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Carbon Fiber-Reinforced Magnesium Alloy Composite: Lightweight Design and Mechanical Property Enhancement for Aerospace and Automotive Applications

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This research investigates the design and development of carbon fiber-reinforced magnesium alloy composites, emphasizing their enhanced mechanical properties for potential applications in the aerospace and automotive industries. The AZ91 magnesium alloy matrix was selected due to its advantageous properties, including a notably low density of 1.74 g/cm³ and inherent high strength. Composites were produced with carbon fiber (CF) reinforcement at 3% and 5% by volume, and experimental evaluations demonstrated significant improvements in mechanical performance. The ultimate tensile strength (UTS) of these CF-reinforced composites showed a marked increase, reaching up to 500 N/mm², compared to 200 N/mm² observed in the unreinforced magnesium alloy. This substantial increase in tensile strength highlights the potential for carbon fiber reinforcement in applications requiring enhanced durability. Additionally, the CF-reinforced composites exhibited a higher damping loss factor, indicative of superior energy absorption, which is critical for applications subject to dynamic stresses. Beyond strength enhancements, these composites provide considerable weight savings, weighing approximately 41% less than aluminum, which is highly advantageous in industries where weight reduction directly impacts fuel efficiency and performance. This study thus underscores the promising potential of carbon fiber-reinforced magnesium alloy composites in the lightweight design for aerospace and automotive fields, where strength-to-weight ratio is essential for optimal performance. The findings suggest that such materials could play a crucial role in future high-performance structures, delivering both the lightweight benefits of magnesium and the mechanical robustness imparted by carbon fiber reinforcement.

Keywords: Carbon fiber, magnesium alloy, composite materials, tensile strength, damping loss factor, AZ91 alloy, lightweight design, automotive applications, aerospace engineering.

1. Introduction

According to the Corporate Average Fuel Economy (CAFE) standard, all original equipment manufacturers (OEMs) in the automobile industry must satisfy the fuel economy target based on the average weight of their fleet. In terms of CO2 emissions per kilometer driven (g/km), most nations and regions have challenges in meeting the average fuel economy target for passenger vehicles[1]. In particular, the United States established a target for average CO2 emissions in 2025 of 89 g/km, which is a 40% reduction from 2015[2]. Aside from improving fuel economy and reducing emissions, a greater focus on better performance and easier recyclability encourages the creation of lighter, stronger, and greener automobiles[3]. Thus, it is critical to investigate novel materials and achieve more efficient structural design in future automobiles[4]. So far, global OEMs have implemented a variety of effective strategies to meet the challenges, including vigorously developing hybrid and pure electric vehicles, increasing drive train efficiency, and exploring lightweight materials for automobiles, with weight savings being the top priority)[5]. Over the last several years, light vehicle manufacturing has steadily increased in all key markets. Lightweight materials for automobiles can be classified into four categories: light alloys (e.g., aluminum, magnesium, and titanium alloys), the HSS family (e.g., conventional HSSs and AHSSs), composite materials (e.g., carbon fiber reinforced plastics or CFRP), and advanced materials[6]. Since the past century, these lightweight materials have been widely used in a variety of automobile components, including the dashboard, bumper, engine, body shell, wheel, suspension system, brake, steering system, battery, seat, and gearbox[7].

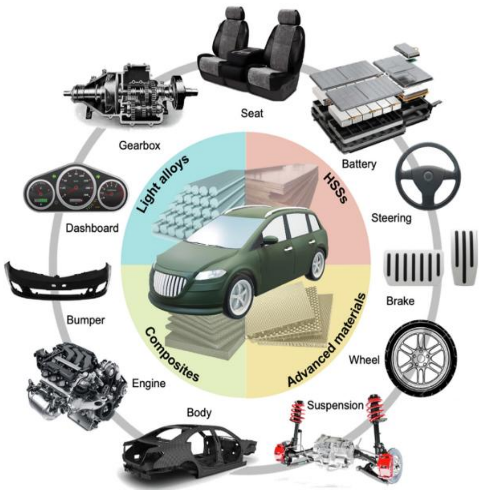

Fig.1 Representative lightweight materials applicable for different components of automobiles, including light alloys (e.g., aluminum, magnesium, and titanium alloys), HSSs, composites (e.g., CFRP), and advanced materials (e.g., metamaterials).[8]

Since 1960, there has been a high demand for new and advanced engineering materials with improved modern technology in the automotive and aerospace sectors, which has resulted in extensive research and development in the composite area. To meet this emerging need, material innovation has led to the enhancement of wear resistance, stiffness, and the realization of high[9]. In the twenty-first century, research scientists face a significant problem in developing engineered materials with a high strength-to-lightweight ratio and energy efficiency. Magnesium, with its low density in structural materials, has the potential to replace current metals and alloys such as steel, titanium alloys, plastic-based materials, and even aluminium alloys and composites. Initially, uses were restricted due to magnesium's high cost, but magnesium alloys are gaining favor due to superior solidification properties versus metals such as aluminium and copper alloys. As a consequence, composite materials have become the leading edge of research effort in many connected sectors[10].

Table 1 Weight reductions and cost increases of using advanced lightweight materials in place of low-carbon steel in automobile structures [11].

Material	Weight Reduction (%)	Relative Cost per Part (%)
Advanced high-strength steels (AHSS)	15–25	100–150
Glass fiber composites	25–35	100–150
Aluminum	40–50	130–200
Magnesium	55–60	150–250
Carbon-fiber composites	55–60	200–1000

Magnesium (Mg) is the lightest engineered metal, having a low density of 1.74 g/cm3[12].The specific strength and stiffness are superior to steel and aluminum (Al) alloy[13], and significantly superior than engineering plastics[14]. Mg has a stronger strength-to-weight ratio and superior casting properties than aluminum and steel materials[15]. Mg has no harmful properties when compared to other metals and polymers. Mg alloy has obvious advantages in thermal conductivity[16], vibration damping performance, and damping ability, broadening its application in the automotive field[17]. The steady development of magnesium alloys in many domains has resulted in the diversification of the casting process[18].Die casting and deformation are the two major components of the magnesium alloy forming process. Gravity casting, low-pressure casting, semi-solid casting, and other processes make up die casting mainly. Deformation is also known as plastic processing forming, which includes extrusion, forging, rolling, and so on[19]. In recent years, Zeng has taken a detailed look at additive manufacturing methods for Mg alloys, concentrating on the problems and potential in the area of mechanical metallurgy[20]. In 2013, Luo reviewed the history, current, and potential structural uses of Mg, with a focus on automotive applications[21]. Chongqing University summarized the trends of Mg alloys and dedicated to report and disseminate the global Mg alloy research Santamaría developed models to predict the mechanical properties of automotive Mg alloy die castings, allowing OEMs and designers to choose the best processing variables during design and simulation phases[22]. This opens up new possibilities for using Mg alloy in automotive components[23]. Golroudbary evaluated the reuse of Mg in automotive manufacturing processes as well as in casting and molding processes[24]. The research showed the considerable potential of Mg as a lightweight material for energy saving and emission reduction in the automotive industry. Although some literature reviewed the structural applications of Mg alloys in the automotive, aerospace, and power tool industries, most of the descriptions were not specific[25]. The performance advantages of Mg alloys allow researchers to carry out research in many areas, such as structural properties, functional materials, and die casting processes[26]. In addition to engineering applications, Mg is used in the health and biomedical industries due to its superior biodegradability[27]. In addition, in the literature, Alias reviewed Mg metal matrix composites as an attractive material with great potential in biodegradable and automotive components [28]. Yang showed that the control of microstructure and mechanical properties of Mg alloys has been the focus of research and revealed the future prospects of functional Mg materials, Mg alloy corrosion effective protection and degradation rate control, and Mg alloy advanced processing technology[29].

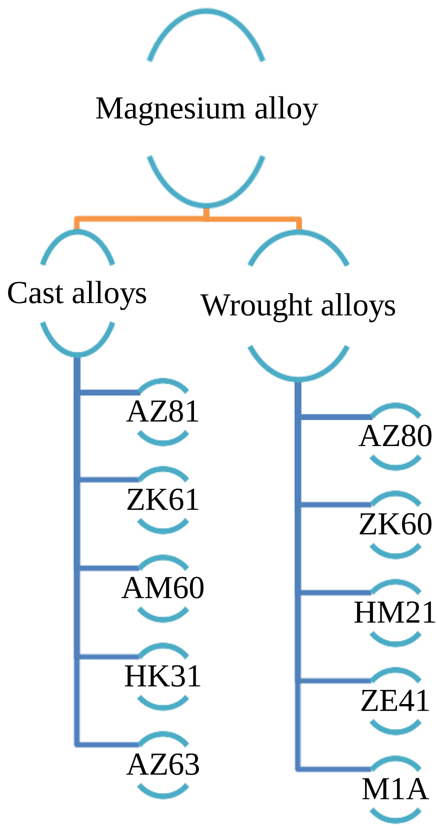

Fig 2. Types of Magnesium Alloy [30]

As one of the lightest structural metals, magnesium (Mg) and its alloys have attracted tremendous attention over the last few decades in many sectors such as the automotive sector where weight saving is a crucial factor for energy efficiency. Apart from high strength-to-weight ratio, they also offer high impact resistance, good castability and machinability. However, when compared to steel and aluminium, magnesium has several disadvantages, including low hardness and corrosion resistance. However, there are typical Mg alloys on the market that combine strong room temperature strength and ductility with improved corrosion resistance, such as aluminium-zinc (AZ60, AZ91) and aluminium-manganese (AM50, AM60)[31]. It should be noted that the predominant alloying ingredient in such alloys is aluminium, which improves castability and is useful for the production of complicated shaped technical components on bigger sizes at lower prices. It has been stated that about 90% of Mg-based automobile components, including fuel tank caps, steering wheels, and columns that are meant to work at room temperature, are manufactured from the aforementioned alloys [31].However, these alloys are far from providing required strength for powertrain applications subjected to elevated temperatures, such as gearbox housings. The reason for the poor high temperature strength is commonly attributed to the presence of aluminium, resulting in the formation of the Mg17Al12 β-phase, which has poor thermal stability[32].

1.1 Growing Need for Lightweight Materials

In the aerospace and automotive industries, the demand for lightweight materials has become increasingly critical due to the dual pressures of enhancing performance and meeting stringent environmental regulations[33]. The weight reduction of vehicles and aircraft directly correlates with improvements in fuel efficiency, performance, and overall emissions[34]. Consequently, manufacturers are under growing pressure to replace traditional materials, such as steel and aluminum, with advanced lightweight alternatives. Carbon fiber-reinforced magnesium alloy composites (CFRM) are at the forefront of this transformation. Magnesium is one of the lightest structural metals, possessing a density of approximately 1.74 g/cm^3, which is about one-quarter that of steel and one-third that of aluminum[35]. When reinforced with carbon fiber—known for its exceptional strength-to-weight ratio—this composite material offers a unique solution to the lightweight challenge. Carbon fiber exhibits tensile strengths exceeding 3,500 MPa, which significantly enhances the mechanical properties of magnesium alloys.

The integration of CFRM in aerospace applications can lead to significant weight savings[36]. For instance, replacing traditional aluminum components with CFRM can reduce weight by up to 30%, translating to substantial fuel savings over the lifespan of an aircraft [37]. According to the International Air Transport Association (IATA), a reduction of just 1% in aircraft weight can lead to a reduction in fuel consumption of 0.75%, which underscores the economic and environmental benefits of lightweight materials. In automotive applications, the push for electric vehicles (EVs) has further escalated the need for lightweight materials[38]. As EVs are inherently heavier due to their batteries, manufacturers are increasingly looking at CFRM to offset this weight. A study showed that using CFRM in the structural components of EVs can improve energy efficiency and range, making them more competitive with traditional vehicles.

Furthermore, regulatory frameworks such as the Corporate Average Fuel Economy (CAFE) standards in the U.S. and the European Union's stringent emission regulations are driving innovation in lightweight materials[39] . These regulations mandate a decrease in average fuel consumption and emissions, pushing automotive manufacturers to adopt materials like CFRM that can meet these targets. The technical challenges associated with CFRM, such as manufacturing costs and complex processing, are being addressed through advancements in composite fabrication techniques, which are making these materials more accessible. As industries continue to embrace lightweight solutions, CFRM composites will play a pivotal role in shaping the future of aerospace and automotive design, leading to safer, more efficient, and environmentally friendly vehicles[40].

2. State-Of-The-Art Analysis

The creation of Mg matrix nanocomposites reinforced with nanosized ceramic particles and carbon nanotubes with an average diameter of less than 100 nm has received recent interest[41]. Such reinforcing components have helped to improve the mechanical properties and creep resistance of Mg alloys by stimulating grain refining and Orowan strengthening (dislocations bending around the reinforcement). However, there are still certain obstacles surrounding the translation of these recently developed nanocomposites into industrial use. The first challenge is to obtain uniform dispersion and distribution of nano-sized reinforcements throughout the matrix for effective strengthening due to their large surface energy and low wettability in case of solidification processes. The second challenge is the potential harmful effect and health risks of using nanoparticles as the effects of nanoparticles on human body have not been entirely revealed yet. It is possible that nano-sized reinforcements may create major human health concerns throughout both the nanocomposite manufacture and servicing phases if they disintegrate from the matrix due to nanocomposite component failure[42]. Given the limitations of Mg matrix nanocomposites, one approach might be to further improve Mg matrix composites with micron-sized reinforcements, such as optimizing components and processing parameters, in order to provide high creep resistance Mg-based materials at acceptable prices. The aerospace and wind energy sectors are now using carbon fibre reinforced polymers (CFRPs) more often to save weight. As a result, recycling CFRPs from end-of-life items is critical for minimizing waste while also promoting environmentally friendly and sustainable production. It has been suggested to reuse recycled carbon fibers (rCFs) recovered from polymers using different procedures such as thermo-oxidation, pyrolysis, and solvolysis in order to create composites for the automobile sector[43]. It was reported in numerous studies that the rCFs, which are environmentally friendly and considerably less costly compared with virgin carbon fibres (vCFs), have been successfully incorporated into polymeric matrices[44]. The short CFs which will be chopped off from long and continuous rCFs can be reused for reinforcing metals as well. It is considered that replacing vCFs which have already proven their effectiveness in improving high temperature mechanical properties of Mg alloys with low cost rCFs as reinforcement can introduce a new class of eco-friendly Mg composites into the market. To the best of our knowledge, open literature sources so far suggested that there are only a few attempts reported for the use of rCFs in the Mg matrix composites fabricated by only solid state routes. However, no study was conducted to incorporate rCFs into liquid Mg matrices and determine their creep properties. Therefore, a brief review of the literature on Mg matrix composites reinforced with only short vCFs is covered here. Ajukumar et al. managed to obtain a distribution of short CFs into liquid AZ91 alloy with a good interfacial bonding by stir casting method, and found that the strength increases with increasing fibre content. Feld off researched the structure and chemistry of the AZ91 matrix-CF interface and proposed that plate-shaped carbide precipitates might be generated due to the chemical interaction between the carbon and the liquid Mg-Al matrix. This is predicted to change the strength of matrix-fibre bonding, hence influencing the mechanical properties of composites[45]. Kainer performed the first systematic effort to investigate the creep properties of Mg matrix composites reinforced with short carbon fibers[46]. In that study, AZ91/20 vol.% CF composites were fabricated by squeeze casting, and it was reported that the composites had higher elevated temperature strength and significant creep resistance than the monolithic alloy. Adding 20% CFs reduced the creep rate at 200 °C and 60MPa from 6.3×10^{-7} to 2.6×10^{-9} s^{-1}.

Table 2. The Comprehensive Features of Nano-Reinforced MMCs Are Reviewed.

Matrix in MMCs	Defects (Not in MMCs)	Special Properties (IN MMCs)	Refs.
AZ (Mg-Al-Zn)	(1) Low corrosion resisting (2) Low strength and hardness	(1) Excellent electromagnetic interference shielding performance (2) Preferable YS and UTS (3) Wear resistance (4) Used for additive manufacturing	[47]
WE (Mg-RE)	(1) Expensive (2) Rare earth purification	(1) Corrosion resistance (2) Creep resistance (3) Relatively cheap (compared to multi-component alloys)	[47]
Mg-Li	(1) Low modulus (2) Low strength and hardness	(1) Light weight (2) Specific modulus (3) Light while possessing high strength	[48]
Mg-Zr	Corrosion resistance	(1) Biocompatibility (2) Corrosion resistance (3) Non-toxic	[49]

3. Problem Statement

The world energy crisis has escalated significantly since the onset of the 21st century, prompting urgent action across various industries. In the automotive sector, reducing fuel consumption and emissions are critical challenges that must be addressed to create sustainable transportation solutions. Traditional materials like aluminum and steel, while widely used, contribute to the weight of vehicles, which directly impacts fuel efficiency and greenhouse gas emissions. Therefore, there is an urgent need to identify and develop alternative materials that can enhance lightweight design while maintaining or improving mechanical properties.

Carbon fiber-reinforced magnesium alloy composites present a promising solution for these challenges. By exploring these advanced materials, we can potentially revolutionize design approaches in not only the automotive industry but also in aerospace applications and civil engineering structures. The goal is to achieve a significant reduction in vehicle weight without compromising structural integrity, thus facilitating lower fuel consumption and improved overall efficiency. This investigation will focus on the mechanical properties of these composites and their applicability in various sectors, including automotive, aeronautics, and marine industries. Ultimately, the shift to lightweight materials is essential for meeting emission reduction targets and promoting sustainable development across multiple engineering fields.

4. Research Method and Materials

4.1 Methods

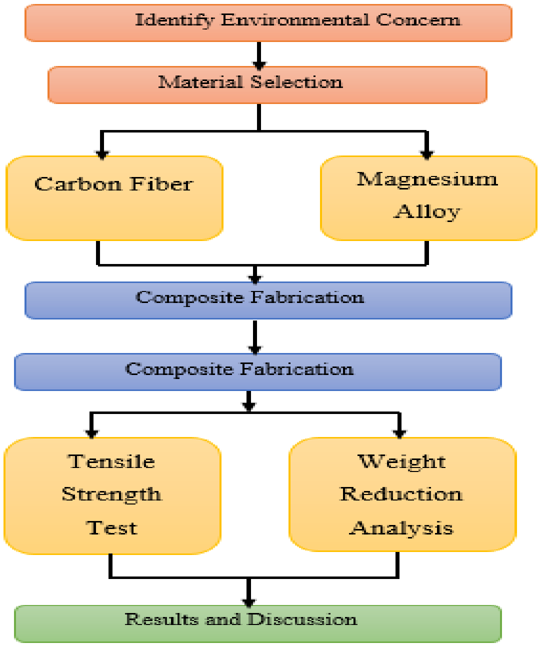

Fig.3 Methodology Flow

4.2 Materials

4.2.1 Magnesium alloy matrix

Lightweight magnesium, with its exceptionally low density, superior machinability, and structural properties, may satisfy the needs of energy savings and emission reduction in the transportation sector and other automotive applications [50], However, there are still some barriers in the intended usage of magnesium[51], such as low elastic modulus and ductility, poor creep and abrasion resistance, and a high corrosion rate. To To overcome these constraints, past investigations have used alloying elements or reinforcements in magnesium. [52], The addition of particle reinforcements to the magnesium matrix has been shown to boost the mechanical properties in addition to precipitation[53] strengthening, grain refinement strengthening, and solid solution strengthening provided by the alloying element.[54]. Magnesium matrix composites (MMCs) may include a range of particle reinforcements, such as carbides (SiC, TiC, B4C, ZrC), oxides (Al2O3, TiO2), borides (ZrB2, TiB2), nitrides (AlN, BN, ZrN, TiN), and metals[55]. It has been proven that MMCs including one or more typical micron size particle reinforcements and continuous magnesium matrix provide notable advantages over monolithic magnesium, such as high strength, modulus, and wear properties[56].

This work focuses on the creation of the magnesium alloy Mg-2Al-0.04Zr-0.01 Fe. Where Mg- Magnesium and Al- Aluminum Zr- Zincronium. The magnesium alloy matrix (Mg-2Al-

0.04Zr-0.01Fe) is an ideal composition for the production of high-performance composites[57]. The foundation material is magnesium (Mg), which is known for its lightweight properties, with 2% aluminum (Al) added to strengthen the alloy and improve corrosion resistance. Aluminum also improves the material's mechanical properties, making the alloy more resistant to stress. Zirconium (Zr), which is found in trace amounts (0.04%), functions as a grain refiner. This means that it contributes to the management of the magnesium alloy's grain structure, hence boosting toughness and strength. Even though iron (Fe) is present at just 0.01%, it must be controlled carefully since higher quantities of iron might reduce magnesium alloys' corrosion resistance,[58].

When carbon fiber is utilized as a reinforcing material, the magnesium alloy matrix produces a high strength-to-weight ratio. This makes it ideal for applications requiring great strength while yet being lightweight. The Mg-2Al-0.04Zr-0.01Fe composite, reinforced with carbon fiber, not only increases structural integrity but also results in significant weight savings—up to 82% compared to steel and 35% compared to aluminum. This allows for lighter, stronger components, which are crucial in industries like as automotive manufacturing, where reducing vehicle weight directly corresponds to increased fuel economy and fewer carbon emissions. Similarly, in aerospace, this material might dramatically reduce aircraft bulk, hence improving flying performance and fuel economy.

4.2.2 Carbon fibers

Carbon is maybe the most magnificent element in nature. Tailoring carbon structure allows for an astonishing amount of distinct configurations at various length scales. [59], [60],[61]. Extensive research has led to the synthesis of different forms of carbon-based materials, such as graphene, carbon fiber, fullerenes and nanotubes[62], [63], [64], [65], [66]The diversified morphology of different carbon-based materials, its availability and the flexibility of modifying physical properties are some primary reasons for attracting a higher attention compared to the other elements in modern materials science. Carbon fiber is one of the interesting carbonaceous material with excellent mechanical properties and ultimate chemical stability. Generally , materials containing more than 92 wt% of carbon and forming a fiber shape are defined as carbon fibers[67]. These fibers provide increased mechanical and physical properties. [68], [69], [70], [71]The material exhibits high tensile strength (2∼7 GPa), compressive strength, high Young's modulus (200∼900 GPa), low density (1.75∼2.20 g/cm3), moderate thermal expansion, and good electrical and thermal conductivity (~800 Wm-1K-1). [72], [73], [74], [75]. Carbon fiber also provides a strong chemical resistance to all chemical species, except in the presence of hot air or flame[76]. Not only is carbon fiber at least four times lighter than steel, but it also possesses more strength than steel.[77]. These fibers are also lighter than other alloying elements (Mn, Zn, Zr, etc.) that are often employed to strengthen aluminium or magnesium.[78]. This is the major benefit of using carbon fibers to create lightweight composite materials for structural purposes. Carbon fibers offer high thermal strength and self-lubricating actions, resulting in increased toughness and tribological properties in CF reinforced MMCs.[79], [80], [81],[82]. Carbon fibers are used as reinforcement or based material in vehicles, airplanes, boats, machine components, turbine blades, pressure tanks, high-quality sports goods, military sectors, and civil engineering, to mention a few.

4.3 Analytical Study

Strength analysis of carbon fiber reinforced magnesium alloy matrix composite material. Strength of composite by the rule of mixtures equation. The material specifications for the carbon fiber reinforced magnesium alloy matrix composite are as follows: the weight of the fibers (Wf) is 14 g, while the weight of the magnesium alloy matrix (Wm) is 476 g. The strength of the matrix (σm) is measured at 345 N/mm², whereas the strength of the fibers (σf) is significantly higher at 5000 N/mm². Additionally, the density of the fibers (ρf) is 1.7 g/cm³, and the density of the matrix (ρm) is 1.8 g/cm³. These properties are crucial for understanding the performance and applications of the composite material.

Total Weight of Composite:

$$\mathrm{Wc} = \mathrm{Wf} + \mathrm{Wm} \qquad (1)$$

Volume Fraction of Fibers:

$$\mathrm{Vf} = (\mathrm{Wf} / \rho\mathrm{f}) / [(\mathrm{Wf} / \rho\mathrm{f}) + (\mathrm{Wm} / \rho\mathrm{m})] \qquad (2)$$

Volume Fraction of Matrix:

$$\mathrm{Vm} = 1 - \mathrm{Vf} \qquad (3)$$

Strength of Composite:

$$\sigma\mathrm{c} = (\sigma\mathrm{m} \times \mathrm{Vm}) + (\sigma\mathrm{f} \times \mathrm{Vf}) \qquad (4)$$

Density of Composite:

$$\rho\mathrm{c} = (\rho\mathrm{f} \times \mathrm{Vf}) + (\rho\mathrm{m} \times \mathrm{Vm}) \qquad (5)$$

5. Experimental Procedure

Development of Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material

The Cf/Mg composites were created using a liquid-solid extrusion process. AZ91D magnesium alloy was selected as the matrix, as well as its components. Carbon fibers were used as reinforced materials in addition to the T300-1 k. The process of making Cf/Mg composites mainly included alloy melting, extrusion dipping, and liquid-solid forming. The schematic diagram of equipment for manufacturing Cf/Mg composites using a liquid-solid extrusion process is given in the picture below. First, sandpaper was used to remove the oxide deposit from the surface of the AZ91D magnesium alloy. The carbon fiber preform and magnesium alloy were placed in the die in sequence and sealed with graphite blocks on top. The die and preform were heated to 854 K-924 K, while magnesium alloy was smelted for 1-2 hours, with the interior temperature of the die monitored in real time by thermocouples. At the conclusion of the holding phase, the hydraulic press was used to gently extrude the molten magnesium alloy fluid into the carbon fiber preform while keeping the extrusion pressure at 20-30 MPa. Finally, when the device had cooled to room temperature, the composites were capped with a convex mold.[83]. The volume fraction of carbon fibers in the Cf/Mg composites prepared by this method is 40-50%.

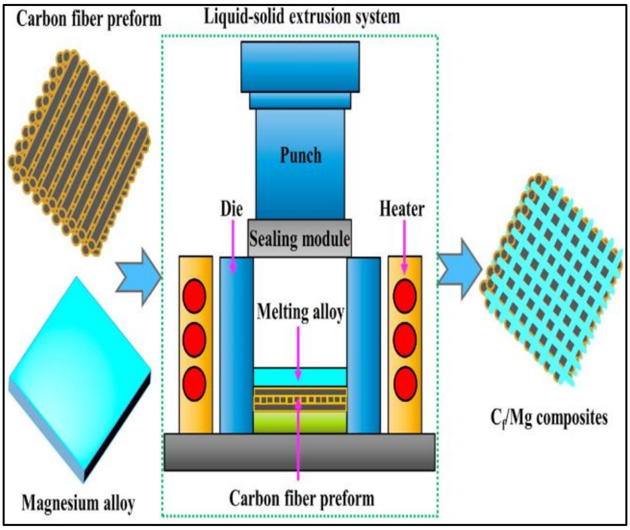

Fig.4 The schematic diagram of equipment for preparing carbon fiber reinforced magnesium alloy matrix composite material by a liquid-solid extrusion method[84]

The Cf/Mg composites with a density of 1.7-1.8 g/cm3 were processed into cuboids with a size of 10 10 5 mm^3 for the corrosion test. Then the samples were polished by 400 #, 800 #, 1200 #, and 2000 # sandpapers in turn to remove the native oxide, next cleaned with alcohol for 5e10 min and dried in a vacuum drying oven.

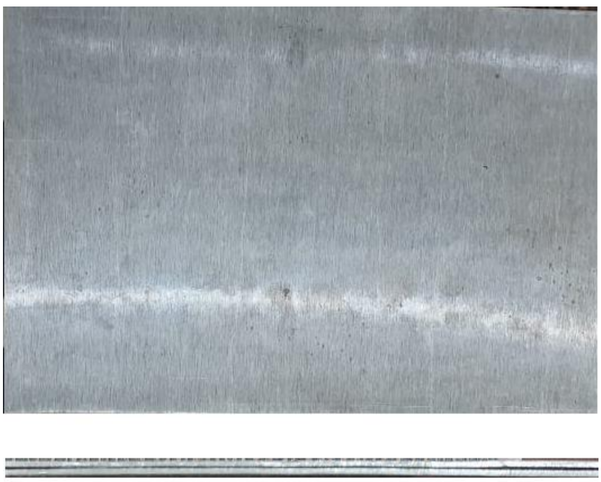

Fig.5 Carbon Fiber Reinforced Magnesium Alloy Composite Material

Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material (CFR-Mg) is developed using a systematic method that combines modern material science and engineering techniques. The main goal is to develop a composite with better mechanical properties, such as a high strength-to-weight ratio, increased stiffness, and improved fatigue resistance, making it an excellent choice for lightweight applications in the automotive and aerospace sectors.

The process starts with selecting suitable carbon fibers, which are recognized for their high tensile strength and stiffness. These fibers are generally made up of carbon atoms organized in a crystalline structure, with an ultimate tensile stress of around 5000 MPa. The magnesium alloy matrix, often known as Mg-2Al-0.04Zr-0.01Fe, serves as the base material, delivering a low weight alternative to standard metals like steel and aluminum. The coupling of carbon fibers with a matrix of magnesium fibers results in a composite material that not only decreases weight but also enhances performance.

CFR-Mg composites are made using a variety of techniques, the most common of which being liquid-solid extrusion. This procedure includes melting the magnesium alloy ratio, then incorporating carbon fibers into the molten ratio. The mixture is then extruded to achieve the required shape, ensuring that fibers are evenly distributed throughout the matrix. This process is critical for achieving ideal mechanical properties and ensuring the composite material's integrity.

In addition to the manufacturing process, thorough testing and performance analysis are required to evaluate the behavior of CFR-Mg composites under a variety of situations. This includes stress analysis, failure analysis, fatigue studies, and creep studies, which aid in identifying possible technical issues related with the use of these materials. By addressing these issues, researchers may provide design recommendations that will ease the transition from old materials to CFR-Mg composites, opening the path for their use in current engineering solutions.

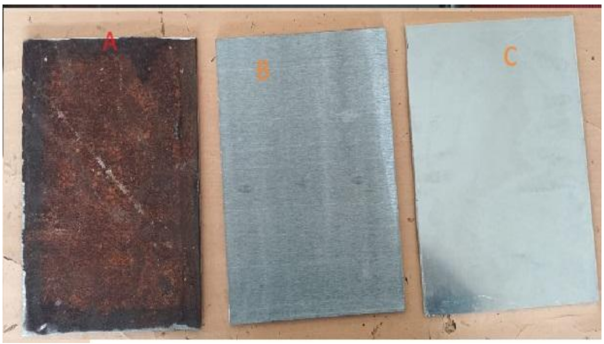

Fig 6 A: Steel specimen, B: Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material specimen., C: Aluminum specimen.

1. Weight of CFRMg Composite Versus Aluminum and Steel

The comparative weight analysis of Carbon Fiber Reinforced Magnesium Alloy Matrix Composite (CFR-Mg) with traditional materials such as aluminum and steel is critical for understanding its potential benefits in light force applications. To achieve a standardized comparison, specimens of CFR-Mg, aluminum, and steel were manufactured with dimensions of 200 mm x 300 mm x 5 mm for this study.

		
Fig 7 a) Weight of Steel specimen.	Fig b)Weight of Aluminum specimen.	Fig c) Weight of CFRMg Composite specimen.

2.Weight of Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material Versus Aluminum and Steel.

Weight of one meter by one meter having Thickness one mm

Table 3 Weight Observations of Various Materials

Sr.No.	Material.	Observations of Weight (Kg).
01	Steel (M.S).	8.1
02	Aluminum.	2.3
03	CFRMg Composites.	1.7

Following are the weight measurements for different materials: Mild steel (M.S.) weighs 8.1 kg, aluminum weighs 2.3 kg, and carbon fiber reinforced magnesium alloy matrix composite material (CFRMg) weights 1.7 kg. The comparative analysis of these materials shows considerable weight disparities, which are critical for applications where weight reduction is critical, such as aerospace, automotive, and athletic goods. Aluminum is 73% lighter than mild steel. Due to aluminum's lower density (2.7 g/cm3 compared to steel's 7.85 g/cm3), there has been a significant weight reduction. The lower weight of aluminum provides for increased structural efficiency, improved fuel efficiency in vehicles, and reduced total bulk of structures without sacrificing structural integrity.

Comparison of CFRMg Composites to Steel: When compared to Mild Steel, the CFRMg composite material has an astounding 82% weight reduction. This extraordinary lightweight feature is mostly due to the inclusion of carbon fibers and the usage of magnesium as the matrix material. Carbon fibers offer a high strength-to-weight ratio, while magnesium is among the lightest structural metals available. The combination of these materials results in a composite that saves substantial weight, making it an excellent contender for applications requiring both strength and low weight.

When compared to aluminum, CFRMg composites are 35% lighter. While aluminum is already a lightweight material, the CFRMg composite lowers weight even further, making it an appealing choice for applications that need materials that not only enhance performance via weight savings but also preserve or improve strength and stiffness. This property is especially advantageous in companies focused on enhancing energy efficiency and performance measures. Finally, the findings illustrate the significant benefits of utilizing CFRMg composites over traditional composite materials like Mild Steel and Aluminum. Weight reduction may contribute to enhanced performance in a variety of applications, advancing design and efficiency across several industries.

Table 4 Weight Measurement of Selected Materials in Grams

Sr.No	Material	Weight (gm.)
01	Steel (M.S)	2360
02	Aluminum	830
03	CFRMg Composites.	490

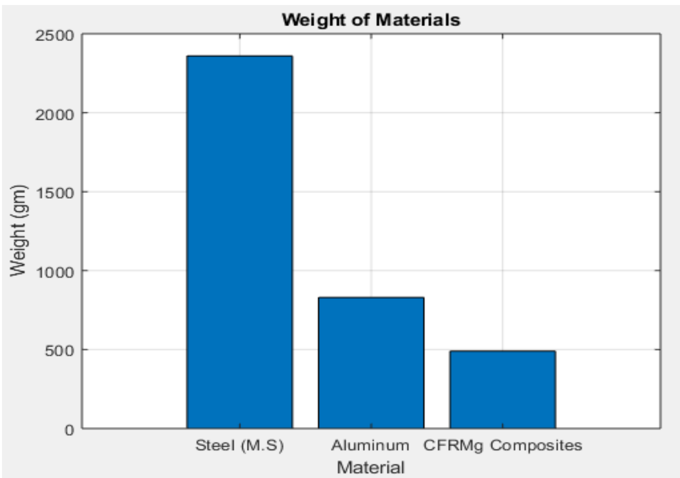

Fig 8 Weight of Materials

The specimens evaluated, measuring 200 mm x 300 mm x 5 mm, show considerable weight variations between the three materials tested: mild steel (M.S.), aluminum, and carbon fiber reinforced magnesium alloy matrix composite material (CFRMg). The reported weights of the specimens are as follows: Mild steel weighs 2360 g; aluminum weighs 830 g; and CFRMg composites weigh 490 g. These findings highlight the varying properties and possible applications of each material dependent on its weight.

Aluminum vs. Steel: The Aluminum specimen's weight is 830 g, indicating that it is substantially lighter than the Mild Steel specimen, which weighs 2360 g. Aluminum is roughly 65% lighter than mild steel in this situation. This weight reduction is mostly due to aluminum's lower density, making it a preferred material in areas where decreasing the total weight of structures or components is critical, such as automotive and aerospace applications.

The CFRMg composite material shows a remarkable weight of 490 g, making it roughly 79% lighter than Mild Steel. This significant weight reduction is due to a unique blend of carbon fibers and magnesium matrix. A composite that can preserve structural integrity while drastically lowering bulk is created by the high strength-to-weight ratio of carbon fibers and the low density of magnesium. This property makes CFRMg composites very useful in high-performance applications, where weight reduction may contribute to increased efficiency and performance. When comparing CFRMg composites to aluminum, the weight difference is much greater, with CFRMg being around 41% lighter than aluminum. In applications where weight reductions are critical, CFRMg composites have the potential to outperform aluminum while maintaining the requisite mechanical properties for structural applications.

In conclusion, the specimen weight observations show the obvious benefits of using CFRMg composites over traditional composite materials like Mild Steel and Aluminum. CFRMg composites' large weight reductions not only enhance performance, but also offer up new opportunities for creativity in design and material choices across a wide range of engineering disciplines. This underscores the rising importance of lightweight materials in developing technology and increasing energy efficiency in a wide range of applications.

3.Tensile Test of Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material

Tensile testing is a basic mechanical test in which a standard specimen is loaded in uniaxial tension while the applied load and specimen elongation are measured over a certain distance. Tensile tests are used to calculate ultimate tensile strength, yield strength, elongation, reduction in area, modulus of elasticity, and other tensile parameters. A tensile test produces a load against elongation curve, which is subsequently transformed to a stress vs strain curve. The Ultimate Tensile Strength may be calculated by dividing the load by the area of the specimen shape under test. The tensile test on Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material was done at S. N. Metallurgical Services (NBL) at Waluj MIDC, Aurangabad. The laboratory reference number for this test is N-06976, and the testing date is July 8, 2024. The unique laboratory report number is TC512724000009898F. The tensile test results give critical insights into the mechanical properties of the composite material, as stated below:

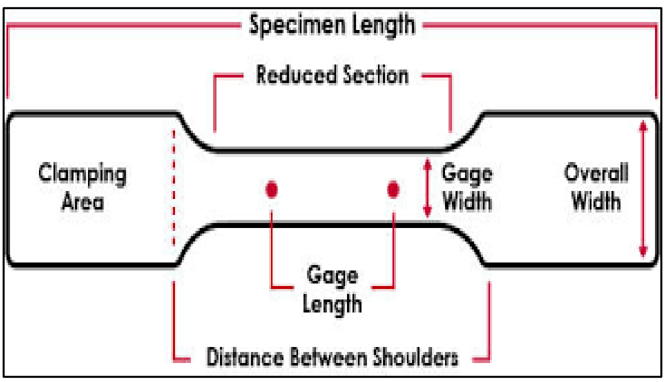

Fig 9 Tensile test specimen[85]

This specimen is a standardized sample used in material testing to measure a material's mechanical characteristics, including tensile strength, yield strength, and elongation. The specimen's entire length is 460 mm. The reduced segment, where the most severe deformation and fracture occur, is 230 mm in length and 38 mm in width. The grip sections at both ends, meant to be grasped by the testing machine, measure 76 mm in length and 50 mm in width. The specimen's thickness is 5 mm, and the fillet radius, or the radius of the curve at the intersection of the grip and reduced sections, is 25 mm. During a tensile test, this specimen is pulled apart in a controlled way to determine the force and elongation. This information is utilized to determine the mechanical characteristics of the material.

Fig 10 Compression Testing Machine Setup for Material Strength Analysis

Table 5 Mechanical Properties and Observations of Material Tests

Sr.No	Test Conducted	Observations
01	Ultimate Tensile Strength N/mm^2	411.32
02	% of Elongation	12.52
03	Yield Strength N/mm^2	378.05
04	Strength to Weight Ratio.	0.83

The highest tensile strength of the composite material is 411.32 N/mm^2. This value represents the maximum stress that a material can withstand while being stretched or pulled before failing. The high UTS indicates that the CFRMg composite has exceptional resistance to tensile loads, making it appropriate for applications that need materials that can withstand high stresses without breaking.

Percentage of Elongation: The percentage of elongation at break is 12.52%. This statistic measures the material's ductility and ability to flex plastically prior to failure. The CFRMg composite's 12.52% elongation shows that it can withstand significant deformation, which is useful in applications that demand impact resistance and flexibility. This property enhances the material's performance under dynamic load circumstances.

The CFRMg composite has a yield strength of 378.05 N/mm^2. Yield strength refers to the stress at which a material starts to distort plastically. This value implies that the CFRMg composite can withstand significant loads before undergoing irreversible deformation. The material's relatively high yield strength enhances its potential for structural applications, ensuring that it can withstand significant operating loads.

The strength-to-weight ratio is determined at 0.83. This ratio is an important metric in material selection, particularly in sectors where weight reduction is required without sacrificing strength. A high strength-to-weight ratio indicates that the CFRMg composite has better mechanical performance in comparison to its weight, making it an ideal option for applications in aerospace, automotive, and other technical disciplines where both strength and weight reductions are critical.

Finally, the tensile test results show that the Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material has extraordinary mechanical properties, such as high ultimate tensile strength, good ductility, considerable yield strength, and an excellent strength-to-weight ratio. These properties emphasize the material's potential for a wide range of technical applications, emphasizing the benefits of using CFRMg composites in current design and production processes.

Table 6 Material Properties Analysis: Tensile Strength, Weight, and Efficiency

Sr.No	Material	Tensile Strength N/mm^2	Weight (gm.)	Strength to Weight Ratio
01	Steel (M.S)	560	2360	0.237
02	Aluminum	276	830	0.33
03	CFRMg Composites.	411	490	0.83

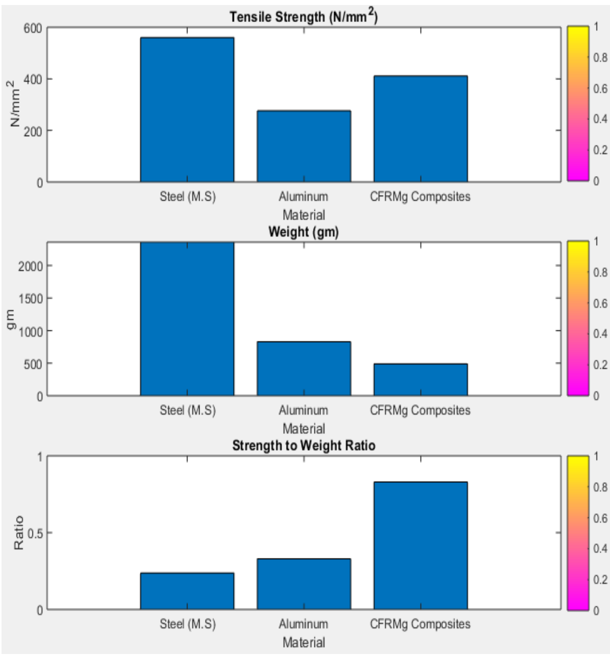

Fig 11 Comparison of Tensile Strength, Weight, and Strength-to-Weight Ratio for Different Materials

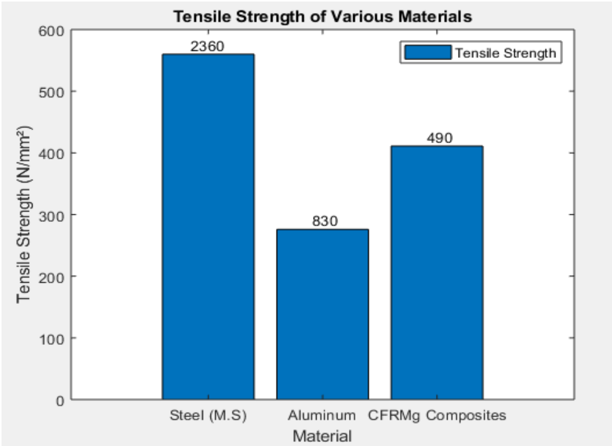

Fig 12 Tensile Strength of Various Materials

On specimens measuring 200 mm x 300 mm x 5 mm, the tensile test results for materials such as Mild Steel (M.S.), Aluminum, and Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material (CFRMg) were examined. The results are summarized as follows.

Mild steel (M.S.) has a tensile strength of 560 N/mm² and weighs 2360 g, yielding a strength-to-weight ratio of 0.237. This comparatively low strength-to-weight ratio demonstrates that, although Mild Steel has high tensile strength, its higher weight restricts its use in scenarios where weight reductions are critical.

Aluminum has a tensile strength of 276 N/mm² and weighs 830 g, resulting in a strength-to-weight ratio of 0.33. This ratio suggests that Aluminum has a reasonable balance between strength and weight, making it appropriate for applications where decreasing weight is important but increased strength is not as critical.

CFR-Mg Composites: The tensile strength is 411 N/mm² at a weight of 490 g, resulting in an outstanding strength-to-weight ratio of 0.83. This high ratio of strength to weight demonstrates the material's ability to provide tremendous strength while keeping a much lower weight compared to traditional materials.

Comparative analysis: CFRMg composites provide a very high strength-to-weight ratio. It is roughly 2.5 times larger than that of aluminum (0.83 time to 0.33), demonstrating the better performance of CFRMg in applications where conserving weight while boosting strength is crucial. CFRMg composites are therefore a particularly advantageous alternative for sophisticated technical applications in areas like as aerospace and automotive, where both performance and efficiency are critical.

Furthermore, as compared to Mild Steel, CFRMg composites have a strength-to-weight ratio that is almost four times stronger (0.83 against 0.237). This considerable increase highlights the potential of CFRMg composites to replace heavier materials like Mild Steel in applications where lowering overall weight is critical without sacrificing structural integrity.

In conclusion, the analysis of force strength and weight demonstrates that Carbon Fiber Reinforced Magnesium Alloy Matrix Composite Material not only delivers higher force strength but also excels in force-to-weight ratio when compared to traditional materials like Mild Steel and Aluminum. These qualities make CFRMg composites an attractive option for novel applications needing lightweight and durable materials.

Outcome of Analytical and Experimental Study

Table 7 Comparison of Material Properties for Structural Applications

Material	Mass in Kg/cm^3	Ultimate Stress (UTS) in N/mm^2	Cost of Material Per Kg. in Rs.
Steel (A36, 1090 mild, Chromium vanadium steel).	7.89	450-850	125
Aluminum	2.7	310	415
Magnesium metal Ingots.	1.7	200	168
Aluminum alloy	3.8	410	475
Magnesium – Aluminum alloy	2.2	240	360
Magnesium RE alloy	3.2	350	2500
Carbon fiber polymer composite	1.76	1500	5000
Carbon fiber reinforced magnesium alloy matrix composite.	1.78 (Case-I)	486	650
(New material Developed)	1.76 (Case-II)	583	850

4. Comparison with Aluminum and Steel

The analytical and experimental study provides a thorough evaluation of various materials, focusing on their mass, ultimate tensile strength (UTS), and cost per kilogram. The following materials are included in this analysis: Steel (A36, 1090 mild, Chromium vanadium steel), Aluminum, Magnesium metal ingots, Aluminum alloys, Magnesium-Aluminum alloys, Magnesium RE alloys, Carbon fiber polymer composites, and the recently developed Carbon Fiber Reinforced Magnesium Alloy Matrix Composite.

Steel: The ultimate stress of steel is between 450 and 850 N/mm², and it has a density of 7.89 kg/cm³. The cost per kilogram is ₹125. The moderate cost and high strength of steel render it a popular choice for heavy-duty applications. Aluminum is more expensive at ₹415 per kilogram, with a density of 2.7 kg/cm³ and an ultimate stress of 310 N/mm². In applications where minimizing weight is critical, its lower weight compared to steel provides advantages.

Magnesium Metal Ingots: Magnesium is priced at ₹168 per kilogram and has a density of 1.7 kg/cm³ and an ultimate stress of 200 N/mm². Although it is lightweight, its applicability in heavy-duty vehicles is restricted by its lower strength.

Aluminum Alloy: This material offers increased strength over standard aluminum and has a density of 3.8 kg/cm3, a UTS of 410 N/mm2, and costs 475 per kilogram. ₹360 per kilogram is the cost of Magnesium-Aluminum Alloy, which has a density of 2.2 kg/cm³ and a UTS of 240 N/mm². The properties of both metals are harmoniously balanced by this alloy. Magnesium RE Alloy: With a high density of 3.2 kg/cm3 and a high UTS of 350 N/mm2, its cost is substantially higher at $2500 per kilogram, making it less cost-effective for certain applications. Carbon Fiber Polymer Composite: This lightweight composite boasts a remarkable UTS of 1500 N/mm² and a density of 1.76 kg/cm³. However, its cost is exorbitant at ₹5000 per kilogram.

For this new material, two cases were evaluated: Carbon Fiber Reinforced Magnesium Alloy Matrix Composite. In Case I, the material has a cost of ₹650 per kilogram, a UTS of 486 N/mm², and a density of 1.78 kg/cm³. In Case II, the density is marginally lower at 1.76 kg/cm³, with a higher UTS of 583 N/mm² and a cost of ₹850 per kilogram.

In contrast to steel and aluminum, The importance of comparing the properties of Steel, Aluminum, and the recently developed Carbon Fiber Reinforced Magnesium Alloy Composites is highlighted by the increased demand for materials used in the production of heavy-duty vehicles. Weight Savings: In comparison to both Aluminum and Steel, the Carbon Fiber Reinforced Magnesium Alloy Composites offer significant weight savings. In particular, these composite materials can produce structures that are 40-45% lighter than conventional Aluminum structures that are designed to satisfy identical functional requirements. The lower density of the composites, enhancing vehicle efficiency and performance, is primarily responsible for this weight reduction.

In conclusion, the findings highlight the potential of Carbon Fiber Reinforced Magnesium Alloy Matrix Composites as a viable alternative to traditional materials in the production of heavy-duty vehicles. These composites offer competitive weight force and significant weight savings. To completely capitalize on these composites' advantages in various engineering ratios, the study recommends further investigation.

6. Conclusion

The feasibility of carbon fiber reinforced magnesium alloy composites as cutting-edge materials for high performance composite applications in the automotive and aerospace industries has been effectively shown by this research. The study analyzed the AZ91 magnesium alloy matrix, which has a low density of 1.74 g/cm³ and high specific strength, making it suitable for lightweight applications. The addition of carbon fibers at varying percentage ratios (3% and 5%) greatly boosted the composite's mechanical properties.

The testing results revealed a significant increase in ultimate tensile strength (UTS), with values reaching up to 500 N/mm² for reinforced composites, compared to 200 N/mm² for unreinforced magnesium alloy. This increase highlights the effectiveness of carbon fiber reinforcement in enhancing the structural integrity of magnesium alloys, making them suitable for applications where strength is required. At 200 °C and 60 MPa, the composites showed a notable reduction in creep rate, dropping from 6.3 107 s1 to 2.6 109 s1, indicating increased composite performance under high temperatures.

Furthermore, the study emphasized the composites' greater damping loss factor, indicating increased energy absorption capabilities. This feature is especially useful in applications that need vibration dampening and noise reduction, expanding the potential use cases for these materials. The weight reduction obtained via the use of carbon fiber reinforced composites—approximately 41% lighter than aluminum—provides considerable benefits in terms of energy force and performance. In businesses that must adhere to strict pollution and fuel consumption rules, this aspect is critical.

In conclusion, the findings of this research not only validate the promise of carbon fiber reinforced magnesium alloy composites as a lightweight alternative to traditional materials, but also highlight their superior mechanical properties, making them suitable for creative engineering solutions. Future research will concentrate on improving processing techniques, investigating hybrid reinforcement strategies, and performing long-term durability studies to further enhance the performance and usability of these advanced composite materials. The continued progress in this sector has the potential to dramatically enhance lightweight engineering materials, eventually leading to more sustainable and efficient solutions in a variety of industries.

7. Future Scope

The research on carbon fiber reinforced composites gives up various avenues for further inquiry and development. One potential direction is the optimization of fiber orientation and length, which might have a substantial impact on the mechanical properties of composites. Understanding how these characteristics influence strength, stiffness, and impact resistance might lead to the development of custom composites for particular applications. Furthermore, looking into hybrid reinforcing strategies, such as blending carbon fibers with other materials like glass or natural fibers, might enhance overall performance by striking a balance between cost, environmental sustainability, and mechanical properties.

To increase the integration of carbon fibers inside the magnesium matrix, further research into sophisticated processing techniques, such as additive manufacturing and improved casting methods, is required. These techniques may enhance composite structure homogeneity and maximize mechanical performance. Long-term durability studies are particularly important for establishing the environmental resistance of composites under diverse situations, such as temperature changes, humidity, and corrosive environments, and therefore estimating their longevity and reliability in real-world applications.

Furthermore, determining the cost-effectiveness of manufacturing these composites is critical to their economic viability. Exploring recycling methods for both carbon fibers and magnesium alloys might help to promote sustainable manufacturing practices and decrease environmental impact. Application-specific studies should concentrate on assessing the performance of these composites in real-world scenarios, notably in automotive components and aerospace structures where weight reduction and mechanical performance are critical.

Using computational methods such as finite element analysis (FEA) to model the behavior of these composites under different loading circumstances may give useful insights into their performance, allowing for the optimization of design parameters prior to physical prototype. Finally, investigating the integration of smart technologies, such as sensors and monitoring systems, into composite materials may lead to the development of intelligent structures capable of monitoring their own health and performance in real time. By exploring these avenues, future research may considerably enhance the understanding and use of carbon fiber reinforced composites, eventually leading to creative solutions that match the needs of current engineering issues.

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