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REVIEW

An Overview of the Mechanical and Tribological Characteristics of Non - Ferrous Metal Matrix Composites for Advanced Engineering Applications

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A B S T R A C T

The ever increasing service requirement of industries like automobile, aerospace, marine, infrastructure and transportation have evolved non-ferrous metal matrix composites with different combinations of ceramic and soft reinforcements which have resulted in the improvement of their tribo-mechanical properties as compared to an unreinforced alloy. Secondary reinforcements provide safe disposal of agro-industrial waste thereby reducing environmental degradation. The scanning electron micrographs reveals fairly uniform dispersal of reinforcement in metal matrix if proper conditions are maintained and porosity levels are found to be in acceptable range. The density, hardness, wear resistance, tensile strength, fatigue strength and impact strength of non-ferrous composites have been found to be either comparable or superior to an unreinforced alloy with minimum weight and cost. The purpose of current study is to explore the nonferrous composites and propose their application area based on material properties. An attempt has been made for indepth review on the effect of controllable process parameters on tribo-mechanical properties of the non-ferrous composites. The study concludes that non- ferrous composites with single or more than one reinforcement have superior tribo-mechanical characteristics making them suitable for design of high performance, low cost and low weight to strength ratio components.

1. INTRODUCTION

In modern era with stiff competition in market the demand of low cost high performance materials have led the researchers to strive for novel materials with desirable tribo-mechanical properties at relatively low cost. The basic goal of the researcher is to optimize the objective function of cost and performance with the result research is now focused on evolving hybrid non-ferrous metal matrix composites (MMC) to replace the traditional conventional materials [1]. The hybrid MMC have more than one reinforcement so as to get the advantage of both these reinforcements in mechanical characterization of the composite [2]. The coefficient of thermal expansion of MMC is low whereas its resistance is high when subjected to wear conditions. Further the strength of composite is high and at same time its weight is comparatively less which makes it an excellent substitute to conventional materials in the industry [3].

1.1 Composite

Composite material is composed of two or more materials combined in such a way so as to take advantage of both materials. The material used in a composite is such that one material overcomes the deficiencies of other material and vice versa [4]. Unlike an alloy both the constituents of composite retain their physical and chemical properties. Matrix and reinforcement constitute two insoluble phases of the composite, each preserving its individual character in the composite [5]. The matrix is the main continuous phase while reinforcement is the discontinuous phase in the matrix of the composite. The metal matrix generally used for engineering applications includes aluminum, magnesium, copper and tungsten while various reinforcement additions to improve the tribo mechanical attributes of composite are silicon carbide (SiC), boron carbide (BC), flyash, alumina, rice husk ash, bamboo leaf ash, coconut shell ash etc. The composites thus formed have better physical and tribo-mechanical aspects as compared to parent metal.

2. INVESTIGATION OF MICROSTRUCTURE

The main motive of the researcher is to maintain the proper conditions during melt solidification and speed of the stirrer to develop homogeneous composites which can be established through micrographs. Improper temperature conditions during solidification leads to formation of agglomerates which hamper the mechanical strength of the developed composite. The type of reinforcement and its distribution determine the characteristics of the composite [6]. The primary factors that influence the reinforcement distribution are fluidity and wettability as suggested by Hanumanth and Irons [7]. The various findings of the researchers pertaining to microstructural attributes of the developed non-ferrous composites are reviewed and discussed below.

M. V. S. Babu [8] studied the fatigue strength of Babbitt/Ilmenite nano-composite fabricated using ultrasonic probe assisted stir casting. The microstructure of nano-Ilmenite reinforced Babbitt shows big dark circles of Cu_6Sn_5 intermetallic distributed in tin matrix and tiny black spots reveal nano reinforcement dispersion in tin matrix thereby suggesting uniform dispersion of intermetallic and nano reinforcement in tin matrix by ultrasonic assisted stir casting (Fig. 1).

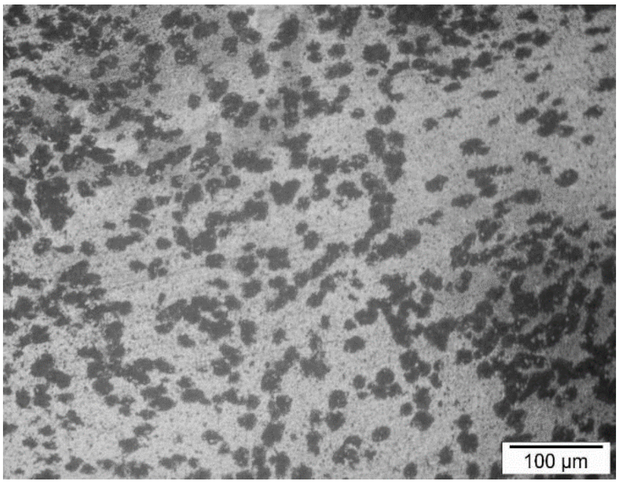
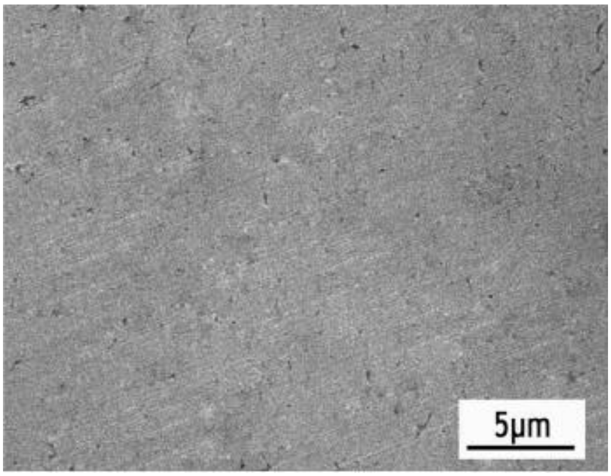


Fig. 1. SEM image of Babbitt/Ilmenite metal matrix nano composite [8].

Yanxia [9] studied the effect of addition of graphene nano sheet with Ni nanoparticles in Cu matrix. The hybrid graphene nanosheet (GNS)-nickel were first developed by chemical reduction method and then reinforced in Cu-matrix by spark plasma sintering. The SEM images shows the white phase (GNS) dispersed homogeneously in grey Cu matrix phase and no agglomerations of GNS were observed. The Ni nanoparticles prevent the agglomeration of GNS by anchoring on its laminate structure and hence ensures proper dispersion. The homogeneous distribution of GNS was further confirmed from the images as there were no pores or cracks on surface (Fig 2).

According to another study by B. Praveen Kumar [10] Al-4.5%Cu/BLA composite was developed via vortex casting. Micrographs revealed good interfacial bond with some degree of porosity due to entrapped gas in the melt within acceptable levels. The XRD analysis of the composite showed the presence of SiO_2, Al_2O_3, Fe_2O_3 and Cu suggesting uniform dispersal of reinforcement in the composite (Fig.3). The results are in line with [8,9].



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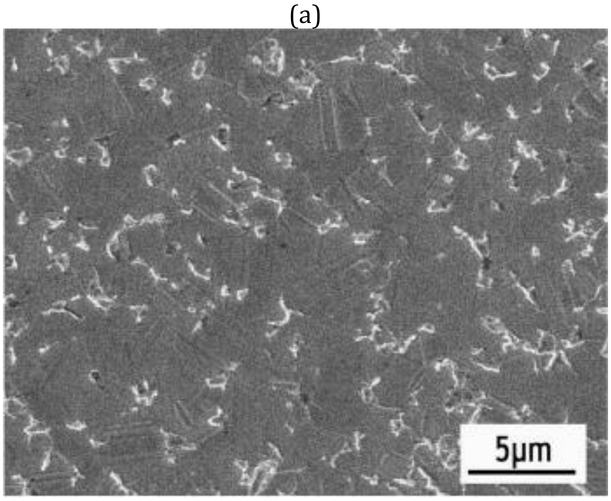
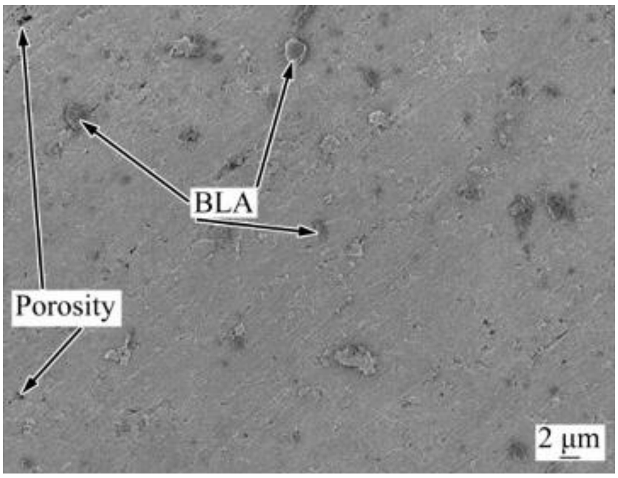


(b)

Fig. 2. Micrographs of (a) Cu and (b) 1 vol.% GNS – Ni/Cu composites [9].



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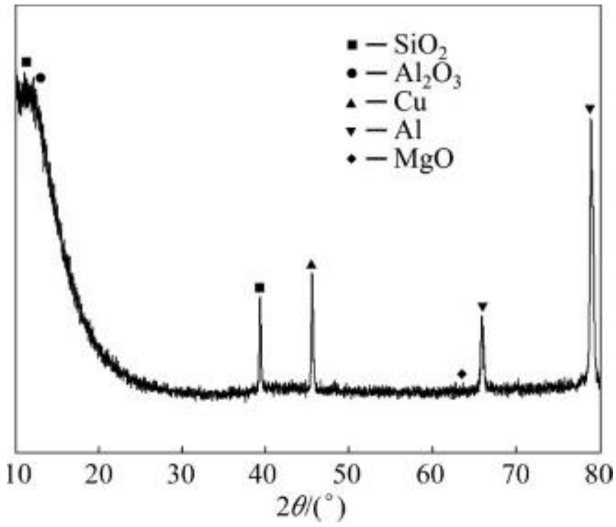


(b)

Fig. 3. (a) SEM image and (b) XRD analysis of Al-4.5%Cu-6BLA composite [10].

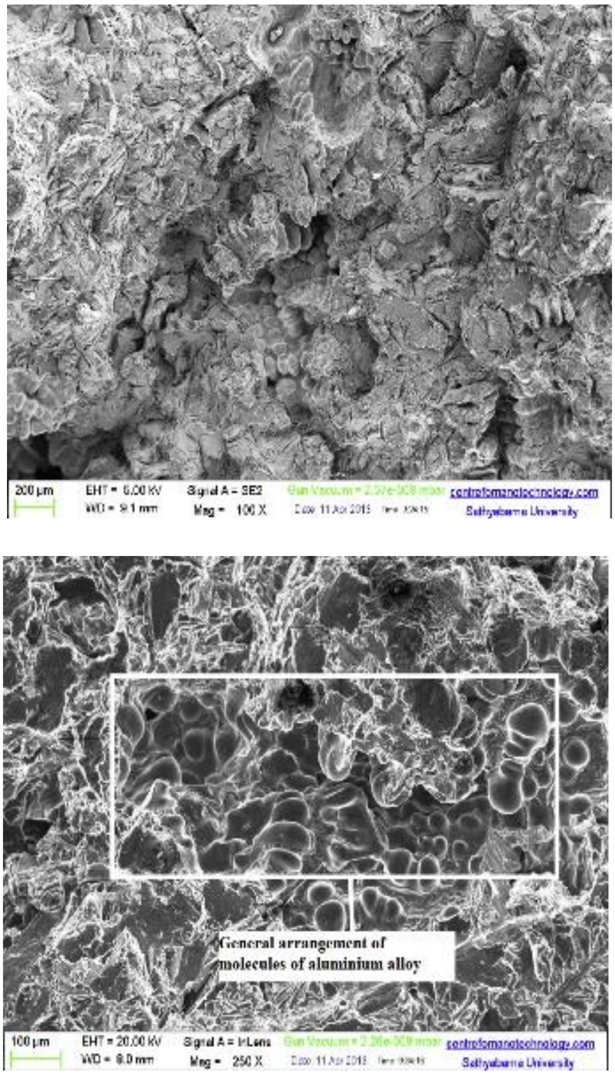
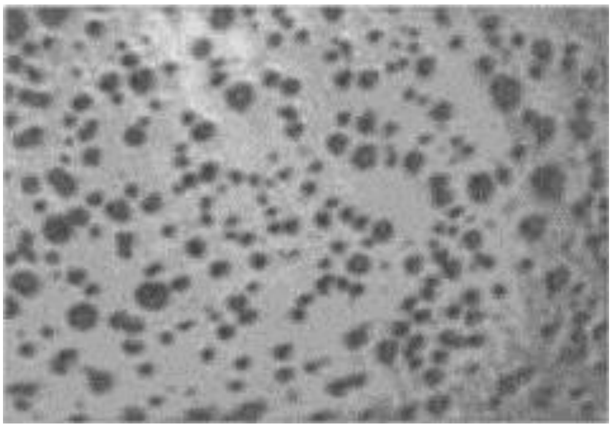


Fig. 4. Fractured tensile specimen of the composite and formation of micro-cracks [11].

B. Vijaya Ramnath [11] investigated LM25/Al_2O_3/B_4C metal matrix composite. The microstructure reveals non uniform dispersal of alumina and boron carbide in the metal matrix due to improper stirring along with formation of cracks and porous sites as a result of improper casting conditions. The scanning electron micrographs of fractured tensile specimen of the composite reveals microcracks in the matrix and non-uniform distribution of alumina and boron carbide in LM25 alloy with dark boron carbide particles at centre which are surrounded by lighter aluminium particles at outer periphery (Fig. 4).

A similar study of microstructures conducted by Boopathi et al. [12] in which aluminium alloy Al 2024 was reinforced with different compositions of flyash and SiC reveals non uniform distribution in single reinforcement composite because of segregation of particles due to gravity in the melt whereas SEM images of Al/SiC/flyash hybrid composite showed homogeneous distribution of reinforcements in matrix (Fig. 5).



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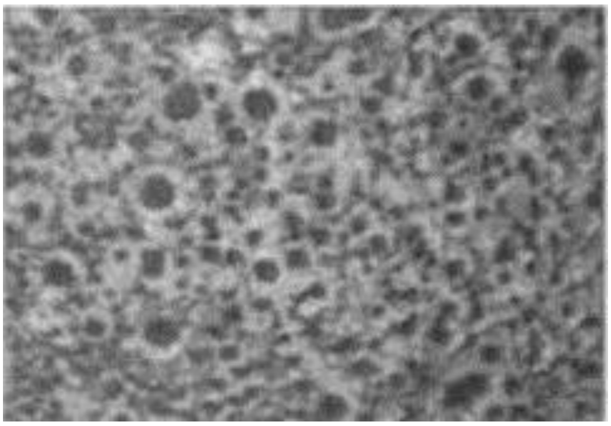
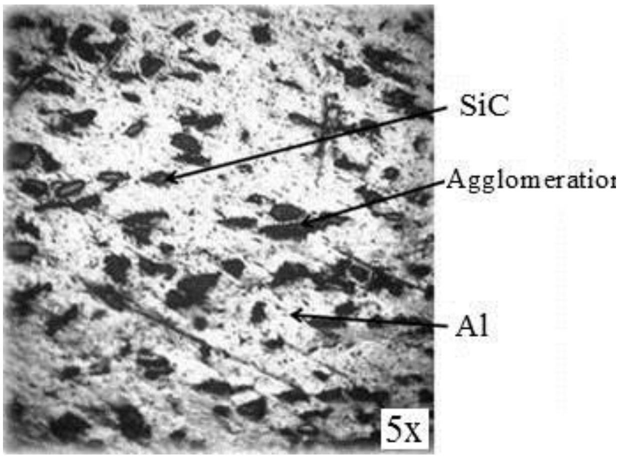


(b)

Fig. 5. Optical micrograph of Al2024/10%SiC/10 % flyash composite (a) before and (b) after etching [12].

Another study of microstructure conducted by Akm Asif Iqbal [13] in which aluminium powder was reinforced with SiC nanoparticles shows almost uniform distribution of reinforcement with localized agglomeration due to improper manual mixing (Fig. 6).



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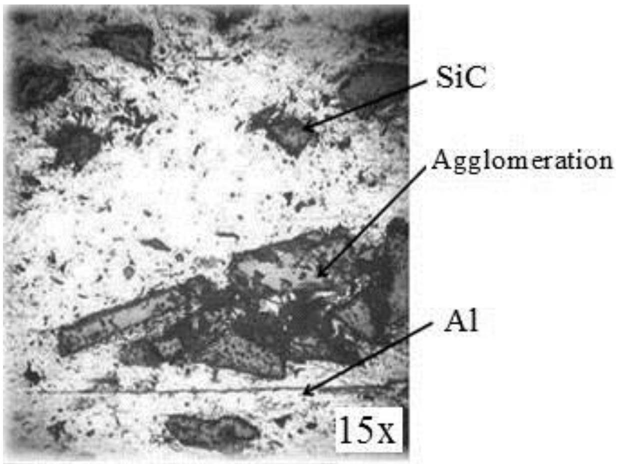

(b)

Fig. 6. Micrographs of 90% Al/10 % SiC composite at (a) 5X and (b) 15X magnification [13].

Non-ferrous composites fabricated by various techniques under controlled conditions have shown uniform dispersion of one phase in another, resulting in their superior physical, mechanical, and tribological properties, making them potential replacements for conventional monolithic materials in advanced engineering applications. Microstructural aspects of non-ferrous composites and their proposed application areas are listed in Table 1.

Table 1. Microstructural aspects of non -ferrous composites.

Composite/Method	Microstructural characterization	Morphology Techniques	Application	Reference
AA5154-SiC/Stir casting	Uniform dispersion and good interfacial bonding.	FESEM, XRD	Automobiles	[14]
Al7075-SiCnp/ultrasonic cavitation assisted stir-casting	Homogeneous particle distribution and grain refinement with no trace of oxides and impurities.	EDS, XRD	Structural, marine	[15]
Cu-Invar/Spark plasma sintering	The finer invar particles cluster to form semi coherent interface whereas coarse particles were randomly distributed in the matrix to form non-coherent interface.	FETEM, XRD	Electronic packaging material	[16]
TC21-GNPs/Spark plasma sintering	GNPs were evenly distributed over the surface of TC21 and sandwich interface of TiC and TiC coated GNPs bands in the sintered composite were formed.	XRD, EDS, SEM, TEM	Aerospace	[17]
Al-Ti-TiC-CNTs-AZ31/laser cladding and high speed friction stir processing	The composite prepared by laser cladding had no defects such as pores, spatters and refined microstructure with sound metallurgical bonding and it was significantly densified when subjected to high speed friction stir process.	SEM, EDS, XRD	Biomedical, power industries	[18]
AA7075-8% graphite-25SiC/Microwave sintering (Powder metallurgy)	No agglomeration without any secondary phases and clean interface.	SEM, EDS, XRD	Defense and aerospace	[19]
Ti-6Al-4V(TC4)-Cu-graphene oxide/Powder metallurgy and spark plasma sintering	The unreacted graphene oxide, TiC and Ti_2C intermetallics co-exist in the composite which improved its tribological properties.	SEM, EDS, XRD, Raman and XPS spectroscopy	Brake discs, automobiles, biomedical implants	[20]
YT5 cemented carbide-carbon-carbon composite using Ni-Cu-Ti foils as intermediate layer/transient liquid phase diffusion bonding	Good interfacial bonding with no defects for bonding temperatures greater than eutectic point of the interlayers was observed. The dense and continuous intermetallic brittle compounds were formed at high bonding temperature by diffusion and chemical reactions resulting in brittle fracture at YT5/C-C joints.	SEM, EDS, XRD	Aero engine components, airplane brakes, mechanical fasteners	[21]
TiB_2-$AlSi_7Mg$/Powder metallurgy and hot extrusion	Densification of as extruded composite was observed due to reduction of pores along with refinement of grains and silicon optimization as a result of shielding effect of TiB_2 agglomerates hindering dissolution of silicon in the composite.	OM, SEM, XRD, TEM	Aerospace and automobile	[22]

3. PHYSICAL PROPERTIES

The hard ceramic reinforcement additives are responsible for the increment in the density of base alloy during development of composite whereas addition of certain light weight reinforcements lead to the decrement in density of hybrid composites [23]. Boopathi et al. [12] determined density of Al-SiC, Al-flyash and Al-SiC–flyash composites experimentally and the study concluded that there was linear decrement of the composite density as the reinforcements were light weighed. A similar study conducted by Sahin and Murphy [24] revealed that density of the Al 2014/SiC coated boron fibre composite deceases linearly with increase in volume percentage of fibre reinforcement (Fig. 7) which was in agreement with [12].

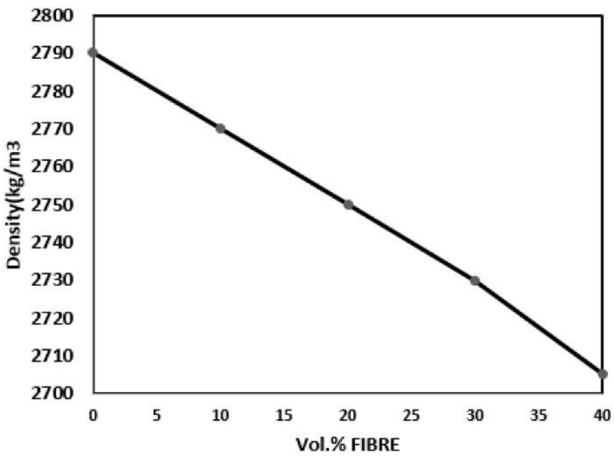

Fig. 7. Density variation with % volume of fibre [24].

Rajmohan [25] reported that (Al/SiC/Mica) hybrid composites have higher density than (Al/SiC) ceramic composites and the density of hybrid non-ferrous composite vary in direct proportion with increase in percentage of mica which was in accordance to the observations made by Sahin [26] that density increase has a straight line relationship with percentage reinforcement. Das et al. [27] measured the density of aluminium matrix composite (AMC) experimentally applying Archimede's principle using Archimedes apparatus fitted to Mettler Toledo make precision balance. It was reported that the density of reinforced AMC was less than unreinforced alloy but the density of reinforced alloy increased with increase in % of SiC_p. This may be due to high porosity levels in the composite as compared to unreinforced alloy but with increase in %wt. of SiC_p there was increase in density of composite as the local agglomerations of the SiCp increases with an increase in percentage content (Fig. 8, Fig. 9). This fact was validated by V. Mohanavel who noticed that there was an increase in density of AMC AA6351/SiC from 2.69 gm/cm^3 to 2.796 gm/cm^3 with increase in percentage of SiC [28]. The size of the particles reinforced in the matrix influenced the density of the composite. Smaller the size of particles more is the density because of more number of SiC_p particles in the given area. The porosity level increases with an increase in percentage of reinforcement as validated by Prasad et al. [29] because of entrapment of gas and shrinkage during solidification.

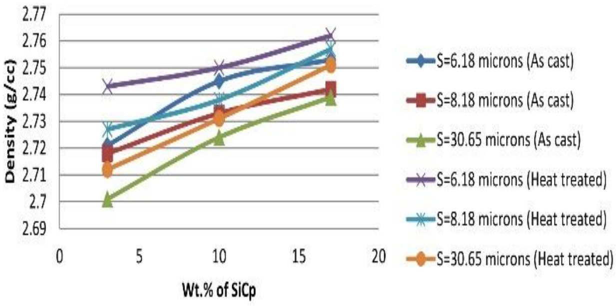

Fig. 8. Variation in density with % reinforcement of different particle sizes both cast and heat treated [27].

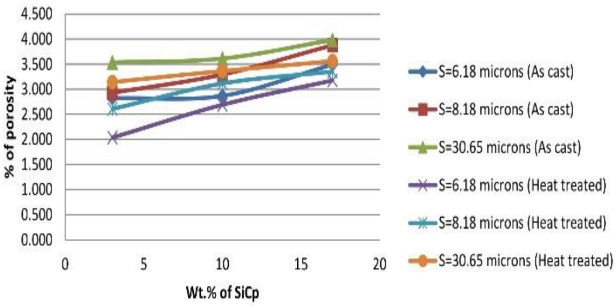

Fig. 9. Variation of porosity with % reinforcement of different particle sizes both cast and heat treated [27].

Rao et. al. [30] observed that the density of Al6061 and Al7075 alloy increased with an increase in % reinforcement SiC and Al_2O_3 respectively. The results were similar to those determined by Mohanavel et al. [28]. Further the density of Al 7075/Al_2O_3 composite was more than Al6061/SiC composite because ceramic reinforcement Al_2O_3 have higher density than SiC. Alaneme et al. [31] studied the porosity level of hybrid Al7075/BLA/SiC composite and observed that composite density decreases with increase in percentage weight of bamboo leaf ash since it is a soft, light weight reinforcement [12,23,24] without showing any appreciable trend in porosity levels which was maintained at acceptable level of 4%. K. Soorya Prakash [32] studied the effect of addition of SiC and graphite on density of magnesium matrix. The density of both the Mg-SiC and Mg-Gr composites increases with an increase in percentage content of the reinforcements since both SiC and Gr are high density reinforcements. The densities of Mg-5%Gr and Mg-10%Gr composites are less than their respective ceramic counterparts but more than the base alloy. Nine samples were developed with different percentage of SiC and graphite (Table 2.) and trends of hardness and density is depicted in Fig. 10.

Table 2. Composition of fabricated samples [32].

Sample No.	%Wt SiC	%Wt Gr	%Wt Magnesium
I	0	0	100%
II	5	0	95%
111	10	0	90%
1V	0	5	95%
V	0	10	90%
V1	5	5	90%
V11	5	10	85%
V111	10	5	85%
IX	10	10	80%

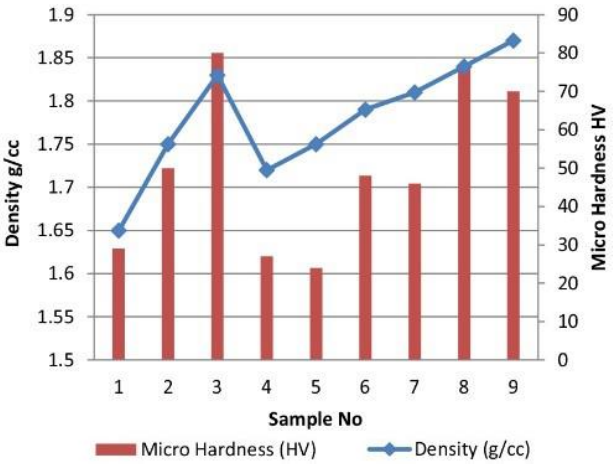

Fig. 10. Variation in density and hardness of samples as in Table 2 [32].

Improvement in the thermo - physical properties of non - ferrous composites fabricated via different manufacturing techniques under controlled conditions have been reported by various researchers (Table3.).

4. MECHANICAL BEHAVIOUR

4.1 Hardness and wear resistance

V. Mohanavel [49] studied the hardness of AA 6351 AMC with addition of graphite and noticed that as graphite particles were added the hardness of the AMC decreased and was lower than even that of base alloy. The dissemination of graphite particles in the matrix was not homogeneous and the density of graphite was low thus leading to decrease in hardness (Fig. 11). He further validated his research by reinforcing SiC in AA6351/SiC AMC from 0% to 20% in interval of 4% and conducting Rockwell hardness test at constant 15 kg load [28]. The results obtained clearly showed that with an increase in % wt. of SiC the hardness of the composite was enhanced by 61.7% as compared to the base alloy (Fig. 12). This may be attribute to uniform dispersion of ceramic high density SiC particles in matrix and creation of high dislocation density which provide additional resistance to plastic deformation.

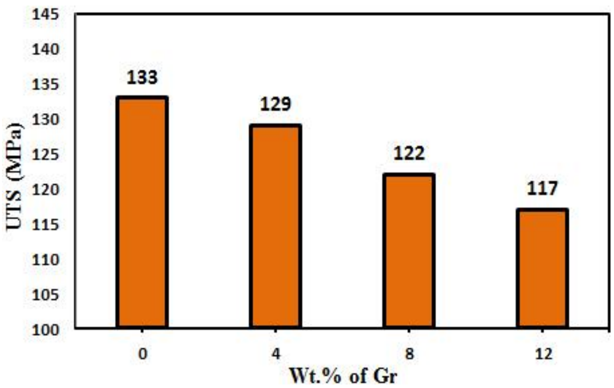

Fig. 11. Variation in hardness of AA6351/Gr composite with increase in % wt. graphite [49].

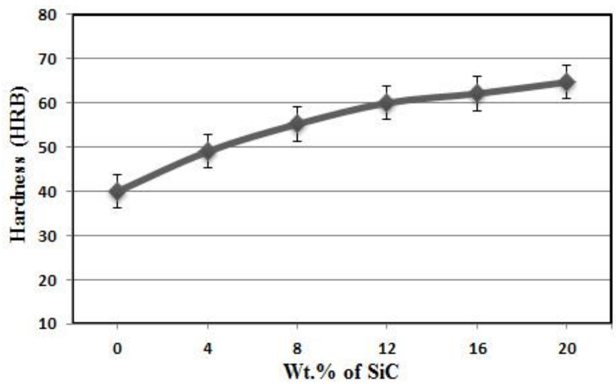

Fig. 12. Variation in hardness of AA6351/Si composite with increase in % wt. SiC [28].

Table 3. Thermo-physical properties of non-ferrous composites prepared by diverse techniques.

Composite	Fabrication Technique	Research findings	Reference
AA5083/Flyash	High temperature vacuum stir casting	Increase in fly ash percentage decreased the density of the composite owing to its lower density than the matrix and also increased the void content of the composite.	[33]
LM25/SiC/Gr	Double stir casting	There is decrease of 1.19% in porosity of LM25/4%SiC/2%Gr compared to base metal.	[34]
Al 5083/SiC	Conventional and ultrasonic stir casting	Composites were prepared with varying percentage of SiC (3%, 5%, 8% and 10%) and the density of the composite prepared with ultrasonic stir casting was found to be higher at all percentage levels of SiC than stir casting due to proper dispersion of SiC in matrix melt.	[35]
Al7075/Cr/SiC_p	Squeeze casting	Improvement in the thermo-physical properties of hybrid composite was reported. Addition of 50 vol.% SiC and 5 vol. % Cr in Al7075 alloy resulted in higher thermal conductivity and lower thermal expansion of hybrid composite as compared to 50 vol. % and 55 vol.% SiC reinforced metal matrix because of good interface conduction between chromium particles and aluminium melt.	[36]
Al/0.5wt.% GNP	Powder metallurgy	The improvement in mechanical properties were reported at cost of insignificant loss of physical properties. Thermal and electrical conductivity of the composite decreased by 2.4% and 6.7% with addition of 0.5% GNP in the pure aluminium powder with 65% increase in tensile strength.	[37]
Cu/Graphite	Flake powder metallurgy	Addition of 15% Cu granules in Cu-10% Gr composite improved electrical conductivity of the composite by 6.73% as a result of good interfacial bonding between Cu granules and the composite powder.	[38]
Al/Graphene	Melt filtration and powder metallurgy	Composites were prepared via both techniques and maximum hardness of the composite at optimized was found to 21.5% and 15% higher than baseline with porosity level ten - fold and doubled using powder metallurgy and melt filtration techniques respectively. The high percentage of micro porosities in the composite fabricated via powder metallurgy was due to un-sintered material and oxide formation while porosities in the composite prepared via melt filtration was due to gas trapped in the melt.	[39]
CuCrZr/CuZrAl Metallic glass	Spark plasma sintering	Volume fraction of metallic glass affected the electrical conductivity of the composite. There was an improvement in electrical conductivity for metallic glass content less than 30 wt. % with maximum electrical conductivity exceeding 20% International Annealed Copper Standard (IACS) was reported as a result of good interfacial cohesion.	[40]
La_2O_3/Cu	Spark plasma sintering	Electrical conductivity of the composite was found to be the function of sintering temperature. Higher the sintering temperature more is the grain size which increases the conductivity of the composite. The conductivity of the Cu-La alloy is limited even at large grain size due to presence of solid solution elements. The electrical conductivity of the composite as high as 92.79% of IACS was reported.	[41]
AA1050/6.5 vol.% Silica fume	Bobbin tool friction stir process(BT-FSP)	Double side friction stirring tool with travels speeds of 100 and 200 mm/minute was used to fabricate the composite. The crystalline grain size of the composite was found to be less than as-cast and processed AA1050 resulting in strengthening of the composite due to pile up of dislocations. Further with increase in travel speed the grain size diminished there by improving mechanical properties of the composite.	[42]

AA2024/SiC/BN/VC	Friction stir process	The hybrid composite shows 60% less thermal conductivity as compared to base alloy with improved mechanical strength due to grain refinement and low thermal conductive reinforcements. Electrical conductivity of the composite varies with the volume fraction of the reinforcement. Increase in vol. % of reinforcements indered the free movement of electrons resulting in diminished electrical conductivity.	[43]
Al-10 wt. %Cu	Microwave sintering and friction stir process	The composite was synthesized via powder metallurgy technique using microwave sintering followed by friction stir process. Its high electrical conductivity and low weight allow it to replace heavy conductors in electrical applications.	[44]
Graphite/Cu/Ti	Microwave activated sintering	Copper and titanium powders were sintered with graphite flakes both in microwave and conventional vacuum tube furnace. Rapid microwave sintering causes better dispersion of graphite in copper matrix and also refined the grain size of Cu particles. The thermal conductivity of the microwave-sintered composite was found to be 78% higher than that of conventional sintering, making it ideal for usage as an electronic packaging material.	[45]
Cu/GrNi/Cu	Vacuum hot pressing treatment	Initially nickel was electro deposited on graphite film followed by electro-deposition of copper on nickel coated graphite film with subsequent vacuum hot pressing. Intermediate nickel layer improved interfacial bond between graphite and copper enhancing the thermal conductivity of composite foil. Increase in volume fraction of graphite from 30% to 60%, enhanced thermal conductivity of the composite by 45.6%.	[46]
Cu mesh/AZ31 Mg foil	Diffusion bonding	AZ31 Mg foil and 200 mesh Cu were cut into circular pieces and stacked one on top of the other in a graphite mold placed in an induction furnace under hydraulic pressure. Thermal conductivity of the composite enhanced with increase in temperature as a result of better bonding and for diffusion-bonded composite it was found to be 109.4% greater than that of the AZ31 Mg alloy while maintaining its low weight.	[47]
Cu/Al/Ni/SiC	Accumulative roll bonding(ARB)	Copper, aluminium, and nickel sheets of the same size were stacked alternately and reinforced with SiC particles (2 μm and 15 μm). Cu/Al/Ni/SiC (15 μm) had higher thermal conductivity for each roll pass because large size SiC particles trapped at the interface provides a better heat flux channel across the composite, enhancing its thermal conductivity.	[48]

Abhijeet B. Chougule [50] studied the hardness of AA2219 alloy with varying %wt. of TiO_2 used as reinforcement. The weight % taken at three levels are 3%, 5% and 10%. He fabricated 3 samples via powder metallurgy technique and compared the hardness with unreinforced alloy (Fig. 13). Increase in percentage reinforcement had direct proportion with the hardness of AMC and it was found that hardness number increased by 45.31% which makes it highly suitable for aerospace applications and is in agreement with [28].

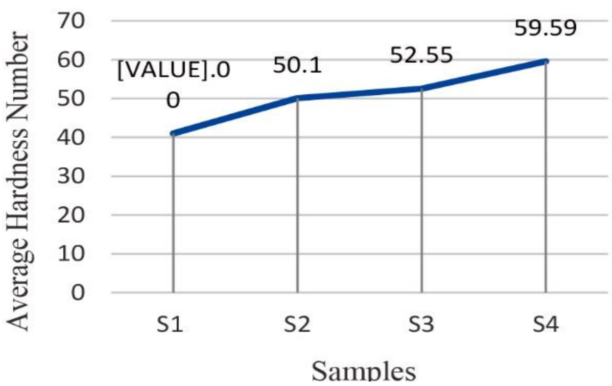

Fig. 13. Variation in average hardness number of AA219/TiO_2 composite with increase in TiO_2 [50].

S. W. Maseko [51] reinforced ZrB_2 in titanium matrix to increase the hardness of titanium MMC for structural, marine and anti-ballistic applications. The powder metallurgy technique was employed to disperse ceramic reinforcement in titanium matrix followed by spark plasma sintering. Three samples with different percentage composition of reinforcement (5%, 10% and 15%) were prepared. It was observed that the maximum hardness of 595 Hv on Vickers scale was obtained for 10% wt. reinforcement sample as compared to 495 Hv for 5% wt. reinforcement sample and 571 Hv for 15% wt. reinforcement sample (Fig. 14). The minimum number of TiB whiskers were found in sample 1 at 5 percent reinforcement. With further increase in percentage reinforcement to 10 % the number of TiB whiskers contributing to hardness becomes maximum. As percentage reinforcement increases from 10% to 15% the snow white like phase of $(Zr_{1-x} Ti_x) O_2$ increased at expanse of TiB whiskers leading to decreased hardness of sample 3.

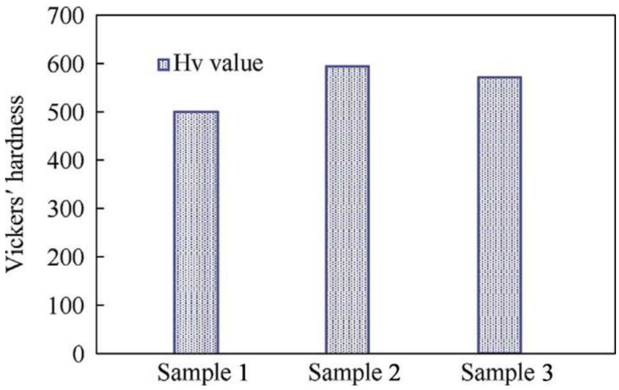

Fig. 14. Variation in Vickers hardness of Titanium matrix reinforced with ZrB_2 [51].

K. Soorya Prakash [32] investigated the effect of addition of SiC and Gr to magnesium matrix. The use of SiC as ceramic reinforcement enhanced the hardness of composite as compared to the base metal whereas addition of graphite reduces the hardness of the composite as graphite is soft reinforcement and also because of its self-lubricating property which is in line with [28,49]. It was also noted that for same percentage weight of SiC reinforcement in hybrid Mg-SiC–Gr composite there was decline in hardness with increment in percentage weight of soft graphite reinforcement. The wear resistance of hybrid magnesium MMC developed have increasing trend as result of addition of both reinforcements when compared with base metal. R. S. Rana [52] developed AA 5083–SiC nano composite utilizing vortex casting and Design of experiment (DOE) method was employed to assess the impact of the variables on the composite hardness and to predict the optimal set of process parameters for maximizing hardness. The correlation between hardness and process variables was obtained from DOE technique as:

$$H = -0.63\ W + 0.0472\ T - 0.0200\ S - 4.2 \tag{1}$$

The maximum hardness as measured on the Rockwell hardness B scale was found to be 19.4 at optimal controllable process parameters of 2% weight reinforcement (SiC), casting temperature of 760°C and 550 rotations per minute of stirrer.

V. Sreenivasan et al. [53] indicated that the development of aluminum red mud composite with monotonous reinforcement particle distribution may be processed through stir casting technologies and 14 weight percent of red-mud reinforcement is the optimal combination for more beneficial functional characteristics of the material with regard to hardness. C. Saravanan et al. [54] carried out another analysis in which it was found that the stir casting was most cost-effective method for the manufacturing of non-ferrous MMC, where the optimal speed range for stirring was 300 rpm to 600 rpm, and with the result hardness of aluminium MMC increased by 30% relative to the base alloy. M. K. Singh and R. K. Gautam [55] have carried out an investigation which conformed with [54] that the stir-casting process is an inexpensive and efficacious solution for the development of copper matrix composites and the hardness of the composite was found to be more than pure copper metal. The Al /Al_2O_3 MMC was examined for its mechanical characteristics with help of Taguchi technique by Chennakesava Reddy [56]. An increase in brittleness was observed which also ameliorates hardness as a result of embrittlement at grain boundary caused due to increase in percentage volume of Al_2O_3. Sylvester et al. [57] found that to achieve optimal process variables for maximum hardness of aluminum 6063 alloy, 5 weight percent addition of medium carbon fibers at stirring speed of 500 rpm for 5 minutes at 740°C temperature was to be maintained. Viktor et al [58] drew the conclusion that when 15 weight percent SiC was processed at 740°C melting temperature with a 100 rpm rotational rate for 20 minutes, this mixing condition proved as the best parameters for the Al-SiC composite processing via stir casting method. Additionally, the hardness of the Al-SiC composite was fundamentally influenced due to SiC content which contributes to 70.72 percent for the increased hardness. Sadi et al. [59] observed that the optimum performance with regard to hardness of the aluminium/ SiC composite was obtained by applying the Taguchi technique and the optimal set of parameters for maximizing hardness were addition of 15-weight percentage reinforcement at a temperature of 740° C with a stirring time of 10 minutes at 300 rpm. Also, the wear properties of the Al-SiC composite were fundamentally enhanced due to SiC content which contributes to 88.67 percent and is consistent with [58].

Ravi C. Naikar [60] created composites using varied amounts of red mud (3%, 6%, and 9%) as reinforcement. He came to the conclusion that red-mud increased the wear resistance of aluminium 6061 alloy, and that the highest wear resistance was attained when 3% red-mud was reinforced in the alloy. The impact of various reinforcements on magnesium and its alloys was studied by Abhijit Dey and Krishna Murari Pandey [61]. In comparison to base magnesium alloy, magnesium matrix composite has greater sliding wear resistance. They established that adding boron carbide to magnesium matrix enhanced the materials flexural and interfacial bonding strengths. Using the stir casting technique, Aatthisugan et al. [62] fabricated AZ91D/BC/Graphite composite comprising of both ceramic BC and soft graphite reinforcements which displayed improved tribological attributes. R. R. Navthar [63] manufactured Babbitt-2% SiC composite via vortex casting and observed that there was increase in wear resistance of the composite. Umanath et al [64] analyzed the tribological attributes of the aluminium alloy reinforced with different weight percentage of silicon carbide and aluminium oxide. The composite with 5% wt. reinforcements had poorer wear resistance than the composite with 15 %wt. reinforcements. A composite with a high percentage of reinforcement, less rotational speed, higher counter face, and low applied stress was found to have a low wear rate. The observed fracture mechanism was both ductile and brittle in character. Aluminum alloy reinforced individually with SiC, Al_2O_3 and RM was examined by Singla et al. [65]. In comparison to the base aluminium 6061 alloy, composite reinforced with each of these reinforcements exhibits greater hardness and wear resistance. Wear rate lowers as silicon carbide and aluminium oxide weight percentage rise, however for red mud the trend was the same up to 7.5 % wt. only, after which wear rate began to rise. The decrease in wear resistance was due to increase in viscosity of the aluminium 6061 composite above 7.5 percent weight of red mud leading to formation of agglomerates. Radhika et al. [66] developed and examined the wear characteristics of aluminium/alumina/graphite composite and discovered that sliding distance has the greatest impact on the wear rate and its wear resistance rises with increase in reinforcement content.

4.2 Tensile and yield strength

Jebeen Mosses [67] prepared AA6061/15% TiC composite via stir casting route to establish relationship between controllable casting parameters and ultimate tensile strength (UTS). The parameters chosen for study were stirring time, stirring speed, casting temperature and blade angle. Tensile specimen were prepared as per ASTM E8M standards. The UTS of the composite was increased up to 300 rpm and then begins to show downward trend. The rotation of the stirrer causes vortex which dispersed the reinforcement in the metal matrix by centrifugal effects thereby increasing the tensile strength. Further increase in speed beyond 300 rpm leads to sucking the atmosphere air into aluminium melt thereby entrapping gas leading to porosity which resulted in the downward trend of tensile strength beyond 300 rpm stirring speed. The stirring time also show similar effect on UTS which increased up to 15 minutes of stirring and then started showing downward trend due to gas entrapment leading to formation of pores thereby reducing ultimate tensile strength. The inclination of blade angle with horizontal affects the dispersion rate. With increase in blade angle up to 30° the dispersion rate of TiC in the matrix increased due to increase in centrifugal currents in the melt. At blade angles above 30° the air trapped due to centrifugal effects was not released during solidification thereby causing porosities which are confirmed with help of micrographs. The casting temperature affects the tensile strength in similar fashion. Up to casting temperature of 830°C cooling rate was optimum to drive out the entrapped gases maintaining reasonable porosity and UTS increased with increase in temperature. With further increase in temperature beyond 830°C the absorption of gas increased as it was directly proportional to temperature. Since casting temperature and cooling rate are inversely proportional and so with increase in casting temperature beyond 830°C relatively low cooling rate could not match high absorption rate of gases entrapped and thus producing high porosity level thereby reducing UTS (Fig. 15 a, b, c, d).

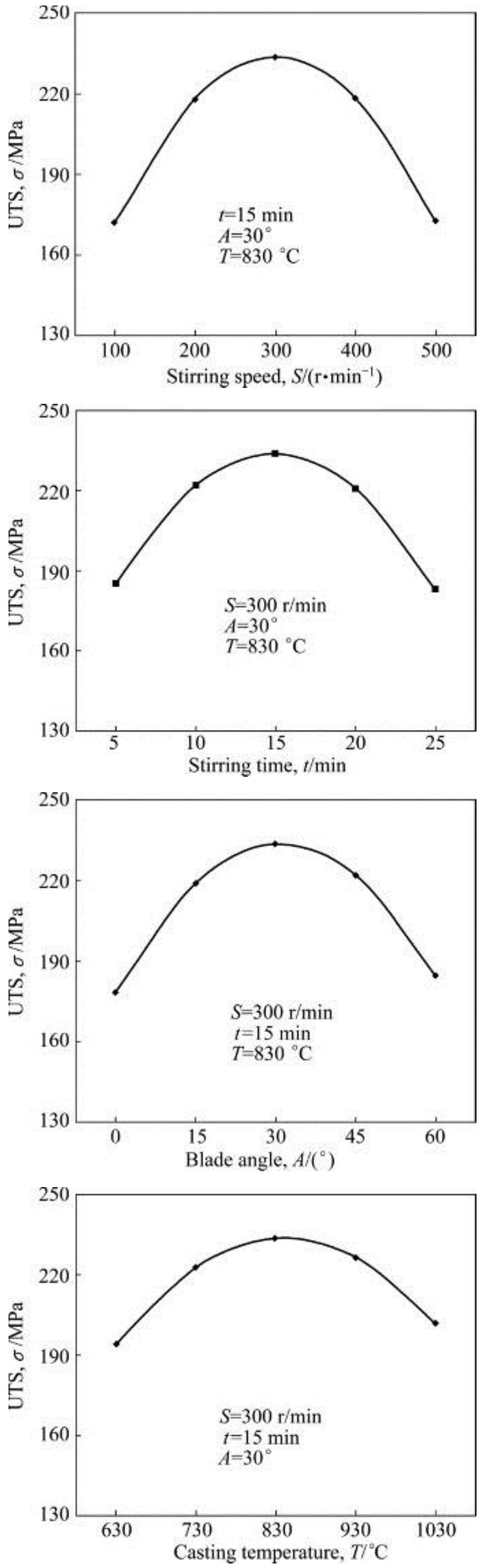

Fig. 15. Variation of ultimate tensile strength with test parameters [67].

Jaswinder [68] investigated the effect of red mud (RM) on hybrid aluminum 2024/SiC/RM composite prepared via stir casting route. SiC was fixed at 5% mass fraction and mass fraction of RM varied from 5% to 20%. The sample for tensile test was extruded with gauge length of 62.5mm and diameter 12.5 mm. The influence of red mud particle size, % red mud and ageing time on tensile strength was studied using Taguchi optimization technique and it was found that percentage RM has maximum influence on tensile strength having percentage contribution of 42.58% calculated by ANOVA while ageing time has percentage contribution of 24.70%. The particle size was not significant in the analysis as its p value determined was more that 0.05. With increase in % RM at fixed SiC, tensile strength increased because of increase in the interfacial area between matrix and reinforcement. He compared the tensile strength of hybrid aluminium alloy at optimum conditions of controllable parameters with the unreinforced alloy and found that tensile strength increased by 34% approximately.

B. Ravi [69] reinforced AA6061 with BC via vortex stir casting. With increase in the reinforcement content the interfacial bonding of the phases increased. Boron carbide has thermal expansion coefficient of about 0.217 times that of aluminium matrix. This difference in thermal expansion coefficient caused thermal mismatch which resulted in high dislocation density in matrix. Further addition of B_4C in matrix causes the reinforcement to take load from matrix thus increasing the strength of matrix. The above factors collectively contribute to increase the tensile strength of composite (Fig. 16). The improvement in tensile strength of composite with addition of reinforcement was about 23.9% which is in agreement with [68].

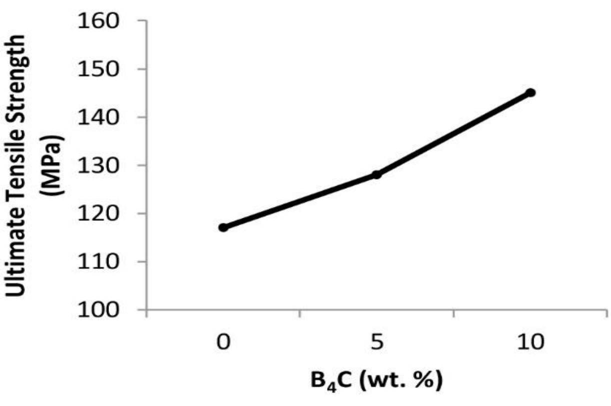

Fig. 16. Variation in UTS of AA6061/B_4C composite with % wt. of reinforcement [69].

Bhaskar Chandra Kandpala [70] investigated AA 6061/Al_2O_3 aluminium MMC for tensile strength. His research findings are in line with [68, 69]. With increase in % reinforcement Al_2O_3 from 5 to 20%, UTS was increased from 150 MPa to 310 MPa. M.V.S Babu [71] enhanced the mechanical properties of Tin Babbitt by addition of nano - Ilmenite in a Babbitt alloy via the ultrasonic stir casting technique. The controllable parameters which included the stirring period (ST), reinforcement weight percentage and ultrasonic processing time (UT) were selected and response surface methodology (RSM) optimization technique predicted the optimum tensile strength of the composite. Computerized Universal testing machine was utilized for performing 20 tensile tests for samples made with variable process parameters and in which the reinforcement particle size was held steady at 56 nm. The pertinent observations obtained were:

a) The tensile strength was enhanced and was proportional to stirring time until a certain limit after which it reduces in alignment with [67]. For ultrasonic treatment time, the same pattern was identified. The reason for such behavior was that the partial solid melt cooled down with time and the viscosity rises and so the mixing of nano-reinforcement decreases when stirring time (ST) and ultrasonic treatment (UT) were enhanced.

b) The tensile strength of the nano-composite was significantly influenced by the weight percent of reinforcement. When the percentage weight of Ilmenite was increased, the tensile strength was enhanced to the maximum limit and then falls because the dispersion was initially uniform up to a certain point and then the clustering occurs and agglomerates emerge in the matrix, which decreased the traction intensity with increase in the percentage reinforcement.

c) As computed by RSM technique, the maximum tensile strength of Babbitt-Ilmenite metal matrix nano-composite (MMNC) was found to be 127.172 MPa at optimal controllable parameters (Table 4.)

Table 4. Optimum controllable parameters for maximum tensile strength of Babbitt/Ilmenite MMC [71].

ST (minutes)	UT (minutes)	% wt. of reinforcement
7.67	7.86	1.39

Confirmation experiments were conducted to establish the validity of above results. The maximum tensile strength as determined from confirmation tests was found to be 125.6 MPa at the optimum process parameters. Shuxu Wu [72] investigated the effect of stainless steel, titanium and aluminium alloy on AZ31 magnesium matrix which was prepared by pressure infiltration technology. There was improvement in tensile strength of metal matrix composite interpenetrated by metal reinforcement as compared to AZ31 magnesium matrix. The enhancement in tensile strength of the composites was attributed to superior mechanical properties of reinforcement material as well as even distribution of finely grain reinforcement particles in metal matrix thereby developing good interface between reinforcement and matrix. The better interface developed between the two resulted in effective load transfer from matrix to reinforcement thereby leading to improved mechanical properties. Amongst the metal matrix composite interpenetrated by metal reinforcement, MISC (metal matrix composite interpenetrated by stainless steel reinforcement) have the most superior mechanical properties followed by MITC (metal matrix composite interpenetrated by titanium alloy reinforcement) and MIAC (metal matrix composite interpenetrated by aluminium alloy reinforcement). The tensile strength of MISC, MITC and MIAC had improved by 47.9%, 41.7% and 16.7% respectively when compared with AZ31matrix (Fig. 17).

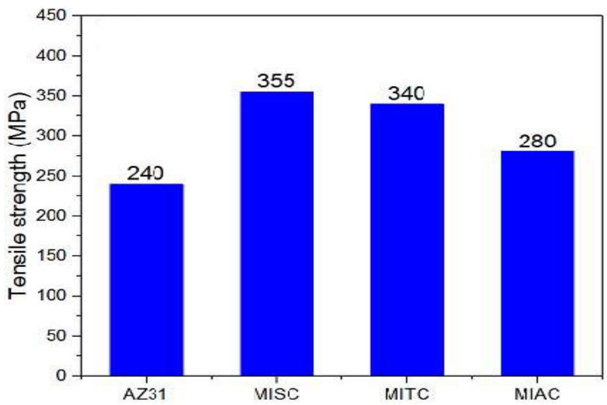

Fig. 17. Improvement in tensile strength of MISC, MITC and MIAC composites with respect to AZ31 matrix [72].

Yanxia Tang [9] studied the effect of addition of graphene nano sheet with Ni nanoparticles in Cu matrix. The hybrid graphene nanosheet (GNS)-nickel were first developed by chemical reduction method and then reinforced in Cu-matrix by spark plasma sintering. The SEM images shows the white phase GNS dispersed homogeneously in grey Cu matrix phase and no agglomerations of GNS are observed. The Ni nanoparticles prevent the agglomeration of GNS by anchoring on its laminate structure and hence ensures proper dispersion. The homogeneous distribution of GNS was further confirmed from the images as there were no pores or cracks on surface. It was observed that by addition of 1% vol. GNS in Cu matrix there was increment of 61% in Young's modulus and 94% in yield strength as compared to pure copper. The addition of GNS in Cu matrix resulted in significant increase in mechanical properties which was in agreement with the result obtained from Al-GNS and Mg-GNS hybrid composites [73,74]. Zhen Cao [75] fabricated titanium matrix composites reinforced with graphene nano-flakes (GNF) via powder metallurgy technique. The graphene flakes (0.5%) and Ti6Al4V powder were subjected to hot isostatic pressing at temperature of 700°C and 150 MPa pressure followed by forging at constant temperature of 900°C. The paper reported that addition of 0.5% graphene nano-flakes in Ti alloy increases the tensile and yield strength of composite without any appreciable decrease in ductility thereby proving it to be the most effective reinforcement for structural applications (Table 5.). The increase in tensile strength was attributed to the fact that GNF were well distributed in titanium alloy as can be observed from the micrographs and effective load transfer between metal matrix and GNF results in superior strength of the MMC. Further in situ formation of TiC between the graphene and titanium interface lead to strengthening of the MMC. The ductility of the MMC was maintained as wrinkled surface of GNF was flattened and straightened during plastic deformation thereby maintain ductility at high strength.

Table 5. Comparison of unreinforced Ti and Ti/GNF composite with regard to mechanical strength [75].

Sample	UTS (MPa)	Yield Strength (MPa)
Ti	942 ±3	850±5
Ti+0.5%GNF	1058±3	1021±2

Chao [76] synthesized TiB_2/Ti-6Al-4V hybrid composite by hot isostatic pressing. The reinforcement TiB_2 was varied from 3 % to 8%. The tensile strength of the composite showed upward trend up to 5% but further increase in the reinforcement from 5% to 8% decreased tensile strength drastically. The increase in the reinforcement beyond 5% leads to formation of continuous TiB agglomerates in the matrix thus decreasing the tensile strength. The TiB needle network evolves from discontinuous to quasi continuous to continuous thereby forming agglomerates which hamper the tensile strength. The results were in agreement with [67,71].

4.3 Impact strength

Omkar Bamane [77] observed improvement in the impact strength of AA 7075 alloy with increment in percent weight of MWCNT (Fig. 18) because of its softness and low density, so reinforcing it to the alloy contributed to increased ductility that enhanced the toughness as well as impact strength of the composite.

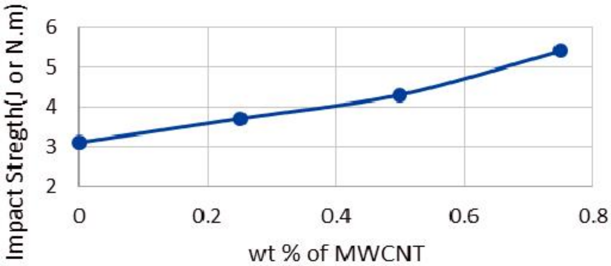

Fig. 18. Variation in impact strength of composite with wt. % of MWCNT [77].

N. Lokesh [78] investigated the hybrid Al6063/TiO_2/Cu composite prepared by stir casting for impact strength. Three samples with varying % wt. of Cu ranging from 5 to 15 percent and fixed percent of TiO_2(10%) were stir casted and Charpy test using test procedure IS 1757-1988 was performed on the specimen (Fig. 19). It was observed that with increase in copper from 5% to 15% the impact strength decreased by 28.57% though there was marginal increase in hardness by 4.4%. This was opposite to trend as observed by Omkar Bamane [77].

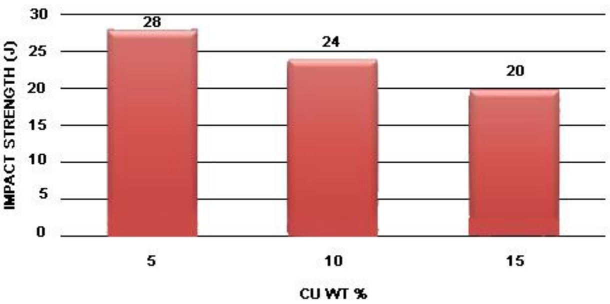

Fig. 19. Variation of impact strength with wt. % of Cu [78].

The influence of SiC on impact strength of AA6351 was studied by V. Mohanavel [28]. He observed that the composite with 20 % SiC had 73% enhanced impact strength than AA6351 (Fig. 20). The strong interfacial adherence causes shifting of load from AA6351 alloy to SiC thereby strengthening the composite by enhancing impact strength which is according to the findings of Omkar Bamane [77].

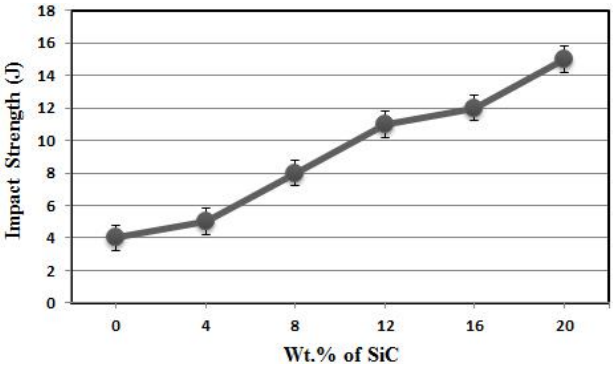

Fig. 20. Impact strength of AA6351/SiC composite vs % wt. of SiC [28].

The influence of boron carbide on LM24 aluminum alloy was studied for the impact strength of the composite developed by Keshav Singh [79]. The results obtained tallied with the antecedent studies [28,77]. The boron carbide was varied from 3% to 7%, and the impact strength improved by 52.94% at 7 percent weight boron carbide in LM 24 alloy in comparison with the unreinforced alloy (Fig. 21).

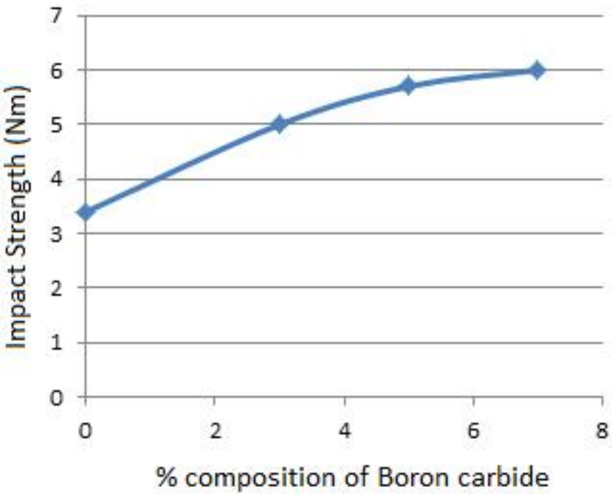

Fig. 21. Variation in impact strength of composite with % wt. of boron carbide [79].

Raj Kumar [80] reinforced AA 6063 aluminium alloy with SiC via stir casting route and used Taguchi technique to optimize impact strength of the composite by creating L16 orthogonal array. Sixteen set of experiments were conducting with four controllable factors at four levels each. The controllable factors along with their levels are tabulated in Table 6.

Table 6. Controllable parameters along with their levels [80].

Controllable Parameters	Level 1	Level 2	Level 3	Level 4
% wt. SiC	3.5	6.5	9.5	12.5
Pouring temperature (°C)	680	700	720	740
Stirring speed (rpm)	200	300	400	500
Stirring time (min)	10	15	20	25

The maximum impact energy for the developed composite as determined from S/N graphs generated by Taguchi technique was at the following levels of controllable parameters: % wt. SiC = 12.5, pouring temperature = 720°C, stirring speed = 500 rpm and stirring time of 25 minutes. The most influencing factor from ANOVA analysis was found to be % wt. of SiC with 99.09% contribution followed by pouring temperature, stirring time and stirring speed. A similar study to optimize the impact strength of aluminium AA 6061/RM composite developed via stir casting route using Taguchi optimization technique was conducted by N. Panwar [81]. He developed L25 orthogonal array with 5 levels of three controllable variables which were percentage reinforcement, particle size and ageing time. The study revealed that most influencing parameter was particle size with 79.12 % contribution followed by ageing time and % reinforcement which was not in line with [80]. He explained that increased particle size create larger voids allowing greater dislocation movement promoting increased ductility and impact strength.

4.4 Fatigue strength and Fracture toughness

Through the economical ultrasonic stir casting process, M. V. S. Babu [8] developed Babbitt-Ilmenite MMNC to examine the influence of Ilmenite on fatigue properties of Babbitt. The fatigue tests were performed on rotating fatigue testing machine at three stress levels of 50%, 70% and 90% of UTS [82]. The specimen were subjected to tensile tests on computerized universal testing machine (UTM) and the average of three values was deemed to be final

UTS of the specimen. The count of experiments conducted were four, five and seven at three levels of 50%, 70% and 90% of ultimate tensile strength respectively [83]. The Wohler curves showed that the fatigue strength of MMNC was improved by 71.42 percent in contrast to the unreinforced alloy (Fig. 22).

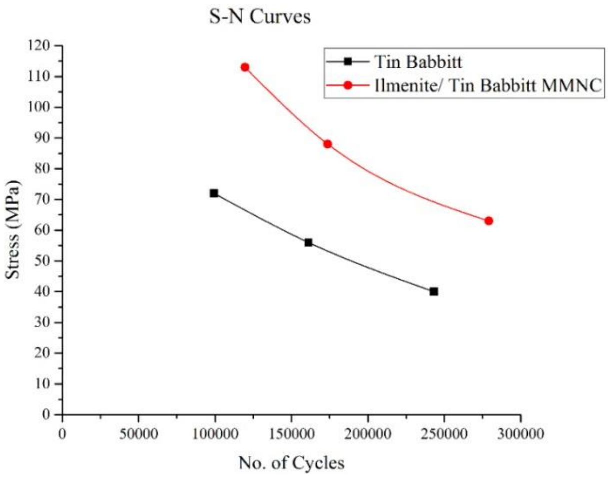

Fig. 22. SN curves for Tin Babbitt and Tin Babbitt-Ilmenite MMNC [8].

S. Divagar [84] reinforced nano particles of SiC and Al_2O_3 in AA 7075-T651 aluminium alloy to form nano composite via stir casting route to study their impact on fatigue life for aerospace applications. Three specimen were prepared with 5%, 10% and 15 % SiC whereas percentage of Al_2O_3 was fixed at 5% and fatigue tests were conducted by advanced rotating beam fatigue testing machine. It was observed that fatigue strength of the nano composites was directly proportional to percentage of nano particle reinforcement. With an increase in volume fraction of nano reinforcement the fatigue strength of the composite was increased. It was found out experimentally that the fatigue strength of AA 7075-T651 +10% SiC + 5% Al_2O_3 was 12.13% more than the base alloy. C. S Ramesh [85] performed a similar study to investigate the effect of addition of Si_3N_4 on Al6061 alloy prepared via stir casting method. Both as cast and hot forged composites were submitted to fatigue tests and showed superior fatigue strength than base alloy in accordance with [84] and it increased with increase in reinforcement content. However it was established that hot forged composites exhibits better fatigue strength in comparison to as cast composites. T. S. Srivatsan [86] reinforced AZ31 magnesium alloy with carbon nanotubes (CNT) using melt deposition and subsequent hot extrusion technique to compare the fatigue characteristics of unreinforced magnesium alloy with reinforced AZ31/1vol. % CNT composite at load ratio (R) equal to 0.1 and -1 (Fig. 23). The endurance strength of the composite at the tested load ratios improved by 40% in comparison to unreinforced alloy and the enhancement in high cyclic fatigue strength of the fabricated composite with addition of CNT at both load ratios was 200% when compared with unreinforced alloy at same maximum stress level.

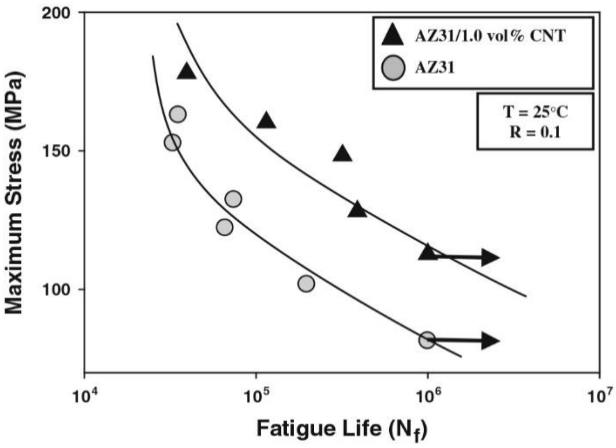

Fig. 23. Maximum stress Vs fatigue life of AZ31 alloy and AZ31/1%vol. CNT composite at $R = \sigma_{max}/\sigma_{min} = 0.1$ [86].

A similar study conducted by T. S. Srivatsan and C. Godbole [87] to study the effect on AZ31 magnesium alloy with addition of nano alumina particles reveals that the AZ31/1.5%vol. Al_2O_3 composite exhibits 36% and 28% improvement in endurance strength at R=0.1 and -1 respectively. The results of improvement in endurance strength for AZ31 magnesium alloy with addition of nano alumina particles were similar to [86]. Titanium metal composites (TMC) are primarily designed for fatigue strength and particularly for unidirectional composite system the fatigue behavior was found to be superior than the unreinforced alloy [88]. The fibre reinforced titanium composite (FRTC) have superior fatigue properties in comparison to monolithic alloys [89-93] and the improvement in fatigue strength at higher temperatures was more predominant [90]. The fatigue strength of discontinuously reinforced titanium composite(DRTC) was less than FRTC and was dependent on volume fraction of reinforcing particles [94]. With increase in volume fraction of reinforcing particles ductility and fracture toughness of the composite decreases.

Keneth Kanayo [95] studied the fracture toughness of Al/Mg/Si/alumina/RHA composite. He concluded that the hybrid aluminium composite developed by addition of RHA in single alumina reinforced Al/Mg/Si alloy resulted in higher fracture strength. The fracture mechanism observed in aluminium alloys was generally particle or interfacial cracking. The hard and brittle ceramic reinforcement have low strength to resist rapid cracking therefore addition of relatively soft reinforcement RHA results in the increase in fracture toughness of hybrid composite. Another study conducted by A. O. Aluko [96] established the fact that fracture toughness of Al 6063/SiC composite increases significantly with ageing treatment when compared to as cast composite due to formation of fine Mg_2Si precipitates in Al-6063 matrix during ageing. In order to evaluate fracture toughness circumferential notch tensile specimen were prepared and subjected to tensile loading till fracture on UTM to determine the fracture toughness of as cast and aged specimen. K. K. Alaneme and B. O. Ademilua [31] investigated the effect of addition of BLA in single reinforced Al/SiC composites. Addition of soft BLA reinforcement increases the fracture toughness of single reinforced composite. The hybrid Al/SiC/BLA hybrid composite have better fracture toughness than single reinforced ceramic composite which is line with [95]. M. A Maleque [97] examined the fracture mechanism of Al-Mg-SiC_p composite and the influence of percentage weight of reinforcement and temperature on its fracture toughness. With increase in the reinforcement content the crack propagation was restricted since SiC acts as obstruction to dislocation movement thus increasing the fatigue life of the composite. At room temperature the composite experiences brittle fracture with fast propagation of trans-granular cracks across the grains resulting in lower fracture toughness. With increase in temperature there was a transition from brittle to ductile fracture and necking occurs prior to fracture. Consequently energy required for crack propagation and dislocation movement increases thereby improving fracture toughness of composite at elevated temperature.

5. TRIBOLOGICAL BEHAVIOR

Basavarajappa [98] studied the tribological characteristics of in situ Al-TiC composite prepared by adding activated charcoal in the aluminium-titanium melt. The composite specimen were prepared with 3%, 6% and 8% weight reinforcement. The wear tests were conducted at constant load and speed conditions with varying reinforcement percentage. At constant load and speed, the wear rate decreased as the TiC weight percentage increased. This was due to the fact that TiC are ceramic particles which when reinforced in the matrix by in situ process disperse well within the matrix thereby improving the tribological characteristics of the composite. S. Gopalakrishnan [99] investigated AA 6061 aluminium composite reinforced with titanium carbide by stir casting for dry sliding wear. The wear test was carried on pin - disc apparatus with pin shaped specimens of diameter 6mm and length 50 mm. A set of 16 experiments were conducted using DOE approach. The controllable parameters chosen were percentage weight of reinforcement, sliding velocity and load. It was observed that there was marginal increase in rate of wear with increase in % TiC which was opposite to the trend of wear as observed by Basavarajappa [98] and it increased linearly with sliding speed and load. The increase in wear rate with increase in velocity was attributed to softening of matrix due to elevated temperatures and with increase in normal load, friction and so the wear increased.

B. Leszczynska - Madej [100] studied tribological properties of heat treated B82 Tin Babbitt with 1.5% lead (Pb). The samples of rectangular specimens 20x4x4 mm were annealed at about 150°C for two, eight, twenty four and forty eight hours and tested for wear on block on ring tester both in dry and wet conditions at rotational speed of 136 rev/min and load of 67N. The heat treatment not only promotes refinement of precipitates in bearing alloy but also leads to uniform distribution and high degree of dispersion of lead in tin alloy matrix which otherwise was in clusters in cast ingot thereby improving wear resistance of an alloy. The coefficient of friction and wear loss observed under wet conditions was much lower than under dry lubrication condition because of difference in mechanism of wear in both cases. Friction wear under wet conditions using TU-32 oil was due to scratching while under dry conditions, adhesion and fissuring were responsible for the wear. Further it was concluded that 48 hours annealed alloy was superior in tribological properties to all other specimen under wet conditions. Dinaharan [101] studied the effect of flyash (10% by vol.) on wear and hardness of AZ31 magnesium alloy prepared by stir casting and friction stir processing (FSP) routes. The tribometer used to determine the wear characteristics of reinforced composite revealed that the composite prepared by FSP have 33% lower wear rate than that prepared by conventional stir casting. The lower wear rate of composite prepared by FSP was due to higher hardness as compared to stir casted composite which is in accordance with Archard's wear law. FSP route of developing composite applies high compressive forces thereby closing micro pores resulting in higher density and hardness of composite. T. Rajmohan [25] studied the effect of reinforcing mica and SiC in Al 356 alloy on its wear properties. The process parameters chosen were sliding speed, load and mass fraction of mica. The ANOVA technique revealed that load was the significant factor governing wear followed by mass fraction of mica and velocity of sliding. With increase in load there was substantial increase in wear loss in accordance with Archard's law whereas with increase in sliding velocity at constant load, the wear loss increased initially but at higher sliding velocities there was increase in temperature leading to softening of composite thereby decreasing wear loss. The wear loss in mica reinforced composite was less at higher loads as compared to ceramic reinforcement as the nature of wear at high loads show transition from abrasion to delamination with oxide layer visible in microstructure suggesting considerable generation of heat at the interface resulting in softening of surface and reducing wear loss even at higher loads.

M. Srinivasan [102] compared wear behavior of the magnesium alloy AZ31B and nano-composite AZ31B-Al_2O_3-Ca and concluded that wear resistance of nano-composite was more than the alloy. Formation of oxide layer at higher temperature was visible in microstructure of nanocomposite which resulted in thermal softening leading to less wear rate of the composite at relatively high sliding velocities which is in agreement to the wear behavior as established in [25]. Magnesium alloy based composites having superior tribological characteristics makes them potential material to be used in military and manufacturing industries. R. Dabral [103] investigated the wear behavior of aluminium 6061 reinforced with red mud at elevated temperature and concluded that specific wear rate depends predominantly on sliding distance, load and percentage red mud rather than on size of particles and sliding velocity. Wear loss of the composite reduced as sliding distance and proportion of red mud increased. Further with increase in temperature worn morphology changed from abrasive to delamination with subsequent softening of matrix and so wear rate increases due to loss of wear resistance at high temperature. Sandeep Khelge [104] studied the effect of reinforcing silicon dioxide and graphite in LM22 aluminium alloy. The results obtained from wear tests revealed that wear rate of hybrid composite reduces with increase in percentage reinforcement which is in agreement to [103] but it increases with load and sliding distance due to debris removal from damaged worn surface caused by continuous grooves due to sliding. B. S. Praveen Kumar [105] optimized the wear properties of AA8011/boron nitride composite using Taguchi technique taking four controllable parameters as percentage reinforcement, applied load, sliding speed and sliding time. With increase in percentage reinforcement of boron nitride wear rate decreases as the reinforcement particles improve the roughness of composite and hence its wear resistance [103,104].

5.1 Influence of solid lubricants on tribological behavior of non-ferrous metal matrix composites

Suresha [106] studied tribological characteristics of Al-SiC-Gr hybrid composite and reported that with increase in percentage of solid lubricant upto 7.82 % the wear of the aluminium composite decreases because of formation of protective layer between the contact surfaces but with further increase in percentage of reinforcement there was decline in its fracture toughness causing increased wear rate. Increase in load and sliding distance bears a direct proportion to wear rate [104]. Kumar et al. [107] reinforced aluminium Al-7075 alloy with 7% SiC and 3 % graphite and deduced that its specific wear rate was lower than Al-7075 for all combinations of process variables. He applied RSM technique and inferred that load is the most predominant factor followed by sliding speed and distance with regard to specific wear. N. Radhika et al. [108] used Taguchi optimization technique to determine wear characteristics of Al-Si10Mg +alumina +graphite hybrid composite. Load, sliding speed and sliding distance were taken as operating variables and it was found that sliding distance was the most predominant factor for wear rate contributing 46.8% whereas sliding speed was the least contributing factor with 14.1% contribution. It was found that wear rate increases with load while it decreases with sliding speed and distance [103]. The decrease in wear loss with increase in velocity was due to abrasive action of SiC on counter-face forming oxide layer between pin and disc thereby reducing wear rate while increase in sliding distance reduces wear rate due to abrasive resistance provided by ceramic reinforcement and self-lubricating property of graphite which provide intermediate layer between pin and disc.

5.2 Influence of ceramic reinforcement on tribological behavior of non-ferrous metal matrix composites

Uvaraja and Natrajan [109] reinforced aluminium alloy with boron and silicon carbide to study its wear performance. Taguchi analysis was carried to determine the optimum conditions for minimum wear and coefficient of friction. The contribution of factors for optimizing wear was found to be percentage reinforcement with 30.99% contribution followed by applied load (29.96%) and sliding speed (29.89%). It was further analyzed that wear loss increased with increment in load but decreased with increase in speed and volume fraction. Rajmohan et al. [25] reinforced HAMC with SiC (10%mass) and Mica (0-6%mass). The ANOVA analysis predicted that load was the main factor influencing wear loss of composite followed by mass fraction of mica. Further it was observed that wear rate increased with increment in load but decreased reasonably with increase in sliding velocity. The mechanism of wear changes from abrasion to delamination with increase in load.

5.3 Influence of agro based reinforcement and mechanically mixed layer (MML) on tribological behavior of non-ferrous metal matrix composites

Alename [110] reinforced Al-Mg–Si matrix with different mass percent of RHA and SiC to develop a low cost composite with reasonably good wear characteristics. It was found that 1:1 and 3:1 weight ratios of rice husk and SiC results in coefficient of friction similar to single reinforced alloy (SiC or RHA) thereby predicting that RHA can be used as secondary reinforcement to develop composites at low cost with reasonably good wear performance. Alename and Olubambi [111] concluded that addition of alumina in Al-Mg–Si alloy leads to minimum wear rate as compared to hybrid composite with RHA as secondary reinforcement and it remains constant during whole time of investigation. With increase in secondary reinforcement the wear mechanisms transits from abrasive to adhesive in nature. The wear rate increases with time as the worn debris glued to surface of the composite are adhered to hard pin sliding against the surface. The sliding motion of the hard pin surface against metal composite results in formation of metallic oxides due to high temperature resulting from sliding motion of pin against the surface. These oxides form layer over the surface thereby reducing wear rate. The hardness of layer is more than that of composite and are called mechanically mixed layer (MML). Rajmohan et al. [25] observed that wear rate of Al/SiC/mica hybrid composite decreased with increase in sliding velocity beyond the transition velocity. Low wear rate at high sliding speed is attributed to the fact that there is softening of composite due to high temperature and formation of MML resulting in lower wear rate. The results were in agreement to the wear behavior as predicted in [102]. These films were broken into debris on further sliding. Basavarajappa [112] observed that wear rate of Al2219/SiC/graphite hybrid composite decreases with increase in speed beyond 4.5 m/s due to oxidation of iron present in counter surface and formation of mechanically mixed layer while sliding against hard SiC particles. Li and Tandon [113] found that wear rate of aluminium composites were influenced by MML formed with materials from counter-surface, matrix and particles. MML thus formed delayed the transition from mild to severe wear and once removed leads to direct metal to metal contact and it cannot be formed again.

6. FUTURE PROSPECTS OF NON FERROUS METAL MATRIX COMPOSITES

6.1 Choice of material

The main focus of the industries nowadays is to develop products and equipment which give high performance with low cost. In order to achieve this aim hybrid non- ferrous metal matrix composites are developed with high strength /weight ratio. The hybrid composites developed with ceramic reinforcements like SiC, BC, alumina and secondary soft reinforcements like RHA, BLA, RM, coconut shell ash, possesses unique physical, mechanical and tribological properties that are not possible with single ceramic reinforcement. The hybrid composites thus developed have the prospects to take over the conventional materials used in industries because of their low weight, less cost and better efficiency. Hybrid aluminium composites can be used for design of components in aerospace and automobiles industries. The SiC will provide strength to aluminium alloy whereas red mud as secondary reinforcement will reduce cost of the composite. Babbitt-Ilmenite composite can be extensively used in bearing and automobile industry. The composite developed by ultrasonic vortex casting have shown better mechanical and tribological characteristics as compared to unreinforced Babbitt metal which is presently used extensively in manufacturing of bearings and automobile parts. Addition of graphene nano-flakes and zirconium dibromide increases the hardness and tensile strength of titanium alloys without compromising the ductility thereby making them suitable for structural and antiballistic applications. Magnesium alloy based composites possess high strength and biocompatibility by virtue of which they are extensively used in biomedical applications and holds promising future in advance applications of orthopedics. The focus of researchers nowadays is the safe disposal of industrial and agro waste to reduce environment degradation. To achieve it hybrid composites are being developed with agro-industrial waste as green reinforcement which not only are cost effective but also provide better tribo-mechanical properties to the composite as compared to unreinforced alloy and make them suitable for advanced engineering applications.

6.2 Wear performance

In the design and production of components including brake rotors, engine blocks, pistons, gears, bearings, axles, and equipment related to aerospace and marine applications, hybrid non-ferrous MMC have demonstrated their potential to offer greater flexibility. Investigation of these composites for sliding wear applications is therefore urgently needed as there is an immense scope for the researcher to develop database of wear performance and prediction of their improvement in wear characteristics for advanced industrial applications. Determining the wear characteristics of these composites under the influence of various test parameters which have substantial impact on their wear will help to explore these materials for sliding wear applications. Depending on the traits of worn surfaces, wear debris, and tribo-induced layers, the wear of composites against the counter-face can also be studied [114]. The results thus obtained based on a range of experimental data gathered with various wear test methods, can help to evaluate the tribological properties of these composites and create database of wear performance which will enhance the performance of non-ferrous MMC for advanced engineering applications under sliding wear conditions.

7. LATEST TRENDS IN MANUFACTURING OF NON FERROUS COMPOSITES

In recent years, new techniques have been evolved to manufacture non-ferrous metal matrix composites economically with improved tribo-mechanical properties for advanced engineering applications such as structural, anti-ballistic, automotive, aerospace, and marine. The pertinent observations drawn from the investigation of mechanical and wear properties of non-ferrous composites fabricated via latest techniques and their proposed application area is presented in Table 7.

Table 7. Fabrication characteristics of non –ferrous metal matrix composites.

Fabrication technique	Matrix	Reinforcement	Inference	Applications	Reference
Ultrasonic stir casting	Al -7075	SiC	Improvement in yield strength and wear resistance by 94.52% and 79.8% respectively with addition of 2wt.% SiC in Al8075 alloy.	Aeronautical and automotive industries	[115]
Combined stir and squeeze casting	Al-5083	SiC	Improvement in hardness, compressive strength and wear resistance of the composite prepared by combined process as compared to stir casting technique.	Transportation and marine	[116]
Powder metallurgy	AA-4015	BC, TiC	Taguchi philosophy predicted optimum test parameters which include sintering time, temperature and pressure to optimize hardness and compressive force.	Structural and aerospace	[117]
Vacuum sealed stir casting	Al-7075	SiC, MoS_2	Taguchi approach was implemented to predict optimum controlling factors which include percentage reinforcements and stirring speed. The enhancement in tensile strength and Vicker hardness of the composite was reported as 25% and 35.9% respectively with respect to base alloy.	Civil construction and bio –medical applications	[118]
Powder metallurgy	AA-2024	SiC, Gr	Taguchi-ANOVA model was used to propose optimum controlling parameters and their significance for tribological aspects of the composite. Low levels of sliding distance, load and high levels of graphite resulted in better sliding wear characteristics of the composite with sliding distance as the most influential parameter.	Defense equipment	[119]
Spark plasma sintering	TiC powder	SiC whisker	Hardness and flexural strength was found to be the function of sintering temperature ranging from 1800°C to 2000°C having maximum values at sintering temperature of 1900° C.	Rocket nozzle throat liners	[120]
Spark plasma sintering	TiB_2	SiC	The effects of sintering temperature (1700-2000°C) and time (3-10 minutes) on mechanical properties of TiB_2/20% SiC were investigated. The optimum conditions for hardness, flexural strength and fracture toughness were found to be sintering temperature of 1900°C for 10 minutes.	Jet engine parts	[121]
Vacuum sintering	Al-Mg-Zn alloy	SiC (varying), Al_2O_3 (fixed)	Al7075 alloy was reinforced with 2% Al_2O_3 and SiC was varied from 2 to 6%. The hardness and compressive strength of the composite at 6% SiC was 14% and 24% respectively higher than base alloy.	High temperature semiconductor and bio-medical devices	[122]
Accumulative orthogonal extrusion process (AOEP)	AA7034	TiB_2	AOEP improves the ductility of the high Zn content composite without affecting the strength of the composite. High yield strength (700 MPa) at uniform elongation of 6% can be achieved at 8% wt. TiB_2.	Aircraft and navigation	[123]
Electromagnetic stir casting	Al6063	SiC (5% and 10%)	The resistance to indentation and tensile strength of the composite with 5% SiC was reported to improve by seventeen and eighteen percent respectively and with 10% addition of SiC the improvement was observed to be twenty five and thirty seven percent respectively.	Automobile and aerospace	[124]

Microwave sintering	Copper	ZrB_2	The nano ZrB_2 particles ranged between 0 to 12 % were dispersed in powdered copper by ball milling in microwave oven and tube furnace at 650°C in atmosphere of Argon. The samples sintered in microwave oven were found to have better mechanical properties such as density, hardness, compressive strength, abrasion resistance and flexural strength than tube furnace.	Crank shaft sprockets, planet gear carriers	[125]
Spark plasma sintering	Ti powder	TiB_2, Fe	Wear tests were performed on composites with varying B contents from 10% to 30 %(Fe is fixed) under varying load conditions(10-25 N). The wear rate for all composites was found to decrease with increase in load and wt. percentage of TiB content.	Chemical, marine, medical	[126]
Diffusion bonding	WC-Co, 7Cr7Mo2V 2Si steel	Ni foil	WC-Co cemented carbide and steel were diffusion bonded with Ni foil as interlayer in vacuum. The brittleness of the composite was reduced and shear strength is doubled with 4 μm thick Ni layer at bonding temperature of 1050°C for 1 hour.	Mold manufacturing	[127]
Friction stir processing	Magnesium	B_4C (10% fixed)	The mechanical properties of the composite fabricated with conventional single tool friction stir process was compared with double pin tool process. The use of double pin increases the stirred vortex width and causes extra shear effect resulting in improvement of hardness, tensile strength and wear resistance of the composite.	Helicopter transmission casings and gearboxes	[128]
Combined powder metallurgy and hot extrusion process	AlSi7Mg	TiB_2 (2% fixed)	The powders were compacted at 300°C for 1 hour at 165 MPa pressure and then heated up to 560°C for 2 hours to accomplish sintering. The sintered billets were extruded at 350° C and given T6 heat treatment. The as –extruded composites were found to have excellent yield strength without sacrificing fracture toughness because of refinement of grains and precipitation strengthening.	Internal combustion engine components	[129]

8. CONCLUSION

8.1 Aspects related to mechanical characteristics

Vortex stir casting has been the most economical and widely used technique to develop high performance low cost composites for wide range of engineering applications ranging from automobile to aerospace industries, marine, biomedical, construction and so on. SEM micrographs have clearly shown uniform dispersal of reinforcement in metal matrix if proper conditions are maintained and therefore hybrid non-ferrous composites are being developed with varying percentage of ceramic and soft reinforcements. The combined use of ceramic and soft reinforcements to develop hybrid non-ferrous composites for manufacturing products results in better physical and mechanical attributes of the components when compared with unreinforced alloy or ceramic reinforced composite with porosity levels in acceptable range. Ceramic reinforcements like SiC, Al_2O_3, BC and BN provide hardness, tensile strength and wear resistance whereas secondary reinforcements like flyash and rice husk ash improves fracture toughness, impact strength, fatigue strength and reduces weight and cost of composite without influencing their mechanical properties. The industrial and agro waste reinforcements used to develop composites not only serve the purpose of manufacturing components with high strength to cost ratio but also ensure their safe disposal to prevent environmental degradation. Taguchi and RSM are the most common optimization techniques of DOE adopted by researchers to optimize the mechanical properties of the developed composite. The controllable factors commonly used to design the experiment plan are percentage reinforcement, stirring speed, stirring time, particle size, mold preheat temperature and ageing time. The literature survey revealed that reinforcement variation from 10 to 20 percent and stirring speed range of 300-600 rpm are the optimum fabrication parameters. Further percentage reinforcement is the most contributing parameter towards optimization of mechanical properties of composite followed by stirring speed.

8.2 Aspects related to tribological characteristics

The study of sliding wear characteristics of composites have revealed that addition of reinforcements improved its tribological properties as compared to an unreinforced alloy. It is found that with increase in percentage reinforcement wear resistance of the composite increases. Solid lubricants like graphite forms protective layer between the counterpart and metal surface and lowers wear rate of the composite whereas secondary reinforcements like RHA results in developing low cost composite with good sliding wear characteristics comparable to single reinforced composite. Addition of ceramic reinforcements decreases the wear rate of composite which remain constant with time and it was found that wear rate of single ceramic reinforced composite was less than hybrid composite with RHA as secondary reinforcement. Further the wear performance of single ceramic reinforced composite is found to be better at elevated temperatures. Addition of secondary reinforcement in hybrid composites results in transition from abrasive to adhesive wear thereby increasing the wear rate which was found to be time dependent. Taguchi and RSM have been successfully employed to optimize wear characteristics of the composite with % reinforcement, sliding distance, sliding speed and load as process variables. Percentage reinforcement and load are the predominant contributing factors with regard to optimization of wear characteristics of composite followed by sliding distance. Sliding velocity may not be the predominant controlling factor but it indirectly influence the worn morphology of composites through temperature change leading to formation of MML which affects the wear rate. The studies over the period of time have revealed that in general wear rate increases with load and sliding distance whereas it decreases with percentage reinforcement and sliding velocity. There may be change in the trends due to formation of oxide layers. At low load and sliding speed abrasive wear takes place whereas at their higher values adhesive wear is prevalent which is responsible for delamination and plastic deformation leading to wear failure. The optimization of true tribo-system for evaluation of tribological characteristics of hybrid non-ferrous MMC is possible by considering both reinforced matrix and unreinforced counterparts.

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