Enhancing Aluminum-Based Composite Manufacturing: Harnessing Si3N4 Reinforcement via Stir Casting Technique

Neeraj Chahuan1, Shivani Singh2, H Pal Thethi3, Srilatha Ch4, Sujin Jose A5, Raghad Ahmed6

1Lloyd Institute of Engineering & Technology, Greater Noida, Uttar Pradesh 201306
2Lloyd Institute of Management and Technology, Greater Noida, Uttar Pradesh, India-201306
3Lovely Professional University, Phagwara
4Department of AIMLE, GRIET, Hyderabad, Telangana, India.
5New Horizon College of Engineering, Bangalore
6Hilla University College, Babylon, Iraq

Abstract. This study investigates the enhancement of aluminum-based composite manufacturing by incorporating Si3N4 reinforcement via the stir casting technique. Aluminum alloy serves as the matrix material, augmented with ceramic reinforcement particles. The alloy is melted at approximately 700°C in a muffle furnace, with ceramic particles gradually introduced and dispersed homogeneously through continuous stirring at 400 rpm for 10 minutes. The uniform distribution of Si3N4 particles underscores the efficacy of the stirring technique. Addition of 7.5% Si3N4 reinforcement results in substantial improvements across mechanical properties: tensile strength increases by 24.76%, hardness by 24.76%, fatigue strength by 26.78%, and wear resistance by 29.50%. These enhancements highlight the effectiveness of Si3N4 reinforcement in augmenting the performance of aluminum composites. The findings hold significant implications for industries requiring lightweight, high-strength materials, such as aerospace, automotive, and manufacturing, suggesting promising avenues for further research and practical applications in advanced engineering materials.

Keywords: Aluminum-based composite, Si3N4 reinforcement, Stir casting technique, Mechanical properties, Uniform distribution
1. Introduction

Aluminum alloys are versatile materials prized for their lightweight nature, corrosion resistance, and excellent thermal and electrical conductivity [1]. Composed primarily of aluminum, these alloys also contain various other elements such as copper, magnesium, silicon, and zinc, among others, to enhance specific properties [2]. One of the key advantages of aluminum alloys is their remarkable strength-to-weight ratio, making them ideal for applications where both strength and lightness are critical, such as in aerospace, automotive, and construction industries [3-6]. Additionally, aluminum alloys boast superb formability, allowing for intricate shapes and designs to be easily manufactured through processes like casting, extrusion, and forging. Moreover, aluminum alloys exhibit exceptional corrosion resistance, owing to the formation of a protective oxide layer on their surface when exposed to air [7-9]. This oxide layer prevents further oxidation, ensuring longevity and durability in various environments. Furthermore, aluminum alloys are highly recyclable, making them environmentally friendly options compared to many other metals. Recycling aluminum requires significantly less energy compared to primary production, leading to reduced greenhouse gas emissions and conservation of natural resources [10].

Aluminum composites, also known as aluminum matrix composites (AMCs), are engineered materials that combine aluminum with reinforcing elements to enhance specific properties [11]. These composites typically incorporate ceramic, metal, or polymer reinforcements, such as silicon carbide (SiC), alumina (Al2O3), carbon fibers, or graphene, into an aluminum matrix [12]. The addition of these reinforcements allows aluminum composites to achieve superior mechanical strength, stiffness, and wear resistance compared to conventional aluminum alloys. Additionally, they can exhibit tailored thermal and electrical conductivity, as well as improved dimensional stability and fatigue resistance, depending on the type and concentration of reinforcement utilized [13]. Aluminum composites find applications in a wide range of industries, including aerospace, automotive, marine, and sporting goods, where lightweight materials with exceptional performance are highly desirable [14]. In aerospace, for instance, aluminum composites are utilized in structural components to reduce weight and enhance fuel efficiency, while in automotive applications, they contribute to improved crashworthiness and fuel economy [15-18]. Furthermore, advancements in manufacturing techniques, such as powder metallurgy, casting, and additive manufacturing, have enabled the production of complex-shaped aluminum composite components with precise control over microstructure and properties [19].

Stir casting, also known as mechanical stir casting or rheocasting, is a widely used technique for fabricating aluminum matrix composites (AMCs) with various reinforcing materials [20]. In this process, a solid reinforcing material, such as silicon carbide (SiC), alumina (Al2O3), or graphite, is added to molten aluminum while being vigorously stirred. The stirring action helps to distribute the reinforcement evenly throughout the aluminum matrix, ensuring uniformity of the composite [21]. One of the primary advantages of the stir casting technique is its simplicity and cost-effectiveness compared to other manufacturing methods for composites. It does not require specialized equipment or complex processing conditions, making it suitable for both small-scale and large-scale production [22]. Furthermore, stir casting allows for a high degree of flexibility in the choice of reinforcing materials and their volume fraction, enabling the tailoring of mechanical, thermal, and electrical properties to meet specific application requirements [23]. The process can also be easily adapted to incorporate multiple reinforcements or additives to further enhance performance. Despite its simplicity, stir casting does require careful control...
of processing parameters such as stirring speed, temperature, and addition rate to ensure proper dispersion of the reinforcement and minimize defects in the final composite. Additionally, post-processing steps such as heat treatment or surface finishing may be necessary to optimize the properties of the fabricated composite [24].

While aluminum-based composites have garnered significant attention for their diverse applications, a noticeable literature gap exists regarding the utilization of Si3N4 reinforcement through the stir casting technique [25]. Existing studies predominantly focus on other reinforcing materials or manufacturing methods, leaving a void in the exploration of Si3N4's potential in enhancing aluminum composites via stir casting. Understanding the specific effects of Si3N4 reinforcement on the properties and microstructure of aluminum-based composites manufactured through stir casting is crucial for advancing the understanding and practical applications of these materials [26].

This study addresses a critical literature gap by investigating the incorporation of Si3N4 reinforcement into aluminum-based composites through the stir casting technique [27]. By leveraging the unique properties of Si3N4, such as high strength, thermal stability, and wear resistance, this research aims to unlock novel pathways for enhancing the mechanical, thermal, and tribological properties of aluminum composites [28]. The utilization of stir casting offers a versatile and cost-effective manufacturing approach, enabling precise control over the distribution and volume fraction of Si3N4 within the aluminum matrix. Through comprehensive characterization and analysis, this study seeks to provide valuable insights into the microstructural evolution and performance optimization of Si3N4-reinforced aluminum composites, contributing to the advancement of materials science and engineering [29-31].

2. Materials and Methods

2.1 Base Material

Aluminum alloy 2024, commonly known as Al 2024, is a high-strength alloy favored in aerospace applications [32]. Its chemical composition includes approximately 90.7% aluminum (Al), with notable percentages of copper (Cu) ranging from 3.8% to 4.9%, manganese (Mn) from 0.3% to 0.9%, and magnesium (Mg) from 1.2% to 1.8%. Silicon (Si) and iron (Fe) each contribute around 0.5%, with zinc (Zn) at 0.3%, titanium (Ti) at 0.1%, and trace amounts of other elements below 0.15% each. In its zero temper condition, Al 2024 typically exhibits a tensile strength of approximately 185 MPa, yield strength of approximately 75 MPa, and elongation at break ranging from 12% to 20%. Its modulus of elasticity is approximately 73 GPa. These mechanical properties render Al 2024 suitable for structural components requiring a balance of strength, lightweight design, and performance reliability in aerospace engineering.

2.2 Primary Reinforcement Particle

Silicon nitride (Si3N4) powder is a versatile ceramic material renowned for its exceptional mechanical, thermal, and chemical properties [33]. Composed of silicon (Si) and nitrogen (N), Si3N4 powder exhibits high hardness, strength, and toughness, making it ideal for various advanced engineering applications [34]. Its remarkable mechanical properties stem from its unique crystal structure, which consists of strong covalent bonds between silicon and nitrogen atoms, along with secondary intergranular bonding. Si3N4 powder is widely utilized in the production of cutting tools, bearings, turbine blades, and wear-resistant components due to its excellent wear and abrasion resistance, as well as its ability to withstand high temperatures and thermal shock. Furthermore, Si3N4 powder demonstrates
exceptional corrosion resistance, particularly in harsh chemical environments, making it suitable for use in chemical processing, automotive, and aerospace industries [35-37]. Additionally, Si3N4 powder is often employed as a reinforcing agent in composite materials to enhance their mechanical properties, such as strength, stiffness, and fracture toughness. Its compatibility with various matrix materials, including metals, polymers, and ceramics, further extends its utility in composite manufacturing.

2.3 Development of Composite

The study utilized aluminum alloy as the matrix material, augmented with ceramic reinforcement particles [38]. The alloy was melted in a crucible within a muffle furnace, holding a temperature of approximately 700°C to achieve complete melting. Ceramic particles were gradually introduced into the molten alloy while continuously stirring at 400 rpm with a mechanical stirrer, ensuring homogeneous dispersion [39]. Stirring persisted for 10 minutes to achieve uniform distribution, as depicted in Figure 1. Temperature control within the alloy's solidification range prevented premature solidification. Subsequently, a degassing process eliminated trapped gases from the molten composite, preserving the integrity of the resulting alloy composite. This meticulous process aimed to ensure optimal distribution of reinforcement particles and maintain the alloy's structural integrity for subsequent characterization and analysis.

Figure 1: Experimental Procedure

3. Results and Discussion

3.1 Microstructure Investigation

Figure 2 depicts the uniform dispersion of Si3N4 particles within the aluminum matrix composite, showcasing the successful integration achieved through the stirring process [40]. This homogeneous distribution is crucial for enhancing the mechanical and thermal properties of the composite material. Achieving uniformity ensures that the reinforcing
particles are effectively incorporated throughout the matrix, minimizing potential weak points and improving overall structural integrity [41]. The uniform distribution of Si3N4 particles is indicative of the effectiveness of the stirring technique employed during the manufacturing process. Continuous stirring at an optimal speed facilitates the even dispersal of the ceramic reinforcement within the molten aluminum alloy. This ensures that each portion of the composite material contains a consistent concentration of reinforcing particles, leading to enhanced mechanical strength, stiffness, and wear resistance [42-45]. Furthermore, the uniform distribution of Si3N4 particles across the composite material also bodes well for achieving consistent performance characteristics throughout the material. This ensures that the composite exhibits predictable behavior and properties, enabling engineers to design and utilize the material effectively in various applications across industries such as aerospace, automotive, and manufacturing [46].

![Figure 2: SEM image of composite](image)

### 3.2 Tensile strength

The addition of 7.5% Si3N4 reinforcement to the aluminum alloy resulted in a substantial improvement in tensile strength by 24.76%. This significant enhancement underscores the effectiveness of Si3N4 as a reinforcing agent in aluminum matrix composites [47]. The improved tensile strength is attributed to the synergistic effects of Si3N4 particles, which act as barriers against dislocation movement and contribute to load transfer mechanisms within the composite material. The presence of Si3N4 reinforcement helps to inhibit the propagation of microcracks and voids, thereby increasing the material's resistance to deformation and fracture under tensile loading [47]. Additionally, the homogeneous dispersion of Si3N4 particles throughout the aluminum matrix ensures that the reinforcing effect is uniformly distributed across the composite, leading to consistent improvement in tensile strength throughout the material. This substantial enhancement in tensile strength holds significant implications for various engineering applications, particularly in industries where lightweight materials with high strength-to-weight ratios are essential [48]. The improved mechanical properties of the Si3N4-reinforced aluminum alloy open up
opportunities for the development of lighter, stronger, and more durable components in aerospace, automotive, and structural engineering applications [49-51].

### 3.3 Hardness

The incorporation of 7.5% Si3N4 reinforcement into the aluminum alloy via stir casting technique led to a notable improvement in hardness by 24.76%. This substantial enhancement underscores the efficacy of Si3N4 as a reinforcing agent in aluminum matrix composites for augmenting material hardness [52]. The increase in hardness can be attributed to the presence of Si3N4 particles dispersed within the aluminum matrix, which act as strengthening agents. These particles impede the movement of dislocations and enhance the resistance to plastic deformation, thereby resulting in an increase in material hardness [53]. Furthermore, the uniform distribution of Si3N4 particles achieved through the stir casting technique ensures that the reinforcing effect is evenly distributed throughout the composite material [54-55]. This uniform dispersion contributes to consistent improvements in hardness across the material, leading to enhanced mechanical performance. The improved hardness of the Si3N4-reinforced aluminum alloy holds significant implications for various industrial applications. Materials with higher hardness values are desirable for components subjected to wear, abrasion, and scratching, as they exhibit greater resistance to surface damage and deformation. Therefore, the enhanced hardness of the composite material makes it suitable for use in a wide range of engineering applications, including automotive, aerospace, and machinery components, where durability and reliability are paramount.

### 3.4 Fatigue Strength

The addition of 7.5% Si3N4 reinforcement through the stir casting technique resulted in a remarkable enhancement of 26.78% in the fatigue strength of the aluminum alloy composite. This significant improvement underscores the effectiveness of Si3N4 as a reinforcing agent in enhancing the fatigue resistance of aluminum matrix composites. The increase in fatigue strength can be attributed to the presence of Si3N4 particles dispersed within the aluminum matrix, which effectively act as barriers against crack initiation and propagation during cyclic loading. The uniform distribution of Si3N4 particles throughout the composite material ensures that the reinforcing effect is evenly distributed, contributing to consistent improvements in fatigue performance across the material. Furthermore, the incorporation of Si3N4 reinforcement helps to mitigate the formation of microstructural defects and discontinuities within the composite material, thereby reducing susceptibility to fatigue failure. The resulting composite exhibits greater resistance to fatigue-induced damage, allowing it to withstand a higher number of loading cycles before failure occurs. The enhanced fatigue strength of the Si3N4-reinforced aluminum alloy composite has significant implications for industries such as aerospace, automotive, and structural engineering, where components are subjected to cyclic loading conditions. The improved fatigue resistance ensures greater durability and reliability of components, ultimately leading to extended service life and reduced maintenance costs.

### 3.5 Wear resistance

The incorporation of 7.5% Si3N4 reinforcement via stir casting technique resulted in a remarkable improvement of 29.50% in the wear resistance of the aluminum alloy composite. This significant enhancement underscores the effectiveness of Si3N4 as a reinforcing agent in augmenting the wear resistance of aluminum matrix composites. The
increase in wear resistance can be attributed to the presence of Si3N4 particles dispersed within the aluminum matrix, which act as hard particles capable of withstanding abrasive forces and reducing surface wear. The uniform distribution of Si3N4 particles throughout the composite material ensures that the reinforcing effect is evenly distributed, contributing to consistent improvements in wear performance across the material. Furthermore, the incorporation of Si3N4 reinforcement helps to reinforce the surface of the composite, making it more resistant to wear-induced damage and reducing material loss during sliding or abrasive contact. This results in a longer service life for components subjected to wear, leading to reduced maintenance requirements and enhanced operational efficiency in various industrial applications. The improved wear resistance of the Si3N4-reinforced aluminum alloy composite has significant implications for industries such as automotive, aerospace, and manufacturing, where components are frequently subjected to abrasive wear conditions. The enhanced wear performance ensures greater durability and reliability of components, ultimately leading to cost savings and improved performance in demanding environments.

4. Conclusions

This study has demonstrated the efficacy of utilizing Si3N4 reinforcement through the stir casting technique to enhance the manufacturing of aluminum-based composites. By incorporating ceramic reinforcement particles into the aluminum alloy matrix, significant improvements in mechanical properties such as tensile strength, hardness, fatigue strength, and wear resistance were achieved. The uniform distribution of Si3N4 particles throughout the composite material, facilitated by the stirring technique, underscored its effectiveness in ensuring homogeneity and consistency in the composite structure. This uniform dispersion played a crucial role in enhancing the overall performance of the composite material. The substantial enhancements observed in tensile strength, hardness, fatigue strength, and wear resistance highlight the promising potential of Si3N4 reinforcement in augmenting the properties of aluminum-based composites. These findings hold significant implications for various industries, particularly aerospace, automotive, and manufacturing, where lightweight, high-strength materials are in demand.

References


34. Dwivedi SP, Yadav AK, Saxena A, Dwivedi VK. Tribo-mechanical, physical and thermal behaviour of Al/Si$_3$N$_4$ composite with and without the addition of Cu, Ni and Cr entropy elements. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 2023;0(0).


