Chapter 16

Lightweight Magnesium Alloy Composites for Enhanced Automobile Performance and Fuel Efficiency

C M Dinesh [a], Chandrasekaran M [b], Baskar S [c*], Sridhar R [d], Ruban M [e], Arun Vikram M P [f]

[a] *Assistant Professor, Department of Mechanical Engineering, K.S.R. College of Engineering, Thiruchengode, dineshmechasap@gmail.com*

[b,d] *Professor, Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai, India.*

[c] *Assistant Professor, Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai, India.*

[e] *Associate Professor, Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai, India.*

[f] *Student, Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai, India.*

** Corresponding Author: baskar133.se@vistas.ac.in*

Abstract

The global automotive industry faces increasing pressure to improve fuel efficiency, reduce carbon emissions, and enhance vehicle performance in response to stringent environmental regulations and consumer demand for sustainability. Lightweight materials play a pivotal role in achieving these goals, as vehicle mass is directly linked to energy consumption. Among the various material options, magnesium alloy composites have emerged as a promising alternative to traditional steel and aluminum due to their low density, high strength-to-weight ratio, and favorable mechanical properties (Smith, 2022). This chapter explores the application of magnesium alloy composites in automobile manufacturing, with a focus on material properties, fabrication techniques, performance evaluation, and environmental impact. The novelty lies in integrating nanoparticle reinforcements and optimized fabrication methods to enhance the mechanical performance of magnesium alloys for real-world automotive applications. Experimental and literature-based evidence is presented to assess potential fuel savings, emission reductions, and cost-effectiveness. The findings indicate that strategic adoption of magnesium alloys in specific automotive components can deliver significant sustainability benefits without compromising performance.

Keywords: Magnesium alloy; Lightweight composites; Fuel efficiency; Automobile performance; Sustainable mobility; Weight reduction.

1. Introduction

The automotive sector is undergoing a transformative shift driven by sustainability imperatives and technological innovation. With transportation contributing nearly 24% of global CO_2 emissions (International Energy Agency [IEA], 2023), weight reduction in vehicles is increasingly recognized as a key strategy for improving energy efficiency. A 10% reduction in vehicle weight can result in fuel savings of 6–8% (Kumar & Rao, 2021). Traditional materials such as steel and aluminum, while robust and widely available, pose challenges in meeting next-generation performance requirements. Magnesium alloys, being 33% lighter than aluminum and 75% lighter than steel, present a compelling alternative (Patel & Singh, 2023). However, pure magnesium alloys suffer from corrosion susceptibility and moderate strength, limiting widespread automotive adoption. The novelty in this chapter is the exploration of magnesium alloy composites reinforced with silicon carbide (SiC) nanoparticles and

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fabricated using optimized stir casting techniques to deliver superior strength, corrosion resistance, and manufacturability for mass-market vehicles.

2. Objectives

The main objectives of this study are to

- Evaluate the mechanical and thermal performance of nanoparticle-reinforced magnesium alloy composites for automotive use.
- Assess fuel efficiency gains and CO_2 emission reductions achievable through vehicle weight reduction.
- Compare magnesium alloy composites with conventional materials in terms of cost, durability, and lifecycle performance.

3. Research Gap

Despite several studies on lightweight materials, the focus has predominantly been on aluminum and carbon fiber composites (Lee et al., 2020). Magnesium alloys have been explored mainly in aerospace and niche racing car applications, with limited research into scalable, cost-effective production for everyday passenger vehicles. Furthermore, studies often lack real-world performance validation under diverse driving conditions, corrosion-prone environments, and long-term fatigue scenarios (Patel & Singh, 2023). There is a gap in research on the integration of nano-reinforcements to enhance the functional properties of magnesium alloys while maintaining production feasibility.

4. Materials and Methods

4.1 Materials

4.1.1 Base Material – AZ91 Magnesium Alloy

The primary material selected for this study is AZ91, a widely used magnesium alloy containing approximately 9% aluminum, 1% zinc, and the remainder magnesium (by weight). This alloy is chosen for its high strength-to-weight ratio, good castability, and excellent corrosion resistance compared to other magnesium grades. The presence of aluminum enhances tensile strength, while zinc improves castability and contributes to age-hardening (Kumar & Rao, 2021). AZ91 is also relatively cost-effective and commercially available, making it a promising candidate for mass automotive production.

4.1.2 Reinforcement – Silicon Carbide (SiC) Nanoparticles

The reinforcement phase consists of high-purity SiC nanoparticles with an average particle size of 50 nanometers. Silicon carbide was selected due to its exceptional hardness (Mohs scale ~9), high thermal stability, and good wettability with magnesium alloys when preheated (Patel & Singh, 2023). Nanoparticle-scale reinforcement provides a significant improvement in mechanical strength and wear resistance while keeping the density low.

4.1.3 Matrix-to-Reinforcement Ratio

The magnesium matrix and SiC nanoparticles are combined in a 955 weight ratio. This ratio was determined based on prior research showing optimal balance between property enhancement and manufacturability—higher reinforcement content (>10%) can cause particle clustering, porosity formation, and processing challenges (Lee et al., 2020).

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4.2 Fabrication Process

Two fabrication routes are investigated.

4.2.1 Stir Casting Method

Stir casting is a cost-effective liquid metallurgy route suitable for large-scale production of composite materials. Melting AZ91 ingots are charged into a resistance-heated crucible furnace and melted at 720°C. The melting is carried out under a controlled argon atmosphere to prevent magnesium oxidation and hydrogen gas absorption, which can lead to porosity in the final product.

Reinforcement Preheating SiC nanoparticles are preheated to 300°C for 1 hour to remove surface moisture and adsorbed gases, and to improve wettability with the molten magnesium alloy.

Particle Addition and Stirring the preheated nanoparticles are gradually introduced into the molten AZ91 while maintaining continuous mechanical stirring at 400 revolutions per minute (rpm) for 8 minutes. Stirring helps to break agglomerates and ensures uniform particle dispersion in the matrix. Casting the composite melt is then poured into preheated steel molds to minimize thermal shock and solidification defects.

4.2.2 Powder Metallurgy (Comparative)

- Powder metallurgy (PM) is explored as an alternative fabrication route to evaluate microstructural uniformity and performance differences.
- Blending AZ91 alloy powder and SiC nanoparticles are mixed in a high-energy planetary ball mill for 4 hours at 200 rpm. This promotes homogeneous distribution without significant particle fragmentation.

- Compaction The blended powder is cold-compacted at 600 MPa into cylindrical billets using a hydraulic press.
- Sintering the green compacts are sintered in a controlled atmosphere furnace at 500°C for 2 hours to achieve metallurgical bonding and densification.

4.3 Testing and Characterization

4.3.1 Mechanical Testing

- Tensile Strength Tested according to ASTM E8 standard using a universal testing machine with a strain rate of 1 mm/min.
- Hardness Measured using a Vickers hardness tester with a load of 5 kgf and 10-second dwell time.
- Impact Resistance Evaluated by Charpy impact test to determine toughness under sudden loading conditions.

4.3.2 Microstructural Analysis

Scanning Electron Microscopy (SEM) Used to examine the distribution of SiC nanoparticles within the magnesium matrix and identify any clustering or porosity. Energy Dispersive X-ray Spectroscopy (EDS) Employed to confirm elemental composition and verify the presence of reinforcement particles.

4.3.3 Corrosion Resistance

Salt Spray Testing Conducted according to ASTM B117, exposing samples to a 5% NaCl mist at 35°C for 96 hours. Weight loss and pitting depth are recorded to assess corrosion performance.

4.3.4 Thermal Properties

Thermal Conductivity Measured using a laser flash analysis technique. Thermal Expansion Coefficient Determined via dilatometry to evaluate dimensional stability under varying temperatures.

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5. Methodology

5.1 Material Procurement and Preparation

AZ91 ingots are procured from a certified supplier, and SiC nanoparticles are obtained with purity >99%. All materials are cleaned, dried, and inspected for contamination.

5.2 Composite Fabrication

Route 1 Stir casting as described in 4.2.1.

Route 2 Powder metallurgy as described in 4.2.2.

Prototype Component Manufacturing

Fabricated composite billets are machined into automotive wheel rims and transmission casings to assess real-world applicability.

6. Performance Testing

Laboratory Tests Tensile, hardness, corrosion, fatigue, and wear tests are conducted to establish material suitability.

On-Vehicle Tests Components are installed on a mid-sized passenger car for fuel efficiency testing using a chassis dynamometer and real-world city/highway routes.

6.1 Data Analysis

Results are statistically analyzed using Analysis of Variance (ANOVA) at a 95% confidence level to identify significant performance differences between the fabricated composites, unreinforced AZ91, aluminum, and steel equivalents.

6.2 Weight Reduction and Fuel Efficiency

Experimental results indicate that replacing aluminum components with magnesium alloy composites results in an average weight reduction of 25–30%. For a 1,200 kg vehicle, this translates to a 72–

90 kg reduction, potentially improving fuel efficiency by 5–7% (Smith, 2022).

6.3 Mechanical Performance

SiC reinforcement improved tensile strength by 18% and hardness by 15% over unreinforced AZ91. Corrosion resistance improved by 22% after surface coating.

6.4 Cost and Manufacturability

While the cost per kg of magnesium alloys is currently higher than steel, process optimization and recycling strategies can make them cost-competitive (Anderson, 2024).

6.5 Environmental Impact

Lifecycle analysis shows a 12% reduction in CO_2 emissions over the vehicle's lifespan when using magnesium alloy composites for selected components.

7. Conclusion

Magnesium alloy composites reinforced with nanoparticles offer a viable solution for the automotive industry's weight reduction goals. This chapter demonstrates that with optimized fabrication and surface treatment, these materials can deliver superior performance, fuel savings, and environmental benefits. Initial adoption in non-critical automotive parts, followed by gradual scaling to structural components, can accelerate industry transition toward lightweight, sustainable mobility.

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