Development And Characterization of Al6065 Aluminum Matrix Composites Reinforced with Almond Shell Ash

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Abstract — Aluminum matrix composites (AMCs) have gained considerable attention in recent years owing to their superior strength-to-weight ratio, enhanced wear resistance, and improved corrosion performance compared to conventional alloys. This study presents a comprehensive comparative analysis of aluminum-based composites reinforced with silicon carbide (SiC), cenospheres, and corn cob ash (CCA), fabricated using both conventional stir casting and ultrasonic-assisted stir casting techniques. The influence of reinforcement type, weight fraction, and processing method on key properties such as tensile strength, hardness, corrosion resistance, and tribological behavior is systematically evaluated. The results indicate that the incorporation of hard ceramic particles significantly enhances tensile strength and hardness through effective load transfer and grain refinement mechanisms. However, excessive reinforcement leads to particle agglomeration, resulting in localized defects and reduced mechanical performance. Corrosion resistance is observed to improve due to the formation of a stable oxide layer and improved interfacial bonding. In terms of tribological performance, optimal wear resistance is achieved at moderate reinforcement levels, particularly in composites containing agro-waste-based reinforcements such as corn cob ash. Furthermore, the application of the Adaptive Neuro-Fuzzy Inference System (ANFIS) demonstrates high accuracy in predicting wear behavior, highlighting its potential for advanced material design and optimization.

Keywords: Aluminum Matrix Composites, Silicon Carbide, Cenosphere, Corn Cob Ash, Stir Casting, Ultrasonic Casting, Wear Behaviour, Corrosion Resistance, ANFIS

I. INTRODUCTION

The rapid evolution of modern engineering applications has significantly increased the demand for materials that can simultaneously offer high strength, reduced weight, improved wear resistance, and enhanced corrosion performance. Conventional engineering materials, although widely used,often fail to meet these combined requirements, especially in critical sectors such as aerospace, automotive, and marine industries. In this context, aluminum matrix composites (AMCs) have emerged as a promising class of advanced materials due to their ability to combine the desirable properties of metals and ceramics.

Aluminum and its alloys are extensively utilized because of their low density, good corrosion resistance, and excellent machinability. However, their relatively low hardness and poor wear resistance limit their applicability in high-load and high-friction environments. To address these limitations, reinforcement materials are incorporated into the aluminum matrix, leading to the development of AMCs with significantly improved mechanical and tribological properties. Among various reinforcement materials, silicon carbide (SiC) has been widely adopted due to its high hardness, thermal stability, and excellent load-bearing capability.

In addition to conventional ceramic reinforcements, lightweight fillers such as cenospheres have gained attention due to their ability to reduce the overall density of composites while maintaining structural integrity. Cenospheres, being hollow and inert particles, contribute to improved thermal stability and damping properties without significantly compromising strength. Furthermore, recent research has focused on the utilization of agro-waste materials such as corn cob ash (CCA) as reinforcement. These materials not only enhance wear resistance due to their silica-rich composition but also promote environmental sustainability by utilizing industrial and agricultural waste.

The fabrication technique plays a crucial role in determining the final properties of AMCs. Among various processing methods, stir casting is widely preferred due to its simplicity, cost-effectiveness, and suitability for large-scale production. However, conventional stir casting often suffers from challenges such as non-uniform particle distribution, poor wettability, and particle agglomeration. These issues can significantly affect the mechanical performance of the composite. To overcome these limitations, advanced processing techniques such as ultrasonic-assisted stir casting have been developed. The introduction of ultrasonic vibrations into the molten metal improves particle dispersion through cavitation effects, resulting in enhanced microstructural uniformity and improved interfacial bonding.

Another important aspect of AMC research is the evaluation of tribological behavior, which is critical for applications involving sliding or contact surfaces. The presence of hard reinforcement particles reduces material loss by acting as load-bearing elements and minimizing direct metal-to-metal contact. However, the wear performance is highly dependent on factors such as reinforcement type, particle size, distribution, and operating conditions. Therefore, optimizing these parameters is essential for achieving superior performance.

In recent years, artificial intelligence (AI)-based techniques have been increasingly applied in material science to predict material behavior and optimize performance. Models such as Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) have demonstrated significant potential in accurately predicting wear characteristics based on input parameters such as reinforcement percentage, applied load, and sliding velocity. The integration of such computational approaches reduces experimental efforts and accelerates material development.

Despite extensive research in this domain, most studies have focused on individual aspects such as mechanical properties, fabrication techniques, or wear behavior. There is a lack of comprehensive studies that integrate multiple reinforcement systems, processing methods, and performance characteristics into a unified framework. Therefore, the present study aims to provide a detailed comparative analysis of aluminum matrix composites reinforced with silicon carbide, cenospheres, and corn cob ash, fabricated using both conventional and ultrasonic-assisted stir casting techniques. The study systematically evaluates the influence of reinforcement type, composition, and processing method on mechanical properties, corrosion resistance, and tribological performance, along with the application of AI-based models for performance prediction.

II. Materials and Methods

A. Materials

The selection of appropriate matrix and reinforcement materials plays a critical role in determining the overall performance of aluminum matrix composites. In the present study, aluminum alloys such as Al7075, Al5083, and Al6061 are considered as matrix materials due to their widespread industrial applications and favorable mechanical and corrosion-resistant properties. Among these, Al7075 is particularly known for its high strength and is extensively used in aerospace applications, whereas Al5083 exhibits excellent corrosion resistance, making it suitable for marine environments. Al6061, on the other hand, offers a balanced combination of strength, machinability, and weldability, and is commonly employed in structural applications.

To enhance the performance of the aluminum matrix, different types of reinforcements are incorporated. Silicon carbide (SiC) is used as a primary reinforcement due to its high hardness, stiffness, and thermal stability. The addition of SiC particles significantly improves the load-bearing capacity of the composite and restricts plastic deformation under applied stress. In addition to SiC, cenospheres are used as secondary reinforcements. These are lightweight, hollow spherical particles primarily composed of silica and alumina, obtained as byproducts from thermal power plants. Their inclusion helps in reducing the overall density of the composite while maintaining adequate mechanical strength.

Furthermore, corn cob ash (CCA), an agro-waste material rich in silica, is used as an eco-friendly reinforcement. The use of CCA not only contributes to improved wear resistance but also promotes sustainable material development by utilizing agricultural waste. The chemical composition and particle size distribution of the reinforcements are carefully controlled to ensure uniform dispersion and effective bonding with the matrix material.

B. Fabrication Method

The composites are fabricated using the stir casting technique, which is widely recognized for its simplicity, cost-effectiveness, and suitability for large-scale production. In this process, the aluminum alloy is melted in a graphite crucible at temperatures ranging between 750°C and 800°C to obtain a homogeneous molten matrix. The molten metal is maintained at this temperature for a sufficient duration to ensure complete melting and uniformity.

Prior to their addition, the reinforcement particles such as SiC, cenospheres, and CCA are preheated to temperatures around 250°C to 300°C. This preheating process helps in removing moisture and improving the wettability of the particles with the molten aluminum. The preheated reinforcements are then gradually introduced into the molten metal in predetermined weight percentages.

Mechanical stirring is carried out using a motorized stirrer at speeds ranging from 400 to 600 rpm for a duration of approximately 10 to 15 minutes. The purpose of stirring is to achieve uniform distribution of reinforcement particles within the matrix. However, conventional stir casting often leads to issues such as particle clustering and non-uniform dispersion, especially at higher reinforcement concentrations.

To overcome these limitations, ultrasonic-assisted stir casting is employed as an advanced fabrication technique. In this method, ultrasonic vibrations are introduced into the molten metal using an ultrasonic probe operating at high frequencies (typically around 20 kHz). The ultrasonic energy generates cavitation effects within the melt, which help in breaking particle clusters and improving dispersion. This results in a more refined microstructure with reduced porosity and enhanced interfacial bonding between the matrix and reinforcement.

After thorough mixing, the molten composite is poured into preheated metallic molds and allowed to solidify under ambient conditions. The solidified samples are then removed and machined into standard test specimens according to ASTM specifications for further characterization.

C. Mechanical Testing

The mechanical properties of the fabricated composites are evaluated through tensile and hardness tests. Tensile testing is conducted using a universal testing machine (UTM) in accordance with ASTM E8 standards. The specimens are subjected to uniaxial tensile loading at a constant crosshead speed until fracture occurs. The tensile strength, yield strength, and elongation are recorded to assess the mechanical performance of the composites.

Hardness measurements are carried out using a Vickers microhardness tester as per ASTM E92 standards. A diamond indenter is applied to the specimen surface under a specified load, and the resulting indentation is measured to determine hardness values. Multiple readings are taken at different locations on each specimen to ensure accuracy and consistency.

D. Corrosion Testing

The corrosion behavior of the composites is evaluated using electrochemical techniques in a simulated saline environment. Potentiodynamic polarization tests are conducted in accordance with ASTM G3 standards using a three-electrode system. The composite sample serves as the working electrode, while a reference electrode and counter electrode are used to complete the circuit.The tests are performed in a sodium chloride (NaCl) solution, typically with a concentration of 3.5 wt.%, which simulates marine conditions. The corrosion rate is determined from the polarization curves, and parameters such as corrosion potential and corrosion current density are analyzed to assess the corrosion resistance of the composites.

E. Wear Testing

The tribological behavior of the composites is studied using a pin-on-disc wear testing apparatus in accordance with ASTM G99 standards. Cylindrical specimens are prepared and brought into contact with a rotating disc under controlled conditions. The tests are conducted under varying loads, sliding speeds, and reinforcement percentages to evaluate the wear performance.

The wear rate is calculated based on the volume loss of the specimen during the test, while the coefficient of friction is measured to understand the sliding behavior. The worn surfaces are further examined to identify the dominant wear mechanisms such as abrasive wear, adhesive wear, or oxidative wear.

F. Microstructural Analysis

Microstructural characterization of the composites is carried out using scanning electron microscopy (SEM). The samples are prepared through polishing and etching to reveal the internal structure. SEM images are used to analyze the distribution of reinforcement particles, grain structure, and the presence of defects such as porosity or agglomeration.

Energy dispersive X-ray spectroscopy (EDS) is also employed to confirm the elemental composition and distribution of reinforcement particles within the matrix. The microstructural analysis provides valuable insights into the relationship between processing conditions and material properties.

III. RESULTS AND DISCUSSION

The results obtained from mechanical, corrosion, and tribological testing demonstrate that reinforcement content and fabrication technique significantly influence the performance of aluminum matrix composites. The following sections present a detailed analysis of tensile strength, hardness, corrosion behavior, and wear characteristics.

A. Mechanical Properties

SiC (wt.%)	Tensile Strength (MPa)	Hardness (HV)
0	220	100
2	235	110
4	250	120
6	263	128
8	255	130

Table 1: Mechanical properties of AMC with varying SiC content.

The data presented in Table 1 indicates that the tensile strength increases with reinforcement up to 6 wt.% SiC and then slightly decreases due to particle agglomeration.

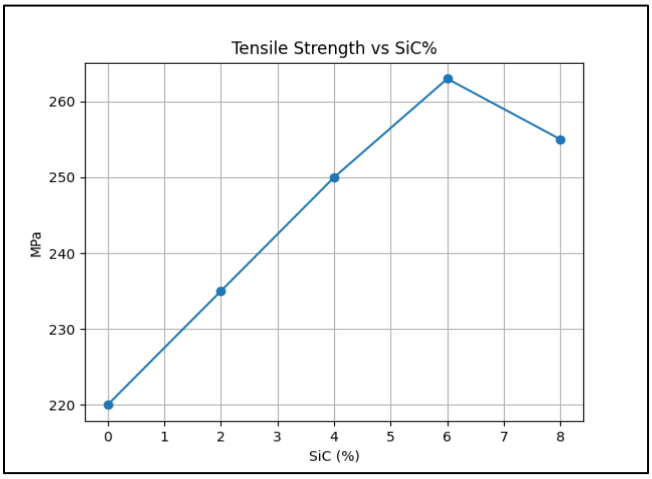

Fig. 1: Tensile Strength vs SiC%

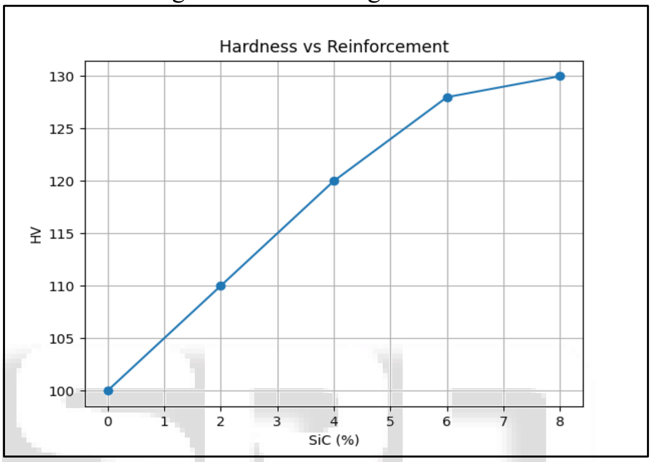

Fig. 2: Hardness vs Reinforcement

B. Corrosion Behavior

The corrosion resistance of the composites improves with increasing reinforcement content due to the formation of a stable oxide layer and enhanced interfacial bonding between the matrix and reinforcement. Uniform distribution of particles reduces localized corrosion sites and improves overall durability in saline environments.

SiC (wt.%)	Corrosion Rate	Efficiency (%)
0	High	—
2	Moderate	30
4	Low	45
6	Lower	52
8	Lowest	58.67

Table 2: L Corrosion characteristics of AMC with varying SiC content

The data presented in Table 2 indicates that the corrosion rate decreases progressively with increasing SiC content, demonstrating improved resistance due to the formation of a protective oxide layer.

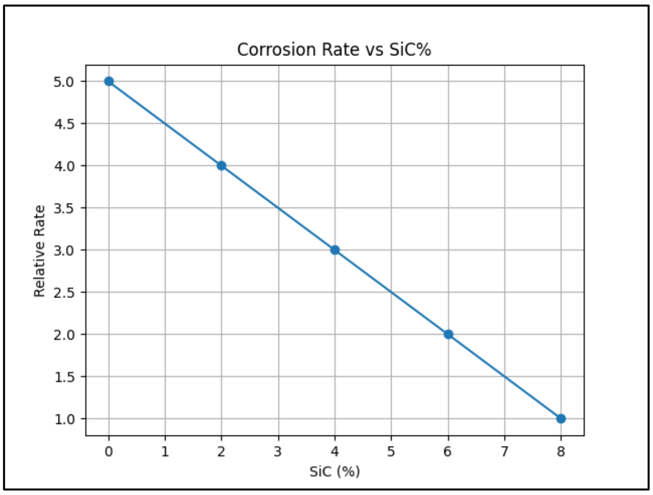

Fig. 3: Corrosion Rate vs SiC%

As shown in Fig. 3, the corrosion rate decreases with increasing reinforcement content. This behavior is attributed to improved microstructural stability and reduced porosity, which limits the penetration of corrosive agents.

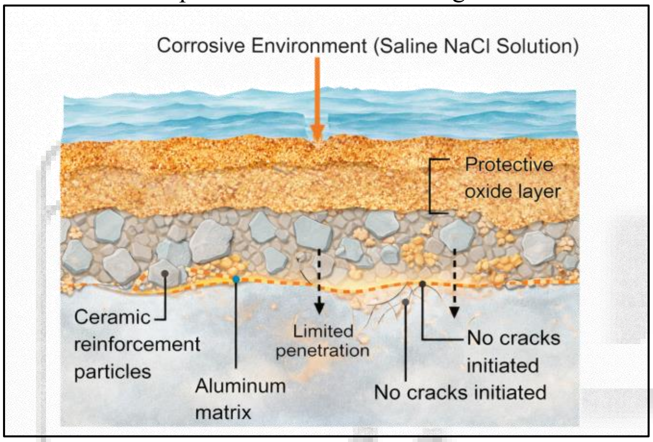

Fig. 4: Corrosion protection mechanism showing oxide layer formation in aluminum matrix composites under saline environment.

C. Wear Behavior

The tribological performance of aluminum matrix composites is significantly influenced by the type and percentage of reinforcement. The addition of hard particles such as corn cob ash (CCA) enhances wear resistance by acting as load-bearing elements and reducing direct contact between sliding surfaces. At optimal reinforcement levels, a protective tribolayer is formed, which minimizes material loss and improves overall wear performance.

CCA (wt.%)	Wear Rate (mm^3/m)	Wear Resistance
0	0.0065	Low
2	0.0060	Moderate
4	0.0055	Highest
6	0.0058	Slight decrease

Table 3. Wear rate variation with CCA reinforcement

The data in Table 3 shows that the wear rate decreases with increasing reinforcement up to 4 wt.% CCA, indicating improved wear resistance due to effective particle distribution.

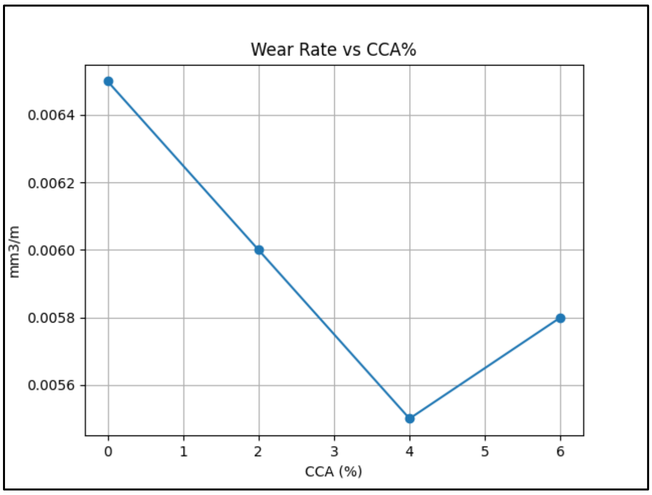

Fig. 5: Wear Rate vs CCA%

As shown in Fig. 5, the wear rate decreases initially and reaches a minimum at 4 wt.% CCA, after which a slight increase is observed. This increase is attributed to particle agglomeration and detachment under higher reinforcement conditions.

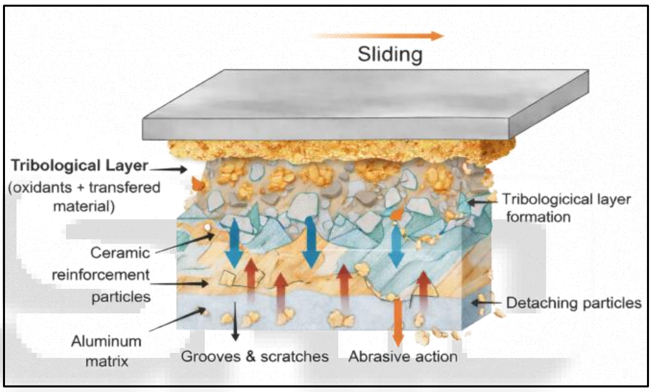

Fig. 6: Wear mechanism in reinforced aluminum matrix composite

D. Microstructure and AI Modeling

Microstructural analysis of the fabricated composites reveals that the distribution of reinforcement particles plays a crucial role in determining material performance. Uniform dispersion of particles leads to improved bonding between the matrix and reinforcement, resulting in enhanced mechanical properties. In contrast, agglomeration of particles creates weak zones that act as crack initiation sites, thereby reducing strength and durability.

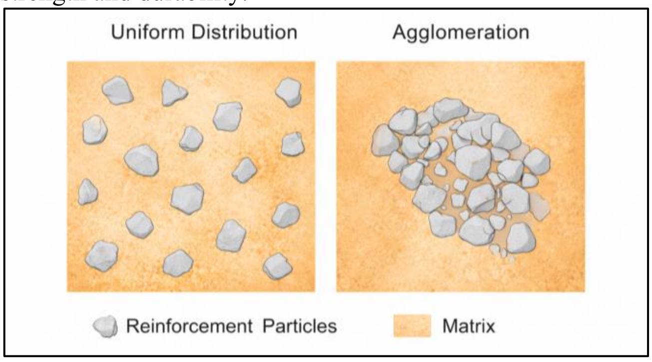

Fig. 7. Microstructure showing uniform particle distribution and agglomeration in composites.

As shown in Fig. 7, uniformly distributed particles contribute to better load transfer and structural integrity, whereas clustered particles lead to stress concentration and reduced performance.

E. AI Modeling (ANFIS)

Artificial intelligence techniques are employed to predict the wear behavior of the composites based on input parameters such as reinforcement percentage, load, and sliding speed. Among the models used, the Adaptive Neuro-Fuzzy Inference System (ANFIS) demonstrates superior prediction capability due to its ability to model nonlinear relationships effectively.

Model	Accuracy (%)
Regression	90
ANN	96
ANFIS	98

Table 4: Prediction accuracy of different models

The results in Table 4 indicate that ANFIS provides the highest prediction accuracy compared to other models.

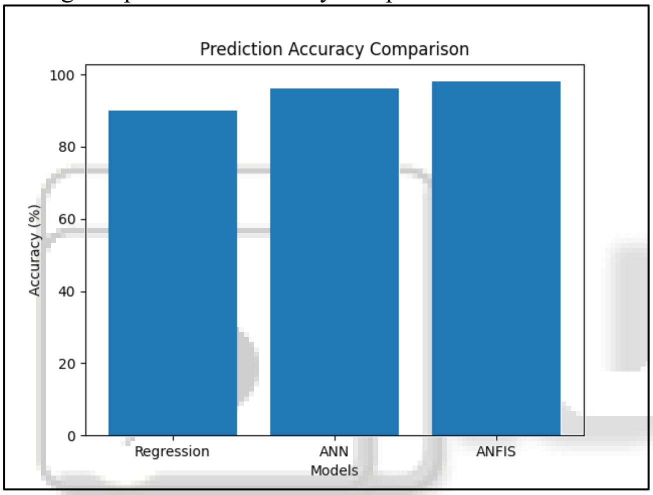

Fig. 8: Comparison of prediction accuracy of different models

As shown in Fig. 8, ANFIS outperforms other models due to its hybrid learning capability, making it suitable for predicting complex material behavior.

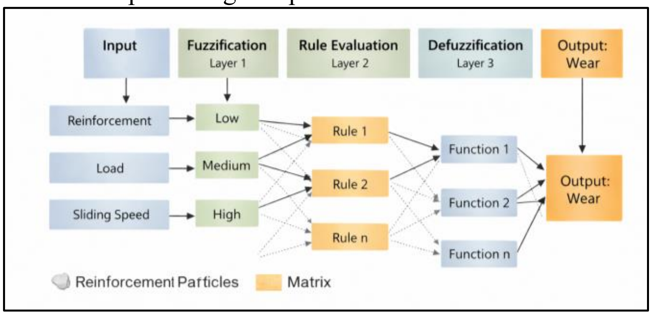

Fig. 9: ANFIS model structure for wear prediction

The ANFIS model integrates neural networks and fuzzy logic to accurately predict wear behavior based on multiple input parameters.

IV. Conclusion

The present study provides a comprehensive evaluation of aluminum matrix composites reinforced with silicon carbide, cenospheres, and corn cob ash, fabricated using both conventional stir casting and ultrasonic-assisted stir casting techniques. The results clearly demonstrate that the incorporation of reinforcement particles significantly enhances the mechanical, corrosion, and tribological performance of the base aluminum alloy.

The tensile strength and hardness of the composites were found to improve with increasing reinforcement content due to effective load transfer, grain refinement, and restriction of dislocation movement. However, beyond an optimal reinforcement level, a slight reduction in mechanical performance was observed, primarily due to particle agglomeration and poor interfacial bonding. This indicates the importance of maintaining an optimal reinforcement percentage for achieving superior material properties.

The corrosion analysis revealed that the addition of reinforcement particles improves corrosion resistance through the formation of a stable oxide layer and reduction in porosity. Uniform distribution of particles plays a crucial role in minimizing localized corrosion and enhancing durability in aggressive environments. Similarly, the tribological study indicated that wear resistance is significantly improved at moderate reinforcement levels, particularly in composites containing agro-waste materials such as corn cob ash. The formation of a protective tribological layer reduces material loss and enhances surface stability during sliding.

Furthermore, the comparison of fabrication techniques showed that ultrasonic-assisted stir casting provides better particle distribution, reduced defects, and improved interfacial bonding compared to conventional methods. This results in enhanced overall performance of the composites.

The application of artificial intelligence models for wear prediction demonstrated that the Adaptive Neuro-Fuzzy Inference System (ANFIS) achieves the highest accuracy among the models considered. This highlights the potential of integrating computational techniques with experimental studies to optimize material design and reduce experimental efforts.

Overall, the study concludes that hybrid aluminum matrix composites reinforced with ceramic and agro-waste materials offer a promising solution for developing lightweight, high-performance, and sustainable engineering materials. Future work can focus on optimizing processing parameters, exploring new reinforcement combinations, and applying advanced modeling techniques to further enhance composite performance.

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