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Latest Research Development in Aluminum Matrix with Particulate Reinforcement Composites – A Review

A.Thirumoorthy[a], T. V. Arjunan[b], K. L. Senthil Kumar[c]

[a]*Assistant Professor, Department of Mechanical Engineering, Shree Venkateshwara Hi-Tech Engineering College, Gobi, Erode, 638455, India*
[b]*Professor, Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Coimbatore, 641 109, India*
[c]*Professor, Department of Mechatronics, Bannari Amman Institute of Technology, Sathyamangalam, Erode, 638401, India*

Abstract

The usage of aluminum based composite is increasing day by day in the entire manufacturing sectors due to their unique properties such as high strength to weight ratio, good mechanical properties and better durability. Subsequently a lot of research has taken place in aluminum composite material with addition of carbides based particulate reinforcement. But in the present competitive market, the manufacturing sectors seek for the better properties, manufacturing easy nature and eco-friendly based materials. It's observed that there is tremendous research gap for excellent properties improvement and eco-friendly materials. This present study gives sump-up of the latest developments taken place in aluminum based composite and other particulate reinforcement effects. The tribologoical behavior of aluminum based composite has been covered. This study is focused on AA6061 and AA7075 alloy due to commercial easy available and it's widely used for structural purpose in manufacturing sectors. From this current study, it's clearly identifies that the many research has been done only on addition of carbides and few oxides based reinforcements. No much adequate research on addition of nitrides and oxides particulates reinforcement in aluminum alloys has been done. The properties can be improved by addition of nitrides reinforcement and also by combination of oxides with nitrides. Even there is research gap in utilization of advance characterization techniques in composites characterization study.

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Keywords: Strength to Weight Ratio, Characterization Techniques, Aluminum Composite, Particulate Reinforcement, Nitrides, Oxides.

1. Introduction

In the present competitive market, there is a huge demand for the superior materials which is having different properties in single material. The demand properties required is such as high core toughness, high surface hardness, high corrosion resistance, better weld ability and machiability. The best material to answer the above problem that is

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material having different property combination is composite material. A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. The present study covers the history and latest development taken up in the field of composite material.

1.1. Composite material

The composite materials consist of two constituents such as reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part [34]. Composite materials are usually classified on the basis of the physical or chemical nature of the matrix phase, e.g., polymer matrix, metal-matrix and ceramic composites. In addition there are some reports to indicate the emergence of Inter metallic-matrix and carbon-matrix composites.

Composites are being commercialized in three major fields [22]: polymer-matrix composites (PMCs), metal-matrix composites (MMCs), and ceramic-matrix composites (CMCs). Other classification schemes based on a matrix/fibre notation, such as Al/SiC and 6061/SiC/40p-T6 for aluminium reinforced with silicon carbide and boron- and carbon-fibre reinforced polymers (BFRP or CFRP), are also being used. The recognition of the three basic types of composites is based on the nature of the matrix material. Each of these types may make use of particle or either discontinuous (short fibre) or continuous fibre reinforcement for property enhancement. It must be realized that systems reinforced with particulate, discontinuous and continuous fibres give rise to different physical and mechanical properties, and that they must be utilized accordingly.

Particulate-reinforced systems can be divided into two categories: dispersion-strengthened, and particle strengthened or particle-reinforced systems. In dispersion strengthened systems, small particles (Φ between 0.01 and 0.1 μm) are dispersed in the matrix that acts as the major load-bearing constituent. In particle-strengthened composites, larger particles ($\Phi > 0.1$ μm) are incorporated in the matrix and the load is shared by the matrix and the particles. To determine the physical and mechanical properties of composites, use is made of expressions known as mixture rules. The density ρm of a composite, for example, consisting of particles evenly dispersed in a matrix, is given by $\rho_m = f_1\rho_1 + f_2\rho_2 + f_3\rho_3 + \ldots\ldots\ldots f_i\rho_i$. Where, ρi refers to the density and fi to the volume fraction of the individual components i. In these systems, the reinforcing particles actually impede slip, thus increasing resistance to plastic deformation of the matrix, which is the main load carrying constituent. Mixture rules for the dispersed phases of spherical particles can be applied even to irregularly shaped or plate like particles, provided the orientation is completely random and the aspect ratio (length to width) is relatively low.

1.2. Metal Matrix Composite

The automotive industry recognizes that weight reduction and improved engine efficiency will make the greatest contribution to improved fuel economy with current power trains. This is evidenced by the increased use of aluminum alloys in engine and chassis components. Aluminum and magnesium castings in this sector have grown in leaps and bounds over the past five years to help engineers design and manufacture more fuel-efficient cars. The low density and high specific mechanical properties of aluminum metal matrix composites make these alloys one of the most interesting material alternatives for the manufacture of lightweight parts for many types of vehicles. With wear resistance and strength equal to cast iron, 67% lower density and three times the thermal conductivity, aluminum MMC alloys are ideal materials for the manufacture of lightweight automotive and other commercial parts. MMC's desirable properties result from the presence of small, high strength ceramic particles, whiskers and fibers uniformly distributed throughout the aluminum alloy matrix. Aluminum MMC castings are economically competitive with iron and steel castings in many cases. However, the presence of these wear resistant particles significantly reduces the machinability of the alloys, making machining costs higher due mainly to increased tool wear. As a result, the application of cast MMCs to components requiring a large amount of secondary machining has been somewhat stifled. Most components do not require the high performance capability of aluminium MMCs throughout their entirety. An unreinforced cast alloy may accommodate the stresses in these areas. Reinforcement of only the high stress regions of a component is referred to as selective reinforcement. This approach to component design and manufacture optimizes the material for the application, reduces the cost of the cast MMC part, and lowers machining costs. Metal matrix composites (MMCs) are increasingly becoming attractive materials for advanced aerospace applications because their properties can be tailored through the addition of selected reinforcements. It is well known that the elastic properties of metal matrix composites are strongly influenced by microstructural parameters of the reinforcement such as shape, size, orientation, distribution and volume fraction. Metal-matrix composites (MMCs) exhibit the ability to withstand high tensile and compressive stresses by the transfer and distribution of the applied load from the ductile matrix to the reinforcement phase.

In situ composite structures, such as aluminium containing silicon in amounts above the solubility limit are formed by solidification. However, the compositions and relative amounts of the two phases are limited to a narrow range, controlled by growth kinetics and equilibrium conditions. Artificial composite structures do not exhibit these limitations in composition. These MMCs are fabricated by the addition of a reinforcement phase to the matrix by the use of several techniques such as powder metallurgy, liquid metallurgy and squeeze-casting. The reinforcement phase is generally one of the following: continuous boron or graphite fibres or hard particles such as SiC and Al2O3 in discontinuous particulate or whisker morphology. The volume fraction of reinforced particles or whiskers is generally within the range 10-30%.

2. Review of the Literature

2.1. Mechanical properties

Michael et al. [26] Studied on Aluminum matrix hybrid composites with particulates reinforcement and its philosophies; mechanical, corrosion and tribological characteristics. The presented on the new generation of hybrid composites, which involve the use of agro and industrial waste derivatives, improved performance in comparison with the unreinforced alloy, have been established. However, the degree of improvement of hybrid AMCs, which contains fly ash over the single, reinforced AMC containing synthetic reinforcement still need to be studied. The hybrid AMCs reinforced with agro waste derivatives have shown that high performance levels can be maintained in AMCs at reduced production cost even at about 50% replacement of synthetic reinforcement with the agro waste.

Ashok et al. [5] investigated on addition of SiC reinforcement will improve wear properties. Due to the property of high hardness and high thermal conductivity, SiC after accommodation in soft ductile aluminium base matrix, enhance the wear resisting behaviour of the Al – SiC metal matrix composite. Swamy et.al [2] found that increasing the graphite content within the aluminum matrix results in significant increases in the ductility, UTS, compressive strength and Young's modulus, but a decrease in the hardness. The properties of the cast Al6061-WC composites are significantly improved by varying the amount of WC. It was found that increasing the WC content within the matrix material, resulted in significant improvement in mechanical properties like hardness, tensile strength, and compressive strength at the cost of reduced ductility. Highest values of mechanical properties like hardness, tensile strength and compressive strength were found at 3 wt% WC.

Mahendra Boopathi et.al [23], noticed that, tensile strength, yield strength and hardness was improved by increasing the area fraction of reinforcement in matrix. The percentage rate of elongation of the hybrid MMCs is decreased significantly with the addition of SiC and fly ash into Al2024 alloy

Pawar, et al [27] has developed Aluminium Based Silicon Carbide Particulate Metal Matrix Composite for Spur Gear. Silicon carbide particle reinforced aluminium matrix composite (AMCs) were prepared by stir-casting with different particle weight fraction (2.5%, 5%, 7.5%, and 10%) the following conclusions has been drawn,

a) Hardness of Al-SiC is much better than the aluminum metal. In case of increased silicon carbide content, the hardness, and material toughness are enhanced and highest value is obtained at 10% SiC content.
b) More uniform distribution of SiC particles can be found if composite is prepared by powder metallurgy than stir casting; however stir casting is more economical.
c) These composites can be used for making power transmitting elements such as gears, which are subjected to continuous loading.
d) Stress distribution obtained in FEA analysis shows highest stress value at tip of the teeth.

Shen et.al. [31] presented, Microstructure and mechanical properties of Al-7075/B_4C composites fabricated by plasma activated sintering. Increasing the B_4C fraction increased the bending strength, hardness, and compressive yield strength of the finished composite. However, adding too much B_4C decreased the hardness and bending strength because of the formation of B_4C agglomerates. Adding an appropriate amount of B_4C particles can significantly improve the bending strength, hardness, and compressive yield strength of the composite. At 7.5 wt.% B_4C, the Vickers hardness, bending strength, and compressive strength of the resultant composite were 184.3 HV, 813 MPa, and 895 MPa, respectively.

Aluminum based silicon carbide particulate metal matrix composite has been developed, the following are findings [25], Increase of silicon carbide percentage in composite which increases hardness, impact strength and normalized displacement have been observed. The best results has been obtained at 25% weight fraction of 320 grit size SiC particles. Maximum Hardness obtains 45.5 BHN & Maximum Impact Strength 36 N-m. Fig.1 shows the increase of hardness with silicon carbide. Homogenous dispersion of SiC particles in the Al matrix shows an increasing trend in the samples prepared by without applying stirring process, with manual stirring and with 2-Step method of stir casting technique respectively.

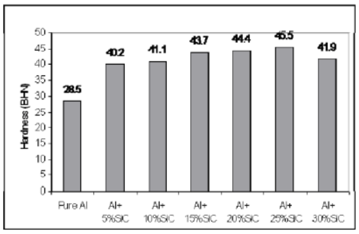


Fig. 1. Increase of Hardness with SiC Particulates

Jerry Andrews Fabian, et.al [18] investigated on densification behaviour of Aluminium reinforced with Tungsten Carbide (WC) particulate Metal Matrix Composite processed by Powder metallurgy route. It is observed that increase in WCp composition invariably increases the density of Al. Green density of 2.69g/cm^3 and sintered density of 2.7g/cm^3 was achieved for Sample A (aspect ratio 1.0) with a relative density of 93.73%. For aspect ratio 0.5 the maximum sintered density achieved was 2.67g/cm^3. Further densification is possible for aspect ratio 0.5 with increase in WCp by another 2 to 5% mass fraction.

The mechanical properties of the composites are of immense importance in the application point of view. Researchers proposed the modified rules of mixture are effective in predicting strength properties, upper and lower bound values of the modulus of the composites. 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 [26-33]. Although 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.

2.2. Tribological properties

Wear is the progressive loss of material due to relative motion between a surface and the contacting substance or substances. Micro-cracks or localized plastic deformation are the forms of wear damage. Wear may be classified as abrasion wear, adhesive wear, fatigue wear, surface and fretting, tribo-chemical, cavitation and erosion wear. The wear rate determination is influenced by the properties of the opposing surfaces and the surface finish, material intrinsic surface properties, speed, load, temperature.

Elangoa, et al. [14], studied the tribological properties of hybrid metal matrix (LM25+SiC +TiO_2), this research concluded that the particulate reinforcement composite has high strength, hardness and wear resistance when compared with matrix material the wear resistance increases in the hybrid composite material when the SiC and TiO_2 is added as reinforcement. Unreinforced aluminium alloy exhibits more wear followed by SiC binary metal matrix composites and then hybrid metal matrix composite (LM25+SiC+TiO_2). The wear rate decreases with increasing TiO_2 volume content of the reinforcement, the reason is lubricating property and hardened nature of the TiO_2 particulate favours for the increased wear resistance.

G.Baskaran, et al [13] carried out the characterization study of Aluminium Based Metal Matrix Composite Reinforced with TiC and TiO_2". In this study, Al-TiC-TiO_2 composite material was successfully fabricated and the effect of TiC and TiO_2 was studied on the mechanical properties of composite material such as wear for all loads, sliding velocity and sliding distance, hardness, and density was studied by conducting experimental tests. Hardness, density and wear rate was increased with the increases in TiC and TiO_2 content in Al composite material.

Devaraju Aruria et al. [8] 2013, has investigated on "Wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites [(SiC + Gr) and (SiC + Al_2O_3)] fabricated by friction stir processing". The findings are micro-hardness increases due to presence and pining effect of hard SiC and Al_2O_3 particles. Low wear rate was exhibited in the Al–SiC/Gr surface hybrid composite due to mechanically mixed layer generated between the composite pin and steel disk surfaces which contained fractured SiC and Gr. The presence of SiC particles serves as load bearing elements and Gr particles acted as solid lubricant. Tensile properties are decreased as compared to the base material due to the presence of reinforcement particles which make the matrix brittle.

Veeresh Kumar et.al. [12] investigated on Mechanical and Tribological Behavior of Particulate Reinforced Aluminum Metal Matrix Composites. The findings are the wear performance of hard ceramic reinforced aluminium matrix composites was reviewed with particular emphasis on the mechanical and physical factors and material factors also with the effect of lubrication, work hardening, Mechanical Mixed Layer, heat treatment etc. All the factors have considerable effect on the tribological performance of Al-MMC and counter-face metal couples. The ceramic reinforced Al-MMCs will have better wear resistance than the unreinforced alloys. Finally there is an immense potential, scope and opportunities for the researchers, in the field of prediction of mechanical and tribological properties of the particulate reinforced metal matrix composites by using soft computing techniques.

Prasada et al. [32] has developed Al MMCs, reinforced with SiC and Al_2O_3 particulates. Finally, concluded that particulates will reduce the weight and increase the engine efficiency and thereby reduce fuel consumption and vehicle emissions. Replacing cast iron engine components with light-weight Al alloys requires overcoming the poor adhesion and seizure resistance of Al by dispersing SiC, Al_2O_3 or graphite particles in Al. Considerable reduction in wear and friction is achieved by use of these particulates. Furthermore, increased cylinder pressures (and therefore, higher engine performance) are possible because Al MMCs can withstand high mechanical and thermal loads, and reduce heat losses by permitting closer fit that can be achieved because of lower thermal expansion coefficient of Al MMCs.

Satpal Kundu et al [33] carried out research on Dry Sliding Wear Behavior of Aluminium/SiC/Al_2O_3/Graphite Hybrid Metal Matrix Composite Using Taguchi Technique. The following findings were obtained, Wear rate (Al6061T6/10%SiC/10% Al_2O_3/5% Graphite MMC) was highly influenced by applied load, sliding speed and sliding distance respectively and interaction term L*S (Load*Speed) [27.08%] was found most predominant among different interaction parameters. Coefficient of friction(Al6061T6/10%Sic/10% Al_2O_3/5% Graphite MMC) was highly influenced by applied load, sliding speed and sliding distance respectively and interaction term L*D (Load*Distance) [18.78%] was found most influencing term among different interaction parameters.

2.3 *Microstructure analysis*

Jufu Jiang, et.al. [19] investigated on Compression Mechanical Behavior of 7075 Aluminum Matrix Composite Reinforced with Nano-sized SiC Particles in Semisolid State. The following are concluded,

a) The microstructure of the 7075 AMCs reinforced with nano-sized SiC particles before semisolid compression consists of fine and spheroidal solid grains surrounded by liquid phase. Semisolid compression led to a nonuniform plastic deformation of solid grains. Solid grains deformed slightly in the locations near to free surface due to the dependence of deformation on liquid flow (LF) mechanism and flow of liquid incorporating solid grains (FLS) mechanism. Obvious plastic deformation occurred in the central location and location contacting to die due to the contribution of plastic deformation of solid grains (PDS) to deformation. Fig. 2. Microstructure of the 7075 AMCs reinforced with nano-sized SiC particles before and after semisolid compression:(a) location 1 before semisolid compression, (b) location 1 after semisolid compression, (c) location 2 before semisolid compression, (d) location 2 after semisolid compression, (e) location 3 before semisolid compression, and (f) location 3 after semisolid compression.

b) Isothermal temperature and soaking time have an important influence on the macro appearance of the samples compressed in solid state and semisolid state. The destruction cracks of the samples compressed at solid state temperature is parallel to compression direction. However, the destruction forms of the samples compressed at semisolid temperatures consist of cracks parallel to compression direction and partial collapse. The destruction depends on the cracks parallel to compression direction upon a soaking time of 5 min.

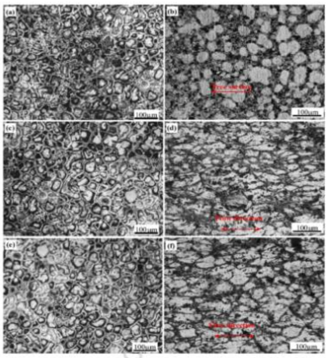


Fig.2 Microstructure of 7075 AMCs reinforced with nano sized SiC particles

When the soaking time is 10 min, the destruction depends on partial collapse and cracks parallel to compression direction. When the soaking time is more than 15 min, the destruction only depends on partial collapse. Compression velocity affects slightly on the appearance of the sample.

Subhranshu Chatterjee, et al [36] studied effect of microstructure and residual stresses on nano-tribological and tensile properties of Al_2O_3 and SiC-reinforced 6061-Al metal matrix composites. Microstructure and residual stresses exert significant influence on the wear and tensile properties of 6061- Al/Al_2O_3 and 6061-Al/SiC composite samples. Residual stresses are generated due to the difference in the coefficient of thermal expansion of the matrix and reinforcement and type and size of the reinforcement. Differences in their values are attributed to the different forming techniques used for fabrication. Effect of residual stresses is also reflected on the wear property of the composites. Due to the higher residual stress wear tracks of 6061-Al/SiC showed higher amount of debris than 6061-Al/Al_2O_3 composite which is also attested by the higher wear rate of the former. Tensile study revealed show better UTS and ductility due to the induced stresses in the matrix.

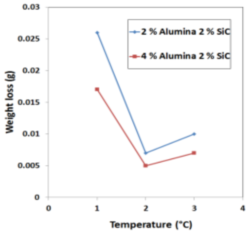
Sima et.al [34] reported that as-cast A356 aluminium alloy processed by friction stir processing at various rotation rates was subjected to microstructural analysis and dry sliding wear tests. Friction stir processing resulted in a significant microstructural modification and improvement in wear behavior of A356. Wear resistance improvement was attributed to significant modification in size, morphology and distribution of SiC particles, grain refinement, and hardness enhancement. Furthermore, it was found that higher tool rotation rates were more effective to refine microstructure and consequently increase wear resistance.

2.4 Effect of Heat Treatment

Jayashree et al. [28] carried out the literature survey and concluded that there is further study scope to determine and compare the properties of welded joint in untreated and heat treated condition to improve the quality of welded joint and highlighted on the behavior of SiC particles in metal matrix composites during welding by microstructure examination and improvement in mechanical and physical properties after precipitation hardening process.

Achutha Kini et al [36] studied the Characterization of Aluminium 6061 Hybrid Composite. The specimens are successfully cast by stir casting method and subjected to age hardening treatment. It’s observed that the lower the aging temperature, higher is the peak hardness value. Higher the aging temperature, shorter is the peak aging duration for the peak hardness. Higher the weight percent of the alumina, higher is the peak hardness value. Lower the weight percent of alumina longer is the peak aging duration. Wear resistance of the composite is better when aged at lower temperature. Both wear resistance and hardness are better in heat treated condition compared to as cast condition. Microstructure recorded shows good dispersion of reinforcements in the matrix without agglomeration and porosity. Fig. 3(a) shows the effect of age temperature on wear rate.

Burak [6], analyzed Age Hardening Response of an Al/TiC Hot Pressed Multi-Layered Composites. The level of hardness attained in the hot pressed laminated composite and its unaged counterpart was seen and concluded that peak hardness for multi-layered composite (Fig. 3 (b)) was observed, when the aging period was extended up to approximately 12h. The hardness of the composite upper surface (A) increased from approximately 112 to 175HV in 12h. The highest wear resistance was obtained for T6 thermal treatment condition. The maximum hardening of the matrix was obtained when the composite material was solubilied at a temperature of 560^0C for 3 hours, quenched in ice water at 0^0C and ageing done at a temperature of 175^0C for 7 hours.



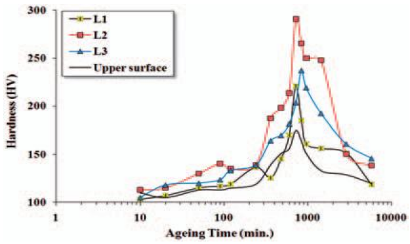


Fig.3 (a) The effect of age temperature on weight loss (b) Age hardening curves of composites - artificially aged at 180^0C.

It was found that the heat treatment Al-T6 7 hours was the one that provided the matrix greater hardness and therefore it was the one, which gave the MMC the higher wear resistance.

3. Conclusion

The above literature survey indicates very clearly that the mechanical and tribological properties of aluminum based composite has been improved by addition of carbides and oxides based particulate reinforcement. Even some researchers has investigated that the addition of graphite and fly ash in aluminum alloys shows better properties. Other observation from this study is application of developed composites to moderate temperature application only.

The following are scope has been identified for further study,

a) Design and development of aluminum based composite for high temperature application.

b) Effect of nitrides and combination of oxides with nitrides particulate reinforcement on tribological and mechanical properties of Aluminum based composite.

c) Utilization of advanced characterization techniques for the material characterization study purpose. The most of researchers have used only Classical Diffraction, Spectroscopic and Microscopical techniques for characterization study. However, not been used advanced state-of-the-art techniques such as positron annihilation spectroscopy (PAS), small-angle neutron scattering (SANS), small-angle X-ray scattering (SAXS) and others.

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