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ALUMINIUM MATRIX COMPOSITES: THE PARTICLE INCORPORATION IN THE LIQUID METALLURGY TECHNIQUE

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Abstract: Advance composite materials like Al/SiC metal matrix composite is gradually becoming very important materials in manufacturing industries e.g. aerospace, automotive and automobile industries due to their superior properties (light weight, low density, high strength to weight ratio, high temperature and thermal shock resistance, superior wear and corrosive resistance etc.). The distribution of the reinforcement particles in the matrix alloy is influenced by several factors such as rheological behaviour of the matrix melt, the particle incorporation method, interaction of particles and the matrix before, during, and after mixing. Non–homogeneous particle distribution is one of the greatest problems in casting of metal matrix composites. The solidification of the melt containing suspended SiC particles is done under selected conditions to obtain the desired distribution. To obtain a suitable dispersion, in our research, the stir casting method is analysed. The present work was focused on metal matrix composites for the development of light–weight structural materials. In this study, recycled aluminium used as metal matrix with SiC particles reinforcement are prepared by the stir casting method.
Keywords: Al/SiC metal matrix composite, reinforcement particles, particle incorporation method, stir casting

1. INTRODUCTION

The development of advanced materials has opened a whole new approach to manufacturing engineering. In the past, the designer has started with a material and has selected discrete manufacturing processes to transform it into the finished structure.[1–12] With the new tailored materials, the designer starts with the final performance requirements and literally creates the necessary materials and the structure in an integrated manufacturing process.[1,4–7] Thus, with tailored materials, the old concepts of materials, design, and fabrication processes are merged together into the new concepts of integrated design and manufacturing.[8–12]

In the last years the metal matrix composites have attracted growing interest of the automotive, aeronautical, electronic, and space industries. [1–3,7–9] These materials are alluring because combine high values of ratio strength/density, wearing resistance, stiffness, good thermal conductivity and stability, as well as an excellent formability which enables the production of complicated forms. Their applications to make high technology devices justify that these materials be considered as advanced materials. Good wear resistance, along with high specific strength, favours metal matrix composites use in automotive applications like engine and brake parts.[4,8–12] Tailorability is a key advantage of all types of composites, but is particularly so in the case of metal matrix composites. In this sense, tailorable coefficient of thermal expansion and thermal conductivity make them good candidates for precision machinery.[4,7–10] Metal matrix composites can be designed to fulfil requirements that no other materials, including other advanced materials, can achieve. There are a number of niche applications in automotive and aerospace structures that capitalize on this advantage.

Composites generally consist of fibrous or particulate reinforcements held together by a common matrix, as illustrated in figure 1. Continuous fibre reinforcement enhances the structural properties of the composite far more than particles do. However, fibre–reinforced composites are also more expensive and difficult to fabricate.[3,4,7,8]

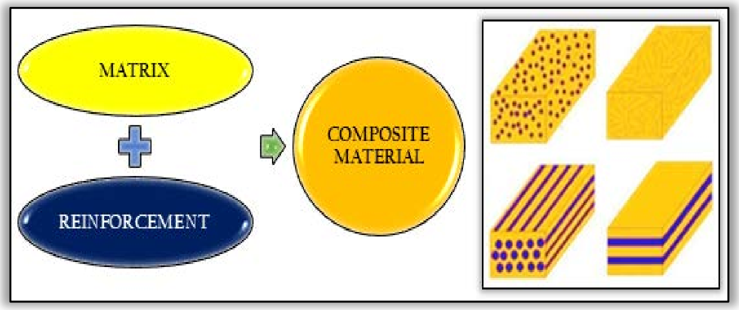

Figure 1. Composite materials components

Materials consisting of metallic matrices, reinforced with ceramic particles or fibres, are known as metal matrix composites.[4,7–12] Usually, they consist of a low–density metal, such as aluminium or magnesium, reinforced with fibres or particulate of a ceramic material, such as silicon carbide or graphite.[2,4,7–10] Properties of a composite material are determined by the following factors:

- the materials utilized as component phases in the composite,
- the geometric shapes of the constituents and resulting structure of the composite system, and
- the manner in which the phases interact with one another.

The volume fraction of the reinforcement is typically in the range 10–70%. Metal matrix composites can offer a range of property enhancement over monolithic alloys.[7–12]

2. DEVELOPMENT OF METAL MATRIX COMPOSITES

There are two types of discontinuous reinforcement for metal matrix composites: particulate and whiskers. But, the particulate will always have a cost advantage. Composites reinforced with particulate (discontinuous types of reinforcement) can have costs comparable to unreinforced metals, with significantly better hardness, and somewhat better stiffness and strength.[10–15] Continuous reinforcement (long fibre or wire reinforcement) can result in dramatic improvements in metal matrix composites properties, but costs remain high. Continuously and discontinuously reinforced metal matrix composites have very different applications.[1–12] The most common types of particulate are alumina, boron carbide, silicon carbide, titanium carbide, and tungsten carbide.[1–3,7–15]

In principle, whiskers should confer superior properties because of their higher aspect ratio (length divided by diameter). However, whiskers are brittle and tend to break up into shorter lengths during processing. This reduces their reinforcement efficiency, and makes the much higher cost of whisker reinforcement hard to justify.[13,8–12] Development of improved processing techniques could produce whisker reinforced metal matrix composites with mechanical properties superior to those made from particulates. It is also more difficult to pack whiskers than particulate, and thus it is possible to obtain higher reinforcement – matrix ratios with particulate.[1,7,11–15] Higher reinforcement percentages lead to better mechanical properties such as higher strength. The most common type of whisker is silicon carbide, but whiskers of alumina and silicon nitride have also been produced.[13–18]

In terms of tailorability, a very important advantage in metal matrix composites applications, particulate reinforcement offers various desirable properties.[12–15] Boron carbide and silicon carbide, for instance, are widely used, inexpensive, commercial abrasives that can offer well wear resistance as well as high specific stiffness. Titanium carbide offers a high melting point and chemical inertness which are desirable properties for processing and stability in use.[12–15] Tungsten carbide has high strength and hardness at high temperature. In composites, a general rule is that mechanical properties such as strength and stiffness tend to increase as reinforcement length increases. Particulate can be considered to be the limit of short fibres. Particulate–reinforced composites are isotropic, having the same mechanical properties in all directions.

The most studied metal matrix composites have matrix aluminium with ceramics as reinforcement and among the latter the most spread used are Al_2O_3 and SiC because their densities are similar to that of aluminium. [1–3,7–31] Use of B_4C is promising because the high resistance to wearing and density slightly lower that of aluminium. The introduction of silicon carbide particulate into aluminium results in materials having lower coefficients of thermal expansion, a desirable property for some types of applications. By choosing an appropriate composition, the coefficient of thermal expansion can be near zero in some metal matrix composites.[7,13–15] They also tend to be good heat conductors. Using high thermal conductivity graphite fibres, aluminium–matrix or copper–matrix metal matrix composites can have very high thermal conductivity, compared with other types of composites.[2]

The development of metal matrix composites was primarily directed to the continuous–fibre reinforced metal matrix composites, such as boron/aluminium (B/Al), graphite/aluminium (Gr/Al) and graphite/magnesium (Gr/Mg) composites. Despite the successful production of these metal matrix composites, they fabrication was limited by the concerns related to the manufacturing processes, phase's inspection and cost. The availability and affordability of continuously reinforced metal matrix composites remains a significant barrier to their manufacturing.[2,4,5]

Concurrently, discontinuously reinforced metal matrix composites, such as silicon–carbide particulate reinforced aluminium (SiCp/Al) and graphite particulate reinforced aluminium Gp/Al composites, were developed cost effectively both for automotive applications and commercial applications. Having in view the properties, commercial availability and life–cycle affordability of existing discontinuously reinforced light metals or alloys, the particulate materials could be integrated in a light matrix, using innovative design and affordable manufacturing methods to produce automotive systems and subsystems that provide tangible benefits. However, in the absence of adequate resources, it is difficult to surmount the technical and cost barriers.[2,4,5]

3. METAL MATRIX COMPOSITES TECHNOLOGIES

Because metal matrix composites technology is hardly beyond the stage of research at present, costs for all methods of producing metal matrix composites are still high. Manufacturing methods must ensure good bonding between matrix and reinforcement, and must not result in undesirable matrix/ reinforcement correlation.[10–31] Metal matrix composites costs are currently very high and depends on many factors including shape, type of matrix and reinforcement, reinforcement volume fraction, reinforcement orientation, primary and secondary fabrication methods, tooling costs, and volume of the production. Costs are very volume sensitive, high costs keeping volumes low, and low volumes meaning high costs. Of course, some materials are inherently expensive and will never be cheap enough for widespread commercial use, regardless of volume.[7,10–15].

Metal matrix composites can be produced by many different techniques.[10–31] The focus of the selection of suitable process engineering is the desired kind, quantity and distribution of the reinforcement components (particles or fibres), the matrix alloy and the application.[10–31] Metal matrix composite's production processes can be divided into primary and secondary processing methods, though these categories are not as distinct as is the case with monolithic metals. Primary processes (those processes used first to form the material) can be broken down into combining and consolidation operations. Secondary processes can be either shaping or joining operations.[10–15] By altering the manufacturing method, the processing and the finishing, as well as by the form of the reinforcement components it is possible to obtain different characteristic profiles, although the same composition and amounts of the components are involved.

Three group of processing methods have been primarily used to develop metal matrix composites:

- high–pressure diffusion bonding, as a common solid–state processing technique for joining similar or dissimilar metals, with many variants of the basic diffusion bonding process, although all of them involve simultaneous application of pressure and high temperature
- casting or liquid infiltration, which involves infiltration of a fibrous or particulate reinforcement preform by a liquid metal, and
- powder–metallurgy techniques, where the matrix and the reinforcement powders are blended to produce a homogeneous distribution, and which typically involves cold pressing and sintering, or hot pressing to fabricate primarily particle– or whisker–reinforced metal matrix composites.

More specifically, the diffusion–bonding and casting methods have been used for continuous–fiber reinforced metal matrix composites.[2,10,12,20–22] Discontinuously reinforced metal matrix composites have been produced by powder metallurgy and pressure–assist casting processes. Metal matrix composites such as B/Al, Gr/Al, Gr/Mg, and Gr/ Cu have been manufactured by diffusion bonding for prototype automotive components such as tubes, plates and panels.[8,9,12,17] Metal–based matrix composite maintains receptiveness to processing techniques that are traditionally used for the conventional unreinforced materials. Aluminum alloy–based metal matrix composites find important applications where specific stiffness is important and are produced by stir casting as well as powder metallurgy routes.[16,19,20–22].

Qualities of aluminium metal matrix composites are sensitive to not only the type of reinforcement but also the method of production. Particularly, in case of particulate reinforced aluminium metal matrix composites, selection of the method depends on particulate geometry, particulate strength and reactivity between particulate–alloy matrices. The basic requirements of the processing routes are the homogeneous distribution of the reinforcement in the matrix and enhancement in the properties of the composite. In any production process, superior quality of the product can be achieved only when the process is run with the optimum parameters. The mechanical properties of composites are influenced by the size, shape, and weight fraction of the reinforcement materials, as well as potential reactions at the matrix/reinforcement interface.

Amongst the various processing techniques, stir casting appears to be the most promising route for the production of aluminium matrix composites because of its simplicity and ability to manufacture composites on an industrial scale economically. Stir casting is a primary process of composite production whereby the reinforcement ingredient material is incorporated into the molten metal by stirring. Stir casting process was used as a production technique to produce aluminium based silicon carbide particulate metal matrix composites. [16,23–31] Its advantages lie in its simplicity, flexibility and applicability to large quantity production.

Broadly, manufacturing metal matrix composites in the solidification state, using stir–casting entails generating a matrix's blend afterwards, with the initiation of a reinforcement substance into the dissolve. The process of producing the composites by stir–casting is illustrated in Figure 2.

Stir casting is a suitable technology for these composite materials.[16,23–31] With stir casting, granular particles are embedded in melted matrix using different technologies followed by mechanical mixing or pressing and casting, resulting a composite material. This method is most economical to fabricate metal matrix composites with discontinuous fibres or particulates. In this process, matrix alloy (recycled aluminium) was superheated over its melting temperature. The reinforcement is introduced in the created vortex of liquid metallic material by

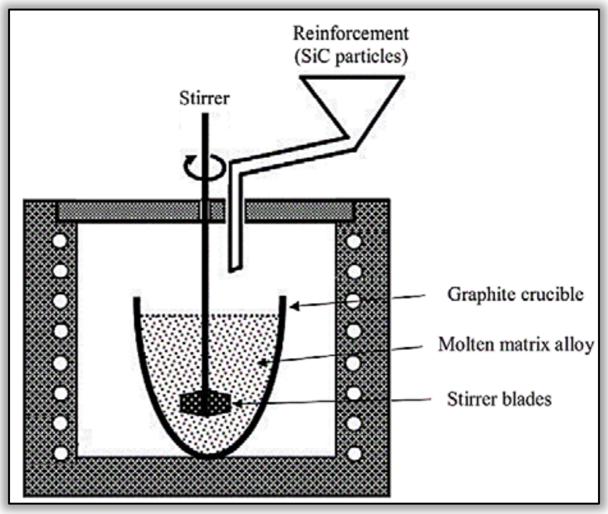

Figure 2. Production of composite materials by stir–casting vortex method

mechanical mixing. In this sense, a mechanical stirrer with a blade, coated with a refractory material was introduced into the melt.

At this temperature, the preheated SiC particles were introduced into the slurry and mixed. Reinforcement is uniformly distributed in melt, then the composite material resulted can be casted. In this process, a strong bond between matrix and reinforcement is achieved at high obtaining temperatures. In a stir casting process, the particulate reinforcing phases are distributed into molten aluminium by mechanical stirring. To create and maintain a good distribution of the reinforcement material in molten matrix a vortex method is used. The distribution of the particles in the molten matrix also depends on the geometry of the mechanical stirrer, stirring parameters, placement of the mechanical stirrer in the melt, melting temperature, and the characteristics of the particles added. Obtaining in liquid state of composite materials, when granular particles remain in contact with melted alloy of matrix for a long time and locally can result in a reaction between the two. The melt at around 750–780°C was poured into preheated permanent metallic moulds, left for solidification and removed from the mould.

The melt is agitated vigorously by using a mechanical stirrer in order to create a fine vortex. The pre–treated particulates are introduced at a predetermined rate into the vortex and agitation is continued for 8–10 minutes at an average stirring speed of 500 rpm to achieve complete mixing of the reinforcement with the aluminium melt. Then, the composite slurry is poured into preheated moulds to obtain the required component. The various advantages of stir–casting process are given below:

- mass production process
- simple and economical
- near net shaped casting

Both particulate and whisker can be used. All particles types are an important material form for metal matrix composites. The distribution of particles in the composite matrix is random, and therefore strength and other properties of the composite material are usually isotropic. The strengthening mechanism generally based on particle size.

- The microscopic size is represented by very fine powders (around 1 mm) distributed in the matrix in concentrations of 15% or less. The occurrence of those powders results in dispersion–hardening of the matrix, in which dislocation movement in the matrix material is restricted by the microscopic particles. In effect, the matrix itself is strengthened, and no considerable portion of the applied load is carried by the particles.
- As particle size improved to the macroscopic range, and the proportion of imbedded material increases to 25% and more, the strengthening mechanism changes. In this case, the applied load is shared between the matrix and the imbedded phase. Strengthening occurs due to the load–carrying capacity of the particles and the bonding of particles in the matrix.
- Flakes and short fibert are fundamentally two–dimensional particles, small flat platelets.

The resultant molten alloy, with ceramic particles, can then be used for die casting, permanent mould casting, or sand casting. Stir casting is suitable for manufacturing composites with up to 30% volume fractions of reinforcement.

4. CONCLUDING REMARKS

The need for advanced engineering materials in the areas of aerospace and automotive industries had led to a rapid development of metal matrix composites. Among the lightweight materials used in the transport industry (road, rail or aviation) are the composite materials with metal matrix (metal matrix composites) which have good mechanical and tribological characteristics (friction, wear resistance) improved by reinforcing of metallic alloys with particulate reinforcement, short or very short fibres (whiskers).

Stir casting is a suitable technology for these composite materials. The used reinforcements can be classified as fibres, whiskers and particulates based on the length–to–diameter ratio called the aspect ratio. Fibres have high aspect ratios, while whiskers have low aspect ratios. But, particulates are micro–materials in form of powder and have very low aspect ratios. They have approximately equal dimensions in all the directions. The appearance of the particle may be spherical, cubic, or platelets.

The major advantages of particulate reinforced aluminium metal matrix composites compared to monolithic alloys are as follows:

- Improved strength and stiffness
- Less density(weight)
- Enhanced high–temperature properties
- Controlled thermal expansion coefficient
- Improved and tailored electrical performance
- Improved resistance to abrasion and wear
- Better damping capabilities

Particulate reinforced aluminium metal matrix composites are produced by dispersing the particulates in the aluminium alloy matrix. The particulate can be spherical, cubic or platelets. Generally, ceramic particulates of dimensions that are approximately equal in all directions with the diameter typically in the order of a few microns are used. These composites become economical alternatives to the monolithic alloys due to their improved specific strength, stiffness and wear resistance combined with better physical properties such as low density and low coefficient of thermal expansion. Even though the specific strength of this composite is not up to the mark, advantages like ease of processing, low processing cost and isotropic properties make them as potential candidates for various applications in aerospace, automotive, marine and military sectors. Moreover, the qualities of this composite can further be enhanced by using the secondary forming processes. Usually, silicon carbide, aluminium oxide, boron carbide, titanium carbide, titanium oxide and graphite are used as reinforcements.

Concurrently, whisker reinforced aluminium metal matrix composites are manufactured by using short fibres called whiskers. They are mainly used for structural and non–structural applications. Generally, they have randomly orientated short fibres or flakes. Materials used as whiskers in aluminium metal matrix composites are alumina, alumino–silicate, silicon carbide and graphite. Mechanical properties of these composites are superior compared to particulate reinforced aluminium metal matrix composites, but they are very expensive to produce than the particulate reinforced aluminium metal matrix composites. Hence their use is commercially limited.

Silicon carbide is a very hard and strong material. Silicon carbide particulates have attained a prime position among the various discontinuous dispersions available for the synthesis of metal matrix composites. This is due to the fact that introduction of SiC to the aluminium matrix substantially enhances the strength, the modulus, the abrasive wear resistance and thermal stability. The density of SiC (3.2g/cm^3) is nearer to that of aluminium alloy (2.7g/cm^3). Furthermore, SiC is easily available and has good wettability with aluminium alloys.

Note

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