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Processing and Properties of Aluminium Matrix Composites: A Short Review

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ABSTRACT

Aluminium matrix composites which are new in the category of metal matrix composites have wide potential of satisfying present industrial needs. Aluminium has low density and has capability to resist corrosion hence its matrix composites have become significant matter of concern in the field of metallurgy. The reinforcing materials for the fabrication of aluminium matrix composites could be in the form of whiskers, particulates or fibres, their volume fractions ranging up to 70%. Different properties of the composites can be obtained depending upon the industrial applications by following different processing routes and reinforcements. Certain combinations of reinforcements and processing routes have also been conceptualized for the design of AMC's. These have wide range of applications including defense, aerospace, sports, automotive due to their low density and highly precise mechanical properties. This paper attempts to review the various processing techniques for the fabrication of AMC's and their applications. Description of microstructure and the change in the properties of the material together with intrinsic and extrinsic effects are summarized in the paper.

Key words: Aluminium matrix composites, reinforcements, processing techniques, applications, microstructure

INTRODUCTION

Composite is a material in which two materials with different physical and chemical properties are combined together to produce a material having distinguishing characteristics from its individual constituents [2]. Composites can be classified as: metal matrix, polymer matrix, and ceramic composites on the basis of physical and the chemical properties of the material matrix. This paper emphasis on metal matrix composites and more explicitly on aluminium matrix composites. AMC's are made by reinforcing non-metallic or ceramic materials like Aluminium Oxide (Al_2O_3) and Silicon Carbide (SiC) into the matrix phase i.e. aluminium or its alloy. The ratio of reinforcements and their distribution into the matrix plays an important role in determining the properties of the AMC's. For example: reinforcement of 60% volume of aluminium fibre increases the elastic modulus to 240GPa from 70GPa of pure aluminium. Similarly; hardness, tensile strength and density of AMC's are increased by reinforcing SiC particulates into the aluminium matrix.

Current engineering applications require lighter as well as stronger materials i.e. major focus is given on strength to weight ratio. Modern manufacturing sector demands for materials with broad range of properties like high thermal resistance, minimum wear rate, good damping properties, high specific stiffness etc. Hence the high performance and light-weight aluminium matrix composites can be one of the viable solutions for fulfilling various demands of the industry. In this review paper, overview is given on the various processing techniques for fabricating AMC's along with microstructure, applications and properties.

TYPES OF AMCs

As per the type of reinforcements, AMC can be categorized into five types:

- Short fibre and whisker reinforced aluminium matrix composites (SFAMCs)
- Mono filament reinforced aluminium matrix composites (MFAMCs)
- Continuous fibre reinforced aluminium matrix composites (CFAMCs)
- Particle reinforced aluminium matrix composites (PAMCs)
- Hybrid aluminium matrix composites

Short Fibre and Whisker Reinforced Aluminium Matrix Composites (SFAMCs)

The characteristics exhibited by SFAMCs lies in between CFAMCs and PAMCs. The aspect ratio of the reinforcements it contains is more than 5 and are discontinuous in nature. The production of short fibre and whisker reinforced aluminium are done either by infiltration route or by PM (powder metallurgy) process. The mechanical characteristics of whisker reinforced AMCs surpass that of PAMCs. These type of composites are the very first composites to be used in pistons [3]. Squeeze infiltration is one such process for the production. Figure 1 depicts detailed microstructure of SFAMCs. Nowadays usage of reinforcements in the form of whiskers has reduced due to various health hazards.

Mono Filament Reinforced Aluminium Matrix Composites (MFAMCs)

Figure 2 shows the hybrid composite of MFAMCs having 10% SiC and 4% graphite particulates [4]. The production of MFAMCs takes place by chemical vapour deposition also coined as CVD of either boron or SiC into the core of fibre made up of carbon or W wire. The size of fibres is as large 100 to 150µm diameter. The main purpose of aluminium matrix is the distribution and transferring of load. These type of composites are directional in nature. The bending flexibility in case of multifilament is more than that of monofilament. MFAMCs are generated by techniques such as diffusion bonding. The strength of composite is less when the orientation is perpendicular to the orientation of fibre. Maximum load is carried by the matrix due to the reinforcement. No matrix deformation takes place because of mechanical restraint and hence strength of these type of composites is more and the composite is stiff. MFAMCs are restricted to formation of alloy matrices which are super plastic in nature.

Continuous Fibre Reinforced Aluminium Matrix Composites (CFAMCs)

One of the detailed type of AMC is CFAMCs. It is widely used in practice. In this type of reinforcement, the fibres are continuous in nature. The reinforcements of these composites are of the form of SiC, carbon or alumina fibres. In size the diameter of CFAMCs is not more than 20µ. Fibres here can be either parallel or pre woven and these are braided before the production of the composite [5]. Also, 40% of the fibre fraction by volume for the AMC is produced by the process of squeeze infiltration techniques. Very recently 60 volume% continuous fibre of alumina reinforced having elastic stiffness and tensile strength of somewhat 240 GPa and 1500 MPa has been developed by 3M^{tm} corporation. Pressure infiltration route method is commonly used for the production of these types of composites. The microstructure of CFAMCs is shown in fig 3.

Particle Reinforced Aluminium Matrix Composites (PAMCs)

Particle reinforced aluminium matrix composites generally comprise of ceramic reinforcements which are equiaxed in nature with the aspect ratio does not exceeding 5. PAMCs are manufactured either by the liquid state or solid state methods. Processes such as stir casting, infiltration process and in situ reaction synthesis comes under the category of liquid state methods and Powder Metallurgy is one of the solid state methods [6]. The cost of PAMCs is less than CFAMCs. Considering the mechanical properties, they are inferior to SFAMCs and CFAMCs but much better than that of unreinforced aluminium alloys. They are generally borides, carbides or oxides. For e.g. Al_2O_3, SIC or T_iB_2. It is used for the application such as structural and resistance and hence is present in less than 30% of volume fraction. It is more than 70% in case of electronic packaging. The composites are used for the operations of secondary forming such as extrusion, forging etc. [4]. Figure 4 depicts the composite of aluminium matrix having 40 vol% of silicon carbide reinforcement.

Hybrid Aluminium Matrix Composites

In recent times the latest development other than the above four AMCs is hybrid AMC. Hybrid composites are those in which reinforcements are of more than one type. For example mixture of CFAMCs and PAMCs.

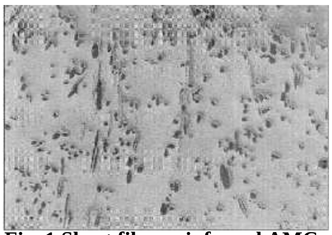

Fig. 1 Short fibre reinforced AMC

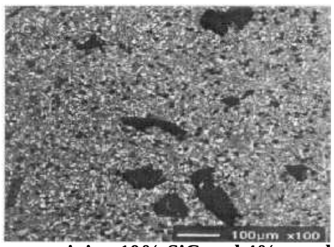

Fig. 2 Composite containing 10% SiC and 4% graphite particles [4]

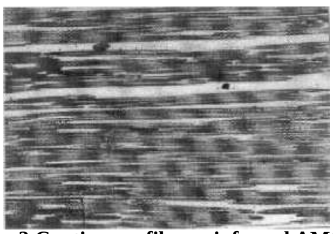

Fig. 3 Continuous fibre reinforced AMC

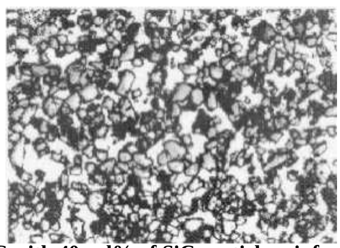

Fig. 4 AMC with 40 vol% of SiC particle reinforcement [4]

PROCESSING ROUTES FOR ALUMINIUM MATRIX COMPOSITES

There are two main groups in which the processing routes for fabricating AMC's can be classified:

1. Liquid State Processes
2. Solid State Processes

LIQUID STATE PROCESSING

There are four processing routes which come under the category of liquid state processing: Stir casting, spray deposition, infiltration process, in-situ reaction synthesis.

Stir Casting

Stir casting was initiated by S. Ray in 1968 [7]. It is the process in which the reinforcements are introduced into the molten magnesium with the help of constant stirring action and then the mixture is allowed to solidify. The most commonly used method for attaining constant stirring action is known as vortex technique. In this method, the vortex of molten magnesium is created with the help of rotating impeller and the pre-heated ceramic particles are allowed to incorporate into the metal. It is difficult to achieve uniform distribution of reinforcements into the metal matrix due to the segregation of reinforcing particles and their settling during solidification process. Hence the final dispersal of particles into the matrix depends upon the wetting between the molten aluminium and particulate reinforcement, rate of solidification and relative density [8].

Spray Deposition

Spray deposition method can be classified into two categories: thermal spray process, osprey process [9]. Thermal spay process is the one in which molten bath is used to produce droplet stream and the later one is the process in which cold metal is continuously feeded into heat injection zone. The spray process has been widely used for producing AMC's by injecting reinforcements which may be in the form of whiskers, particulates or fibres into the spray. It is difficult to attain uniform distribution of reinforcements into the metal matrix by this method but the composites formed by spray deposition process are not very expensive [10].

Infiltration Process

Infiltration process is the one of the most economic processing method for fabricating AMC's. In this process, aluminium in molten form is injected into the spaces between the porous structure of the reinforcements which may be continuous or short fibres, whiskers or particulates [11]. Reinforcements are allowed to mix with liquid carrier and a binder to prepare slurry which is further infiltrated as in paper making process. After this process, the preform is heat treated to enhance the binding properties of the binder. The composites formed by infiltration process are porous to some extent and possess local vibrations due to the uneven distribution of reinforcements into the metal matrix [12].

In-Situ Reaction Synthesis

In-situ reaction synthesis is one of the recently adopted processing route in which the fabrication of reinforcements into the metal matrix is done with the help of certain chemical reactions between elements and compounds [13]. Liquid-liquid, solid-liquid, liquid-gas and other salt reactions fall in the category of in-situ or reactive processing method. DIMOX process is one of the common examples of this process. This is the process in which a ceramic preform is kept in a crucible and Al-Mg alloy is placed on the upper part of the crucible. The assembly is allowed to heat at desired temperature surrounding a gas mixture containing nitrogen. There are some thermodynamic restrictions on the nature and composition of the reinforcements but a uniform arrangement of reinforcements and clean interface between them can be obtained by this method [14].

SOLID STATE PROCESSING

Powder metallurgy and diffusion bonding are the two processes which comes under the category of solid state processing methods.

Powder Metallurgy

Powder metallurgy is the process in which metal alloy and the reinforcements are uniformly mixed, degassed and sintered under high temperature conditions [15]. It is one of the most versatile technique for producing AMC's. In this method, the primary material is firstly powdered into small particles and then the ceramics and metal in powdered form are allowed to mix in the required proportions depending upon the requirement of properties of the composites. Then the mixture allowed entering a mould where due to high temperature and pressure fabrication of ceramics into metal matrix is completed [16].

Diffusion Bonding

Diffusion bonding is a solid state processing technique which is commonly used to produce mono filament reinforcement AMC's. Bonding is due to the inter-diffusion of atoms across the surfaces of particulates and metal

[17]. The production of 6061 Al-boron fibre composites is done by the mentioned bonding process. This process has ability to process large variety of metal matrices but regular distribution of fibres into the metal matrix is difficult to achieve**.** Moreover, complex components and shapes are difficult to obtain by diffusion bonding technique.

IMPACT OF CERAMIC REINFORCEMENTS ON ALUMINIMUM MATRIX BEHAVIOUR IN AMCs

The presence of large amount of ceramic reinforcements effects the behaviour of a given aluminium matrix in its composite. It leads to the change in behaviour during the heat transfer or manufacturing [18]. As large as 10% volume fraction can cause the change including: intrinsic and extrinsic effects.

INTRINSIC EFFECTS

Intrinsic property is considered as the property of a system at the microstructure level. It is not affected by the form of material or the amount of the material. These effects cause change in microstructure of the material and results in thermal stresses [19]. Intrinsic effect also causes heat treatment aspect. These changes importantly modify and widen the physical, tribological and other properties.
Some of the salient features due to the reinforcements of ceramics are:

- Solidification structure of AMCs
- Age hardening characteristics of alloy effected by ceramic reinforcements
- Thermal residual stresses

Solidification Structure of AMCs

Due to the reinforcements, the solidification conduct of alloys is altered into several alloys. The reinforcements act as a hurdle to diffusion of solute and thermal heat. It limits fluid convection and also the induction of instabilities. The instabilities are morphological in nature. Various phrases of morphological depend upon the arm spacing and their relative magnitude. Figure 5 shows that the secondary dendrite arm spacing abbreviated as DAS is less than interfibre spacing [4]. It can be observed from the microprobe scans that the solute content is higher at the surface of the fibre as compared to the interfibre region. Heterogeneous nucleation reduces the size of grain. Generally, alumina fibres or SiC does not affect the grain size of Al-4.5Cu however great reduction in matrix grain size is possible due to TiC reinforcement [20].

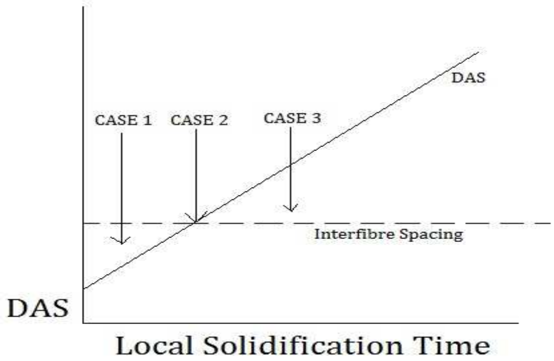

Fig. 5 DAS and interfibre spacing [4]

Age Hardening Features of Alloys of Aluminium Due to Ceramic Reinforcements

The heat treatment technique used to enhance the yield strength of materials is known as age hardening. Along with the initiation of ceramic reinforcements, the modifications by introducing ceramics in age hardening are dependent upon the size, volume fraction, constituent, morphology and the process of production [21].

The major modifications are:

- Reinforcement alloys show accelerated ageing with comparison to unreinforced alloys. E.g. Al-Cu-Mg based allows.
- Along with the pressure of the TIC particle, there is reduction in ageing kinetics of 7075 alloys.
- The peak temperature is inversely proportional to the volume fraction. In S1 the peak temperature decreases with the increase of volume fraction [4].
- By the existence of fibres, the characteristics of 6061 aluminium alloy are altered.

Thermal Residual Stresses

While cooling, large amount of thermal stresses are introduced in AMC and also witness's fabrication temperature at 500^0c. Many variables such as the kind of reinforcement radius, volume fraction etc. are related to the development of stresses and its magnitude [22]. As an example, in the matrix of Al-30 vol% Silicon carbide particulates, more than 200 MPa of stresses are present. These thermal stresses results in balanced yielding and also determines the creep behaviour and fatigue of aluminium matrix composites [23].

EXTRINSIC EFFECTS

Extrinsic properties are defined as those properties which are not inherent in nature. In order to obtain significant enhancement for Al MMCs in sliding resistance, incorporation of ceramic augmentation in alloys of aluminium is essential [24]. The wear resistance of the composites is measured by pin on disc apparatus. The extrinsic effects of the reinforcement of SiC particulates are of great advantage in brake pad tribocouple [25]. The wear resistance of the discs of AMC is further increased by the formation of adherent tribolayer at the region of contact. The tribolayer formation on disc of AMC against the brake pad of automobile is as shown in fig 6. The applications of aluminium matrix composites in automobiles for manufacturing light weight discs can be confirmed the figure.

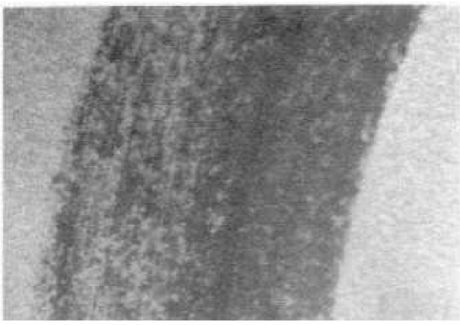

Fig. 6 Picture showing the formation of tri-bolayer on the surface of AMC (disc) slid against the brake pad [4]

APPLICATIONS OF AMCs

The reinforcements of various types in aluminium matrix by both solid state and liquid state methods have come up with wide variety of applications of aluminium matrix composites. Particle reinforced aluminium matrix composites have been widely used in mechanical assemblies, automotive and aerospace industries [26]. These composites are also used in braking system of cars and trains. The baseball shafts, skating shoe, bicycle frames, carrier plates etc. are also manufactured by PAMCs. SiC reinforced AMCs are used in military tanks as track shoes. They are also used in piston-cylinder arrangement [3]. CFAMCs find its application in electrical industry due to high electrical and thermal conductivity and large dimensional accuracy. These type of composites are also used in making automatic push rods, brake callipers, in motors for making retainer rings [27]. The excellent speed of the motors is possible due to these thin walled rings. Hence AMCs due to their light weight and precise physical and chemical properties finds wide range of applications in manufacturing sector.

CONCLUSION

On the basis of review carried out, there is no deny in the statement that study of aluminium matrix composites have become an important aspect in the field of metallurgy. Various processing techniques along with their specific applications and microstructure of composites formed have been identified in the paper. Stir casting process which comes under liquid state processing methods was found to preponderate because of the cost effectiveness and readily varying process parameters. The physical and chemical properties of composites are dependent upon the type and ratio of reinforcements into the matrix. Although some demur still exists, but aluminium matrix composites are rapidly finding their way to be commercially used due to their high strength and light weight properties.

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