Review Article

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Magnesium matrix composites reinforced with silicon carbide (SiC) nanoparticles: a review

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Abstract

Magnesium (Mg) matrix composites reinforced with silicon carbide (SiC) nanoparticles have garnered significant research interest as a new generation of lightweight, high-strength materials. This review explores fabrication techniques for Mg/SiC nanocomposites and critically examines the impact of SiC nanoparticles on the mechanical strength, wear behavior, thermal stability, and corrosion resistance of magnesium-based composites, elucidating the underlying theoretical and experimental mechanisms. Also, technical challenges including particle uniformity, strong bonding at the interface, and environmental considerations are discussed. Finally, the major challenges and issues facing the development of Mg/SiC nanocomposites are assessed and a comprehensive roadmap for the future is outlined.

Keywords: Mg-based composites; SiC nanoparticles; Microstructure; Mechanical properties

1. Introduction

1.1. The importance of Mg as a lightweight metal and its applications

Mg is a light, silvery-white metal that holds great importance in numerous industries because of its distinct characteristics. Here, we address the significance of Mg and its primary uses:

Mg is among the lightest structural metals, possessing a density of 1.74 g/cm³ (approximately two-thirds of aluminum and one-quarter of steel). This renders it extremely important in applications where reducing weight is essential, such as in the transportation, aerospace, and automotive sectors [1]. Mg alloys provide outstanding strength-to-weight ratios, rendering them perfect for components that are high strength-to-weight ratio and strong [2,3]. It is simple to machine, enabling the creation of intricate components with great accuracy. This metal possesses excellent damping characteristics, allowing it to efficiently absorb vibrations and noise. This is advantageous in areas such as automotive parts and electronics [4]. It also efficiently conducts heat and electricity, which makes it applicable in electronic and thermal management fields [5]. Mg is entirely recyclable [6], aiding sustainability and minimizing environmental effects. Mg plays a crucial role as an alloying component in aluminum alloys (e.g., 5000 and 6000 series), enhancing strength, corrosion resistance, and weldability [3,7].

Mg and its alloys are widely utilized in industries such as automotive, aerospace, electronics, filtration, and sports equipment [8]. Moreover, recent research has focused on developing biodegradable magnesium-based alloys and composites for advanced biomedical applications, including orthopedic implants, tissue scaffolds, and cardiovascular stents [9–15]. Although Mg offers numerous benefits, it also presents certain drawbacks, including its susceptibility to corrosion, flammability, and expense [16]. Mg is susceptible to corrosion, particularly in moist or salty conditions, which restricts its application in various cases [17].

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In its pure state, it is extremely flammable, necessitating cautious handling. Although Mg is plentiful, its extraction and processing can be costly when compared to other metals such as aluminum. On the other hand, biodegradable Mg faces challenges in biomedical applications, such as its rapid degradation in physiological environments and insufficient mechanical strength for load-bearing implant applications [18–21].

Table 1 Application of Mg and Mg alloys

No	Industry	example	Ref.
1	Automotive	Engine blocks, transmission cases, steering wheels, seat frames to reduce vehicle weight and improve fuel efficiency, Structural Components	[22]
2	Aerospace	Aircraft seats, gearboxes, and engine components to reduce weight without compromising strength , Satellites and Spacecraft (reducing launch costs)	[23]
3	Electronics	Laptop Casings and Smartphones, Heat Sinks (heat dissipation)	[24]
4	Medical	Biodegradable Implants e.g., screws and stents, Surgical Tools	[25–28]
5	Industrial Applications	Machinery Components ,Tooling (due to machinability)	[29]
6	chemical and metallurgical	Titanium Production (Kroll process) , - Desulfurization	[30]
7	Pyrotechnics and fireworks	Fireworks, flares, and incendiary devices	[31]
8	Sports and recreation	Bicycles and Golf Clubs, portable Camping Gear	[32]
9	Energy Storage	Batteries (eg., Mg-ion batteries due to its high energy density and abundance)	[33]
10	Construction	Lightweight Panels and temporary structures	[34]

1.2. The need to enhance the mechanical and wear properties of Mg

Improving the mechanical and wear characteristics of Mg and its alloys is essential for realizing their complete capabilities in industrial and commercial uses [35]. Mg is the lightest metal used in structures; however, its natural drawbacks, including low strength, insufficient wear resistance, and limited fatigue capability [36], limit its application in several high-demand situations. Pure Mg exhibits low tensile strength and hardness [37], which restricts its application in load-bearing scenarios; hence enhancing mechanical properties (such as tensile strength, yield strength, and hardness) enables Mg to substitute heavier materials like aluminum and steel in structural uses. Mg exhibits poor wear resistance [38], rendering it inadequate for uses that involve friction, abrasion, or sliding contact, thus improving wear resistance is crucial for applications such as gears, bearings, brake parts, and industrial machinery, where longevity is vital. Mg alloys frequently display inadequate fatigue resistance [39], posing a significant drawback for parts exposed to cyclic stress. Due to its biocompatibility and biodegradability, Mg is appropriate for temporary implants such as screws, plates, and stents [40]. Nonetheless, its diminished mechanical strength and swift corrosion in body fluids restrict its application [41]. Additionally, it possesses excellent thermal conductivity, yet improving its characteristics can render it more appropriate for heat dissipation uses. Conversely, Mg is quite soft, which restricts its use in applications that demand significant hardness and wear resistance. Consequently, the necessity to improve the mechanical [42] and wear attributes of Mg stems from its ability to transform industries by providing high strength-to-weight ratio, eco-friendly, and high-performance options. By overcoming its natural constraints, Mg can be utilized in a broader spectrum of applications, including automotive, aerospace, biomedical, and electronics. Enhancing these characteristics promotes energy efficiency, safety, and technological advancement, making Mg an essential material for the future. Current studies in alloy creation, composite substances, and surface technology persist in expanding the potential applications of Mg.

2. Mg properties and challenges

2.1. Mechanical and physical properties of Mg and Mg alloys

Mg and its alloys are recognized for their low weight, impressive strength-to-weight ratio, and superior machinability [43], making them appealing for use in aerospace, automotive, and biomedical sectors. Nonetheless, their mechanical characteristics can differ greatly based on the alloy formulation, manufacturing techniques, and reinforcement substances (e.g., SiC NPs). Table 2 summarizes the mechanical characteristics of Mg and its alloys, whereas Table 3 shows their physical characteristics**.**

Table 2. Mechanical properties of Mg and Mg alloys.

No.	Property	Pure Mg	Mg alloys	Ref.
1	Density	1.74 g/cm^3	Depending on alloying elements	[24]
2	Tensile Strength	90–190 MPa.	200–400 MPa (depending on alloying elements and processing	[22]
3	Yield Strength	20–80 MPa	100–300 MPa	[3]
4	Elongation Ductility	10–15%.	5–20% (varies with alloying and processing	[44]
5	Elastic Modulus	45 GPa (relatively low compared to other structural metals like steel or aluminum		[45]
6	Hardness	35–45 HV	50–100 HV	[46]
7	Fatigue Strength	Relatively low compared to other metals, but can be improved with alloying and reinforcement		[39]
8	Fracture Toughness	Moderate, but can be enhanced with proper alloying and composite design		[47]

Table 3. Physical properties of Mg

No.	Property	Specifications	Ref.
1	Melting Point	~650 °C (1202 °F)	[48]
2	Thermal Conductivity	156 W/m·K (good thermal conductivity	[49]
3	Electrical Conductivity	~22.6 MS/m (moderate electrical conductivity	[50]
4	Coefficient of Thermal Expansion	~25–26 µm/m·K (relatively high, which can lead to thermal stresses	[51]
5	Corrosion Resistance	Poor in pure form due to high reactivity, but can be improved with alloying (e.g., Al, Zn, rare earth elements) or coatings	[52]

2.2. Inherent limitations of Mg and Mg alloys

Mg has various intrinsic drawbacks, one being its lower strength in comparison to other structural metals such as aluminum or steel. Pure Mg exhibits a comparatively low tensile strength, generally between 90 and 190 MPa. This restricts its application in scenarios demanding significant load-bearing strength. The strength of Mg in comparison to other metals is markedly less than that of aluminum (with a tensile strength ranging from 100 to 550 MPa) and steel (with a tensile strength ranging from 400 to 2000 MPa), attributable to its hexagonal close-packed (HCP) crystal structure, as well as the grain size and microstructure of Mg. The HCP structure of Mg restricts the number of slip systems for deformation, resulting in reduced ductility and lower strength under stress [53]. Coarse grain structures and contaminants in Mg alloys may further diminish its strength [54]. Mg and its alloys display inadequate fatigue resistance, particularly when subjected to cyclic loading conditions. This is because of its low resistance to the initiation and propagation of cracks, and it is also vulnerable to stress concentrations resulting from microstructural defects [55]. Additionally, it has low hardness and is susceptible to wear in abrasive or sliding environments. This restricts its application in scenarios that involve friction or interaction with tougher materials [56]. Mg is very reactive and susceptible to corrosion, particularly in moist, salty, or acidic conditions. This occurs because a non-protective oxide layer develops on its surface, along with galvanic corrosion when in contact with other metals [57].

Mg can catch fire, particularly in powdered or thin forms. It can catch fire at temperatures near 500 °C, presenting safety hazards in high-temperature situations, as their ease of ignition and flammability constitutes a negative safety characteristic that limits their favorable strength-to-weight ratio [17]. Its HCP structure restricts plastic deformation, leading to limited ductility at room temperature [58].

3. Introduction of SiC NPs and their properties

3.1. Structural and physical properties of SiC

Silicon carbide is versatile material with a wide range of properties due to its varied production methods and microstructures[59–64]. SiC crystals consist of silicon (Si) and carbon (C) atoms bonded via strong tetrahedral covalent bonds (bond energy = 4.6 eV) formed by sp^3 hybrid orbitals. SiC's unique properties, such as wide bandgap, high thermal conductivity, thermal stability, and radiation resistance, make it suitable for demanding applications, particularly in electronics. It is ideal for high-power and high-temperature devices with switching speeds of 5–100 kHz and substrates for Group IIIB nitride thin films used in optoelectronic and microelectronic devices. Its atomic arrangement closely matches that of AlN and AlGaN solid solutions, making it a good substrate material. SiC has Advantages for Electronics such as High critical electric field strength, High saturation electron drift velocity, Ability to be doped with donor and acceptor atoms that ionize at room temperature and Formation of a native SiO_2 oxide layer, which can be grown thicker for specific device applications [65]. Fig.1 shows summary of some SiC properties.

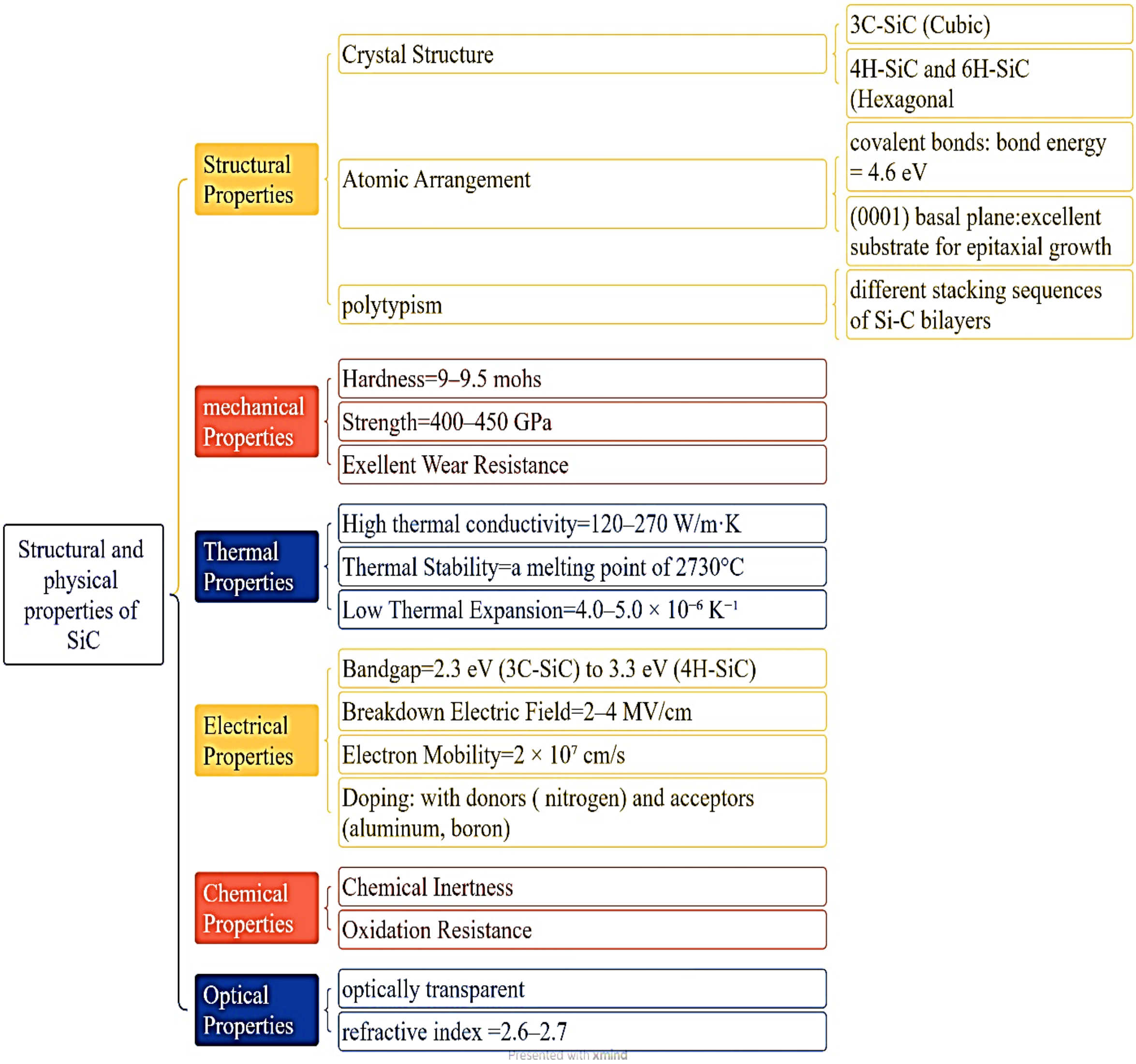

Fig. 1. Summary of SiC properties [66].

3.2. The role of SiC NPs for improving Mg properties

Mg matrix composites strengthened with SiC NPs are a prominent research field because of their promise for lightweight, high-strength materials, particularly in aerospace, automotive, and biomedical fields. Nonetheless, there are numerous difficulties linked to these composites [67]. The addition of SiC NPs to Mg or its alloys can significantly modify and enhance their properties. SiC NPs act as a reinforcing phase in Mg matrix composites, leading to improvements in mechanical, thermal, and wear properties [68,69].

3.2.1. Microstructural properties

The addition of SiC NPs into Mg alloys significantly influences their microstructure, leading to enhancements in mechanical properties. Grain refinement, distribution of secondary phases, and dislocation generations are key effects of SiC NPs on microstructure. SiC NPs contribute to the refinement of the grain structure in Mg alloys. This is primarily due to the NPs acting as nucleation sites during solidification, which restricts the growth of α-Mg dendrites [70,71]. As can be seen in Fig. 2, the size of α-Mg grains in SiC_{np}-free Mg-25Zn-7Al (Fig. 2a–d), is larger than in SiC_{np}-Mg-25Zn-7Al (Fig. 2e–h), for the same cooling rate. Therfore, a finer solidification microstructure can be obtained through the addition of SiC NPs, indicating enhanced grain nucleation [71].

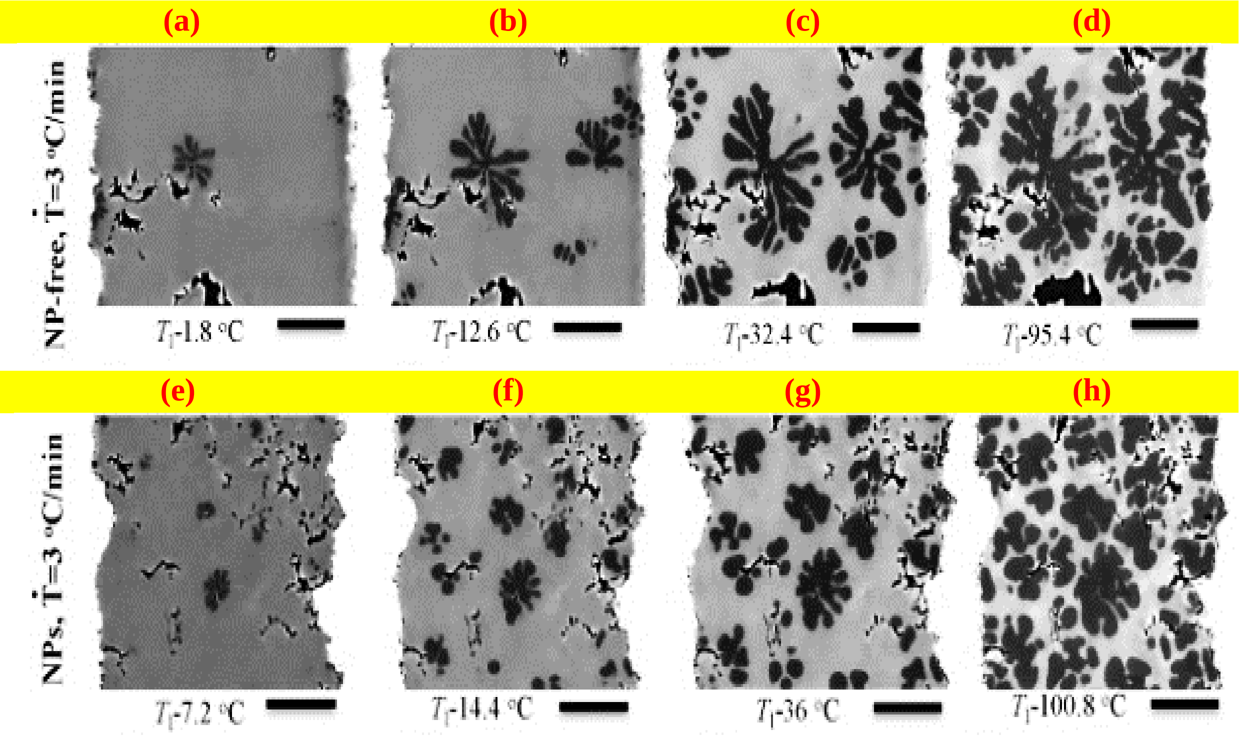

Fig. 2. Solidification dendritic structures of SiC_{np}-free Mg-25Zn-7Al (a-d) and SiC_{np}- Mg-25Zn-7Al (e-h) alloys in a cooling rate of 3 °C/min. Scale bar is 300 μm. Note that in the figure light grey = liquid, dark grey = dendrite, black = pore [71].

The presence of SiC NPs results in a more uniform and finer grain distribution, which is beneficial for the mechanical properties of the alloy [72]. Huang et al. [73] investigated the effect of adding 1 wt.% and 2 wt.% SiC on the microstructure of AZ61. According to their findings, the addition of SiC NPs affects the distribution of secondary phases within the Mg matrix. For instance, in AZ61 Mg alloy composites, the β-$Mg_{17}Al_{12}$ phase is significantly dissolved at grain boundaries after heat treatment, enhancing ductility [73]; also, there was large amount of β-$Mg_{17}Al_{12}$ secondary phase at grain boundaries which effects on mechanical properties due to its brittleness. The addition of SiC leads to reduce the thickness of this phase and refine the microstructure of AZ61 alloy [74]. Also, in the AXM520 alloy, the continuous network of the $(Mg, Al)_2Ca$ phase becomes fragmented and discontinuous with increasing SiC content, which helps inhibit crack propagation [74].

3.2.2. Mechanical Properties

SiC NPs act as a strengthening agent by hindering dislocation movement (Orowan strengthening) and providing load transfer from the matrix to the particles. This results in improved tensile strength, yield strength, and hardness of the Mg matrix. The high stiffness of SiC NPs increases the overall elastic modulus of the composite [75]. Also the addition of SiC NPs can improve fatigue life by slowing crack formation and progression. The SiC-reinforced Mg nanocomposite has good mechanical properties due to grain refinement, microstructural changes, and effective reinforcement by SiC NPs. This is in contrast to typical composites, where increased strength often comes at the sacrifice of ductility. Nie et al. [76] investigated the mechanical properties of of Mg alloy, before and after reinforcement by SiC NPs. According to their results, the SiC/Mg nanocomposite shows simultaneous improvements in ultimate tensile strength (UTS), yield strength (YS), and elongation to fracture compared to the unreinforced Mg alloy. This improvement is distinct from traditional composites reinforced with micro-sized particles or fibers, which often sacrifice ductility for strength. The yield strength is influenced by grain size according to the Hall–Petch equation [76]:

$$\sigma_y = \sigma_0 + K_y d^{-1/2} \tag{1}$$

where σy is the yield strength, σ_0 and Ky are material constants, and d is the mean grain size.

For HCP metals like Mg, grain refinement significantly enhances yield strength due to the higher Ky value, which is related to the limited number of slip systems in HCP structures [76]. The as-cast AZ91 alloy's brittle $Mg_{17}Al_{12}$ phase creates a continuous network at grain boundaries, lowering tensile strength. The SiC/AZ91 nanocomposite improves strength by converting the $Mg_{17}Al_{12}$ phase from massive to lamellar and refining the grain structure. The SiC NPs bond well with the matrix, further strengthening the nanocomposite. The combined effects of discontinuous and refined $Mg_{17}Al_{12}$ phase, refined α-Mg grains, and SiC NP addition are responsible for the enhanced tensile properties [77]. SiC nanoparticles are more effective than microparticles at promoting particle hardening mechanisms, leading to significant increases in mechanical strength. A fine and uniform dispersion of SiC NPs optimizes the balance between strengthening effects (from non-deforming particles) and interparticle spacing, maximizing yield strength [78].

The well-dispersed SiC NPs account for the considerable improvement in mechanical characteristics and ductility in Mg-4Zn nanocomposites. NP strength results from Orowan strengthening, increased dislocation density, and load-bearing effects. Unlike in microparticle-reinforced composites, where Orowan strengthening is minimal, it becomes extremely effective in nanocomposites because dislocations must bend around NPs to avoid them. Even a tiny volume fraction of NPs can dramatically increase yield strength, in contrast to typical Mg composites reinforced with microparticles or fibers, which require 10-30 vol% reinforcement phases to attain comparable results. This makes nanocomposites more efficient and effective in terms of enhancing mechanical performance [78,79].

3.2.3. Hardness and wear resistance

SiC NPs improve the wear resistance of Mg by acting as a hard, abrasive-resistant phase. This is particularly beneficial in applications where Mg components are subjected to sliding or abrasive wear [80]. The NPs can reduce the friction coefficient, improving the tribological properties of the composite. Higher SiC content reduces dislocation movement, increasing hardness. The density of dislocations and the number of reinforcing NPs are crucial in increasing the composite's hardness. SiC NPs improve the hardness of the Mg alloy by acting as hard reinforcements inside the matrix. SiC is a ceramic substance with excellent hardness and strength that improves the overall mechanical properties of the Mg matrix. Ponhan et al. [81] showed that the hardness of nanocomposites increases as the weight fraction of SiC NPs increases. Increasing SiC concentration from 10% to 20% increased hardness from 51.79 HV to 79.23 HV (53% increase), and increasing the SiC amount from 20 to 30 wt% resulted in a lower hardness [81].

The increase in hardness is attributed to strengthening mechanisms involving interactions between SiC NPs and dislocations in the Mg matrix. SiC NPs act as barriers to dislocation movement. Dislocations must bow around the NPs, reducing their mobility and limiting plastic deformation. The presence of SiC NPs further increases dislocation density, reducing the average distance between dislocations and impeding their movement [81]. Also, the addition of SiC NPs changes the dendritic structure into a globular equiaxed structure. Dendrites are tree shaped crystalline formations that commonly develop during the solidification of metals. Dendrites develop during solidification as a result of inconsistent cooling rates. The inclusion of SiC nanoparticles interferes with this process by offering nucleation sites for new grains, resulting in a more uniform, globular structure. This transformation is beneficial because globular equiaxed grains reduce stress concentrations and improve mechanical properties [82]. The transformation to globular equiaxed grains and finer precipitates enhances the mechanical properties of material. The resistance to twinning deformation further increases the ability of material to withstand stress without failing. The HCP structure of Mg has limited slip systems, making twinning a primary deformation mechanism under shear stress. SiC NPs are hard and act as obstacles to the movement of twin boundaries. This requires additional energy for deformation, effectively strengthening the material [83]. As SiC NPs content increased, the hardness of Mg alloy increase. This trend continues up to a certain point (in this case, 0.15% nano-SiC), after which further addition of nano-SiC does not significantly improve hardness. Compared to the unreinforced Mg-Al-Sr alloy (which has a hardness of 50.79 HB), the hardness of the composite increased by approximately 26%. Hardness is directly related to wear resistance. A harder material generally has better resistance to wear. The composite with 0.15% nano-SiC (which has the highest hardness) also exhibits the best wear resistance, as indicated by the lowest wear rate. The wear rate of the unreinforced Mg-Al-Sr alloy is 1.677×10^{-5} mm³/mm. With the addition of 0.15% nano-SiC, the wear rate decreases to 1.033×10^{-5} mm³/mm. This reduction in wear rate demonstrates the improved wear resistance of the composite material [83].

3.2.4. Creep Properties

Mg has a hexagonal close-packed structure with limited slip systems, making deformation dependent on temperature and grain size. Grain boundary sliding and dislocation glide in non-basal systems become more prominent with decreasing grain size. However, SiC NPs hinder grain boundary sliding and dislocation motion, enhancing creep resistance. SiC NPs pin grain boundaries and disperse within the matrix, significantly increasing creep resistance [84].

The steady-state creep rate ($\dot{\varepsilon}$) is commonly described by the equation [85]:

$$\frac{d\varepsilon_\sigma}{dt} = A\,\sigma^n \,\exp\left(-\frac{Q_c}{RT}\right) \tag{2}$$

A: A constant of proportionality.
σ: The applied stress.
n: The stress exponent, which indicates the sensitivity of the creep rate to stress.
Q_c: The activation energy for the rate-controlling deformation process.
R: The universal gas constant.
T: The absolute temperature.

This equation describes how creep rate depends on stress, grain size, and temperature, with the exponential term accounting for thermally activated processes. For materials strengthened by dispersed particles (e.g., SiC NPs in Mg composites), the standard creep rate equation is often modified. This is because dislocations must overcome the resistance posed by the dispersed particles. A threshold stress is introduced to account for the additional stress required for dislocations to bypass or detach from the particles. This refinement reflects the enhanced creep resistance in dispersion-strengthened materials due to the interaction between dislocations and particles. Ganguly and Mondal [84] investigated the effects of adding SiC NPs to an AZXY9120 Mg alloy, focusing on the microstructure and creep behavior of the resulting nanocomposites. According to their finding, the volume fraction of the β-$Mg_{17}Al_{12}$ phase decreases as the amount of SiC NPs increases and the morphology of this phase changes from bulky and lamellar structures in the alloy to finer, linearly oriented lamellae in the nanocomposites. The SiC NPs aid in grain refinement by offering locations for heterogeneous nucleation of the α-Mg phase, limiting grain expansion and decreasing total grain size. Consequently, the nanocomposites show improved creep resistance because of the inclusion of SiC NPs, which hinder punch penetration and lower the creep rate.

They explained the mechanisms of dislocation climb during creep deformation in pure Mg, Mg-based alloys, and nanocomposites [84]. Dislocation climb occurs via vacancy diffusion, which can happen through two mechanisms: Volume/lattice diffusion at high temperatures and dislocation core/pipe diffusion at lower temperatures. For pure Mg and Mg-based alloys, the activation energy for bulk diffusion is 135±10 kJ/mol, while for pipe diffusion, it is 92±10 kJ/mol. In the studied materials the unreinforced Mg alloy has an activation energy of 115.5±3.2 kJ/mol, indicating a transition from pipe diffusion to lattice diffusion. The Mg/SiC_{np}

nanocomposites had activation energies closer to pipe diffusion (101.9–103.8 kJ/mol), suggesting that pipe diffusion remains the dominant mechanism. The analysis of activation energy and stress exponent values confirms that dislocation climb controlled by pipe diffusion is the primary rate-controlling mechanism for creep deformation in the nanocomposites. In contrast, the unreinforced Mg alloy transitions to lattice diffusion due to its higher activation energy. This distinction highlights the influence of SiC NP reinforcement on the diffusion and creep behavior of Mg-based materials. Ferkel and Mordike [86] investigated the creep behavior of Mg strengthened by SiC NPs. They suggested dislocation-controlled creep dominates over grain boundary sliding or diffusion-controlled mechanisms and activation energy values for creep fall between those for core/grain boundary diffusion and lattice diffusion.

4. Manufacturing methods of SiC_{np} reinforced Mg composites

Several methods have been developed to produce Mg matrix composites reinforced by nano SiC particles, each with its own advantages and limitations [87]. The most important of these methods will be discussed below:

4.1. Powder Metallurgy

Powder metallurgy is one of the most prevalent methods employed for the fabrication of SiC NP-reinforced Mg matrix composites [88,89]. Powder metallurgy consists of powder preparation, compaction, and sintering process steps [86,90]. Mg powder and SiC NPs are mixed in a specific proportion in the powder preparation step with the help of high-energy ball mill [91,92]. Methods such as ball milling are used to improve the distribution of NPs. Penther et al. [93] examined a high-energy planetary ball mill was used to co-mill the Mg/SiC nanocomposite. It was demonstrated that following mechanical milling, finer particles with a narrower size distribution are produced when SiC NP concentration is increased. The powders are then mixed together and pressurized in steel dies at high pressure (typically 200-400 MPa) to promote the densification of the first stage. Finally, the samples are sintered at high temperature (typically 500-600 °C) in a controlled atmosphere (e.g., argon or nitrogen) to activate the welding of the particles into the final structure. The advantages of this process include uniform NP distribution, precise chemical composition control, and improved mechanical properties. The drawbacks of this process include the fact that equipment is costly, it is time-consuming, and it has no limitations on part size. Ponhan et al. [81] shown that during mechanical alloying, no undesired phases were produced by interfacial interactions between Mg and SiC NPs in the milled nanocomposite powder. Additionally, the findings demonstrated that when the milling time increased, the Mg–SiC sintered sample's relative density and hardness value both improved. However, by adding more SiC NPs, the Mg–SiC nanocomposite's relative density considerably dropped while its hardness significantly increased. In their investigations, Suryanarayana and Al-Aqeeli [94] and El-Eskandarany [95] shown that mechanical mixing can result in Mg matrix composites with better mechanical properties.

4.2. Casting

Casting is one of the traditional and cost-effective methods for producing Mg matrix composites. In this method, Mg is melted in resistance or induction furnaces, and SiC NPs are added to the melt and distributed by mechanical or ultrasonic stirring [83,96]. Wang et al. studied on the Mg/SiC_{np} composites produced by ultrasonic method [97]. They concluded that the ultrasonic approach is an effective and practical way to disperse SiC NPs in Mg alloy. The advantages of casting method include low cost, the possibility of producing large parts, and high production speed. However, the disadvantages of this method are the heterogeneous distribution of NPs, Mg oxidation, and poor adhesion between NPs and the matrix. Matin et al. [82] investigated AZ80/SiC nanocomposites produced using the sir casting process. They discovered that adding SiC NPs led to an increase in the work hardening rate compared to unreinforced alloy, which caused to enhance the tensile strength and hardness of the produced composite.

4.3. Friction Stir Processing (FSP)

FSP is a novel method for producing metal matrix composites [99]. In this method, a high-speed rotating tool is introduced into the metal surface, and the friction between the tool and the metal causes heat generation and softening of the metal. Then, SiC NPs are added and distributed in the softened area. The advantages of this method include uniform distribution of NPs and improvement of surface properties. However, the limitations in the dimensions of the parts and the high cost of the equipment are the disadvantages of this method. According to Deepan et al.'s research [100], FSP can enhance the mechanical characteristics of composites and improve the dispersion of SiC NPs in the Mg matrix. Sun et al. [101] studied on the mechanical properties and microstructure of Mg/SiC np composites produced by FSP. They reported that AZ63/SiC nanocomposite was successfully produced by FSP. A homogenous distribution of SiC particles was observed in the composite and no agglomeration of NPs was observed in the composite matrix. Also, no reaction products were reported in the composites. Sadooghi and Rahmani [86] studied on the mechanical properties of Mg matrix composite reinforced by nano- and micro- SiC produced by FSP. FSP procedure that creates nanocomposites for altering the microstructure and enhancing material qualities because the multi-pass FSP process because of the extended period of heat exposure causes more strengthening phases to occur and the matrix to be distributed uniformly.

4.4. Shear compaction processing

In the shear compaction processing mechanism, the two main parts of the experimental setup for the shear compaction processing procedure are a stirring tool and a container with a cylindrical central hole. Three tension bolts are used to secure the backing plate to the container. This container is attached on the computer numerical control table, vertical milling machine and serves as a die during the operation. The scrolling face of the stirring tool can help with the instrument's stirring motion. The procedure begins by filling the container with the machining chips, which are then at room temperature and gently compressed along the feed direction. The SiC particles are put on top of the compressed chips following chip compaction. After that, a rotating stirring tool with a predetermined feed rate and rotational speed is inserted into the container. The chips in the cavity are softened and completely consolidated by the enormous quantity of friction-induced heat produced by the rotation and translation along the feed direction. Chips and SiC particles are better mixed because to the tool's scrolling face. The final thickness of the created composite disk was specified by first determining a specific plunge stroke for the stirring tool based on the quantity of added chips. When the stirring tool reaches the plunge stroke, the procedure has to be stopped [87].

Shear compaction processing (SCP), a novel synthesis technique, is created to create Mg-based composites using nano-sized SiC particle reinforcement and Mg machining chips. The procedure involves loading and gently compacting Mg machining chips into the container before adding SiC NPs on top of the compressed Mg chips. At a chosen spindle rotation speed and feed rate, a scroll-faced rotating tool with a specified diameter is inserted into the Mg chips. The softened materials are compacted and synthesized to create a nanocomposite disk because of the enormous amounts of heat generated [103]. Narvan et al. [103] investigated on Mg/SiC nanocomposite were produced by shear compaction processing method. According to the findings, the most efficient way to create composite disks free of defects was to increase the rotational speed to 500 rpm. The composite disk created by the 500 rpm rotational speed had a decent dispersion of nano-sized SiC particles. According to the microstructural investigation, SiC particles were evenly dispersed throughout the Mg matrix and formed a strong bond with it.

5. Conclusions

Mg reinforced with SiC NPs has been considered as an attractive option in the aerospace, automotive, and medical industries due to its unique combination of properties such as light weight, high strength, and wear and corrosion resistance. Studies show that SiC NPs have a significant effect on improving the hardness, mechanical strength, and creep behavior of these composites. In addition, the microstructure resulting from the uniform distribution of NPs in the Mg matrix plays a key role in preventing grain growth and increasing thermal stability. Optimization of production methods, including casting, powder metallurgy, and severe plastic deformation processes, can help improve structural homogeneity and optimize mechanical properties. However, challenges such as problems in uniform distribution of NPs, improving the bonding between the reinforcing particles and the matrix, and increasing the formability of these materials are still of interest to researchers. Finally, future research should focus on developing advanced methods to better control the microstructure, increase the stability of NPs in the field, and optimize manufacturing processes to broaden the use of these composites in industrial and biomedical applications.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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