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Fabrication and Characterization of Aluminum Metal Matrix Composites Reinforced with MgO and Bamboo Leaf Ash

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Abstract

The development of metal matrix composites (MMCs) has gained significant attention in recent years due to their enhanced mechanical and thermal properties. Among various MMC systems, the aluminium metal matrix composites (AMMCs) have shown promising potential in various engineering applications. This study presents an overview of the fabrication of Al-MgO-BLA composites using the stir casting process, a widely employed technique for producing MMCs. Aluminium has been used as the matrix material, while MgO and bamboo leaf ash as the reinforcement material to create composites. A total of 8 samples have been made of two combinations: Al-96wt%,3% MgO,1%BLA and Al-92wt% 6% MgO,2% BLA. Final samples have undergone tensile, impact, and hardness tests. Scanning electron microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDS) have been performed to investigate the morphology and elemental composition of the samples. The average increase in Ultimate Tensile Strength (UTS) is approximately 56.15%, and in Brinell Hardness Number (BHN) is approximately 257% with the addition of reinforcements. SEM analysis confirmed a uniformly distributed MgO and BLA reinforcement with minimal porosity, and no significant particle agglomeration. EDS confirmed the presence of Mg, Al, Si, and O, validating the successful synthesis of the Al–MgO-BLA composite with expected elemental distribution.

Keywords

Aluminum Metal Matrix Composites (AMMC), Magnesium Oxide (MgO), Bamboo Leaf Ash (BLA), Stir Casting.

1. Introduction

Composite materials were developed in the 20th century to combine the distinct properties of different materials, thereby enhancing their overall performance. They offer design flexibility, as well as corrosion and fatigue resistance, making them ideal for use in aerospace, automotive, and marine applications. Developed to achieve lighter, stronger materials, they combine different components to create new properties, with reinforcing particles bearing most of the load while a weaker matrix provides support. The addition of the reinforcing particle stiffens and strengthens the product, significantly increasing its ability to withstand structural loads (Huang et al., 2023). Composites are often separated into two main tiers. In general, the matrix constituent forms the initial level of classification. Composite materials generally fall into three main categories depending on the type of matrix used: ceramic matrix composites, metal matrix composites, and organic (often polymer-based) matrix composites. In each of these composite systems, the matrix plays a crucial role as the continuous phase that constitutes the entire component. The matrix material surrounds and binds the reinforcement, providing structural integrity and support. The strategic combination of matrix and reinforcement results in composites with superior mechanical, thermal, and chemical properties compared to individual materials. This synergy enables composites to excel in diverse industries, ranging from aerospace and automotive to construction and sports equipment (Simões, 2024). These composites possess four to six times the tensile strength of aluminium and steel, enabling simpler designs with fewer joints (Graham et al., 2014). The discovery of novel materials that can meet the higher performance demands is a significant issue in materials science, which has led to the creation of Metal Matrix Composites (Nosonovsky et al., 2011). Metal matrix composites can be fabricated through several established methods, including stir casting**,** powder metallurgy**,** squeeze casting, and infiltration techniques. Each of these offer different levels of control over particle dispersion, porosity, and interfacial bonding (Sarmah & Gupta, 2024). The most common method for producing MMCs is stir casting, which is a relatively simple and inexpensive for fabricating metal matrix composites (Abdizadeh et al., 2014).

There is a growing demand for sustainable and low-cost reinforcements in metal-matrix composites (MMCs) to make high-performance materials more environmentally friendly and economical. Bamboo leaf ash (BLA), an agricultural waste product, can be an interesting option as it contains a high fraction of silica and other oxides, and has been shown to improve mechanical properties in aluminum composites (Olaniran et al., 2019). Meanwhile, MgO particles are well known for enhancing hardness, wear resistance, and thermal stability in aluminum MMCs (Irhayyim et al., 2020). This study aims to fabricate Al- MgO- BLA metal matrix composites by stir casting method, evaluate the mechanical properties such as the tensile, hardness and impact strength, and characterize the microstructure using SEM and EDS analysis.

2. Literature Review

Aluminum metal-matrix composites (MMCs) reinforced with both ceramic and agro-waste materials have been widely studied to balance performance and sustainability. (Irhayyim et al., 2020) used nano-MgO and graphite in an Al matrix via powder metallurgy and showed improved hardness and wear resistance. (selvarasu, 2023) produced Al–6061 MMCs with MgO (50 µm) and SiC via stir casting, demonstrating increases in tensile strength and good particle distribution. (ERTEN et al., 2023) reinforced Al-7075 alloy with MgO and SiC and reported favorable mechanical characteristics. (Abdizadeh et al., 2014) reported that Al–nano MgO composites fabricated via stir casting and powder metallurgy exhibited increased hardness and compressive strength, with casting samples showing higher density and lower porosity. (Dwivedi et al., 2021) fabricated Al composites reinforced with SiC and MgO using stir casting and observed that MgO significantly improved tensile strength and hardness, though a slight decrease in toughness was reported. (Mahesh et al., 2024) produced AA6061 hybrid composites with MgO and SiC via stir casting and found that increasing MgO and SiC content enhanced both tensile and compressive strength.

The application of bamboo leaf ash (BLA) is well highlighted by previous studies. (Alaneme K. k.; Adewuyi E.O., 2013) fabricated Al-Mg-Si composites with Al_2O_3 and BLA via double-step stir casting, finding that higher BLA content slightly reduced tensile strength but improved fracture toughness. (KUMAR & BIRRU, 2017) developed Al–4.5 wt%Cu/BLA composites, which showed that adding 2–6% BLA increased hardness and yield strength, though ductility decreased. Similarly, (Shridhara et al., 2015) worked with Al–Cu alloy reinforced by BLA and graphite, reporting enhancements in wear resistance, hardness, and tensile strength. (Ben & Olubambi, 2024) studied various agro-ash reinforcements in MMCs, and highlighted both performance benefits and sustainability aspects. (Parveez et al., 2021) analyzed microstructure and mechanical behavior of Al–BLA stir-cast composites, noting acceptable porosity and good reinforcement bonding. (Kulkarni et al., 2019) surveyed multiple agro-waste ashes (including BLA) in Al MMCs, finding consistent improvements in hardness and moderate gains in tensile strength. (Sharma et al., 2024) reviewed recent advances in stir-cast Al-based composites, noting that heterogeneity is often a limiting factor in mechanical performance. (Tamiloli & Rajesh, 2022) employed a two-step stir casting method to incorporate SiC and MgO into Al6061, achieving uniform particle distribution and improved mechanical properties. (Dhanalakshmi et al., 2015) fabricated Al MMCs reinforced with coated SiC particles using the conventional stir casting method, and found improved tensile strength, impact strength, and microstructural bonding between the matrix and reinforcements.

These studies suggest that combining MgO for strength and BLA for sustainability in an Al matrix could produce lightweight, high-performance MMCs. However, few studies have examined their combined effect on microstructure and mechanical properties, which motivates this study on Al-MgO-BLA metal matrix composite.

3. Methodology

Pure aluminum (99.8% purity) was used as matrix material, while laboratory grade MgO (97% purity) and bamboo leaf ash was employed as reinforcements. Aluminum and MgO was collected from local market. Bamboo leaves were first collected from trees and dried under the sun for a day. The dried up leaves were burnt at 200°C for 2 hours continuously to remove moisture. The collected ash was then heated at a furnace at 800°C until a grayish white color was attained.

3.1 Composite Production

Stir casting is currently being utilized commercially and is typically thought of as an immensely promising technique. Its simplicity, versatility and scalability for mass production are its advantages. It has particular attraction since it permits the use of an old-fashioned metal processing procedure, hence reducing the product's overall cost. This liquid metallurgical method enables the fabrication of very large-sized components and is the most cost effective way to create metal matrix composites. In the fabrication process, the furnace initially was heated to 700°C. Pure aluminum bars were used as the matrix material, which was heated until completely melted. The following proportions of reinforcing elements were used to create two samples: a) 1 wt% BLA + 3 wt% MgO + 96 wt% Al, b) 2 wt% BLA + 6 wt% MgO + 92 wt% Al. Once the aluminum was fully liquefied, the preheated reinforcement particles were incorporated into the melt. After the addition of reinforcing particles, stirring was initiated to disperse the particles uniformly throughout the molten metal. The stirring action helped in achieving a homogeneous distribution of particles and prevented their settling at the bottom of the melt. Once the stirring process was completed, the mixture was poured into a pre-prepared mold or die cavity. The poured mixture undergoes solidification within the mold, resulting in the formation of the desired shape. Cooling rates and solidification conditions influenced the final microstructure and properties of the composite material. After solidification, the casting was typically subjected to various post-processing steps such as heat treatment, machining, and surface finishing to achieve the desired final properties and dimensions. Figure 1 shows a flow chart of the working procedure of the composite production.

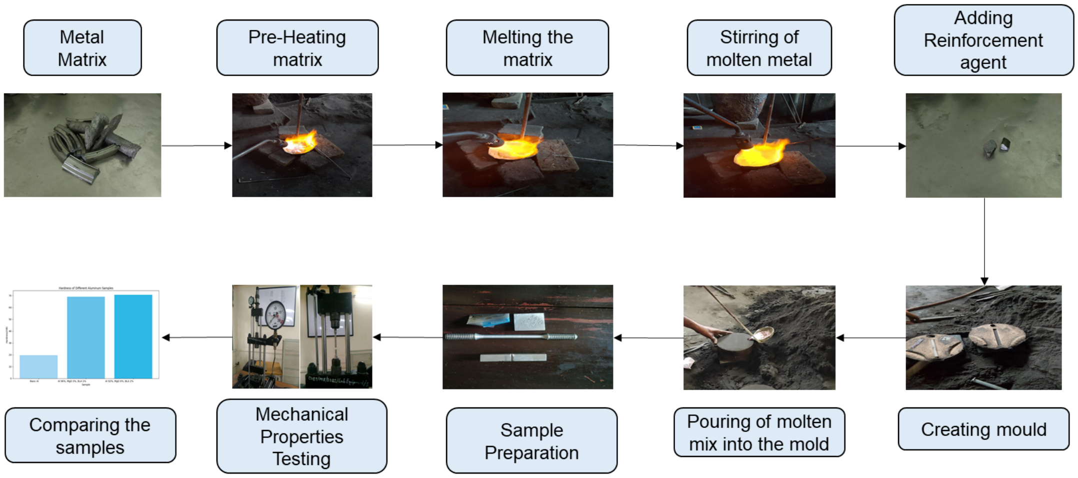


Figure 1. Flow Chart of Working Procedure

3.2 Mechanical Property Test

For finding the mechanical properties of a metal composite tensile test, impact test and hardness is commonly used. Tensile test (Uniaxial) is the most widely utilized for finding the mechanical strength of the isotropic materials. Tensile test and hardness test was carried out for the prepared samples. The tensile test run was conducted at room temperature by universal testing machine for high experimental accuracy. In order to determine the Brinell hardness of a work piece, a 5 or 10-mm diameter hardened steel or tungsten carbide ball is used to apply a constant load, typically in the range of 500–3000 N, for a predetermined amount of time (10–30 s). A standardized high strain rate test that gauges the energy a material absorbs during fracture is the Charpy V-notch test.

3.3 Microstructure Test

The microstructure of the prepared samples was observed by an scanning electron microscope. The cast specimen was cut into square shape of dimension 6 mm diameter and 3 mm thick from different samples of prepared composites. The metallography operations grinding, polishing and etching was followed to prepare the sample before observations.

4. Results and Discussion

4.1 Tensile Test Analysis

Tensile Testing was carried out using the Universal Testing Machine. Table 1 shows the UTS of composites containing the different volume percentage of Al-MgO-BLA.

Table 1. Result of Ultimate Tensile Test

Sample No.	**Number of %**	**Ultimate Tensile Strength (MPa)**
1. Basic Al	-	113.73
2. Al-MgO-BLA	96%, 3%, 1%	183.28
3. Al-MgO-BLA	92%, 6%, 2%	171.96

Basic aluminum exhibits a tensile strength of approximately 110 MPa (Mathur et al., 2019). In our experiment, the Ultimate tensile strength (UTS) of Al-96%, MgO-3%, BLA-1% is 183.28 MPa. The UTS of Al-92%, MgO-6%, BLA-2% is 171.96. The Ultimate Tensile Strength increased as the reinforcement was added. This is happened because addition of reinforcement enhances the material's atomic structure and form intermetallic compounds that strengthen the material. Figure 2 demonstrates that reinforcing aluminum with MgO and Bamboo Leaf Ash significantly enhances its tensile strength.

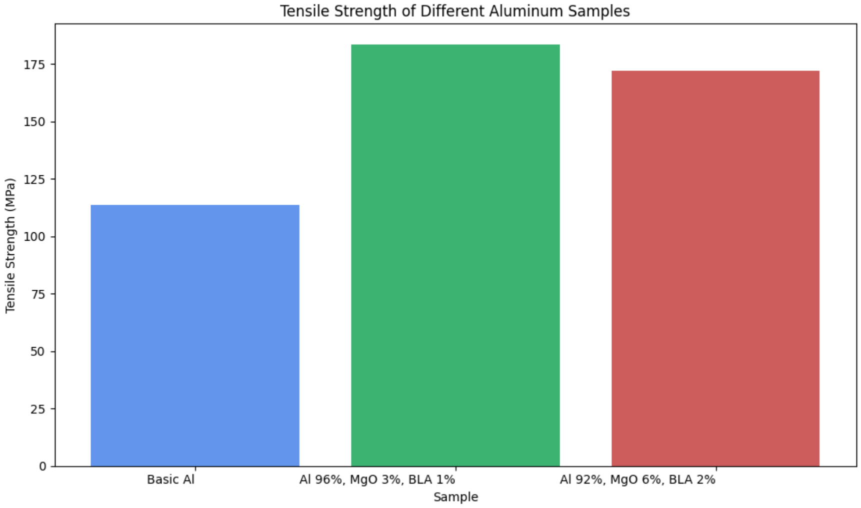


Figure 2. Comparison of Tensile Strengths for Different Samples

4.2 Brinell Hardness Test Analysis

Hardness test was carried out using the Universal Testing Machine. Table 2 shows BHN for different samples.

Table 2. Result of Brinell Hardness Test

Sample No.	**Number of %**	**Brinell Hardness**
4. Basic Al	-	19.6
5. Al-MgO-BLA	96%, 3%, 1%	69.17
6. Al-MgO-BLA	92%, 6%, 2%	70.66

The Brinell Hardness of pure aluminium is around 19.6HB (Jain et al., 2019). In our experiment, the Brinell Hardness Number (BHN) of Al-96%, MgO-3%, BLA-1% is 69.17. The BHN of Al-92%, MgO-6%, BLA-2% is 70.66. So, the Brinell Hardness increases with the introduction of reinforcement. This is because of the interfacial bonding between matrix and reinforcement phase which plays a vital role in determining the hardness of a composite. Figure 3 illustrates the hardness of different aluminum samples.

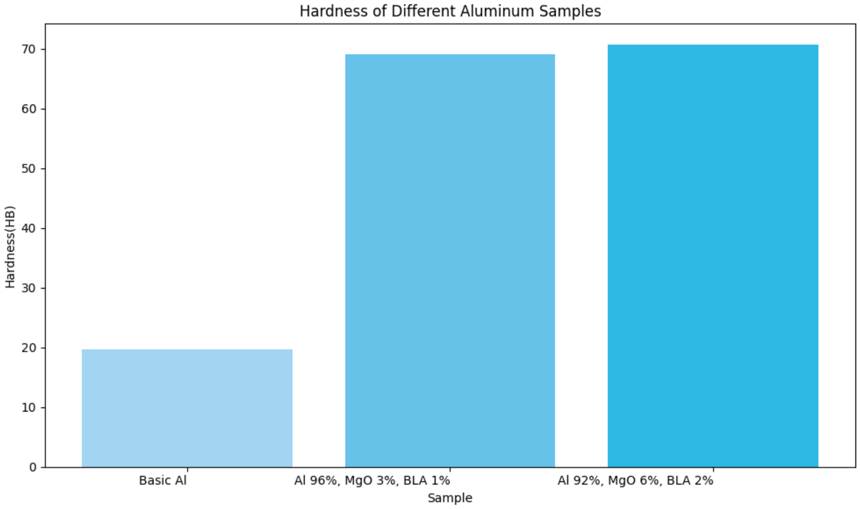


Figure 3. Hardness Test Comparison for Different Samples

4.3 Impact Test Analysis

A digital impact tester (Charpy) machine was used for measuring impact energy & strength which gives the impact value directly. Table 3 shows the comparison of energy and strength of the different composites.

Table 3**.** Result of Impact Test

Sample No.	Number of %	Energy (J)	Strength (J/cm^2)
7. Basic Al	-	15.3	17.18
8. Al-MgO-BLA	96%, 3%, 1%	11.7	14.6
9. Al-MgO-BLA	92%, 6%, 2%	7.67	8.84

From the experiment, we can see the impact energy and impact strength of Al-97%, Sn-3% are 8.1 J and 11.2 J/sq. cm., the impact energy and impact strength of Al-96%, MgO-3%, BLA-1% are 11.7 J and 14.6 J/sq. cm., the impact energy and impact strength of Al-92%, MgO-6%, BLA-2% are 7.67 J and 8.84 J/sq. cm. They are relatively high than many other aluminium composites such as Al-SiC Composites (Pitchayyapillai et al., 2017) or Al-Mg composite. Figure 4 shows the graphical comparison of energy and strength of different samples.

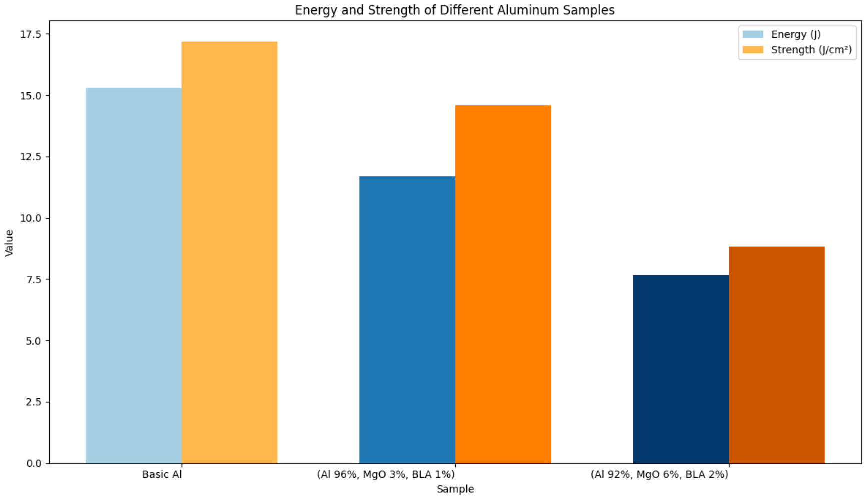
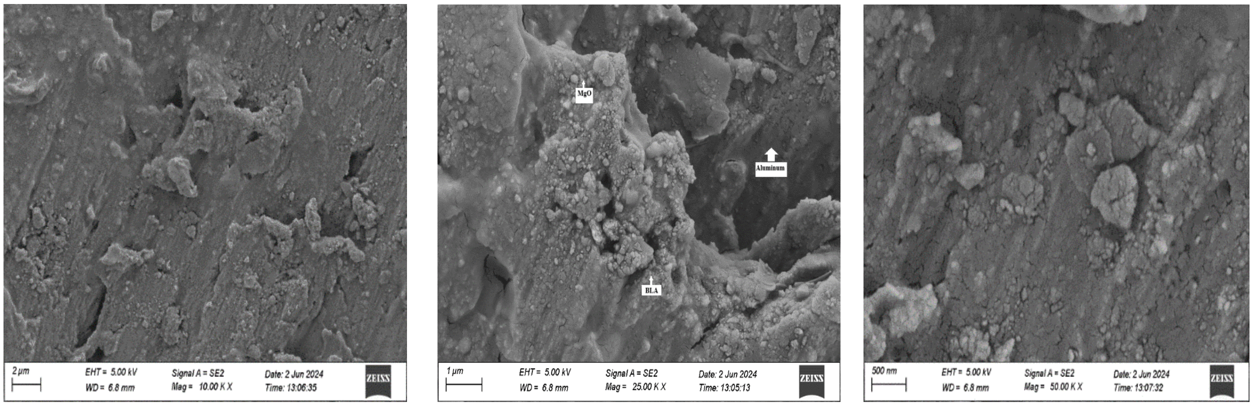


Figure 4. Comparison of Impact Test Results Among Different Samples

4.4 Scanning Electron Microscopy (SEM) Test Result

SEM Test has been done to learn about the morphology and the microstructure of the composite material. From the SEM images, the reinforcing particles (MgO and BLA) appeared to be uniformly distributed within the aluminum matrix, which is crucial for achieving consistent mechanical properties throughout the material. The MgO particles (120 µm) and Bamboo Leaf Ash (40 µm) inclusions exhibited distinct shapes and sizes. MgO particles were more spherical, while Bamboo Leaf Ash particles had irregular, flake-like structures. The interface between the aluminum matrix and the reinforcing particles were well-bonded, indicating good wetting and interaction during the stir casting process. This is essential for load transfer and overall composite strength. There were minimal pores or voids visible in the microstructure, suggesting that the stir casting process was effective in minimizing porosity, which can negatively affect the composite's mechanical properties. The images showed minimum signs of agglomeration of the reinforcing particles, which is positive indication that the dispersion techniques were effective. Figure 5 presents the microstructure of the Al-96%, MgO-3%, BLA-1% composite at different magnifications to highlight structural details. Image (a) at 10.00 KX provides an overview of the composite's general microstructure, showing the distribution of phases. Image (b) at 25.00 KX reveals finer features and phase boundaries more clearly. Image (c) at 50.00 KX shows detailed morphological characteristics, allowing closer examination of grain structure and interface features within the composite.



(a) (b) (c)

Figure 5. Microstructure of Al-MgO-BLA composite at (a) 10.00 K X magnification, (b) 25.00 K X magnification, (c) 50.00 K X magnification

4.5 Energy Dispersive X-Ray Spectroscopy (EDS) Test Result

This test has been done to identify and quantify the elemental composition of the composite's microstructure. Figure 6 shows a spectroscopy of Al-96%, MgO-3%, BLA-1% composite graph from the test result.

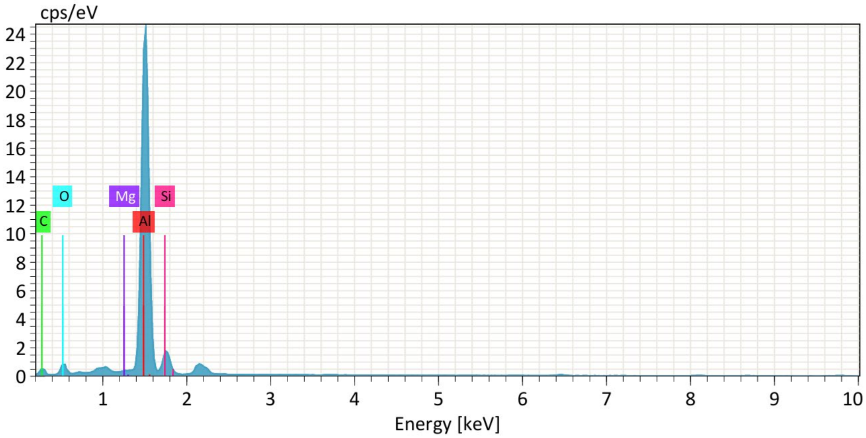


Figure 6. EDS Graph of Al-MgO-BLA composite

5. Conclusion

In this study, Al-MgO-BLA composites were fabricated via stir casting with different weight percentages. As MgO and BLA reinforcements were added to the metal matrix, we observed a clear rise in Ultimate Tensile Strength and Brinell Hardness Number, demonstrating that the MgO and BLA particles effectively reinforce the aluminum framework. However, this brought a gradual reduction in impact resistance, highlighting the classic strength-versus toughness trade-off inherent in metal composites. Scanning Electron Microscopy (SEM) analysis provided valuable insights into the microstructural characteristics of the composites. The homogeneous distribution of reinforcing particles within the aluminum matrix ensured consistent mechanical properties throughout the material. The well-bonded interface between the aluminum matrix and the reinforcing particles indicated effective load transfer and interaction during the stir casting process. Additionally, minimal porosity and the absence of significant particle agglomeration were observed, further contributing to the improved performance of the composites. Altogether, these findings suggest that Al–MgO-BLA composites offer a promising combination of strength and hardness for engineering uses. Overall, our findings show that Al–MgO-BLA composites created by stir casting can deliver a balanced package of hardness and strength suitable for many engineering applications. Future work will focus on tweaking stir-casting parameters and post-cast heat treatments to fine-tune their performance.

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