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# Fibre-reinforced metal matrix composites—a review

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**Abstract**

In recent years, there has been an increasing demand from automotive, space and aeronautical industries for materials possessing high specific strength, better wear resistance and stability at high temperatures. The process of improving the properties of conventional engineering materials has led to the technique of reinforcing polymers, ceramics and metals with particles, fibres and whiskers, thus leading to the production of composites. Because of the higher ductility and ease of fabrication than ceramic matrix composites (CMCs) and better environmental stability and stiffness than polymer matrix composites (PMCs), metal matrix composites (MMCs) have become popular and are widely used. This paper outlines the various production techniques and mechanical properties of MMCs. Further, it shows that Al- and Zn-based composites exhibit tremendous improvement in all mechanical properties as compared to the unreinforced base alloy.

**Keywords**: High specific strength, wear resistance, stability, reinforcing polymers, ceramics, metals

## 1. Introduction

Technological innovation, improved energy planning, enhanced property requirements and sky-rocketing costs have mandated the need for development of newer materials. The aerospace industry and many other industrial sectors are under constant pressure for materials development in order to achieve improved performance. In view of this, efforts have been on to improve the properties of monolithic materials by suitable alloying and modification of microstructures. As a part of this evolutionary process, composite materials have arrived, and are making great inroads into several sectors of industry.

In fact, composites are not new but date back to many centuries. The use of straw in the manufacture of bricks and the use of hair to strengthen plasters marked the use of composites in ancient civilization. However, the actual production of composite materials for industrial use has commenced only in the middle of this century. The superb performance of composite materials in a variety of applications has given a major thrust to the production and use of newer composites in large quantities.

Composites are combinations of two or more identifiable constituents which possess properties superior to that of the materials which constitute them, and encompass a wide range of materials whose properties can be tailored to satisfy certain design requirements. Composite materials have tremendous potential for providing light-weight components exhibiting high strength, high stiffness, good wear resistance and improved elevated temperature properties[1]. Composites generally comprise two main constituents, *viz.*, matrix material and reinforcement. The matrix holds the reinforcement in position and transfers the applied load to the reinforcements. The reinforcements, on the other hand, impart strength and stiffness to the matrix.

## 2. Types of composites

Composites can be classified into three main groups according to the matrix material, *viz.*, polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs). Polymer materials have found extensive use as matrix materials in aerospace applications. Only in the late seventies, metals and ceramics were explored as matrix materials. MMCs offer higher ductility than CMCs and better environmental stability than PMCs. In addition, MMCs offer considerable improvement in transverse strength, shear strength, electrical and thermal conductivities and resistance to erosion and abrasion.

### 2.1. *Matrix materials in MMCs*

Ever since the work on metal matrix composites started, aluminium and its alloys have enjoyed patronage as matrix materials because of the escalating demand for light-weight and high-strength components. Magnesium alloys and titanium alloys are also used as matrix materials to produce composites; the reactivity of magnesium with the atmosphere makes processing difficult. The high reaction of titanium, resulting in the formation of intermetallics with many reinforcement materials, has led to the conclusion that titanium-based cast MMCs are much more difficult to produce than Al- and Zn-based composites[2]. Of late, zinc and copper alloys have attracted considerable attention as matrix materials.

### 2.2. *Reinforcements*

Appropriate reinforcement material has to be selected to suit a given matrix material. The most commonly used reinforcements are particles, whiskers and fibres (continuous as well as chopped). The particles improve the mechanical properties of a matrix by dispersion strengthening and by blocking the movement of dislocations. On the other hand, fibre reinforcement does not strengthen the matrix but unites with it to form a strong composite body. The fibres carry most of the applied load and are not generally considered as barriers to dislocation motion[3].

When particles are added as reinforcements, they impart isotropic properties, whereas whiskers and fibres, provide a certain amount of directionality. The properties of a fibre-reinforced composite are superior in the direction parallel to the axis of the fibres than the properties in transverse direction. The commonly used reinforcements to a metallic matrix are ceramics, as they have high stiffness, strength, high temperature stability and compatibility to various metals. SiC, $Al_2O_3$, graphite, alumino silicate, boron and zirconia in various forms have been the usual choice as reinforcements. The most widely used ceramic fibres and their properties are listed in Table I.

**Table I**
**Properties of discontinuous fibres used in MMCs[4]**

| *Fibre* | *Normal* l *(mm)* | *size used d (μm)* | *Density (g\cc)* | *UTS (GPa)* | *E (GPa)* |
|---|---|---|---|---|---|
| Carbon T300 | 2.5 | 7.8 | 1.75 | 3.45 | 230 |
| SiC (Nicalon) | 1–6 | 10–16 | 2.55 | 3.00 | 195 |
| $Al_2O_3$ FP | 3–6 | 15–25 | 3.96 | 1.70 | 380 |
| $Al_2O_3$ (Saffil) | 0.1–1 | 1–5 | 3.30 | 2.00 | 300 |
| Saffil HA | 0.1–1 | 1–5 | 3.40 | 1.50 | 300 |
| Fibre frax | 1–3 | 1–3 | 2.73 | 1.50 | 105 |
| Alumino-silicate | 2–5 | 1–7 | 3.00 | 0.80 | 150 |

The behaviour of fibre-reinforced MMCs is strongly dependent on the following:

(*a*) fibre orientation,
(*b*) aspect ratio of the fibres,
(*c*) mechanical properties of the fibres,
(*d*) mechanical properties of the matrix, and
(*e*) the nature of the bond between the matrix and the fibres.

Fibre-reinforced composites have certain distinct advantages over their particle- reinforced counterparts. Most of the high-strength, high-stiffness materials fail because of propagation of flaws. A fibre of such a material is inherently stronger than the bulk form because the size of the flaw is limited by the small diameter of the fibre. In addition, if equal volumes of fibrous and bulk materials are compared, it is found that even if a flaw does produce failure in a fibre, it will not propagate to fail the entire assemblage of fibres as would happen in bulk material. Further, a preferred orientation may be used to increase the length-wise modulus and strength well above isotropic values. The high strength and moduli can be conveniently tailored to high load directions[5].

## 3. Applications of MMCs

Based on the trends today, next generation aircraft would have up to 65% of their structural weight made of advanced composites[5]; a good proportion of these would be MMCs. Many motor car manufacturers in USA and Japan have already started using engine parts made of MMCs. DuPont, USA, has successfully substituted Al-based MMC automotive diesel engine connecting rods for conventional forged steel rods. Toyota, Japan, has opted for automobile engine pistons using Al alloy as the matrix material, and Kawool (alumino-silicate) and Saffil (alumina) fibres as reinforcements[6]. Table II shows the major automotive applications of MMCs, and Table III their potential market.

## 4. Production of MMCs

MMCs can be fabricated through the following processing techniques.

**Table II**
**Major automotive applications of MMCs[4]**

| *MMC System* | *Component* | *Property* |
|---|---|---|
| $Al-SiC_p$<br>$Al-TiC_p$<br>$Al-Fibre-Frax_p$ | Piston | Wear resistance<br>high strength |
| $Al-Al_2O_{3f}$ | Piston ring groove | Wear resistance |
| | Piston crown | Fatigue and creep resistance |
| $Al-Al_2O_{3\,c.f.}$ | Connecting rod | Specific stiffness and strength |
| | Drive shaft | Specific stiffness, Fatigue strength |
| $Al-SiC_p$ | Gear shift fork | Specific stiffness |
| | Transmission components | Reduced weight, Wear resistance |
| | Brake rotor | Wear resistance |
| | Caliper liner | |
| $Al-SiC_w$ | Connecting rod | Specific stiffness, Fatigue strength |
| $Al-Gr_p$ | Cylinder liner | Gall resistance |
| | Bearings | Reduced friction |
| | Bushings | Wear resistance |
| Mg–Stainless steel wires | Connecting rod | Increased stiffness, Fatigue strength |

p: particles, f: chopped fibres, w: whiskers and c.f.: continuous fibres

1. Powder metallurgy
2. Diffusion bonding
3. Spray co-deposition
4. *In-situ* solidification
5. Casting methods.

Of the above, casting route has been widely accepted as the most economical, simple and viable method for composite fabrication. Casting technique can be further classified as follows.

### (*a*) *Vortex method*

In this method, the dispersoids are introduced into the liquid metal and stirred continuously at a constant temperature until the slurry is poured into a die and allowed to solidify.

**Table III**
**Potential market for MMCs (million US$)[1]**

| *Matrix type* | *1988* | *1993* | *2000 (Projection)* |
|---|---|---|---|
| Aluminium | 12.0 | 35.0 | 78.3 |
| Magnesium | 2.0 | 8.9 | 20.0 |
| Titanium | 1.0 | 2.6 | 14.1 |
| Copper | 1.4 | 5.5 | 28.3 |
| *In-situ* | 1.6 | 6.5 | 25.6 |
| Others | 0.4 | 3.3 | 7.0 |

The wetting of the reinforcement by the molten alloy is a pre-requisite for adopting this process. Chances of segregation of the dispersoids and entrapment of air during stirring are the limitations of this method.

### (*b*) *Compocasting*

In compocasting or rheocasting process, the reinforcements are added to a vigorously agitated semi-solid alloy and cast to the required shape. The unique advantage of this method is that on remelting the dispersoids do not get rejected as in the case of vortex method.

### (*c*) *Infiltration method*

This method can be classified into two categories:

(*i*) pressureless infiltration,
(*ii*) pressure infiltration.

The reinforcement bundle or the preform is placed inside a die and liquid metal is poured over it. In the first method the penetration of liquid metal into the pores of the preform is caused either by atmospheric pressure or by vacuum suction. In the second, a hydraulic press is employed to produce pressure over the liquid metal. This method is also known as 'squeeze casting'.

### 4.1. *Squeeze casting process*

The following features of squeeze casting make it highly suitable for commercial application[7]:

(*i*) Capability of mass production,
(*ii*) Easier operational parameters,
(*iii*) Improvements in the wettability of the reinforcements by the liquid metal,
(*iv*) Better metallurgical quality of matrix alloys due to solidification under pressure,
(*v*) Ability to reinforce only selected regions of components.

As mentioned already, in the squeeze casting method of composite production, the liquid metal is introduced into a porous 'preform' by means of squeeze pressure and the metal is allowed to solidify under pressure. Of all the composite fabrication techniques available, squeeze casting has become one of the most accepted routes for efficient and effective manufacture of MMCs using fibre preforms[6]. The following steps are involved: (*i*) Preform making, and (*ii*) Pressure infiltration of liquid metal.

### 4.1.1. *Preform architecture*

A fibre preform is essentially the starting point. A preform is a pre-arranged pattern of fibres with selected porosity level. Following are the basic steps involved in the preform fabrication:

(*a*) The fibres are dispersed in a suitable liquid medium and formed into a slurry to achieve uniform distribution and to avoid reinforcement flocculation.

(*b*) A suitable binder (organic or inorganic) is added to the mixture.

(*c*) The slurry is then poured into a die and subjected to vacuum filtration coupled with compression to form the required shape.

(*d*) The wet preform is dried and fired at a high temperature (1200–1400° C) to develop sufficient strength.

Preforms have been produced using various binders. The binder content in the preform is usually limited to 5% by weight of the reinforcement[8]. Latex, PVA, colloidal silica, sodium silicate, acid phosphates and acrylic emulsion are some of the binders with which preforms have been fabricated successfully. In the preforms, fibrous reinforcements are usually distributed randomly in a planar orientation. Hence, composites produced through preform technique will have reinforcements in two directions only and a certain amount of directionality cannot be avoided.

The silica binding method poses some serious problems in aluminium alloy composites. Silica in the binder reacts with aluminium and gets reduced to Si. The Si forms large precipitates in the composite and can become the fracture initiation sites. Further, oxygen released from $SiO_2$ traps the alloying elements like Mg around the reinforcements and the matrix becomes soft, losing its age-hardening ability.

The following method of binderless sintering is suggested to address these problems[9]. $Al_2O_3$ fibres are mixed with fine alumina powder and this mixture is dispersed in water. After complete dissemination of the fibre lumps, the mixture is filtered and lightly pressed to obtain the required height. The wet preform is then heated to over 1300° C to realize binderless sintering. This temperature apparently enhances the crystallization of reinforcement, and due to the presence of fine powder, the fibres are well bonded to give preform with sufficient strength.

### 4.1.2. *Infiltration through squeeze casting*

In the squeeze casting method (Fig.1), the preform is securely held in a die, the liquid metal is poured over the preform and the hydraulic press is actuated to cause infiltration of the liquid metal into the pores of the preform. Liquid metal penetration through the adjoining reinforcement fibres is a complex process and involves the following three stages. In the first stage, wetting of the reinforcement by the matrix occurs. In the intermediate stage, different phenomena such as fluid flow, heat/mass transfer and part of solidification take place; in the final stage, solidification gets completed and the microstructure assumes its final form[10].

Wettability of the matrix alloy with the reinforcement fibres is an important phenomenon for spontaneous invasion of matrix alloy into the capillaries of the preform. It is well documented that the wetting angle for any alloy/reinforcement combination should be less than 90°; otherwise, a critical pressure $P_c$ is required to improve wettability; $P_c$ is given by[11]

$$P_c = -2[Y_{LV} \cos 0/R]$$

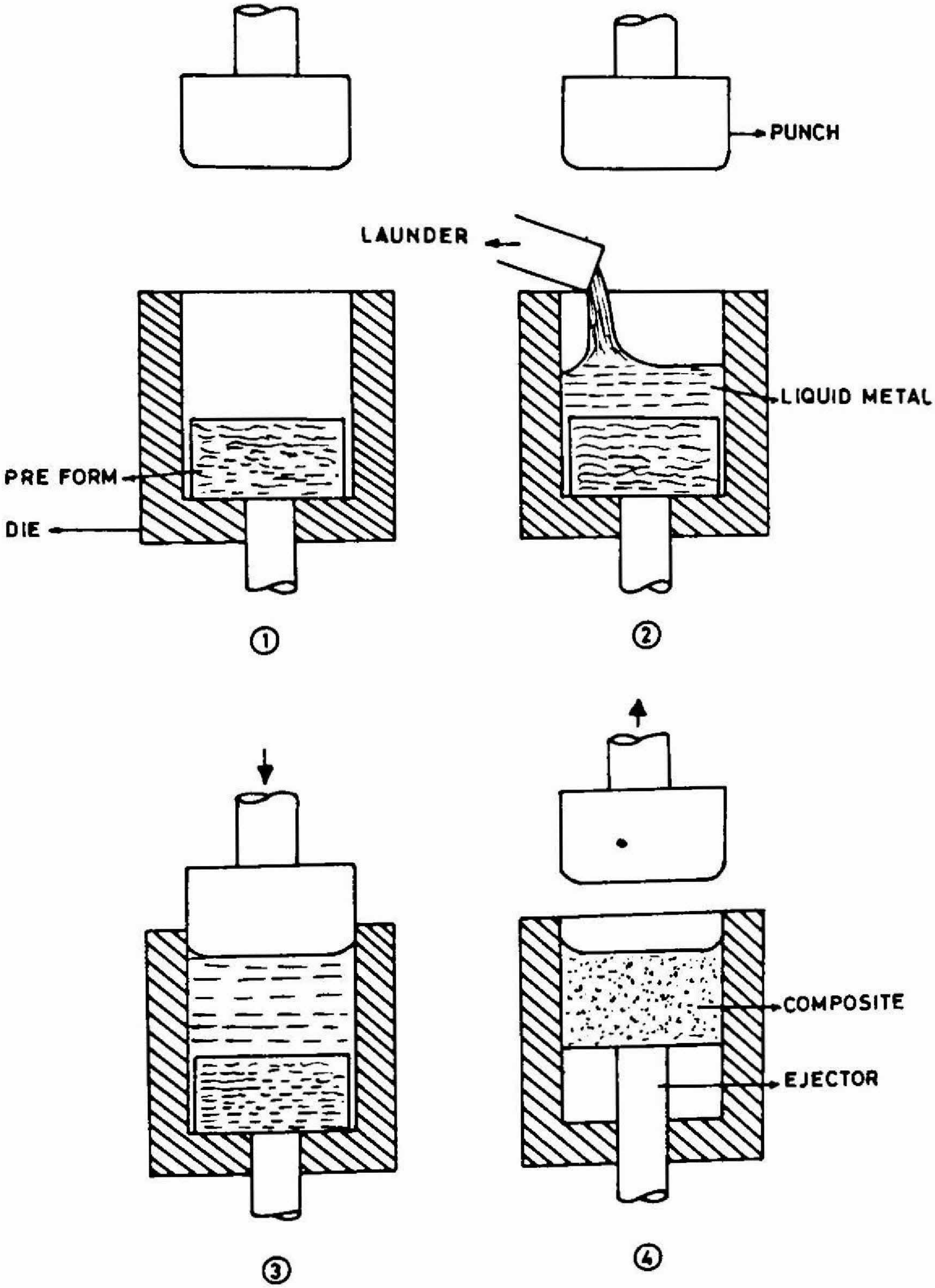

Fig. 1. Squeeze casting of composite material using fibre preform[4].

where $Y_{LV}$ is the liquid/vapour surface tension, 0, the liquid/solid contact angle, and $R$, the pore or capillary radius.

A good interfacial adhesion can be achieved only when sufficient wetting occurs. By providing a suitable coating to the reinforcements, wettability can be improved considerably. Interfacial adhesion can also be modified by selective addition of alloying elements.

In the squeeze casting technique, the following process parameters have to be carefully studied and optimized for any particular alloy/reinforcement system to obtain sound castings:

*(i)* Temperatures of the preform and die,
*(ii)* Temperature of the liquid metal,
*(iii)* Applied pressure,
*(iv)* Time of application of pressure.

The temperature of the preform and die are directly related to the time required for solidification. Too high a preform temperature would initiate reactions with the metal, and low die temperature would result in incomplete infiltration. Overheating the liquid metal would lead to oxidation of the metal. The pressure has to be carefully selected as higher pressures may damage the reinforcement fibres.

Still, one can have a choice of the process variables to suit specific matrix–reinforcement combinations. 6061 Aluminium alloy/silicon carbide whisker composite has been fabricated by heating the preform and metal to 770°C. The applied pressure over the liquid metal was varied from 25 to 100 MPa[7]. Similarly, it has been reported that A356 alloy has been successfully infiltrated into alumino-silicate preforms, heating the metal and preform to 1000° C and keeping the die at room temperature[12].

The pressure of the melt on the preform before and during infiltration means that a considerable force is acting on the preform resulting in some compression of the preform. This compression causes a 5–10% volume decrease in the porous space and consequently a corresponding increase in the fibre content[13], which leaves a higher proportion of fibres at the bottom of the casting.

## 5. Structure and properties of fibre-reinforced composites

### 5.1. *Microstructure*

The arrangement of fibres in the matrix is one of the factors which determines the mechanical properties of a fibre-reinforced composite. The dispersion technique (disseminating the fibres in a liquid medium) to produce fibre preforms seems to have a control over the fibre spacing as it allows the fibres to arrange themselves in planar random orientation.

Intermetallic phases containing impurities are brittle in nature and they always crack earlier than the matrix thus leading to failure of the composite at lower loads. The presence of silica binder in the preforms increases the possibility of producing a brittle

a. b.

FIG. 2. Microstructures of mullite reinforced Al- and Zn-based composites[15]. a. LM6 + 10% mullite; b. ZA-12 + 10% mullite.

interfacial bonding and also results in macroscopic and microscopic segregation of alloying elements such as Mg[9].

Magnesium in the matrix alloy is a welcome factor as MG can penetrate into porous alumina fibres to form a good interfacial adhesion[14]. Mg and Si, the two alloying elements, give hardening ability to the matrix, especially in Al–Si alloys[9,12]. The presence of particles < 100 µm may be deleterious to the performance of the infiltrated composites due to stress concentrations at the particles.

The microstructure of Al-12 Si alloy and Zn-12 Al alloy reinforced with alumino silicate fibres (10% by volume) are shown in Figs 2a and b[15]. Though ethyl silicate binder has been used, no reaction zone is observed here. The occurrence of long fibres in the microstructure indicates that the fibre orientation is essentially planar random. The smaller particles are also seen in the photograph.

### 5.2. *Hardness*

The hardness of the base alloy matrix is improved considerably by the addition of reinforcement fibres. This has been clearly demonstrated by many research workers. The increase in hardness can be attributed to the presence of fibres which are invariably harder than the matrix.

Brinell hardness values of Al-12Si alloy and ZA-12 alloy reinforced with mullite fibres are presented in Table IV. The increase in the Brinell hardness number with increase in fibre volume fraction is clearly seen.

Similar results obtained by Zhu and Lu[16] for ZA-12 alloy reinforced with alumina fibres are shown in Fig.3.

### 5.3. *Tensile strength*

Assessment of the tensile strength of the composites has led to contradictory conclusions. Tensile strength of random short fibre composite systems is a complicated function

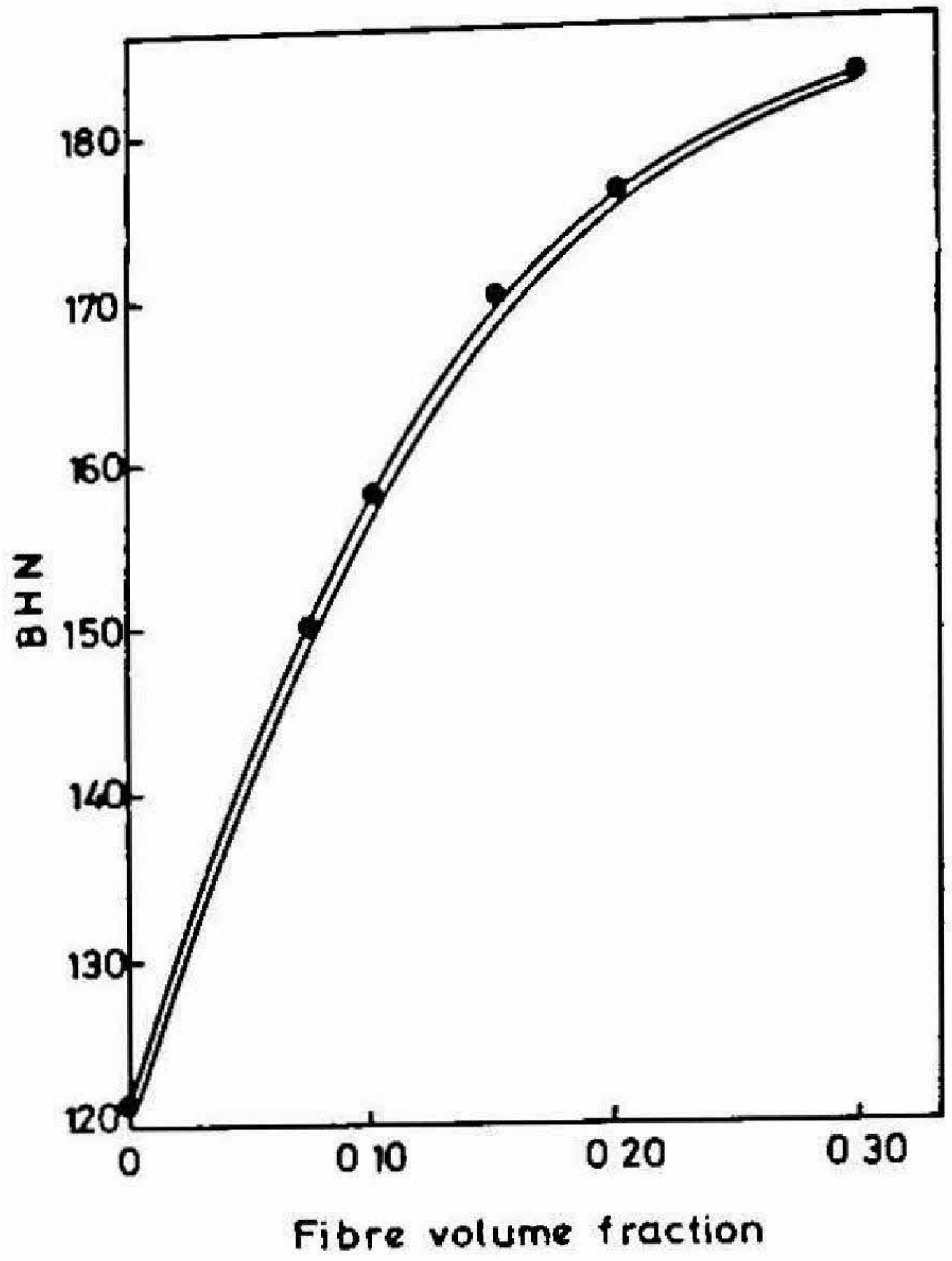

FIG. 3. Effect of fibre volume fraction on the hardness of the composites at room temperature[16].

of many variables such as fibre orientation, aspect ratio of fibres, strength of fibres and the matrix, interfacial shear strength, residual stress, crack sensitivity of the matrix and bonding conditions between fibres and the matrix[7]. A simple rule of mixture (ROM) has been found to be inadequate to predict the tensile strength of the composites precisely. Several modifications in ROM have been suggested by researchers but their reliability with various matrix-reinforcement systems has to be verified experimentally.

At room temperature, the tensile strength of the MMCs is usually lower than that of the base alloy (Table V).

But at elevated temperatures, the composites exhibit a better load-bearing capacity than the base alloy. Several Al and ZA alloys are reported to lose most of their strength

**Table IV**
**Hardness values of Al-12Si and ZA-12 alloy composites[15]**

| | *Brinell hardness number* | |
|---|---|---|
| | *Al-12Si alloy* | *ZA-12 alloy* |
| Base alloy | 66 | 121 |
| With 10% mullite | 73 | 124 |
| With 20% mullite | 82 | 136 |

**Table V**
**Tensile strength of LM6 and ZA-12 base alloys and composites at room temperature[15]**

| | *Ultimate tensile strength (MPa)* | |
|---|---|---|
| | *LM6 alloy* | *ZA-12 alloy* |
| Base alloy | 196 | 335 |
| With 10% mullite | 175 | 260 |
| With 20% mullite | 186 | 265 |

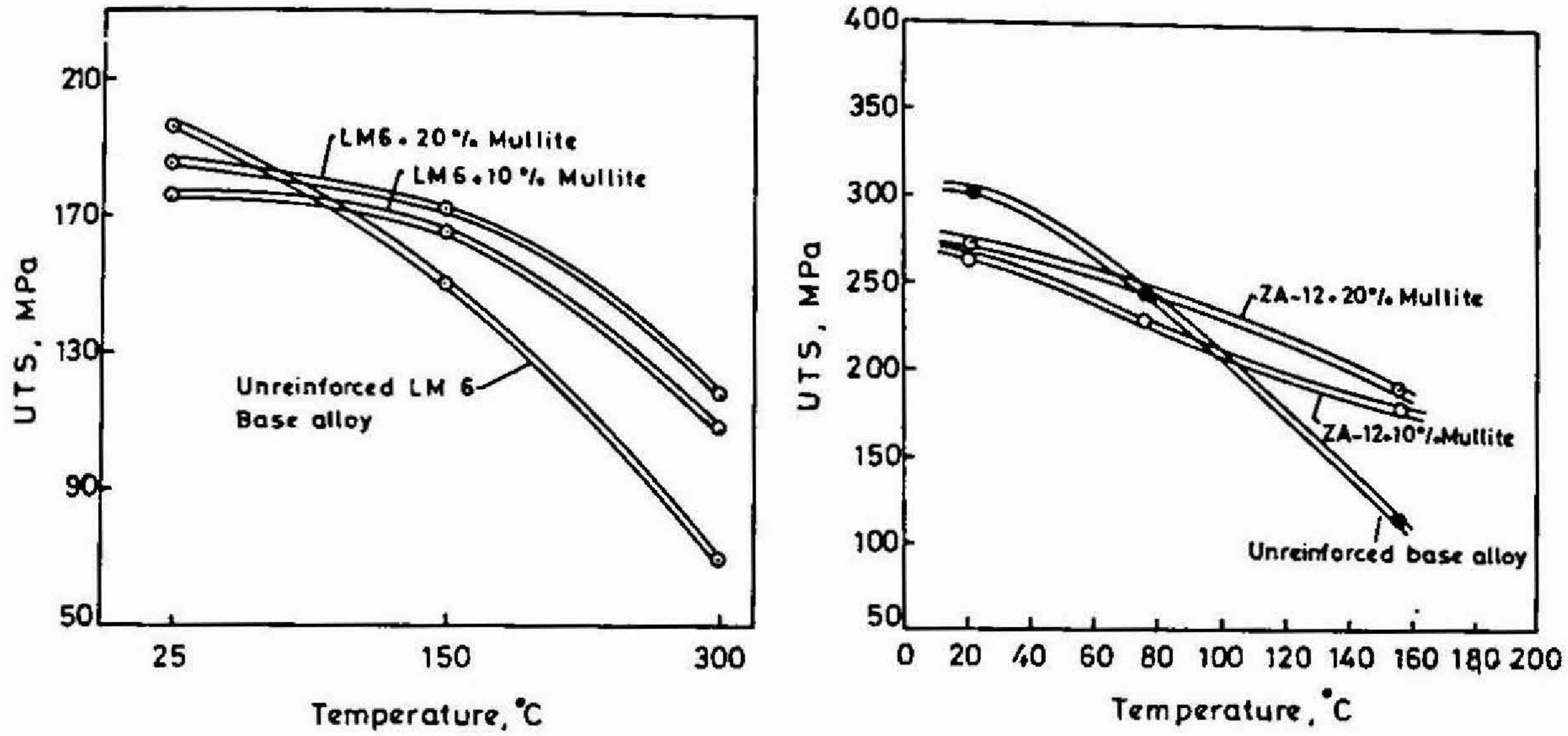

FIG. 4. Influence of temperature on UTS of Al- and Zn-based alloys and composites[15]. a. Al-12 Si alloy, b. Zn-12 Al alloy.

above 100° C. But selective reinforcements to these alloys enhances their strength appreciably. Experimental results shown in Fig. 4 confirm this fully[15]. The improvement at higher temperatures is due to the fact that the plastic flow of the matrix is impeded by the reinforcement fibres and effective load transfer from the matrix to the fibres takes place.

## 5.4. *Elongation*

The elongation of the composites is much lower when compared to that of the base alloy both at room and at elevated temperatures. The improvement in the tensile strength can be exploited only at the expense of ductility. The ductility values of Al-12Si alloy with and without fibre reinforcements are listed in Table VI. Similar result has been reported by Musson and Yue[17] (Table VII).

## 5.5. *Wear resistance*

Many engineering applications of MMC components call for improved tribological properties. In fact, high strength of MMCs coupled with better wear resistance is a major reason for their rapidly enlarging demand.

**Table VI**
**Elongation (%) of Al-12Si alloy without and with reinforcements[15]**

| | *at room temperature* | *at 150° C* | *at 300° C* |
|---|---|---|---|
| Base alloy | 11 | 15 | 28 |
| With 10% mullite | 2 | 3 | 4 |
| With 20% mullite | 1 | 2 | 3 |

**Table VII**
**Elongation (%) of Al 7010 alloy and Al-5Mg alloy and composite at room temperature[17]**

| | *7010 alloy* | *Al-5Mg alloy* |
|---|---|---|
| Base alloy | 10.5 | 13.8 |
| With 15% alumina | < 0.2 | 2.0 |

Superior wear resistance of composites has been clearly established by several investigators. It has been shown that incorporation of small amounts (5–10% by volume) of fibres is adequate to improve the wear resistance appreciably. If the reinforcement is efficiently bonded to the matrix, MMCs generally show much better sliding wear than the unreinforced matrix.

Al-12Si alloy reinforced with 10% mullite fibres shows a notable improvement in adhesive wear resistance (Fig. 5). At 20% mullite reinforcement the improvement in resistance to adhesive wear is very high (about 90%) when compared to the base alloy. Identical observations have been made for ZA-12 alloy-based composites also (Fig. 6).

### 5.6. *Fracture toughness*

Fracture toughness of a fibre-reinforced MMC material is mainly dependent on the brittleness of the fibres and the interfacial bonding. The efficiency of the interfacial bonding can be characterized by the fibre pull out of a fractured surface. A weak interfacial adhesion brings about very extensive fibre pull out whereas a high interfacial adhesion causes the breakage of the fibres close to the fracture plane of the matrix.

Fracture toughness of a composite material is much inferior to the fracture toughness of the base alloy. The brittle ceramic fibres facilitate crack propagation in the matrix by cleavage. Reinforcement of alumina fibres to ZA-8 alloy reduces the fracture toughness

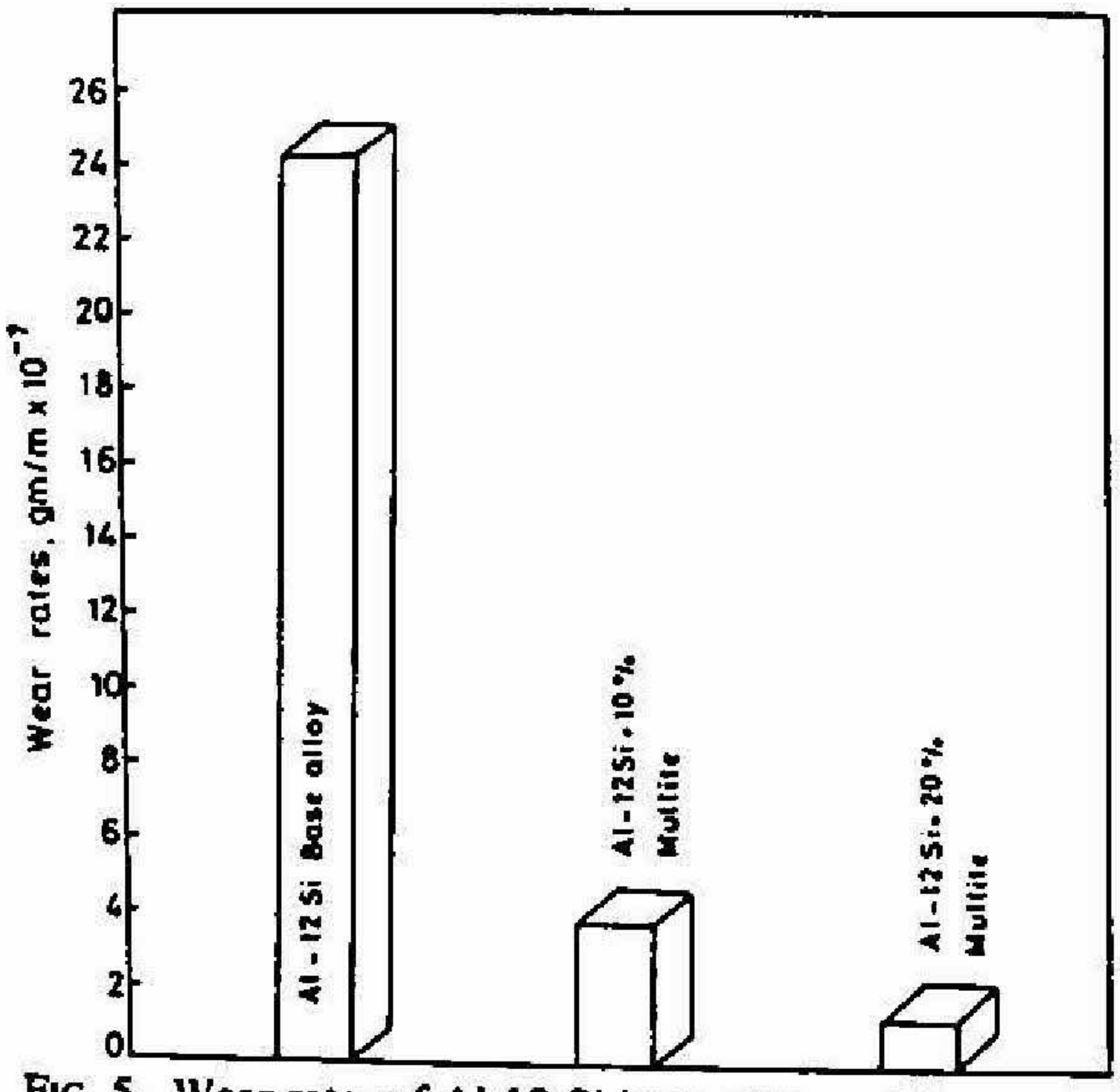

FIG. 5. Wear rates of Al-12 Si base alloy and its composites[15].

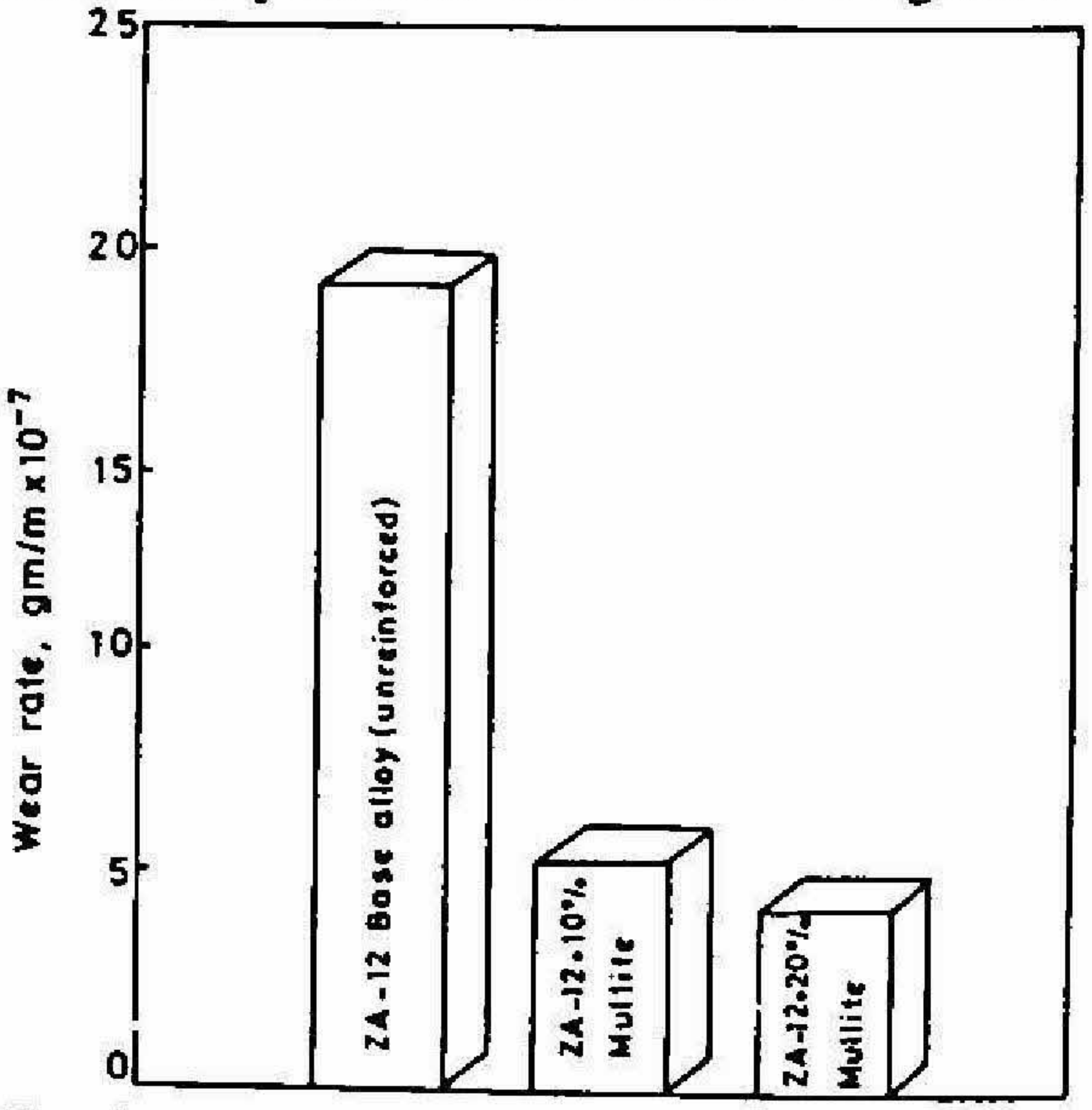

FIG. 6. Wear rates of ZA-12 base alloy and its composites[15].

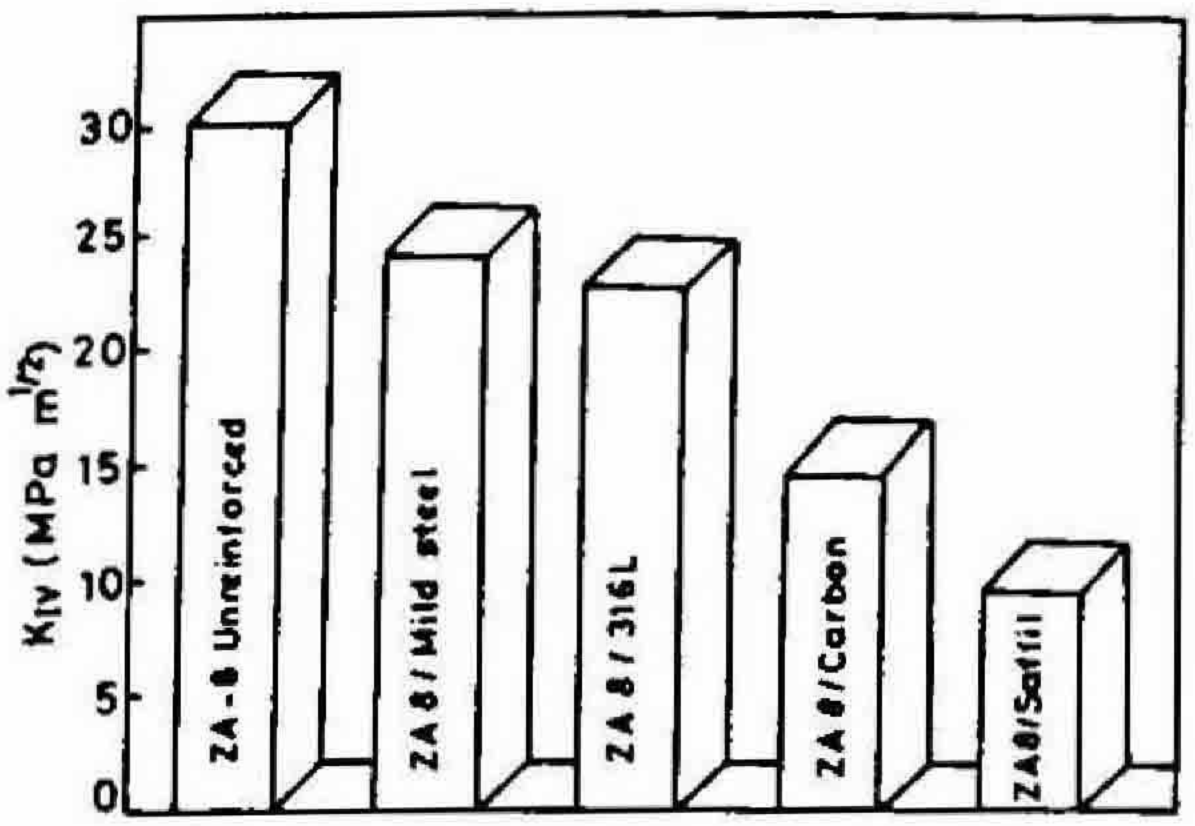

FIG. 7. Fracture toughness values of ZA-8 alloy and its composites[18].

drastically (Fig.7). On the other hand, when the same alloy is reinforced with steel fibres (mild steel and austenitic stainless steel-316L), the loss in toughness is much less. This suggests that if the fibres are more ductile than the matrix alloy and if the interfacial adhesion is low enough, a contribution to toughness may arise from the plastic straining of fibres bridging the crack wake[18].

## 6. Conclusions

1. Fibre-reinforced MMCs can be conveniently fabricated through various casting processes such as vortex method, compocasting and squeeze casting route. Of the above, squeeze casting method is highly compatible for various matrix reinforcement combinations and for various volumes of fibres. The operating parameters such as preform and die temperature, melt superheat and the applied pressure are to be appropriately selected for a particular alloy-reinforcement system to achieve satisfactory bonding conditions between the matrix and the reinforcement.

2. MMCs produced under optimum process environment show uniform distribution of reinforcement fibres. The interfacial bonding between the matrix and the reinforcement is free from porosity or formation of brittle oxide layer.

3. The hardness of the base alloy steadily increases with the addition of fibres.

4. At room temperature, the tensile strength of the MMCs is slightly lower than or equal to that of the unreinforced alloy. But at elevated temperatures, MMCs exhibit 70–80% higher tensile strength than the base alloy. The ductility of the composite is invariably lower than that of the unreinforced alloy, irrespective of the operating temperature.

5. Wear resistance of base alloys is improved tremendously with a small (5–10% by volume) addition of reinforcement fibres.

6. Fracture toughness of the MMCs is solely dependent on the ductility of reinforcing fibres and the nature of interfacial bonding. The fracture toughness of MMCs is invariably lower than that of the base alloy.

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