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Review Article

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A Comprehensive Overview on Magnesium Metal Matrix Composites

Rawad Aljabr*, Sandeep Karmakar, Nikhil Bharat, B. Rangilal and P.S.C. Bose

Mechanical Engineering Department, National Institute of Technology, Warangal, Telangana, India

***Correspondence to:**
Rawad Aljabr
Mechanical Engineering Department,
National Institute of Technology, Warangal,
Telangana, India.
E-mail: ra712191@student.nitw.ac.in

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Abstract

Magnesium-metal matrix composites (Mg-MMCs) are fascinating because of the significant role they may play in a wide range of applications after being reinforced with metals and ceramics to improve their mechanical characteristics and resistance to wear and corrosion. During the last decades, several effective technologies have been developed to manufacture Mg-MMCs with strong interfacial bonding and uniformly dispersed reinforcements, which ultimately leads to improved performance. The current study provides a rundown of the Mg composite reinforcements that are most commonly used, with a specific focus on the various classes of ceramics, as well as their influence on the microstructure characteristics and mechanical behaviour of Mg composite.

Keywords

Magnesium, Composite, Reinforcements, Applications

Introduction

The design of materials has changed over the past decades, moving more toward the creation of lightweight and affordable materials with good properties and also environmentally benign. At the same time, MMCs have attracted a lot of attention over the past several years, which has greatly increased their use in various industries [1]. MMC is a material made up of at least components, the first of which must be metal. Additional components may also include different metals or other materials, such as ceramics or waste materials. The primary objective of the reinforcement phase is to fortify the matrix, which transfers load to the dispersal phase. The effectiveness of load transfer through the interface between the phases determines the behaviour and performance of composite materials [2]. MMCs are divided into numerous classes based on the materials employed in their matrix, most significantly the composites made of aluminum, magnesium, titanium, copper, and super-alloys [3]. Among them, Mg and its alloys are categorized as the lightest engineering structural metal. Low density (1.74 g/cm^3) and high specific strength are the most important properties of Mg and Mg alloys. These features in addition to good castability, machinability, and strong damping capabilities make Mg and Mg alloys suitable for a greater set of engineering applications especially in aerospace and automotive industries where lowering fuel use and, as a result, lowering CO_2 emissions, are crucial factors in energy conservation and environmental protection [3, 4]. Also, Mg and Mg alloys can be used in biomedical applications because they are bioactive and biodegradable. They promote faster healing and then provide a lower incidence of needing another surgery. Therefore, Mg and Mg alloys are more suited to replace titanium and other biocompatible materials since their elastic modulus is similar to that of the human body [3]. However, their low elastic modulus and poor strength prevent them from being widely used in important engineering applications. Reinforcements can be used to make Mg-based composites, which

will overcome these inherent limitations. These reinforcements can be ceramics, metallic and nanoscale carbon-based materials [4]. The use of ceramic and metallic particles as reinforcements is one technique to enhance the mechanical characteristics of Mg and Mg alloys. The several types of particle reinforcements include carbides such as SiC, B_4C, TiC and ZrC, oxides such as Al_2O_3 and TiO_2, nitrides like BN, AlN, TiN and ZrN, borides like TiB_2 and ZrB_2, and particulate metals such as Ti, Mo, Cu and Ni [5]. Controlling the porosity of the composite depends heavily on the amount of reinforcing. The different types of reinforcement offer the composite good wettability. Therefore, improving the mechanical properties of composites depends significantly on the reinforcement mechanism [3]. Figure 1 depicts the overview of the application and fabrication of Mg-MMCs.

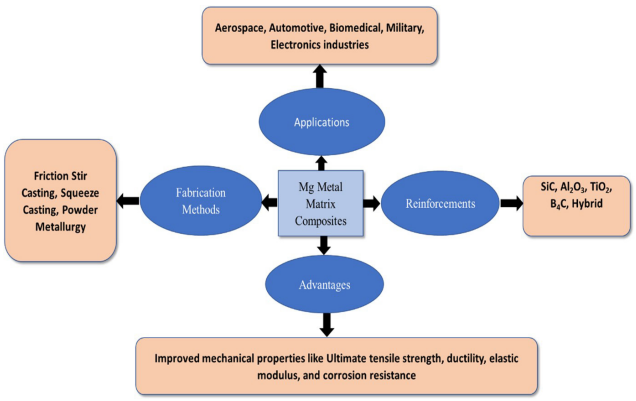


Figure 1: Overview of Mg-MMCs with their applications and fabrication technique.

Reinforcement Material Used in Mg-MMCs

SiC particulate reinforced Mg-MMCs

Luo [6] developed a casting process to fabricate SiC particulate reinforced pure Mg and AZ91 alloy by conventional casting process. He concluded that, it is necessary to optimize the parameters of the developed process to achieve good distribution of the particles and interfacial bonding, and consequently improved mechanical properties for SiC reinforced Mg composites compared with unreinforced pure Mg and AZ91 alloy. Zhou et al. [7] used semisolid stirring casting technology to fabricate the AZ91 magnesium alloy composite reinforced with bimodal size SiC_p. It was concluded that improved mechanical properties for nano and micron SiC_p reinforced AZ91 composite compared with homogeneous micron SiC_p/AZ91composite. Kumar et al. [8] fabricated composites made of Mg alloy and SiC using the stir casting method and studied the wear behavior of AZ91 alloy composites with different percentages (3%, 6%, 9%, and 12%) of SiC particulates. SiC reinforced AZ91 composites were shown to have greater microhardness than unreinforced AZ91 alloy. In comparison to unreinforced composites, SiC reinforced composites had a lower friction coefficient and rate of wear. This is because SiC_p in composites has better hardness and grain refinement. Lim et al. [9] examined the wear properties of silicon carbide particulate reinforced MMCs. The findings showed that the composites had marginally better wear resistance at lower loads, however SiC_p didn't seem to be helpful in lowering wear rates. Mahdy et al. [10] produced Mg-MMC reinforced with SiC under an inert gas atmosphere by applying compo-casting technique. The findings reveal a striking increase in hardness value, tensile strength, and 0.2% yielding strength. The addition of SiC to the base matrix was evidenced by the improvement in overall mechanical characteristics. The increase in strength with respect to change in SiC can be seen from figure 2.

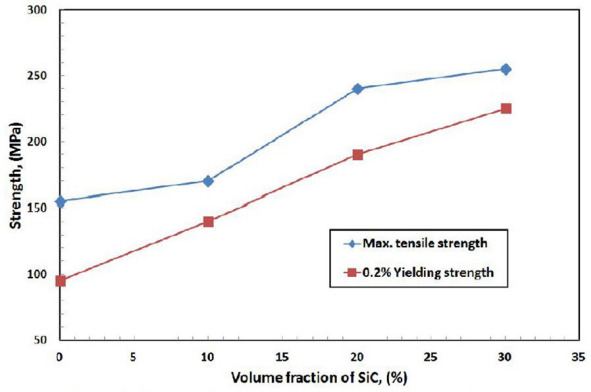


Figure 2: Variation of strength with respect to different volume fraction of SiC [10].

B_4C particulate reinforced Mg-MMCs

Jayabharathy et al. [11] used the disintegrating melt deposition process and subsequently hot extrusion to examine the impact of adding nano-B_4C on the microstructure characteristics and mechanical properties of the Mg composite material containing 5.6Ti% and 3Al%. They found that the inclusion of nano B_4C and Al3Ti intermetallic compounds in a magnesium matrix results in an increase in both ductility and strength. Sankar et al. [12] incorporated B_4C nanoparticles into the AZ91 alloy using powder metallurgy at different weight percentages (5, 10, 15, and 20%), and investigated the tribological properties of AZ91/B_4C nanocomposites. as a result of the incorporation of B_4C nano scale particles, the hardness and wear resistance of AZ91/B_4C nanocomposites were improved. Chinthamani et al. [13] fabricated AZ91 Mg alloy reinforced with nano B_4C particles at various wt.% (5, 10, 15, and 20) by powder metallurgy technique. The wear resistance and strength of the base material are increased by B_4C reinforcement in the Mg matrix. Compared to the unreinforced alloy, nano B_4C reinforced composites showed better wear resistance. Jutanaiman and Syahrial [14] employed stir casting to manufacture a Mg composite using micro B_4C as the reinforcing particle. Because there are more B_4C particles present, the wear rate is lowered, and the mechanical properties of the Mg composite are improved. Aydin et al. [15] used powder metallurgy and hot pressing to create AZ91-MMCs reinforced with three percentages (10, 20, and 30 wt.%) of B_4C particles. In this study, mechanical characteristics, density, and microstructure were examined. The findings showed that AZ91 composites' hardness, wear resistance, and compression strength significantly improved with a uniform distribution

of particles throughout the matrix and the inclusion of B_4C particulates.

Al2O3 reinforced Mg-MMCs

Kumar et al. [16] investigated in depth the mechanical properties and wear behavior of composites made of AZ91D Mg and Al_2O_3. Utilizing the ultrasonic-assisted stir casting technique with optimal parameters, composites were created. The weight percentages of the Al_2O_3 reinforcement powder were changed to 0, 1.5, and 2.25, respectively. They found that an improvement in the wear resistance and hardness with increasing the percentage of reinforcements. Also, the addition of Al_2O_3 refined grain structure and improved morphology. Dieringa et al. [17] studied the compressive and tensile creep behaviour of 20 vol.% Al_2O_3 reinforced AE42 Mg-MMCs which is fabricated by direct squeeze casting. The results revealed that the high temperature creep resistance of Mg alloys was increased, and the drawback of poor high temperature creep characteristics was overcome. Arokiasamy et al. [18] studied the material characteristics of pure Mg reinforced with SiC and Al_2O_3 hybrid MMCs produced by friction stir technique. The microhardness was undoubtedly increased by the Mg-MMC. The particles distribution of SiC and Al_2O_3 was uniform. Raj et al. [19] fabricated Mg-MMC of AZ91D reinforced with varying wt.% of SiC and Al_2O_3 (0 and 0, 3 and 3, 6 and 3, and 9 and 3, respectively) using the squeeze casting method. They researched the mechanical characterization of them. The density, hardness, and tensile strength of the hybrid Mg-MMCs increased with a greater weight percentage of SiC/ Al_2O_3 nano particulates. Huang et al. [20] investigated how AM60/Al_2O_{3p} nanocomposites performed mechanically when subjected to equal channel angular extrusion (ECAE). The stir casting method was used to create the Mg-MMCs for ECAE, which comprise 1 wt.% nano sized Al_2O_3 particles. The ductility and other mechanical characteristics of AM60 Mg alloy can be improved by employing reinforcing particles. It was shown that the grain refining performed by ECAE in the AM60 MMCs was significantly more successful.

TiO_2 particulate reinforced Mg-MMCs

Pallai et al. [21] created a pure Mg reinforced with TiO_2 using the powder metallurgy technique. They investigated the mechanical characteristics and conducted microstructural analyses. SEM (scanning electron microscope) was used to check that the particles were evenly distributed throughout the matrix. The inclusion of reinforcing particles significantly enhanced the hardness as shown in figure 3 and tensile properties of the composites. Rahmani et al. [22] utilized hot quasi-static compaction to generate Mg-MMCs from pure Mg that was reinforced with TiO_2 and ZrO_2 nanoparticles. They did this by changing the volume fraction from 0 to 1.5, 3, and 5 for 25 minutes while the temperature was kept at 450 °C and the pressure was kept at 600 MPa. Experiments were carried out in order to determine the density of the samples, as well as their ultimate compressive strength, level of hardness, and thermal expansion coefficient. According to the data, an increase in the volume fractions % of nanoparticles led to a lower relative CTE and density, in addition to improvements in UCS and hardness. The results showed that Mg-TiO_2 had a lower relative density compared to Mg-ZrO_2, which was another discovery that emerged from the investigation. Jayabharathy et al. [23] looked at the mechanical and wear behaviour of AZ91 reinforced with TiO_2 and graphene using stir casting technique. Hybrid composites had a 10% increase in base matrix material hardness over AZ91 Mg alloy. Hybrid composites exhibit improved wear resistance. The test showed that softer materials have higher coefficients of friction than harder materials. Pillai et al. [24] examined the mechanical parameters of pure Mg reinforced TiO_2 particles with different

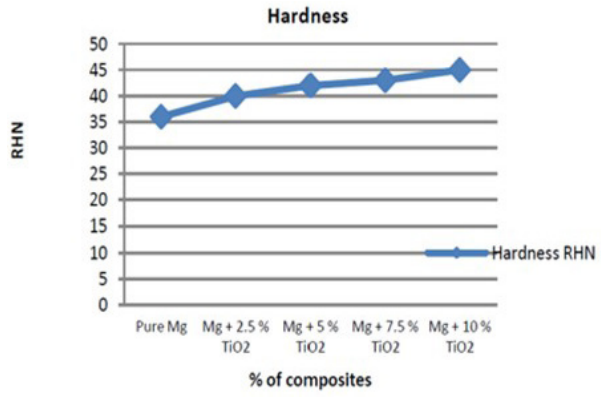


Figure 3: Variation of hardness with different composition of TiO_2 [21].

Table 1: Application and fabrication method of Mg-MMCs.

Sl. No.	Composition	Fabrication Method	Mechanical Properties	Application	Reference
1	Mg + SiC	Powder metallurgy	Improvement in hardness, compressive strength, and impact Strength.	Antenna structures and Helicopter transmission structures integrated circuit materials, satellite structures	[36]
2	Mg + B_4C	Stir casting	increase composite hardness, composite impact value, Reduce the composite wear rate,	Automotive industry	[14]
3	AM60 + Al_2O_3	Squeeze casting	Increase tensile strength and decrease ductility,	Automotive industry	[37]
4	AZ31 + Al_2O_3 + SiC	Powder metallurgy	Increase mechanical properties and hardness,	Automotive industry	[31]
5	Mg + TiO_2	Vacuum stir casting	Increased hardness, yield strength, and ultimate tensile strength.	Powertrain, chassis, braking, suspension, and steering, as well as some engine components	[24]

weight percentages of 2.5, 5, 7.5, and 10, with the use of the vacuum stir casting method and the argon as a shielding gas. The manufactured composite materials' densities were fairly close to the theoretical value. The addition of reinforcing particles significantly enhanced the composites' hardness, yield strength, and ultimate tensile strength. Radhakrishnan et al. [25] studied the mechanical behavior of pure Mg reinforced with TiO_2 by using the powder metallurgy technique for various weight fractions. The homogeneous distribution of TiO_2 over the Mg matrix was verified by a SEM image. Hardness was improved by the use of reinforcement.

Metallic particulate reinforced Mg-MMCs:

Hassan et al. [26] created Ti particle reinforced magnesium composites by employing a novel disintegrated melt deposition process and then heated extrusion. The findings demonstrated high interfacial integrity of Ti particles in Mg matrix, limited porosity, and a generally uniform dispersion of Ti particulates inside the matrix material. according to tensile behavior characterization, when Ti reinforcement was included, yield strength and ductility improved by 0.2%, but the UTS suffered as a result. Seetharaman et al. [27] used the mechanical ball-milling approach to add 5.6% of Ti with 3% of Cu powders to Mg powder. Mechanisms of Orowan strengthening and grain refining are responsible for the composites' dramatically improved mechanical characteristics. The eutectic phase of Mg_2Cu greatly refined the matrix grains. Strength and plasticity both improved throughout the Ti_3Cu phase. Wong and Gupta [28] prepared Mg-based composites strengthened with various nano Cu particle concentrations successfully by using the powder metallurgy route. It was noted that the mechanical properties of Mg composites were higher than those of pure Mg due to the existence of a continual network structure formed of the particles of nano scale-Cu and a Mg_2Cu intermetallic phase's dispersion within the grains. Hassan and Gupta [29] developed a novel disintegrated melt deposition technology followed by hot extrusion to produce Ni reinforced Mg materials. The findings revealed that Ni particles were distributed uniformly throughout the metal matrix, and integrity of the interface of the Mg matrix containing the particulates of Ni was good. Hence mechanical properties were improved due to the presence of Ni reinforcement even in comparison to the highly strengthened Mg alloy AZ91 reinforced with SiC at a substantially greater volume percentage. Vahida et al. [30] created biocompatible Mg composites by adding Nb metallic reinforcements using a powder metallurgy route linked to the ball milling method. During the milling operation, Nb particles induce a greater lowering in the Mg powders sizes. The Mg matrix contained Nb reinforcements distributed uniformly without formation of intermetallic phases. As a result, the mechanical characteristics are enhanced under compressive loading, up to 20% Nb.

Hybrid particulate reinforced Mg-MMCs

With the powder metallurgy method, Karthick et al. [31] synthesized MMC materials from a Mg alloy (AZ31) matrix with Al_2O_3 and SiC as the reinforcing ceramic phase. The results revealed that the reinforcing particles were unevenly distributed inside the Mg matrix, which significantly improved the material's mechanical and hardness properties. Al-maamari et al. [32] created a hybrid MMC out of Mg, SiC, and graphite by using a mechanical alloying procedure. The resulting microstructure of the sintered MMCs indicated that the reinforcement was evenly distributed across the matrix. When judged against both the starting material and the Mg composite reinforced with graphite, the hybrid MMCs that were generated demonstrated much improved mechanical characteristics. Stir casting was utilized by Aatthisugan et al. [33] to make hybrid composites out of Mg (AZ91D) and graphite with B_4C reinforcement particles. This research demonstrated that the wear resistance and strength of Mg composites are significantly improved by the addition of B_4C as a hard reinforcement and graphite as a soft reinforcement, when compared with the unreinforced AZ91D alloy and the AZ91D-B_4C composites. Vijayakumar et al. [34] generated hybrid Mg composites by employing the method of the stirring-squeeze cast process with (3%, 6%, and 9%) of SiC reinforcement and (3%) of BN particles with AZ91D alloy. They did this in order to produce the composites. The hybrid composite saw improvements in both its mechanical characteristics and its resistance to corrosion as the degree of SiC reinforcement increased from 0 to 9 wt.%. Using the stir casting process, Lingaraju et al. [35] created hybrid Mg composites by combining Mg with nano-reinforcements of TiC (Titanium carbide), B_4C, and HBN (Hexaboron nitride). Adding B_4C, TiC, and HBN, in varying ratios, reinforced the Mg-based AZ91 Matrix, increasing its hardness, wear resistance, and ultimate tensile strength.

Conclusion

This paper studied the influence of using various types of reinforcements on the resulting microstructure of Mg-MMCs and their mechanical properties. Different types of Mg-MMCs were created by different dimensions, configurations, and categories of reinforcement elements to be able to

Table 2: Mechanical properties of Mg-MMCs [38].

Sl. No.	Composition (%)	Yield Strength (Max) MPa	Hardness (Max) (HV)	Compression Strength (Max) MPa
1	Mg + (4, 8, 12)% SiC	-	70 for 12% SiC	548 for 12% SiC
2	Mg + (1, 3, 5, 10)% CNF	114 for 3% of CNF	46.7 for 1% of CNF	221 for 1% of CNF
3	AZ91 + (3, 6, 9)% TiC	-	91 for 9% of TiC	45 for 9% of TiC
4	AZ91 + (30) wt.% B_4C	176	124	420
5	AZ91 + (0, 1, 1.5, 2)% of Al_2O_3		99.06 for 2% of Al_2O_3	-

increase the range of engineering application of magnesium. A brief study is done on the impact of adding reinforcements like Al_2O_3, SiC, B_4C, TiO_2, and others. The proper manufacture and appropriate reinforcing of Mg-MMCs in accordance with the specifications are the primary factors for the composition of microstructure and mechanical behaviour. Most common fabrication method used for making Mg-MMCs are stir casting, powder metallurgy, squeeze casting, and others. Addition of reinforcements like Al_2O_3 and TiO_2 increases the grain refinement, density, tensile properties in addition to hardness whereas reinforcements like SiC and B_4C increase the friction coefficient and ductility respectively. SiC particle reinforced Mg matrix composites are more resistant to wear and creep than Al_2O_3 reinforced Mg-MMCs. Only a few studies on metallic-reinforced Mg composites have been carried out so far. The weight of Mg-based composites will be affected negatively when considerable amounts of metallic reinforcement are added since they have a substantially higher density than the Mg matrix. Due to the fact that hybrid composites combine the properties of their additional reinforcements, they may be used in a broad variety of contexts. Important aspects that contribute to the widespread use of Mg hybrid composites include the meticulous management of the reinforcing phase, as well as the development of production processes that minimize costs.

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None.

Conflict of Interest

There is no conflict of interest.

Credit Author Statement

Rawad Aljabr: Conceptualization, Methodology, Experimentation; Sandeep Karmakar: Writing - original draft preparation; Nikhil Bharat: Writing - original draft preparation; B. Rangilal: Writing - original draft preparation; P.S.C. Bose: Data analysis. All the authors read and approved the manuscript.

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