CHAPTER 1

INTRODUCTION

1.1 Background

Metal-Matrix composites (MMCs) are materials with a high potential for exploitation in novel applications. MMCs offer higher specific modulus, specific strength, higher operating temperature, and greater wear resistance, when compared to the unreinforced metals. MMCs provide the opportunity to tailor these properties for aerospace and automotive industry and other light weight applications. In the past few years, MMCs have become candidates for engineering components, such as automotive drive shafts, high-speed train brake rotors and aero-engine components. However, MMCs also have some disadvantages compared with metals. Chief among these are the higher cost of fabrication for high-performance MMCs, and lower ductility and toughness.
1.2 Metal Matrix Composites

Metal matrix composites are a broad family of materials aimed at achieving an enhanced combination of properties. MMCs usually consist of a low-density metal, such as aluminum or magnesium called the matrix, reinforced with particulate or fibers of a ceramic material called the reinforcement, such as silicon carbide, alumina or graphite [1-3]. The addition of a ceramic reinforcement phase in monolithic metal alloys significantly alters their mechanical and physical properties, as well as deformation behavior. With proper control, this alteration can be exploited to increase the performance of metal alloys. To date, the attainment of higher strength and stiffness has been the prime motive behind the development of MMCs [4].

Initially, MMCs were developed with the use of fibers as continuous reinforcement in the matrix of composites for the aerospace industry. The result was a material of high strength, modulus and wear resistance and low thermal expansion. Although this material provided the high specific strength and modulus desired to achieve weight savings for aerospace, the cost and limiting fabrication methods restricted the use of continuous-fibre reinforced MMCs to high cost applications.

Discontinuously reinforced composites with short fibres, platelets or particles of ceramic, such as alumina or silicon carbide have applications in those areas where the best properties may not be required and where their presence could be cost effective. For example, cost-weight-stiffness components, such as engine static structures do not require the level of properties available with continuously reinforced composites [5-6].

Work continued on the development of MMCs and resulted in the introduction of
lower-cost discontinuous reinforcements with simpler fabrication methods. Although
the discontinuous MMCs did not provide the highest strength levels of the continuous
reinforcements, their enhanced properties (when compared to monolithic metals), ease
of fabrication and lower cost expanded the market opportunities for these MMCs [7].

1.2.1 Matrix Materials

The choice of a matrix alloy for an MMC is dictated by several considerations. Of par-
ticular importance is whether the composite is to be continuously or discontinuously
reinforced. The use of continuous fibers as reinforcements may result in transfer of
most of the load to the reinforcing filaments and hence composite strength will be gov-
erned primarily by the fiber strength. The primary roles of the matrix alloy then are
to provide efficient transfer of load to the fibers and to blunt cracks in the event that
fiber failure occurs and so the matrix alloy for a continuously reinforced MMC may be
chosen more for toughness than for strength. On this basis, lower strength, more duc-
tile, and tougher matrix alloys may be utilized in continuously reinforced MMCs. For
discontinuously reinforced MMCs, the matrix may govern composite strength. Then,
the choice of matrix will be influenced by consideration of the required composite
strength and higher strength matrix alloys may be required.

Additional considerations in the choice of the matrix include potential reinforce-
ment/matrix reactions, either during processing or in service that might result in de-
graded composite performance; thermal stresses due to thermal expansion mismatch
between the reinforcements and the matrix; and the influence of matrix fatigue be-
havior on the cyclic response of the composite. In MMCs intended for use at elevated
temperatures, an additional consideration is the difference in melting temperatures
between the matrix and the reinforcements.

1.2.2 Reinforcement Materials

Reinforcement materials in MMCs are second phase additions to a metallic matrix
that result in some net properties improvement such as specific strength and stiffness.
Generally, most reinforcement materials for MMCs are ceramics (oxides, carbides,
nitrides, and so on) which are characterized by their high strength and stiffness both
at ambient and elevated temperatures. Examples of common MMC reinforcements
are SiC, Al₂O₃, TiB₂, B₄C, and graphite.

The role of the reinforcement varies with its type in structural MMCs. In particu-
late and whisker reinforced MMCs, the matrix is the major load bearing constituent.
The role of the reinforcement is to strengthen and stiffen the composite by preventing
matrix deformation by mechanical restraint. This restraint is generally a function of
the inter-particle spacing-to-diameter ratio. In continuous fiber reinforced MMCs, the
reinforcement is the principal load bearing constituent, the metallic matrix serves to
bond the reinforcement and transfer and distributes the load. Discontinuous fiber rein-
forced MMCs display characteristics between that of continuous fiber and particulate
reinforced composites. Typically, the reinforcement increases the strength, stiffness
and temperature capability of MMCs. When combined with a metallic matrix of
higher density, the reinforcement also serves to reduce the density of the composite,
thus enhancing properties such as specific strength [8].

1.3 Aluminum MMCs

Aluminum is the most popular matrix for the metal matrix composites (MMCs). Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity.

A wide range of aluminum alloys in various forms have been incorporated in MMCs. The density of most aluminum alloys is near that of pure aluminum, approximately 2.7 g/cm$^3$. Pure aluminum melts at 1220°F (660°C); this relatively low melting temperature in comparison to most other potential matrix metals facilitates processing of Al-based MMCs by casting methods and solid state routes, such as powder metallurgy. Aluminum alloys are broadly classified as either wrought or cast materials; furthermore, many wrought compositions are also available in powder form. The term wrought indicates that the material is available primarily in the form of mechanically worked products such as rolled sheet, plate or foil, various extruded shapes, tubing, forgings, wire, rod, or bar. Many wrought aluminum alloy compositions are well suited for extrusion and most discontinuously reinforced aluminum (DRA) MMCs, whether initially consolidated via powder metallurgy or casting methods, are processed in this manner. Aluminum alloys intended for use in production of castings are generally available as ingots of varying size or in other forms suitable for remelting. Applications of such cast materials have included the production of cast components using
DRA, with stirring to suspend particles in the liquid metal prior to casting and solidification of the article. The designation schemes for both wrought and cast alloys are based on the major alloying additions. Wrought alloys are designated by four digits while cast compositions are designated by three digits. Both wrought and cast alloy compositions may be further classified according to the method of obtaining mechanical properties: heat treatable or non-heat treatable. Heat treatable refers to alloys that can be strengthened by heat treatment. Wrought alloys of the 2XXX, 6XXX and 7XXX series are generally heat treatable and those that contain major additions of lithium (for example, some 8XXX alloys) are also heat treatable. Non-heat treatable alloys are those that are not appreciably strengthened by heat treatment. Wrought alloys of the 1XXX, 3XXX, 4XXX and 5XXX series are generally non-heat treatable [8].

Aluminum matrix composites (AMCs) have been widely studied since the 1920s and are now used in sporting goods, electronic packaging, armours and automotive industries. They offer a large variety of mechanical properties depending on the chemical composition of the Al matrix. They are usually reinforced by Al₂O₃, SiC, C but SiO₂, B, BN, B₄C, AlN may also be considered. Chemical reaction during processing can occur between the Al matrix and the ceramic reinforcements. Silicon carbide can be particularly problematic in Al-based MMCs. Alumina is less reactive than SiC in Al alloys. Thus Compared with SiC, Al₂O₃ based MMCs are stable and inert and has better corrosion and high temperature behavior [10,11]. The aluminum matrices are in general Al-Cu-Mg (2xxx), Al-Mg-Si (6xxx) alloys. As proposed by
the American Aluminum Association the AMCs should be designated by their constituents: accepted designation of the matrix / abbreviation of the reinforcement’s designation/arrangement and volume fraction in % with symbol of type (shape) of reinforcement. For example, an aluminum alloy AA6061 reinforced by particulates of alumina, 22% volume fraction, is designated as “AA6061/Al₂O₃/22p”.

Among the various and numerous applications, a few examples, are: (1) Brake rotors for German high speed train ICE-1 and ICE-2 developed by Knorr Bremse AG and made from a particulate reinforced aluminum alloy (AlSi₇Mg+SiC particulates) supplied by Duralcan. (2) The braking systems (discs, drums, calipers or back-plate) of the New Lupo from Volkswagen made from particulate reinforced aluminum alloy supplied by Duralcan. (3) AMC continuous fiber reinforced pushrods produced by 3M for racing engines. These pushrods weigh 40% as compared to steel, are stronger and stiffer, and have high vibration damping. (4) AMC wires also developed by 3M for the core of a electrical conductors.

1.4 Processing Routes

A critical step in the processing of MMCs reinforced with ceramic particles is the insertion of these particles in the metal matrix alloy. This greatly influences the strength of the composite since it is controlled by the metal-particle interfacial bond strength. The most important aspect of the microstructure is the distribution of the reinforcing particles, and this depends on the processing and fabrication routes involved, as well as the relative size of the matrix and reinforcing particles. Quality control objectives
include the elimination of excessive interfacial reaction during processing, particularly for melt routes, and also the avoidance of microstructural defects such as poor interfacial bonding, internal voids and clustering of the reinforcement. Particulate MMCs are most commonly manufactured either by a melt incorporation and casting technique or by powder blending and consolidation. Other routes include reactive processing or spray co-deposition. An overview of the common processing routes employed to produce MMCs is discussed in the following section.

1.4.1 Stir Casting

Stir Casting involves stirring the melt with solid ceramic particles and then allowing the mixture to solidify. This can usually be done using fairly conventional processing equipment and can be carried out on a continuous or semi-continuous basis. A concern is to ensure that good particle wetting occurs. Difficulties can arise from the increase in viscosity on adding particles or, especially, fibers to a melt. The viscosity should be sufficiently low to allow casting operations to be carried out. Also, microstructural inhomogeneities can also arise, notably that of particle agglomeration and sedimentation in the melt. Redistribution as a result of particle pushing by an advancing solidification front can also be a problem.

Stir casting usually involves prolonged liquid-ceramic contact at elevated temperature, which can cause substantial interfacial reaction. This has been studied in detail for Al-SiC alloys which are predominant among cast aluminum alloys, in which the formation of Al$_4$C$_3$ and Si can be extensive [2]. This both degrades the final proper-
ties of the composite and raises the viscosity of the slurry, making subsequent casting difficult. The rate of reaction is reduced, and can become zero, if the melt is Si-rich. The reaction kinetics and Si levels needed to eliminate it are such that it has been concluded that casting of Al-SiCp involving prolonged melt holding operations is suited to conventional (high Si) casting alloys, but not to most wrought alloys. The presence of silicon in aluminum significantly reduces the tendency of aluminum to react chemically with SiC and form Al$_4$C. This latter compound severely embrittles SiC-reinforced Al MMCs even when present in small quantities [8].

### 1.4.2 Powder Blending and Consolidation

Blending of metallic powder with ceramic fibers or particulate is a versatile technique for MMC production. This is usually followed by cold compaction, canning, evacuation, degassing and a high temperature consolidation stage such as Hot Isostatic Pressing (HIP) or extrusion as shown in Figure 1.1 and Figure 1.2, respectively. Achieving a homogeneous mixture can be difficult, particularly with fibers. A feature of much powder route material is the presence of fine oxide particles, usually present in Al-MMCs in the form of plate-like particles a few tens of nm thick, constituting about 0.05-0.5 vol%, depending on powder history and processing conditions. This fine oxide tends to act as a dispersion strengthening agent and often has a strong influence on the matrix properties, particularly at high temperature.

MMCs produced by powder blending are commonly extruded. This can generate alignment of fibers parallel to the extrusion axis, but often at the expense of