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ENHANCING MATERIAL PERFORMANCE: A REVIEW OF MAGNESIUM-BASED METAL MATRIX COMPOSITES

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Abstract

Magnesium Matrix Composites (Mg-MMCs) are emerging as highly promising materials for aerospace and defence applications due to their low density and favourable mechanical properties. Compared to conventional engineering materials, these composites exhibit improved specific strength, stiffness, damping behaviour, wear resistance, creep, and fatigue properties when reinforced with various elements. This paper provides an overview of the effects of different reinforcements in magnesium and its alloys, highlighting their advantages and drawbacks. Key phenomena such as interfacial transition, agglomeration effects, fibre-matrix bonding, and particle distribution challenges are discussed in detail. The impact of reinforcements on microstructure and mechanical properties, including tensile strength, yield strength, ductility, strain, hardness, wear, and fatigue, is critically analyzed. The study also reviews processing techniques, characterization, and the tribological and mechanical behavior of Mg-MMCs, with a focus on reinforcements like carbon nanotubes (CNT), carbonaceous materials, fullerenes, SiC, Al_2O_3, TiC, B_4C, and graphene. Observations indicate that ceramic reinforcements enhance hardness and strength but reduce ductility, whereas titanium-based metallic reinforcements improve both ductility and strength. Significant applications of various magnesium MMCs are also examined.

Keywords: *Magnesium, MMC, Reinforcement, Hardness, MMC Fabrication method*.

1. Introduction

Magnesium (Mg) is a highly sought-after material in engineering applications due to its exceptional lightness. Amongst all structural metals, Mg boosts the lowest density, making it a prime candidate for weight reduction strategies in various fields [1]. This property is particularly attractive for applications in transportation (aircraft, automobiles) and portable electronics, where minimizing weight translates to improved fuel efficiency and increased portability [2]. However, pure magnesium is limited in strength and ductility, especially at room temperature. This restricts its applicability in load-bearing components [2]. To overcome these limitations and unlock the full potential of Mg's lightweight advantage, researchers have explored the development of composites using Magnesium Metal Matrix (Mg-MMCs). Mg-MMCs are a class of composite materials where magnesium serves as the matrix (continuous phase) and is reinforced with a secondary phase of typically ceramic or carbon-based materials [2-3]. These reinforcements are strategically chosen for superior strength and stiffness and embedded within the magnesium matrix. The resulting composite material exhibits a synergistic combination of properties, capitalizing on the lightness of Mg and the enhanced mechanical performance offered by the reinforcements [4]. The advancement of Mg-MMCs has attracted much attention from researchers since the potential for significant improvements in various properties compared to unreinforced magnesium. Let's delve deeper into the specifics of Mg-MMCs, exploring the types of reinforcements employed, the fabrication techniques used, and the range of properties achievable through this class of composite materials. Composite materials are specially engineered to meet the demands of structural applications, combining strength, stiffness, and toughness while minimizing weight. Unlike traditional materials, composites blend two or more unique materials with different properties [5]. They are designed to be anisotropic and inhomogeneous, meaning their properties vary in different directions and locations within the material. Typically, composites are made up of a matrix material, which is lighter and softer, and a reinforcement material. These materials can be continuous or discontinuous phases within the composite. Composites are classified according to the kind of matrix and reinforcement used to categorise them. Fig. 1 shows the classification of composites.

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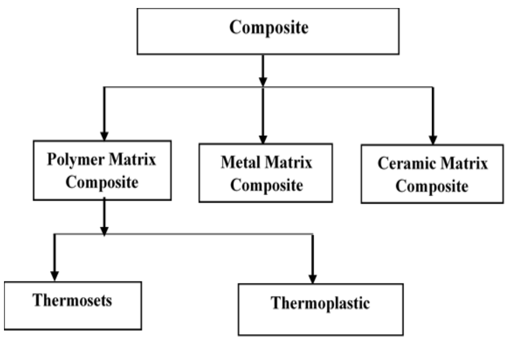

Fig. 1 General classification of composite based on matrix phase

2. Classification of composite based on the type of reinforcement

Reinforcement in composites refers to strengthening materials added to enhance mechanical properties [6]. Classification often involves categorizing composites based on the type of reinforcement used, such as particulate, fibrous, or laminar reinforcements. Each kind has distinct qualities and applications, influencing the composite's overall performance and suitability for several sectors, including aerospace, automotive, and construction. Classification of Composite based on the type of reinforcement shown in Fig. 2.

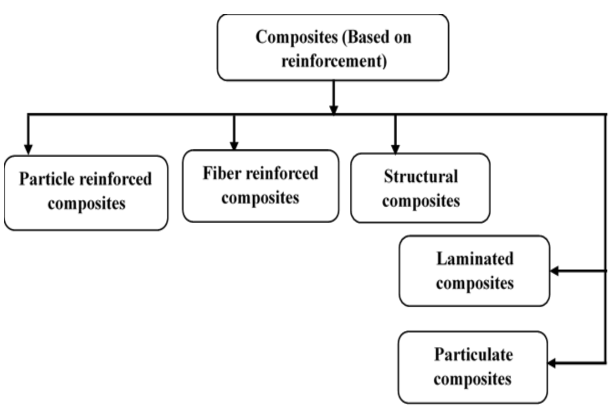

Fig. 2 Classification of composite based on the type of reinforcement

3. Magnesium-based nanocomposites

Magnesium (Mg) based nano composites have attracted much interest recently due to their promising properties and potential applications across multiple fields. These composites typically consist of magnesium as the matrix material, reinforced with nano-sized particles or fibers, such as Boron Carbide (B4C), carbon nanotubes (CNTs), graphene, ceramic nanoparticles, or metallic nanoparticles [7]. One of the key motivations for developing Mg-based nano composites is to improve the mechanical qualities of pure magnesium, which has limitations in strength and ductility. By incorporating nano-sized reinforcements, such as nanoparticles or fibers, into the magnesium matrix, it is possible to improve mechanical characteristics, like strength, stiffness, and toughness, while maintaining or even improving other desirable qualities, such as low density and biocompatibility. The dispersion of nano-sized reinforcements within the magnesium matrix is crucial for achieving the desired characteristics of the composite material. Various fabrication techniques, including powder metallurgy, mechanical alloying, and electrodeposition, have been used to distribute nanoparticles uniformly or fibers within the magnesium matrix.

In addition to mechanical properties, Mg-based nanocomposites exhibit enhanced thermal and electrical properties compared to pure magnesium. The high surface area-to-volume ratio of nano-sized reinforcements can improve heat dissipation and electrical conductivity, making these composites attractive for thermal and electronics applications. Furthermore, Mg-based nanocomposites have shown promise in biomedical applications due to their biocompatibility and bioresorbability [8]. These materials can be tailored to match the mechanical properties of natural bone tissue, making them appropriate for use in orthopedic implants and tissue engineering scaffolds. However, despite all of their advantages, challenges remain in the fabrication and commercialization of Mg-based nanocomposites. Issues such as achieving a homogeneous dispersion of nano-sized reinforcements, controlling grain size and orientation, and optimizing processing parameters to prevent degradation within the magnesium matrix are areas of ongoing research. According to recent research, optimizing the fabrication processes and exploring new reinforcement materials is necessary to improve the qualities of Mg-based nanocomposites. Researchers have, for instance, looked into using hybrid reinforcements, such as combining carbon nanotubes with ceramic nanoparticles, to provide synergistic effects and enhance the system's overall composite material performance.

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4. Fabrication of composite material process

Fine alloy powder and high-purity ceramic particles are mixed using the powder metallurgy technique to create Metal Matrix Composites (MMCs). This involves blending the powder and particles for uniform dispersion, cold pressing to form a green body, degassing to remove surface moisture, and sintering under controlled conditions. The process can remove oxide skin on particulate surfaces through hot pressing and degassing in an inert environment. To achieve full density, hot pressing is utilized, allowing for a high-volume fraction of reinforcement in the matrix. While powder metallurgy offers homogeneous reinforcement distribution, its complexity and high cost of materials make it less appropriate for large-scale manufacturing [9]. Examples of MMCs produced through this method include AZ91/A1:O, AZ91/SiC, AZ91/TiO, AZ91/TiC, AZ31/WC, and AZ80/BC. Spray deposition is a method of spraying molten metal onto a surface using gas. Sun et al. [10] indicated how this method permits high-speed production and the creation of MMCs by adding reinforcement particles. Spencer et al. [11] used cold spray deposition to enhance wear and corrosion resistance. Physical vapor deposition involves applying thin layers to surfaces by condensing vaporized materials. Using this method, Hoche et al. [12] demonstrated coating magnesium alloys with nitrides like TiN and CrN. Sivapragash et al. [13] focused on optimizing sputtering parameters for ZrO coatings on AZ91 alloy.

In-situ composites involve hard particles formed within the metallic matrix during processing via chemical reactions. These particles are well-dispersed, stable, and bond well with the matrix. Krishnan et al. [14] created Mg-TiC in-situ composites via mechanical alloying. Shamekh et al. (2012) explained the formation mechanism of TiC-TiB in the A291 matrix. Ajith Kumar et al. [15] and Sahoo & Panigrahi [16] analyzed the mechanical characteristics and microstructure of in-situ TiC-TiB hybrid composites. Stir casting is a technique used to make metal matrix composites, typically for composites with particulate reinforcement rather than fibers, due to the difficulty of forming fibers without pressure. When casting, it is crucial to think about the chemical reaction between the matrix and the reinforcement, as well as with the atmosphere. Adding reinforcement increases the molten metal's viscosity, which can be managed by covering the melt with flux or inert gas to reduce oxidation and maintaining the temperature above a certain point. Since the molten metal's density is lower than the reinforcement's, stirring at a certain speed prevents settling. Mechanical vibration and magnetic fields can improve the wetting properties of the particulates. Kumar et al. [17] developed a stir casting process for matrix composites made of magnesium alloy, which inspired this research on magnesium MMC using the same technique. The flow chart shown in Fig. 3 outlines the most common techniques used to produce MMC powders, along with the methods for bulk manufacturing.

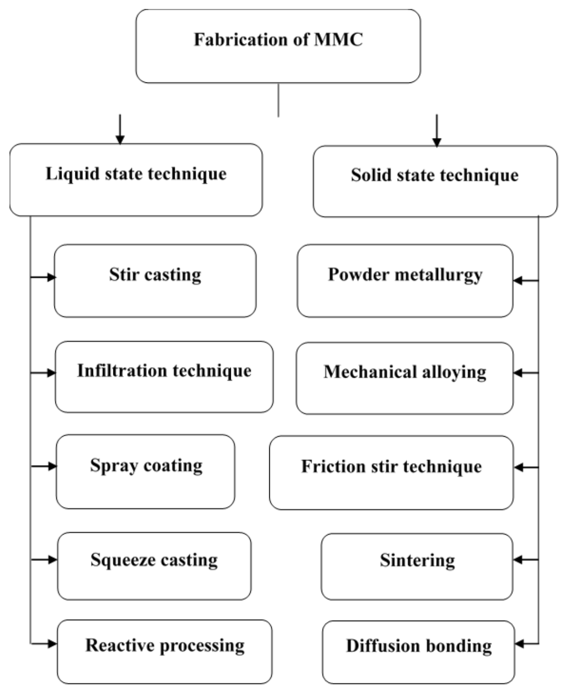

Fig. 3 MMC composites fabrication technique

5. Processing of Particulate Reinforced MMC

Metallurgists have developed numerous processing methods to create a metal matrix reinforced with particle composites (MMCs) and optimize their mechanical properties. These methods have two categories: (i) Production of MMC and (ii) Consolidation or forming operations. Commonly employed methods include powder metallurgy, deposition processing, reactive processing (in situ), melt infiltration, and stir casting [18]. The processing methodology for particulate MMC is detailed in Table 1, with subsequent subsections providing brief introductions to these processes. Additionally, Table 1 outlines the processing methodology for particulate MMC, offering further insights into these techniques.

Table 1 Techniques for manufacturing particulate reinforced MMC [18]

S No	MMC Fabrication Method	Cost	Application	Inference
1	Powder metallurgy	expensive	used to produce small objects, such as bolts, pistons, valves, etc.	• High volume fractions of particulate are possible • Powders are expensive • not for near-net-shape parts.
2	Stir casting	least expensive	fundamental method for MMCs, applied in the aerospace and automotive industries	• applicable for large-scale manufacturing • low volume fractions up to 30%
3	Squeeze casting	expensive	widely used in the automotive industry, like connecting rods	• lower porosity • molds needed • Large capacity presses are needed
4	Melt deposition technique	moderately expensive	used to produce structural shapes such as rods, beams, etc.	• uniform distribution • high strengths
5	Liquid metal infiltration	moderately expensive	used to produce tubes, rods, and structural shapes	• Filament-type reinforcement usually is used
6	Reactive processing (in situ)	least expensive	utilized in the quick solidification process for use in space and automobile applications	• involve a chemical reaction • excellent and thermodynamically stable reinforcement

6. Characterization of Mg-based MMC

The study by Jayalakshmi et al. [19] delved into the mechanical properties of magnesium-based metal matrix composites (MMCs), highlighting the significant impact of varying volume fractions on hardness values. They found that a higher volume fraction (25%) led to a notable increase in hardness compared to the unreinforced base alloy. Additionally, tensile tests conducted at different temperatures revealed temperature sensitivity, with the ultimate tensile strength decreasing substantially at higher temperatures. Conversely, Lim et al. [20] noted enhanced elastic modulus, macro-hardness, and density in Mig-Al-SiCp compared to Mg-Al. Furthermore, they noted that adding SiCp reinforcement slightly improved wear resistance at lower loads but resulted in comparable wear rates at higher loads and speeds. Building upon this, Lim et al. [21] showed that including alumina particulates into magnesium composites improved macro-hardness, ultimate tensile strength, dynamic modulus, and density. Notably, the 1.11 vol.% alumina-reinforced Composite showed improved resilience to wear under severe sliding conditions. Jiang et al. [22] and Poddar et al. [23] investigated the effects of particulate reinforcements on hardness and wear rates, with observations of increased hardness and reduced wear rates in the composite materials in contrast to monolithic magnesium. Additionally, Tang et al. [24] explored the mechanical properties of magnesium matrix composites reinforced with W14Al86 alloy particles, noting fluctuations in the highest tensile strength and hardness with varying milling times. Lastly, Dudina et al. [25] concluded that a composite matrix reinforced with magnesium alloy metallic glass exhibited higher toughness, yield strength, and fracture strength than cast magnesium alloy, with reduced deformation percentages. This comparison was shown in Table 2.

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Table 2 Mechanical properties of the Mg alloy–metallic glass composite and the Mg alloy [25]

Materials	Hardness (HV)	Yield strength (MPa)	Fracture strength (MPa)	Deformation (%)
Mg alloy-metallic glass composite	123	325	542	10.5
Mg alloy (cast)	68	143	404	21.0

Various researchers have extensively investigated the tribological and mechanical characteristics of magnesium-based composites made of metal matrix. Hong et al. [26] explored the thixotropic compression deformation behaviour of SiCp-AZ61 magnesium matrix composites, noting that the flow stress rises with increasing volume fractions of SiC particles and is sensitive to temperature and strain rate. Güleryüz et al. [27] reported on the Brinell hardness values, highlighting that the most rigid material was attained with 9 wt.% BC reinforced Mg composite, while the highest flexural resistance was observed with Mg-B4C (3% by weight). Li et al. [28] demonstrated that adding MgBOrw and B4Cp significantly enhances the flexural properties of magnesium matrix composites. Muley et al. [29] observed a decrease in grain size and an increase in ultimate compressive strength and hardness with the addition of silicon particles to AZ91 composites. Wang et al. [30] discovered that the ultimate tensile strength (UTS) increased with micro-SiCp content up to 15%, attributed to grain refinement, althrough decreased with higher particle contents due to aggregation. Bhingole et al. [31] studied the mechanical properties of dispersed magnesium alloy composites, noting that AZ91-6.5-UST has better mechanical qualities than AZ91 alloy, with reinforcement leading to improved wear resistance. Selvam et al. [32] examined dry sliding wear behavior in a magnesium matrix supplemented with zinc oxide nano-composites, observing an increase in sliding and load-related wear rate velocity but a decrease in coefficient of friction with sliding distance. Rashad et al. [33] reported significant improvements in hardness and mechanical properties by adding Al-GNPs particles into pure magnesium. Nie et al. [34] found that increased multidirectional forging passes led to ultimate tensile strength and yield strength enhancements but decreased elongation to fracture in SiCp-A291 nanocomposites.

Sankaranarayanan et al. [35] demonstrated the fabrication of high-performance magnesium composites by incorporating NoTi (3, 6, and 10 vol.% %) metallic glass reinforcement. Their study revealed that including NoTi amorphous reinforcement notably decreased the matrix grain size and increased hardness compared to pure Mg. Compressive loading tests showed a significant 80% increase in the strength of pure Mg with the incorporation of Ni50T150 amorphous particles, without majorly impacting ductility. Moreover, the developed Mg/Ni50T150 composites exhibited improved strength under tensile loads due to efficient load transfer and matrix strengthening.

7. The tribological and mechanical characteristics of metal matrix hybrid composites based on magnesium

Zhang et al. [36] investigated the tensile behavior and microstructure of magnesium AM60-based hybrid composites with alumina reinforcement (Al2O3) fibers and particles. They observed a uniform dispersion of ceramic reinforcements within the matrix alloy without agglomeration, leading to improved elastic modulus, tensile strength, and hardness compared to the matrix alloy. Viney et al. [37] also researched magnesium-based hybrid composites' tribological and mechanical characteristics. The mechanical properties and wear behavior of AL6061-4%Mg-Fly ash (10%, 15%, and 20%) and AL6061-4%Mg-4%Graphite-Fly ash (10%, 15%, and 20%) composites with a hybrid metal matrix were investigated. Tensile strength was seen to rise with the addition of fly ash, although the use of graphite reduced tensile strength and hardness. The composite with 4% Mg and 15% fly ash exhibited the highest tensile strength, whereas the composite with 4% Mg and 20% fly ash showed the highest hardness.

8. Reinforcement materials for the synthesis of Mg-MMCs, aluminum oxide (Al_2O_3) reinforcement with Mg metal matrix

In their comprehensive literature review, Victor et al. [38] examined the behavior of the constant stress tensile creep of ALO-reinforced AZ91 magnesium-based composite, highlighting the significant improvement in creep resistance compared to the matrix alloy. They attributed this enhancement to efficient load transfer between matrix plastic flow and fibers, with TEM studies revealing better fiber-matrix interface bonding during creep exposure. Jayalakshmi et al. [39] delved into the tensile behavior of AM100 magnesium composites and alloys at various temperatures, emphasizing the influence of precipitates on the alloy’s inherent brittleness. Bakkar and Neubert [40] explored the corrosion behavior of Al,

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O, fiber-strengthened magnesium AS41 composite in watery mixtures with varying NaCl contents and pH values, noting a reduction in corrosion resistance when galvanic corrosion is absent but chloride concentrations are higher between fibers and matrix. Cay et al. [41] focused on porous alumina-reinforced magnesium composites, revealing an average pore diameter rise in response to rising porosities and demonstrating greater yield strength and reduced density than cast dense magnesium. Lu et al. [42] investigated the friction and wear behavior of nano-alumina and CNTs reinforced magnesium matrix composites, finding higher wear resistance in comparison to FSP AZ31 alloy and significantly lower wear in hybrid composites (0.1%A, O +0.2%CNTs)/AZ31 at higher loads. Srinivasan et al. [43] explored the feasibility of joining alumina reinforced AZ318 magnesium nanocomposites via solid-state welding, observing increased joint efficiency with friction and forging pressure but decreased efficiency with friction time. Bhingole et al. [44] synthesized AZ91 alloy matrix composites, including in situ reactive hard MgO production and Al, O, particles, leading to improved ultimate strength, hardness, and strain hardening exponent, along with enhanced sliding wear resistance because of stronger surfaces and evenly distributed hard oxide particles. Lastly, Nguyen et al. [45] investigated the wear behavior of A231B/nano-ALO composite, mg alloy AZ318, and its nano-composites, revealing a gradual reduction in wear rate over a range of sliding speeds for both normal loads, though at low speeds, the when compared to the alloy, the composite showed higher wear rates. Huang and Lin [46] developed AM60/Al2O3 reinforced Mg-MMCs to enhance mechanical characteristics via Equal Channel Angular Extrusion (ECAE). Additionally, they employed the stir-casting technique to produce lightweight composites with 1 wt%, 2 wt%, and 5 wt% nano-sized Al2O3 particulates for subsequent ECAE application. Thirugnanasambandham et al. [47] proposed Mg-MMCs reinforced with 50 nm-sized Al_2O_3 using the stir-casting method to investigate wear properties, testing under 10 N and 20 N loads at various sliding speeds. Song-Jeng Huang et al. [48] examined AM60/Al2O3 MMCs using ECAE and further explored AM60's reinforcement with 1 wt% Al_2O3 particles via stir casting for ECAE. Tarasankar et al. [49] studied AZ91E alloy reinforced with Al_2O_3 to optimize wear attributes of MMCs, analyzing with 1 wt% reinforcement, a 10 N applied load, and 500 meters of sliding distance. Niranjan et al. [50] investigated AZ91-MMCs reinforced with different proportions of weight Al2O3 for surface integrity. Sameer Kumar et al. [51] fabricated nanocomposites of AZ91E with Al2O3 to enhance wear resistance, ductility, and hardness using the stir-casting approach. Amandeep Singh and Niraj Bala [52] introduced Mg-Al2O3 MMCs for synthesizing and evaluating wear and hardness performance with different weight percentages.

9. SiC reinforced Mg-MMCs

Huang, Song Jeng et al. [53] investigated the fabrication of SiCp/AZ61 reinforced Mg-MMCs using the stir casting technique. They enhanced the micro-plastic distortion of the material through a heat treatment process. According to their research, incorporating five weight percent of SiCp into the AZ61 Mg-MMC significantly reduced ductility and shear strength. S. Seshan et al. [54] studied the fracture behavior and tensile strength of discontinuously SiC-reinforced AZ91 and Mg-6Al alloys. They used SiC particles with a size of 20 microns in their experiments. Janusz Lelito et al. [55] proposed a method to embed SiC strengthened materials into the grain of AZ91 alloy MMC's structure. They performed simulations to analyze the effects of cooling rates, the grain thickness of the AZ91/SiC matrix, SiC particle diameter, and mass fraction on the qualities of the material. Lim et al. [56] focused on the wear efficiency of AZ91 Mg-MMCs reinforced with SiC particles. Their research revealed insights regarding how SiC reinforcement improves wear resistance. Juanyuan et al. [57] fabricated Mg-MMCs reinforced with 5 wt% WS2 and 15 to 20 wt% SiC using the powder metallurgy (PM) technique. They aimed to enhance the wear and friction characteristics of the composites, achieving improvements in these areas. S. Dinesh Kumar et al. [58] also employed the PM technique to develop Mg-MMCs reinforced with SiC. Their research highlighted improvements in the mechanical characteristics of the resulting composites. Enrique et al. [59] introduced a co-continuous ceramic reinforced MMC, which combined metallic and ceramic components. They used a solid-state method to create the reinforcement and enhance the material’s properties. Jianghoa Shen et al. [60] studied the reinforcement of Mg-MMCs with 5 to 15 wt% SiC nanoparticles, referring to these as MM Nano Composites (MMNC). They found that incorporating 10% SiC nanoparticles significantly enhanced the composites' ultimate yield and tensile strength. Paridhi Malhotra et al. [61] fabricated a hybrid MMC by combining 7075 aluminum with 10 wt% SiC and Mg alloy nanoparticles. This composite, Al 7075/10%-SiC/Mg, was evaluated based on its performance. The electrode wear rate (EWR) and material removal rate (MRR) are specifically measured during EDM rotary working. Kavimani et al. [62] developed hybrid composites by incorporating different weight percentages of SiC and reduced Graphene Oxide (r-GO) into AZ31 Mg alloy. They tested the performance of these composites under various sliding distances, velocities, and loads. R. Arrabal et al. [63] investigated the effects of plasma electrolytic oxidation on Z071 alloy reinforced with 12% SiCp. They achieved a hardness of 3.4 GPa after a processing time of 100 minutes, indicating enhanced specific toughness and low density. Karthick et al. [64] proposed a hybrid AZ31 Mg-MMC reinforced with both SiC and Al_2O_3. Their results showed a significant improvement in hardness, reaching up to 75.16 HV. Various studies have investigated the effects of SiC particles on the mechanical characteristics and microstructure of magnesium matrix composites. One study explored how particle size affects these properties in SiCp/AA291 magnesium composites. A 2% volume proportion of submicron SiCp particles was discovered to refine grains and enhance strengthening significantly. However, increasing 5% and 10% of the volume fraction led to reduced mechanical properties due to particle agglomeration. Despite this, the overall strengthening effect improved with higher volume fractions [65]. Nie et al. [66] studied the composition and characteristics of magnesium composites strengthened with tiny SiC particles. They noted that adding micro-SiC particles decreased the matrix's grain size. Mg and Al phases changed from coarse plates to lamellar precipitates at 3 vol.% SiCp/A291, suggesting strong interfacial bonding. Moreover, tensile and yield strength improved, while elongation remained constant. Shen et al. [67] examined the impact of bimodal SiC particles on the mechanical characteristics and microstructure of AZ318 magnesium composites post-hot extrusion. The research showed that bimodal SiC particles significantly improved tensile and yield strength relative to the monolithic AZ318 alloy and single-size SiCp reinforced composites. Wang et al. [68] explored a novel casting method strengthened magnesium composites with micro-SiC particle reinforcement with the aid of ultrasonic treatment. Ultrasonic treatment enhanced mechanical properties, refined grain size, and significantly improved elastic modulus, yield strength, and tensile strength with increasing particle content. Wang Zhao-hui et al. [69] used ultrasonic methods to fabricate SiC nanoparticle-reinforced magnesium composites, which achieved uniform dispersion and efficient grain refinement, leading to improved mechanical properties. SiC nanoparticles also acted as heterogeneous nucleation sites for Mg grains. Hu Lianxi and Wang Erde [70] used a modified two-step squeeze casting method to fabricate SiC whisker (SiCw)/ZK51A composites with magnesium matrix. This method significantly raised the mechanical strength and modulus without interfacial reactions, proving SiC whiskers to be stable reinforcements. Shen et al. [71] also studied bimodal-sized SiC particulates (micro and nano) in magnesium composites with different micro-particle volume fractions. Post-hot extrusion, the bimodal SiCp distribution and mechanical attributes greatly improved. The tensile and yield strength of A2318/SiC composites were stronger at 1 vol.% compared to other compositions, though elongation to fracture decreased. Chen et al. [72] studied the microstructure of composites made of magnesium reinforced with submicron SiC particles, deformed at room temperature. The TEM analysis showed submicron SiC particles promoted dislocation multiplication, increased dislocation density with tensile strain, and enhanced composite strength. Single submicron SiC particles and the matrix bonded nicely. alloy after tensile testing. Garcés et al. [73] used synchrotron radiation to examine the impact of ceramic particles on the twinning mechanism in magnesium composites. They found that as the volume percent of reinforcement increased, the twins' volume fraction immediately saturated. Zhou et al. [74] researched the effects of various SiCp volume ratios on the mechanical characteristics and microstructure of AZ91 magnesium composites. Submicron SiCp was more successful in refining the grain compared to micron SiCp. Higher volume ratios improved yield strength but weakened interface bonding, increasing the number of dimples. Wang et al. [75] examined the impact of SiC particles situated on the micro-arc oxidation process of magnesium composites. They found that SiC particles damaged the integrity and electrical insulation of the MAO coating, decreasing its growth efficiency and corrosion resistance. Xue et al. [76] used the MAO technique to create corrosion-resistant ceramic coatings on SiCp/AZ31 composites. The coatings significantly improved corrosion resistance, which depended on the coating thickness. Tiwari et al. [77] researched the corrosion behavior of SiC reinforced Mg-matrix composites, finding that the corrosion resistance dropped as the volume percentage of SiC increased. Higher corrosion rates were associated with the surface film's fault, though galvanic corrosion had little impact. Arrabal et al. [78] researched the corrosion behavior of electrolytic oxidation of silicate plasma coatings on magnesium composites. They found that corrosion initiated around Al-Mn inclusions and developed into general corrosion. The resistance to corrosion and hardness increased with higher reinforcement proportions. Pitting and outer layer hydration were the main corrosion mechanisms in PEO-treated specimens.

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10. TiC reinforced Mg-MMC

Narayanasamy et al. [79] investigated TiC-reinforced Mg-MMCs manufactured via the P/M process with varying TiC content (0-20 wt.%). Microstructural analysis revealed inhomogeneous and agglomerated TiC particles on Mg-20TiC surfaces above 15% TiC content. Hardness increased with TiC content up to 15%, but only slightly improved from 15% to 20%, with negligible impact on wear. Mg composites with TiC showed improved microhardness, reduced wear, and higher friction coefficients than pure Mg. In the study by Gu et al. [80], TiC reinforced MMCs were fabricated using a Transient Liquid Phase (TLP) approach, incorporating an aluminum interlayer. By manipulating temperature and time, specifically at a connection temperature of 460°C, the aluminum concentration in the junction decreased over time, resulting in variations in the microstructure properties due to the presence of Al12Mg17 and TiC. Consequently, the quantity of Al12Mg17 showed a decreasing trend. Saranu et al. [81] further explored the creation of AZ91D Mg nanocomposites reinforced with TiC under various weight percentages using the Powder Metallurgy (PM) technique, with a particle size of 40 µm. Additionally, Dash et al. [82] investigated AZ91D Mg-MMCs strengthened with TiC for mechanical and tribological performance assessment.

11. FeO, reinforced hybrid Mg-MMC

Rodriguez et al. explored the addition of nano-alumina or nano-iron oxide, up to 5% by weight, to a Magnesia matrix. They investigated crystalline phases and microstructure properties through scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis of specimens sintered at 1600 °C for 4 hours. Physical properties were described by density and porosity, as mechanical characteristics were evaluated using a cold crushing strength (CCS) test. They also examined the chemical activity of slag attacks. Nano-iron oxide facilitated the formation of magnesioferrite spinel, enhancing sintering and improving bonding structure. In contrast, nano-alumina led to magnesium-aluminate spinel formation, resulting in inferior properties compared to nano-iron oxide addition [83].

12. Graphite particulate reinforced Mg-MMC

According to Aatthisugan et al. [84], they utilized graphite particles (with a particle size of 50 µm and reinforcement levels ranging from 5% to 20%) in Mg matrix composites, fabricated via stir casting methods. They employed a dynamic mechanical analyzer to assess the damping capacities of these composites. Results indicate a notable influence of graphite particles on damping capacities, with an initial increase in strain observed up to 15 volume % graphite reinforcement, followed by a decrease beyond this threshold.

13. Nano-sized alumina particulates reinforced Mg-MMCs

The mechanical characteristics of (Mg)-based metal-matrix composites (MMCs) reinforced with 1.11 vol.% of nano-sized alumina particles are reported to be superior to those of composites with higher levels of micron-sized reinforcements, according to Lim et al. [85]. These composites especially show better ductility than pure magnesium. According to earlier research, smaller particle sizes preserve the advantages of greater hardness and strength during sliding wear tests by reducing delamination wear. In this study, pin-on-disc dry sliding tests against hardened tool steel at sliding speeds ranging from 1 to 10 m/s under a constant load of 10 N are used to examine the wear properties of magnesium composites with variable nano-sized alumina content (up to 1.11 vol.%). The outcomes demonstrate that increased reinforcement improves wear resistance, particularly at higher speeds. FESEM analysis identifies abrasion, adhesion, and thermal softening as the primary wear mechanisms, with no evidence of delamination, a common issue in MMCs with micron-sized reinforcements.

14. CNT reinforced Mg MMC

In recent studies, authors explore [86] that the incorporation of carbon nanotubes (CNTs) into magnesium (Mg) matrices has shown significant potential to improve the physical and mechanical characteristics of lightweight, high-performance nanocomposites. However, the equitable distribution of CNTs within the Mg matrix remains challenging and depends on fabrication process parameters. Key factors influencing the properties of CNT-reinforced Mg composites include the weight percent and length of CNTs, uniform distribution, and the quality of interfacial bonding and alignment between the magnesium matrix and the CNTs. This analysis looks at current developments in the fabrication methods, properties characterization, and applications of Mg-based composites reinforced with CNTs. It addresses these composites' mechanical responses and corrosion behaviors, evaluates various strategies to overcome fabrication challenges, and explores their potential applications in aerospace, medical, and automotive industries as future structural materials. In their study, Turan et al. [87] introduced Multi-Walled Carbon Nanotubes (MWCNT) reinforcement and a hybrid compound of MWCNT-based Graphene nanoplatelets (GNPs) to enhance the AZ91 Mg alloy's wear behavior. They produced composites using a semi-powder metallurgy method. Muhammad Rashad et al. [88] proposed a hybrid model, CNTs GNPs, to address limitations of solo GNPs reinforcement. Yunpeng Ding et al. [89] presented a novel CNT-strengthened Mg nanocomposite using a PM method, achieving a Yield Strength (YS) of 454 MPa and compression strength of 504 MPa. In the study by Li et al. [90], examining the tribological behavior of a magnesium alloy, bulk carbon nanotube (CNT) reinforced magnesium matrix composites were the primary goal of the investigation. Reduced solidification rates resulted in clustering at grain boundaries, which was shown to have impacted the distribution of CNTs within the composites. Compared to the matrix alloy, the ultimate tensile strength (UTS) and yield strength (YS) were significantly increased at greater solidification rates due to the strong interfacial bonding produced. The Kelly-Tyson formula agreed with experimental tensile values, and it was also discovered that the mechanical qualities improved at greater solidification rates. Xiaomin Yuan et al. [91] studied the microstructural characterization of multi-walled carbon nanotubes (MWCNTs) reinforced magnesium alloy composites fabricated via powder compact laser sintering. Their findings revealed thorough sintering of the composites with fully dense and uniform microstructures, resulting in high microhardness and grain refinement compared to monolithic AZ91D. Incorporating MWCNTs enhances laser absorption, increasing temperature and cooling rates, thus improving the toughness of the composites. Mui Hoon Nai et al. [92] explored the enhancement of interfacial characteristics when carbon nanotubes are coated with a metallic layer of nanoscale thickness. Carbon nanotubes are reinforced in magnesium composites. The study demonstrated that a nickel coating on the CNTs improved adhesion between Mg/Ni-CNT particulates. This resulted in grain size refinement and improved dispersion of the reinforcements in the Mg matrix. This led to simultaneous enhancements in microhardness, ultimate tensile strength, and yield strength of the Mg/Ni-CNT composites. Jianguo Li et al. [93] investigated the effect of hybrid reinforcements (Mg, B, O,w, and B, Cp) on magnesium matrix composites, revealing a remarkable enhancement in flexural properties compared to singular composites. Most of the Mg B, Ow, and B, Cp fractured within the matrix, indicating strong interfacial adhesion between the matrix and reinforcements. A novel technique for processing BC particulate-reinforced magnesium matrix composites was put forth by Yantao Yao and Liqing Chen [94], emphasizing enhancing the wettability between the metal melt and the ceramic preform. The successful manufacturing of boron carbide particulate-reinforced magnesium matrix composites was accomplished by adding a tiny quantity of metal powder with a higher melting point to the ceramic preform. This increased the liquid-solid interfacial tension and improved infiltration.

15. Mg-MMCs reinforced using B_4C

The study examines powder metallurgy-produced magnesium matrix composites reinforced with B4C particles (P/M) methods, with 10%, 13%, and 20% fractions. It delves into the precipitation behavior within these composites, highlighting how the presence of B4C promotes the nucleation of Mg17A112 where the interface meets the reinforcement and the matrix, thus enhancing heterogeneous precipitation. The incorporation of B4C particulates significantly elevates the hardness of the composites. Notably, the composite's wear rate with 20% B4C reinforcement is lower than that of the 10% B4C composite. Utilizing the P/M process, the researchers successfully fabricated magnesium matrix composites with 10%, 15%, and 20% B4C reinforcement, resulting in improved hardness and resistance to wear [95]. Jianguo Li et al. [96] researched the effect of Mg2B2O5 whiskers and B4C particulates as hybrid reinforcements on MMCs. Their study demonstrated a remarkable enhancement in the flexural characteristics of the composites after adding these reinforcements. Specifically, the flexural properties of the composite materials upon addition are 29% higher than those of the singular composite, attributed to an increased dislocation density in the hybrid composite's matrix. The fracture behavior analysis revealed that most of the Mg2B2O5 whiskers and B4C particulates fractured within the matrix, indicating comparatively high interfacial bonding strength between the reinforcements and matrix. In a related study, Yantao Yao and Liqing Chen [97] proposed a new procedure for producing magnesium matrix composites enhanced with B4C particles. Their strategy concentrated on enhancing the metal melt's wettability with the ceramic preform throughout the metal melt infiltration composite's construction phase. They could lower the liquid-solid interfacial tension and the surface tension of the magnesium melt by lightly incorporating a small amount of metal powder with a higher melting temperature into the ceramic preform. Introducing Ti powder, which is immiscible with the magnesium melt, into the B4C preform as an infiltration inducer successfully assisted the manufacturing of boron carbide particulate-reinforced magnesium matrix composites. Aydinet et al. [98] researched AZ91 Mg-MMCs reinforced with B4C using different weight fractions, ranging from 10 to 30 wt%, utilizing the powder metallurgy (PM) technique. Their research focused on the wear behavior of these composites under various load conditions. The results showed that including B4C significantly improved the material properties, increasing hardness, yield strength (YS), and UTS.

16. Fiber-reinforced Mg MMC

Feng Wu et al. [99] researched combining graphene and carbon fiber materials to reinforce Mg-MMCs. Their research highlighted the significant presence of Mg17Al12 particles intermittently dispersed along the border sheet. This investigation into the microstructural effects and reinforcement mechanisms provided insights into the potential enhancements due to the hybrid reinforcement approach in mechanical properties. In their study, Xuezhi Zhang et al. [100] investigated the tensile behavior of metal matrix composites (MMCs) based on magnesium AM60 and reinforced with alumina (Al2O3) fibers at 90 MPa of pressure. They evaluated the tensile characteristics of AM60 alloy without reinforcement, Al2O3 fiber-reinforced AM60 alloy, and hybrid composites. The results indicated a significant improvement in tensile properties with the inclusion of fibers, although this enhancement came at the expense of reduced ductility compared to the unreinforced alloy. The study also identified consistent patterns of localized damage, such as fiber fracturing of the matrix, damage and cracking, and interface debonding, which correlated with the observed tensile properties.

17. Conclusion

In this study, the various reinforcement materials, as well as the tribological and mechanical performance of MMCs, were examined. To improve the engineering applications of Mg alloys, different MMCs were developed using various fabrication methods, dimensions, configurations, and reinforcement elements. The choice of reinforcement materials and methods significantly affects the microstructure and mechanical performance of MMCs. Though offering attractive mechanical properties, graphene nanoplatelet (GNP) reinforcement has limitations in transferring these properties effectively, reducing its overall impact. Al_2O_3 and SiC reinforced Mg alloys exhibit superior fiber-matrix relationships compared to carbon nanotubes (CNTs), resulting in higher tensile strength, lower thermal expansion, and increased hardness. CNT-reinforced MMCs, however, provide high tensile strength and low mass density due to reduced friction coefficients, making them lighter than Al_2O_3-based MMCs. SiC reduces corrosion resistance, but other reinforcements enhance it. Additionally, organic materials like fly ash enhance hybrid composites' tribological and mechanical characteristics. Mg-MMCs are highlighted for their flexibility, reliability, cost-effectiveness, eco-friendliness, and biodegradability, with standard fabrication methods including stir casting, friction stir processing, and powder metallurgy.

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