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Processing, Reinforcement Coatings and Interfaces in AMCs-A REVIEW

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ABSTRACT: Metal matrix composites reinforced by nano-particles are very promising materials, the nano-particles can improve the base material in terms of wear resistance, damping properties and mechanical strength, fatigue and fracture. Different kinds of metals, predominantly Al, Mg and Cu, have been employed for the production of composites reinforced by nano-ceramic particles such as carbides, nitrides, oxides as well as carbon nanotubes. The main issue of concern for the synthesis of these materials consists in the low wettablity of the reinforcement phase by the molten metal, which does not allow the synthesis by conventional casting methods. Several alternative routes have been presented in literature for the production of nano-composites. This work is aimed at reviewing the most important manufacturing techniques used for the synthesis of bulk metal matrix Nanocomposites. Moreover, the strengthening mechanisms responsible for the improvement of mechanical properties of nano-reinforced metal matrix composites have been reviewed and the main potential applications of this new class of materials are envisaged. The interface between the matrix and reinforcement plays a crucial role in determining the properties of metal matrix composites (MMC). Surface treatments and coating of the reinforcement are some of the important techniques by which the interfacial properties can be improved. This review reports the state of art knowledge available on the surface treatments and coating work carried out on reinforcements such as carbon/graphite, silicon carbide (SiC) and alumina (Al2 O3) and their effects on the interface, structure and properties of aluminium alloy matrix composites. The metallic coatings improved the wettablity of reinforcement but at the same time changed the matrix alloy composition by alloying with the matrix. Ceramic coatings reduce the interfacial reaction by acting as a diffusion barrier between the reinforcement and the matrix. Multilayer coatings have multifunctions, such as wetting agent, diffusion barrier and releaser of thermal residual stress. The roles of reinforcement coating as a means of ‘‘in situ hybridising’’ and ‘‘in situ alloying’’ are described

KEYWORDS: Aluminium metal matrix nano composites (AMNCs), Reinforcement, Mechanical properties and stir casting

I. INTRODUCTION

MMNC (Metal matrix nano composites) are metals reinforced with other metal, ceramic or organic compounds. They are made by dispersing the reinforcements in the metal matrix. Reinforcements are usually done to improve the properties of the base metal like strength, stiffness, conductivity, etc. Aluminium and its alloys have attracted most attention as base metal in metal matrix composites [1]. Boron Carbide is one of hardest known elements. It has high elastic modulus and fracture toughness. The addition of Boron Carbide (B4C) in Al matrix increases the hardness. Most of study stated in literature has been dedicated to Al composite like A359, 6061, 6063, 7075, A357 [2-4]. Research work on Al2219 as hybrid composite is less. However, Al2219 made its name in applications like contact parts of airframe and fuel tank of rockets [5-6]. The primary objective of this study is developing hybrid aluminium metal matrix composite using Al2219 reinforced with Boron Carbide (B4C) and Molybdenum Disulphide (MoS2), Silicon carbide, Aluminium oxide, zircon, and Fly ash. Among the various matrix materials available, aluminium and its alloys are widely used in the fabrication of MMCs. This is because of the fact that they are light in weight, economically viable, amenable for production by various processing techniques and possess high strength and good corrosion resistance. Major fabrication methods used for aluminium metal matrix composites are stir casting, squeeze casting, compo casting, and infiltration, sprays deposition, direct melt oxidation process and powder metallurgy. The interface between the matrix and the reinforcement is the critical region that is affected during the fabrication. If this interface is not tailored properly, it can lead to the degradation of the properties of the composites. The problems associated with

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the interfaces are the interfacial chemical reaction, degradation of the reinforcement, lack of wettablity with the matrix, Hence, it is a difficult exercise to design optimized interfaces common and suitable for all systems. Some of the methods to obtain desired interfaces with better properties are the modification of the matrix composition, coating of the reinforcement, specific treatments to the reinforcement and control of process parameters. Among these, the most important technique to improve interfacial properties is that of coating of the reinforcement. Reviews dealing with different aspects of interfacial problems and their effect on properties have been published earlier [7-15]. This paper aims to review the state of the art knowledge available on the surface treatments of reinforcements such as carbon/graphite, silicon carbide (SiC) and alumina (Al2 O3) and their effect on interface, structure and properties of aluminium alloy matrix composites.

II. PROCESSING OF ALUMINIUM METAL MATRICS COMPOSITES

Primary processes for manufacturing of AMCs at industrial scale can be classified into two main groups

A. **Solid state processes:**

Powder metallurgy:

The powder metallurgy press and sinter process generally consists of three basic steps: powder blending (pulverisation), die compaction, and sintering. Compaction is generally performed at room temperature, and the elevated-temperature process of sintering is usually conducted at atmospheric pressure and under carefully controlled atmosphere composition. Optional secondary processing such as coining or heat treatment often follows to obtain special properties or enhanced precision. The tooling and equipments require for powder metallurgy are very expensive, therefore becomes main issue with low production volume. It's difficult to produce large and complex shaped parts with powder metallurgy. [16]

Fatigue is an important design consideration for PM parts subject to cyclic stresses. In general, the fatigue strength of press-and-sinter aluminium PM parts is about half that of wrought alloys with similar composition (ASM, 1998). Because of the involvement of pores, the fatigue of a sintered aluminium alloy may differ appreciably from that of a cast or wrought alloy. At present experimental data on the fatigue of sintered aluminium alloys are still very limited (Grayson et al., 2006) [16]

Centrifugal casting:

It is a casting technique that is typically used to cast thin-walled cylinders. It is used to cast such materials as metal, glass, and concrete. It is noted for the high quality of the results attainable, particularly for precise control of their metallurgy and crystal structure. In the centrifugal casting process, molten metal is poured into a spinning die. The die can be spinning either on a vertical or horizontal axis depending on the configuration of the desired part. Ring. And cylinder type shapes are cast vertically; tubular shapes are made with the horizontal centrifugal process.

Aakanksha suryawanshi et, al., [17] concludes the defects in centrifugal casting decreases the strength and quality of product and avoiding defects is one of the major problem in centrifugal casting

B. **Liquid state processes**:

Liquid state processes include stir casting, compo casting and squeeze casting spray Casting and in situ (reactive) processing, and ultrasonic assisted casting [18].

Squeeze casting:

Squeeze casting is the combination of the casting and forging processes that can be done with help of high pressure when it is applied during melt solidification. Applying pressure on the solidification of molten metal could change melting point of alloys which enhances the solidification rate. Moreover it refines the micro and macrostructure; it is helpful to minimize the gas and shrinkage porosities of the castings.

Krishna P et, al.,[19] concludes One of the greatest drawbacks that inventors of squeeze casting have encountered is the configuration of re-entrant cavities and internal passages that use the core. One of the possible solutions brought up was creating a core from conventional sand coring. Although this method seemed like a valid solution, the high temperatures from molten metal easily penetrated the core made from sand. Along the way, other inventors have also come up with different methods such as using traditional salt cores, but like sand coring, they are equally, if not more susceptible to stress and cracking.

Manjunath Patel GC et,al.,concludes Although much research efforts reported in the available literatures, still the process industries and researchers are not getting powerful modelling tools to improve the squeeze cast components.

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The use of statistical tools establishes the input-output relationship and provides the complete insight of the process, but fails to meet specific industry requirements.

Stir casting:

Siddesh Kumar N G et, al., [20] shows Metal matrix hybrid composites are fabricated by using liquid metallurgy technique (stir casting). The resistance furnace used for casting purpose. Monolithic Al2219 is taken for charge into crucible made from graphite and Al 2219 is heated above liquids temperature up to 7500 -8000 C for melting. The mixed Al2O3 and MoS2 were added in to molten metal; stirring is carried out at 150- 200 rpm for time duration of 5 min. The particles started distribute around monolithic Al 2119 and then slurry is poured in to cast iron mould.

Niranjan D B et, al, [21] Concludes The reinforcement used is boron carbide and Molybdenum disulphide. The resistance furnace used for prepare hybrid composite by two stage stir casting technique. The Al2219 matrix melted at action is accomplished by zirconium coated stainless steel at 250 rpm about 5-6 min.

Bharath.et.al (2014) synthesized metal matrix composite using 6061Al as matrix material reinforced with ceramic Al2 temperature 750ºC. The preheated reinforcements B4C and MoS2 [at 250ºC] were introduced to molten metal. Stirring O3 particulates using stir casting technique [22]. Ramnath.et.al (2014) fabricated metal matrix composite with aluminium alloy, alumina (Al2O3) and boron carbide by stir casting which involved the mixing of the required quantities of additives into stirred molten aluminium [23]. Hossein.et.al (2014) manufactured Al–nano MgO composites using A356 aluminium alloy and MgO nanoparticles via stir casting. Introduction of MgO nanoparticles to the Al matrix caused increasing of the hardness values. [24]. Padmavati.et.al (2014) investigated the friction behaviour of Al6061 with various percentage volumes of Multiwall carbon nanotubes and Silicon Carbide reinforcement through stir casting method. Under mild wear conditions, the composite exhibited lower wear rate and friction coefficient in contrast to Aluminium. [25]. Rajeshkumar.et.al (2014) manufactured composite material by reinforcement of SiC, Al_2O_3, and graphite particles into the matrix of Al alloy. Addition of reinforcement enhanced the mechanical, metallurgical and tribological properties of composite produced as compared to the original alloy of aluminium. [26]. Hariprasad.et.al (2014) explored the wear behaviour of Al 5083 composites manufactured by stirring technique reinforced with Al2 O3 and B4 C. The exploration of wear resistance inferred that with the increase of weight percentage of reinforcements wear resistance increased along with light adhesive wear of the samples. [27]. Shashiprakash.et.al (2014) investigated A356/SiC metal matrix composite made-up by electromagnetic stir casting. It was inferred that type of fabrication process and percentage of reinforcement are the effectual factor influencing the mechanical properties. [28]. Suresh.et.al (2014) reinforced Al6061 with various percentages of TiB2 particles by using high energy stir casting method. The tensile and ultimate strength of the Al6061 increased with increase in the amount of TiB2.Wear resistance and coefficient of friction of Al6061 alloy by the addition of TiB2 decreased with increased TiB2.[29]

Mazahery.et.al (2013) investigated, the effect of the volume fraction of the nano-SiC particles on the mechanical properties of the Al–Si matrix composites fabricated by stir casting technique. The yield strength and tensile strength increased, but the elongation decreased with the increase in the volume fraction of the SiC particles. [30]. Karabaei.et.al (2013) used a novel approach to fabricate Al2 O3 nanoparticles reinforced aluminium composites. To avoid agglomeration of nanoparticles in matrix. Al2 O3 nanoparticles were separately milled and were incorporated into A356 alloy via stir casting method [31]. Tahamtan.et.al (2013) fabricated Al2 06 / Al2 O3 p cast composites by the injection of reinforcing particles into molten Al alloy in two different forms i.e. as Al2 O3 particles and milled particulates of alumina in the process of stir casting [32].Umanath.et.al (2013) investigated the wear behaviour of Al6061-T6 discontinuously reinforced with silicon carbide (SiC) and aluminium oxide (Al2 O3) composite. The results revealed that the wear resistance of the 15% hybrid composite is superior to that of the 5% composite. [33]

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Table 1 Comparative evaluation for different techniques used in fabrication of AMMNCs

Method	Range of shape and size	Range of volume. fraction	Damage to reinforcement	Cost
Stir casting	wide range of shapes; Larger size; up to 500 kg	Up to 0.3	No damage	Less expansive
Squeeze casting	limited by pre form shape Up to 2cm height	Up to 0.5	severe damage	Moderate expansive
Powder metallurgy	wide range; restricted size		reinforcement fracture	Expansive
Spray casting	Limited shape, large shape	0.3-0.7		Expansive

FACTORS AFFECTING PROCESS: Information collected through various research papers show the following factors which affect the stir casting Process are

1. Speed of stirring
2. Time duration of stirring
3. Stirring temperature

1.1. SPEED OF STIRING

It is reported by several authors that uniform distribution of the reinforcement particles is necessary for the improvement in the properties of the particulate MMCs like hardness, toughness, tensile strength etc. The low rpm of the stirrer applies less shearing force on the matrix metal and there is no space for the reinforcement particles (dispersed phase) to distribute uniformly throughout the matrix [34]. Moreover the dispersed phase has the tendency to agglomerate and form clusters. This happens due to the absence of the required force to resist it. At higher speeds of the stirrer the shearing force applied on the matrix metal is higher which creates the passage for the dispersed phase to move inside through the vortex created by stirring. The energy supplied by high speed rotation of the stirrer is strong enough to disperse the particles of the dispersed phase which causes uniform distribution of the dispersed phase into the matrix [34]. It was also founded out by the researchers that on increased stirrer speeds there is chance for the gas particles to move inside the matrix and increase the porosity.

2. TIME DURATION OF STIRRING

It plays a very important role in uniform distribution of dispersed phase into the matrix. Less time duration of stirring causes the clustering of the particles of reinforcement [35]. It is also seen that some portions of the matrix were found without inclusions of the reinforcement particles. Fabricated at 600 rpm: (a) 5 min stirring; (b) 10 min stirring; (c) 15 min stirring. As it is clear time of stirring, the distribution of the dispersed phase also increases which in turn improves the mechanical properties of the composite material.

C. STIRRING TEMPERATURE

It is also one of the most prominent parameters which affect the stir casting process. [36] On increasing the temperature of the matrix metal the viscosity decreases and the distribution of the particles is affected. The chemical reaction between reinforcement particles and metal matrix is accelerated on increasing the temperature of the melt.

From all the above literature we gone which concludes among the various processes of manufacturing prevalent for discontinuous nano hybrid metal matrix composites, particularly stir casting is accepted as a favourable method, which is also commercially viable. Stir casting is advantageous for mass production of composites for being simple and flexible in nature along with cost effectiveness. As it is low-cost comparably and also offers wide selection of materials. Further, it produces better bonding of reinforcements with the matrix, due to the uniform stirring action.

It is also attractive because, in principle, it allows a conventional metal processing route to be used, and hence minimizes the final cost of the product. This liquid metallurgy technique is the most economical of all the Available routes for metal matrix composite production and allows very large sized components to be fabricated.

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III.TYPES OF REINFORCEMENTS TO ALUMINIUM METAL MATRIX COMPOSITES (AMCs)

1. SILICON CARBIDE REINFORCED AMC

The mechanical properties of SiC reinforced AMCs have been studied extensively. The studies found that with the increase in reinforcement ratio, tensile strength, hardness and density of AMC material increased, but impact toughness decreased [37, 38]. A comprehensive study has been carried out to investigate the fatigue and fracture behaviour of AMC reinforced with SiC particles. These studies concluded that the fatigue damage initiates on the particle-matrix interface and it propagates by the particle fracture and interface deboning [39, 40] Srivatsan et al. [41] have investigated the high cycle fatigue and fracture behaviour of 7034/SiC/15p-UA and 7034/SiC/15p-PA MMC. The modulus, strength and the ductility of the two composite microstructures decreased with an increase in temperature. The degradation in cyclic fatigue life was more pronounced for the under-aged microstructure than the peak-aged microstructure. Also, for a given ageing condition, increasing the load ratio resulted in higher fatigue strength. Prabhut et al. analysed the influence of stirring speed and stirring time on distribution of particles in SiC AMC. Uniform hardness values were achieved at 600 rpm with 10min stirring. Chawla et al.[42]. They found that increasing volume fraction (10%, 20% and 30%) and decreasing particle size (down to 5 μm) resulted in an increase in fatigue resistance.

2. ALUMINIUM OXIDE REINFORCED AMC

Aluminium oxide (Al2O3), commonly referred to as Alumina, possesses strong ionic inter atomic bonding giving rise to its desirable materials characteristics. Thus, this Al2O3 material attracted significant attention to the researchers while producing AMC and many studies has been carried out to investigate the mechanical and fatigue properties of Al2O3 reinforced metal matrix composites to ensure the effective utilization of the AMC. The characterization of A359/Al2O3 MMC developed by electromagnetic stir casting method was investigated by Kumar et al. [43]. Their study revealed that the electromagnetic stirring action helps to produce smaller grain size MMC and maintains good bonding in Al2O3 particle-matrix interface. Park et al. [44] investigated the effect of Al2O3 in Aluminium for volume fractions varying from 5-30% and found that the increase in volume fraction of Al2O3 decreased the fracture toughness of the MMC. This is due to decrease in inter-particle spacing between nucleated micro voids. Abouelmagd [45] studied the hot deformation and wear resistance of powder metallurgy aluminium metal matrix composites. It was found that the addition ofAl2O3 andAl4C3 increases the hardness and compressive strength. The addition ofAl4C3 improved the wear resistance of the MMC. Jong et al. [46] compared the properties of two aluminium metal matrix composites Al-B_2O_3-TiO_2 system and Al-B-TiO_2 system. Al-B_2O_3-TiO_2 had more fatigue strength then Al-B-TiO_2.

3. BORON CARBIDE AND MOLYBEDNUM DISULFIDE REINFORCED AMC

Boron carbide (B4C) is one of the most promising ceramic materials due to its attractive properties including high strength, low density, extremely high hardness (the third hardest materials after diamond and boron nitride), good chemical stability, High fracture and fatigue. Therefore the manufacturing process of boron carbide and molybdenum disulfide reinforced AMC has widely investigated by many of researcher.

Siddesh et al.[47] Concludes the hybrid composites were successfully fabricated by taking B_4C and MoS_2 reinforced Al 2219 using stir casting technique.$K_2T_iF_6$ halide salt was incorporated in order to improve wettablity between Al and B_4C and also achieve uniform and fairly metal from matrix Al2219 to steel surface.

Siddesh et al. [48] concludes Al 2219 reinforced B4C and MoS_2 were produced effectively by stir casting technique. fairly uniform distribution of B4C and MoS_2 particles were observed with addition of $K_2T_iF_6$ improves wettablity and two stage addition elements clustering of particles XRD analysis shows the phases of Al, B_4C and MoS_2 confirms the incorporation of reinforcements were present in hybrid composites. The mechanical properties like ultimate tensile strength and yield stress of hybrid composites decreases due to crack propagation and particle pull out of MoS2 particle. The fracture surface of Al 2219 shows ductile fracture with dimple and tear ridges pattern.

Haftirman et al. [49] concludes that fatigue crack growth of aluminium alloy decreases significantly with increasing thickness, and the crack initiates very fast on aluminium alloy material. Based on the number of cycles was found similar result that the crack size of 12.7 mm was faster than size of 20 and 15.8 mm. This conclusion should assist the designer in optimizing aluminium alloy selection for fracture resistant aluminium engineering structures.

M. N.Choudhari et al.[50] concludes the homogenous dispersion of B_4C particles exhibits a grater wettablity with aluminium alloy was observed during microstructure evaluation under optical microscope with the increment of B_4C reinforcement in Al 2219 alloy matrix both fatigue and fracture improved as compared to base metal.

Niranjan D B et al. [51] investigates the prepared composite having uniform distribution of B4C and MoS2 this is by examine the composite under FESEM. By adding B4C and MoS2 it makes increase in bearing load to open the crack front. As compared to base alloy and all composites, the composite Al2219-3 wt% B4C-5 wt%MoS2 is higher

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load withstand but affected to comparatively less fracture toughness to Al2219-3 wt% B4C-4 wt%. But rise in adding Molybdenum disulphide makes increase in extension after crack and increase in load to open the crack front because of its soft nature property.

Niranjan D. B[52] concludes Effect of addition of reinforcement comprise the interparticle arrangement, makes strong obstacle to open the crack front, which results in increase in fracture toughness up to 27% maximum for Al2219-3%B4C-4%MoS2 hybrid composite.

4. FIBER REINFORCED AMC

Ding et al. [53] investigated the low cycle fatigue behaviour of the pure Al reinforced with 20% Al2O3 fiber in total strain controlled mode. They found that the predicted fatigue lives coincide with the observed fatigue lives over a wide range of strain amplitudes for a wide range of test temperatures. However, the predicted fatigue live coincide best with the observed fatigue lives only at the large levels of cyclic plastic strain and total strain. Ding et al. [54] investigated the behaviour of the unreinforced 6061 aluminium alloy and short fibre reinforced 6061Al alloy MMC. They found that the addition of high-strengthAl2O3 fibres in the 6061 aluminium alloy matrix will not only strengthen the microstructure of the 6061 aluminium alloy, but also channel deformation at the tip of a crack into the matrix regions between the fibres and therefore con- strain the plastic deformation in the matrix which leads in reduction of fatigue ductility. Woei-Shyan Lee et al. [55] studied the effects of strain rate on the properties and fracture behaviour of laminated Carbon fiber reinforced 7075-T6Aluminium alloyed found that the flow stress increases with strain rate, but decreases with temperature. Work hardening rate decreases with increase n strain and temperature. Greater density of Al debris and fiber fracture was found at high strain rate for all temperature.

5. ZIRCON REINFORCED AMC

Jenix Rina et al. [56] compared the properties of Al6063 MMC reinforced with Zircon Sand and Alumina with four different volume fractions of Zircon sand and Alumina with varying volume fractions of (0+8)%, (2+6)%, (4+4)%, (6+2)% and (8+0)%. The hardness and the tensile strength of the composites are higher for (4+4) %. In this combination, the particle dispersion is uniform and the pores are less where inter-metallic particles are formed. Sanjeev Das et al. [57] comparatively studied the abrasive wear of Al-Cu alloy with alumina and Zircon sand particles and found that wear resistance of the alloy increases significantly after the addition of alumina and zircon particles. However, zircon reinforced composites showed better wear resistance than that of alumina reinforced composite due to its superior particle matrix bonding. Scudino et al. [58] investigated the mechanical properties of Al-based metal matrix composites reinforced with Zircon-based glassy particles produced by powder metallurgy. The test results showed that the compressive strength of pure Al increases by 30% with 40% volume of glass reinforcement. While the volume fraction of the glassy phase increasing to 60%, the compressive strength further increases by about 25%.

IV. WETTING OF A REINFORCEMENT

Wetting of reinforcement by molten metal, an important aspect in MMC synthesis, is favoured by the formation of strong chemical bonds at the interface. The presence of oxide films on the surface of molten metal and the adsorbed contaminant on the reinforcement surface generally leads to non-wetting of the reinforcement with molten metal. The wettablity of a solid by a liquid is indicated by the contact angle.

The contact angle between solid, liquid and gas/vapour is related by the Young— Dupre's equation,

$$\gamma_{LV} \cos\Theta = (\gamma_{SV} - \gamma_{SL}) \quad (1)$$

where, γ_{LV} is the surface tension of the liquid metal, γ_{SV} is the surface energy of the solid, and γ_{SL} is the solid/liquid interfacial energy. Based on the above equation, the contact angle Θ, can be decreased by increasing the surface energy of the solid, γ_{SV} decreasing the solid/liquid interfacial energy, γ_{SL} or by decreasing the surface tension of the liquid, γ_{LV}. The liquid is said to wet the solid when $\Theta<90°$, that is, when $\gamma_{SV}>\gamma_{SL}$. Some of the techniques to improve metal-reinforcement wettablity include metallic coatings on the reinforcements, addition of reactive elements, such as magnesium, calcium or titanium, to the melt and heat treatment of particles before addition.

V. NATURE OF INTERFACE

The nature of interface has a strong influence over the properties of the metal matrix composites. Strengthening in the composites by the reinforcements is dependent on the strength of the interfacial bond between the matrix and the reinforcement. A strong interfacial bonding permits transfer and distribution of the load from the matrix to the

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reinforcement. The properties such as stiffness, fracture toughness, fatigue, and coefficient of thermal expansion, thermal conductivity and creep are also affected by the nature of the interface. A mechanical bonding arises from mechanical interlocking between the matrix and reinforcements in the absence of all chemical sources of bonding and it is significant only in the case of fibre-reinforced composites such as the brass—tungsten fibre system [59]. Chemical bonding occurs when the atoms of matrix and reinforcement are in direct contact and is accomplished by exchange of electrons. This type of bonding can be metallic, ionic or covalent. An interface with a metallic bond is more ductile than other bonds, and is desirable in metal matrix composites.

VI. INTERFACIAL CHEMICAL REACTION

During processing of metal matrix composites, a chemical reaction occurs at the interface between the matrix and the reinforcement in some systems. In such cases, it leads to the formation of an interface reaction product layer with properties differing from those of either the matrix or the reinforcement. The extent of chemical reaction and the type of reaction products formed are dependent on the processing temperature, pressure and atmosphere, matrix composition and surface chemistry of reinforcements. Interfacial reaction can decrease the interfacial energy of the metal/ reinforcement interface and improve adhesion through chemical bonding. The extent of the chemical reaction has a strong influence over the physical and mechanical properties of the composites. Further, the reaction products formed during processing may continue to form during service as well, thereby resulting in progressive improvement or degradation of the properties.

The following interfacial reaction is observed during the synthesis of carbon-reinforced aluminium metal matrix composites wherein the carbon can be either in the form of particulate or fibre based on graphite, pitch or PAN

$$4Al_{(l)} + 3C_{(S)} \rightarrow Al_4C_{3(S)} \quad (2)$$

$$\Delta F933K = -172 \text{ kJ mol}^{-1}$$

The reaction tendency of carbon fibre with molten aluminium is observed to be severe when the melt temperature exceeds about 900 K. Aluminium carbide formations occurring by the degradation of fibres decreases their strength. A discontinuous reaction product has been observed at the interface of the aluminium—graphite particle system when the melt temperature and contact time exceed 1023 K and 4 h, respectively [60].

In silicon carbide-reinforced aluminium metal matrix composites, SiC is thermodynamically unstable in molten aluminium at around temperatures exceeding 1000 K [60]. The SiC reacts with molten aluminium [62, 63] to form Al4 C3 rejecting metallic silicon according to the reaction.

$$4Al_{(l)} + 3SiC_{(S)} \rightarrow Al_4C_{3(S)} + 3Si_{(S)} \quad (3)$$

$$\Delta F1000K = -51.3 \text{ KJ mol}^{-1}$$

These reaction products have also been observed to cover SiC_P by Lee et al. [64] using SEM as However, the above reaction can be suppressed by having a matrix alloy containing higher silicon content. A few per cent of carbon and SiO2 present in Nicalon fibres (b-SiC) react with molten aluminium to form Al4 C3 (Equation 2) and Al2 O3,Si (Equation 4), respectively

$$4Al_{(l)} + 3SiO_{2(S)} \rightarrow 2Al_2O_{3(S)} + 3Si_{(S)}$$

$$\Delta F1000K = -24 \text{ KJ mol}^{-1} \quad (4)$$

Alumina (Al2 O3) is considered as an ideal dispersoid because of its good interfacial compatibility and nondegrading surface with liquid aluminium. However, in most of the aluminium alloys of interest containing magnesium as an alloying element, magnesium reacts with alumina according to

$$3Mg_{(l)} + Al_2O_{3(S)} \rightarrow MgO_{(S)} + 2Al_{(l)}$$
$$\Delta F1000K = -76.63 \text{ KJ mol}^{-1} \quad (5)$$
$$3Mg_{(l)} + 4Al_2O_{3(S)} \rightarrow 3MgAl_2O_{4(S)} + 2Al_{(l)}$$
$$\Delta F900K = -13 \text{ KJ mol}^{-1} \quad (6)$$

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MgO may form at high magnesium levels ('1.5 wt % Mg) and low processing temperatures, while spinel forms at low magnesium levels ((1.5 wt% Mg) [65]. Table I gives the possible reaction products and precipitates at the interface with various aluminium alloy matrices and reinforcement combinations [66—73].

VII. INTERFACES AND COMPOSITE PROPERTIES

Most of the mechanical and physical properties of the metal matrix composites such as strength, stiffness, ductility, toughness, fatigue, creep, coefficient of thermal expansion, thermal conductivity and damping characteristics, are dependent on the interfacial behaviour. The interface plays a crucial role in transferring the load efficiently from the matrix to the reinforcement. The strengthening and stiffening of composites are dependent on the load transfer across the interface. High bond strength is required at the interface for effective load transfer. A strong bond is usually formed with the reaction between the matrix and the reinforcement, the reaction product determining the nature of the bond. A brittle reaction product at the interface makes the composite crack at lower strains. The presence of coarse intermetallic precipitates at the interface, as in Al—Cu—Mg/SiC composites, is also detrimental to mechanical properties. Even though the interface is free from reaction products, the tensile properties are dependent on the nature of the bonding. Studies on Al/SiC, Al/B4 C, Al/TiC and Al/TiB2 composites show that Al/TiC has the highest yield and ultimate tensile strengths [74]. This is due to the better bond integrity at the Al/TiC interface. In unidirectional reinforced composites, the longitudinal tensile strength and crack growth initiation resistance are found to be insensitive to the nature of the interface. However, the weak interface exhibits extensive deboning and reduces the transverse and tensional strengths of the composite [75]. The ductility of the composites is also largely influenced by the interfaces [76, 77]. Al/TiC composites are more ductile compared to Al/Al2 O3 and Cu/Al2 O3 due to better interfacial bonding arising out of the metallic bond [76]. The toughness of the composite is influenced by crack deflection or fibre pull-out. In unidirectional composites, a weak interface is desirable for increased toughness when a crack propagates along the fibre, whereas a strong interface is required to prevent low energy failure when a crack is parallel to the fibre.

TABLE I Reaction products formed and precipitates at the interface with various reinforcements in aluminium alloys

Matrix	Reinforcement	Reaction products and precipitates	References
Al	C	Al4 C3	[66]
Al	SiC	Al4 C3 , Si	[66, 67]
Al—Mg	SiC	Al4 C3 , MgO, Mg2 Si, MgAl2 O4	[68]
Al—Cu—Mg	SiC	CuMgAl2 , MgO	[69, 70]
Al—Mg	Al2 O3	MgAl2 O4	[71]
Al—Cu	Al2 O3	CuAl2 O4	[72]
Al—Li	Al2 O3	α-LiAlO2 , LiAl5 O8 , Li2 O	[72, 73]

particulate composites, when particles are more rigid than a matrix with a weak bond, the increased toughness is due to crack blunting effects and it appears that the same effect could be obtained by dispersion of voids [30]. When a bond is strong and the particles are less rigid than the matrix, an increase in toughness can be obtained by increasing the amount of material undergoing substantial massive plastic deformation. High residual stresses are developed in composites, when they are cooled from the processing temperature to room temperature due the mismatch in the coefficient of thermal expansion (CTE) between the fibre and matrix. As a result, within certain composite systems, radial, circumferential and/or longitudinal cracks are observed at the fibre matrix interface region [31, 32]. In particulate composites, the strengthening is also attributed to the thermal mismatch strain present at the particle matrix interface. Fatigue properties of composites are also influenced by the interface. Investigations on Al/graphite composites show that the fatigue crack propagation rate (FCPR) is higher than in Al/zircon composites having better bond strength at the interface [81, 82]. This reveals that a weaker interface enhances the FCPR. Studies on the Al/SiC composite having high bond strength at the interface show that a fatigue crack cannot propagate across the SiC particle unless it changes direction significantly and the crack deflection greatly reduces the FCPR [83]. Creep resistance of a particulate composite is determined with respect to creep threshold stress which is the index of resistance to creep. The creep threshold stress depends on the load transfer at the matrix— reinforcement interface which is dictated by the interface bond integrity. Al/TiB2 in situ composites show higher creep resistance compared to powder metallurgy (P/M) processed Al/TiB2 owing to the stronger interface and fine particle size in the former [74]. Studies on Al/15% TiC composites with 0.7 and 4 lm particles show that composites with 0.7 lm particles exhibit lower CTE due to a

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greater interfacial area. The lattice distortion is observed close to the matrix reinforcement interfaces. Studies on Al/SiC composites with particle sizes from 0.7—28 lm show that thermal conductivity increases with increase in particle size [84]. Fine particles have a larger interfacial area and the interface acts as a thermal barrier. 6090 Al/SiC composites with particles in the range 10—28 lm show a higher thermal conductivity than unreinforced alloy, probably due to an excellent bonding at the interface [85]. Interfaces with reaction products act as stronger barrier to thermal conductivity than cleaner ones. In Ti/SiC composites with a 0.5 lm reaction layer of Ti5 Si3, thermal conductivity is similar to that of unreinforced matrix. With a thick reactive layer (1 lm), the thermal conductivity reduces markedly.

VIII. COATING OF REINFORCEMENT

Coating of reinforcement is one of the successful techniques adopted to prevent the interfacial reaction and enhance the wetting of the reinforcement. Coating also prevents the diffusion of liquid metal into the reinforcement. Different types of coatings given to reinforcements are metallic, ceramic, bilayer and multilayer coatings containing metals and/or ceramics and are system-specific. The various coating techniques adopted aim at attaining a better, uniform and thin layer coating without degradation of the reinforcement properties. Some of the important coating techniques are chemical vapour deposition (CVD), physical vapour deposition (PVD), thermal spraying, sol—gel process, electrolytic, electroless and cementation methods. Because the type, purpose and process of the coating vary from system to system, they are discussed individually for the three most important reinforcements used in the aluminium matrix, namely carbon, silicon carbide and alumina.

1. Carbon

Carbon is one of the important reinforcements used in the fabrication of aluminium matrix composites. These composites find wide applications in aerospace, defence and electrical applications due to their high specific strength, high-temperature properties and excellent thermal and electrical conductivities. Carbon is most widely used in the form of graphite particles or fibres based on pitch or polyacrylonitrile (PAN). The major problems associated with the processing of carbon-reinforced aluminium metal matrix composites are the non-wetting of carbon by liquid aluminium at lower processing temperature (950—1050 K) and the reaction between carbon and aluminium at higher processing temperature. At around 1273 K [86], carbon becomes wetted and reacts with aluminium to form aluminium carbide at the interface which, in turn, reduces the strength of the composites [87, 88]. To overcome the above, various coatings are applied to the carbon fibres to suppress the reaction and improve wettablity at lower temperature. Techniques such as chemical vapour deposition, electrolytic and electroplating, are used to coat the fibres. The important metallic coatings used to coat the fibres are copper [89-96] and nickel [93, 9-106]. Other coatings investigated include silver [107], vanadium [108], titanium [104, 109], molybdenum [104] and tantalum [104]. Nickel [110-114] and copper [115—118] coatings on graphite particles have also been studied. Nickel and copper coatings on carbon fibre prior to dispersion, enhanced its wettablity with molten aluminium [119, 120]. The deposition of metals on carbon fibres is made by cementation, electroless and electrolytic processes. Among the various coating techniques mentioned above, the electroless coating method [90] has been reported to yield the best results with ultimate tensile properties of coated fibre near to that of uncoated fibres, whereas electrolytic and cementation processes exhibit lower tensile properties compared to uncoated fibres (Table II). However, coating thickness of 0.2—0.6µm yields better properties irrespective of the coating method adopted. With thickness below 0.2µm, coating is discontinuous and dendrite-type growth is observed above 0.6µm over the continuously coated fibre surface. The International Nickel Company (INCO) [99] is now commercially supplying nickel-coated carbon fibres and other refractory particulates for composite reinforcements with a very thin nickel coating (0.2—1 µm range) through the Monds process.

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TABLE II Influence of metallic coatings and coating methods on the strength of carbon fibre [42]

Coating material	Coating method	UTS (GPa)	Elongation %
Uncoated		2.6—3.2	
Ni	Cementation	1.5—1.81	0.8
	Electroless	2.4—2.81	1.23
Cu	Electrolytic	1.5—2.25	1.35
	Cementation	1.32—2.53	1.1
	Electroless	1.79—3.66	1.8

The coating material, coating techniques and thickness also play important roles in the properties of the fabricated metal matrix composites. The various metallic coatings given to carbon fibre and their influence on composites are described in Table III.

TABLE III Important metallic coatings on carbon fibre and their effects

Coating material	Coating method and optimum thickness	Matrix	Composite fabrication technique	Effects	Reference
Copper	Electroless(0.3 µm)	Al	Liquid metal infiltration	1.Improved wetting 2.Uniform distribution of fibres	[91]
Nickel	Electroless(0.2—0.4 µm)	Al	Centrifugal pressure infiltration	1. Improved the throwing power of precipitant into the multifilament	[93]
Nickel	Electroless (0.2 µm)	Al	Stir casting	1.Good wetting 2.NiAl3 around fibres	[97]
Titanium	Chemical vapour deposition	Al	Liquid metal infiltration	1.Difficult to coat due to reaction 2. Rutile and anatase are formed.	[109]
Silver	Electroless plating	Al-6063	Liquid metal infiltration	1.Promoted wetting 2. Interfacial reaction between Al and C	[107]

The ceramic coatings utilized include SiC [123—127], TiC [125], B4 C [125], Al2 O3 [128], TiBx [129], TiO2 [130], SiO2 [106], ZrC [131, 132] and TiB2 [133]. The main function of ceramic coatings over carbon fibre is to act as a diffusion barrier to the aluminium matrix. The SiC has been coated using different techniques, such as chemical vapour deposition, solution coating, etc. Wang et al. [123] have developed a technique of coating SiC on carbon fibre by benzene solution of polycarbosilane and reinforced SiC-coated fibre carbon in Al-10Si alloy. It has been observed that SiC coating effectively improved the resistance to oxidation of bare fibres and the wettablity between the fibre and the molten metal. Thus, the interfacial chemical reaction is prevented (Fig. 9) thereby increasing the strength of composites to 189% of that with bare carbon fibres. B4 C is effective in chemical protection of the fibre as well as against oxidation during processing of the composites. TiC coating is not effective in the protection of fibres. The paralytic carbon coating on pitch P55 fibre improves the UTS in Al—4.5Mg MMC from 576 MPa to 669 MPa. The effects of various ceramic coatings on interfaces of MMCs are given in Table IV.

The wetting of carbon fibres is also promoted by the presence of a reactive salt such as K2 ZrF6 [134, 135]. Surface treatment of carbon fibres with an aqueous solution of K2 ZrF6 improves wetting by liquid aluminium at low processing temperatures. A decrease in contact angle from 165° to values as low as 50°—60° at temperatures slightly above the melting point of aluminium, has been observed. The reduction in contact angle is directly related to the amount of K2 ZrF6 spread on the fibre surface. The proposed mechanism for the wetting improvement involves two steps: (a) the reaction of K2 ZrF6 with aluminium to form K3 AlF6 , other fluoride species and intermetallic, and (b) dissolution of the alumina thin layer by the K3 AlF6 thus formed, enabling wetting of the carbon fibre. In many cases, single-layer coatings have only limited functions, such as wetting agent or diffusion barrier. In addition to the above functions, coatings can have many other functions such as releasing the residual stress and adjusting the interfacial shear strength during fabrication, when suitable multilayer coatings are used. Some of the bilayer and multilayer coatings studied are pyrolytic carbon C1 /TiC, C1 /TiN, C1 /SiC [136—138], SiO2 /Cu [139], Al2 O3 /Al or Ni or Ti

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[128], C/Si [140] and C/SiC/Si [141, 142]. The bilayer carbon—silicon gradient coating using chemical vapour deposition on the surface of carbon fibre has improved the oxidation resistance of the fibre greatly, and the tensile strength of C/Si coated fibre is higher than that of Si, SiC or SiO2 monolayer-coated carbon fibre. The studies on C/TiC, C/TiN and C/SiC coated carbon fibres infiltrated with aluminium alloys have shown that C/SiC and C/TiN are more effective as a reaction barrier than C/TiC, and C/SiC double layer coating is the best of these barrier coatings [135]. To promote wetting of ceramic-coated carbon fibre, K2 ZrF6 treatment is a must which is evident from the full infiltration of SiC/K2 ZrF6 -coated carbon fibre in a short time with aluminium.

TABLE IV Ceramic coatings on carbon fibres and their effects on interfaces in aluminium matrix composites.

Coating material	Coating method	Composite fabrication technique	Effects	Reference
SiC	CVD	Squeeze casting	1.Effective protection of fibres during processing	[125]
Al2 O3	Ion-plating	—	1. Good reaction barrier. 2.Poor wettablity	[128]
SiO2	SiO2 coated and pre-treated with K2 ZrF6	Gravity infiltration	1.Higher modulus of elasticity. 2. Lower strength due to fibre degradation	[106]
TiO2	Sol—gel	Liquid infiltration	1. No reaction at TiO2 /C interface. 2.Improved wetting with formation of (Al, Ti)O2 mixed oxide	[130]

8.2. Silicon carbide

The influence of various ceramic coatings as a possible barrier against degradation of SiC particles with aluminium has been understood. Some of the important ceramic coatings studied include SiO2 [154—162], BN [163], Al2 O3 [154, 1157, 1164—166], TiO2 [154, 167], MgO [168] and oxides of antimony and tin [169]. Other types of coatings investigated are Ni—P [170, 171], bilayer coatings of TiC/C [172] and coatings with reactive salts such as K2 ZrF6 [135]. Table V lists the various ceramic coatings given to silicon carbide and their effects on the interface and properties of aluminium composites. The oxide coating on SiC has good impact as a barrier coating by reducing the degradation of SiC during composite fabrication. The SiO2 coating is given mainly by the thermal oxidation of the SiC particulates [161]. During the fabrication of the composites based on Al—Si—Mg alloys with oxidized SiC particles, the SiO2 layer reacts with liquid aluminium alloy to form a polycrystalline layer of MgAl2 O4 spinel and Mg2 Si. In high magnesium content alloys, fine MgO crystals are more likely to form than MgAl2 O4 . Hence, in the as-cast condition, SiC1 are covered by complex oxide layers. Remelting studies of these composites carried out at 1073 K have revealed that the oxide layer is stable at this temperature and less degradation of the particles occurs compared to composites reinforced with as received particles. The thickness of the MgAl2 O4 layer depends on the thickness of the SiO2 layer on the SiC particles. A lower oxidation level leads to a thinner layer of MgAl2 O4 in the composite, resulting in less effective protection. However, a thicker layer results in a brittle interface, thus lowering the strength of the composite. The other type of oxide coatings is mostly carried out by the sol—gel or dry-mixing technique. The SiC particles have been coated with Al2 O3 and MgO using the sol—gel technique [173]. The coating is about 50 nm thick. Fig. 10 shows the silicon content in the commercially pure aluminium as a function of exposure time of coated and uncoated SiC1 in the melt at 990 K. There is a significant reaction between the particles and liquid aluminium during infiltration at 990 K. The above observation suggests that dissolution of TiO2 coating occurs when the TiO2 -coated SiC1 comes into contact with the liquid metal. BN coating is also given to SiC whiskers [115]. SiC whiskers are pre coated ion plating technique has been observed not only to improve the wettablity of SiC but also protect the fibre against degradation when in contact with molten aluminium [172].

8.3. Alumina

The alumina in a pure aluminium matrix is considered to be the ideal dispersoid with no chemical reactions. But, when aluminium alloys are used as the matrix, the Al2 O3 reacts with alloying elements such as magnesium. The other major problem is its lower wettablity below 900 K [174]. In order to enhance its wettablity, metallic coatings such as nickel [158, 175], cobalt [176, 178] and palladium [179] have been applied to alumina. MgO-coated alumina particles [131] have been found to improve the properties of composites compared to as-received ones. The deposition of nickel on alumina is made by nickel ions from a solution under hydrogen pressure in the presence of ammonia as a

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complexing agent. The optimum conditions devised for coating nickel include an [[NH3]/Ni2`] ratio of 1: 6, a hydrogen pressure of 2760 kPa at 448 K, and an addition of 0.04 gl~1 [174]. The formation of Al9 Co2 and Co2 O3 phases has been observed at the interfaces [176]. The fractographic analysis of the above composite has revealed a change-over of fracture behaviour from interfacial debonding to matrix deformation.

IX. CONCLUSION

Several challenges must be addressed in order to strengthen the engineering usage of AMCs such as processing Technique, impact of reinforcement and effect of reinforcement on the mechanical properties and its corresponding Applications. The major conclusions derived from the prior works carried out can be summarised as below:

- The increase in reinforcement ratio and decrease in reinforcement particle size significantly improves the mechanical and fatigue properties of AMCs.
- The increase in volume fraction of Al2O3 decreases the fracture toughness of the AMCs. The addition of fly ash particles as reinforcement is advantages for obtaining high structural homogeneity in AMCs.
- The Al2219 reinforced B4C and MoS2 were produced effectively by stir casting technique, fairly uniform distribution of B4C and MoS2 particles were observed. With addition of K2TiF6 improves wettablity and two stage addition eliminate clustering of particles.
- The fracture surface of Al2219 shows ductile fracture and dimple pattern in nature, whereas for hybrid composites both brittle and ductile fracture with dimple and tear ridges pattern. The specific wear rate at low sliding velocity is low and for higher sliding velocity is high and as the sliding velocity increases the specific wear rate increases.
- The homogenous dispersion of B4C particles in the metal matrix was exhibit a greater wettablity with aluminium alloy, was observed during microstructure evaluation under optical microscope. With the increment of B4C reinforcement in Al 2219 alloy matrix, both fatigue life and fracture toughness gets improved due to reinforcement type, size and uniform distribution of particles in the matrix. Analysis shows that, 4 wt% of B4C reinforcement in Al 2219 matrix has improved the fatigue life by 63.97% and fracture toughness by 33.34% over Al 2219 alloy.
- Effect of addition of reinforcement comprise the interparticle arrangement, makes strong obstacle to open the crack front, which results in increase in fracture toughness up to 27% maximum for Al2219-3%B4C-4%MoS2 hybrid composite.
- Metallic coatings improve the wettablity of the reinforcement and prevent the excessive interfacial reaction by enrichment of the coated metal in the matrix near to the interface. The metal coating process is economically viable, but leads to unwanted alloying.
- A ceramic coating reduces the interfacial reaction by acting as a diffusion barrier between the reinforcement and the matrix. Most of the ceramic coating techniques are expensive. Multilayer coating leads to the multifunctional behaviour of the coatings such as wetting agent, diffusion and reaction barriers and releaser of thermal residual stress.
- Reinforcement coating can act as ‘in situ hybridizing’ and ‘in situ’ alloying’ agents, during the fabrication of the composites. However, appropriate techniques need to be developed for achieving controlled thickness coatings. Both multifunctional coatings and the effect of coating as hybridizing and alloying agents need detailed study.

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