

## Study on Tribology, Microstructure and Mechanical Properties of Metal Matrix Composites – A Review on Advanced Applications



### Engineering

KEYWORDS :

<b>S.Prabakaran</b>	Department of Mechanical Engineering, Karpagam University, Coimbatore-641021.
<b>G.Chandramohan</b>	Director – Academic, Sri Krishna College of Technology, Coimbatore-641042.
<b>P.Shanmugasundaram</b>	Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore – 641032.

### ABSTRACT

*Characterization of Metal matrix composites like Tribology/wear, Mechanical properties, manufacturing processes and microstructure were explored in this study. It was found that number of composites were having high wear resistance and coefficient of friction, high hardness and compression strength, enhanced specific strength. However Al6061 composites reinforced with mixtures of SiC and Al<sub>2</sub>O<sub>3</sub> particles fabricated by stir casting method resulting increase in wear with the increasing load and sliding distance which was understood and the same was explored for further research work. Few other composites under some specific process was having good mechanical properties, fatigue properties which are explained in this article. Metal matrix composites was demonstrated resulting finer particle distribution, micro segregation in the matrix, and the soundness in quality. Composites from the mixtures of Si and Al phases was demonstrated to result Si grains distributed in the Al matrix homogeneously. At higher stirring speed and stirring time of same resulted better distribution of particles at ununiform hardness.*

### Introduction

Composites are one of the most widely used materials because of their adaptability to different situations and the relative ease of combination with other materials to serve specific purposes and exhibit desirable properties. Area of applications of composites are very wide. Amongst, most predominant applications area are Automotive parts, Civil Aircraft, Military Aircraft, General aviation, Buildings Construction, Bridges construction, Roads construction, Energy Production and Distribution, Timber replacement, Jute Coir Composites, Bamboo based Composites, Rebuilding and Rehabilitation, Tourism House boats, Composite Pressure Vessels, Under Water Vehicles, Deep Ocean Equipments, High pressure accumulator bottles, Medical, Railway locomotives accessories etc. Since the applications are astounding it becomes necessary to go through different composites in detail which are rich in above properties so that we get best mileage out of applications in reality. Keeping this in mind Authors made an extensive survey of relevant articles in reputed journals and made a consolidation of review in this article.

### TRIBOLOGY / WEAR CHARACTERISATION

In this section, articles related to Tribology and wear properties were studied in depth and the results and discussions are consolidated and briefed as given below. Many of composites that are having positive characteristics and few are still under development are also mentioned in this article primarily to explore the research scope.

Abouelmagd [1] investigated Aluminium Metal Matrix Composites under powder metallurgical technique. In this investigation reinforcement particles of Al<sub>2</sub>O<sub>3</sub> and Al<sub>4</sub>C<sub>3</sub> were added to the basic Aluminium matrix then this composite was tested for compression, wear, hardness also. The above said test was conducted at various temperatures and at different velocities. Finally the addition of Al<sub>4</sub>C<sub>3</sub> upto a critical deformation temperature increases the wear resistance, Hardness and Compression strength of composite

Kishawy et al., [2] presented in a paper an analytical model for the prediction of tool flank wear progression during bar turning of particulate reinforced metal matrix composites. This work arrived a technique for analytically predicting the wear progression as function of tool / work piece properties and cutting parameters. The results showed fair relationship between predicted and measured tool wear progression. Er-yong Liu et al., [3] studied Tribological properties of Ni based composites containing silver and molybdenum disulfide from room temperature °C which were prepared by powder metallurgy technique. The results showed that best tribological properties attributed

to the formation of silver molybdate and lubricating tribolayers were obtained when the silver and molybdenum disulfide contents were 20 wt% and 8.5 wt%, respectively.

López et al., [4] adopted a fabrication technique of High Velocity Oxygen-Fuel (HVOF) to deposit aluminium coatings reinforced with silicon carbide particles on Mg-Zn substrates. This research work was to improve the tribological performance of the ZE<sub>4</sub>1A magnesium alloy. The parameters of the thermal spraying system have been optimized in order to maximize the SiC particles incorporation in the aluminium matrix of the coating and to minimize the mechanical deterioration of the light alloy substrate. The wear resistance of the substrates was increased. Ramesh et al., [5] discussed in a research article that Al6061 metal matrix composite reinforced with Nickel coated silicon nitride particles were manufactured by liquid metallurgy route. In Microstructure analysis nickel coated silicon nitride particles were uniformly distributed throughout the matrix alloy. The coefficient of friction and wear rate of both matrix alloy and developed composite decreased with increase in load. coefficient of friction and wear rate were increasing continuously.

Liuje et al., [6] discussed in a research paper that a Back Propagation (BP) neural network was used to study the effects of the *pv* factor and sliding distance on the friction and wear behaviour of 30 wt. % carbon fibre reinforced Poly(Ether)-Ether-Ketone advanced composite (PEEK-CF30) at the critical temperature of 120 °C. The test results reveal BP neural network models can accurately envisage the coefficient of friction and rate of wear by loss in weight based on Pressure, Volume factors and sliding distance. Patrick et al., [7] illustrate in an article that Wear rate of high alloy hardfacing deposit (SHS9290) with silica abrasive is lower than that in Tungsten carbide-Ni based metal matrix composite (MMC). On contrary Wear rate of high alloy hardfacing deposit (SHS9290) with Alumina grit is higher than that in Tungsten carbide-Ni based metal matrix composite (MMC). It means wear rate is dependent on the hardness of the constituent phases relative to the abrasives.

Gopalakrishnan et al., [8] discussed with their experimental results that Aluminium matrix reinforced with titanium carbide (Al-TiCp) composites are fabricated castings with different volume fraction of TiC in an argon atmosphere by an enhanced stir casting method. Specific strength and wear resistance of the composite has increased with higher % of TiC addition.

Gongjun Cui et al., [9] studied Tribological behaviors of Cu-6Sn-6Zn-3Pb alloy sliding against AISI321 stainless steel under sea water, distilled water and dry sliding conditions on a pin-on-

disc tester. This study resulted the friction coefficient in distilled water is the largest and in dry-sliding is smallest. In Sea water and distilled water the wear mechanism is microplough and plastic deformation and have lubrication and corrosive effects.

Umanath et al.,[10] investigated Aluminum-base hybrid composites reinforced with mixtures of SiC and  $Al_2O_3$  particles have been fabricated on an Al6061 alloy by stir casting method. Wear resistance and Co-efficient of Friction has been investigated as a function of applied load and Volume fraction of the reinforcement particles. The results show that, the reinforcement of the metal matrix with SiC and  $Al_2O_3$  particulates upto a volume fraction of 25% reduces the wear rate at room temperature. The results also show that the wear of the test specimens increase with the increasing load and sliding distance.

#### CHARACTERISATION BY MECHANICAL PROPERTIES

Articles related to Mechanical properties are studied in detail and the results and discussions are consolidated and discussed as given below. This gives an insight to the reader as to what composites are best chosen with respect to different applications. Nevertheless positives are there still a few composites are yet to do intensive research work.

Lahaie et al.,[11] investigated the effects of hydrostatic extrusion on particle cracking and on the subsequent tensile properties of some prototypical particle reinforced metal-matrix composites. Extrusion prior to tensile testing has the effect of saturating the flow stress of MMC and limiting the tensile values because of the very low hardening rate of the matrix. Particle cracking during extrusion causes a further reduction in ductility. Youn [12] made an investigation of the effect of volume fraction and reinforcement sizes on mechanical properties in cylinder liner part of Metal Matrix Composites with process parameters of pressure and velocity.

Glage et al.,[13] discussed in detail in a research study that the mechanical behaviour of newly developed metal matrix composites (MMCs) in terms of compression and fatigue properties. The matrix of the MMCs consists of a high-alloyed metastable austenitic cast steel, which shows the Transformation Induced Plasticity. As reinforcing phase MgO partially stabilized  $ZrO_2$  is used which can also undergo a martensitic phase transformation. The samples were produced by infiltration of the cast steel into open foam structures made of  $ZrO_2$  with porosities of 30 and 50 ppi. The fatigue properties were investigated under total-strain and stress control. The martensitic phase transformation of the austenitic steel matrix was investigated using a ferroscope sensor. Yuan et al.,[14] made a Numerical analysis to simulate the tensile test of particle reinforced metal matrix composite for predicting the micro stress/strain field and macro tensile stress/strain curve. The axis symmetric cell model consisting of interface, matrix and reinforced particle was used for this work. Smaller reinforcement aspect ratio leads to smaller micro stress in composites.

Hongjian Zhang et al.,[15] programmed, developed and discussed, the progressive damage method for predicting the strength of Comeld composites joints by considering the structural failure criterion based on 3-D finite element method. Mechanical properties of Comeld composites joints vary from the Uncomeld composites. The strength prediction method was applied to predict the strength of Comeld joints in this article. Experimental results were in compliance with the prediction and hence this novel technology could be applied in metal-composite joints. Yu Zhu et al.,[16] carried out a series of investigations to evaluate mechanical properties and drying shrinkage of Engineered Cementitious Composites (ECC) with 70% combination mineral admixtures of Fly Ash (FA) and ground granulated blast furnace slag (SL). Purpose was to develop a kind of green ECC with high tensile ductility and strong enough matrix strength, especially at early age. Results show that ECC with combination mineral admixtures can achieve strain hardening behavior; tensile capacity of ECC can be more than 2.5% at 90 days. Incorporating SL into matrix can slightly increase drying shrinkage of

ECC. ECC with 30% SL and 40% FA presents the lowest drying shrinkage at later ages.

Sinha et al.,[17] conducted a series of research on magnesium based metal-matrix composites using submicron SiC (4.8–15.4 wt%) and micron sized Ti (2.7 wt%) particulates for finding scratch hardness. Results could be correlated with composites' bulk mechanical properties such as the normal hardness, the elastic modulus and the yield strength. Also the scratch hardness correlates well with the normal hardness and the elastic modulus increase with an increase in reinforcing particulates by weight. These composites have higher tendency to initiate brittle cracks at the edges and wear debris in comparison to pure Mg. Ti which is marginally added increases the scratch resistance of the composites. Balasivanandha Prabu et al.,[18] made an analytical work on effect of volume fraction of SiC and diameter of the fiber on interfacial stress/strain characteristics of 6061 Al/SiC metal matrix composites using finite element method. With ANSYS 5.4 model and appropriate boundary conditions, the influence of fiber diameter and volume fraction of the fiber on the stress transfer from matrix to fiber was studied. The results show that debonding which is initiated by the shear is more pronounced in the interfacial element near the axis of symmetry. Also when load increases maximum shear stress occurs just inside the model at some distance from the free end of the unit cell.

Necat Altinkok et al.,[19] made a research study wherein density and tensile strengths properties of  $Al_2O_3$ /SiC particle reinforced metal matrix composites (MMCs) are predicted by designing a back-propagation neural network that uses a gradient descent learning algorithm. Composites are produced by stir casting process. As a prototype,  $Al_2O_3$ /SiC powder mix has been prepared by reacting of aqueous solution of aluminium sulphate, ammonium sulphate and water containing SiC particles. Density and tensile strengths of dual ceramic reinforced Al matrix composites have been investigated at room temperature. Neural network is applied using the data obtained in experimental process. Hence using neural network density and tensile strengths of fabricated MMCs had been accurately predicted for different SiC particles

Liu et al.,[20] investigated a process of fabrication of aluminum metal matrix composites reinforced with tungsten carbide (WC) particles through warm accumulative roll bonding. The process confirmed to have excellent WC particle distribution in the Al matrices, and no reaction between Al and WC was observed. Introduction of 3 vol% WC particles to the Al matrix composite in this process lead to significantly enhanced properties of The tensile, hardness, and wear.

Onur Sayman et al.,[21] discussed after an investigation that an Elastic-plastic stress analysis is carried out on symmetric cross-ply [08/908]2 and angle-ply aluminum metal-matrix laminated plates under thermal loads varying linearly along the thickness. This investigation was based on Tsai-Hill criterion for yield criterion applying boundary layer conditions and subsequently an analytical solution is performed for satisfying thermal Elastic-plastic stress-strain relations and boundary conditions for small plastic deformations. The composite material is assumed to harden linearly. Finally these work resulted residual stresses distributions along the thickness of the plates are obtained.

Narayana Murty et al.,[22] arrived a methodology for the development of processing maps, a simple instability condition for assessing the extent of plastic deformation in a work piece prior to the formation of defects, on the Ziegler's continuum principles.  $Al_2O_3$  particulate reinforced metal matrix composite was considered for this work. Instability maps at different strain levels were superimposed while delineating the unstable regions in the processing maps. The 'stable' and 'unstable' regions in the processing maps identified from the present instability condition have been compared with the reported microstructural observations of the deformed compression specimens. It was noted that the domain of instability increases with the in-

creasing volume fraction of the SiC particles. The optimum hot working conditions for these composites were also suggested in this article.

Ding et al.,[23] investigated and derived a new method of writing analytical expressions a new method of defining the yield behavior of short fiber reinforced metal matrix composite for the stress strain response of short fiber reinforced metal matrix composites. The effects of the material parameters say fiber volume fraction, fiber aspect ratio, fiber end distance and matrix strain hardening coefficient on the deformation behavior of composite were also investigated. It was demonstrated that there is a close relationship among the stress strain partition parameter and the deformation behavior of the composite. The effect of the material parameters on the initial yield behavior can be revealed well by this method. The predicted elastic modulus and yield stress are in compliance with the experiments. Park et al.,[24] published an article wherein Aluminium-magnesium-silicon alloy reinforced with  $Al_2O_3$ -based polycrystalline ceramic microspheres fabricated by a liquid metallurgy route, have been investigated for a stress of fully reversed loading. Fatigue testing was conducted on both smooth round bar and notched round bar specimens. Unreinforced Al 6061-T6 also processed by a liquid metallurgy route were also studied. Result revealed that the powder metallurgy processed composites gave longer fatigue lives than the matrix alloy. As per their investigation failure mechanisms were determined from examination of the fracture surfaces and the crack profiles.

#### MICROSTRUCTURE CHARACTERISATION

Articles related to Composites Microstructure characterisation are studied and the results and discussions are consolidated and given below. This gives an outline informations about Microstructure properties of composites with reference to different applications.

Chen Tijun et al.,[25] investigated the effects of Ti content and the alloying elements of Si and Cu on the microstructures of casting *in situ* Al<sub>3</sub>Ti-Al composites. The morphologies of Al<sub>3</sub>Ti phase are not only determined by Ti content, but are also related to the alloying elements. As per their discussion the grain refining role of Al<sub>3</sub>Ti phase in the pure Al and Al-Cu based composites is more effective than that in the Al-Si based composite. Result showed that corrosion resistances of the composites are dependent on both the corrosion characteristics of the corresponding matrixes and the distribution of Al<sub>3</sub>Ti platelets. Lin et al.,[26] made an intensified study of the microstructure of tensile, impact and three-point bending samples of aluminum alloy/SiC(p) composites produced by die casting. The results show that in impact samples, SiC particulates cluster along the left and right edges of the

section vertical plane with the notch plane, and near the notch. In tensile and three-point bending samples, they were distributed uniformly in the matrix. Porosities seen near the notch in the impact samples. The authors discuss on mould flow as the quantity of SiC particulate is less from the shot biscuit to the bending section of the sprue and SiC particulate is clustered in the protrusive region where the injector pins are situated.

Sozhamannan et al.,[27] discussed the methodology of microstructure based elastic-plastic finite element analysis of particle reinforced metal matrix composites. This model can be applied to predict the failure of two dimensional microstructure models under tensile loading conditions. The finite element analysis models were generated in ANSYS, using SCM images. The percentage of major failures and stress-strain responses were predicted numerically for each microstructure. From the results of experiments done it is evident that the clustering nature of particles in the matrix dominates the failure modes of particle reinforced metal matrix composites. Kennedy et al.,[28] discussed in an article that the combination of spontaneous particle entry and close crystal structure matching in the Al-TiB<sub>2</sub> and Al-TiC systems, results in low particle-solid interfacial energies and the generation of good spatial distributions of the

reinforcing phase in the solidified composite castings. The reinforcement distribution is largely insensitive to the cooling rate of the melt and the majority of the particles are located within the grains. Modulus increases after TiC and TiB<sub>2</sub> particle additions are greater than those for Al<sub>2</sub>O<sub>3</sub> and SiC due to wetting of the reinforcement by the liquid. Furthermore results show Stiffness and ductility of TiC-reinforced composites were higher than that of TiB<sub>2</sub> reinforced composites.

Brett A. Bednarczyk [29] presented a micro/macro theory for determining the coupled thermo-electro-magneto-elasto-plastic behavior of arbitrary composite laminates. Electro Magneto Generalised Methods of Cells has been reformulated to improve its computational efficiency and has been extended to admit arbitrary anisotropic local material behavior and inelasticity. The other model the Author explained was a classical lamination theory, which had been extended for arbitrary anisotropic material behavior and electro-magnetic and inelastic effects. The end result was homogenized behavior of the composite plies that constitute the thermo-electro-magneto-elasto-plastic laminate. XinYan Yue et al.,[30] narrated in an article about a micro structure and mechanical properties of a three layered material B<sub>4</sub>C/Al, B<sub>4</sub>C/TiB<sub>2</sub> and B<sub>4</sub>C composites using a two-step method for both hot pressing and aluminum infiltration in vacuum. The three-layer B<sub>4</sub>C/Al-B<sub>4</sub>C/TiB<sub>2</sub>-B<sub>4</sub>C composite showed good interfacial bonding. The microstructures of both B<sub>4</sub>C/TiB<sub>2</sub> and B<sub>4</sub>C layers showed no apparent changes before and/or after aluminum infiltration. The three-layer composite showed improved fracture toughness than that of B<sub>4</sub>C material and higher comprehensive hardness than that of B<sub>4</sub>C/Al material.

Sharifitabar et al.,[31] discussed in this research paper like microstructures and hardness profiles across the interface of friction stir welded joints between monolithic 2024-T<sub>4</sub> aluminum alloy (AA) and Al/Mg<sub>2</sub>Si metal matrix cast composite (MMC) and effects of one and two welding passes on these parameters. Results showed that there were complicated patterns of materials flow in the stir zone (SZ) especially in samples welded in two passes. Stirring caused fragmentation and rearrangement of Mg<sub>2</sub>Si large particles in the stir zone and thermo mechanically affected zone (TMAZ) of MMC, respectively. Hardness variation in the sample welded in two passes was observed and there was alternating decrease and increase in hardness value at the joint interface.

Balasivanandha Prabu et al.,[32] investigated microstructure-based finite element analysis of particle-reinforced metal-matrix composite (PRMMC) to evaluate the stress-strain and failure behavior. The microstructure with random particle arrangement and particle clusters were analysed. The failures such as particle fracture, interface decohesion and matrix yielding were predicted for particle clustered and non-clustered microstructures. The effects of particles arrangement on the failure mechanisms were analysed and discussed in this article. Balasivanandha Prabu et al.,[33] in this study have explained the effect of stirring speed and stirring time on distribution of SiC particles with high Al alloy. Brinell hardness test was also done. The results revealed that at lower stirring speed and lower stirring time particle clustering was more along with uniform hardness. At higher stirring speed and stirring time resulted better distribution of particles at nonuniform hardness.

Xinming Zhang et al.,[34] investigated effects of Si addition (1.0 wt.%) on microstructure and mechanical properties of Mg-8Gd-4Y-Nd-Zr alloy. The results indicated that the addition of Si led to the formation of Mg<sub>2</sub>Si and (RE + Si)-rich particles, which enhanced the Young's modulus of the alloy while decreased the yield strength and ultimate strength.

#### CONCLUSIONS

Al matrix with Al<sub>4</sub>C<sub>3</sub> reinforcement under powder metallurgical composites upto a critical temperature increases wear resistance, hardness and compression strength. Best Tribological properties are achieved from Ni based composites with Silver and Molybdenum disulphide under powder metallurgy technique. By depositing Aluminium coatings reinforced with

silicon carbide particles on Mg–Zn substrates fabricated under High Velocity Oxygen-Fuel (HVOF) is very effective for enhancing wear resistance. Wear rate of high alloy hardfacing deposit (SHS9290) with Alumina grit is higher than that in Tungsten carbide–Ni based metal matrix composite (MMC). The Metal matrix Composite consists of a high-alloyed metastable austenitic cast steel with MgO and ZrO<sub>2</sub> as reinforcement can undergo a martensitic phase transformation whose fatigue properties and compression are found to be encouraging. Structural properties of fine fly ash particles reinforced with Al–7Si–0.35Mg alloy composite was evaluated, resulted in a well-dispersed and relatively agglomerate and porosity free fly ash particle dispersed composites. Microstructures and hardness profiles across the interface of friction stir welded joints between monolithic 2024-T4 aluminum alloy (AA) and Al/Mg<sub>2</sub>Si metal matrix composite resulting complicated patterns of materials flow in the stir zone in samples welded in two passes. Microstructure-based finite element analysis of particle-reinforced metal–matrix composite to evaluate the stress–strain and failure behavior was investigated. The failures such as particle fracture, interface decohesion and matrix yielding were predicted for particle clustered and non-clustered microstructures. At lower stirring speed and lower stirring time particle clustering of SiC particles with high Al alloy was more along with uniform hardness. At higher stirring speed and stirring time of same resulted better distribution of particles at ununiform hardness.

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