MRL-TN-562

AR-006-282

REINFORCEMENT - MATRIX INTERFACE EFFECTS
IN METAL MATRIX COMPOSITES
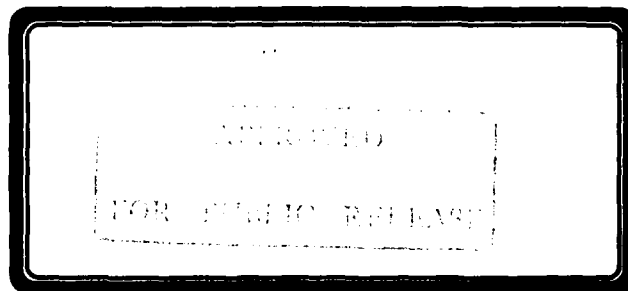
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AD-A220 021

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Reinforcement-Matrix Interface Effects in Metal Matrix Composites

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Abstract

Many properties of metal matrix composites are strongly influenced by the nature of the reinforcement-matrix interface. This in turn depends upon factors such as pretreatment of the fibres and composite fabrication techniques. The nature of the reinforcement-matrix interface is most commonly studied by electron spectroscopic techniques, which can give information about the degree of bonding between the reinforcement and matrix, and the formation of additional phases in the matrix material or at the interface. The use of these techniques to investigate the inter-relationship between fabrication techniques, interface properties and mechanical properties is described, and a number of specific examples are given.

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Contents

Reinforcement-Matrix Interface Effects
in Metal Matrix Composites

1. Introduction

Metal matrix composites (MMCs) have high specific strength and specific modulus and have the potential for high fracture toughness and environmental resistance. They therefore have the potential to replace metal alloys in many applications.

1.1 Composition

MMCs are generally composed of a ductile matrix containing strong brittle fibres, whiskers or particles. Continuous fibres may be metallic or ceramic. Beryllium (low density and high modulus), steel (high strength and low cost) and tungsten (high modulus and refractory) are the major metals used as continuous reinforcements. Continuous ceramic reinforcements include alumina, silicon carbide, silicon nitride, boron carbide and boron nitride. Boron and carbon fibres are also used as continuous reinforcement. Discontinuous reinforcement generally takes the form of silicon carbide or alumina whiskers or silicon carbide particles. The more important MMC systems, such as boron/aluminium (B/Al), carbon/aluminium (C/Al), alumina/aluminium (Al_2O_3/Al), silicon carbide/aluminium (SiC/Al), alumina/magnesium (Al_2O_3/Mg), and silicon carbide/titanium (SiC/Ti) are those reinforced with non-metallic fibres.

The design and form of MMCs have evolved with the development of fabrication techniques for both reinforcing materials and assembly of the composite. These techniques are also important factors in determining the nature of the reinforcement-matrix interface, and are therefore briefly considered.

1.2 Reinforcement Fabrication Techniques

The use of steel rods to reinforce concrete and glass is an established building technique, and the use of steel wires in tyres is also commonplace. The use of metal fibres to reinforce other

metals, however, depends upon the ability to make fibres of the diameter required for optimum reinforcement at a sufficiently low cost. Conventional fabrication techniques, such as drawing, are satisfactory for diameters down to 0.1 mm, below which the processing costs become prohibitive [1]. Smaller diameter wires may be made more economically by a process first developed by Taylor [2]. The wire is coated with a sheath of glass, which is heated until it softens and the core wire softens. The coated wire is then drawn, and the glass coating is etched away. There also exist proprietary processes for producing fine metallic wires, the details of which are not generally available [1].

The first B/Al composites were developed in the 1960s, following the discovery of the halide reduction process for making boron fibres [3]. The first high-modulus carbon fibres were prepared in 1961 [4], with successful development of carbon fibre reinforced MMCs taking place in the 1970s. The 1960s also witnessed the first interest in alumina and silicon carbide reinforcements. Alumina fibres are now widely available. They are made by dry spinning from an alumina slurry [5] or by a sol-gel technique starting with solutions of metal alkoxides [6]. Silicon carbide fibres may be formed by chemical vapour deposition onto tungsten or carbon substrates [7] or by controlled pyrolysis of silicon-containing polymers [8, 9]. Although the latter process is substantially cheaper, the resultant fibre properties are inferior [10].

Silicon carbide in particulate form is made by reacting silica with carbon at high temperatures, and is widely available for refractory and abrasive uses. Silicon carbide whiskers are generally obtained by vapour phase growth. However, the process results in a non-uniform distribution of whisker sizes and a concomitant spread in properties. In the early 1970s a process based on rice hulls, which contain silica, was developed [11]. Upon heating, the silica reacts with carbon to give both silicon carbide whiskers and particulates. These are subsequently separated by a wet process.

1.3 Fabrication of Metal Matrix Composites

MMCs are generally fabricated using either solid or liquid state techniques.

Solid state fabrication techniques include hot vacuum pressing of layers of metal foil and appropriately spaced fibres, and hot vacuum pressing or hot isostatic pressing of fibres which have been coated with the matrix material by plasma spray, chemical or physical vapour deposition. In both techniques the fibres are generally held in place with fugitive binders which are baked off before the consolidation cycle. The former technique is used commercially to make B/Al [12] and SiC/Ti composites [13], while the latter technique may be used to make a wide variety of composites [14]. Powder metallurgy techniques may also be used to make particulate or whisker reinforced MMCs [15] and have the advantage of being able to produce near nett shape composites. Near nett shape production can result in significant cost savings; because MMCs are more resistant to wear, they are much more difficult, and therefore more expensive, to machine and grind than metal alloys.

All liquid state fabrication techniques rely upon the infiltration of molten metal between the fibres, whiskers or particulates. Whiskers and particulates must be properly dispersed in order to achieve good wetting and distribution. This is generally achieved by mechanical agitation [16]. Fibres present a particular problem for liquid infiltration fabrication, because they must generally be properly aligned prior to infiltration. For this reason, continuous fibre composites are generally fabricated using solid state techniques.

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2. Applications of Metal Matrix Composites

Although MMCs have been demonstrated to be superior to metal alloys for many applications, their higher cost in the past has restricted their usage to applications where weight, high temperature or wear properties are critical. The most common application has been in the aerospace industry, where high-strength, heat-resistant components are required. Specific applications include space structures (e.g. radiator panels), rocket nozzles, airfoil surfaces and turbine blades. Many of these applications call for lightweight aluminium and/or titanium alloys reinforced with very stiff continuous fibres such as boron, carbon, stainless steel, beryllium, tungsten or silicon carbide. A particular advantage of graphite/aluminium composites is their low coefficient of thermal expansion, which makes them well suited to applications where temperature extremes are encountered, e.g. space applications. More recently, fibre reinforced MMCs have been used in automotive applications following the lead of the Toyota Motor Company, who in the early 1980s selectively reinforced pistons in diesel engines [17]. Current automotive applications include connecting rods, pistons, cylinder liners and high speed shafts. Discontinuous fibre MMCs and particulate reinforced MMCs have been used primarily as abrasive or abrasion resistant materials. Particular applications include brake linings and cutting tools.

3. Interfacial Bonding in Metal Matrix Composites

The interaction between the reinforcement and the matrix was recognised at an early stage as a critical factor in determining the properties of the resulting MMC. It is necessary to control both the reinforcement-matrix interfacial bonding, in order to optimise mechanical properties, and diffusion and reaction at the interface, in order to minimise fibre degradation.

The reinforcement-matrix interface in MMCs, as in other composites, can rely on mechanical bonding or chemical bonding. Although the former type of bonding has been demonstrated in tungsten wire/aluminium [18] and alumina/aluminium [19] MMCs, chemical bonding is much more common.

Chemical bonding between the reinforcement and matrix must be considered in conjunction with other factors. Because of the fabrication techniques and the disparity between the physical properties of ceramics and metals, obtaining a satisfactory interface between the reinforcement and matrix can represent a serious problem. Different coefficients of thermal expansion in the reinforcement and matrix may result in residual stresses in the composite as a result of the fabrication process. Thermal cycling may also induce stresses in the MMC if the coefficients of thermal expansion are different [20]. This problem has been observed for a wide variety of systems, including boron/aluminium, boron/magnesium, and silicon carbide/aluminium [21, 22]. Surface energy differences may also give rise to problems through incomplete wetting of the reinforcement by the molten metal, leading to structural weaknesses in the composite and to clumping in the case of particulate reinforced composites. There may also be undesirable chemical reactions between the molten metal and the fibre surface, with the possible formation of eutectic compounds. The case of carbon/aluminium illustrates some of these difficulties. Poor wettability is a major problem in this composite system. Although wettability improves above 1000°C [23], a chemical reaction between the carbon and aluminium takes place above 500°C, resulting in the

formation of brittle aluminium carbide [24]. Reactions between the reinforcement and matrix are governed by diffusion, which can be reduced by applying coatings to the fibres or by adding alloying elements to the matrix. For example, the problem of reaction between carbon fibres and molten aluminium may be solved by codeposition of titanium and boron on the carbon fibre prior to composite fabrication [25]. The application of surface coatings to the fibres may also help to improve fibre wettability; silica coated carbon fibres are much more readily wet by molten magnesium than uncoated carbon fibres [26]. Boron fibres may also be coated to improve wetting; a B_4C coating on boron fibres reduces reaction with titanium and aluminium matrices, while a coating of SiC reduces reaction between boron fibres and aluminium matrixes [27, 28]. Chemical bonding and/or improved wetting between the reinforcement and matrix may also be promoted by modifying the matrix composition. Impurities may be chosen to react selectively with the fibre to give a thin fibre surface layer which will be wetted by the matrix. The most successful example of this technique is the addition of small quantities (2-3%) of lithium to aluminium in order to promote adhesion to alumina fibres [29]. The lithium is believed to react with the alumina to form a lithium aluminate, which is more readily wet by the aluminium. The addition of low melting point metals such as indium, lead and thallium to aluminium has also been shown to enhance wetting of carbon fibres [30].

4. Interface Effects on Mechanical Properties

The most commonly desired properties in MMCs are strength, fracture toughness, creep behaviour, fatigue resistance, corrosion resistance, and damping. The relative importance of these properties depends upon the application, and they are influenced by a number of factors including the reinforcement-matrix interface. These factors are now discussed, with specific reference to reinforcement-matrix interactions.

4.1 Strength

Probably the most important factor in the development and use of MMCs is their improved strength relative to the matrix materials, particularly at high temperatures. For this reason, the effects of the reinforcement-matrix interface on composite strength have been well studied. The strength achieved for a given matrix material depends mainly upon satisfactory wetting of the reinforcement by the liquid metal, with a strong bond being required for efficient load transfer. The greatest mechanical strength is given by continuous fibres. These composites are highly anisotropic with maximum tensile strength in the fibre direction. The axial and transverse tensile strength generally vary linearly with fibre volume fraction, although the effect on transverse tensile strength is much smaller [29]. For B/Al composites the axial tensile strength also increases when the B fibres are chemically polished. The transverse tensile strength is not significantly affected [31]. This effect is postulated to be due to a reduction in stress concentrations associated with reaction products on the polished fibres.

For whisker reinforced MMCs the tensile strength of the reinforcement-matrix interface is not the dominant factor in composite strength. McDanels [32] has shown that for silicon carbide whiskers in aluminium alloys, the most important factor in determining

ultimate tensile strength is the choice of matrix alloy. The ultimate tensile strength for a whisker reinforced composite is frequently observed to be significantly greater than the unreinforced material only at high temperature. This phenomenon has been investigated for short alumina fibres in aluminium alloys by Friend [33], who has shown that the behaviour can be explained by a simple rule of mixtures analysis, with the strength of the composite controlled primarily by the matrix properties. The temperature dependence of the composite strength can thus be explained by the effect of temperature on matrix properties.

4.2 Fracture Toughness

The fracture toughness of MMCs depends upon many factors, including the type, size, orientation and distribution of the reinforcing phase, the properties of the matrix, and the effect of processing on microstructural properties such as the level of porosity and component segregation within the matrix. These factors themselves may depend either directly or indirectly upon the interactions between the reinforcing phase and the matrix.

Ceramic fibre reinforced MMCs often have poorer toughness than the matrix material. For good toughness in these materials, fibres with a high in situ strength and a low density of critical flaws, which could act as crack initiators, are required. For discontinuous fibre reinforced MMCs such as silicon carbide/aluminium, it has been shown [32] that higher fracture energies can be obtained by using cleaner matrix powder, better mixing and increased mechanical work during fabrication. These last two factors lead to better fibre wetting and a stronger fibre/matrix interface with fewer flaws. Unlike ceramic matrix composites and some polymer matrix composites, a stronger fibre/matrix bond in MMCs does not necessarily reduce composite toughness, because the fracture path is dominated by matrix failure rather than interfacial failure [34].

Fracture toughness of particulate reinforced MMCs is generally better than that of short fibre reinforced MMCs, and is dependent on the particulate size and distribution, and inhomogeneous internal stresses [35]. The case of silicon carbide particulate/aluminium MMCs has been studied in detail by Arsenault [36], who found that the fracture process is matrix controlled for silicon carbide particle sizes up to 20 microns, above which fracture of the silicon carbide begins to dominate. Interfacial failure is not a major mechanism. The crack initiation fracture toughness does not depend upon silicon carbide particle size, but the crack growth fracture toughness increases with particle size.

4.3 Creep Behaviour

In continuous fibre MMCs in which the reinforcement and matrix have similar melting points, both will creep at high temperatures. However, in MMCs where the reinforcement is ceramic, e.g. silicon carbide or alumina, melting temperatures are vastly different and the matrix creep is orders of magnitude greater than that of the fibres, which will deform elastically in the creeping matrix [37]. The creep rate will therefore not be constant, but will decrease and approach zero as the strain in the fibres approaches an equilibrium value. The effect of the fibre/matrix interface on this phenomenon has not been extensively investigated, although a stronger coupling between the fibres and the matrix might be expected to reduce the rate of creep.

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In discontinuous fibre and particulate reinforced MMCs steady-state creep is achieved because the matrix can flow around the particles or the fibre ends.

4.4 Fatigue Resistance

Fatigue resistance is also an important property where MMCs can give benefits over the corresponding unreinforced metals. In this case, the reinforcement-matrix interface is critical. Studies of silicon carbide particulate reinforced aluminium have shown that unbonded silicon carbide particles and non-silicon carbide intermetallics were fatigue crack-initiation sites [38]. Unbonded silicon carbide particles occur when clusters of particles are present. The fatigue life is therefore critically dependent upon the distribution of silicon carbide particles in the composite, which is largely a function of the wetting behaviour of the particles. Good mixing during processing of the composite is essential for satisfactory wetting of the particles or whiskers.

4.5 Corrosion Resistance

Because the reinforcement is contained within the matrix, it is possible to use MMCs in environments in which the unprotected reinforcement would corrode. However, because MMCs are heterogeneous materials, problems with galvanic corrosion may be encountered, especially around the exposed fibre ends in continuous fibre reinforced composites. A particular example of this is carbon/aluminium composites which experience galvanic corrosion between the carbon and the aluminium, because carbon is cathodic in nature, while aluminium is anodic [39]. Silicon carbide fibre/aluminium composites are also subject to galvanic corrosion in wet environments, with corrosion occurring at the exposed fibre/matrix interfaces (N. Garrard, unpublished results, MRL). This problem is less likely to occur with particulate composites because of the lack of continuous paths, but particulate composites may be subject to the clumping problems already described.

At elevated temperatures the heterogeneous nature of MMCs also gives rise to the potential for interactions between the reinforcement and the matrix, by chemical reaction or diffusion of the metal matrix into the reinforcement. These possibilities are related to both the temperature and the nature of the interface. If the temperature at which the composite is used is much lower than the original processing temperature, there should be minimal reaction between the reinforcement and matrix. If the reinforcement has had a diffusion barrier applied prior to processing, then higher use temperatures should be possible. However, prolonged use at elevated temperatures may result in reaction occurring, with degradation of composite properties.

4.6 Damping Properties

As heterogeneous materials, MMCs offer a greater potential for damping than more homogeneous materials such as metals. Because of the cost of MMCs, however, the major interest to date has been on space applications, where stability control is vital. There is also the potential, however, for noise and vibration reduction around machinery.

Because damping is fundamentally a dissipation of energy, the major work on MMCs for noise reduction has centred around the reinforcement-matrix interface. Misra et al. [40] have carried out an extensive study of damping by carbon/aluminium MMCs, using a variety of techniques including transmission electron microscopy (TEM) and acoustic emission. The TEM results revealed dense dislocation networks adjacent to the fibre/matrix interfaces. These dislocation networks arise because of the differences in thermal coefficient of expansion between fibre and matrix, and account for the strain amplitude dependence of the composite damping. The acoustic emission tests indicated that fibre breakage and interfacial failure are also important sources of energy dissipation. In view of these factors, some mismatch in reinforcement and matrix properties is desirable, and a strong reinforcement-matrix interface is probably not required, for effective damping properties.

5. Characterisation of the Interface in Metal Matrix Composites

Although the effectiveness of the bonding/wetting techniques already described can be determined by measuring the mechanical properties of the resultant composites, the mechanisms by which improvements occur can only be confirmed by characterisation of the reinforcement-matrix interface. The interface morphology may be analysed using techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), or X-ray diffraction. Chemical information about the reinforcement-matrix interface may be derived from spectroscopic experiments using scanning Auger microscopy (SAM) and standard Auger electron spectroscopy (AES). However, these techniques are usually used as an adjunct to electron microscopy.

Electron microscopic techniques have been used to characterise the reinforcement-matrix interface in a variety of MMC systems. However, there has been very little work carried out in a systematic manner; most studies have included only one reinforcement and one or two matrix materials, and characterisation of the interface has generally been conducted as part of wider studies which also include mechanical testing. The results have therefore been specific to the system studied, and have not led to ready generalisation. Nevertheless, electron microscopic techniques have yielded insights into the physical processes involved in the fabrication of specific MMCs.

SEM and TEM have been particularly useful in identifying new phases formed by reaction between the fibre and matrix. Hall et al. [41] have examined the fibre/matrix interface in B/Al composites using SEM and TEM and have found that prolonged isothermal exposure causes a fibre/matrix reaction with the formation of at least four different boride phases. Hall [42] has also used TEM to evaluate the effectiveness of nickel coatings on carbon fibres in a magnesium matrix. If the cooling rate is too slow, a brittle nickel-magnesium eutectic compound forms, resulting in poor composite strength.

SEM and TEM are also useful for examining microstructural properties of the matrix material, for example, porosity, variable grain sizes and dendritic structures. Rawal et al [43] have used TEM to study the fibre/matrix interface morphology in diffusion bonded carbon/aluminium composites. These composites have no voids, but are characterised by three distinct matrix morphologies. Distinct matrix morphologies have also been observed by Mortensen et al [44] for aluminium matrices reinforced with silicon carbide

fibres. It is clear from these studies that the presence of the fibres may have a considerable effect on the solidification of the matrix materials.

6. Summary

The reinforcement-matrix interface in MMCs is an important factor in determining the mechanical properties of these composites, through its effect on strength, toughness and environmental resistance. The interface may be controlled by surface treatment of the reinforcement phase, by modification of the matrix, or by changes in fabrication techniques. Analysis techniques such as SEM, TEM and X-ray diffraction offer a means to probe the interface region and examine how it is affected by changes in manufacturing methods, and how it in turn affects important composite mechanical properties.

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DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TN-562	AR-006-282	Unclassified

TITLE

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REPORT DATE	TASK NO.	SPONSOR
November 1989	DST 88/148	DSTO

FILE NO.	REFERENCES	PAGES
G6/4/8-3763	44	15

CLASSIFICATION/LIMITATION REVIEW DATE	CLASSIFICATION/RELEASE AUTHORITY
	Chief, Materials Division MRL

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Metal fibers   Matrix materials

SUBJECT GROUPS	0071F

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