Study on Fabrication of Magnesium based Metal Matrix Composites and its improvement in Mechanical and Tribological Properties- A Review

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Abstract: The present study, based on the literature review, reinforcing material, processing route, mechanical and tribological properties of Mg based metal matrix composites containing single and multiple reinforcement. Magnesium composites are new class metal matrix composites widely used in aerospace and automobile industries due to their low density, good mechanical properties, better corrosion and wear resistance, low thermal coefficient of expansion as compared to conventional metals and alloys. The performance of composites depends upon the right combination and composition of reinforcement material with the matrix material. This paper presents few of the available literature review the combination of reinforcement material with magnesium matrix metal. Magnesium metal matrix composites with reinforcement(s) and filler materials are finding increased applications because of improved mechanical and tribological properties. Addition of reinforcing materials such as Al2O3, SiC, B4C, metallic glass, etc., is one of the ways to enhance various mechanical and tribological properties of Mg based MMCs. When graphite is added composites decrease in tensile and hardness was observed whereas with graphite addition specific wear rate decreases. Waste materials may used as reinforcement such as fly ash, rice husk ash, etc. for low cost reinforcement which may results in better mechanical and wear properties.

1. Introduction

A composite material is a material system composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents. The phases are combined at a macroscopic level and are not soluble in each other. The term phase indicates a homogeneous material, such as a metal or ceramic in which all of the grains have the same crystal structure, or a polymer with no fillers. The primary phase forms the matrix within which the secondary phase is imbedded. The imbedded phase is sometimes referred to as a reinforcing agent, because it usually serves to strengthen the composite. The reinforcing phase may be in the form of fibers, particles, or various other geometries. Metal matrix composites (MMCs), as the name implies, have a metal matrix. Metal matrix composite materials are considered as the one of the new class of engineering materials. Metal Matrix Composites have many advantages over monolithic metals such
as: higher specific modulus, higher specific strength, better properties at elevated temperatures, and lower coefficient of thermal expansion.

In the present study, magnesium (Mg) is used as the matrix material because it is lightest in nature and having very good vibration and damping characteristics. Because it is not sufficiently strong in its purest form, it is alloyed with various elements in order to gain certain specific properties, particularly a high strength-to-weight ratio. Magnesium is also an alloying element in various nonferrous metals. Magnesium alloys are also used in structural and non-structural application where light weight is primary importance. Magnesium MMCs have great use potential in the structural components in the aerospace and automobile industries mainly because of their low density and high specific strength.

2. Reinforcing materials and processing routes for the synthesis of Mg based MMCs.

There are number of solid and liquid phase processing routes are available for synthesis of magnesium based metal matrix composites with various types’ reinforcement, their size, volume fraction etc. Solid phase process consist of consist of powder metallurgy technique where as liquid phase process consist of liquid metal matrix and solid reinforcement. Jayalakshmi et al. [1] had made composites by magnesium alloy AM100 (Mg–9.3 to 10.7Al– 0.13Mn) - Alumina (Al2O3) through squeeze casting techniques. Three volume fractions (viz. 15, 20 and 25%, respectively) of fiber performs were used. Lim et al. [2] had prepared Mg-9Al/SiCp composites by power metallurgy. Lim et al. [3] fabricate magnesium composites reinforced with nano-sized alumina particulates by stir-casting. Jiang et al. [4] have studies the fabrication of B4C (10, 15 and 20 vol. % B4C) particulate reinforced magnesium matrix composite by powder metallurgy. Poddar et al. [5] prepared MMC by using SiC (15 vol. %) reinforced cast magnesium matrix composites (AZ91D) by stir casting process. Tang et al. [6] had studied mechanical properties of magnesium matrix composites reinforced with 10 wt. % W14Al86 alloy particles by squeeze-casting. Dudina et al. [7] had studied magnesium alloy (AZ 91) matrix composite reinforced with metallic glass by using powder metallurgy (P/M) technique. Hong et al. [8] studied thixo compression deformation behavior of SiCp (3%, 6% and 9% volume fraction)/AZ61 magnesium matrix composites by stir-casting. Güleryüz et al. [9] studied Production of B4Cp (3%, 6%, 9% by weight) reinforced magnesium metal matrix composites by powder metallurgy. Li et al. [10] had prepared magnesium matrix composites reinforced with Mg2B2O5w and B4Cp through squeeze casting. Alaneme et al. [11] studied mechanical behavior of rice husk ash (0, 2, 3, and 4 wt %) – Alumina reinforced Al-Mg-Si alloy matrix hybrid composites fabricated by two-step stir casting. Muley et al. [12] prepared the ultrasonically processing in situ AZ91/ Si (3 and 5 wt %) composites. Wang et al. [13] investigated the microstructure and mechanical properties of micro-SiCp (5–20%) reinforced magnesium matrix composites fabricated by stir casting assisted by ultrasonic treatment processing. Bhingole et al. [14] synthesized AZ91 alloy matrix composites by in situ reactive formation of hard MgO and Al2O3 particles from the addition of magnesium nitrate to the molten alloy. Application of ultrasonic vibrations to the melt increased the uniformity of particle distribution, avoided agglomeration, and decreased porosity in the castings. Zhang et al. [15] tensile behavior and microstructure of magnesium AM60-based hybrid composite containing Alumina (Al2O3) fibers - ceramic particles through squeeze casting. Viney et al. [16] had studied the comparison of mechanical properties and effect of sliding velocity on wear properties of AL6061- 4%Mg- Fly ash (10%, 15% and 20%), AL6061- 4% Mg- 4% Graphite- Fly ash (10%, 15% and 20%) hybrid metal matrix composite by stir casting. Selvam et al. [17] fabricated magnesium matrix nano-composites by Powder metallurgy using zinc oxide (0.5 vol. %) as the reinforced particle. Rashad et al. [18] had prepared magnesium composites reinforced with graphene nano platelets through powder metallurgy
processes. Magnesium and its composites taken as pure Mg, Mg–1Al–0.09GNPs, Mg–1Al–0.18GNPs, and Mg–1Al–0.30GNPs. Nie et al. [19] investigated microstructures and mechanical properties of SiCp/AZ91 magnesium matrix nanocomposites processed by semisolid stirring assisted ultrasonic vibration and multidirectional forging. Nguyen et al. [20] reported tribology characteristics of magnesium alloy AZ31B and Al2O3 fabricated by disintegrated melt deposition technique, followed by machining and hot extrusion. Sankaranarayanan et al. [21] developed a high performance magnesium composites using Ni50Ti50 (3, 6 and 10 vol. %) metallic glass reinforcement fabricated by microwave assisted rapid sintering technique followed by hot extrusion.

3. The Mechanical and Tribological properties of magnesium based metal matrix composites.

Mechanical properties determine the behavior of a material when subjected to mechanical stresses. The mechanical properties are determined from different strength test, these includes tensile strength, compression test, three-point flexural strength, hardness test, impact strength etc. Tribological properties such as wear rate define the progressive loss or removal of material from the surface. Jayalakshmi et al. [1] investigated that highest volume fraction (25%) resulted in a hardness value (165 BHN) that is nearly twice that of the unreinforced base alloy (85 BHN). Tensile tests were conducted at four different test temperatures, viz. 25 (room temperature), 100, 150 and 200°C, respectively. The ultimate tensile strength of the unreinforced base alloy is very sensitive to temperature and undergoes a drastic reduction in strength as the test temperature increases. At the highest test temperature the strength drops to almost one-third of its room temperature value. The % elongation of the alloy increases initially with increasing test temperature. Lim et al. [2] reported that elastic modulus, macro-hardness, and density of Mg-Al/SiCp shows higher than Mg-Al. The volumetric wear rates for the Mg–9Al alloy and its SiCp-reinforced composite shows that wear rates are greater at the higher load of 30 N. At the lower load of 10 N, the addition of SiCp reinforcement brings slight but consistent improvement to the wear resistance of the Mg-Al alloy (about 15–30%), except at the highest speed of 5 m/s, where the wear rates are nearly equal. Lim et al. [3] has been observed that the macro-hardness, UTS, dynamic modulus, and density of the composite increases with addition of 0.22, 0.66 and 1.11 vol.% of alumina particulars to the Magnesium. The volumetric wear rates for monolithic magnesium and its composites indicates that the 1.11 vol.% alumina-reinforced composite, being the best performer shows an improvement in the wear resistance of 1.3 times at the lowest speed of 1 m/s, and more importantly, up to 1.8 times under the higher-speed, and thus, more severe sliding conditions. Jiang et al. [4] observed that the hardness of B4C/Mg composites with 20 vol. % B4C particulate is higher than that of as-cast magnesium ingot. The volumetric wear rate of B4C/Mg composite is obviously less than that of as-cast magnesium ingot as expected. Poddar et al. [5] investigated mechanical properties of SiC (15 vol.%) reinforced cast magnesium matrix composites (AZ91D) and reported that the increase in hardness and elastic modulus compared to Mg-15 vol.% of SiC monolithic composite containing 15 μm size SiC particles is significantly higher than the composite with 150 μm size particles. The ultimate tensile strength and ductility of composite materials was reduced compared to unreinforced alloy. Tang et al. [6] have studied mechanical properties of magnesium matrix composites reinforced with 10 wt.% W14Al65 alloy particles and reported that the UTS increased from 360 to 458MPa with increasing the milling time from 0.5 to 2 h, and then decreased to 278MPa as for 4 h. The hardness continuously increased with increasing the milling time. Dudina et al. [7] had studied magnesium alloy (AZ 91) matrix composite reinforced with metallic glass. It was concluded that hardness, yield strength, fracture strength of Mg alloy–metallic glass composite is higher than Mg alloy (cast). The % of deformation of Mg alloy–metallic glass composite is less than Mg alloy. The Comparison of hardness, yield strength, fracture strength, and % deformation of Mg alloy-metallic glass composites and Mg alloy (cast) is shown in Fig. 1.
Fig. 1. Comparison of hardness, yield strength, fracture strength, and % deformation of Mg alloy-metallic glass composites and Mg alloy (cast).

Hong et al. [8] studied thixotropic compression deformation behavior of SiCp /AZ61 magnesium matrix composites. The flow stress of SiCp/AZ61 composites increases with the increase of volume fractions of SiC particles. The flow stress of semi-solid SiCp/AZ61 composites is sensitive to temperature and strain rate. The lower the temperature and the larger the strain rate, the higher the flow stress. Güleryüz et al. [9] reported Brinell hardness values of the samples seen that the highest hardness value was obtained with 9 wt. % B4C reinforced Mg composite. Flexural strength value of the samples show that Mg-B4C (3% by weight) gives highest flexural resistance value. Li et al. [10] had prepared magnesium matrix composites reinforced with Mg2B2O5 and B4Cp and reported the additions of Mg2B2O5w and B4Cp can remarkably enhance the flexural properties of the composites. Muley et al. [12] investigated that the addition of Si particles grain size decreased by as much as 30% to 45% in 3 and 5 wt % Si/AZ91 composites. Both the hardness and the ultimate compressive strength increased by almost 90% upon addition of 5% Si. Wang et al. [13] reported that the UTS increased as the micro-SiCp increase from 0% to 15% due to grain refinement, but UTS decreased when the particle contents increased from 15% to 20% due to particle aggregations. SEM images of the composites with different volume fraction shows that Particle distribution was uniform in the composites except the distribution of 5 vol% composite. In addition, there were some micro-aggregations in the 20% composites. Bhingole et al. [14] had studied the mechanical properties of MgO–Al2O3–MgAl2O4 dispersed magnesium alloy composites. It is reported that the AZ91-6.5-UST composite specimens exhibited best mechanical properties with its hardness, yield strength and strain hardening exponents higher by 64%, 43%, and 115%, respectively, as compared to the AZ91 alloy. As the amount of reinforcement increased, the MMCs became more wear resistant. Selvam et al. [17] the dry sliding wear behavior of zinc oxide (0.5 vol. %) reinforced magnesium matrix nano-composites reported that wear rate was found to increase with the load and sliding velocity. However, the coefficient of friction decreased as the sliding distance increased. Rashad et al. [18] had reported the addition of Al-GNPs particles into pure magnesium has significantly improved the hardness values. From tensile test it is observed that, a 131% enhancement in Young’s modulus, a 49.5% enhancement in yield strength and a 74.2% increment in fracture strain. Nie et al. [19] reported that increase in the number of multidirectional forging (MDF) passes leads to decrease of the un-recrystallized regions in the microstructure and the increase of degree of dynamic recrystallization (DRX). The influence of multidirectional forging on microstructures and mechanical properties of a SiCp/AZ91 nanocomposite shows that after 1 MDF pass, yield strength and ultimate tensile strength of the nanocomposites are significantly enhanced while the elongation to fracture is decreased. Nguyen et al. [20] reported
tribology characteristics of magnesium alloy AZ31B and Al₂O₃. Test conditions included load–speed settings of 1, 3, 5, 7 and 10 m/s sliding speeds under a 10 N normal load, and 1, 3 and 5 m/s speeds under 30 N load. It is observed that at low speeds the wear rates of composites are higher than that of AZ31B and increased with the increase in amount of nano-alumina. This is mainly attributed to lower yield strengths of the composites. Fig. 2 shows the volumetric wear rates of AZ31B and its composites at different sliding speeds and loads.

![Volumetric wear rate of AZ31B and its composites at different sliding speeds and loads.](image)

(Nguyen et al. (2015))

Sankaranarayanan et al. [21] developed a high performance magnesium composites using Ni₅₀Ti₅₀ (3, 6 and 10 vol. %) metallic glass reinforcement and reported that the addition of Ni₅₀Ti₅₀ amorphous reinforcement significantly reduced the matrix grain size and increased the hardness when compared to pure Mg. Under compressive loads, the incorporation of Ni₅₀Ti₅₀ amorphous particles has significantly enhanced the strength of pure Mg (by 80%) without largely affective the ductility. Under tensile loads, the developed Mg/Ni₅₀Ti₅₀ composites exhibit enhanced strength due to efficient load transfer and matrix strengthening.

4. The Mechanical and Tribological properties of magnesium based metal matrix hybrid composites

Hybrid composites consist of more than two materials. Hybrid composites substitute the single reinforced composites because of superior mechanical and tribological properties. Alaneme et al. [11] studied mechanical behavior of rice husk ash (0, 2, 3, and 4 wt %) – Alumina reinforced Al-Mg-Si alloy matrix hybrid composites. It is observed that the hardness of the hybrid composites decreases slightly with increase in RHA content. Tensile strength reductions of 8% and 13%, and specific strengths which were 3.56% and 7.7% lower were respectively observed for the 3 wt% and 4 wt% RHA containing hybrid composites. The specific strength, percent elongation and fracture toughness of the 2 wt% RHA containing hybrid composite was however, higher than that of the single Al₂O₃ reinforced and other hybrid composite compositions. Zhang et al. [15] tensile behavior and microstructure of magnesium AM60-based hybrid composite containing Alumina (Al₂O₃) fibers and Al₂O₃ ceramic particles investigated that the microstructure analyses with both optical and scanning electron microscopy show that the ceramic reinforcement including both the particles and fibers are dispersed uniformly in the matrix alloy without agglomeration. The mechanical properties evaluation indicates that the hybrid reinforced composite has improved elastic modulus, tensile strengths and hardness in comparison to the matrix alloy. Viney et al. [16] had studied the
comparison of mechanical properties and effect of sliding velocity on wear properties of AL6061-4%Mg- Fly ash (10%, 15% and 20%), AL6061-4% Mg -4% Graphite- Fly ash (10%, 15% and 20%) hybrid metal matrix composite. Tensile strength increases with addition of fly ash. Similarly when graphite was added then a decrease in tensile and hardness was observed. The composite with 4%Mg, 15% Fly ash found to be maximum tensile whereas composite of 4%Mg, 20% Fly ash was found to be of maximum hardness. Specific wear rate decreases with addition of fly ash up to a certain volume and thereafter with further addition of fly ash specific wear rate increases (as shows in Fig. 3.). From Fig. 4 it is clear that with addition of graphite when compared with same percentage of fly ash specific wear rate decreases.

![Fig. 3 Effect of Volume percentage on specific wear rate](image1)

(Viney Kumara et al. (2014))

![Fig. 4 Comparisons of 10% fly ash to 10% fly ash with 4% graphite](image2)

(Viney Kumara et al. (2014))

5. Conclusion

From the above literature survey, it is concluded that:

- A number of processing routes are available for the synthesis of Mg based MMCs either on solid or liquid processing. These are squeeze casting, powder metallurgy, stir-casting, disintegrated melt
deposition technique, two-step stir casting, ultrasonic processing, stir casting assisted by ultrasonic treatment processing, semisolid stir casting assisted ultrasonic vibration and multidirectional forging, microwave assisted rapid sintering technique etc. Out of these processing route stir casting is the one of the simplest and low cost synthesis method of MMCs.

- The process parameters such as stirring speed, preheating temperature of reinforcement, time of stirring, stirring temperature, pouring temperature etc., plays an important role on improvement of distribution of reinforcement in magnesium based MMC in an stir casting process.
- Addition of reinforcing metallic materials such as Al₂O₃, SiC, B₄C, metallic glass, etc., is one of the way to enhance various mechanical and tribological properties of Mg based MMCs especially load bearing capacity.
- When graphite is added composites decrease in tensile and hardness was observed whereas with graphite addition specific wear rate decreases.
- The mechanical properties also depend upon the size of reinforcing material. If the size of reinforcing material increases the ultimate tensile strength and ductility of composite materials was reduced compared to unreinforced alloy.
- The improvement of mechanical as well as tribological properties with addition of organic materials such as fly ash; rise husk ash etc., in hybrid composites.
- Various waste materials may used as reinforcement such as fly ash, rice husk ash, etc. for low cost reinforcement which may results in better mechanical and wear properties. Further the use of fly ash can avoid the problem of waste disposal.
- Very limited work has been reported regarding addition of organic material to magnesium matrix composite. Hence addition of organic material to magnesium matrix composite should be further explored.

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