Magnesium Matrix Composites for Aircraft and Automobile Application - A Review

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***Abstract*—A number of international leading initiatives and extra-large businesses have begun investing in the design, research, development, and engineering of magnesium alloys after realizing their significance. As one of the lightest structural metals on the market today, magnesium's stiffness, specific strength, damping behavior, and creep resistance are all significantly impacted by the addition of reinforcing components to the metal matrix. As a result, magnesium has drawn more study interest and is still a popular subject in the automotive, aerospace, and biomedical sectors. This situation has led to the creation of magnesium composites with the goal of achieving better physical and mechanical qualities. This work discusses a number of relevant subjects while summarizing the impacts of different reinforcements in magnesium MMCs. The effects of various reinforcements in magnesium MMCs are highlighted in this article, along with an analysis of their benefits and drawbacks. For researchers working on magnesium-based MMCs, this review could be a thorough technical reference.**

***Index Terms*—magnesium,MMCs, reinforcements,magnesium matrix composite,Mg composite mechanical Properties**

I. Introduction

The need for lighter accessories is growing rapidly in the automotive and aerospace industries. The primary benefit of magnesium essence matrix mixes over aluminum essence matrix mixes is that they offer a new 15–20% weight reduction without sacrificing quality. Compared to traditional accessories, essence matrix mixes supported by boron carbide and molybdenum disulphide offer a substantial benefit. These mounts are used to improve essence matrix mixes tensile strength and hardness. These days, there is a very high demand for accessories that are stronger, more resilient to wear and tear, lighter, and more durable. Certain mixtures are very strong, but because they are heavier, they are more likely to fail due to crack propagation. Given this, extensive research into Metal Matrix Composites(MMC) essence matrix mixtures has been conducted over the past few decades. Certain mixes are lighter than other essences and their blends, much as Mg-MMCs and Al-MMCs. They consequently discover a thriving industry in fields like automobiles and airplanes. Magnesium mixtures have a remarkably high specific strength in contrast to other reliable engineering mixes. Magnesium mixtures also maintain superior machinability, commendable castability, and outstanding damping capacity. According to additional research in this area, magnesium-based MMCs are utilized in defense systems such as dumdums (expanding bullets) and their components and are around 17–22 percent lighter than aluminum mixtures. Crucial components of magnesium's operation include stiffness, creep resistance, energy immersion, etc. Wheel designs, frames, steering buses, and other components all use magnesium and its mixtures. [1]

II. Types of Reinforcement for Magnesium MMC

Reinforcements are essential for evaluating the mechanical properties of Mg-MMC. The categories of reinforcement are equivalent in determining the mechanical properties of the composites. The presence of reinforcing elements is crucial in lowering the porosity of composite materials. The subsequent discussion pertains to the various reinforcements. [2]

A. Carbonaceous Reinforcement

*1) **Carbon Nanotubes (CNTs)**:* Carbon nanotubes represent a carbon allotrope characterized by one nanometer or less in diameter [3] [4]. Carbon nanotubes generally exhibit either a single wall or multiple walls . The magnesium matrix composite has extensively employed multi-walled structures. Carbon nanotubes (CNTs) function as reinforcement materials. It maintains a low density while enhancing overall mechanical properties. Goh et al. made Mg/MWCNT samples using powder metallurgy and fractions of 0.06, 0.18 and 0.3 wt% [4]. Composites exhibited increased porosity with an elevated concentration of CNT, while their density remained essentially unchanged. Looking at the coefficient of thermal expansion results, we can see that Mg/CNT is more thermally stable than pure Mg. The composite hardness remained stable, while the ultimate tensile strength showed a slight increase [3] [5].

The relationship between Mg and CNTs is predominantly mechanical; however, the microstructure demonstrates substantial adhesion between the two materials. The even distribution of carbon nanotubes (CNTs) in magnesium (Mg) makes it hard to use CNTs with high aspect ratios as reinforcement, especially when the CNT weight percentage is high. Carbon nanotubes, because of their significant length, which may extend to tens of micrometers, will eventually aggregate due to entanglement. Because these clusters are there, the magnesium particles and carbon nanotubes won't be able to bond well before the tensile test, which could cause small cracks in the magnesium. The fissures serve as a persistent source of plastic instability, leading to material failure marked by diminished ductility. [4]The clustering of CNTs may lead to an increase in the porosity of the Mg matrix. The results of the work of the fracture (WOF) test demonstrate that nanocomposites exhibit specific properties [3]. Adding up to 0.18 wt% CNTs makes the material more resistant to breaking than pure Mg which is solid. The phenomenon is attributed to the improved ductility and yield strength of nanocomposites. The WOF decreases as the CNT count increases, likely due to enhanced clustering effects, which ultimately result in increased porosity. In a different study, MMCs were made with AZ91D alloy composites that were reinforced with MWCNTs in weights of 0.5, 1, 3, and 5. The findings demonstrated that incorporating 1 wt% CNT into the AZ91D alloy enhanced its tensile strength. Small carbon nanotubes, about 5 nm long, are thought to have a uniform effect on the near surface of magnesium alloy powders when they are mixed in three different directions [4]. Elevated CNT concentrations enhance porosity and galvanic corrosion owing to their cathodic properties. Uniform dispersion of carbon nanotubes is crucial, as aggregation compromises the material's integrity [4] [6]. These findings underscore the necessity for meticulous regulation of CNT content and distribution to enhance the characteristics of magnesium-based composites for engineering applications. [6]

*2) **Graphene Reinforcements**:* By the application of directional freeze-drying and magnesium oxide coating, graphene was uniformly integrated into the magnesium matrix, this enhanced the mechanical prop erties such as hardness, elastic modulus, and compressive strength [7]. The liquid-solid pressure infiltration technique im proved wettability and dispersion by a huge margin, resulting in superior and better material performance [7]. The results obtained from mul tiple research activities conducted indicate that this is the method that offers a cost-efficient and effective means of creating high strength metal matrix composites, presenting considerable potential for structural and lightweight applications in the aerospace and automotive industries [7].The enhancement of magnesium by making use of graphene nanoplatelets (GNPs) to create biodegradable implants with much better mechanical properties and corrosion resistance. The incorporation of GNPs increased the compressive strength, ductility, and corrosion resistance, by a huge scale at the same time preserving biocompatibility. The findings from the research conducted shows that GNPs diminished galvanic corrosion and enhanced the structural integrity of the composites, rendering them suitable for load-bearing biomedical applications. Since the application is related to biomedical the aspect of biocompatibility becomes very important. The cytotoxicity assays validated the material's safety for biological applications. The results underscore the promise of Mg-GNP composites as advanced biomaterials for orthopedic and cardiovascular implants, tackling issues related to stress shielding and biodegradation [8]. The influence of temperature on the mechanical properties of graphene-reinforced magnesium composites through molecular dynamics simulations is another important domain [9]. The findings from multiple research articles point towards the fact that graphene reinforcements greatly improve the strength and Young's modulus of magnesium, but at the same time this affects phase transitions during compressive stress. Graphene to a very good extent obstructs dislocation migration, hence increasing the composite's resistance to deformation [8]. Even though this is a good thing in the case of elevated temperatures the material's modulus and strength are greatly decreased as a result of thermal softening. Proper optimization of Gr/Mg composites for high-temperature applications, illustrating graphene's potential to enhance the mechanical stability and durability of lightweight structural materials. [9]

B. *Ceramic Reinforcements*

*1) **Silicon Carbide (SiC)**:* The thermal degradation of silicone-based composites which are reinforced with carbon fibers and silicon carbide powder which play very important roles in aerospace thermal protection systems. Research that is mostly experimental demonstrated that an increase in silicon carbide enhances thermal insulation, but at the same time the CF concentration influences mechanical strength but diminishes thermal efficiency [10]. These findings highlight the fact that both are needed in the appropriate amount with respect to the applications. Numerical simulations have provided the information that the composites used for the experiments functioned as thermal barriers, with the CF-reduced composite (M2) exhibiting very high heat resistance [10]. The findings show the necessity of balancing thermal insulation with mechanical performance in aeronautical applications [10] The findings from a particular study demonstrate that SiC particles are evenly dispersed, improving mechanical characteristics without negative interactions between the matrix and reinforcement. The yield strength and hardness exhibited substantial enhancement, with AZ91 composites demonstrating a 70 percent increase in hardness. This can also be applied to and used in the idea of using Sic as a reinfrocement for magnesium matrix The benefits of magnesium injection molding in attaining uniform particle distribution and enhancing mechanical characteristics for lightweight structural applications are very high and it finds a large amount of applications [11].The influence of various SiC reinforcement dimensions (nanowires, nanoparticles, and submicron particles) on the microstructure and strength of Mg-Zn-Y composites highlights the significant benefits of employing SiC reinforcements. The findings indicate that SiC nanowires exhibit superior mechanical performance attributable to efficient grain refinement and dislocation strengthening. The research indicates that dynamic recrystallization is influenced by SiC size, with nanowires enhancing grain boundary contacts and facilitating increased yield strength and tensile strength [12].

*2) **Boron Carbide (B_4C)**:* Boron carbide shows notable thermal stability, low density, high hardness, and very high abrasion resistance [13]. It has not been widely utilized as a reinforcement element in magnesium matrix composites. The B_4C-reinforced magnesium matrix composite was analyzed. 10, 20, and 30 percent B_4C reinforcement was incorporated using the powder metallurgy method. The composite's porosity showed considerable variation, while its density remained unchanged [14]. The microhardness of magnesium reinforced with boron carbide exceeded that of unreinforced magnesium, with the Mg + 30 percent B_4C sample exhibiting the highest hardness level. The unconfined compressive strength (UCS) of reinforced composites is inferior to that of pure magnesium . An increase in reinforcement content led to enhanced wear resistance. Grain boundaries are clearly identifiable in pure magnesium [13]. Magnesium matrix composites are reinforced with varying weight percentages ofB_4C(3, 6, and 9%) through the powder metallurgy method. The composites underwent sintering in a vacuum furnace at 590°C for 9 hours X-ray diffraction analysis revealed the presence of Al_2O_3, MgO, and MgB_2 phases in the composites. The sintered density decreased significantly with increasing B_4C content; however, the hardness values increased when unreinforced magnesium was analyzed [14]. The compressive strength demonstrated significant improvement at a 3 wt percent concentration. Concentration of B_4C reinforcement. This supports the benefits of choosing Boron Carbide as reinforcements [13] .

*3) **Aluminum oxide**:* Aluminium oxide (Al_2O_3) is a great reinforcement in magnesium metal matrix composites (Mg-MMCs). With this reinforcement the the mechanical and microstructural characters are improved by a huge margin [15]. Al_2O_3 particles improves the tensile strength and hardness at the same time decreasing weight by a decent margin [15] [16]. Al_2O_3 when used as a reinforcement improves wear resistance, which is suitable for high-durability applications [17] [18]. Microstructural analysis by the usage of Scanning Electron Microscopy (SEM) shows a homogeneous distribution of Al_2O_3 particles inside the magnesium matrix, enhancing mechanical characteristics and reducing porosity, as a result of this it improves bonding and structural integrity [17]. Stir casting is a prevalent and economical production technique for Mg-MMCs incorporating Al_2O_3, wherein variables like as stirring velocity, temperature, and particle preheating affect the ultimate characteristics [18]. Advanced methodologies such as Equal Channel Angular Processing (ECAP) enhance grain structure and optimize reinforcement distribution [18] [19]. Mg-MMCs reinforced with Al_2O_3 are widely utilized in the automotive and aerospace sectors due to their superior strength-to-weight ratio, which is crucial for lightweight and robust materials [19].

*4) **Titanium Carbide**:* Titanium carbide (TiC) is a prevalent reinforcement in magnesium metal matrix composites (Mg-MMCs), recognized for its capacity to improve mechanical strength and wear resistance [20]. TiC-reinforced Mg-MMCs demonstrate enhanced compressive and tensile strength, especially at elevated temperatures, attributable to grain refinement and robust interfacial bonding [21]. TiC enhances microhardness but it may also induce brittleness, which would need meticulous adjustment of particle size and content to obtain a compromise between strength and ductility [21] [22]. The homogenization procedure is essential for achieving homogeneous distribution of TiC, hence enhancing mechanical performance. Examination which is microstructural shows the presence of uniformly distributed TiC particles, creating networks which are penetrating between eachother that affect the overall strength [23]. These composites are heavily used in the automotive and aerospace sectors due to their superior strength-to-weight ratio and damping characteristics [24] [23]. TiC reinforcement enhances wear resistance, mkaing Mg-MMCs suitable for high-durability applications. Issues like as brittle fracture and the impact of processing parameters, including temperature and strain rate, highlite the meticulous attention to enhance performance [24].

III. Applications

A. Aerospace

The low density and excellent strength-to-weight ratio of Magnesium MMC provide remarkable weight reduction in aeronautical components, which improves fuel efficiency and overall performance [25]. These composites demonstrate enhanced mechanical properties, including elevated tensile and compressive strength, along with better hardness, with reinforcements such as silicon carbide , aluminum oxide , and titanium carbide further augmenting their performance. Mg-MMCs provide superior wear and corrosion resistance, guaranteeing longer life in challenging aerospace conditions [26]. Their very low value of coefficient of thermal expansion ensures thermal stability, structural integrity amid high temperature fluctuations is maintained [21]. The most popular reinforcements that are used are ceramic particles such as silicon carbide , aluminum oxide , and boron carbide , in addition to sophisticated nanoparticles such graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and titanium nanoparticles, which augment strength and toughness [25] [26] [21]. Obstacles persist in attaining consistent reinforcing distribution and enhancing corrosion resistance, necessitating continued investigation into refined production methods. Mg-MMCs are extensively utilized in structural aerospace components owing to their robustness, while their thermal stability and wear resistance render them appropriate for high-stress engine components [21]. These achievements establish Mg-MMCs as an essential material for future aerospace developments [27].

B. Automotive

Magnesium alloys have excellent mechanical characteristics and density, making them advantageous for composite material applications [21]. We combine silicon carbide with magnesium to create novel materials through squeeze-casting and stir-casting techniques [21]. A composite material composed of magnesium alloy may utilize platelets and ceramic particles as reinforcement materials.Magnesium metal matrix composites (Mg-MMCs) are progressively employed in the automotive sector owing to their lightweight characteristics and enhanced mechanical properties [28] [29]. Their reduced density markedly decreases vehicle weight, enhancing fuel efficiency and decreasing pollutants. Mg-MMCs demonstrate elevated strength-to-weight ratios, superior tensile and compressive strength, and increased hardness, rendering them suitable for diverse automotive components [29]. Wear and corrosion resistance relative to pure magnesium is much better, guaranteeing prolonged lifetime this is provided by the mmc [27]. The low value of coefficient of thermal expansion contributes to the preservation of dimensional stability over fluctuating heat conditions. Typical reinforcements consist of ceramic particles like silicon carbide, aluminium oxide, and boron carbide, which improve mechanical and tribological characteristics [30]. Carbon-based materials such as carbon nanotubes and graphene nano platelets (GNPs) enhance strength and ductility, whereas hybrid reinforcements amalgamate fibers and particles for enhanced performance [31]. Mg-MMCs are extensively utilised in engine components such as pistons and cylinders for their superior thermal stability, in structural elements for weight reduction, and in brake systems where their wear resistance improves performance [30].

IV. CHALLENGES IN USING MAGNESIUM MMCS

Magnesium metal matrix composites (Mg-MMCs) present several challenges due to the inherent properties of magnesium and its interactions with reinforcing materials. One big problem is oxidation and flammability. Magnesium is very reactive and quickly oxidizes at high temperatures. It can also catch fire in the air, which is very dangerous during processing [32]. Another important problem is distributing reinforcements evenly. It's hard to get reinforcement particles like ceramics or fibers to spread out evenly because their density and surface energy are not all the same. This causes them to stick together and have uneven properties [21]. Additionally, interfacial reactions between magnesium and reinforcement materials can result in the formation of brittle intermetallic phases, weakening the composite, while poor bonding at the interface further affects mechanical performance. Porosity is another concern, as gas entrapment during casting or compaction can lead to pores that reduce the material's density and strength, necessitating precise control of processing parameters to enhance quality. Furthermore, machining difficulties arise due to the low ductility of Mg-MMCs, which makes them susceptible to cracking and chipping, while the presence of hard reinforcements increases tool wear and manufacturing costs. Lastly, thermal expansion mismatch between magnesium and the reinforcement materials can introduce residual stresses, leading to warping or cracking during thermal cycling [32]. To solve these problems, we need to carefully choose the materials, use advanced processing methods, and make sure that the manufacturing parameters are just right so that Mg-MMCs work better and last longer.

V. MANUFACTURING TECHNIQUES

A. Liquid Metallurgy

1) ***Stir casting****:* Stir casting is one of the most widely used manufacturing techniques for the fabrication of magnesium metal matrix. This process involves the mixing and stirring of molten magnesium with reinforcements which are usually particles. It is mostly used due to its simplicity, cost-effectiveness and its ability to be used for mass production. [33], [34]

The most common reinforcement particles include silicon carbide (SiC), alumina (Al_2O_3), titanium carbide (TiC), and various nanoparticles. [33] With the help of this process, uniform distribution of reinforcement particles can be achieved, which leads to refined grain structures and improved mechanical properties. The main challenge attributed to this process is the agglomeration of particles; to combat this new techniques such as ultrasonic stir casting is developed. In this process ultrasonic vibrations are used for the dispersion of material within the magnesium matrix, leading to better microstructural uniformly [35]. To improve the tribological properties of the MMC, hybrid reinforcements can be used, such as a mixture of Sic and graphite. [36] The addition of particles like Sic and Al_2O_3 increases the hardness, tensile strength and wear resistance of the magnesium MMC. [36] To achieve the best result, the optimisation of the parameters is critical. These parameters include temperature, reinforcement particle size and stirring speed. [34] The optimized parameters achieved in one experiment were at a stirring speed of 312.8 rpm, a stirring time of 11.9 min, and a weight fraction of particles of 9.9 wt%. [37]

2) ***Squeeze casting****:* Squeeze casting is an extensively used method of synthesizing magnesium-based metal matrix composites (MMCs) for producing stronger components of both qualities. During the densifying of molten metal, it relies on high-pressure application to obtain a dense, defect-free composite structure with complete interlocking of reinforcement particles within a magnesium matrix. [38], [39] Amongst the most common reinforcements (e.g. silicon carbide (SiC) and aluminium oxide (Al_2O_3)) [40], the matrix is uniformly populated with these reinforcing, leading to a considerable improvement in the mechanical characteristics of the material. Magnesium MMCs fabricated using squeeze casting show substantial enhancement in tensile strength and yield strength as well as hardness over conventional magnesium alloys; tensile strength improves by up to 18 % and Young's modulus increases by 58%. The addition of reinforcements such as SiC and (Al_2O_3) lowers the wear rates itself(around 28% with 12 wt% SiC) [40]. Furthermore, it comes with the benefit of providing a sharper finished surface which serves as an added advantage to automotive applications. [39] Yet advancing uniform wettability of the molten magnesium with reinforcement particles is a bottleneck in creating a perfect interface, which could be resolved by employing preform squeeze casting. In addition, the magnesium properties of spinel MMCs are also impacted by thermal and cyclic mechanical responses twice (dislocation generation, and material damping). [41]

B. Powder Metallurgy

Powder metallurgy (PM) is a widely used technique for fabricating magnesium-based metal matrix composites (Mg-MMCs). It is due to their ability to produce precisely shaped products with superior mechanical properties and reduced machining costs. [42]–[44] The key benefits of using magnesium are due to its low density and corrosion resistance properties, which are crucial for applications in aerospace, biomedical, automotive, and defence industries. [42], [44] Mg-MMCs produced via PM exhibit high hardness, wear resistance, and improved tensile and compressive strengths. [42], [43] The addition of reinforcements such as SiC (enhances hardness, wear resistance, and maintains low thermal expansion) [43], ZrO_2 (improves mechanical properties such as tensile and compressive strength) [42], Al_2O_3 (increases mechanical strength and corrosion resistance) [45], and TiC [43] (enhances workability and mechanical properties, especially at higher temperatures) enhances these properties further.

The major challenges faced during this process are oxidation, which can be mitigated through coating techniques such as paraffin coating. [45] Porosity and reinforcement distribution are also major considerations, as they are crucial for achieving desired mechanical properties and corrosion resistance. [44]

C. Additive Manufacturing

Additive manufacturing (AM) has emerged as a promising technique for producing magnesium-based metal matrix composites (MMCs) due to its ability to create complex structures with high precision and short production cycles. It also allows for customization of magnesium matrix composites with uniform and complex structures which is difficult to attain by traditional techniques. [46], [47] Techniques like selective laser melting (SLM) and laser-engineered net shaping (LENS) have better material utilization rates causing less wastage of material. [47] They also provide high specific stiffness and strength, good dimensional stability, and excellent shock absorption performance. [47] This process also faces a lot of challenges especially related to the high reactivity of magnesium which can cause sudden combustion when exposed to high-powered energy sources. [48] Cracks can also form in the finished product due to factors like poor fusion and bonding. [47] To achieve a defect free product optimizing the process of parameters is crucial. [49]

D. Pressure Infiltration

Pressure infiltration is a technique for fabricating magnesium-based (MMCs). In this process, molten magnesium is injected into a preform of reinforcing materials under high pressure, which then solidifies to form a composite material.

There are many key techniques in this process such as Vacuum pressure infiltration where a vacuum is used to remove the air from the preform before pressure is been applied to to infiltrate the molten magnesium. This process has shown that there are significant increases in compressive strength and ductility of the composite. [50] Gas Pressure Infiltration (GPI) is another process where the pressure of the gas is used to drive the molten magnesium into the preform. This process is mainly used for composites with high-quality composites with uniform reinforcement distribution and uniform microstructure. [51] There is another novel technique called Liquid-Solid Extrusion which includes extrusion with liquid metal infiltration which leads to composites with reduced defects and excellent mechanical properties. [50] The overall advantages of these processes are the improvement of mechanical properties which includes higher compressive strength and ductility [50], [52], reduction of common casting defects like porosity and matrix/reinforcement interface separation [50], [52], [53]. Hence the improved interfacial bonding which leads to better performances of these composites. To get these mentioned advantages the process parameters must be implemented perfectly these include the arrangement and the type of reinforcement used. For example, the usage of carbon fiber and SiC in particle form are used due to their compatibility. [53], [54] The prepared preform and the amount of pressure used during the process are also key factors as they affect the infiltration of the matrix. [54]

VI. Conclusion

Mg-MMCs are promising materials for aerospace and automotive applications due to their superior mechanical and damping properties. Overcoming manufacturing challenges will enhance their industrial adoption. They provide substantial weight savings compared to aluminium and by using reinforcements such as boron carbide, silicon carbide, aluminium oxide and titanium carbide, improves the hardness, tensile strength, and wear resistance of magnesium MMCs,which is perfect for aircraft and automobile application.

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