INVESTIGATION ON MECHANICAL PROPERTIES OF ALUMINUM METAL MATRIX COMPOSITES – A REVIEW

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Abstract. Light weight Aluminium alloys are extensively used in aircraft, supercars, and marine applications owing to its corrosion resistance and density. However, the mechanical properties like stiffness, tensile properties and tribological characteristics are far inferior than steels and titanium alloys. The tribomechanical properties of existing Aluminium alloys can be improved by adding suitable reinforcement agent and heat treatment techniques. In this review, effect of different reinforcement on mechanical properties and tribological characteristics of Aluminium Metal Matrix Composites (AMMC) were discussed in detail. Also, various fabrication processing techniques like solid state processing, liquid state processing and in-situ processing on tribological behavior of AMMC is discussed.

Keywords: AMMCs, Tribological Behaviour, Mechanical Properties, Processing Techniques

1. Introduction:
At present in worldwide there is a surge of need and requirement for the advanced materials in order to obtain desired properties. Metal Matrix Composites (MMCs) reinforced with reinforcement like Sic, Quarry dust are very auspicious materials for aerospace, industry and defense applications. Metal matrix composites blend the metallic alloys and reinforcement’s properties which results in wards superior characteristics. Vast amount of research is done on aluminium based metal matrix composites, due to its extraordinary properties like good strength to weight ratio, improved corrosion resistance, good mechanical properties and wide range of applications. MMCs has reduced the overall weight, pollution and fuel consumption within the aircraft and automobiles. It has found that processing techniques for MMCs such as powder metallurgy, vacuum hot pressing, co-spray deposition process, squeeze casting, and stir casting methods are generally selected for the preparing MMCs. But of all these methods, stir casting method is selected to other methods because it is simple, easy and parameters can be readily varied and monitored [1].

Stir Casting method is the inexpensive and economical method available for the fabrication of Aluminium Metal Matrix Composites (AMMCs). The advantages of stir casting method are flexible, simple and mass production. The micro-sized SiC particles are used as reinforcement
particles for the fabrication of AMMCs. The addition of Mg improves the wettability between molten metal and reinforcement [2]. Stir-squeeze bottom pouring is a new method used for fabrication of SiC nanoparticle with aluminium matrix composites. Step one is melting the Aluminium in furnace. Next, stirring the molten metal and adding the reinforcement particles. Then reheating the matrix and mixing the already heated reinforcements. Then again stirred for homogeneous distribution of the reinforcements into matrix and then, squeeze casting process was done for aluminium composites [3]. The Hybrid metal matrix composites have specific special properties. The ceramic reinforcements like aluminium oxide, SiC, zirconia, Boron carbide are added to aluminium matrix to boost mechanical properties. The intention of the research is to find out the mechanical behaviour of Al7075 alloy strengthened with three types of ceramic reinforcements, viz. SiC, Al2O3, and 1 wt. % of Mg. The results of the mechanical properties like compressive strength, tensile strength, hardness and impact strength are compared. It has been found that the results are better than standard Al7075. The tensile strength and impact strength of the metal matrix nano-composites are tested under the universal testing machine. Hardness test is done on a Vickers hardness machine [4].

Friction stir processing (FSP) is the process of developing surface properties that can vary grain size, strength and surface roughness, etc. In this process, a hard-rotating tool pass through the workpiece and advances forward. The surface composites can be formed by friction stir processing. It is a highly efficient green process. To produce this composite, the reinforcing ceramic powder is inserted in the aluminium metal matrix. In this process, the reinforcing particles go through the surface of metal at a certain depth is shown in Figure 1. The benefits of friction stir processing are the refinement of the grain matrix and hardness of the composites. The other benefit is quality of workpiece is increased [5].

Figure 1 Schematic of Friction Stir Process

Mica and SiC reinforcement particles were fused into Aluminium 356 alloy by stir casting process. SiC reinforcement is combined with Al356 and mica to produce tough hybrid aluminium composites. The mechanical properties of Al356 alloy composites are calculated [6]. There was a 10% rise in tensile strength and no modification in fracture toughness by addition of 1.5% of Mg. Density, impact strength and stress properties of 5, 10 and 15 wt.% of SiC reinforced Al MMC, the effect of SiC reinforcement proportion on machining, and the goods of machining specification such as cutting speed, rate of feed and depth of cut on wear of tools and surface roughness has been reviewed [7]. The another method of fabricating MMC is vacuum stir casting process. The mechanical and microstructural results of the composites produced by this technique are investigated. This process is isotropic and homogeneous in nature. It has a strong chemical bond between a matrix and reinforcement. The schematic view of vacuum stir casting setup is shown in Figure 2. The homogeneous distribution of the reinforcement in composite is major factor in preparing AMMCs[8].
A mixture of ZrO$_2$, MoS$_2$ and Ni with differing weight percentages are used as the reinforcement. In terms of self-lubricating properties, MoS$_2$ has the ability to withstand more loads than graphite. The superior hardness and wear resistance are achieved by fabrication of hybrid aluminium composites. The composites having more than one reinforcement are called Hybrid Composites. The cost of the MMC product is minimized [10]. The impact of the machining parameters like cutting speed and forces, surface finish is studied. The surface condition of the workpiece and the wear of the tool and the cutting forces are inspected and compared. Disordered particulate reinforced aluminium metal matrix composites bars of 80 mm in diameter is used for experimentation [11]. The dislocation formation in the composites undoubtedly increase the strength of the aluminium composites. The necessary dislocation produced during initial matrix plastic deformation also strengthens the composite. The void initiation is avoided by the generation of dislocations and reserved in the matrix to allow for deformation. The particle size effects and distribution of particle in the matrix and the corresponding mechanical properties are studied [12].

Age Hardening is the process of heat treatment which increases the strength of metals. It is also called as Precipitation Hardening. It increases the tensile and yield strength. But the precipitates forbid the movement dislocations in the matrix. The precipitate hardening influence of the Al7075 MMCs on mechanical properties is studied [14]. The fly ash reinforced aluminium 6061 alloy exposed that tensile strength and ductility of composite are decreased when the fly ash weight percentage is increased [18]. The nano composite of Al7075 and SiC is also processed by cold and hot dynamic compaction. The investigations are carried out under quasi-static loading conditions [19].

2. Fabrication Techniques

The processing techniques of aluminium composites are grouped into liquid state and solid-state process. The various types of liquid State process are listed below
- Stir Casting [20]
- Melt Infiltration [21]
- Squeeze Casting [22]
- Melt Oxidation [23]
- Compo Casting [24]

Some of the solid-state process are given below
- Powder Metallurgy [25]
- Spray Deposition [26]
- Chemical Vapour Deposition [27]
Electroplating [28]  
Diffusion Bonding [29]

The commonly used manufacturing processes are Stir Casting [20], Powder Metallurgy [25], Spark Plasma Sintering [30], Ultrasonic assisted casting [31], Ball Milling [32]. The detailed discussion of the above process are done.

2.1. Powder Metallurgy Method

Powder metallurgy is a method in which particulate materials are developed into finished and semi-finished products. The basic steps of the technique are manufacture of powders, powder blend, compressing of powder in a die and sintering. Powder metallurgy method is applicable for materials in the form of powder. It reduces scrap loss and also machining time. This technique is suitable for large number of components. Lauri et al. [33] made nano composites of Al and (1 vol. % of size 30nm) SiC through high energy planetary milling and then by powder metallurgy method and sintering. They are tested the formation of nano composites by changing the parameters of milling. The arrangement of the composites is elaborated in Figure 3. The distribution of the ball size of 10mm used for 20 hours milling better than the ball size of 20mm for same time at the speed of 360 rpm. Gallardo et al. [34] formed nano composites of Al2024 and (0 to 5) wt % nano SiC through the ball milling followed by the method of powder metallurgy. The process of milling took place about 2h. It is found that there is a uniform distribution of the reinforcements of SiC in the Al2024 alloy matrix and there is no formation of crack. These results are found from the SEM and TEM micrographs is shown in Figure 4.

Figure 3. Composites 20 h milled and sintered (a) 360 rpm, 10mm balls (b) 360 rpm, 20mm balls [33]

Figure 4 TEM images of composites (a) SiC distribution in the matrix (b) grain boundaries of SiC (c) interaction of dislocation lines with SiC [34]

2.2. Ball Milling

Ball milling is a process in which grinding balls squash and break down the material into small sizes. The important factors of the ball milling are the rotation speed, sample quantity, size, time of grinding and number of grinding balls. The sample homogeneity can be upgraded by increasing the number of grinding balls. Hot isostatic pressing method enhances the uniform distribution of ball milled powder. Feng et al. [35] made nano composites of Al5083 and (6.5 vol. % of 25nm size) SiC in
three steps. The first step is cryomilling, next step is HIP consolidation, and the last step is hot rolling process. The SEM and TEM images in Figure 5 shows that the reinforcement was distributed uniformly in the matrix, the interface bonding between SiC and Al5083 matrix was good. Knowles et al. [38] formed nano composites of Al 6061 and (10, 15) wt % of 500 nm size SiC through three steps. The initial step is through high energy ball milling followed by hot isostatic pressing and the last step is extrusion process. The SEM images in Figure 6 exposed that particles in the Al6061 matrix were distributed homogeneously with less number of clustering of the nano particles.

![Figure 5](image5.png)

**Figure 5** Al5083/SiC composite (a) SEM image of uniform distribution of SiC (b) TEM image (c) TEM image of inter particle region in rolling direction [35]

![Figure 6](image6.png)

**Figure 6** TEM image of extruded (a) Al 6061 (b) Al 6061 with 15 wt. % SiC composite [36]

2.3. Ultrasonic Assisted Casting

Ultrasonic assisted casting is a process of melting the materials by ultrasonic waves during or after the adding the reinforcement and then followed by casting. The principle of this method is creation of the high intensity ultrasonic waves which creates transitory cavitation and acoustic streaming in liquids. This method is more fortunate in preparing the composites with uniform dispersion of reinforcements in small scale at laboratories and also suitable for large scale production. Bulk production requires high source of power. By this technique Dehnavi et al. [37] fabricated metal matrix composites of A413 and (0.5, 1, 1.5, 2) wt. % SiC and 0.5 wt. % Mg at nano level. The A413 was melted in the crucible of graphite with the assistance of resistance furnace under argon atmosphere. The SiC reinforcements are preheated in a muffle furnace for one hour at 1000°C. Then the preheated reinforcements were added to the melt and stirred mechanically by using stirrer which is made of graphite for 30 min at a 650-rpm speed. The slurry was treated ultrasonically at a frequency of 20 kHz and 350W power for 10 to 20 min and then drained into a preheated grey cast iron die. Yong et al. [38] synthesized metal matrix composites of A356 with (2 wt. % of size 30nm) SiC by this method. The SEM images of composites as casted showed that there is no uniform distribution in the matrix of SiC particles and formation of clusters of SiC particles and the reinforcement particles were distributed uniformly along the A356 matrix alloy in a composite fabricated from ultrasonic assisted casting method is shown in Figure 7.
Spark plasma sintering is a high-speed powder strengthening sintering process. This process is capable of treating nonconductive as well as conductive materials. The basic idea of spark plasma sintering process is based on the phenomenon of electrical spark discharge. It passes low voltage pulse current temporarily which generates spark plasma at high energy in local areas between the particles. The temperatures in this process were lower than the traditional sintering temperatures. The processing time of the material is 5 to 25 min. It establishes strong control over microstructure and grain growth. Sivaiah et al. [39] fabricated composites of Al 5083 with 10 wt.% SiC through high energy ball milling and then by spark plasma sintering process. They studied the samples of composites with SEM images in Figure 8 and XRD plots for the ball milled Al 5083 matrix which has crystalline grain size, it is found to be 25nm and after spark plasma sintering it was coarsened up to 30nm.

Sherif et al. [40] synthesized Al composites with (2, 5, 7, 10) vol. % of size 5nm SiC by this spark plasma sintering process. The SEM images revealed the uniform distribution of the reinforcement particles in the matrix. The XRD analysis in Figure 9 after the ball milling time 0ks and 86ks showed no formation of Al4C3 and Si.
2.5. Stir Casting Method

Stir casting is a liquid state process for fabrication of composite materials. In this process the mechanical stirrer is used to mix the reinforcement particles with metal matrix which is in molten state. Then the composite material which is in liquid state is casted by traditional casting methods and conventional metal forming techniques. Ali et al. [41] fabricated nano composites of A356 and (0 to 4.5 vol. %) SiC and 1 wt.% Mg by stir casting method. The aluminium matrix is melted to a temperature of 750°C and at a stirring speed of 600rpm for 15 min by stirring with graphite impeller. From the SEM image in figure 10, it is found that the reinforcement particles in the A356 alloy matrix are distributed uniformly.

![SEM image of 2.5 vol. % SiC](image1)

Figure 10 SEM image of 2.5 vol. % SiC [41]

3. Mechanical Properties

3.1. Hardness

Hardness is defined as the ability of the material to resist plastic deformation. The resistance to indentation or scratch is termed as hardness. Vickers, Brinell and Rockwell hardness testers are the commonly used hardness measuring instruments. \( H_c = V_r H_r + V_m H_m \) is the rule used to find hardness of the composite theoretically where \( c \) stands for composites, \( r \) stands for reinforcement, \( m \) stands for matrix and \( V \) stands for volume, \( H \) stands for hardness. It helps in calculating approximate hardness values [42]. Several researchers have contributed regarding the reinforcement effects on hardness of composites which are summarized as follows;

The microhardness increases (linearly) considerably in the content of SiC and Al2O3 particle reinforcement relative to Al 7075 alloy. It can be found that the microhardness of composites was greater than that of its base Al7075 alloy is shown in Figure 11. This is due to the presence of aluminium oxide (Al\(_2\)O\(_3\)) and silicon carbide (SiC) particles in the Al7075 matrix [4].

![Microhardness](image2)

Figure 11 Wt.% of reinforcement vs microhardness values [4]
The hardness value of the composites reinforced with varying mass fractions of mica. It is found that the hardness of Al/10SiC−6mica composite is lower when compared with Al/10SiC−3mica composite. Thus, the hardness of the MMCs rises more or less with the fraction of volume of reinforcement particulates in the matrix alloy [6]. The reinforcements such as SiC, aluminide and Al2O3 [43-45] are mostly preferred to enhance higher hardness in the composite. TiC when diffused in Al matrix, improves the hardness to weight ratio. Also, it transmits thermodynamic stability to the composites [46-48]. Abdulhaqq et al. [49] and Lloyd et al. [50] found the importance of hard ceramic particles in improving the hardness of Al-MMCs. Deuis et al. analyzed that the increase in the hardness of the MMCs having ceramic reinforcement not only depends on the reinforcement size but also on the composite structure and excellent interface bonding [51].

![Figure 12 Variation of Vicker’s Hardness Al6061-SiC and Al7075-Al2O3 Composites](image)

![Figure 13 Variation of Brinell’s Hardness of Al6061-Al2O3 and Al7075-SiC Composites](image)

The composites produced with respect to the above explanation are subjected to hardness test which are done in the Vicker’s and Brinell’s hardness testing machines and the results are calculated. From the Figures 12 and13, it can be found that the hardness of composites was higher than that of its base alloy. Also, the hardness of the composite is found to boost with increased filler content.

3.2. Tensile Strength

The tensile properties of the Aluminium 7075 alloy and its composites is inspected on a computerized universal testing machine which has the capacity of 50KN. As per ASTM E8 standards, the specimens are prepared for the testing of the product. Figure 14 explains the difference of tensile strength of the composites with the different weight portions of Al2O3 (20–30 nm) and SiC (50 nm) reinforcement particulates. It is observed that the tensile strength increased with a rise in the weight fraction of Al2O3 and SiC [4].
The results from the tensile tests of composites which are mica reinforced shows that the aluminium composites reinforced with 10% SiC and 3% mica particle have the greater tensile strength of 150 MPa and the tensile strength of 148 MPa is found in the aluminium composite with 10% SiC and 6% mica particle. The outcomes reveal that when the mass fraction of mica increases, the tensile strength of the composites rises up to certain value and then decreases [6]. The mechanical properties of the composites depend on the structure and properties of the reinforcement materials. The strong interface between matrix and reinforcement is achieved due to increase in value of elastic modulus and strength of the composites [52]. The strength of Al₂O₃, SiC, TiC [56], and TiB₂ particulate reinforced Al-MMCs is increased at the loss of reduced ductility, by hiking the volume percentage of ceramic phase and by reducing the reinforcement size in the composite [52-55]. The heat treatment of the composites under aged condition before and after fabrication improves mechanical properties [57].

The theoretical expression for tensile yield stress of matrix and composites are given by Pₘ = cαᵧ where Pₘ is hardness or yield pressure, c is constant value and αᵧ is tensile yield stress [57]. The tensile strength of AlSiMg₂ composites depending on reinforcement ratio is described in Fig. 15. There had been hike in the tensile strength of produced composites when a 180MPa of tensile strength for metal mould casting is considered. Specifically, in 10 wt.% of SiC reinforced composite there had been 100% and 56% rise in testing with the matrix material of sand casting and matrix material of metal casting, respectively. However, in 15 wt.% of SiC reinforced composite material the tensile strength of composite is decreased because of broken particles in the structure.

**Figure 14** Wt.% of reinforcement versus UTS [4]

3.3. **Compressive Strength**

The investigations revealed that the compressive strength progressively increased by the increase in wt.% of the reinforcement i.e., Al₂O₃ and SiC which contributed the metal matrix. The ideal compressive strength was noticed at 4% aluminium oxide and silicon carbide. The graph of increase in compressive strength is shown in Figure 16. The inclusion of the reinforcements in the
matrix particle creates cores which lead to the bulk development of grains. It enhances better strength of the composites [4].

![Figure 16 Wt.% of reinforcement vs compression strength [4]](image)

The aluminium composites which has 10 wt. % SiC reinforced shows better compressive strength than aluminium composites having 5wt. % SiC and pure base aluminium alloy. The aluminium metal matrix having 70 nm size of SiC particles have outstanding mechanical properties. In the Figure 17 the samples of different sizes containing 10 wt. % SiC are shown. From that 70 nm size of SiC particles are having maximum compressive strength of 601MPa [59].

![Figure 17 variation of the compressive strength of composites having different sizes of SiC particles [59]](image)

4. Conclusion

This review suggests the ideas, experimental results gathered, and conclusions made over the years by various investigators in the work of particle reinforced Al-MMCs. This paper also exposes the fabricating techniques of the composites and mechanical properties of SiC particle reinforced Al-MMNCs. The SiC reinforced Al-MMNCs exhibits better mechanical properties over the unreinforced base alloys. The commonly used fabrication technique in the making of Al-MMNCs is stir casting as it is the cheapest method. The ultrasonic assisted casting and spark plasma sintering are more expensive processes which can be used for high sensitivity parts. The hardness, compressive strength and tensile strength of the composites were reviewed. It is concluded that when the reinforcement contents are increased in the matrix material, the hardness and tensile strength of the composites are also increased. The review on mechanical properties were done with respect to strength.

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