Fabrication Methods, Mechanical Properties and Industrial Applications of Metal Matrix Composite Materials

by Dr Thoguluva Raghavan Vijayaram

1.0 INTRODUCTION

Metal matrix composite (MMC) materials are composed of an element or alloy matrix in which a second phase is embedded and distributed to achieve some property improvement. Based on the size, shape and amount of the second phase, the composite property varies. It has outstanding benefits due to the combined metallic and ceramic properties, thereby yielding improved physical and mechanical properties. In fact, it represents a new generation of engineering materials in which a strong ceramic reinforcement is incorporated into a metal matrix to improve its properties including specific strength, specific stiffness, wear resistance, corrosion resistance and elastic modulus. It combines the metallic properties of matrix alloys such as ductility and toughness with the ceramic properties of reinforcement such as high strength and high modulus, leads to greater strength in shear and compression, and higher service-temperature capabilities. Thus, they have significant scientific, technological and commercial importance.

In this paper, the fabrication methods, mechanical properties and industrial applications of different types of MMCs are discussed in a comprehensive manner. MMCs are materials that are attractive for a large range of engineering applications. They are a family of new materials, which are attracting considerable industrial interest and investment worldwide. The microstructure of the processed composites influences and has a great effect on the mechanical properties. Generally, increasing the weight fraction of the reinforcement phase in the matrix leads to increased stiffness, yield strength and ultimate tensile strength. However, the low ductility of particulate reinforced MMCs is a major drawback which prevents their usage as structural components in some applications [1].

MMCs are composites with a metal or alloy matrix. It has a higher elastic modulus, resistance to elevated temperatures, toughness and ductility. The limitations are higher density and a greater difficulty in processing parts. Because of their high specific stiffness, lightweight and high thermal conductivity, boron fibres in an aluminium matrix have been used for structural tubular supports in the space shuttle Orbiter. MMCs with silicon carbide fibres and a titanium matrix are being used for the skin, beams, stiffeners and frames of a hypersonic aircraft, which is under development. Other applications are in the form of bicycle frames and sporting goods. Composite materials are continuously displacing traditional engineering materials because of their advantages of high stiffness and strength over homogeneous materials formulations [2].

2.0 FABRICATION METHODS

The fabrication of particulate and discontinuously reinforced aluminium based MMCs can be achieved by standard metallurgical processing methods such as powder metallurgy, direct casting, rolling, forging and extrusion, while the products can be shaped, machined and drilled by using conventional machining facilities. Composite materials are characterised by good mechanical properties over a wide range of temperature. The choice of the processing method depends on the property requirements, cost factor consideration and prospects of future applications.

Composite materials with a metal or alloy matrix, which can be produced either by casting or powder metallurgy methods, are considered as potential material candidates for a wide variety of structural application in the transportation, automobile and sporting goods manufacturing industries due to the superior range of the mechanical properties they possess [3]. Conventional secondary fabrication methods can be used to produce a wide range of composite product forms, making them relatively inexpensive compared to other advanced composites reinforced with continuous filaments. The composite properties are enhanced in terms of increased strength, decreased weight, ability to withstand higher service temperature, improved wear resistance and higher modulus of elasticity. The main advantage of composites lies in the tailorability of their mechanical and physical properties to meet specific design criteria.

During the production of MMCs, several oxides are used as reinforcements, in the form of particulates, fibres or as whiskers. For example, alumina, zirconium oxide and thorium oxide particulates are used as reinforcements in aluminium, magnesium and other metallic matrices. Very few researchers have reported on the use of quartz as a secondary phase reinforcement particulate in an aluminium or aluminium alloy matrix due to its aggressive reactivity between these materials [4]. Preliminary studies have shown that the contact between molten aluminium and silica-based ceramic particulates completely destroyed the second phase microstructure due to the reduction reaction which provokes the infiltration of the liquid metal phase into the ceramic.

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Previous works carried out using continuous silica fibres as reinforcement phases in the aluminium matrix has shown that even at temperatures nearer to 400°C, silica and aluminium can react and produce a transformed layer on the original fibre surface as a result of solid diffusion between the phases and due to the aluminium-silicon liquid phase formation. In the processing of MMCs, one of the subjects of interest is to choose a suitable matrix and reinforcement material. In some cases, chemical reactions that occurred at the interface between the matrix and its reinforcement materials have been considered harmful to the final mechanical properties and are usually avoided. Sometimes, the interfacial reactions are intentionally induced, because the new layer formed at the interface acts as a strong bond between the phases [5].

3.0 ENHANCEMENT OF MECHANCIAL PROPERTIES IN COMPOSITES

MMC materials are defined as materials whose microstructures comprise a continuous metallic matrix phase into which a second phase, or phases, has been artificially introduced. This is in contrast to conventional alloys whose microstructures are produced during processing by naturally occurring phase transformations. MMCs are distinguished from the more extensively developed resin matrix composites by virtue of their metallic nature in terms of the physical and mechanical properties and by their ability to lend themselves to conventional metallurgical processing operations. Electrical conductivity, thermal conductivity and non-inflammability, matrix shear strength, ductility and abrasion resistance, ability to be coated, joined, formed and heat treated are just some of the properties that differentiate MMCs from resin matrix composites. They are a class of advanced materials which have been developed for weight-critical applications in the aerospace industry. Reinforced composites can be made with properties that are isotropic in three dimensions or in a plane [6].

4.0 THE ROLE OF MMCs IN AEROSPACE AND AUTOMOTIVE INDUSTRIES

During the last decade, because of their improved properties, MMCs are being used extensively for high performance applications such as in aircraft engines and, more recently, in the automotive industries. Aluminium oxide and silicon carbide powders in the form of fibres and particulates are commonly used as reinforcements in MMCs and the addition of these reinforcements to aluminum alloys has been the subject of a considerable amount of research work. Aluminium oxide and silicon carbide reinforced aluminum alloy matrix composites are applied in the automotive and aircraft industries as engine pistons and cylinder heads, where the tribological properties of these materials are considered important. Therefore, the development of aluminum matrix composites is receiving considerable emphasis in meeting the requirements of various industries [7].

5.0 INDUSTRIAL APPLICATIONS OF MMCs

Graphite fibres embedded in copper matrix are used to fabricate electrical contacts and bearings. Boron fibres in aluminium are used in compressor blades and structural supports. The same fibres in magnesium are also used to make antenna structures. Titanium-boron fibre composites are used in jet-engine fan blades [8]. Molybdenum and tungsten fibres are dispersed in cobalt-base super alloy matrices to make high temperature engine components.

Squeeze cast MMCs generally have much better reinforcement distribution than compo cast materials. This is because a ceramic preform is used to contain the desired weight fraction of reinforcement rigidly attached to one another so that movement is inhibited [9]. Consequently, clumping and dendritic segregation are eliminated. Porosity is also minimised since pressure is used to force the metal into interfibre channels, thus displacing the gases. Grain size and shape can vary throughout the infiltrated preform because of heat flow patterns. Secondary phases typically

Table 1: Special features and applications of MMCs materials [10]

Metal Matrix Composite Type	Industrial Applications	Special Features
Graphite reinforced in aluminium	Bearings	Cheaper, lighter, self-lubricating, conserves copper, lead, tin, zinc
Graphite reinforced in aluminium, silicon carbide reinforced in aluminium, aluminium oxide reinforced in aluminium	Automobile pistons, cylinder liners, piston rings, connecting rods	Reduced wear, anti seizing, cold start, lighter, conserves fuel, improved efficiency
Graphite reinforced in copper	Sliding electrical contacts	Excellent conductivity and anti seizing properties
Silicon carbide reinforced in aluminium	Turbocharger impellers	High temperature use
Glass or carbon bubbles reinforced in aluminium		Ultra light material
Cast carbon fibre reinforced magnesium fibre composites	Tubular composites for space structures	Zero thermal expansion, high temperature strength, good specific strength and specific stiffness.
Zircon reinforced in aluminium-silicon alloy, aluminium silicate reinforced in aluminium	Cutting tool, machine shrouds, impellers	Hard, abrasion-resistant materials

form at the fibre-matrix interface since the lower freezing solute-rich regions diffuse towards the fibre ahead of the solidifying matrix.

In recent years, the aerospace, military and automotive industries have been promoting the technological development of composite materials to achieve a good mechanical strength/density and stiffness/density ratio. Modern fibre-reinforced or particulate reinforced MMCs are produced via casting techniques. A wide variety of applications due to the low cost of fabrication and achievable engineering properties are shown in Table 1 [10].

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Some of the properties are high longitudinal and transverse strengths at normal and elevated temperatures, near-zero coefficients of thermal expansion, good electrical and thermal conductivities, and excellent antifriction, anti abrasion, damping and machinability properties. The application of composites materials is well established in aircraft technology and these are now applied in fuselage-production technologies as well as in jet engine technologies. Application in car production technology is growing very fast, although it is still not as common as in aircraft technology [11]. Due to mechanical, electrical and heat resistant properties, their application in the electronics industries is also growing considerably. Composite material parts are also applied in electronic sub-assemblies, lasers and computer parts, which can work at a higher temperature and function with better efficiency when compared to conventional electronic materials.

The application of composites in the automotive, transportation and construction industries depends on the choice of cost affordable factor. Apart from the emerging and economical processing techniques that combine quality and ease of operation, researchers are turning to particulate-reinforced aluminium-metal matrix composites at the same time because of their relatively low cost and isotropic properties especially in applications that do not require extreme loading or restricted thermal conditions in the case of automotive components. The presence of aluminium alloys as matrix materials is due to its comparative advantages, including low cost and ease of handling. The space shuttle uses boron reinforced aluminium tubes to support its fuselage frame, which decreases the mass of the space shuttle by more than 145kg. It has also reduced the thermal insulation requirements because of its lower thermal conductivity [12].

The mast of the Hubble telescope uses carbon-reinforced aluminium matrix composites. Precision components in missile guidance systems demand dimensional stability and the geometries of the components cannot change during usage. MMCs such as silicon carbide reinforced aluminium composite satisfy this requirement since they have high micro-yield strength. In addition, the weight fraction of silicon carbide can be varied to have a coefficient of thermal expansion that is compatible with other parts of the system assembly. MMCs are now used in automotive engines, which are lighter than their metal component parts. In addition, MMCs are the materials of choice for gas turbine engines due to their high strength and low weight. The range of MMC materials applications is very large. Some of the important MMC components are applied and used as insulation materials for electrical construction, support for circuit breakers and printed circuits, armours, boxes and covers, antennas, radomes, the top of television covers, cable tracks, windmills, housing cells, chimneys, concrete moulds, domes, windows, facade panels, partitions, doors and furniture.

It is also used in automotive engineering parts such as automotive body parts, wheels, shields, radiator grills, transmission shafts, suspension springs, chassis, suspension arms, casings, highway tankers, isothermal trucks, trailers, wagons, doors, seats, interior panels and ventilation housings. In marine transport, it is used to fabricate hovercrafts, rescue crafts, patrol boats, trawlers, landing gears, anti-mine ships, racing boats and canoes. In air transport, MMCs are used in passenger aircrafts, composite gliders, leading edges, ailerons, vertical stabilisers, helicopter blades, propellers, transmission shafts and aircraft brake discs.

For space transport, it is used to make rocket boosters, reservoirs, nozzles and shields for atmosphere re-entrance. Some of the general mechanical applications include gears, bearings, housing and casings, jack body, robot arms, flywheels, weaving machine rods, pipes, components for drawing table, compressed gas bottles, tubes for offshore platforms and pneumatics for radial frames. It is widely applied in sports and recreation industries to manufacture tennis and squash rackets, fishing poles, skis, poles used for jumping, sails, surfboards, roller skates, bows and arrows, javelins, protection helmets, bicycle frames, golf balls and golf sticks, and oars [13].

7.0 CONCLUSION

It is concluded that MMCs materials are continuously displacing traditional engineering materials because of their advantages of high stiffness and strength over homogeneous materials formulations. These tailored advanced materials have high potential properties engineered for various industrial applications. Composite experts have carried out a detailed investigation on the strengthening mechanism of composites. They have found that the particle size and its weight fraction in MMCs influence the generation of dislocations due to thermal mismatch as well as the effect influenced by the developed residual and internal stresses. The researchers have predicted that the dislocation density is directly proportional to the weight fraction and is due to the amount of thermal mismatch. Consequently, this effect would be significant for fine particles and higher weight fractions.

8.0 ACKNOWLEDGEMENT

The author would like to express his gratitude to the Faculty of Engineering and Technology, Multimedia University, Melaka Campus, Malaysia. ■

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