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Procedia Technology 24 (2016) 379 – 385

Procedia Technology

International Conference on Emerging Trends in Engineering, Science and Technology

(ICETEST - 2015)

Analysis of stir cast aluminium silicon carbide metal matrix composite: A comprehensive review

Sijo M T [a,*], K R Jayadevan [b]

[a]*Research scholar, Government Engineering College Thrissur, Affiliated to Calicut University, Kerala, 680009, India*
[b]*Professor, Department of Mechanical Engineering,Government Engineering College,Thrissur, Kerala, 680009, India*

Abstract

Aluminium silicon carbide metal matrix composites are used in various fields like aerospace, aircrafts, underwater, automobile, substrate in electronics, golf clubs, turbine blades, brake pads etc. Several fabrication techniques are available for the production of aluminium silicon carbide metal matrix composites (Al-SiC MMC). Among the various methods, stir casting route is simple, less expensive, and used for mass production. The main limitations of stir cast Al-SiC MMC are improper distribution of SiC reinforcement in matrix and less wettablity of SiC reinforcement particle with molten Al. Literature survey indicate that various properties of stir cast Al-SiC MMC depends upon fabrication method, volume fraction, shape, size of particles and distribution and properties of constituents. Since metal matrix composites (MMC) lack structural simplicity its analytical modeling is complex. Further, the involvement of several parameters which affect composite properties, makes the experiments difficult. This review paper contemplates the need of simulation or numerical methods for the prediction of mechanical characteristics of Al-SiC MMC.

Keywords: Aluminium silicon carbide metal matrix composites; Stir casting; Simulation;

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1. Introduction

Scientists are continuously trying to improve various properties of engineering materials. This led to new category of materials called composite materials; they are composed of a combination of distinctly different two or more micro or macro constituents that differ in the form of composition and it is insoluble in each other. Composite

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* Corresponding author. Tel.:+91- 9847520278
*E-mail address:*sijomt@rediffmail.com

doi:10.1016/j.protcy.2016.05.052

materials have a continuous, phase called the matrix; and a dispersed, non-continuous, phase called the reinforcement. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. In a composite, each material retains its original properties but when composited it yields superior properties which cannot be obtained separately [1]. Such types of material are developed to satisfy proper mechanical properties which can not be derived from conventional materials. And also composites meet the requirements of specific design and function, along with the desired properties.

According to matrix constituent, composites are classified into organic-matrix composites, metal matrix composites (MMCs) and ceramic-matrix composites. Among these composites, MMCs provide significantly enhanced properties such as higher strength, specific modulus, damping capacity, stiffness, good wear resistance and weight savings. The major disadvantage of MMC usually lies in the relatively high cost of fabrication and of the reinforcement materials. In terms of shape, the reinforcement material may be sub-divided into four major categories (i) Continuous fibres (ii) Short fibres (chopped fibres which are not necessarily having same length) (iii) Whiskers and (iv) Particles. Among various reinforcements, particles are the most common and cheapest reinforcement. While continuous fiber reinforcement MMCs provide the most effective strengthening (in a given direction), particle reinforced MMCs are more attractive due to their cost-effectiveness, isotropic properties, and their ability to be processed using similar technologies which are used for the monolithic materials. Among various matrix materials, aluminium alloy matrix materials possess high tensile strength, good corrosion resistance etc. Similarly among various reinforcements silicon carbide reinforcements are inexpensive; improve yield strength and elastic modulus at little expense of ductility. Silicon carbide as such, because of its high hardness, has got a number of applications such as in cutting tools, jewellery, automobile parts, electronic circuits, structural materials, nuclear fuel particles, etc. Like all composites, aluminum-matrix composites are not a single material but a family of materials whose stiffness, strength, density, thermal and electrical properties can be tailored. The Al-SiC MMC possess wide range of physical and mechanical properties such as high strength, stiffness, low density, high corrosion, wear resistance, low thermal shock, high electrical and thermal conductivity, good thermal properties and good damping capability. Among all materials, composite materials have the potential to replace widely used steel and aluminum, and many times with better performance. Al-SiC MMC’s are used in various fields like aerospace, fuselage skins of high performance aircrafts, underwater, automobile, substrate in electronics, golf clubs, turbine blades, brake pads etc.

2. Manufacturing methods

The manufacturing methods available for Al-SiC MMC can be broadly classified into three types. They are solid phase processes such as powder metallurgy and diffusion bonding, liquid phase processes such as stir casting, infiltration of liquid matrix into the reinforcements and in situ processes, and semi-solid method such as spray and rheo casting and compo casting [2]. These manufacturing methods determine the microstructure and interfacial bond condition between reinforcement and matrix. The difficulty in fabrication of fiber reinforced plastics has made the use of metal matrix composite widely acceptable. Solid phase process such as powder metallurgy, diffusion bonding, are expensive because it needs expensive starting materials such as powder or foil matrix etc. Liquid phase process (casting process) is generally less expensive than solid phase process. In the casting process, high temperature melt is used. High temperature often promotes the chemical reaction between the melt and the reinforcements. The reaction leads to the degradation or disappearance of the reinforcements. The expected properties of the composite would not be obtained if this reaction occurs. So in order to obtain metal matrix composite with good characteristics special techniques are required. The comparisons of various processing techniques are discussed in Table I. Among various manufacturing methods stir casting is generally accepted as a promising route because of low cost, little damage to reinforcement and stir cast components are not restricted by its size and shape [3]. It also possesses advantages like simplicity, flexibility and applicability to large quantity production. [4].

Manufacturing methods used for production of MMCs should ensure uniform distribution of reinforcement in matrix. The non uniform distribution is due to density differences between the reinforcement particles and the matrix alloy melt. The distribution of reinforcement is influenced during several stages including (i) distribution in the liquid as a result of mixing, (ii) distribution in the liquid after mixing, but before solidification. Manufacturing methods should also ensure proper wettability of reinforcement in matrix. Wettability can be defined as the ability of a liquid to spread on a solid surface. It also describes the extent of intimate contact between a liquid and a solid.

TABLE 1. A comparative study of different processing methods (Hashim et al., 1999).

Method	Range of shape and size	Metal yield	Range of volume fraction	Damage to reinforcement	Cost
Powder metallurgy	Wide range, restricted by size	high	-	Reinforcement fracture	Expensive
Squeeze casting	Limited by perform shape up to 2cm height	low	Upto 0.45	Severe damage	Moderately expensive
Spray casting	Limited shape, large size	medium	0.3 to 0.7	-	Expensive
Mechanical stirring	Not limited by size	medium	0.4 to 0.7	Little damage	Moderate
Electromagnetic stirring	Not limited by size	high	0.5 to 0.8	No damage	Moderately expensive

Stir casting process setup is shown in Figure 1. In a stir casting process, the reinforcing phases (usually in powder form) are distributed into molten aluminium by mechanical stirring. Prior to mechanical stirring, the surfaces of both must be properly cleaned in order to minimize the reaction between these two. Introducing reinforcement particles to the stirred molten matrix sometimes will entrap not only the particles but also other impurities such as metal oxide and slag, which is formed on the surface of the melt. During pouring, air envelopes may form between particles, which can alter the interface properties between particles and the melt, and also retarding the wettability between them. A major concern associated with the stir casting process is the segregation of reinforcing particles which is caused by the surfacing or settling of reinforcement particles during melting and casting process. To prevent settling of particles a motor driven agitator is used. Aluminium silicon carbide metal matrix composite will reach a state called mushy state before solidification. Once the mushy state is reached the reinforcement particles remain in its position during solidification. The final distribution of the particles in the solid depends on material properties and process parameters such as the wetting condition of the particles with the melt, strength of mixing, relative density, and rate of solidification. 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. To create and maintain a good distribution of the reinforcement material in molten matrix a vortex method is used. In this method, after the matrix material is melted, it is stirred vigorously to form a vortex at the surface of the melt, and the reinforcement material is then introduced at the side of the vortex. The stirring is continued for a few minutes before the slurry is cast [5].

An interesting recent development in stir casting is a two-step mixing process. In this process, the matrix material is first heated above its liquidus temperature. Then it is cooled down to a temperature between the liquidus and solidus points and kept in a semi-solid state. At this stage, the preheated reinforcement particles are added and mixed. The slurry is again heated to liquid state and mixed thoroughly. The results indicate that the two-step mixing process is quite successful to obtain a uniform dispersion of reinforcement in the matrix. An increasing trend for hardness and impact strength with increase in weight percentage of SiC has been observed [6]. For preheating the reinforcement particles, different researchers have used varying temperature and time (1000^0C for 1.5h in air [7], 1100^0C for 1-3h [8], 850^0C for 8h [9]). Preheating of reinforcement particles prevents the reaction between matrix and reinforcement. Further, preheating of SiC particles assists in removing surface impurities, and altering the surface composition due to formation of SiO_2 layer on the surface.

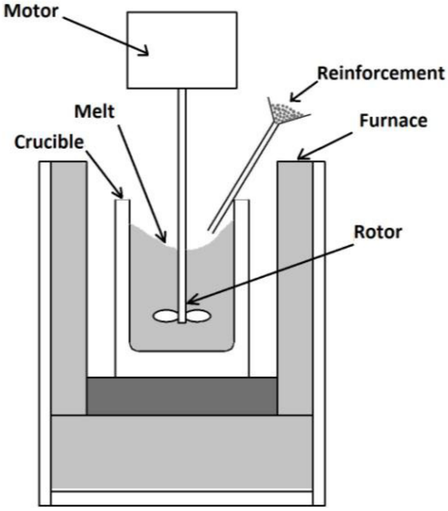

Fig. 1. Stir casting setup

3. Mechanical characterization

Mechanical characterization means identification of composite's mechanical properties which provide the basis for preventing failure of materials in service. The critical mechanical properties of composites are strength related properties, elastic properties, fracture toughness etc. These properties are influenced by the dispersion of reinforcements in the composite and also by the wettability between matrix and reinforcement particles. The dispersion of reinforcement in the composite are analyzed by optical micrographs. Reaction between the reinforcements and the matrix is sometimes too minor to be detected by the optical microscopy. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) or electron probe X-ray microanalysis (EPMA) would be effective in that case. Research work on MMC showed that Al-SiC composites are having clusters of particles and some places are identified without SiC inclusions. This is due to variation in contact time between the SiC particles and molten Al during processing, high surface tension and poor wetting behavior [10]. The reinforcement particles are found to distribute uniformly where the processing temperature range from 750^0C to 800^0C. This is due to reason that viscosity of Al is decreased with increase in processing temperature up to 800^0C. Magnesium (Mg) is added during manufacturing of composites to ensure proper wettability of reinforcement in matrix. This will improve the wettability between Al and SiC particles by reducing the formation of SiO_2 layer on the surface of the SiC [11]. If the surface area of the particles is higher, its wettability is more and hence by using fine sized reinforcement the level of wettability can be enhanced. Also by decreasing the surface tension of the alloy by heating at higher temperature wettability can be improved [12].

By increasing the weight fraction of reinforcement (from 5% to 20 %) composites hardness, elastic modulus, creep resistance, fatigue behavior, tensile strength, density, impact strength and wear resistance are increased but its cooling rate, ductility and forgebility are decreased [13-18]. By increasing the volume fraction of reinforcement the ultimate strength of composite is increased. This is due to fact that more load is transferred to the reinforcement which results in higher ultimate strength. Ultimate strength of composites are found to decrease with increase in holding time (10min, 20min, 30min) [19]. The addition of breadfruit seed hull (husk) or ash particles of size 500 nm to aluminium alloy matrix using a double stir-casting method shows that with the increase in reinforcement weight fraction, the matrix grain size decreases. Also the mechanical properties of the composites are improved over the matrix material, except for the slight decrease in impact energy [20].

MMC elastic properties are strongly influenced by micro structural parameters of the reinforcement like shape, size, orientation, distribution [21, 22]. Particle shape and size play an important role since angular particles can act as stress raisers, whereas rounded particles are favoured for better impact properties. Spherical particles are found to give better ductility than angular shapes [23]. Previous studies show that an increase in fraction of reinforcement results in an increase in elastic stiffness and decrease in Poison's ratio. Increase in particle size causes a slight decrease in Young's modulus due to decrease in interfacial area and dislocation density.

The major failure mechanism of particle reinforced metal matrix composites are (i) particle fracture (ii) interface decohesion and (iii) matrix yielding. Particle fracture failure of composites indicates both ductile and brittle modes of failure [24, 25]. Even though composite possess high modulus of elasticity, specific strength, and excellent heat resistance it has low fracture toughness and low tensile ductility. This is mainly due to differential elastic and thermal properties of matrix and reinforcement that degrade the matrix alloy near the interface and also by stress intensification introduced by the SiC particle geometry [26]. Fracture toughness studies on MMC show that composites reinforced with fine grain particles possess good fracture toughness compared to coarse grain [24, 25].

4. Modeling and simulation

The modeling of composite involves finding the optimal combination of its constituent's properties. Two types of modeling that can be applied to MMC are analytical and numerical modeling. In case of particle reinforced metal matrix composites, the numerical modeling is often more effective than analytical modeling as these composites lack structural simplicity.

Various analytical models used for the prediction of effective properties of composites are Hashin and Shtrikman model, Mura model, Budiansky model, Eshelby model, etc [16]. Hashin and Shtrikman model predicts upper and lower bounds of effective Young's modulus for an isotropic material based on variational principles of linear elasticity. Mura model is only valid for relatively small volume fractions of reinforcing particles and it considers the reinforcement shape as spherical. The effective Young's modulus of composites with spherical reinforcements, with a large volume fraction can be predicted by Budiansky model. Eshelby model considers the reinforcement as ellipsoidal shape in an infinite matrix [16].

Numerical models use finite element analysis to predict the effective properties of composites. One common approach is to use unit cell numerical models, where one or more reinforcements are embedded within the Al matrix, to simulate a composite material with a periodic array of reinforcement. A periodic arrangement of particles with the shape of a unit cylinder, truncated cylinder, double cone and sphere may be simulated using appropriate boundary conditions [16]. In actual practice composite reinforcements may contain sharp corners, so spherical shape is not a good choice. The unit cell model result indicates that unit cylinder particles strengthen the composite more than the other three shapes under a constant reinforcement fraction. In unit cell model the stress/strain history induced by the manufacturing process is to be considered for the correctness and accuracy of the predicted constitutive response of composite materials with mechanical interface [27]. To study the fracture behaviour of Al-SiC filamentary composite another numerical model using an elastic-plastic finite-element analysis is used. In this method the composite is modeled as a two-material cylinder consisting of an inner cylinder simulating the fibre and a surrounding shell simulating the matrix, and is subjected to uniform displacement [28]. An analytical or experimental method is often unable to explore the behavior of a MMC during machining due to the complex deformation and interactions among particles, tool and matrix, so finite element methods are used to investigate the matrix deformation and tool–particle interactions during machining of composites [29].

The existing study on the modeling of mixing of SiC in water doesn't explain the flow characteristics of these fluids. The real time measurement of the flow characteristics during stir casting is very expensive, timeconsuming, and dangerous. A large scale crucible is often selected during stir casting, in the industrial production. But the effect of scale-up to the industrial sized unit is not well-established. Further achieving uniform distribution of reinforcement in such a large scale crucible is yet a matter of concern [30]. Considering the time and the cost involved in setting up and conducting an experiment, computational fluid dynamics techniques appears as a logical alternative to obtain a more precise view of solidification of castings. Moreover experimental methods do not provide a clear understanding of the solidification process as it is highly dangerous to handle high temperature molten metal manually. The CFD software, FLUENT, is widely used for simulation of fluid flow problems. In the past few decades FLUENT has been grown in its capability for addressing a wide variety of fluid problems including mould filling, continuous casting process and alloy solidification, etc. which are of particular interest for researchers.

4. Scope for future work

In recent years, the metal matrix composites are reinforced with carbon nanotubes (CNTs) due to their strengths in excess of 100 GPa and stiffness of 1000 GPa which makes them superior to carbon fibers. Al alloy matrix and the multi-walled carbon nano tubes (MWCNTs) show excellent interfacial bonding and their thermodynamic calculations predict the type of carbide (Al4C3 or SiC) that would form at the matrix–CNT interface as a function of matrix composition and processing temperature. The amount of Al4C3 carbide formation increases with an increase in the CNT content [31, 32]. This concept of adding MWCNT can be extended to stir casting process. MWCNT will effectively transfer load to primary reinforcement (SiC) and it will act as a barrier to dislocation. Thus it will improve the fracture toughness of metal matrix composites. Since stir casting process involves a number of parameters, its effective strategy of experimentation is difficult and costly. Majority of research work carried out till date are following random selection of parameters without proper design of experiments. So incorporation of design of experiments involving all relevant parameters is expected to yield better results. Since aluminium silicon carbide metal matrix composite reaches the mushy state before solidification, it can be simulated by incorporating all relevant parameters using FLUENT software. Such a simulation will lead to an optimum result.

Conclusion

In this paper various advantages of stir casting method over other composite manufacturing methods are explained. From various recent work it is clear that clustering of reinforcement particles, wettability of reinforcement (SiC) in molten aluminium are the prime concern in the production of composites through stir casting. Further, the studies clearly show that mechanical properties of stir cast composite depend upon factors like fabrication techniques, volume fraction, shape and size of reinforcement particles and the distribution and properties of constituents. Also, it is evident that addition of reinforcement up to a particular level increases the mechanical properties. But composites fracture toughness is decreased by the addition of reinforcement. Recent studies in CNT show that it will effectively transfer load to primary reinforcement and it will act as a barrier to dislocation thus improving the fracture toughness of composite. To improve fracture toughness it is necessary that reinforcement should be uniformly distributed. The experimental work to find out the optimum values are difficult and costly. Since stir casting process involves very high temperature, experimentation is difficult and dangerous. So proper simulations of stir casting process considering all relevant factors are necessary to yield good results, and it will help the researchers to identify strategies for experimentation.

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