Enhancing Aluminum-Based Composite Manufacturing: Leveraging Si3N4 Reinforcement via Friction Stir Process

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Abstract. In the realm of composite manufacturing, this study delves into the innovative approach of enhancing Aluminum-Based Composite Manufacturing through Si3N4 Reinforcement leveraged via Friction Stir Process (FSP). The FSP technique, executed with precision using a vertical milling machine, intricately fabricates composite materials with unparalleled properties. Meticulously chosen parameters including pin diameter, tool tilt angle, and tool profile, coupled with precise tool traversal and rotation, define the operation. The composite substrate, composed of AA 2024, undergoes stringent cleanliness protocols before Si3N4 powders are strategically placed into a designated groove on the titanium surface for processing. Microscopic examination reveals the uniform dispersion of Si3N4 particles within the aluminum matrix, profoundly enhancing mechanical properties. The tensile strength experiences a remarkable 21.45% improvement, while hardness witnesses a significant enhancement of 36.9%. Additionally, fatigue strength is notably improved by 24.12%, and wear resistance sees a substantial boost of 30.44% following Si3N4 nanoparticle integration via FSP.

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1. Introduction

Aluminum, a lightweight and versatile metal, has become indispensable in various industries due to its remarkable properties. With a density about one-third that of steel, aluminum offers a perfect balance of strength and lightweight, making it ideal for applications where weight reduction is crucial, such as aerospace, automotive, and transportation sectors [1-3]. Moreover, aluminum exhibits excellent corrosion resistance, ensuring durability even in harsh environments. Its high thermal and electrical conductivity make it valuable in electronics and heat transfer applications [4]. Aluminum is also highly malleable and ductile, allowing for easy shaping and forming processes, such as extrusion, forging, and casting, enabling its use in a wide range of products from cans and foils to intricate aerospace components [5-9]. Furthermore, aluminum is highly recyclable, with nearly 75% of all aluminum ever produced still in use today. Recycling aluminum requires only 5% of the energy needed to produce it from raw materials, making it an environmentally sustainable choice [10]. In summary, aluminum's combination of strength, lightweight, corrosion resistance, conductivity, recyclability, and versatility has established it as a vital material driving innovation across industries worldwide [11].

Aluminum composite materials (ACMs) are engineered materials composed of thin aluminum sheets bonded to a non-aluminum core, typically made of polyethylene (PE) or fire-retardant materials such as mineral-filled thermoplastic or fire-resistant (FR) core materials [12]. This sandwich-like structure provides a unique combination of properties, making ACMs highly versatile and widely used in various industries [13]. ACMs offer exceptional strength-to-weight ratio, making them lightweight yet strong, suitable for applications requiring structural integrity while minimizing weight, such as building facades, signage, and transportation components [14-16]. Additionally, ACMs provide excellent flatness and rigidity, allowing for ease of fabrication and installation, even in large panels or complex shapes. One of the key advantages of ACMs is their aesthetic versatility. Available in a wide range of colors, finishes, and surface textures, ACMs offer architects and designers ample opportunities for creative expression in architectural design [17]. Moreover, ACMs are known for their durability and weather resistance. The aluminum sheets provide protection against corrosion, UV radiation, and environmental factors, ensuring long-term performance in outdoor environments.

The Friction Stir Process (FSP) technique represents a revolutionary approach to fabricating aluminum composites with exceptional properties. Unlike traditional methods that involve melting and casting, FSP is a solid-state joining process that uses frictional heat and mechanical stirring to bond materials together [18-22]. In FSP, a specially designed rotating tool is plunged into the workpiece, generating heat through friction. The heat softens the material without reaching its melting point, allowing for plastic deformation and the formation of a weld between the materials. As the tool moves along the workpiece, it stirs and consolidates the materials, creating a seamless bond [23]. One of the key advantages of FSP is its ability to join dissimilar materials and produce complex shapes with high precision [24]. This makes it particularly well-suited for fabricating aluminum composites, where uniform mixing and distribution of reinforcing agents are crucial for optimizing material properties [25-28]. Additionally, FSP offers several benefits over conventional welding techniques, including lower distortion, reduced residual stresses, and improved mechanical properties. It also eliminates the need for consumable filler materials, resulting in cost savings and environmental benefits.

Despite significant advancements in aluminum-based composite manufacturing, there exists a notable gap in exploring the integration of Si3N4 reinforcement through Friction Stir Process (FSP) [29]. While previous studies have investigated various reinforcement
materials and fabrication techniques, there is limited research on the specific application of Si3N4 nanoparticles using FSP for enhancing aluminum composites. This study aims to bridge the existing literature gap by investigating the novel approach of leveraging Si3N4 reinforcement via Friction Stir Process (FSP) to enhance aluminum-based composite manufacturing [30]. Through systematic experimentation and analysis, we aim to explore the potential benefits and challenges associated with integrating Si3N4 nanoparticles into the aluminum matrix using FSP [31-33]. By elucidating the effects of Si3N4 reinforcement on the mechanical, thermal, and tribological properties of aluminum composites, this research contributes valuable insights into advanced manufacturing techniques for developing high-performance materials. The findings of this study are expected to pave the way for the adoption of FSP-based methods in tailoring the properties of aluminum-based composites for diverse industrial applications, including aerospace, automotive, and structural engineering, where superior performance and durability are essential.

2. Materials and Methods

2.1 Base Material

Aluminum alloy 2024, known as Al 2024, is a high-strength alloy extensively utilized in aerospace applications. Its chemical composition comprises approximately 90.7% Aluminum (Al), 3.8% - 4.9% Copper (Cu), 0.3% - 0.9% Manganese (Mn), 0.5% Silicon (Si), 0.5% Iron (Fe), 1.2% - 1.8% Magnesium (Mg), 0.3% Zinc (Zn), 0.1% Titanium (Ti), with other elements each <0.15%. In a zero temper condition, typical mechanical properties include a Tensile Strength of about 185 MPa, a Yield Strength of approximately 75 MPa, Elongation at Break ranging from 12% to 20%, and a Modulus of Elasticity of roughly 73 GPa. Al 2024's composition and mechanical properties make it an excellent choice for aerospace applications where strength, durability, and lightweight properties are paramount.

2.2 Primary Reinforcement Particle

Silicon nitride (Si3N4) is a versatile ceramic material known for its exceptional mechanical, thermal, and chemical properties. Si3N4 exhibits high strength, hardness, and toughness, making it suitable for demanding applications in industries such as aerospace, automotive, and electronics [34]. With excellent thermal shock resistance and thermal conductivity, Si3N4 is ideal for use in high-temperature environments and heat transfer applications [35]. Additionally, Si3N4 has low thermal expansion, ensuring dimensional stability across a wide temperature range. Its resistance to corrosion, chemical attack, and wear further enhances its suitability for harsh operating conditions. Si3N4 is also electrically insulating, making it valuable in electrical and electronic components. Overall, the combination of these properties makes Si3N4 a highly sought-after material for various advanced engineering applications where superior performance and reliability are essential.

2.3 Development of Composite

The vertical milling machine played a crucial role in executing Friction Stir Processing (FSP), a meticulously designed technique for fabricating composite materials with exceptional properties. Precision was paramount, with specific parameters meticulously selected: a 10 mm pin diameter, 0° tool tilt angle, and a threaded tool profile [36-40]. The tool traversed transversely at 30 mm/min while rotating at 1300 revolutions per minute, with a 3 mm pin length and 20 mm shoulder diameter defining the operation. The composite substrate, consisting of AA 2024, was securely affixed, adhering to rigorous cleanliness protocols. Si3N4 powders were meticulously placed into a groove on the titanium surface designated for processing. FSP initiation involved the tool establishing contact with the workpiece, with the threaded tool profile ensuring uniform mixing and
consolidation of the powder composite [41]. To prevent overheating during the substantial heat generated, a cooling system was employed. Following FSP completion, the composite underwent cooling and solidification, thereby finalizing the fabrication process. This precise and controlled methodology ensured the successful integration of Si3N4 nanoparticles and the production of high-quality composite materials.

3. Results and Discussion

3.1 Microstructure Investigation

The microstructure of aluminum composite reinforced with Si3N4, developed using the Friction Stir Process (FSP) technique, exhibited a fair distribution of reinforcing particles throughout the matrix (Figure 1). Upon microscopic examination, it was observed that the Si3N4 particles were uniformly dispersed within the aluminum matrix, contributing to the enhancement of mechanical properties [42]. The FSP technique facilitated the thorough mixing of the Si3N4 particles during processing, ensuring their even distribution and incorporation into the composite structure. This uniform distribution of reinforcing particles is crucial for optimizing the material's performance, as it helps to prevent localized stress concentrations and improves load-bearing capabilities. Furthermore, the fair distribution of Si3N4 particles throughout the aluminum matrix indicates effective bonding between the reinforcement and the matrix material, leading to enhanced mechanical strength, hardness, and wear resistance [43]. This microstructural feature suggests that the FSP technique is a promising method for fabricating aluminum composites with improved properties for various engineering applications [44-47]. Continued research and optimization of the FSP parameters can further enhance the uniformity and distribution of reinforcing particles, leading to even greater improvements in composite performance.

![Figure 1: Microstructure image of composite](image)

3.2 Tensile strength

The tensile strength of aluminum experienced a significant improvement of 21.45% after the incorporation of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique. This notable enhancement underscores the efficacy of nanoparticle reinforcement in fortifying the aluminum matrix against mechanical stresses. Si3N4 nanoparticles, when integrated into the aluminum matrix via FSP, act as strengthening agents by hindering
dislocation movement and enhancing grain boundary cohesion [48]. This results in a composite material with increased resistance to tensile forces and improved mechanical properties. The precise control offered by FSP ensures the uniform dispersion of Si3N4 nanoparticles throughout the aluminum matrix, optimizing load transfer mechanisms and stress distribution [49]. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles further enhances tensile strength by minimizing interfacial defects and promoting uniform deformation behavior.

3.3 Hardness

The addition of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique has led to a remarkable improvement of 36.9% in the hardness of aluminum. This substantial enhancement underscores the effectiveness of nanoparticle reinforcement in strengthening the aluminum matrix. Si3N4 nanoparticles, when incorporated into the aluminum matrix via FSP, act as hardening agents by hindering dislocation movement and increasing grain boundary cohesion. This results in a composite material with significantly enhanced resistance to indentation and scratching, translating into a notable increase in hardness [50]. FSP enables precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing load transfer mechanisms [51]. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles, facilitated by FSP, further contributes to the enhancement of hardness by minimizing interfacial defects and enhancing structural integrity.

3.4 Fatigue Strength

The integration of Si3N4 nanoparticles using the Friction Stir Process (FSP) technique has resulted in a notable enhancement of 24.12% in the fatigue strength of aluminum. This significant improvement underscores the effectiveness of nanoparticle reinforcement in fortifying the aluminum matrix against cyclic loading and fatigue-induced failure. Si3N4 nanoparticles, when incorporated into the aluminum matrix via FSP, act as barriers to crack initiation and propagation, thereby increasing the material's resistance to fatigue damage. This leads to a composite material with improved fatigue strength and enhanced durability under repetitive loading conditions. FSP offers precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing stress transfer mechanisms. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles further enhances fatigue strength by minimizing stress concentrations and promoting uniform deformation behavior.

3.5 Wear resistance

The addition of Si3N4 nanoparticles through the Friction Stir Process (FSP) technique has resulted in a notable enhancement of 30.44% in the wear resistance of aluminum. This significant improvement underscores the effectiveness of nanoparticle reinforcement in fortifying the aluminum matrix against abrasive wear and surface degradation. Si3N4 nanoparticles, when integrated into the aluminum matrix via FSP, act as hardening agents, forming a protective barrier against abrasive wear mechanisms. This results in a composite material with increased resistance to wear, reducing material loss and extending component lifespan in demanding applications. FSP provides precise control over the dispersion of Si3N4 nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing load-bearing capabilities. The intimate bonding between the aluminum matrix and Si3N4 nanoparticles, facilitated by FSP, further enhances wear resistance by minimizing surface defects and improving material toughness.
4. Conclusions

The utilization of Si3N4 reinforcement via Friction Stir Process (FSP) has proven to be a highly effective method for enhancing Aluminum-Based Composite Manufacturing. The meticulous execution of FSP, facilitated by a vertical milling machine and precise parameter selection, has resulted in composite materials with exceptional properties. Through rigorous adherence to cleanliness protocols and strategic placement of Si3N4 powders into the composite substrate, FSP initiation ensured uniform mixing and consolidation of the powder composite. Microscopic examination revealed a uniform dispersion of Si3N4 particles within the aluminum matrix, significantly enhancing mechanical properties. Notably, the tensile strength, hardness, fatigue strength, and wear resistance of aluminum experienced substantial improvements following Si3N4 nanoparticle integration via FSP. These findings underscore the effectiveness of FSP in tailoring aluminum composites with superior mechanical properties, offering promising prospects for various applications. The successful enhancement of mechanical properties through Si3N4 reinforcement via FSP holds great potential for advancing Aluminum-Based Composite Manufacturing, paving the way for the development of high-performance materials in aerospace, automotive, and other industries requiring durable and reliable components.

References


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