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Research Article

Individual and Combined Effect of Reinforcements on Stir Cast Aluminium Metal Matrix Composites-A Review

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Abstract

In the present study, based on the literature review, the individual and combined effect of reinforcements on Aluminium Metal Matrix Composites is discussed. These Aluminium Metal Matrix composites with individual and multiple reinforcements (Hybrid MMCs) are finding increased applications in aerospace, automobile, space, underwater, and transportation applications. This is mainly due to improved mechanical and tribological properties like strong, stiff, abrasion and impact resistant, and is not easily corroded. In the present scenario, this paper guides researchers and engineers towards proper selection of materials by considering improvement in material properties for relevant application and importance of liquid metal processing technique during manufacturing of Metal Matrix Composites.

Keywords: *Aluminium alloy, Metal Matrix Composites, Hybrid composites, Stir casting*

1. Introduction

The importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the market today more than 200 are composite. Conventional monolithic materials have limitations with respect to achievable combinations of strength, stiffness, and density. In order to overcome these shortcomings and to meet the ever-increasing engineering demands of modern technology, metal matrix composites are gaining importance. Aluminium Metal matrix composites (MMCs) are a range of advanced materials providing properties heithertofore not achieved by conventional materials. These materials range from ordinary materials (e.g., copper, cast iron, brass), which have been available for several hundred years, to the more recently developed, advanced materials (e.g., composites, ceramics, and high-performance steels). Due to the wide choice of materials, today's engineers are posed with a big challenge for the right selection of a material. Among all materials, composite materials have the potential to replace widely used steel and aluminum, and many times with better performance. Replacing steel components with composite components can save 60 to 80% in component weight, and 20 to 50% weight by replacing aluminum parts. Composite materials have become common engineering materials and are designed and manufactured for various applications including automotive components, sporting goods, aerospace parts, consumer goods, and in the marine and oil industries (Warren H. et al 2004).

1.1 Composite materials used instead of metals

Composites have been routinely designed and manufactured for applications in which high performance and light weight are needed. They offer several advantages over traditional engineering materials as discussed below (Sandjay K. Mazumdar 2002).

- Composite materials provide capabilities for part integration. Several metallic components can be replaced by a single composite component.
- Composite materials have a high specific stiffness (stiffness-to-density ratio), as shown in Table 1. Composites offer the stiffness of steel at one fifth the weight and equal the stiffness of aluminum at one half the weight.
- The specific strength (strength-to-density ratio) of a composite material is very high. Due to this, airplanes and automobiles move faster and with better fuel efficiency. The specific strength is typically in the range of 3 to 5 times that of steel and aluminum alloys. Due to this higher specific stiffness and strength, composite parts are lighter than their counterparts.
- The fatigue strength (endurance limit) is much higher for composite materials. Steel and aluminum alloys exhibit good fatigue strength up to about 50% of their static strength.
- Composite materials offer high corrosion resistance. Iron and aluminum corrode in the presence of water and air and require special coatings and alloying. Because the outer surface of composites is formed by

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plastics, corrosion and chemical resistance are very good.

- Composite materials offer increased amounts of design flexibility. For example, the coefficient of thermal expansion (CTE) of composite structures can be made zero by selecting suitable materials and lay-up sequence. Because the CTE for composites is much lower than for metals, composite structures provide good dimensional stability.

Table 1 Typical properties of some engineering materials

Material	Density (ρ) gm/cc	Tensile Modulus (E) (GPa)	Tensile Strength (σ) (GPa)	Specific Modulus (E/ρ)	Specific strength (σ/ρ)
Cast iron	7	100	0.14	14.3	0.02
Steel, AISI1045	7.8	205	0.57	26.3	0.073
Al 2024-T4	2.7	73	0.45	27	0.17
Al6061-T6	2.7	69	0.27	25.5	0.1

1.2 Composite material

Composite material can be defined as a heterogeneous mixture of two or more homogeneous phases that have been bonded together. Many natural materials are composites, such as wood. Other examples are automobile tires, glass fiber-reinforced plastics (GRPs), the cemented carbides used as cutting tools, and paper—a composite consisting of cellulose fibers. Based on the matrix material which forms the continuous phase, the composites are broadly classified into metal matrix (MMC), ceramic matrix (CMC), and polymer matrix (PMC) composites (W. D. Callister 2008).

Polymer-matrix composites (*PMC*s) consist of a polymer resin as the matrix, with fibers as the reinforcement medium. These materials are used in the greatest diversity of composite applications, as well as in the largest quantities, in light of their room-temperature properties, ease of fabrication, and cost.

Metal matrix composites (MMCs) in general, consist of at least two components, one is the metal matrix and the second component is reinforcement. The matrix is defined as a metal in all cases, but a pure metal is rarely used as the matrix. It is generally an alloy. In the productivity of the composite, the matrix and the reinforcement are mixed together. When the matrix is a metal, the composite is termed a Metal-Matrix Composites. Some of the advantages of these materials over the polymer-matrix composites include higher operating temperatures, nonflammability, and greater resistance to degradation by organic fluids.

Ceramic matrix composites (CMCs) consist of ceramic fibers embedded in a ceramic matrix. The matrix and fibers can consist of any ceramic material, whereby carbon and carbon fibers can also be considered a ceramic material. Aluminum oxide and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications.

1.3 Aluminium (Al) matrix selection

The unique thermal properties of aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics. The reason for aluminium being a success over magnesium is said to be mainly due to the design flexibility, good corrosion resistance, low density, good wettability and strong bonding at the interface. Titanium has been used in aero engines mainly for compressor blades and discs due to its higher elevated temperature resistance properly. Magnesium is the potential material to fabricate composite for making reciprocating components in motors and for pistons, gudgeon pins and spring caps. It is also used in aerospace due to its low coefficient of thermal expansion and high stiffness properties combined with low density. Magnesium and magnesium alloys are among the lightest candidate materials for practical use as the matrix phase in metal matrix composites. When compared to other currently available structural materials. Magnesium is very attractive because of its unique combination of low density and excellent machinability. However, it has been reported by several authors that though their low density (35% lower than that of Al) makes them competitive in terms of strength/density values. Magnesium alloys do not compare favorably with aluminium alloys in terms of absolute strength (Warren H. Hunt, et al 2004).

1.4 Al6061-alloy Selection

The families of aluminium alloys are represented by 1XXX, 2XXX, 3XXX upto 8XXX. The first digit gives basic information about the principal alloying elemens as shown in Table 2. The designation system also says something about the hardening of the alloys belonging to a family (R. Gitter 2008). Table 3 shows the nominal composition Wt% of Al-6061 matrix material (J.Jenix Rino, et al (2012) and K.M. Shorowordi et al (2013)). The 1xxx, 3xxx and 5xxx series are so called non-heat-treatable alloys; they gain their strength by alloying (e.g. increasing content of Mg) and work hardening. The 1xxx series designation concerns unalloyed aluminium materials which are distinguished according to their degree of purity. The 8xxx series designations are for miscellaneous types of alloys (i.e. Fe alloys) which cannot be grouped in the other families. The 2xxx, 6xxx and 7xxx series are heat-treatable alloys, which gain their strength by alloy-

Table 3 Chemical composition of Al6061 alloy

Element	Si	Mg	Cu	Cr	Fe	Ti	Zn	Mn	Al	Others
% Wt	0.4 - 0.8	0.8 – 1.20	0.15 – 0.40	0.04 – 0.35	0.70 Max	0.15 Max	0.25 Max	0.15	Rest	0.15 Max

-ing but make use of precipitation hardening as the main mechanism. Among several series of aluminum alloys, heat treatable Al6061 and Al7075 are much explored. Among them Al6061 alloy is highly corrosion resistant, extricable in nature and exhibits moderate strength. It finds vast applications in the fields of construction, automotive, aerospace, marine, and other allied fields. They have been studied extensively because of their technological importance and their exceptional increase in strength obtained by precipitation hardening.

1.5 Components of a composite material

In practice, most composites consist of a bulk material (matrix alloy) and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix.

1.5.1 Bulk material or Matrix alloy

As regards the matrix, most metallic systems have been explored for use in MMCs, including aluminum,iron, zinc, beryllium, magnesium, titanium, nickel, cobalt, copper, and silver. The matrix can be selected on the basis of oxidation and corrosion resistance or other properties. By far the Aluminum (Al), Magnesium (Mg), Titanium (Ti) matrix are used widely (Sandjay K. Mazumdar 2002).

1.5.2 Reinforcement

As for the reinforcement, the materials used are typically ceramics since they provide a very desirable combination of stiffness, strength, and relatively low density. Candidate reinforcement materials include SiC, Al_2O_3, B_4C, TiC, TiB_2, graphite, and a number of other ceramics. The reinforcement is to provide increased stiffness and strength to the unreinforced matrix, ceramic particles with their large elastic modulus and high strength are ideal as the reinforcing particles. Many of the ceramic particles of interest are thermodynamically unstable when they are in contact with pure metals, and will react to form reaction compounds at the interface between the particles and the surrounding matrix.

1.6 Silicon carbide (SiC)

SiC can be used as reinforcement in the form of particulates, whiskers or fibers to improve the properties of the composite. When embedded in metal matrix composites SiC certainly improves the overall strength of the composite along with corrosion and wear resistance. Aluminum MMCs reinforced with SiC particles have up to 20% improvement in yield strength, lower coefficient of thermal expansion, higher modulus of elasticity and more wear resistance than the corresponding un-reinforced matrix alloy systems. 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. For these reasons SiC-particulate-reinforced aluminium composites have found many applications such as brake discs, bicycle frames, aerospace and automotive industry. (A.K. Vasudevan et al 1995 and B. Roebuck 1987).

1.7 Boron carbide (B_4C)

Boron carbide is the third hardest material after diamond and cubic boron nitride, which possesses low density, high degree of chemical inertness, high temperature stability, excellent thermoelectric properties, is an attractive strengthening agent for aluminium-based composites. It could be an alternative to silicon carbide composites in applications where high stiffness and wear resistance are major requirements. One of the solutions is going for boron carbide-reinforced metal matrix composites that are stronger, stiffer, fracture resistant, lighter in weight, and harder, possess higher fatigue strength and exhibit significant improvements over other materials. The lower density, high elastic modulus, high refractoriness and higher hardness of B_4C than SiC and Al_2O_3 make it better reinforcement for high performance MMCs. It has been reported that the interfacial bonding between the aluminum matrix and the B_4C reinforcement seems to be better than that between aluminum matrix and SiC (M.D. Salvador et al 2001 and Suri AK et al 2010).

1.8 Hybrid composites

When at least two reinforcement materials are present in the metal matrix, it is called a hybrid metal matrix composite. Hybridization is commonly used for improving the properties and for lowering the cost of conventional composites. Hybrid MMCs are made by dispersing two or more reinforcing materials into a metal matrix. They have received considerable research and trials by Toyota Motor Inc., in the early 1980s. Hybrid metal matrix composites are a relatively new class of materials characterized by lighter weight, greater strength, high wear resistance, good fatigue properties and dimensional stability at elevated temperatures than those of conventional composites. Due to such attractive properties coupled with the ability to operate at high temperatures, the Al matrix composite reinforced with SiC and B_4C particulate are a new range of advanced materials. The best part of effort in hybrid MMCs compete with super-alloys, ceramics, plastics has been directed towards development of high performance composite with high strength and good tribological properties. It was found that applications of hybrid

Table 2: Standard terminology, with key alloying elements and the main tempers in use for structural application of precipitation hardened semi products

	Mn	Mg	Si	Symbol	Description
Mn	Al-Mn 3XXX			T4	Solution heat-treated and then naturally aged
Mg	AlMgMn 5XXX	AlMg 5XXX	AlMgSi 6XXX	T5	Cooled from an elevated temperature shaping process and then artificially aged
Si		AlSiMg 6XXX	AlSi 4XXX	T6	Solution heat-treated and then artificially aged
Zn		AlZnMg, AlZnMgCu 7XXX		T7	Solution heat-treated and then artificially over aged
Cu		AlCuMg 2XXX		T61	Solution heat-treated and then artificially aged in underageing conditions in order to improve formability
				T64	Solution heat-treated and then artificially aged –mechanical property level higher than T6 achieved through special control of the process 6000 series alloys T7 Solution heat-treated

composites in aerospace industries and automobile engine parts like drive shafts, cylinders, pistons and brake rotors, consequently interests in studying structural components wear behavior (V. C. Uvaraja et al 2012).

2.0 Stir-casting or Compo casting

According to the type of reinforcement, the fabrication techniques can vary considerably. From the contributions of several researchers, some of the techniques for the development of these composites are stir casting/ Compocasting (Y.H. Seo et al 1999), powder metallurgy (X. Yunsheng et al 1998), spray atomization and co-deposition (C.G. Kang et al 1997), plasma spraying (Y.H. Seo et al 1995) and squeeze-casting (S. Zhang et al 1998). The above processes are most important of which, liquid metallurgy technique has been explored much in these days. This involves incorporation of ceramic particulate into liquid aluminium melt and allowing the mixture to solidify. Here, the crucial thing is to create good wetting between the particulate reinforcement and the liquid aluminium alloy melt. The simplest and most commercially used technique is known as vortex technique or stir-casting technique. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller. Ceramic particles and ingot-grade aluminum are mixed and melted. The melt is stirred slightly above the liquidus temperature (600−700°C).

Stir casting offers better matrix-particle bonding due to stirring action of particles into the melts shown in Fig 1. The recent research studies reported that the homogeneous mixing and good wetting can be obtained by selecting appropriate processing parameters like stirring speed, time, and temperature of molten metal, preheating temperature of mould and uniform feed rate of particles. Disadvantages that may occur if process parameters are not adequately controlled include the fact that non-homogeneous particle distribution results in sedimentation and segregation (Z. Zhang et al 1994 and V.P. Mahesh et al 2011). Table 3 shows a comparative evaluation of the different manufacturing techniques used for the fabrication of discontinuously reinforced metal matrix composite techniques (M.K. Surappa 1997).

2.1 Stir casting procedure for Al6061/SiC MMCs

During processing of SiC particle-reinforced aluminum matrix composites, the particles are preheated at 600–800^{o} C for 2 h in order to remove the volatile substances and to maintain the particle temperature closer to melt temperature of 750^{o} C. Also, in SiC particles preheating leads to the artificial oxidation of the particle surface forming SiO_2 layer. This SiO_2 layer helps in improving the wettability of the particle. The Al6061 billets were charged into the furnace and melting was allowed to progress until a uniform temperature of 750^{o} C (which is above the liquidus temperature) was attained, subsequently degassed by passing hexachloroethane (C_2Cl_6) solid degasser.

The melt was then allowed to cool to 600^{o} C (slightly below the liquidus temperature) to a semi-solid state. At this stage, the silicon carbide mixture was added to the melt and manual stirring of the slurry was performed for 20 minutes. An external temperature probe was utilized in all cases to monitor the temperature readings of the furnace. After the manual stirring, the composite slurry was reheated and maintained at a temperature of 750^{o} C $\pm$10^{o} C (above the liquidus temperature) and then mechanical stirring was performed. The stirring operation

Table 3 comparative evaluation of the different manufacturing techniques

Method	Range of shapes and size	Range of Vol. fraction	Damage to reinforcement	Cost
Stir casting	Wide range of shapes	Up to 0.3	No damage	Less expensive
Squeeze casting	Limited perform shape (upto 2cm ht.)	Up to 0.45	Severe damage	Moderately expensive
Powder metallurgy	Wide range; restricted size	0.3 - 0.5	Reinforcement fracture	Expensive
Spray casting	Limited shape; large size	0.3 - 0.7	Reinforcement fracture	Expensive

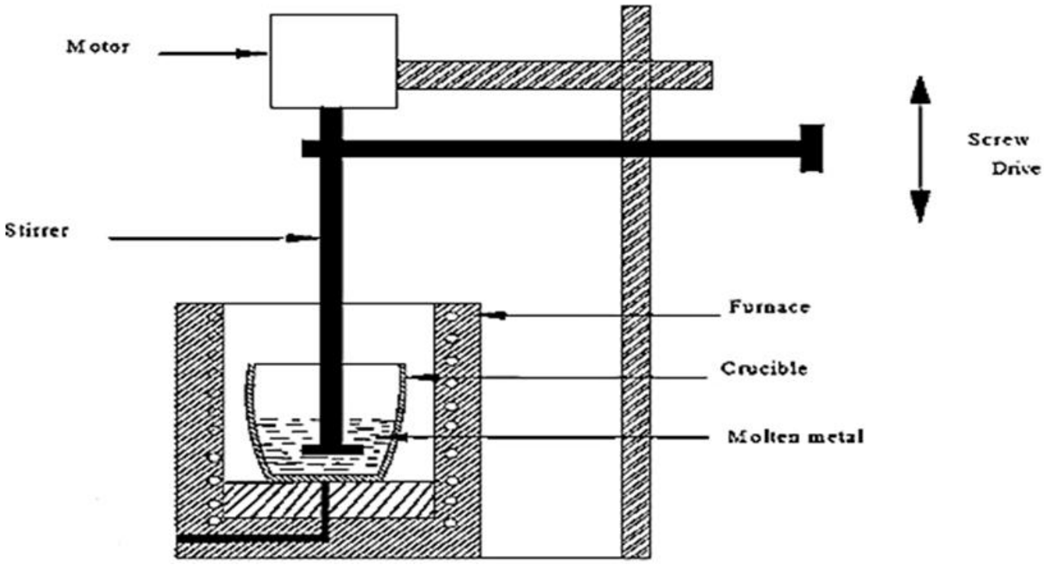

Fig 1. Metal Matrix Composites by casting route through Stir Casting method

was performed for 10 minutes at an average stirring rate of 400rpm. Casting was then performed on prepared sand moulds at a pouring temperature of 720^{o} C. After effective

2.2 Stir casting procedure for Al6061/B_4C MMCs

B_4C powder is preheated at 200 ^{O}C in order to remove the volatile impurities on the surface and improve the wettability of reinforcement particle with the molten metal. The particles are washed in alkali solution to remove some of the surface contaminants present over boron carbide particles. The treated particulates are incorporated into the vortex of the melt created with the help of mechanical impeller with an average speed 400 rpm. The mechanical stirring suspends the particles in the melt and provides uniform distribution of reinforcement particles. The composite melt is poured at 750^{o} C into preheated permanent molds (V.P. Mahesh et al 2011).

2.3 Factors influencing preparation of MMC's

In preparing metal matrix composites by the stir casting method, there are several factors that need considerable attention, including

- The difficulty of achieving a uniform distribution of the reinforcement material;
- Wettability between the two main substances;
- Porosity in the cast metal matrix composites;

In order to achieve the optimum properties of the metal matrix composite, the distribution of the reinforcement material in the matrix alloy must be uniform, the wettability or bonding between these substances should be optimized and the porosity levels need to be minimized (M.K. Surappa 1997).

2.4 Literature review: Manufacturing of MMCs

The results of the several investigations regarding manufacturing of metal matrix composites by stir casting technique by using Aluminium alloys with different reinforcements can be summarized as follows: (V.P. Mahesh et al 2011) studied the effect of surface treated boron carbide-reinforced aluminium matrix *(*Al6061/B_4C) composites by liquid-metal stir-casting technique. It was observed that for B_4C particles, the optimum preheating temperature is 250^{o} C for better dispersion into aluminum matrix by liquid–metal stir-casting technique and the microstructrural analysis have shown uniform distribution of particles in the composite. Heating of the B_4C particles above 300^{o} C leads to the formation of the glassy B_2O_3, which binds and aids sintering to form lumpy and agglomerated B_4C particles. (J Hashim *et al 1999)* studied the technical difficulties associated with low cost stir casting technique used in the production of silicon carbide/aluminium alloy MMCs to attain a uniform distribution of reinforcement, good wettability between substances, and a low porosity material. It was observed that, the composites produced by liquid metallurgy techniques show excellent bonding between the ceramic and the metal when reactive elements, such as Mg, Ca, Ti, or Zr are added to induce wettability. The addition of Mg to molten aluminium to promote the wetting of alumina is particularly successful, and it has also been used widely as an addition agent to promote the wetting of different ceramic particles, such as silicon carbide and mica. Heating silicon carbide particles to 900ºC, for example, assists in removing surface impurities and in the desorption of gases, and alters the surface composition by forming an oxide layer on the surface. It has been recommended that a turbine stirrer should be placed so as to have 35% liquid below and 65% liquid above to reduce porosity level. During stir casting, stirring helps in two ways: (a) transferring particles into the liquid metal as the pressure difference between the inner and the outer surface of the melt sucks the particles into the liquid and (b) maintaining the particles in a state of suspension. The vortex method is one of the better known approaches used to create and maintain a good distribution of the reinforcement material in the matrix alloy. (W Zhou *et al* 1997*)* found that, a two-step mixing method improves the wettability of the SiC particles and ensure a good particle distribution. Before mixing the SiC particles are to be preheated at 1100 *°C* for 1 to 3 hours to make their surfaces oxidized and SiC particles were observed to act as substrates for heterogeneous nucleation of Si crystals in A356, Al6061-10%SiC. (Vikram Singh *et a 2004)* reported that during manufacturing of Al6061/SiC_p composite, it was observed that, there is a loss of Mg content during stirring of MMC fabrication and hence decrease in mechanical properties. The mechanical properties of metal matrix composites after hot rolling were not significantly improved due to the presence of shrinkage cavities and particle cracking, whereas, unreinforced alloys 6061 in rolled condition has high toughness and therefore, crack arrest capability. (Umanath K *et al 2011)* investigated the effect of stir casting by preparing Al6061-SiC-Al_2O_3 Hybrid composites. It was observed that, the vortex method is one of the better known approaches used to create a good distribution of the reinforcement material in the matrix. Good quality composites can be produced by this method by proper selection of the process parameters such as pouring temperature, stirring speed, preheating temperature of reinforcement etc. The coating of an alumina to the blades of the stirrer is essential to prevent the migration of ferrous ions from the stirrer into the molten metal. (Fatih Toptan *et a 2010)* investigated the effect of Al1070 and Al6063 matrix B_4C reinforced composites produced by liquid-metal stir-casting technique. It was observed that, due to the poor wetting of B_4C particles by liquid aluminium, an effective bonding could not be formed on the matrix/reinforcement interface in Al–B_4C composites produced at relatively lower temperatures like 850° C. In order to enhance the wettability of boron carbide powders and improve their incorporation behavior into aluminium melts, potassium fluotitanate (K_2TiF_6) flux was used. The aim of Ti addition in the casting of Al–B_4C composites is to form a reaction layer on the interface that contains titanium carbide (TiC) and titanium boride (TiB2). When Ti is added in the form of K_2TiF_6, K and F contribute to remove the oxide film from the Al surface. (Barbara Previtali *et a 2008)* studied the various factors to improve wettability between reinforcement and matrix interface. Good wettability of B_4C in aluminium (higher than that of SiC) can be found. This is attributed to the formation of a layer of liquid B_2O_3 on the B_4C particles. Due to its low melting point, B_2O_3 exists above 450ºC as a liquid on the surface of B_4C and enhances wettability through a liquid–liquid reaction. The addition of small quantities of Mg (up to 1%) to molten aluminium, which promotes wetting, can be found particularly successful **(**Hashim J, Looney *et al* 2001)**.** Transition from non-wetting to wetting occurs in SiC at high temperatures because of dissociation of surface oxides. Heat treatment of the particles before dispersion into the molten aluminium aids their transfer by causing oxide formation (Urena A *et al* 2004)**.**

2.5 Process variables and their effects on properties

In preparing metal matrix composites by the stir casting method, there are process variable that need considerable attention, including

i) Speed of rotation: The control of speed is very important for successful production of casting. Rotational speed also influences the structure, the most common effect of increase in speed being to promote refinement and instability of the liquid mass at very low speed. It is logical to use the highest speed consistent with the avoidance of tearing (Sanjeev Das *et al* 2006).

ii) Pouring temperature: Pouring temperature exerts a major role on the mode of solidification and needs to determine partly in relation to type of structure required. Low temperature is associated with maximum grain refinement and equiaxed structures while higher temperature promotes columnar growth in many alloys. However practical consideration limits the range. The pouring temperature must be sufficiently high to ensure satisfactory metal flow and freedom from cold laps whilst avoiding coarse structures.

iii) Pouring speed: This is governed primarily by the need to finish casting before the metal become sluggish. Although too high a rate can cause excessive turbulence and rejection. In practice slow pouring offers number advantages. Directional solidification and feeding are promoted whilst the slow development of full centrifugal pressure on the other solidification skin reduces and risk of tearing. Excessive slow pouring rate and low pouring temperature would lead to form surface lap (T. P. D. Rajan, et al 2007).

iv)Mould temperature: The use of metal die produces marked refinement when compared with sand cast but mould temperature is only of secondary importance in relation to the structure formation. Its principal signification lies in the degree of expansion of the die with preheating. Expansion diminishes the risk of tearing in casting. In nonferrous castings, the mould temperature should neither be too low or too high. The mould should be at least 25 mm thick with the thickness increasing with size and weight of casting.

v) Mould coatings: Various types of coating materials are used. The coating material is sprayed on the inside of the metal mould. The purpose of the coating is to reduce the heat transfer to the mould. Defects like shrinkage and cracking that are likely to occur in metal moulds can be eliminated, thus increasing the die life. The role of coating and solidification can be adjusted to the optimum value for a particular alloy by varying the thickness of coating layer. For aluminium alloys, the coating is a mixture of Silicate and graphite in water.

3.0 Literature review: Properties of Metal Matrix Composites

The factors that determine properties of composites are volume fraction, microstructure, homogeneity and isotropy of the system and these are strongly influenced by proportions and properties of the matrix and the reinforcement. The properties such as the Young's modulus, shear modulus, Poisson's ratio, coefficient of friction and coefficient of thermal expansion are predicted in terms of the properties and concentration.

3.1 Physical Properties

3.1.1 Density Measurement

The density measurements were carried out to determine the porosity levels of the samples. The percent porosity, and its size and distribution in cast metal matrix composites play an important role in controlling the mechanical properties. It is thus necessary that porosity levels be kept to a minimum if the desired high performance in service applications would be achieved. Porosity in composites results primarily from air bubbles entering the slurry during the stirring period or as air envelopes to the reinforcing particles (Ray, S *et al* 1993). Many have used alternative stirring processes and reported that porosity levels were within the range of 2-4%, which were referred to as acceptable levels of porosity in cast composites (Kok, M *et al* 2005, and Prabu, S.B *et al* 2006).

The results of the several investigations regarding the density of the Al_2O_3/ SiC/B_4C/Graphite/Zirconium particles reinforced Al6061 and other aluminum alloys can be summarized as follows:

(Kenneth K. *et.al* 2012) found that**, t**he low porosity level (≤ 1.6 % porosity) can be achieved by using borax additive and two-step stir casting technique resulted in the production of Al 6063/SiCp. (Y Sahin *et al* 2003) investigated the effect of Al2024 alloy reinforced with silicon carbide (SiC) metal matrix composites of various particle sizes by molten metal mixing, because of cost effective method. Microstructural examination showed that the SiCp distributions were homogeneous and no interface porosity could be observed. Density of the composite increased almost linearly with the weight fraction of particles. It was found that, increasing amount of porosity with increasing the volume fraction, especially for low particle sizes of composites, because of the decrease in the inner-particles spacing. In other words, with increasing the volume fraction of MMCs during the production stage, it is required that the longer particle addition time is combined with decreasing the particle size. The porosity level increased, since the contact surface area was increased. It is also reported by the early work (M. Zamzam *et al* 1993 and Kok M 1999). Further, (Miyajima *et.al* 2003) reported that the density of Al2024-SiC particle composites is greater than that of Al2024-SiC whisker reinforced composites for the same amount of volume fraction. From the above the increase in density can be reasoned to the fact that the ceramic particles possess higher density. Further, the increased volume fraction of these particles contribute in increasing the density of the composites, also they have stated that the theoretical and measured density values of these composites match to each other. Additionally, the above discussions can be reasoned to the fact that the ceramic particles possess higher density. (Veeresh kumar G.B *et.al* 2011) reported the density of Al6061-SiC composites increases with the incorporation of the hard ceramic reinforcement into the matrix material. The experimental and theoretical densities of the composites were found to be in line with each other. There is an increase in the density of the composites compared to the base matrix. (YU Xiao-dong *et al 2007)* studied the effect of Al5210 alloy reinforced with SiC metal matrix composites with a high volume fraction and various particle size. It was concluded that, the bending strength of SiCp/5210 Al composite with a high volume fraction (50%) increases with decreasing particle size, but the fracture toughness of increases with the increasing particle size. (Swamy A.R, *et al* 2011) noticed that, the properties of the cast Al6061-WC composites are significantly improved by varying the amount of WC. It was found that increasing the WC content within the matrix material, resulted in significant improvement in mechanical properties like hardness, tensile strength, and compressive strength at the cost of reduced ductility. In addition to this, highest values of mechanical properties like hardness, tensile strength and compressive strength were found at 3 wt% WC. (Mahendra Boopathi, M *et al* 2013) noticed that, since SiC and fly ash particles are having low density compared with aluminium., the experimental density values of the Al-SiC, Al-fly and Al-SiC-fly ash composites decreased linearly. The decrease in density of composites can be attributed to lower density of SiC, flyash and SiC-fly ash particles than that of the unreinforced Al. If the theoretical value closely matches with the experimental values indicates the better bonding between the interface between matrix and reinforcement. Similar results were observed by (Rao *et al*. 2010 and Gnjidi *et al*. 2001). It is therefore, to improve the density again, apart from Al-SiC and Al-fly ash composites, the mixture of SiC and fly ash particles were added with aluminium. At higher concentration [(Al/(10%SiC+10%fly ash)], the density is about 54% improvement when compared pure aluminium (Rao, J.B et al 2010 and Gnjidi, Z *et a*l 2001). (G. B. Veeresh Kumar *et al 2010)* studied the effect of Al6061-SiC and Al7075 - Al_2O_3 Metal Matrix Composites having various particle size prepared by stir casting method. It was found that, liquid metallurgy techniques were successfully adopted & uniform distribution of the particles were observed during the preparation of Al6061-SiC and Al7075-Al_2O_3 composites. Silicon carbide and aluminium oxide reinforced particles significantly improves the density of the composites with increased percentage of filler content in the Composites. The Al7075- Al_2O_3 composites exhibits higher density than that of the Al6061-SiC and can reasoned for the higher density values of Al_2O_3. (Umanath K *et al 2011)* observed that the porosity was more pronounced around Al_2O_3 particles than the location around SiC particles due to wetting behavior of Al alloy. It is also observed from the optical micrographs that the porosity of the specimens increase with increasing volume fractions of the particulate reinforcement.

3.2 Mechanical Properties

3.2.1 Hardness

The resistance to indentation or scratch is termed as hardness. Among various instruments for measurement of hardness, Brinell's, Rockwell's and Vicker's hardness testers are significant. Theoretically, the rule of mixture of the type $H_c = V_r H_r + V_m H_m$ (suffixes 'c', 'r', and 'm' stand for composite, reinforcement and matrix respectively and *v* and H stand for volume fraction and hardness respectively) for composites (S.C. Sharma *et al* 2001) helps in approximating the hardness values. (T. Miyajima *et al* 2003) Among the variants of reinforcements, the low aspect ratio particle reinforcements are of much significant in imparting the hardness of the material in which they are dispersed (the hardness of fiber reinforced MMC < whisker reinforced MMC < particle dispersed MMC)].

The results of the several investigations regarding the hardness of the Al_2O_3/ SiC/B_4C/Graphite/Zirconium particles reinforced Al6061 and other aluminum alloys can be summarized as follows:

(Veeresh Kumar *et al* 2010) in the studies of Al6061-SiC, Al7075-Al_2O_3 composites concluded that higher filler content exhibits higher hardness and it can be observed that the hardness of the Al7075-Al_2O_3 composite are higher than that of the composite of Al6061-SiC and is to the fact that the matrix Al7075 and Al_2O_3 possess higher hardness (J.M. Wu *et al* 2000). (Y Sahin *et al* 2003) investigated that, the hardness of the Al2024-SiC composites increased more or less linearly with the volume fraction of particulates in the alloy matrix due to the increasing ceramic phase of the matrix alloy. *(*B. Deuis *et al* 1996) concluded that the increase in the hardness of the composites containing hard ceramic particles not only depends on the size of reinforcement but also on the structure of the composite and good interface bonding. The particulate reinforcements such as SiC, B_4C, Al_2O_3 and aluminide (F. M. Husking et al 1982 and Debdas Roy et al 2005) are generally referred to impart higher hardness. Moreover, these composites exhibit excellent heat and wear resistances due to the superior hardness and heat resistance characteristics of the particles that are dispersed in the matrix (Alpas AT et al 1992, Kulkarni MD, et al 1996 and Kim CK et al 1984).

(Yiicel *et al 1997)* investigated that, the composites containing B_4C powder in the 7075 aluminium alloy matrix exhibit consistently higher hardness values, lower flexure strength and fracture toughness as compared to unreinforced Al7075 alloy. (K. Kalaiselvan *et al* 2011) studied the effect of production and characterization of AA6061–B_4C stir cast composites. It was observed that, the micro and macro hardness of the composites were increased from 51.3 HV to 80.8 HV and 34.4 BHN to 58.6 BHN with the addition of weight percentage of B_4C particles. Addition of reinforcement particles in the matrix increases the surface area of the reinforcement and the matrix grain sizes are reduced. The presence of such hard surface area of particles offers more resistance to plastic deformation which leads to increase in the hardness of composites. It is reported by (C.S Ramesh et al 2009), that the presence of hard ceramic phase in the soft ductile matrix reduces the ductility of composites due to reduction of ductile metal content which significantly increases the hardness value. (Gopi K.R *et al* 2013) observed that hardness of Al6061-Zr-Gr Hybrid MMCs gets improved by 13%, when compared with heat treated as cast condition. This indicates that addition of reinforcements has an influence on the mechanical properties of the Al6061 alloy. The maximum hardness value of 73.5 BHN is observed in 4 and 6% zircon with constant addition of 2% graphite. (H. Ghanashyam Shenoy *et a*l 2012) concluded that hardness of the hybrid composite material increases with wt% of Mica and E-glass content as compared to parent metal. This is because of addition of reinforcement makes the ductile Al6061 alloy into more brittle and hard as silica content increases. (Uvaraj et, al 2012) concluded that, the added amount of SiC and B_4C particles to aluminium alloy enhances higher hardness as compared to unreinforced alloy, due to the fact that these reinforcements act as obstacles to the motion of dislocation. Hybrid composites having Al6061-10 wt% SiC and 3 wt% boron carbide shows optimum combination to obtain high hardness and good toughness. In addition to this it was observed that, hardness of the composites found increased with increased filler content and the increases in hardness of Al6061-SiC-B_4C & Al7075-SiC-B_4C Hybrid composites are found to be 75 to 88BHN and 80 to 94BHN respectively as compared to unreinforced alloy. Al7075-SiC-B_4C exhibits superior mechanical and tribological properties.

3.2.2 Wear characteristics

Wear is the progressive loss of material due to relative motion between a surface and the contacting substance or substances (Peter J et al 1997). The wear damage may be in the form of micro-cracks or localized plastic deformation (U. Sanchez-Santana *et al* 2006). W*ear* may be classified as adhesive wear, abrasion wear, surface fatigue wear and corrosive wear. Wear, the progressive loss of substance from the operating surfaces of the mechanically interacting element of a tribo-system may be measured in terms of weight loss or volume loss. Commonly available test apparatus for measuring sliding friction and wear characteristics in which, sample geometry, applied load, sliding velocity, temperature and humidity can be controlled are Pin-on-Disc, Pin-on-Flat, Pin-on-Cylinder, Thrust washers, Pin-into-Bushing, Rectangular Flats on a Rotating Cylinder and such others.

3.2.3 Factors Affecting Wear of Aluminum based Composite Materials

The principal tribological parameters that control the friction and wear performance of reinforced Al-MMCs are, applied normal load, Sliding speed/velocity/distance, the effect of temperature, and the surface finish and the counterpart (A.P.Sannino *et al* 1995 and R.K. Uyyuru *et al* 2006).

Applied normal load: The specific wear rate of Al-alloy was reported to have decreased with increase in the applied load. Al-alloy easily undergoes thermal softening and re-crystallization at higher temperature compared with the composites because the strength of the composites at higher temperature is greater. As a result, the wear rate of the Al-alloy is increased drastically at higher loads. At low loads, as particles act as load bearing constituents, the direct involvement of Al-alloy in the wear process is prevented (Rang Chen *et al* 1997).

Sliding speed/velocity/distance: The sliding speed influences the wear mechanism strongly and at low sliding speed, the wear rate of the composites is lower. This may happen because at high speed, the micro thermal softening (Q.D. Qin et al 2008) of matrix material may take place, which further, lowers the bonding effect of the reinforced particles with that of matrix material (S. Wilson et al 1997). With the increase of sliding speed/velocity/distance, the wear rate and cumulative wear loss increases for all the materials (G. Ranganath et al 2001).

Effect of temperature: The wear volume increases (A.Martin et al 1996) substantially above a characteristic temperature that exists between the mild and severe wear transition. The composite transition temperature is higher than that of the unreinforced alloy thus the composite suffers lower wear volume. The higher the normal pressure, the lower is the transition temperature (P. Poza et al 2007). The higher thermal conductivity of the reinforcement contributes in improving wear resistance (P. Vissutipitukul et al 2005 and U. Sanchez-Santana et al 2006).

Surface finish and hardness of counterpart: An increase in load generally results in an increased wear rate of both the composite pin and counter-face. Surface roughness affects the wear rate. The higher the roughness, the higher will be the wear rate (U. Sanchez-Santana et al 2006). The counter-face hardness is inversely proportional to the wear rate thus the counter material with a lower hardness reduces the wear resistance due to the mutual abrasion between the counter material and the wear surface of the specimen (Yoshiro.Iwai et al 1995). Wear of the counter-face depends on the mechanism of wear of the composite.

Superior wear resistance is one of the attractive properties in MMCs. It has been found that particulate-reinforced MMCs show wear resistance on the order of 10 times higher than the un-reinforced materials in some load ranges (U. Sanchez-Santana et al 2006).

The results of the several investigations regarding the wear rate Al_2O_3/ SiC/B_4C/Graphite/Zirconium particles reinforced Al6061 and other aluminum alloys can be summarized as follows:

(Yoshiro Iwai et al 1995) found that the initial sliding distance require to achieve mild wear decreased with increasing volume fraction and also severe wear rate decrease linearly with volume fraction. (Alpas and Zhang et al 1994) while investigating the wear of particle reinforced Metal Matrix Composites (MMC) under different applied load conditions identified three different wear regimes. At low load (regime I), the particles support the applied load in which the wear resistance of MMCs are in the order of magnitude better than Al-alloy. At regime II, wear rates of MMCs and Al-alloy were similar. At high load and transition to severe wear (regime III), the surface temperature exceeded the critical value. (D.P.Mondal, et al 1998) opinion was that the applied load affects the wear rate of alloy and composites significantly and is the most dominating factor controlling the wear behavior. The cumulative volume loss increases with increasing applied normal load and the contact surface temperature increases as the applied load increases. (Kowk and Lim, et al 1999) suggested that massive wear occurs if the particles are smaller than the threshold value at higher speeds. (A.Wang and H.J.Rack, et al 1991) reported that the steady state wear rate of 7091Al matrix composite is generally independent of reinforcement geometry (particulate versus whisker) and orientation (perpendicular versus parallel) with the exception of wear at 3.6m/s where the parallelly oriented SiC composite was found to be superior. (Feng Tang et al 2000) studied the effect of dry sliding friction and wear properties of B_4C particulate-reinforced Al5083 matrix composites having 5-10 wt.%. It was observed that, the wear rate of composite having 10 wt.% B_4C was approximately 40% lower than that of composite 5 wt.% B_4C under the same test condition. This experimental clearly indicates a significant effect of the B_4C particles on enhancing the wear resistance of these composites. (S.Y. Yu *et. al* 1997) demonstrated the effects of applied load and temperature on the dry sliding wear behavior of Al6061-SiC composites and concluded that the wear rate decreases with increased applied load. (Liang Y. N. *et al* 1995**)** reported that the MMCs containing SiC particles exhibit improved wear resistance. (Basavarajappa S et al 2007) stated that the microstructural characteristics, applied load, sliding speed and sliding distance affect the dry sliding wear and friction of MMCs. However, they conclude that, at higher normal loads (60N), severe wear and silicon carbide particles cracking and seizure of the composites occurs during dry sliding. In addition to this they have studied the tribological behaviour of hybrid composites with aluminum base Al2219 reinforced by SiC and graphite. They studied the tribological properties of hybrid composites with 5, 10 and 15 % SiC and 3 % Gr obtained with process of liquid metallurgy. The tribological tests show that wear decreases with increasing SiC content in the hybrid composite. With increasing sliding speed and normal load, wear rate of composites is growing. (Ames and Alpas, et al 1995) have studied the tribological testing of hybrid composites with a base of aluminum alloy A356 reinforced with 20 % SiC and 3 to 10 % Gr. The tribological tests are done on tribometer with block on ring contact. The wear rate of hybrid composites is significantly lower than the wear rate of the base material without reinforcements, especially at low normal loads. (Rupa Dasgupta et al 2005) reported the improvement in the hardness, mechanical and sliding wear resistance properties attained as a result of heat treatment and forming composites by adding 15 wt.% of SiC. (M. Babic, et al 2013) found that wear rate on A356/10SiC/1Gr hybrid composites is 3 to 8 times lesser than the wear rate on the base material A356. Wear rate decreases with decrease of normal load and increase of sliding speed. (V. C. Uvaraja, et al, 2012) reported that , wear rate and coefficient of friction decrease with increasing volume fraction of hybrid composite sample with Al6061-SiC- B_4C (5 to 10%Wt). (Umanath K *et al* 2011**)** reported that, the wear rate decreases with increasing volume fraction of SiC and Al_2O_3 reinforcements upto of 25%\ with Al6061 hybrid composites. The coefficient of friction and wear rates of the hybrid composites are less when compared with the matrix alloy and the individual composites. (Veeresh kumar G.B et al 2011**)** reported that, wear resistance of the Al6061-SiC and Al7075-Al_2O_3 composites are higher but the SiC reinforcement contributed significantly in improving the wear resistance of Al6061-SiC composites, which exhibits superior mechanical and tribological properties. (Gopi K.R et al 2013) observed that, there was a considerable improvement in the resistance for wear with addition of zircon and graphite for Al6061 hybrid composite. There was an average of 35% improvement in the resistance for wear at 400 rpm. There was an average of 28% to 30% improvement in the resistance for wear at 800 rpm.

3.2.4 Tensile strength

Tensile properties dictate how the material will react to forces being applied in tension. Uniaxial tensile test is known as a basic and universal engineering test to achieve material parameters such as ultimate strength, yield strength, % elongation, % area of reduction and Young's modulus. The tensile testing is carried out by applying longitudinal or axial load at a specific extension rate to a standard tensile specimen with known dimensions (gauge length and cross sectional area perpendicular to the load direction) till failure. The applied tensile load and extension are recorded during the test for the calculation of stress and strain. ASTM E8: is a standard test method for tension testing of metallic materials. In general, the particle reinforced Al-MMCs are found to have higher elastic modulus, tensile and fatigue strength over monolithic alloys (P.M. Singh et al 1993). Increase in elastic modulus and strength of the composites are reasoned to the strong interface that transfers and distributes the load from the matrix to the reinforcement (Rang Chen et al 1997).

The results of the several investigations regarding the tensile properties of the Al_2O_3/ SiC/B_4C/Graphite/Zirconium particles reinforced Al6061 and other aluminum alloys can be summarized as follows: (J.R. Gomes et al 2005) investigated that, among many ceramic materials, SiC and Al2O3 are widely in use, due to their favorable combination of density, hardness and cost effectiveness. When these reinforcements are combined with Al-MMCs, the resulting material exhibits significant increase in its elastic modulus, hardness, strength and wear resistance. (M.V Ravichandran et al 1992) found that, alumina and other oxide particles like TiO2 etc. have received attention as reinforcing phase with aluminium alloy, as it is found to increase the hardness, tensile strength and wear resistance. (Nikhilesh Chawla et al 2001) studied the effect of Al2080 alloy reinforced with silicon carbide(SiC) metal matrix composites. It was observed that, increase in volume fraction, increases the elastic modulus, work hardening rate, macroscopic yield & tensile strengths, but coupled with lower ductility. **(**YU Xiao-dong *et al* 2007) studied the effect of Al5210 alloy reinforced with SiC metal matrix composites with a high volume fraction (50%) and various particle sizes of 10, 28, 40 & 63μm. It was concluded that, the bending strength of SiCp/5210 Al composite with a high volume fraction (50%) increases with decreasing particle size, but the fracture toughness of increases with the increasing particle size. (Zaklina Gnjidic *et al* 2001) investigated that, the SiC particles increases the yield strength and elastic modulus, but decreases the ultimate compressive strength and ductility of the Al7XXX base alloy. (J. Onoro *et al* 2010) investigated that, the effect of high-temperature mechanical properties of Al6061 with boron carbide (B_4C) shows improvement in the mechanical behavior and the tensile strength of AMCs with B_4C, and aluminium 6061 and 7015 matrix alloys without reinforcing, decreases with increase in temperature during age hardening. (H. Zhang *et al* 2004) concluded that, the strain rate response of aluminum 6092/B_4C composites increases with increasing volume fraction of particulate reinforcement**.** (B.Roebuck et al 1987) concluded that, aluminum metal matrix composites (MMC) reinforced with silicon carbide (SiCp) particles have up to 20% improvement in yield strength, lower coefficient of thermal expansion , higher modulus of elasticity and more wear resistance than the corresponding non-reinforced matrix alloy systems. (Gopal Krishna et al 2013) investigated that, boron carbide (B_4C) particles are very effective in improving the resistance to tensile strength of the Al6061 composite with increase in particle size. The tensile strength of AMCs was found to be maximum (176.37 MPa) for the particle size of 105μ. Increase in the strength is due to the increase in hardness of the composite. (Corbin S.F et al 1994) observed that, the reinforcing phase in the metal matrix composites bears a significant fraction of stress, as it is generally much stiffer than the matrix. Microplasticity in MMCs that takes place at fairly low stress has been attributed to stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles. (A. R. K. Swamy, et al 2011) found that increasing the graphite content within the Al6061matrix results in significant increases in the ductility, UTS, compressive strength and Young's modulus as compared to Al6061-Wc composites. (Mahendra Boopathi, M *et al* 2013) noticed that, Increase in area fraction of reinforcement in matrix result in improved tensile strength, yield strength and hardness. The percentage rate of elongation of the hybrid MMCs is decreased significantly with the addition of SiC and fly ash into Al2024 alloy. (K. Kalaiselvan *et al* 2013) observed that, AA6061–B_4C composites significantly enhanced the tensile strength of aluminum matrix and composites from 185 MPa to 215 MPa. This is mainly due to the strengthening mechanism by load transfer of the reinforcement. The addition of B_4C particles in the matrix induces much strength to matrix alloy by offering more resistance to tensile stresses.

4.0 Conclusions

The exhaustive literature survey presented above reveals that though much work has been reported to improve physical and mechanical properties of different aluminium alloys by using different types of reinforcements, a synergism in terms Al6061 alloy with Silicon carbide (SiC) and Boron Carbide (B_4C) reinforcements of hybrid composites to improve physical and mechanical properties by varying weight percentage or particle size has not been adequately addressed so far. Studies carried out worldwide on different types of reinforcements on hybrid composites, it appears that the combined effect of SiC and B_4C reinforcement on Al6061 alloy by using different manufacturing methods has still remained a less studied area. A further study in this respect is needed particularly by varying weight percentage and particle size of reinforcement by using low cost manufacturing stir casting technique in view of the scientific understanding and commercial importance. Behaviour of hybrid composites under solid particle erosion is another open-ended area in which a lot of meaningful research can be done.

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