aluminium, alloy matrix* | | |
| Graphite flakes | 20-60 | 0.9-0.815 |
| Graphite granules | 15-100 | 1-8 |
| Carbon microballoons | 40, thickness 1-2 | - |
| Shell char | 125 | 15 |
| $Al_2O_3$ particles | 3-200 | 3-30 |
| $Al_2O_3$ fibres | 3-6 mm long, 15 dia | 0-23 |
| $SiC$ particles | 16-120 | 3-20 |
| $SiC$ whiskers | 5-10 | 10, 0-0.5 |
| Mica particles | 40-180 | 3-10 |
| $SiO_2$ particles | 5-53 | 5 |
| Zircon particles | 40 | 0-30 |
| Glass particles | 100-150 | 8 |
| Glass beads (spherical) | 100 | 30 |
| $MgO$ particles | 40 | 10 |
| Sand particles | 75-120 | 36 |
| $TiC$ particles | 46 | 15 |
| Boron nitride particles | 46 | 8 |
| $Si_3N_4$ particles | 40 | 10 |
| Chilled iron | 75-120 | 36 |
| $ZrO_2$ particles | 5-80 | 4 |
| $TiO_2$ particles | 5-80 | 4 |
| Lead particles | – | 10 |
| *Copper alloy matrix* | | |
| Graphite particles | – | 10 |
| $Al_2O_3$ particles | 11 | 5 |
| $ZrO_2$ particles | 5 | 2.12 |
| *Ferrous alloy matrix* | | |
| $TiO_2$ particles | 8 | 10 |
| $CeO_2$ particles | 10 | 10 |
| Illite clay | 753 | 3 |
| Graphite microballoons | – | 5 |
| $TiC$ (*in-situ*) | 10-100 | 30 |

solidification are given in Tables 4 and 5. In addition, several short and long fibre reinforced MMCs have been made by casting techniques.

Continuous fibre reinforced *Gr/Mg*, *Gr/Al*, and several other cast fibre reinforced metals (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 FRMs is the relatively poor wetting and bonding between the fibres and the metals. However, compatibility and bonding between the fibre and the metal in these systems are induced by chemical vapour deposition of a thin layer of Ti and B, or oxides like silica or metals like nickel, onto the fibres to achieve improved wetting. The flexible coated fibres may then be wound or laid-up and held in place with a removable binder for selective metal/alloy reinforcement. They are then incorporated into near-net shape castings by pressure infiltration of molten magnesium. Complex structural components with high volume fraction graphite fibres can be fabricated in this manner in a state-of-the-art foundry. High-strength, high-stiffness fibre FP (100 per cent polycrystalline $\delta$-alumina)/*Mg* composites containing up to 70 vol per cent fibre FP have been prepared by a pressure infiltration process.

For nonwetting metals, fibre *FP* is coated with the metal by vapour deposition or by electroless plating, prior to infiltration. Coatings of *TiB* also have been used for *Gr/Al*, fibre *FP/Al* and *FP/Pb* MMCs. 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. Fibre *FP* reinforced *Al*, *Cu*, *Pb* and *Zn* composites as well as several particle filled MMCs have been synthesized by using reactive agents.

Continuous adherent metallic coatings (for example, *Cu* and Ni) on several nonwetting 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 MMCs 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. Table 6 clearly shows the progress made in this regard since 1965 and that too only for a specific, albeit, a large-volume potential application, namely, cast MMC components for the automobile industry. Additional rapid advances are occurring with processing automation and innovative designs.

### 3.3 Casting Technologies

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

**Table 6. Synthesis of selected cast aluminium-matrix composites of interest to automotive industries over the last 25 years**

| Period | Location* | Composite system | Technique used | Researchers |
|---|---|---|---|---|
| 1965 | Inco | *Al/Gr* | Gas injection and stir casting | Badia, Rohatgi |
| 1968 | IITK, India⁺ | *Al/AL$_2$O$_3$* | Stir casting | Ray, Rohatgi |
| 1974 | IISc., India⁺ | *Al/SiC, Al/Al$_2$O$_3$, Al/Mica* | Stir casting | Rohatgi, Surappa, Nath |
| 1975 | MIT | *Al/Al$_2$O$_3$* (and other particles | Compocasting | Mehrabian, Sato, Flemings |
| 1979 | RRL, India⁺ | Al/Silicate, *Al/TiO$_2$, ZrO$_2$,* | Stir casting | Rohatgi, Ram, Banerjee |
| 1979 | USSR | *Al/Gr* | Stir casting | Gorbunov |
| 1980 | Dural | *Al/SiC* | Stir casting | Skibo, Schuster |
| 1981 | Hitachi, Japan | *Al/Gr* | Pressure casting | Suwa |
| 1982 | DuPont | *Al/Al$_2$O$_3$* | Pressure casting | Dhingra |
| 1983 | Toyota, Japan | Al/Saffil | Squeeze casting | |
| 1984 | RRL, India⁺ | Al/Microballoons | Stir casting | Rohatgi, Das |
| 1984 | Norsk Hydro, Norway | *Al/SiC* | Stir casting | |
| 1985 | Martin Marietta | *Al/TiC* | XD Process | |
| 1986 | MIT | *Al–SiC* | Pressure infiltration | Cornie, Oh, Russel, Flemings |
| 1987 | U Of WI-Milwaukee | Al/Hybrids | Pressure, stir casting | Rohatgi |
| 1987 | Comalco, Australia | *Al/AL$_2$O$_3$* | Stir casting | |
| 1988 | Grenoble France | *Al/SiC* | Stir casting | Milliere, Suery |
| 1989 | Honda, Japan | *Al/Al$_2$O$_3$-C* | Pressure casting | Hayashi, Ushio, Ebisawa |
| 1989 | Lanxide | *Al/Al$_2$O$_3$, Al/SiC* | Pressureless infiltration | Aghajanian, Burke, Rocazella |

Note : This table is only a selected listing of information which was available to the author. There have been several other efforts and some of them have not been published or listed. The periods are approximate; some are based on information about work and others on published work.

* Locations are in the United States unless otherwise directed.

⁺ IITK-Indian Institute of Technology; IISc.-Indian Institute of Science; RRL (1979)-Regional Research Laboratory, Trivandrum;
RRL (1984)-Regional Research Laboratory, Bhopal.

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 fibre 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:

(a) Addition of particles to a vigorously agitated fully or partially solidified alloy (Fig. 11),

(b) Injection of discontinuous phase in the melt with the help of an injection gun (Fig. 12),

(c) Dispersing pellets or briquettes, formed by compressing powders of base alloys and the ceramic phase, in a mildly agitated melt,

(d) Centrifugal dispersion of particles in a melt (this has been done for carbon and glassy microballoons, graphite and alumina particles), and

(e) Spray casting of droplets of atomized molten metals along with particulates on a substrate.

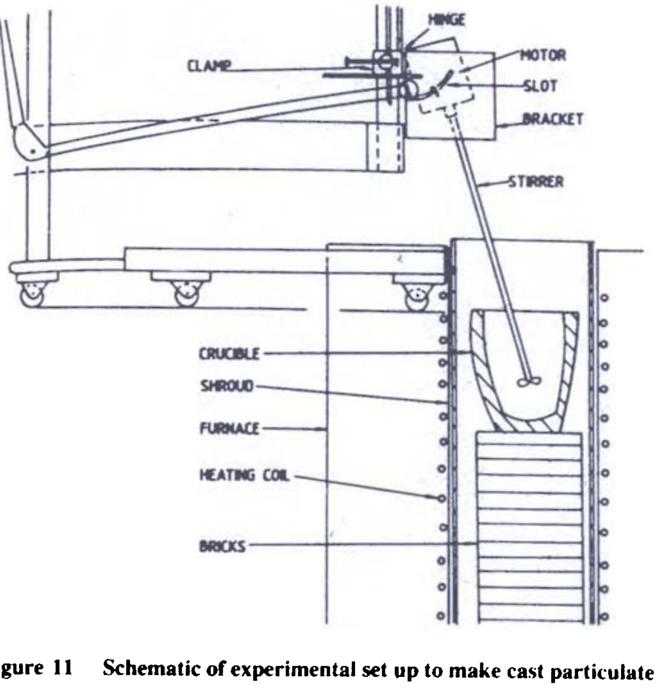



**Figure 11** Schematic of experimental set up to make cast particulate composites.

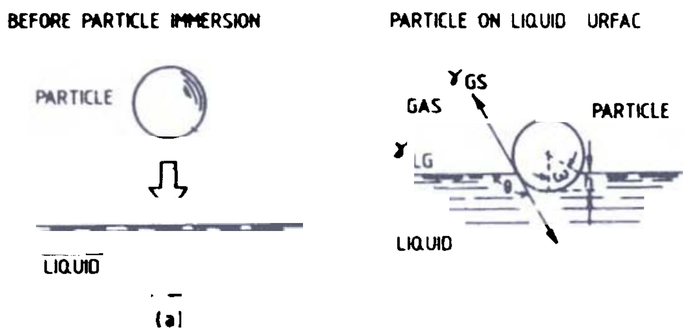



**Figure 12.** **Introducing particles by gas stream.**

In all the above techniques, external force is used to transfer a nonwettable ceramic phase into a melt, and to 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 co-deposition, 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*, $SiO_2$ 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, 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 and shape the melt-particle slurries are briefly discussed below.

### 3.3.1 *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 (for example, 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.

### 3.3.2 *Die Casting*

The relatively rapid freezing rates in metallic molds generally give rise to a more homogeneous distribution of particles in cast matrix. Figures 13 and 14 show a microstructure of a permanent mold gravity die casting of *Al* alloys containing dispersions of graphite and zircon particles.

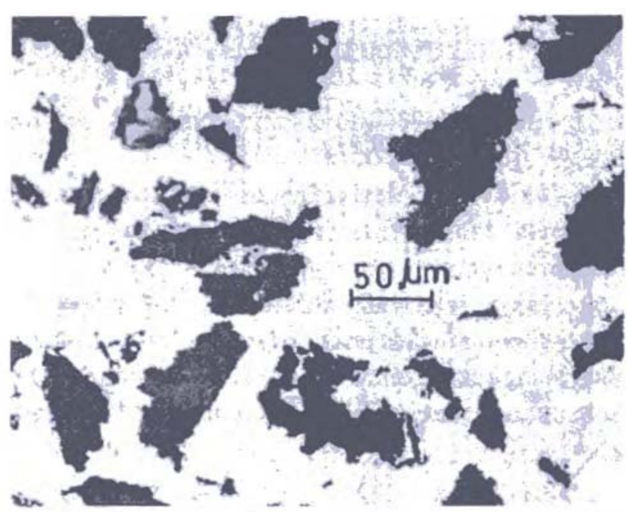



**Figure 13.** **Optical mocrograph showing distribution of graphite particles in the matrix of an aluminium alloy**

### 3.3.3 *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 inner surface is highly lubricating because of graphite enrichment. The outer zone is particle-rich for particles heavier than melt like zircon or silicon carbide (Fig.15); outer zone is abrasion resistant due to these hard particles.

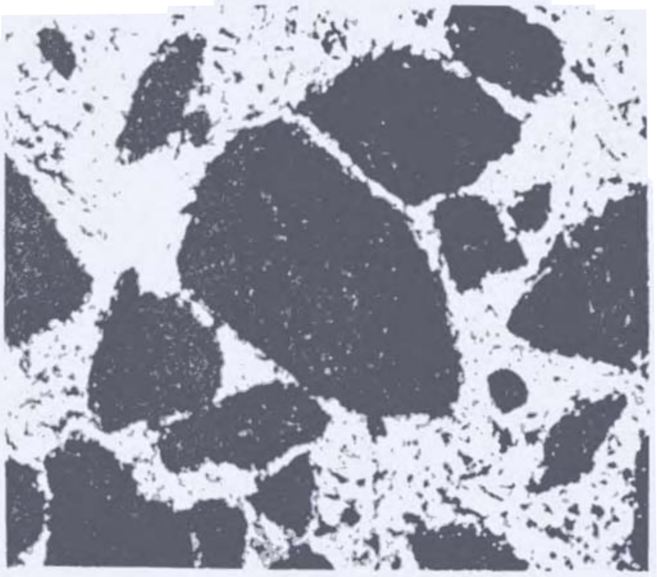


Figure 14. Microstructure of a die cast aluminium alloy-zircon particle composite.

Figure 15. Centrifugally cast aluminium alloy particle composites showing segregation of particles at specific surfaces.

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 (Fig. 16). Up to 8 per cent by weight mica and graphite, and up to 30 per cent by weight zircon particles could be incorporated in selected zones of *Al* alloy by this technique.

### *3.3.4 Compocasting*

Particulates and discontinuous fibres of *SiC*, alumina, *TiC*, silicon nitride, graphite, mica glass, slag, *MgO* and boron carbide have been incorporated into vigorously agitated partially solid aluminium alloy slurries by a compocasting technique. The discontinuous ceramic phase is mechanically entrapped between the pro-eutectic phase present in the alloy slurry which is

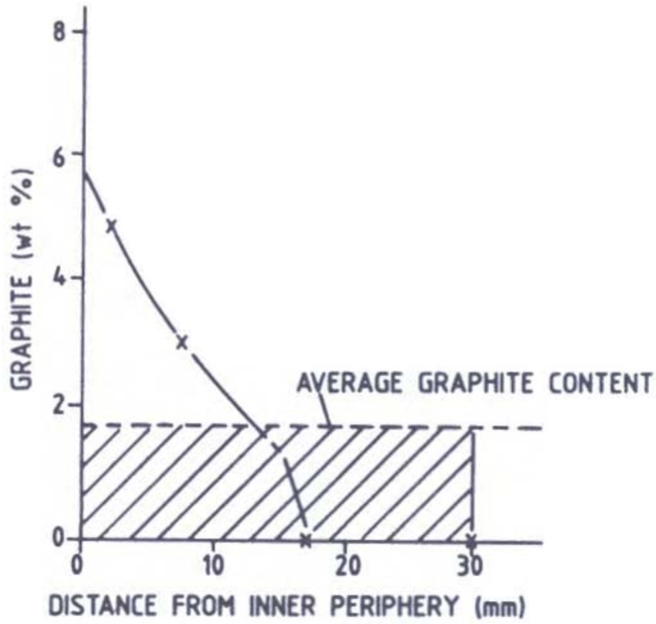



Figure 16. Variation of graphite content with distance from inner periphery of centrifugally cast (average), poured at 710 °C at a speed of 680 rpm.

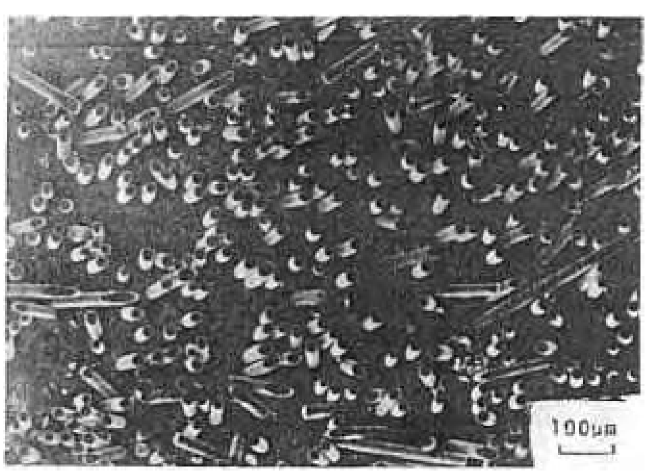



Figure 17. SEM micrograph of electrochemically etched vertical section of cast *Al*-4*Mg*-23 vol % alumina fibre composite showing random planar orientation of fibres (courtesy R. Mehrabian). Mag. 0.96 cm = 150 nm.

held between its liquids and solids 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 17 is a scanning micrograph of a compocast composite showing a random planer arrangement of alumina fibres.

### 3.3.5 *Pressure Die Casting*

Pressure die casting of composites allows larger-sized, more intricately shaped components to be rapidly produced at relatively low pressures (>15 MPa). Pressurized gas and hydraulic ram in a die casting machine have been employed to synthesize porosity-free fibre 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 per cent or more ) of zircon ($ZrSiO_4$) particles can be achieved in pressure die cast *Al-Si-Mg* alloys. Pressure die castings of *Al-Si* alloy 7 wt per cent graphite and *Al*-(4-12 per cent) *Si*-(0.5-10 per cent) *Mg* alloy-alumina particles composites showed considerable improvement in particle distribution, particle-matrix bonding elimination of porosities.

### 3.3.6 *Squeeze Casting*

Squeeze casting or liquid forging of MMCs is a recent development which involves unidirectional pressure

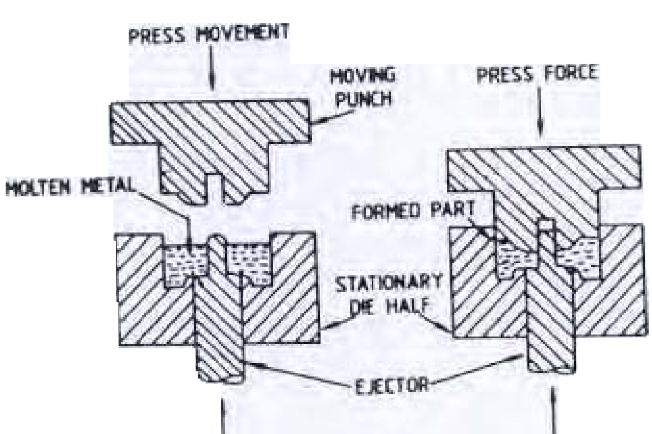



**Figure 18. Squeeze casting technique of composite fabrication.**

application (70-200 MPa) on molten slurry or on fibre-preforms or powderbeds by alloy melts, for pressure infiltration to produce void-free, near net-shape castings of composites (Fig. 18). The Saffill fibre reinforced pistons of aluminium 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) fibre and melt preheat temperature, (ii) infiltration speed and pressure, and (iii) inter fibre spacing.

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

Alternatively, whiskers or particles may be mixed with molten metal prior to squeeze casting. Aluminium alloy composites containing *SiC* and $Al_2O_3$ powders, $a$-alumina (Saffill) fibres, and silicon nitride whiskers have been fabricated by the squeeze casting process.

*SiC* whiskers (<10 $\mu$m dia and 5.50 mm in length) have been dispersed in cast *Al*-(4-5) per cent *Cu* alloy matrix by a squeeze casting technique. The wettability problem was overcome by co-dispersing *SiC* whiskers and aluminium alloy powder (200 $\mu$m average 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, for example, fine grain size, elimination of bulk and interracial properties, increased solid solubility due to hydrostatic pressure and the presence of high-strength *SiC* whiskers.

Plate and tubular composites of *Al* alloys containing continuous or discontinuous *SiC* fibres (Nicalon) can be synthesized by a squeeze casting technique. The *SiC* yarn consisting of about 500 monofilaments (13 $\mu m$ average dia) is mechanically wound around a steel frame or aligned unidirectionally in *Al* vessel. In the case of discontinuous *SiC* fibres, fibre can be chopped and packed in the vessel. The vessel with fibre is preheated in air for good penetration of molten metal-matrix into interfibre space. Then the vessel is put into the mold which is preheated to 230-430°C. The fibre volume fraction of comoposites is controlled by selecting the winding conditions (for continuous fibre) or packing conditions (for discontinuous fibres) before casting.

*3.3.7 Vacuum Infiltration Process*

Several FRMs have been prepared by the vacuum infiltration process. In the first step the fibre yarn is made into a handleable tape with a fugitive binder in a manner similar to producing a resin matrix composite tape (prepreg). Fibre tape are then laid out in the desired orientation, fibre 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 fibre FP/*Al* composites. Graphite fibres are first surface treated and then infiltrated with the molten metal in the form of wires and these coated graphite wires are then diffusion bonded together to form larger sections.

*3.3.8 Investment Casting*

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

*3.3.9 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 *Al* particulates. Rather than allowing the particulate to solidify, as is done in the atomization of metal powder, a substrate is placed in the path of the particulate. The molten particles collide with the substrate and a metalic preform is built up. These techniques can be classified as either powder or casting techniques since they combine both processes.

Recently, Singer and Ozbeck used a spray co-deposition 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 the 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 the molten matrix particle impinging the substrate. When impingment occurs, heat extraction from the splatted matrix particles is very rapid; and the fairly high solidification rate, combined with the fact that the reinfocement phase is in contact with the molten metal only for a very short time, greatly reduces the amount of interfacial reaction that can occur. This in turn minimises the formation of brittle interfacial phases that sometimes degrade the properties of a composite.

Full density is not achieved during the spray co-deposition, and subsequent hot and cold 'ling need to be used to densify the material. The distribution of all the phases tried, including sand, graphite and silicon carbide, appear 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. Recently, considerable work is being done on spray deposition of MMCs in the USA (University of California, Irvine and MIT), and Europe.

*3.3.10 In-situ Process in MMCs*

Several techniques have been used to form desirable particulate *in-situ* in the alloy melt itself. This can be achieved through gas-liquid, liquid-liquid and solid-liquid displacement reactions based on phase diagram principles.

### 3.4 Microstructures

The primary solid ( $\alpha$-aluminium) grows by rejecting solute in the melt while the discontinuous ceramic phase tend to restrict diffusion and fluid flow; $\alpha$-aluminium tends to avoid the discontinuous ceramic phase, as shown in Fig. 13. Primary silicon and the eutectic in *Al-Si* alloys tend to concentrate on particle or fibre surface.

The discontinuous ceramic phase also tend to modify or refine the structure, for example, eutectic *Si-Al* alloys get modified whereas primary *Si* is refined when solidification occurs in the presence of a high volume fraction ceramic phase. At sufficiently slow cooling rates, when the secondary dendrite arm spacing (DAS) in the reinforced alloy is comparable to interfibre (interparticle) spacing, the grain size become large in comparison with the spacing. In this case, fibres (particles) 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 should become free of microsegregation.

Currently, two aspects of microstructure evolution in metal-matrix particulate composite is evincing great interest and activity, and these are:

(a) Heterogeneous nucleation of primary phase on reinforcing second phase particles, usually ceramic ones, for example, graphite, *SiC*, $Al_2O_3$, and orthers.

(b) Particle capturing during solidification within the dendrite, between the secondary arms and at the grain boundaries.

From energy considerations and ease of nucleation, one would expect that a heterogeneous nucleation of primary phase in a eutectic alloy ($\alpha$-aluminium in *Al-Si* alloy) should preferentially occur on the surface of the particles existing in the melt. However, as Table 7 shows, only under very special cases, heterogeneous nucleation actually occurs. Most of the time, the particles, instead of hosting the primary grains, are pushed aside by the growing primary dendrites and get segregated at the grain boundaries forming a mal-distributed and a relatively weaker composite structure.

Many theories and suggestions have been made to predict capture and rejection of particles by the solidifying front, and Table 8 summarizes some of these, including the one based on the simple criterion (Eqn (3)) originally proposed from India,

$$\left[\frac{\lambda_p\, C_p\, \rho_p}{\lambda_l\, C_l\, \rho_l}\right] > \qquad 3)$$

Table 7. Nucleation observed in various cast MMCs

| Alloy system | Reinforcements | Primary phase nucleating on reinforcements |
|---|---|---|
| Hypereutectic *Al-Si* alloy | *C*, $SiO_2$, $Al_2O_3$ | Primary silicon |
| *Al-Mg* | $Al_2O_3$ | None* |
| *Al-Li* | $Al_2O_3$ | None* |
| *Al-Cu* | *SiC*, Graphite, $Al_2O_3$ | None* |
| *Al-Mg* | *Ni*-coated graphite | $Al_3Ni$ |
| *Cu-Sn* | $TiB_2$-coated *C* | $\alpha$-phase |
| *Mg-Al* | *SiC* | None* |
| *Ti-Cu* | *C* | None* |
| *Al-Ti-B* | $TiAl_3$ | $\alpha$-phase |
| *Al-Ti-B* | $TiB_2$ | None* |
| *Al-Ti-B* | $AlB_2$ | None* |

* None indicates that the reinforcements are surrounded by the solidification product of last solidifying fraction of liquid.

$\lambda C$ and $\rho$ are thermal conductivity, specific heat and density, respectively, and the subscripts $p$ and $l$ denote particle and liquid, respectively.

It is generally accepted that the lower and higher $C$ of the particles relative to the melt, are likely to perturb the shape of the local thermal field ahead of the growing tip of the solidifying dendrite.

However, many other factors such as relative surface free energies, convection conditions, buoyancy effect and the viscous drag as well as the size and shape of the particles, all contribute significantly in forming the resulting cast microstructure and determining its property level.

### 3.5 Properties and Applications

At present, fibre-reinforced or particle-filled MMCs 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.

**Table 8. Predictions and experimental observations on capture or rejection of particles in some systems**

| Experimental observation | Particle | Melt | $\frac{\lambda_p}{\lambda_1}$ | Prediction | $\left[\frac{\lambda_p C_p \rho_p}{\lambda_1 C_1 \rho_1}\right]^{1/2}$ | Prediction |
|---|---|---|---|---|---|---|
| Capture | Teflon | Diphenyl | 1.40 | Capture | 1.53 | Capture |
| | | Naphthalene | 1.30 | Capture | 1.53 | Capture |
| | Siliconized glass | Diphenyl | 6.30 | Capture | 2.21 | Capture |
| | | Naphthalene | 6.20 | Capture | 2.30 | Capture |
| | Polystyrene | Diphenyl | 0.92 | Rejection | 1.01 | Capture |
| | | Naphthalene | 0.90 | Rejection | 1.05 | Capture |
| Rejection | Acetal | Diphenyl | 0,05 | Rejection | 1.17 | Rejection |
| | | Naphthalene | 0.52 | Rejection | 0.80 | Rejection |
| | Nylon | Diphenyl | 0.04 | Rejection | 1.19 | Rejection |
| | | Naphthalene | 0.041 | Rejection | 0.20 | Rejection |
| | Graphite | *Al*-11.8*Si*-1.5*Mg* | 0.116 | Rejection | 0.0627 | Rejection |
| | Mica | *Al*-4.5*Cu*-1.5*Mg* | 0.0027 | Rejection | 0.0459 | Rejection |
| | Alumina | *Al*-11.8*Si* | 0.0220 | Rejection | 0.1803 | Rejection |
| | *SiC* | *Al*-4.4*Cu*-0.5*Mg* | 0.3915 | Rejection | 0.4918 | Rejection |
| | Titania | *Al*-11.8*Si*-1.5*Mg* | 0.0523 | Rejection | 0.0523 | Rejection |
| | Zirconia | *Al*-11.8*Si* | 0.0198 | Rejection | 0.239 | Rejection |

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, anti-abration, damping, corrosion and machinability properties.

The high temperature strength of MMCs is enhanced by reinforcements such as *SiC* fibres or whiskers or continuous Borsic (boron fibres coated with *SiC*) fibres. Carbon/*Al* MMCs combine very high stiffness with a very low thermal expansion due to almost zero expansion coefficient of *C* fibres 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 such as 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 alloys. For example, the damping capacity of aluminium 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 19 and 20 show photographs of fan bushes, journal bearings and several other components made from cast *Al*-*Si*-graphite particle composite and cast *A1*-*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-aluminium is for bearings which would be cheaper and lighter in addition to being self lubricating compared to the bearings

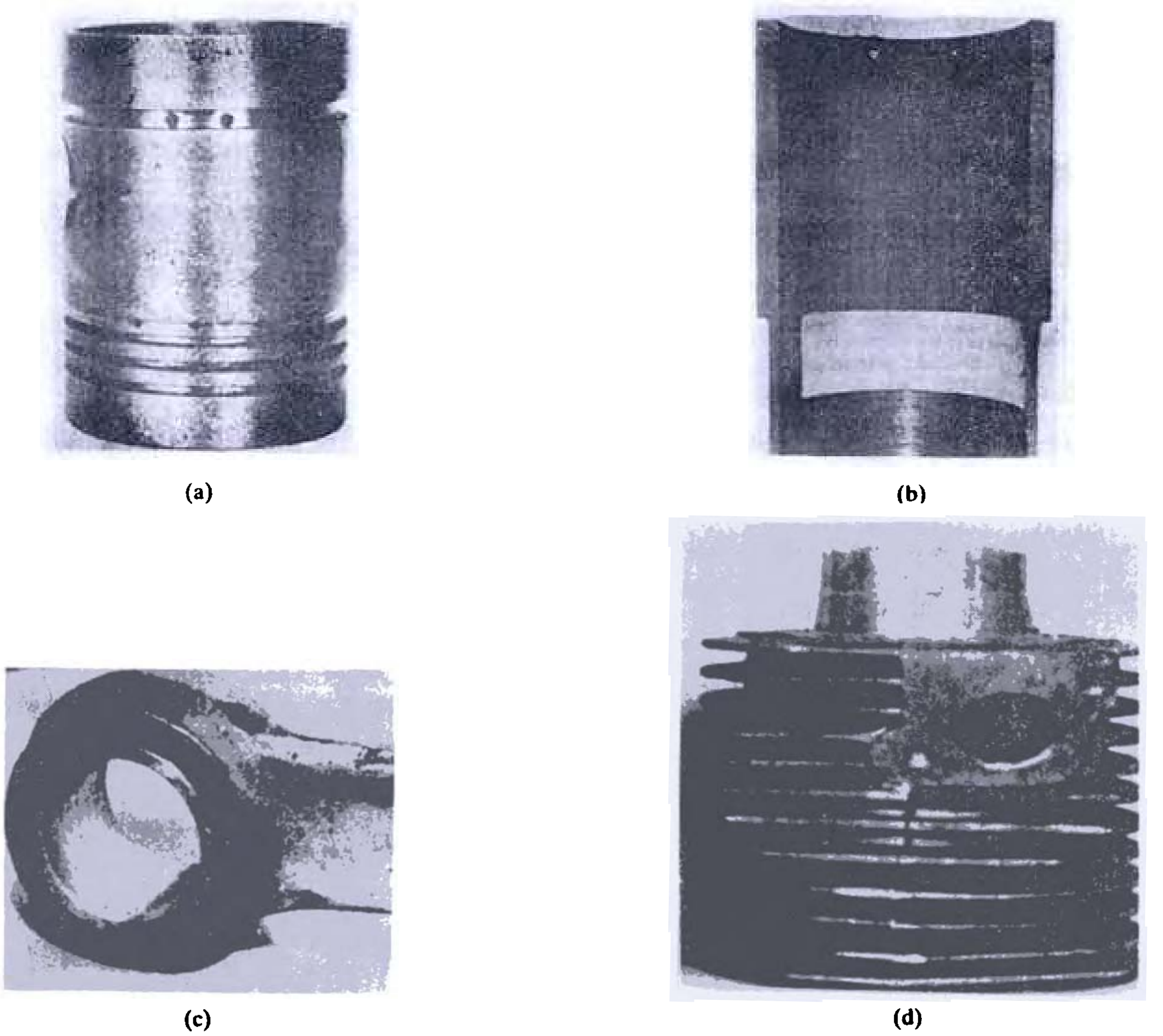



**Figure 19.** Various engineering components of cast MMCs : (a) IC engine piston (*Al-Si-Gr* composite)l, (b) *Al-Si-Gr* composite cylinder liner, (c) connecting rod, and (d) cylinder block.

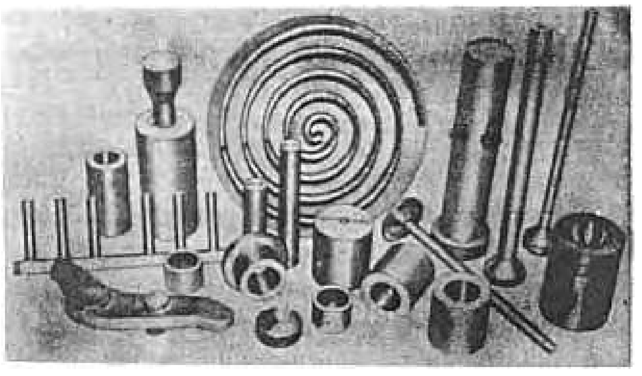


**Figure 20.** Some engineering components made from cast MMCs.

currently being made out of *Cu, Pb, Sn* and *Cd* containing alloys. Cast aluminium- graphite fan bushes experience considerably reduced wear as well as temperature rise during trial at 1400 rpm for 1500 hr.

Some current and potential applications of composites in automotive industry are listed in Table 9 and some typical properties are summarized in Table 10. Cast aluminium-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 aluminium graphite composite in internal combustion engines reduces the overall weight of the engine. Such engine does not seize during cold start or failure of lubricant due to excellent antiseizing properties of graphite-aluminium 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.

## 4. ORGANISATIONS WORKING IN MMC MATERIALS

The United States is one of the most actively involved countries in research and production of MMCs. University-based centres in the United States with substantial activity in processing MMCs include the Centre for Processing and Characterisation of Composite Materials at the University of Wisconsin-Milwaukee, the Massachusetts Institute of Technology, University of Virginia, University of Delaware, University of Florida, Carnegie Mellon University, University of Illinois, Michigan State University, Renesslaer Polytechnic, Pennsylvania State University, University of California at Santa Barbara and Irvine, University of Alabama, and Witchita State University. Several other universities are in the process of opening centres on composite materials with activity in MMCs.

The companies and organisations that are very active in the MMCs in the United States and Canada include the following:

(a) Aluminium Company of Canada, Dural Corporation, Kaiser Aluminium, Alcoa, American Matrix, Lanxide, American Refractory Corporation,

(b) Northrup Corporation, McDonald Douglas, Allied Signal, Advanced Composite Materials Corporation, Textron Specialty Materials,

(c) DWA Associates, MCI Corporation, Novamet,

(d) Martin Marietta Aerospace, Oakridge National Laboratory, North American Rockwell, General Dynamics Corporation, Lockheed Aeronautical Systems,

(e) Dupont, General Motors Corporation, Ford Motor Company, Chrysler Corporation, Boeing Aerospace Company, General Electric, Westinghouse,

**Table 9. Potential automotive applications of MMCs**

| System | Component | Justification |
|---|---|---|
| | | High temperature, fatigue, creep, wear |
| | | Wear resistance, weight reduction |
| | | Weight, stiffness, wear |
| | | High temperature, fatigue, creep, wear |
| | | Specific stiffness, wear, creep |
| | | Wear and seizure resistance, low friction, weight |
| | | specific stiffness, weight |
| | | Weight, reduced friction |
| Suspension | | Damping, stiffness |
| Driveline | | Wear, weight |
| | | Specific stiffness, fatigue |
| | | Wear, weight |
| | | Weight |
| Housings | | Wear, weight |
| | | Wear, weight |
| Brakes | | Wear, weight |

**Table 10. Selected automotive composite materials and properties**

| Manufacturer | Matrix | Reinforcement* | Modulus+ (GPa) | UTS (MPa) |
|---|---|---|---|---|
| Martin marietta and | *Al* base | None | 74 | 221 |
| Amex | *Al* 2219 | *TiC*, 15 vol% | 69-117 | 400 |
| Lanxide | *Al* base | None | 69 | 124-172 |
| | | *SiC* 45-55 vol% | 152-179 | 400-448 |
| | | $Al_2O_3$, 50-70 vol% | 193-262 | 200-276 |
| Dural | *Al* base | None | 72 | 186-262 |
| | *Al* 2014 | $Al_2O_3$, 10-20 vol% | 83-103 | 414-483 |
| | *Al* 6061 | $Al_2O_3$, 10-20 vol% | 83-103 | 241-345 |
| | *Al* A356 | *SiC*, 10-20 vol% | 83-97 | 276-345 |
| Comalco | *Al* base | None | 69 | 310 |
| | *Al* '061 | $Al_2O_3$, 20 vol% | 85 | 330 |
| Honda | *Al* base | None | 69 | 193 |
| | ADC12 | $Al_2O_3(f)$, 10 vol% | 80 | 250 |
| | | Carbon*(f)*, 10 vol% | 70 | 200 |
| | | Carbon*(f)*, 5 vol% | 80 | 230 |

* All reinforcements are particles, with the exception of those used by Honda, which are short fibres (Wrought alloy proper. are for extruded material).

\+ Modulus values were measured at room temperature.

*(f)* fibre

(f) Wright Patterson Air Force Base, (Dayton, Ohio), and

(g) Naval Surface Warefare Centre, (Silver Spring, Maryland).

While the United States had a lead in the use of MMCs in aerospace and Defense weapon applications, Japan has taken the lead in using MMCs on a widespread basis and in large applications such as automotive. In 1982, Toyota was the first company in the world to incorporate MMC pistons in high speed diesel engines. Subsequently, Honda introduced hybrid (alumina-carbon) cylinder liners in passenger cars (Prelude, 1992); these liners increase weight reduction and wear resistance, and are made by pressure casting of preforms. Currently, attempts are underway to develop cast aluminium matrix composites for brake rotor applications in the US, Europe and Japan. Aluminium base composites are currently being used for bicycle frames, tire studs and golf clubs, and are being explored for automobile drive shaft application.

Other countries which have strong activities in composities include England, France, Italy, Norway, Sweden, Denmark, Netherlands, West Germany, Australia, Korea, China, and their details are available in relevant publications on composites. There is rapidly growing body of literature on composites from all over the world, including some on the status of MMCs in different countries, and some of this can be reached through the computerised databases and conference proceedings of ASM International.

## 5. STATE-OF-THE-ART IN MMCs AND IMPERATIVES FOR INDIA

Intensive research in MMCs started about thirty years ago to meet the increasing requirements of properties in aerospace materials to achieve higher speed and higher temperature engines for higher efficiencies. Much of this research was concentrated on ceramic and carbon fibre reinforced metals made by processes of plasma spray and vapour disposition or diffusion bonding of foils with interspersed layers of fibres followed by hot pressing (Fig.2(b)). These multi-stage processes involve several steps, and combined with the cost of long expensive fibres like boron and carbon, the cost of MMCs thirty years ago was several hundred thousand US dollars per pound. Most of these MMCs were used in aerospace applications where weight savings were of paramount importance, and to some extent in selected weapons systems, where cost was hardly of any concern (Table 2).

During the last few years, several developments have occurred in MMCs which have great relevance to India. For instance, the costs of metal-matrix fibre reinforced composites have come down from several hundred thousand dollars per pound to the order of a thousand dollars per pound at this time due to the decrease in costs of continuous fibres. The continuous fibre-reinforced MMCs, therefore, still remain quite expensive for widespread use in countries like India, 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 fibre/particulate composites. The costs of particulate composites like aluminium-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. These composites can be made at even lower costs due to the lower costs of highly skilled manpower in India.

In the early part of development of MMCs, organisations had captive research and production, or contracted small scale production of small quantities of metal-matrix continuous fibre composites. For the first time in the last five years, there are some producers and suppliers of metal-matrix silicon carbide composites both by PM processes and by castings route. For instance, one could today obtain aluminium matrix silicon carbide composites for two to five dollars per pound from Aluminium Company of Canada. In fact in the last six months, Alcan has put up a plant with a capacity to produce twenty five million pounds of aluminium silicon carbide or aluminium-alumina composites per year in Canada, 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 aluminium alloys are cast from shipped primary ingots. Comalco, Australia, produces small quantities of aluminium-alumina particle composites. Norsk Hydro in Europe also plans to become a supplier of cast aluminium- silicon carbide composites. A number of components including pistons, impellers, brake systems, and housings have been cast out of aluminium-silicon carbide composites. This type of cast composite will be the forerunner for widespread use fo metal- matrix ceramic particle composites, with possible secondary processing and use even in India. Dow Chemical can supply small samples of cast magnesium-alumina composites. Likewise DWA Associates and American Composites can supply PM processed aluminium-ceramic particle, whisker and fibre composites. In addition, companies like Textron can supply MMCs with higher melting metals as matrices. There are also a large number of research laboratories which can supply small samples of high melting MMCs, 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, who fabricated a ceramic fibre-reinforced squeezed cast aluminium piston for high speed diesel engines in 1982. This has triggered a flurry of activity in making engine components out of cast MMCs. There is a great deal of activity in trying to make pistons, connecting rods, wrist pins and other engine parts out of aluminium-ceramic fibre 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 fibre, 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 fibres placed in the molds as preforms before casting. More recently, in 1990, Honda has introduced cast MMCs cylinder liners in Prelude passenger cars, these were produced by a modified pressure die casting technique using short fibre hybrid (alumina-graphite) preforms which were cylindrical in shape. These low cost, larger scale mass manufacturable cast MMCs represent the biggest potential for MMC activity in India. The ingredients to make these composites are available in India, or can be imported, and the composite products made will be of immediate use. For instance, aluminium-silicon carbide composites can save considerable amounts of energy and fuel when used in transportation systems, and can free India from the requirements of importing critical strategic minerals and oil that are now not available to meet the full demand.

Another MMC of relevance to India is cast aluminium-graphite particle composite for antifriction applications, which was initially developed in India, as well as in the US, Europe and Japan during the last fifteen years. It has been demonstrated that pistons, cylinder liners, and bearings can be made out of cast aluminium-graphite particle composites. The use of pistons and liners of aluminium-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. Aluminium graphite particle composites can replace much more expensive and heavier bearings made out of bronze and Babbit metals. Many of today's 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 aluminium-graphite particle composites have not been produced in the US and Europe on a large scale, they will be very useful in India where petroleum, and metals like lead, tin, and copper are available at a very high cost and have to be imported. The technology of aluminium-graphite particle composites consists of stirring pretreated graphite particles in the melts of aluminium alloys using very conventional foundry equipment, followed by casting, either in permanent molds, or centrifugal casting machines or in pressure die casting. Most of these technologies are available in India, and these alloys can be mass-produced without much difficulty, with products immediately used in the local industry. Japan has production facilities to make aluminium-graphite and copper-graphite composites, and India has the requisite research base to get into production of these alloys.

In addition to the current use of MMCs in aerospace applications and weapons systems, in the last few years in the developed world, there is interest in using these composites in the automotive applications, in sporting goods like bicycle frames, tennis rackets and golf clubs. The needs of India are much greater in housing, energy generation and transportation, than in faster cars, airplanes, sporting goods, aerospace or Defense systems which are now driving the development of MMCs in the industrial nations.

Another area of concern in India is the lack of availability of reinforcements and organisations producing shaped preforms for incorporation in MMCs. The continuous fibre reinforcements remain very expensive, and their production cannot be set up easily in India. India should initially concentrate on *in-situ* composites made by unidirectional solidification or powder extrusion, where the reinforcements are produced *in-situ* during the process itself, thus eliminating the need for expensive reinforcements. In addition, India should concentrate on particle reinforced MMCs which are inexpensive and have a large scale application possibilities. For instance, emphasis should be given on graphite particle reinforced MMCs since graphite is available either in mineral form or in manufactured form in India; with the relatively easy availability of aluminium, the production of these composites can be set up for use in automotive, railway, scooter and electromechanical machinery industries. The aluminium-graphite particle composites present another advantage in that they are easier to machine compared to monolithic alloys. MMCs containing hard reinforcements like silicon carbide or alumina require special machining techniques and equipment. Likewise attempts should be made to learn to use readily available mineral-based fibres in India, for instance, attempts should be made to use naturally occurring alumino-silicon fibres, or fibres that can be readily made by melt spinning of oxides. These are areas where India can immediately get into the use and manufacture of MMCs. This learning experience with inexpensive particulate MMCs will also set the stage for India to get into the area of high performance metal-matrix continuous fibre composites.

India has substantial activity in cast and PM MMCs (Table 11). It has had world class R&D in cast aluminium particulate composites which was sought even by western countries (Table 6). It is very much due to the first rate scientists in India, and the support they received from Indian funding agencies, that the field of cast metal-matrix particulate composites has advanced so rapidly all over the world. India has the requisite technology base in the metals industry including casting and PM of monolithic alloys and it can get into large scale manufacture of MMCs, especially particulate composites, with the involvement of process engineering companies which already exist within the country.

It will be necessary to coordinate the efforts of scientists and engineers working on composites in different organizations (Table 11) and focus on a selected few composite components which can be manufactured and used in a short time. This may require setting up plants to produce large quantities of cast particulate composite ingots at a central location from where the ingots can be sent to a variety of foundries and secondary processors all over the country. The CSIR research laboratories (including those in Bhopal, New Delhi and Triruvananthapuram) the IITSc, universities, Defense Laboratories and HAL have scientists with experience in small batch production and they can be involved in pilot and full-scale production of composite ingots.

Initially, simple components like bearings and liners should be made particulate composites and proven in transportation systems including railway and two-wheelers. Certain policy modifications mandating the reduction in the weight of transportation systems would help to catalyse the use of cast composites. Eventually India should plan on becoming a leading exporter of cast MMC components like bearings, pistons, liners, connecting rods, wrist pins, etc. It will also be necessary to develop the capability to design components in composite materials, to inspect them for quality, to machine them and to recycle them properly. These issues have still not been resolved even in the western countries.

**Table 11. List of selected organizations working on MMCs in India**

- National Physical Laboratory, CSIR, New Delhi
- Indian Institute of Technology, New Delhi
- Indian Institute of Technology, Kanpur
- Regional Research Laboratory, CSIR, Bhopal
- Regional Research Laboratory, CSIR, Trivandrum
- National Aeronautical Laboratory, CSIR, Bangalore
- Vikram Sarabhai Space Centre, Trivandrum
- Indian Institute of Science, Bangalore
- Banaras Hindu University, Varanasi
- University of Roorkee, Roorkee
- Defence Metallurgical Research Laboratory, Hyderabad
- Hindustan Aeronautics, Bangalore
- Indian Institute of Technology, Bombay

As the learning curve progresses on low and medium performance applications in transportation industry, a select group of engineers should begin to make and test parts for high technology applications like electronic packaging, aerospace applications and smart structures. It will be necessary to develop a culture to identify the talent in MMCs and create conditions to provide them work satisfaction and proper recognition within India.

## 6. ELEMENTS OF EDUCATION AND TRAINING IN MMCs IN INDIA

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 fibres, magnesium graphite fibre composites with negative, zero or low positive coefficient 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 database on manufacture of similar composites. Design of tests requires considerable database on relationships between structure, properties and performance on the specific composite in question.

In addition to the information generated in the West, the scientists in India must be trained to use local resources and facilities to design, fabricate and test MMC materials for use in their own environments. In India, there are large agricultural waste products like paddy husk available; conversion of these resources into high performance whiskers like silicon carbide for reinforcement in MMCs would be and important imperative.

Once the chemistry, structures, shape, size, volume percentages of constituents is decided by structure-property relationship, 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. The process design for India should be of the types which can be used for manufacture in the low technology environment which often prevails in local industries. Computer simulation of performance of composites and the process to manufacture them could save scarce resources in terms of materials and energy wasted in trials. These aspects of design and simulation should form essential features of training in MMCs.

## 7. SUMMARY

Metal-matrix composites with tailored properties have the potential of becoming one of the fastest growing families of new material, which can have a large impact on India. At this time the best performing and most expensive MMCs are being considered for high value -added, relatively low-volume military and aerospace applications. However, automotive and other engine and electromechanical energy applications which require lower cost and higher part volume, are now being commercialized, and these should be of greatest interest to India. With continued development of composites manufacturing processes and improvement in alloy design, including the possible use of particulate composites, high performance and low cost will draw close together. The developments in near future will involve using the casting and powder processes to produce tailored interface, new matrix alloys which will yield higher ductility and toughness along with the higher strength in discontinuous reinforcement composites. The science of predicting properties and performance metal-matrix particulate composites will gain considerable ground. Presently, the low cost particulate composites such as cast aluminium-alumina, aluminium-silicon carbide and aluminium- graphite composites appear to be most promising in India. These composites can be produced 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. India should pay special attention to the possible use of MMCs in energy, housing, and transportation sectors which are of high priority including solar photovoltaics, semiconductor and superconductor industries. India has an excellent research and industrial base for producing MMCs for internal consumption as well as for export. It is necessary to coordinate the efforts of CSIR, Defence Labs, IITs, IISc and universities, and Industries, leading to the manufacture of MMCs.

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