Review of recent Studies in Al matrix composites

R. S. Rana* Rajesh Purohit*, and S.Das**

Abstract: In the past few years, materials R&D has shifted from monolithic to composite materials, adjusting to the global need for reduced weight, low cost, quality, and high performance in structural materials Driving force for the utilization of AMCs in areas of aerospace and automotive industries include performance, economic and environmental benefits. The key benefits of AMCs in Transportation sector are lower fuel consumption, less noise and lower airborne emissions. Various processing techniques for the fabrication of Aluminum matrix composites, testing of their mechanical properties are available. Several processing techniques like ultrasonic assisted casting, , powder metallurgy, high energy ball milling, friction stir casting are recently being used for the production of Aluminum matrix nano composites. During these processing techniques, grain growth takes place due to agglomeration of the reinforcing particles, which changes the microstructures. To control the grain size and agglomeration of nano particles during the processing and retaining the improved microstructure is a challenging task. Further research in this area is still awaited to control the microstructures under various processing conditions This paper reviews recent studies on the processing, microstructure, and mechanical properties of Aluminum-matrix composites.

Index Terms: R&D, AMCs, nanocomposites, Ultrasonic assisting casting ,agglomeration.

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(1) Introduction: During the past few years, materials design has shifted emphasis to pursue light weight, environment friendliness, low cost, quality, and performance. Parallel to this trend, metal-matrix composites (MMCs) have been attracting growing interest.[1-4].MMCs' attributes include alterations in mechanical behavior (e.g., tensile and compressive properties, creep, notch resistance, and tribology) and physical properties (e.g., intermediate density, thermal expansion, and thermal diffusivity) by the filler phase; the materials' limitations are thermal fatigue, thermochemical compatibility, and low-transverse creep resistance. The need for advanced engineering materials in the areas of aerospace and automotive industries had led to a rapid development of metal matrix composites (MMC) [1-2]. For applications in the automotive, transportation, construction, and leisure industries, affordable cost is also an essential factor. Apart from the emerging economical processing techniques that combine quality and ease of operations, [6-8] researchers are, at the same time, turning to particulate-reinforced aluminum-metal matrix composites (AMCs) because of their relatively low cost and isotropic properties[4,6,9] especially in those applications not requiring extreme loading or thermal conditions (e.g., automotive components). Also, the processing problems and commercial difficulties associated with continuously reinforced AMCs[9-10]are contributory to the recent interest in their particulate counterparts; the use of aluminum alloys for the matrix is preferred because of its comparative advantages,[11] including low cost ($1.5/kg) and ease of handling.

In AMC some of the constituent is aluminium/aluminium alloy termed as matrix phase The other constituent is embedded in this aluminium /aluminium alloy matrix and serves as reinforcement, which is usually non-metallic and commonly ceramic such as SiC and Al2O3Properties of AMCs can be tailored by varying the nature of constituents and their volume fraction. The major advantages of AMCs compared to unreinforced materials are as follows:

_ Greater strength
_ Improved stiffness
_ Reduced density(weight)
_ Improved high temperature properties
_ Controlled thermal expansion coefficient
_ Thermal/heat management
_ Enhanced and tailored electrical performance
_ Improved abrasion and wear resistance
_ Control of mass (especially in reciprocating applications)
_ Improved damping capabilities

The major disadvantage of metal matrix composites usually lies in the relatively high cost of fabrication and of the reinforcement materials. The cost-effective processing of composite materials is, therefore, an essential element for expanding their applications. The increasing demand for lightweight and high performance materials is likely to increase the need for Aluminum matrix composites .The availability of a wide variety of reinforcing materials and the development of new processing techniques like ultrasonic assisted casting, , powder metallurgy, high energy ball milling, friction stir casting are recently being used for the production of Aluminum matrix nano composites are attracting interest in composite materials.. This paper reviews recent studies on the processing, microstructure, and mechanical properties of Aluminum-matrix composites.

R. S. Rana* Rajesh Purohit*,S.Das**

*Department of Mechanical Engineering, Maulana Azad National Institute of Technology, Bhoapl-462051 **Advance Material and Processing Research Institute Bhopal

E-mail: r_purohit73@hotmail.com; ravindrarana74@gmail.com

(2) Processing of Aluminum Matrix composites: A key challenge in the processing of composites is to homogeneously distribute the reinforcement phases to achieve a defect-free microstructure. Based on the shape, the reinforcing phases in the composite can be either particles or fibers. The relatively low material cost and suitability for automatic processing has made the particulate-reinforced composite preferable to the fiber-reinforced composite for automotive applications.

Primary processing of AMCs

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

(A). Liquid state processes: Liquid state processes include stir casting , compocasting, squeeze casting spray casting and *in situ* (reactive) processing, ultrasonic assisted casting.

(B). Solid state processes :Solid state process include Powder blending followed by consolidation (PM processing), high energy ball milling, friction Stir Process ,diffusion bonding and vapour deposition techniques. The selection of the processing route depends on many factors including type and level of reinforcement loading and the degree of microstructural integrity desired.

2.1 Stir casting: In a stir casting process, the reinforcing phases (usually in powder form) are distributed into molten Aluminum by mechanical stirring. Stir casting of metal matrix composites was initiated in 1968, when S. Ray introduced alumina particles into an aluminum melt by stirring molten aluminum alloys containing the ceramic powders [11] A typical stir casting process of Aluminum alloy matrix composite is illustrated in Fig. 1 [12].Mechanical stirring in the furnace is a key element of this process. The resultant molten alloy, with ceramic particles, can then be used for die casting, permanent mold casting, or sand casting. Stir casting is suitable for manufacturing composites with up to 30% volume fractions [13, 14] of reinforcement. The cast composites are sometimes further extruded to reduce porosity. refine the microstructure, and homogenize the distribution of the reinforcement. A major concern associated with the stir casting process is the segregation of reinforcing particles which is caused by the surfacing or settling of the reinforcement particles during the melting and casting processes. 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 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 [15, 16].

An interesting recent development in stir casting is a two-step mixing process [27]. In this process, the matrix material is heated to above its liquidus temperature so that the metal is totally melted. The melt is then cooled down to a temperature between the liquidus and solidus points and kept in a semi-solid state. At this stage, the preheated particles are added and mixed. The slurry is again heated to a fully liquid state and mixed thoroughly. This two-step mixing process has been used in the fabrication of aluminum A356 and 6061 matrix composites reinforced with SiC particles. The resulting microstructure has been found to be more uniform than that processed with conventional stirring.

The effectiveness of this two-step processing method is mainly attributed to its ability to break the gas layer around the particle surface. Particles usually have a thin layer of gas absorbed on their surface, which impedes wetting between the particles and molten metals. Compared with conventional stirring, the mixing of the particles in the semi-solid state can more effectively break the gas layer because the high melt viscosity produces a more abrasive action on the particle surface. Hence, the breaking of the gas layer improves the effectiveness of the subsequent mixing in a fully liquid state.

Stir casting allows for the use of conventional metal processing methods with the addition of an appropriate stirring system such as mechanical stirring; ultrasonic or electromagnetic stirring; or centrifugal force stirring [17]. The major merit of stir casting is its applicability to large quantity production. Among all the well-established metal matrix composite fabrication methods, stir casting is the most economical(Compared to other methods, stir casting costs as little as one third to one tenth for mass production [18, 19] For that reason, stir casting is currently the most popular commercial method of producing aluminum based composites. process of stir casting is shown in figure 1.

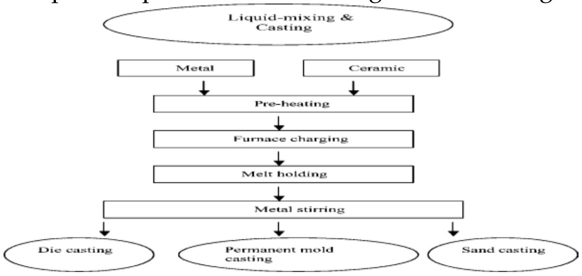


Figure 1(process of Stir Casting)

A. Sakthivel et al study, 2618 aluminum alloy metal matrix composites (MMCs) reinforced with two different sizes and weight fractions of SiCp particles up to 10% weight were fabricated by stir cast method and subsequent forging operation. The effects of SiCp particle content and size of the particles on the mechanical properties of the composites such as hardness, tensile strength, hot tensile strength (at 120^{0}C),and impact strength were investigated. The density measurements showed that the samples contained little porosity with increasing weight fraction. Optical microscopic observations of the microstructures revealed uniform distribution of particles and at some locations agglomeration of particles and porosity. The results show that hardness and tensile strength of the composites increased, with decreasing size and increasing weight fraction of the particles. The hardness and tensile strength of the forged composites were higher than those of the cast samples[100]

2.2 Compocasting: Stir casting is one of the simplest ways of producing aluminum matrix composites. However, it suffers from poor incorporation and distribution of the reinforcement particles in the matrix. These problems become especially significant as there reinforcement size decreases due to greater agglomeration tendency and reduced wettability of the particles with the melt. Development of new methods for addition of very fine particles to metallic melts which would result in more uniform distribution and effective incorporation of the reinforcement particles into the matrix alloy is therefore valuable Compocasting is a liquid state process in which there reinforcement particles are added to a solidifying melt while being vigorously agitated. It has been shown that the primary solid particles already formed in the semi-solid slurry can mechanically entrap the reinforcing particles, prevent their gravity segregation and reduce their agglomeration[20−21]. These will result in better distribution of the reinforcement particles. The lower porosity observed in the castings has been attributed to the better wettability between the matrix and the reinforcement particles as well as the lower volume shrinkage of the matrix alloy.

S. AMIRKHANLOU, B. NIROUMAND Synthesis and characterization of 356-SiCp composites by stir casting and compocasting methods .356-5%SiCp(volume fraction) composites, with average SiCp sizes of about 8 and 3 μm, were produced by injection of different forms of the reinforcement particles into fully liquid as well as semisolid slurries of 356 aluminum alloy and the effects of the injected reinforcement form and the casting method on distribution of the reinforcement particles as well as their porosity, hardness and impact strength were investigated. The results reveal that addition of SiC particles in the form of (Al-SiCp)cp composite powder and casting in semisolid state (compocasting) decreases the SiCp particle size, enhances the wettability between the molten matrix alloy and there reinforcements and improves the distribution of the reinforcement particles in the solidified matrix. It also increases the hardness and the impact energy of the composites and decreases their porosity [105].

2.3 Squeeze casting: Although the concept of squeeze casting dates back to the 1800s [22, 23], the first actual squeeze casting experiment was not conducted until 1931 [24].Squeeze casting process is the combination of gravity die casting and closed die forging. The technique in which metal solidifies under pressure within closed die halves. The applied pressure and the instantaneous contact of molten metal with the die surface produces rapid heat transfer that yields a porous free casting with mechanical properties approaching the wrought product . Squeeze casting offers high metal yield, nil or minimum gas or shrinkage porosity, excellent surface finish and low operating costs. Squeeze casting (also known as extrusion casting, squeeze forming, liquid forging) was developed to produce high quality components. In this process, pressure is applied on the solidifying liquid metal. Due to the intimate contact between the liquid metal and the mold and hence higher rate of heat removal across the metal mold interface, premium quality castings are obtained. The patent on this process seems to be that of James Hollingrake in 1819 from Manchester. The steps involved in this process are: (i) pouring of metered quantity of liquid metal with adequate super heat in to the die cavity, (ii) application of pressure on the liquid metal and maintaining the same till the solidification is complete and (iii) removal of the casting and preparation of the die for the next cycle. These steps are illustrated schematically

The process is basically divided into two types: direct and indirect. What is shown is the direct process, where the squeeze pressure is applied through the die-closing punch itself, whereas in the indirect process, the squeeze pressure is applied after closing of die, by a secondary ram .Specific feature of squeeze casting over conventional die casting:

1. Solidification under pressure enhances internal soundness, thereby increasing the suitability potential for critical applications.

2. Squeeze casting results in a high degree of refinement in the structure of the alloy. Grain size reduction to the extent of 50% of that of the conventionally gravity cast alloy is usually possible finer microstructure

3. In general, material formed by squeeze casting has a fine equiaxed grain structure and exhibit higher toughness than materials formed by gravity casting.

3. Absence of gas/shrinkage porosity.

4. Near net shape, high degree of surface finish and dimensional accuracy.

5. Significant improvement in mechanical properties due to finer microstructure

6. Faster cycle times.

7. In conjunction with high quality reusable dies and thin die coatings, good dimensional reproducibility is possible, matching that of pressure die casting.

8 . In the absence of running or feeding system, a high metal yield approaching 95% can be achieved because all the metal poured into the die is used to form the components.

9. Casting alloys as well as wrought alloys can be squeeze cast to finished shapes; castability and fluidity of the material are of little concern. Suitable for long freezing alloys too.

10. Components of forging quality can be produced by squeeze casting.

Process of Squeeze casting is shown in figure 2

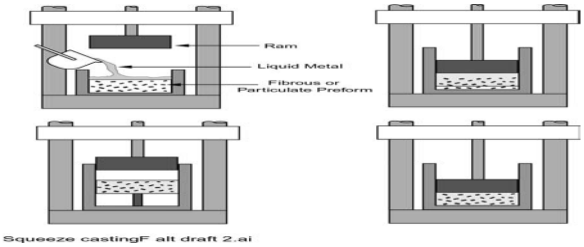


Figure 2 (process of squeeze casting)

Abdulkabir Raji Study was carried out to compare cast microstructures and mechanical properties of aluminium silicon alloy components cast by various means. For this purpose, sand casting, chill casting and squeeze casting methods were used to produce similar articles of the same shape and size from an Al-8%Si alloy. It was observed that the grain size of the microstructures of the cast products increased from those of squeeze casting through chill casting to sand casting. Conversely, the mechanical properties of the cast products improved from those of sand casting through chill casting to squeeze casting. Therefore, squeeze cast products could be used in as cast condition in engineering applications requiring high quality parts while chill castings and sand castings may be used in as cast condition for non-engineering applications or engineering applications requiring less quality parts.[111]

2.4 Powder Metallurgy: Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape (compacted), and then heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: (1) powder manufacture, (2) powder mixing and blending,(3) compacting, (4) sintering. Compacting is generally performed at room temperature, and the elevated-temperature process of sintering is usually conducting at atmospheric pressure. Optional secondary processing often follows to obtain special properties or enhanced precision.

Two main techniques used to form and consolidate the powder are sintering and metal injection molding. Recent developments have made it possible to use rapid manufacturing techniques which use the metal powder for the products. Because with this technique the powder is melted and not sintered, better mechanical strength can be accomplished.

Powder Metallurgy is a highly evolved method of manufacturing reliable net shaped components by blending elemental or pre-alloyed powders together, compacting this blend in a die, and sintering or heating the pressed part in a controlled atmosphere furnace to bond the particles metallurgically. The P/M process is a unique part fabrication method that is highly cost effective in producing simple or complex parts at, or close to, final dimensions. P/M processing provides the following advantages.

Production of complex shapes to very close dimensional tolerances, with minimum scrap loss and fewer secondary machining operations.

Physical and mechanical properties of components can be tailored through close control of starting materials and process parameters.
-Particular properties can be improved through secondary processing operations such as heat treating and cold/hot forming..

The advantages of this processing method include the capability of incorporating a relatively high volume fraction of reinforcement and fabrication of composites with matrix alloy and reinforcement systems that are otherwise immiscible by liquid casting. However, this method requires alloy powders that are generally more expensive than bulk material, and involves complicated processes during the material fabrication. Thus, powder metallurgy may not be an ideal processing technique for mass production.

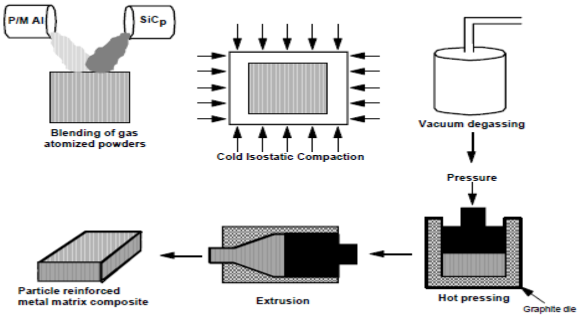


Figure 3 shows process of Power metallurgy

R. Sagar , R. Purohit Al–SiCp composite with 10, 15, 20, and 25 wt% of SiCp were fabricated through die compaction of powders and subsequent sintering at580 ◦C. then Valve seat inserts of this composites were also fabricated through the gravity die casting process. The hardness, density, radial crushing load and surface roughness of the Al–SiCp composites (with different wt % of SiCp) and steel valve seat inserts presently used in engines were measured and compared. The hardness and radial crushing load for Al–15, 20, and25wt%of SiCp composite valve seat inserts were higher than thatof the steel valve seat inserts presently used in engines. The microstructure of the cast and powder metal Al–SiCp composites was also studied[106]

2.5 High energy ball milling: Although casting is the cheapest technique for composite fabrication, it is difficult to use for synthesizing Al with nanosize hard particles due to the extreme gap difference in the thermal expansion coefficients between the two constituents and also because of poor wettability between molten Al (or Al alloys) and hard nanoparticles In addition it may lead to an undesirable reaction between reinforcement and molten Al, producing brittle phases of Al4C3 and Si in case of Al nano SiC particles .To avoid both making brittle phases and particle agglomerations during fabrication of Al/SiC composite ,solid state process such as mechanical alloying (MA) has been suggested .Mechanical alloying of multi-component powders is a solid state process capable to obtain metastable structures as amorphous and nanocrystalline materials with high thermal stability . Powder particles in the ball mill are subjected to high-energy collision, which causes the powder particles to be cold-welded together and fractured. High energy ball milling processes, including attrition mills, SPEX shaker mills and planetary ball mills, have been established as a non-equilibrium mechanical processing technique to achieve solid state reaction of various alloy systems and nanocrystalline materials. The mechanical properties of particle reinforced composites are largely dependent on the reinforcement particle microstructure, distribution and volume fraction[102]

Y. Saberi et al Al matrix composites powers reinforced with SiC was prepared by high energy ball mill. To clarify the role of particle size of SiC on lattice strain and grain size of Al two series of SiC with micron and nano-size were selected. Aluminum and SiC powders were mixed mechanically and milled at different times (2, 5, 10 h) to achieve Al–2.5 vol% SiC and Al–5 vol%SiC composite powders. The produced composites were investigated using X-ray diffraction pattern (XRD) to elucidate the role of particle size, secondary phase content and milling time on grain size and lattice strain of Al matrix. The results showed that an increase in milling time caused to reduce the grain size unlike the lattice strain of Al matrix. At the same condition a faster grain refinement for Al/SiC nanocomposites were observed with respect to Al/SiC composites[102]Lauri Kollo et al composites was produced by mixing aluminium powders with 1 vol.% of silicon carbide(SiC) nanoparticles in High-energy planetary mill. A number of milling parameters were modified for constituting the relationship between the energy input from the balls and the hardness of the bulk nanocomposite materials. It was shown that mixing characteristics and reaction kinetics with stearic acid as process control agent canbe estimated by normalised input energy from the milling bodies. For this, the additional parameter characterising the vial filling was determined experimentally. Depending on the ball size, a local minimum in filling parameter was found, laying at 25 or 42% filling of the vial volume for the balls with diameter of 10and 20mm, respectively. These regions should be avoided to achieve the highest milling efficiency. After a hot compaction, fourfold difference of hardness for different milling conditions was detected. There with the hardness of the Al–1 vol.% nanoSiC composite could be increased from 47HV0.5 of pure aluminium to163HV0.5 when milling at the highest input energy levels.[103] S.S. Razavi Tousi Eet al used the High energy ball milling to produce a nanostructured Al matrix composite reinforced by submicron α-alumina particles and produced compositesofAl–20 wt.% Al2O3. Scanning electron microscopy analysis as well as tap and green density measurements were used to optimize the milling time needed for the completion of the mechanical milling process. Results show that addition of alumina particles as the reinforcement has a drastic effect on the size, morphology and pressability of the powder. Scanning electron microscopy shows that distribution of alumina particles in theAl matrix reaches a full homogeneity after steady state. This would increase the hardness of powder due to anano-structured matrix and oxide dispersion strengthening. High energy ball mill was successfully use to produced submicron metal matrix composites.[107]

2.6 In situ Synthesis: Aluminum matrix composites, reinforced with various ceramic particles suchas SiC, TiC, and AlN, are fabricated through stir casting, squeeze casting ,or powder metallurgy However ,these fabrication processes usually require expensive reinforcement materials and involve complex equipment and procedures, thus imposing a relatively high cost. An alternative route for cost-effective fabrication of metal matrix composites is in situ synthesis method developed in recent years. This method offers a number of attractive features, such as good reinforcement/matrix compatibility, homogeneous distribution of the reinforcing particles, and potentially low cost.

Unlike other fabrication methods of the composite material, *in-situ* synthesis is a process wherein the reinforcements are formed in the matrix by controlled metallurgical reactions. During fabrication, one of the reacting elements is usually a constituent of the molten matrix alloy. The other reacting elements may be either externally-added fine powders or gaseous phases .One of the final reaction products is the reinforcement homogeneously dispersed in matrix alloy. This kind of internally-produced reinforcement has many desirable attributes. For example, it is more coherent with the matrix and has both a finer particle size and amore homogenous distribution. However, the process requires that the reaction system be carefully screened. Favourable thermodynamics of the anticipated reaction. Figure 4 shown in process of In Situ Synthesis

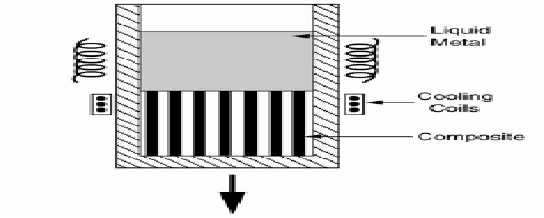


Figure 4 (process of In Situ Synthesis)

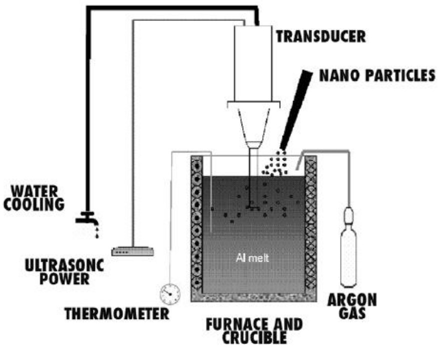
T.V. Christy et al manufactured the Aluminum-TiB2 metal matrix composite containing 12% by weightTiB2p through in-situ process and made the comparison of the mechanical properties and themicrostructure of Al 6061 alloy with Al–TiB2 metal matrix composite Results showed that the composite Al-6061/TiB2/12p was successfully produced by the in-situ reaction procedure. Strings as well as particulate agglomerates were present as distinct microstructural features of the composite. The manufactured Al-TiB2 composite exhibited higher values of hardness, tensile strength and Young's modulus than the base alloy. The ductility of the composite was found to be slightly lower than that of the aluminium 6061alloy[101].

2.7 Pressureless infiltration: The term ''pressureless infiltration'' describes the process by which the voids in the porous body are filled by the liquid metal without the aid of any external pressure [28,29]. During the infiltration process, molten alloys flow through the channels of the reinforcement bed or perform under the capillary action. Certain criteria have to be met for the spontaneous infiltration to occur However, there are some barriers that prevent this method to display it spotential as a feasible technique of composite manufacturing. Paramount of these problems is the slight wetting of the SiC substrate by molten aluminum which is resulted from the formation of oxide layer on the surface of Al melt. Undesirable reactions at the Al/SiC interface are the other obstacle, altering the chemical composition of the molten aluminum and lead to the formation of unwanted phases at the interface, such asAl4C3 and Al3SiC4 [29A]. Pech-Canul et al. [28,29] believe that optimum conditions are to be provided in order that a successful infiltration may be accomplished without using any artificial outer pressure. According to their comments, these optimum conditions include: (1) adding preferably more than 3% magnesium to the aluminum melt, (2) using SiC particles with a thin silicon wafer on the top, (3) providing the internal pressure of 1.2 atm

for the furnace, and (4) changing the internal atmosphere of the furnace to 100% nitrogen [29]. Magnesium is a powerful surfactant that scavenges oxygen from the melt surface and forms the MgAl2O4 spinel at the Al/SiC interface. In addition to increasing the driving force for wetting, the reaction of producing MgAl2O4 spinel consumes the oxygen present in the atmosphere, thins the oxide layer, and thus enhances wetting[13,14]. Besides, application of nitrogen atmosphere not only hinders formation of the oxide layer but also enhances wetting of SiC by Al melt [29].

2.8 Ultrasonic Assisted Casting: In recent years, significant effort has been taken to develop metal matrix nanocomposites (MMNCs) [30-41].Compared with conventional metal matrix composites (MMCs) that are reinforced with micro inclusions, this new class of material can overcome many disadvantages in MMCs [42-43], such as poor ductility, low fracture toughness and machinability. The properties of metals would be enhanced considerably if reinforced by ceramic nanoparticles (less than 100nm). Moreover, MMNCs couldoffer a significantly improved performance at elevated temperatures [36-39] Traditional fabrication methods, such as high energy ball milling, rapid solidification, electroplating, and sputtering etc, can not be used for mass production and net shape fabrication of complex structural components without significant post processing [36-41]. new method that combines solidification processes with ultrasonic cavitation based dispersion of nanoparticles in metal melts has been developed. Ultrasonic cavitation can produce transient (in the order of nanoseconds) micro "hot spots" that can have temperatures of about 5000ºC,pressures above 1000 atms, and heating and cooling rates above 1010 K/s [44]. The strong impact coupling with local high temperatures can potentially break the nanoparticle clusters and clean the particle surface. Since the nanoparticle clusters are loosely packed to gather, air could be trapped inside the voids in the clusters which will serve as nuclei for cavitations. The size of clusters ranges from nano to micro due to the attraction force among nanoparticles and the poor wettability between the nano particles and metal melt.

Donthamsetty Set al prepared the composites by ultrasonic cavitation assisted fabrication and investigate the effect of selected nanomaterials (SiC, B4C, CNTs) on the microstructure and mechanical properties of composite, a new method is used to avoid agglomeration and segregation of particles. Then, tensile specimens with different weight fractions of nanomaterials are cast and tested. The microstructure of the composites is investigated by scanning electron microscopy (SEM). Experimental results show a nearly uniform distribution and good dispersion of the nano-particles within the Al matrix, although some of small agglomeration found. Both hardness and tensile strength are enhanced by incorporation of nano materials into matrix. The enhancement in values of hardness and tensile strength observed in this experiment is due to small particle size and good distribution of the particles, which was confirmed by SEM pictures[110]



Ultrasonic Assiated Casting Process

2.9FrictionStirWelding(FSP): nanoreinforcements in a uniform manner is a critical and difficult task. It should be pointed out that the existing processing techniques for forming surface composites are based on liquid phase processing at high temperatures. In this case, it is hard to avoid the interfacial reaction between reinforcement and metal matrix and the formation of some detrimental phases. Furthermore, critical control of processing parameters is necessary to obtain ideal solidified microstructure in surface layer. Obviously, if processing of surface composite is carried out at temperatures below melting point of substrate, the problems mentioned above can be avoided. Recently, much attention has been paid to a new surface modification technique named friction stir processing (FSP) .FSP is a solid state processing technique to obtain a fine-grained microstructure. This is carried out using the same approach as friction stir welding (FSW), in which a non-consumable rotating tool with a specially designed pin and shoulder is plunged into the interface between two plates to be joined and traversed along the line of the joint. Localized heating is produced by the friction between the rotating tool and the work piece to raise the local temperature of the material to the range where it can be plastically deformed easily. As the rotating tool traverses along the joint line, metal is essentially extruded around the tool before being forged by the large down pressure. It is well known that the stirred zone consists of fine and equiaxed grains produced due to dynamic recrystallization. Though FSP has been basically advanced as a grain refinement technique, it is a very attractive process for also fabricating composites.Mishra et al. [108] fabricated the Al/SiC surface composites by FSP, and indicated that SiC particles were well distributed in theAl matrix, and good bonding with the Al matrix was generated. A. Shafiei-Zarghani et al used friction stir processing (FSP) to incorporate nano-sized Al2O3 into 6082 aluminum alloy to form particulate composite surface layer. Samples were subjected to various numbers of FSP passes from one to four, with and without Al2O3 powder. Microstructural observations were carried out by employing optical and scanning electron microscopy (SEM) ofthe cross sections both parallel and perpendicular to the tool traverse direction. Mechanical properties include microhardness and wear resistance, were evaluated in detail. The results show that the increasing in number of FSP passes causes a more uniform in distribution of nano-sized alumina particles. The microhardness of the surface improves by three times as compared to that of the as-received Al alloy. A significant improvement in wear resistance in the nano-composite surfaced Al is observed as compared to the as-received Al.[109]

(3) The microstructure of Aluminum matrix composites :The key features in the microstructure of a composite material resulting from the interaction between the matrix and the reinforcement usually include the type, size, and distribution of secondary reinforcing phases, matrix grain size, matrix and secondary phase interfacial characteristics, and microstructural defects. The mechanical properties of the composite materials are strongly influenced by these factors.

3.1Types of reinforcement: Two types of reinforcing materials have been investigated for Aluminum matrix composites. The first and most widely used is ceramic. The other is metallic/ Intermetallic Ceramic particles are the most widely studied reinforcement for Aluminum matrix composites. Some common properties of ceramic materials make them desirable for reinforcements. These properties include low-density and high levels of hardness, strength, elastic modulus, and thermal stability .However, they also have some common limitations such as low wettability, low ductility, and low compatibility with a Aluminum matrix. Among the various ceramic reinforcements Al203 , SiC is the most popular because of its relatively high wettability and its stability in a magnesium melt, as compared to other ceramics.

The shape of reinforcement is another factor affecting the reinforcing effect. In a Aluminum matrix composite, the most commonly used reinforcements assume a shape of short fiber/whisker, or particle, or a mixture of these twoconfigurations. Short fiber/whisker reinforced Aluminum alloys usually show better mechanical properties than the particle reinforced Aluminum alloy with some degree of anisotropic behaviors. To overcome the barriers of relatively high cost and the anisotropic properties associated with fiber reinforcement, some recent efforts have been made to reduce the fiber cost by developing a new fibrous material and using hybrid reinforcements that incorporate particles into fibers. For instance, because the cost of aluminum borate whiskers is about only 10% of that of SiC whiskers [45],

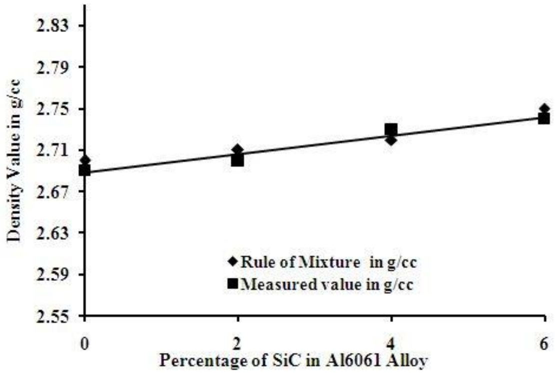
Because of metallic solids will generally have a much better wettability with liquid metals than ceramic powders, the reinforcing of a Aluminum matrix with metallic/intermetallic particulates has recently been examined. The advantages of the metallic reinforcements lie in their high ductility, high wettability and high compatibility with the matrix as compared with ceramics, and their great strength and elastic modulus as compared to the Aluminum matrix.

3.2 Interfacial characteristics: The interface between the matrix and the secondary reinforcing phase plays a crucial role in the performance of composite materials. The key features of the interface are the chemical reactions and the strength of bonding. Interfacial reactions in the Aluminum matrix composite are predominantly determined by the composition of the matrix and the reinforcement materials. A comparison study of the interfacial reactions in pure magnesium and AZ91 alloy based composites reinforced with SiC particles has evinced the effect of a matrix alloy composition on the particle/matrix interfacial phenomena. Porosity also influences the interfacial reactions between the matrix and the reinforcing phases. Porosity might have increased the surface area and thus promoted the reaction. The surface cleanliness of the raw materials is another factor affecting the interface chemical reactions. The parameters of the casting process such as melting temperature and holding time have also been found to change the interface reactions in the Aluminum composite [46].Higher temperature normally accelerates interfacial reactions, as governed by the Arrhenius law. The degree of interfacial reactions can also change the microstructure [46]. To obtain composite materials with the desired microstructure and properties, the interfacial reaction should be controlled through selecting an appropriate matrix alloy, conducting an appropriate surface treatment of the reinforcement, and correctly controlling the process parameters.

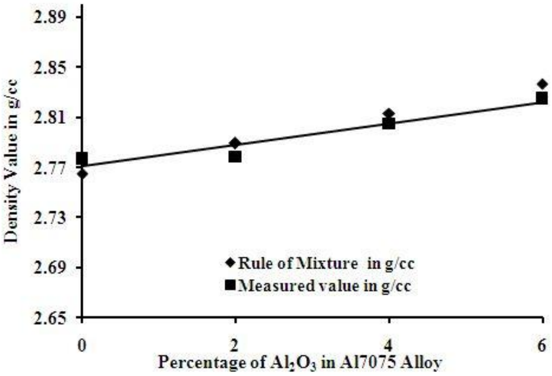
3.3 Porosity and Inclusions: Porosity and inclusions are detrimental to the mechanical Properties of Aluminum matrix composites. The porosity in a composite may arise from a number of sources. These include: theentrapment of gases during mixing, hydrogen evolution, and the shrinkage of the alloy during its solidification. The entrapment of gases depends mainly on the processing method, such as mixing and pouring. Holding time and stirring speed as well as the size and position of the impeller can also significantly affect the porosity formation [47].Usually some water vapour is absorbed on the surface of the added fibers or particles. Once entering the melt, the water vapour can react strongly with Al, forming Al203 and releasing H2. Although gas porosity in casting is much more sensitive to the volume fraction of the inclusions than to the amount of dissolved H2 [48]. In the Aluminum matrix composite, the presence of relatively large amounts of fibers/particles may impose a serious porosity problem if the reinforcement is not properly degased prior to its addition to the melt. This is especially true for finer particles due to the larger number of specific surface areas involved. Inclusion is another major microstructural defect that is deleterious to material properties. The processing of some metal matrix composites requires melt stirring. Some of the conventional methods for removing inclusions, such as flux refining and gas sparging and settling, may no longer be suitable for processing the metal matrix composites[49]. In addition to the inclusion density, the inclusion size is also important in determining the mechanical properties of the composite materials. It was observed [50] that larger inclusions are normally more harmful to the material’s properties. Thus, care must be taken to prevent the formation of inclusions in the magnesium matrix composites.

(4) Properties of Al Composites Materials: From the nature and morphology of the composites, their behavior and properties can be predicted and the factors such as intrinsic properties, structural arrangement and the interaction between the constituents are of much importance. The intrinsic properties of constituents determine the general order of properties that the composite will display. The shape and size of the individual constituents, their structural arrangement and distribution and the relative amount of each contribute to the overall performance of the composite. 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 and the most commonly used approach is based on the assumption that each phase component is Subjected to either iso-stress or iso-strain condition.

4.1 Physical Properties: Density is the physical property that reflects the characteristics of composites. In a composite, the proportions of the matrix and reinforcement are expressed either as the weight fraction (*w*), which is relevant to fabrication, or the volume fraction (*v*), which is commonly used in property calculations. Experimentally, the density of a composite is obtained by displacement techniques [51] using a physical balance with density measuring kit as per ASTM: D 792-66 test method. Further, the density can also be calculated from porosity and apparent density values (sample mass and dimensions) [52]. The results of the several investigations [52-53] regarding the density of the Al2O3/ SiC particle reinforced Al6061 and other aluminum alloys can be summarized as follows: the reinforcements Al2O3 and SiC enhance the density of the base alloy when they are added to the base alloy to form the composite. Moreover, the theoretical density values match with the measured density values of these composites. Further, Miyajima et.al. [55] reported that the density of Al2024-SiCparticle 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. To support the above findings, few composites were developed to study the density. The Al6061-SiC and Al7075-Al2O3 particulate reinforced composites were developed by liquid metallurgy technique (stir casting route). The cast alloy and composite specimens were subjected to density test by two methods, i.e. weight to volume ratio and another being the rule of mixture, the obtained results are shown in the Figures 1 and 2



Theoretical and Experimental Density of Al6061-SiC Composites



Theoretical and Experimental Density of Al7075-Al2O3 Composites

From the above figures, it can be observed that the density of the composite is higher than the base matrix. Also, the density of the composites increased with increase in filler content. Further, the theoretical and experimental density values are in line with each other. The increase in density of composites can be attributed to higher density of reinforcement particles.

4.2 Mechanical Properties of Al Composites: Mechanical properties of metal matrix composites (MMCs) are essentially functions of the manufacturing processes. Surface state and roughness conditions as well as the type of matrix reinforcement and heat treatment influence the mechanical behaviour of the MMCs in service conditions.

The factors such as the porosity of the matrix, volume fraction of the reinforcement and their distribution, agglomeration or sedimentation of particles and particle size, dross and porosities influence the behaviour of the MMC Improving such mechanical properties as tensile strength, hardness, Young's modulus, creep resistance, and fatigue resistance, is usually the major attraction of composite materials.

4.2.1 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 $H_c=V_rH_r+V_mH_m$ (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 [56] helps in approximating the hardness values. 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) [5].The contributions of several researchers regarding the effect of reinforcement on hardness of the composites are summarized as follows; The particulate reinforcements such as SiC, Al2O3 and aluminide [57-59] are generally preferred to impart higher hardness. The coating of reinforcements with Ni [60] and Cu [61], also leads to good quality interface characteristics and hence contribute in improving hardness. TiC when dispersed in Al matrix, increases the hardness to weight ratio. Moreover, it imparts thermodynamic stability to the composites [62-64]. Wu [65] and Deuis [66] attributed this increase in hardness to the decreased particle size and increased specific surface of the reinforcement for a given volume fraction. Sug Won Kima et.al. [21] reasoned the increase in hardness of the composites to the increased strain energy at the periphery of particles dispersed in the matrix. Deuis et.al. 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 [66]. 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 [67-69]. Subramanian [70] incorporated Silicon in Al alloy sand concluded that the higher wt.% of Si improves the hardness of the composites and increased particle size improves the load carrying capability of the composites [71]. The heat treated alloy and composite exhibits better hardness [72-74], however, the over-aged condition may tend to reduce the hardness significantly [75].

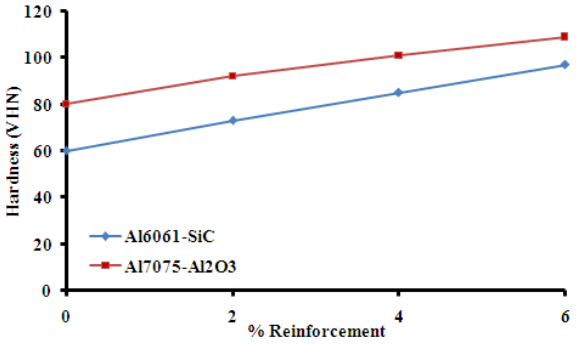


Figure 3. Variation of Vicker's Hardness of Al6061-SiC and Al7075-Al2O3 Composites

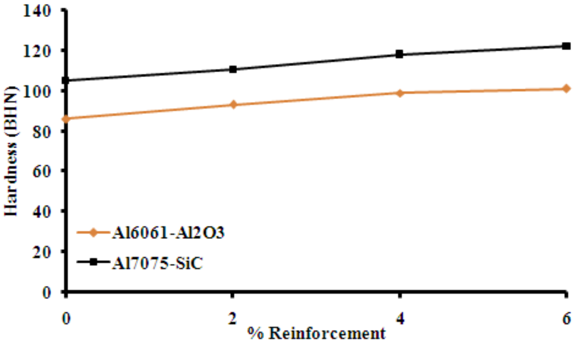


Figure 4. Variation of Brinell's Hardness of Al6061-Al2O3 and Al7075-SiC Composites

The composites developed (as explained above) were subjected to hardness test using the Vicker's and Brinell's hardness testing machines. From the Figures 3 and 4, it can be observed that the hardness of composites were greater than that of its base alloy. Further, the hardness of the composite is found to increase with increased filler content.

4.2.2 Tensile strength*:* In general, the Al-MMCs are found to have higher elastic modulus, tensile and fatigue strength over monolithic alloys [76-79]. In case of heat treatable Al-alloys and their composites, the yield strength of composites increase after heat treatment [80] by reducing the cracking tendency [81] and improving the precipitation hardening [82]. The composites, before fabrication process, are heat treated to an under aged condition as the materials can be shaped more easily and after fabrication, these materials are heat treated to the peak aged condition so as to provide improved mechanical properties [83]. 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 [84]. Further, the studies on Al-MMCs are mainly concentrated on Al–SiC, Al–Al2O3 based systems with limited studies on Al–TiO2composites, though TiO2 particles have excellent mechanical properties [85].

4.2.3 Fracture Toughness: The fracture toughness of a material is assessed in terms of crack tip parameter at the initiation of crack growth. The fracture toughness of the composite decreases with increase in the reinforcement content and size. In the study of fracture toughness characteristics of discontinuously reinforced Aluminium, Mortenson (87) has reported that fracture will occur when the crack tip strain et exceeds over some microstructurally significant characteristic distance (Io), ahead of the crack tip. Under condition of small scale yielding $et = c\delta / x$ where δ is the crack tip opening displacement, x the distance ahead of the crack, and c is a constant of the order of 1. At fracture initiation $et = ef$ over a distance $x = Io$, when $\delta = \delta c$ and, for small scale yielding: $\delta c = CK^2 / E\sigma y$. where K is the stress intensity factor, E is the Young‟s modulus, σy is the yield stress, and C is a numerical constant which depends on the work hardening exponent "n" and the stress state. Typically the value of "C" rangesbetween ~ 0.5-0.6. Klimowicz and Vecchio (86) in Al2O3 reinforced 6061 and 2014 alloys, found that the fracture toughness decreased with aging time, and hence increasing strength, and also continued to decrease even in the overaged condition where the strength was decreasing. Pezzoti & Muller (88) have shown some experimental details that allow the assessment of microfracture processes in alumina-based ceramics and have given experimental and computational conditions allowing the minimization of errors. According to their experimental procedures, a rising R-curve and CTOD trend could be calculated from a knowledge of microstress fields evaluated by fluorescence spectroscopy experiments. They suggest that the fracture behavior of ceramic-based materials with sharp well-defined fluorescence lines can be quantitatively analyzed in terms of the measured microscopic stress fields.

4.2.4 Creep: Creep is defined as the progressive deformation of a material under the action of a constant applied load. Creep does not become significant until temperatures of the order of 0.3 Tm for metals and 0.4 Tm for alloys is reached. Creep behavior in particulate reinforced MMCs is characterized by a progressively increasing creep rate [tertiary creep] over most of the creep life. Kondo et al (89) have investigated the creep behavior of the continuous fiber reinforced unidirectional composites due to the viscoelasticity of the resin matrix assuming that the constituent matrix obeys the nonlinear creep law and the fiber is the linear elastic materials. They have utilized a quasi three-dimensional finite element method, the macroscopic creep behavior of the composites with regular fiber packing is obtained, giving the orthotropic creep law for the composites. Clauer & Henson (90) have reported the enhancement of creep resistance in dispersion-strengthened materials, due to precipitation hardening. In these systems, the enhanced strength is due to the effective blocking of dislocation movement by insoluble particles on the slip plane, rather then the particles actually carrying any proportion of the load. Hence power-law creep rates are significantly curtailed, even at low volume fractions (1%). Barai & Wang (91) have developed a composite model to examine the creep resistance of nanocrystalline solids. This model divides the material into two regions, one the plastically harder grain interior and the other the plastically softer grain-boundary affected zone . The creep rate of each phase is described by a unified constitutive equation that can account for the effect of stress, strain-hardening, and temperature. The increase of creep resistance is attributed to the decrease of grain size through the Hall–Petch effect, but a continuous decrease of grain size would increase the presence of the softer grain boundary affected zone and this in turn could result in the softening effect for the nanocrystalline solid.

4.2.5 Fatigue: The fatigue behaviour of MMCs is very important for many engineering applications involving cyclic or dynamic loading. When the composite materials are subjected to cyclic stress amplitude, the resulting strain amplitude may change with continued cycling. Cyclic strain produces a number of damaging process which affect the microstructure and the resulting cyclic strain resistance and low-cycle fatigue. The cyclic strain amplitude reversals to the failure can be viewed as an indication of the resistance of the composites microstructure to microscopic crack formation, potential propagation and coalescence of the cracks culminating in fracture. The strains are much lower in the composite materials than they would be in the unreinforced material. This is because of the higher elastic modulus and higher proportional limit of the composite material. Many researchers (92-94) have reported the presence of particulate reinforcements results in the development of localised stresses from constraints in matrix deformation around the reinforcing particles. The highly localised stresses contribute to the observed work-hardening behaviour of the composites. The concentration of the localised stresses results from constraints in matrix deformation that occur because of the significant difference in elastic modulus of the constituents of the composite, i.e. the discontinuous particulate-reinforcement and continuous phases and the continuous Aluminium alloy metal matrix. Thimmarayan R et al (95) have reported that the number of cycles for the fatigue failure of the composites increases with the decrease in particle size of the SiCp. It has been shown (96) that the improvement in fatigue life evident in stress life data is eliminated when compared on a strain life basis. Under constant strain amplitude conditions, the MMC is inferior in the low cycle regimes where plastic strains dominate, and in the high cycle regimes, the composite is superior to the unreinforced material. The improvement observed in constant stress amplitude tests reflects the fact that the strains in the composite are lower than those in the unreinforced material at the same stress level.

E. Bayraktar et al Invetigate the static and cyclic deformation behaviour of these two metal matrix composites at roomtemperature; 2124/Al-Si-Cu fabricated by powder metallurgy and AS7G/Al-Si-Mg fabricated by foundry. AS7G composite showed considerable lower mechanical properties regarding to the 2124 composite. In the AS7G composite, the crack generally initiated at the interface (SiC/matrix) with many interface debonding between the SiC particles and the matrix. This was the principal cause of the reduced fatigue strength.[104]

4.2.6 Elongation :Ductility is one of the important aspects in the mechanical properties of composites. The tensile elongation decreases rapidly (97) with the addition of reinforcing particles and with increased aging time in the heat treatable alloys. Matrix deformation between closely spaced elastic particles would be highly constrained, resulting in local stress levels as found by Drucker (98).Lee et al (99) have examined the tensile properties and microstructures of AA6061/SiCp composites fabricated by the pressure less infiltration method under a nitrogen atmosphere. They reported that reaction products (Al_4C_3) which were formed at the interface between SiCp and Al alloy matrix as a result of the in situ reaction has significant effect on the ductility rather than strength.

CONCLUDING REMARKS:

This review presents the views, theoretical and experimental results obtained and conclusions made over the years by varies investigators in the field of aluminum alloy -MMCs. A considerable amount of interest in Al-MMCs evinced by researchers from academics and industries has helped in conduction of various studies and has enriched our knowledge about the processing of Aluminum alloy composites, their physical properties, mechanical properties .Several techniques are followed by researchers for the processing of Aluminum alloy reinforced MMCs.

(1) An optimized combination of surface and bulk mechanical properties may be achieved, if Al-MMCs are processed with a controlled gradient of reinforcing particles and also by adopting a better method of manufacturing . however processing of aluminum nanocomposites with high volume friction of reinforcement with hard particles is really challenging task. There is no clear relation between mechanical properties of the composites, volume fraction, type of reinforcement and surface nature of reinforcements, the reduced size of the reinforcement particles is believed to be effective in improving the strength of the composites.

(2)It has been studied and concluded that the density of the composites increases with the Addition of the hard ceramic reinforcement into the matrix material. In view of the above conclusions on density, experiments were conducted on the Al6061-SiC and Al7075-Al_2O_3 to determine the density by weight to volume ratio and by rule of mixture. 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.

(3) The hardness of the composites was reviewed and on conclusion, it is discovered that as the reinforcement contents increased in the matrix material, the hardness of the composites also increased. Further, the tests conducted to determine the same indicated the (Vickers and Brinell's hardness) increased hardness with increased reinforcement contents when compared with the base matrix. The mechanical properties were reviewed with respect to strength. It is evident that the structures and properties of the reinforcements control the mechanical properties of the composites. The reported literature regarding the variations of the compression strength of ceramic filled aluminum composites are meager.

(4) In general, the Al-MMCs are found to have higher elastic modulus, tensile and fatigue strength over monolithic alloys In case of heat treatable Al-alloys and their composites, the yield strength of composites increase after heat treatment by reducing the cracking tendency and improving the precipitation hardening.

(5) The fracture toughness of the composite decreases with increase in the reinforcement content and size. fracture will occur when the crack tip strain et. exceeds over some microstructurally significant characteristic distance , ahead of the crack tip .

(6) Creep does not become significant until temperatures of the order of 0.3 Tm for metals and 0.4 Tm for alloys is reached. creep resistance increases by the precipitation hardening. The increase of creep resistance is attributed to the decrease of grain size through the Hall–Petch effect.

(7) Ductility is one of the important aspects in the mechanical properties of composites. The tensile elongation

decreases rapidly with the addition of reinforcing particles and with increased aging time in the heat treatable alloys.

References:

1. J.E. Allison and G.S. Cole. *JOM* **45** (1993), pp. 19–24. View Record in Scopus | Cited By in Scopus (122)

2 C.K. Narula and J.E. Allison. *CHEMTECH* **26** (1996), p. 48.

3 N. Chawla, C. Andres, J.W. Jones and J.E. Allison. *Metall. Mater. Trans. A* **29** (1998), p. 2843. View Record in Scopus | Cited By in Scopus (85)

4 Asthana R 1998 *Solidification processing of reinforced metals* (Trans. Tech. Publ.)

5 Clyne TW(ed.) 2000 *Comprehensive composite materials, Vol. 3. Metal matrix composites* (ser. eds) A Kelly, C Zweben (Oxford: Pergamon)

6 Clyne T W 2001 Metal matrix composites: Matrices and processing. In *Encyclopedia of materialsscience and technology* (ed.) A Mortensen (Elsevier)

7 Clyne T W, Withers P J 1993 *An introduction to metal matrix composites* (Cambridge: University Press)
8 Lloyd D J 1999 Particle reinforced aluminium and magnesium matrix composites. *Int. Mater. Rev.* 39: 1–23
8 "Encyclopaedia of Materials: Science and Technology Composites: MMC, CMC, PMC", A Mortensen (ed.), Elsevier, 2001

9 Maruyama B 1998 Progress and promise in aluminium metal matrix composites. *The AMPTIAC NewsLett.* 2(3):

10 Surappa M K, Rohatgi P K 1981 Preparation and properties of aluminium alloy ceramic particle composites. *J. Mater. Sci.* 16: 983–993

11. S. RAY, "MTech Dissertation" (Indian Institute of Technology,Kanpur, 1969).

12. A. LUO, *Metall. Mater. Trans.* A **26A** (1995) 2445.

13 . A. LUO, *Metall. Mater. Trans.* A **26A** (1995) 2445.

14. R. A. SARAVANAN and M. K. SURAPPA, *Mater. Sci.Engng.* A **276** (2000) 108.

15. N. HARNBY, M. F.EDWARD and A. W. NIENOW,"Mixing in Process Industries" (Butterworths, London, 1985).

16 F . A. GIROT, L. ALBINGRE, J . M. QUENISSET and R. NASLAIN, *J. Met.* **39** (1987)

17. P . ROHATGI, *Modern Casting* **April** (1988) 47.

18. M. K. SURAPPA, *J. Mater. Proc. Tech.* **63** (1997) 325.

19 D. M. SKIBO, D. M. SCHUSTER and L. JOLLA, USPatent No. 4786 467 (1988).

20 FLEMINGS M C. Behavior of metal alloys in the semisolid state [J].Metallurgical Transactions, 1991, 22A: 957−981.

21 NAHER S, BRABAZON D, LOONEY L. Development andassessment of a new quick quench stir caster design for theproduction of metal matrix composites [J]. Journal of MaterialsProcessing Technology, 2004, 166: 430−439

22. J . HOLLINGGRAK, Casting Metals, UK Patent 4371 (1819).

23 D. K. CHERNOV, Reports of the Imperial Russian Metallurgical Scoeity, Dec. 1878.

24. V. G. WELTER, *Z. Metallkd.* **23** (1931) 255

25V.M. Playatskii, 'Extrusion Casting of Aluminium', Primary Sources, New York, 1965

26 Lynch, R,F., et al., 'Squeeze Casting of Aluminium', American Foundry men Society Trans., 1975, pp.569-576.

27 wikepedia, powder metallurgy

28 M.I. Pech-Canul,M.M.Makhlouf, J.Mater. Synth. Process. 8 (2000) 35–53.

29 M.I. Pech-Canul, R.N. Katz, M.M. Makhlouf, J. Mater. Process. Technol.108 (2000) 68–77.

29A 30 F. Ortega-Celaya, M.I. Pech-Canul, M.A. Pech-Canul, J. Mater. Process.Technol. 183 (2007) 368–373

30 Q.c.jiang,X.L. Li and H.Y. Wang, Scripto materialia, Volume,48(2003),713

31 S.Rawal,JOM,Vol53,(2001),14

32N,Crainic,A.T. Marques Key engineering materials, Vol 230-232,(2002),656

33T.Yamasaki,Y.J.Zheng,YOgino,MTerasawa,T.Mitamura,T.Fukami materials Science and engineering A Vol. 350A,(2003),168

34 S.Hirsosawa,Y shingemoto,T Miyoshi H. Kanekiyo, Scripta materialia Vol.48 (2003),839

35F. Audebert,F prime,M Galana ,M Tomut,P.J. Warren I.C. Stone B cantor, Materials treasitions vol.43,(2002) 2017

36 X.C. Tong H.S. fang metallurgical and materials transations, vol. 29A,(1998),875

37 X.C. tong H.S. fang, Metallurgical and materials transition ,vol. 29A,(1998),893

38 FK Sautter, Journal of the electrochemical society, vol. 110,(1963),557

39 A.F. Zimmerman,G palumbo, K.T. Aust U. Erb, Materials science and engineering A vol. 328,(2002),137

40 F Niu,B cantor, thin solid film , vol. 320,(1998),184-191

41 R.K. Islamgaliev,N.F. Yunusova ,I.N. Sabira Materials Science and engineering A, vol.319,(2001),877

42 R.J. Arsenault, L.Wang C.R. feng Acta metal material vol. 39,(1990),47

43 V.C. Nardon, K.M. Prewo Scripta metallugica, vol.20,(1986),43

44 S. Suslick ,Y didenko,M.M. fang T. hyeon,K.J. Kolbeck, W.B. Mcnamara,M.M.Mideleni,M.wong, Phil. Tans.R. soc. Lond. ,vol.A 357,(1999),335

45. MINGYI ZHENG, KUN WU, HANCEN LIANG, S .KAMADO and Y. KOJIMA, *Mater. Lett.* **57** (2002) 558.

46 . A. LUO and M. O. PEKGULERYUZ, *Trans. Amer. Foundry's Soc.* **102** (1994) 313.

47 . P . K. GHOSH and S . RAY, *Indian J. Technol*. **26**(2) (1988) 83.

48 . K. J . BRONDYKE and P . D. HESS, *Trans. TMS-AIME* **230**(1964) 1452

49. H. HU and A. LUO, *JOM (USA)* **48**(10) (1996) 47.

50 . G. A. CHADWICK and A. BLOYCE, Magnesium Alloys and Their Applications, Garmisch-Partenkirchen, Germany, April1992, DGM Information sgesellschaft M.B.H., Germany, 1992, p. 93.

51 . B.K. Prasad, "Investigation into sliding wear performance of zinc-based alloy reinforcedwith SiC particles in dry and lubricated conditions", Wear 262 (2007) 262–273

52 . M.D. Bermudez, G. Martinez-Nicolas, F.J. Carrion, I. Martinez-Mateo, J.A. Rodriguez,E.J. Herrera, "Dry and lubricated wear resistance of mechanically-alloyed aluminum-basesintered composites", Wear 248 (2001) 178–186.

53. B.K. Prasad, "Investigation into sliding wear performance of zinc-based alloy reinforced with SiC particles in dry and lubricated conditions", Wear 262 (2007) 262–273.

54 M.R. Rosenberger, C.E. Schvezov, E. Forlerer, "Wear of different aluminum matrix composites under conditions that generate a mechanically mixed layer", Wear 259 (2005) 590–601

55. T. Miyajima, Y. Iwai; "Effects of reinforcements on sliding wear behavior of aluminummatrix composites", Wear 255 (2003) 606–616.

56 S.C. Sharma, "The sliding wear behavior of Al6061–garnet particulate composites", Wear 249 (2001) 1036–1045.

57I.M. Hutching, "Wear by particulates", Chemical Engineering Science, Volume 42, Issue 4, 1987, Pages 869-878.

58F.M. Husking, F. Folgar Portillo, R. Wunderlin, R. Mehrabian, "Comlpsites of aluminium alloys: fabrication and wear behaviour", J. Mater. Sci. 17 (1982) 477-498.

59 Debdas Roy, Bikramjit Basu, Amitava Basu Mallick, "Tribological properties of Ti aluminide reinforced Al-based in situ metal matrix composite", Intermetallics 13 (2005) 733–740.

60Uan JY, Chen LH, Lui TS, "On the extrusion microstructural evolution of Al–Al3Ni in situ composite", Acta Materialia, Volume 49, Issue 2, 2001, Pages 313-320.

61 . Sanjay Kumar Thakur, Brij Kumar Dhindaw, "The influence of interfacial characteristicsbetween SiCp and Mg/Al metal matrix on wear, coefficient of friction and microhardness", Wear 247 (2001) 191–201.

62Rajnesh Tyagi, "Synthesis and tribological characterization of in situ cast Al–TiC composites", Wear 259 (2005) 569–576.

63P.H. Shipway, A.R. Kennedy, A.J. Wilkes, "Sliding wear behaviour of aluminium-based metal matrix composites produced by a novel liquid route", Wear 216 (1998) 160 –171

64S.K. Chaudhury, A.K. Singh, C.S. Sivaramakrishnan, S.C. Panigrahi, "Wear and friction behavior of spray formed and stir cast Al–2Mg–11TiO2 composites", Wear 258 (2005) 759–767.

65J.M. Wu, Z.Z. Li, "Contributions of the particulate reinforcement to dry sliding wear resistance of rapidly solidified Al-Ti alloys", Wear 244 (2000) 147–153.

66 R.L. Deuis, C. Subramaniun, J.M. Yellup, "Abrasive wear of aluminium composites—a review", Wear 201 (1996) 132–144.

67 Alpas AT, Zhang J., "Effect of SiC particulate reinforcement on the dry sliding wear of aluminum–silicon alloys (A356)", Wear 1992; 155:83–104

68 Kulkarni MD, Robi PS, Prasad RC, Ramakrishnan P., "Deformation and fracture behavior of cast and extruded 7075Al–SiCp composites at room and elevated temperatures", Mater Trans, JIM 1996; 37:223–9.

69 Kim CK, Park SY, "A study on the fabrication and mechanical properties of SiC fiberaluminum alloy composites", J Korean Inst Met Mater 1984; 22:185–92.

70 C. Subramanian, "Some considerations towards the design of a wear resistant aluminium alloy", Wear 155 (1992) 193–205.

71 M. Chen, T. Perry, A.T. Alpas, "Ultra-mild wear in eutectic Al–Si alloys", Wear 263 (2007) 552–561.

72 S. Sawla, S. Das, "Combined effect of reinforcement and heat treatment on the two body abrasive wear of al-alloy and aluminum particle composites", Wear 257 (2004) 555–561.

73 W.Q.Song, P.Krauklis, A.P.Mouritz, S.Bandyopadhyay, “The effect of thermal ageing on the abrasive wear behavior of age-hardening 2014 Al/SiC and 6061 Al/SiC composites”, Wear 185 (1995) 125-130.

74 S. Das, D.P. Mondal, S. Sawla, N. Ramakrishnan, “Synergic effect of reinforcement and heat treatment on the two body abrasive wear of an Al–Si alloy under varying loads and abrasive sizes”, Wear 264 (2008) 47–59.

75 Wang .A and H.J. Rack, “Abrasive wear of silicon carbide particulate and whisker reinforced 7091 aluminium matrix composites”, Wear, 146 (1991) 337.

76 A.Martin, M.A.Martinez, J.LLorca, “Wear of SiC-reinforced Al-matrix composites in the temperature range 20-2000C”, Wear 193 (1996) 169-179.

77 H. Sekine, R. Chen, “A combined microstructure strengthening analysis of SiCprAl metal matrix composites”, Composite 6 (1995) 183–188.

78 R. Chen, G.D. Zhang, “Casting defects and properties of cast A356 alloy reinforced with SiC particulates”, Compos. Sci. Technol. 4 (1993) 511–556.

79 P.M. Singh, J.J. Lewandowski, “Effects of heat treatment and reinforcement size on reinforcement fracture during tension testing of a SiCp discontinuously reinforced aluminum alloy”, Metall. Trans. A 24 (1993) 2531–2543

80 Rong Chen , Akira Iwabuchi, Tomoharu Shimizu, “The effect of a T6 heat treatment on the fretting wear of a SiC particle-reinforced A356 aluminum alloy matrix composite”, Wear 238 (2000) 110–119.

81 S. Sawla, S. Das, “Combined effect of reinforcement and heat treatment on the two body abrasive wear of al-alloy and aluminum particle composites”, Wear 257 (2004) 555–561.

82 A. Vencl, I. Bobi, Z. Mi¡skovi, “Effect of thixocasting and heat treatment on the tribological properties of hypoeutectic Al–Si alloy”, Wear 264 (2008) 616-623.

83 J. LLorca, “Failure micro-mechanisms in particulate-reinforced metal matrix composites”, J. Phys. IV, 3 (1993) 1793-1798

84 J.R. Gomes, A. Ramalho, M.C. Gaspar, S.F. Carvalho, “Reciprocating wear tests of Al– Si/SiCp composites: A study of the effect of stroke length”, Wear 259 (2005) 545–552.

85 Rajnesh Tyagi, “Synthesis and tribological characterization of in situ cast Al–TiC composites”, Wear 259 (2005) 569–576.

86 Klimowicz T.F and Vecchio K.S.; in Fundamental Relationships Between Microstructures and Mechanical Properties (ed. M.N. Gungor and P.K.Liaw), Warendale, PA, The Metallurgical Society of AIME (1989) 255-267

87 Mortensen A., in Fabrication of Particulate Reinforced Metal Composites, ASM, International (ed. Masovnave and F.G. Hamel, Material Park, OH, (1990) 235.

88 Pezzotti G, M¨uller W.H.,‟ Micromechanics of fracture in a ceramic/metal composite studied by in situ fluorescence spectroscopy II: fracture mechanics analysis‟, Continuum Mech. Thermodyn. (2004) 16: 471–479.

89 Kondo K, T. Kubo, Masuyama M., ‟Creep behavior of unidirectional composites, Computational Mechanics 14 ,1994,16-27.

90 Clauer A.H. and Hansen N., Acta Metall. Mater., 32 (1984) 269-278

91 Barai P., Weng G. J., ‟Mechanics of creep resistance in nanocrystalline solids‟, Acta Mech 195, 2008, 327–348

92 Hassan S.B., Aponbiede O, Aigbodion VS (2008) J Alloys Compd 466(1-2):268–272

93 Ozben T, Kilickap E, Cakir O (2008) J Mater Process Technol 198:220–225

94 Rohatgi PK, Alaraj S, Thakkar R.B., Daoud A (2007) Compos Part A 38(8):1829–1841

95 Thimmarayan R , Thanigaiyarasu G,‟ Effect of particle size, forging and ageing on the mechanical fatigue characteristics of Al6082/SiCp metal matrix composites‟, Int J Adv Manuf Technol ,2010, 48:625–632

96 Sumita M., Maruyama N. and Nakazawa K., Role of second phase in Fretting Fatigue Strength in a SiC Whisker Reinforced Al Alloy Composite, J. Jpn. Inst. Metals, 57 (1993) 1141-1448.

97 Lloyd D.J., International Materials Reviews, 39 (1) (1984) 1-23.

98 Drucker D.C. : in „High Strength Materials‟ (ed. V. Zackay), New York Wiley., (1965) 795-830.

99 Lee K. B., Sim H. S., Kim S. H., Han K. H., Kwon H.,‟ Fabrication and characteristics of AA6061/SiCp composites by pressureless infiltration technique‟, Journal of Material Science 36 (2001) 3179 – 3188.

(100) zA. Sakthivel Æ R. Palaninathan Æ R. Velmurugan Æ “Rao “Production and mechanical properties of SiCp particle-reinforced” 43(2008) 7047–7056P.

(101) T.V. Christy, N. Murugan and S. Kumar “A Comparative Study on the Microstructures and Mechanical Properties of Al 6061 Alloy and the MMC Al 6061/TiB2/12P” *Journal of Minerals & Materials Characterization & Engineering*, Vol. 9, No.1, pp.57-65, 2010.

(102) Y. Saberi , S.M. Zebarjad,, G.H. Akbari “ On the role of nano-size SiC on lattice strain and grain size of Al/SiC nanocomposite “Journal of Alloys and Compounds 484 (2009) 637–640

(103) Lauri Kollo, Marc Leparoux, Christopher R. Bradbury, Christian Jäggi , Efraín Carre˜no-Morellic, Mikel Rodríguez-Arbaizar “Investigation of planetary milling for nano-silicon carbide reinforced aluminium metal matrix composites” Journal of Alloys and Compounds 489 (2010) 394–400

(104) E. Bayraktar , J. Masounave , R. Caplain , C. Bathias “Manufacturing and damage mechanisms in metal matrix

composites"journal of Achievements in Meterials and Manufacturing 31(2008)294-300

(105) S. AMIRKHANLOU, B. NIROUMAND "Synthesis and characterization of 356-SiCp composites by stir casting and compocasting methods" Trans. Nonferrous Met. Soc. China 20(2010) s788-s793

(106) R. Sagar · R. Purohit "Fabrication and testing of Al-SiCp composite valve seat inserts" International Journal of Adv Manufacturing Technology 29(2006) 922–928.

(107) S.S. Razavi Tousi □, R. Yazdani Rad, E. Salahi, I. Mobasherpour, M. Razavi "Production of Al–20 wt.% Al2O3 composite powder using high energy milling" Powder Technology 192 (2009) 346–351

(108) R.S. Mishra, Z.Y. Ma, I. Charit, Mater. Sci. Eng. A 341 (2003) 307–310.

(109) A. Shafiei-Zarghani, S.F. Kashani-Bozorg, A. Zarei-Hanzaki "Microstructures and mechanical properties of Al/Al2O3 surface nano-composite layer produced by friction stir processing" Materials Science and Engineering A 500 (2009) 84–91.

(110) Donthamsetty S. Damera N. R. Jain P.K. "Ultrasonic Cavitation Assisted Fabrication and Characterization of A356 Metal Matrix Nanocomposite Reiforced with Sic, B4C, CNTs" AIJSTPME (2009) 2(2): 27-34

(111) Abdulkabir Raji " A Comparative Analysis of Grain Size and Mechanical Properties of Al-Si Alloy Components Produced by Different Casting Methods" AU J.T. 13(3): 158-164 (Jan. 2010)