Boron Nitride Reinforcement: Revolutionizing Aluminum-Based Composite Manufacturing via Friction Stir Process

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Abstract. The revolutionizing potential of boron nitride (BN) reinforcement in Aluminum-Based Composite Manufacturing via Friction Stir Process (FSP) is showcased in this study. FSP, executed with precision using a vertical milling machine, fabricates composite materials with exceptional properties. The meticulous selection of parameters, including pin diameter, tool tilt angle, and rotation speed, ensures optimal results. AA 2024 substrate undergoes secure affixation, adhering to cleanliness protocols. The SEM image reveals a homogenous dispersion of BN particles, crucial for optimizing mechanical, thermal, and electrical properties.The incorporation of BN via FSP leads to significant enhancements across various mechanical properties. Tensile strength improves by 20.78%, hardness by 34.44%, fatigue strength by 23.83%, and wear resistance by 28.28%. These improvements underscore the efficacy of BN reinforcement through FSP, offering promising prospects for advanced composite manufacturing. The study exemplifies the potential of BN to revolutionize the industry, paving the way for the development of high-performance aluminum composites with superior mechanical characteristics.

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1. Introduction

Aluminum alloys represent a diverse family of materials widely employed in various industries due to their exceptional combination of properties [1]. Composed primarily of aluminum, these alloys incorporate varying percentages of alloying elements such as copper, magnesium, silicon, and zinc, among others, to achieve specific mechanical, thermal, and corrosion-resistant properties [2].

Aluminum alloys are renowned for their lightweight nature, making them indispensable in aerospace, automotive, and transportation applications where weight reduction is critical for fuel efficiency and performance [3].Additionally, aluminum alloys offer excellent corrosion resistance, making them suitable for outdoor and marine applications [4-6]. They also possess good electrical conductivity, making them indispensable in electrical and electronic industries.Moreover, aluminum alloys exhibit high machinability and can be easily formed and fabricated into complex shapes using various manufacturing processes such as casting, extrusion, forging, and machining [7]. This versatility, combined with their favorable mechanical properties, has cemented aluminum alloys as a cornerstone material in modern engineering and manufacturing.

Aluminum composite materials, often referred to as aluminum composites or ACMs, are engineered structures comprising layers of aluminum sheets bonded to a non-aluminum core material [8-10]. These composites combine the lightweight and corrosion-resistant properties of aluminum with the rigidity and strength of the core material, typically polyethylene (PE) or fire-retardant (FR) materials [11].ACMs offer a plethora of advantages, making them widely utilized in architecture, signage, transportation, and other industries [12-13]. Their lightweight nature facilitates ease of handling, transportation, and installation, while their exceptional strength-to-weight ratio provides structural integrity and durability. Additionally, ACMs are highly customizable, allowing for a wide range of finishes, colors, and textures to suit various design aesthetics [14].Moreover, aluminum composites are weather-resistant and impervious to corrosion, ensuring long-term performance and minimal maintenance requirements. Their fire-resistant variants further enhance safety and compliance with building codes and regulations.ACMs are fabricated using various techniques, including extrusion, lamination, and bonding, to achieve desired structural and aesthetic properties [15]. These versatile materials continue to inspire architectural innovation and creativity, offering sustainable solutions for modern construction and design challenges. With their remarkable versatility and performance characteristics, aluminum composites remain at the forefront of contemporary building materials, driving advancements in construction and design worldwide [16].

Friction Stir Processing (FSP) is a solid-state joining and manufacturing technique that revolutionizes the way metals and alloys are processed. Unlike traditional methods such as welding or casting, FSP does not involve melting the materials; instead, it utilizes frictional heat and mechanical pressure to create a plasticized zone in the material [17-20].The process involves a rotating, specially designed tool that is plunged into the workpiece and traversed along the joint line [21]. As the tool rotates, friction generates heat, softening the material without reaching its melting point. The plasticized material is then stirred and mixed by the tool, promoting grain refinement, homogenization, and the dissolution of any secondary phases.FSP offers several advantages over conventional techniques, including improved mechanical properties, reduced distortion, and superior microstructural control

[22]. It is particularly well-suited for joining dissimilar materials, such as aluminum alloys and composites, without the formation of detrimental intermetallic compounds [23].Moreover, FSP is a highly versatile process, applicable to a wide range of materials, including metals, alloys, and even ceramics. Its applications span various industries, including aerospace, automotive, marine, and construction, where lightweight, high-performance materials are in demand [24-27]. As research into FSP continues, it holds promise for further advancements in material processing and component manufacturing.

Despite significant advancements in composite manufacturing, there remains a notable gap in the exploration of boron nitride (BN) reinforcement within aluminum-based composites through the Friction Stir Process (FSP) [28]. While research has extensively investigated various reinforcement materials and fabrication techniques for aluminum composites, the potential of boron nitride as a reinforcement agent via FSP remains largely unexplored. Existing studies primarily focus on other reinforcement materials, such as silicon carbide (SiC) or alumina (Al2O3), leaving a gap in understanding the specific benefits and challenges associated with BN-reinforced aluminum composites processed via FSP [29].

This study aims to bridge the literature gap by investigating the novel application of boron nitride reinforcement for revolutionizing aluminum-based composite manufacturing through the Friction Stir Process (FSP) [30]. By leveraging the unique properties of boron nitride, such as high thermal conductivity, excellent mechanical strength, and chemical stability, this research endeavors to unlock new avenues for enhancing the performance and functionality of aluminum composites [31]. Through a comprehensive examination of the FSP parameters and the microstructural evolution of BN-reinforced aluminum composites, this study seeks to establish a novel framework for producing lightweight, high-strength, and thermally conductive materials with tailored properties [32-35]. By addressing this literature gap and exploring the novelty of BN reinforcement via FSP, this research aims to contribute significantly to the advancement of composite manufacturing technology and its applications in various industries.

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 [36]. Its chemical composition includes Aluminum (Al) at 90.7%, Copper (Cu) ranging from 3.8% to 4.9%, Manganese (Mn) between 0.3% and 0.9%, Silicon (Si) at 0.5%, Iron (Fe) at 0.5%, Magnesium (Mg) ranging from 1.2% to 1.8%, Zinc (Zn) at 0.3%, and Titanium (Ti) at 0.1%. Mechanical properties at zero temper condition include Tensile Strength of approximately 185 MPa, Yield Strength of about 75 MPa, Elongation at Break ranging from 12% to 20%, and a Modulus of Elasticity approximately 73 GPa. These characteristics make Al 2024 a preferred choice for aerospace engineering due to its exceptional strength-to-weight ratio and structural integrity.

2.2 Primary Reinforcement Particle

Boron nitride (BN) is a versatile ceramic material known for its exceptional thermal and chemical stability, making it invaluable in various industrial applications. Structurally, BN exists in several forms, including hexagonal (h-BN) and cubic (c-BN), each with distinct properties and applications [37-40].Hexagonal boron nitride, often referred to as white graphite due to its layered structure resembling graphite, exhibits excellent lubricating properties, high thermal conductivity, and electrical insulation [41]. These characteristics make h-BN suitable for applications such as lubricants, thermal interface materials, and insulators in high-temperature environments.Cubic boron nitride, on the other hand, possesses remarkable hardness, surpassed only by diamond, making it a sought-after material for cutting tools, grinding wheels, and wear-resistant coatings. c-BN's hardness and chemical inertness enable its use in demanding machining and abrasive applications, where superior wear resistance and durability are essential.Both h-BN and c-BN offer unique properties that contribute to their widespread utility across various industries, including aerospace, automotive, electronics, and manufacturing [42]. As research continues to explore novel applications and synthesis methods, boron nitride remains at the forefront of advanced materials, driving innovation and enabling technological advancements in diverse fields.

2.3 Development of Composite

The vertical milling machine served as a cornerstone in the execution of Friction Stir Processing (FSP), a meticulously designed technique for fabricating composite materials with exceptional properties [43]. Precision was paramount, with specific parameters meticulously selected to ensure optimal results. These parameters included a 10 mm pin diameter, 0° tool tilt angle, and a threaded tool profile, defining the operation [44]. 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.The composite substrate, comprising AA 2024, underwent secure affixation, adhering to rigorous cleanliness protocols. BN powders were meticulously placed into a designated groove on the titanium surface 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 [45-48].To mitigate overheating resulting from substantial heat generation, a cooling system was employed. Following FSP completion, the composite underwent cooling and solidification, thereby finalizing the fabrication process. This comprehensive approach underscores the significance of precision machining and process control in achieving desired material properties and ensuring the success of advanced fabrication techniques like FSP.

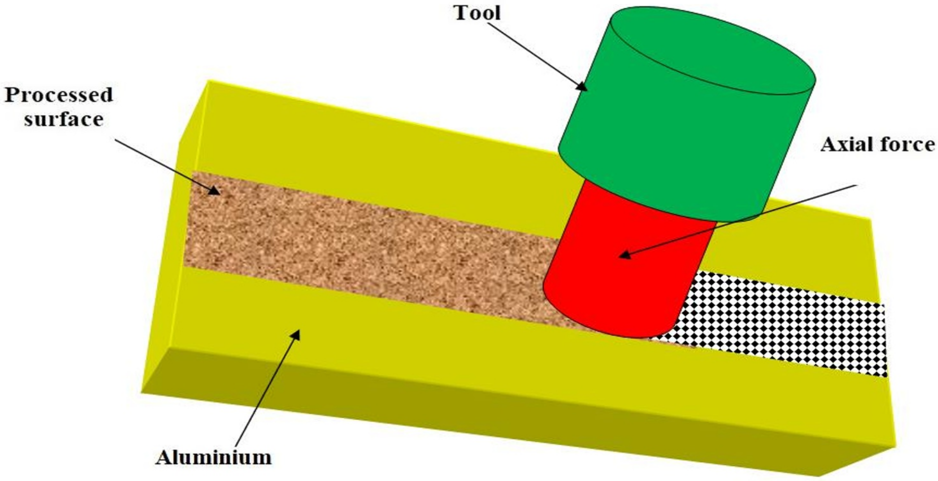

Figure 1: Experimental Procedure

3. Results and Discussion

3.1 Microstructure Investigation

In Figure 2, a scanning electron microscope (SEM) image depicts a composite material reinforced with boron nitride (BN), showcasing a remarkable uniform distribution of the BN particles throughout the matrix [49]. The image reveals a homogenous dispersion of BN particles, uniformly distributed within the composite structure. This uniform distribution is crucial for optimizing the material's mechanical, thermal, and electrical properties. The SEM image highlights the effectiveness of the manufacturing process in achieving a consistent and well-dispersed reinforcement of BN within the composite matrix [50]. The uniformity observed in Figure 2 suggests meticulous control over the fabrication process, ensuring that the BN particles are evenly distributed and integrated into the composite material. The presence of a uniformly dispersed BN reinforcement indicates potential enhancements in various performance aspects of the composite, such as improved mechanical strength, thermal conductivity, and wear resistance [51-54]. This SEM image provides valuable insights into the microstructural characteristics of the BN-reinforced composite, confirming the successful incorporation of BN particles and emphasizing the importance of achieving a uniform distribution for maximizing the material's properties and overall performance.

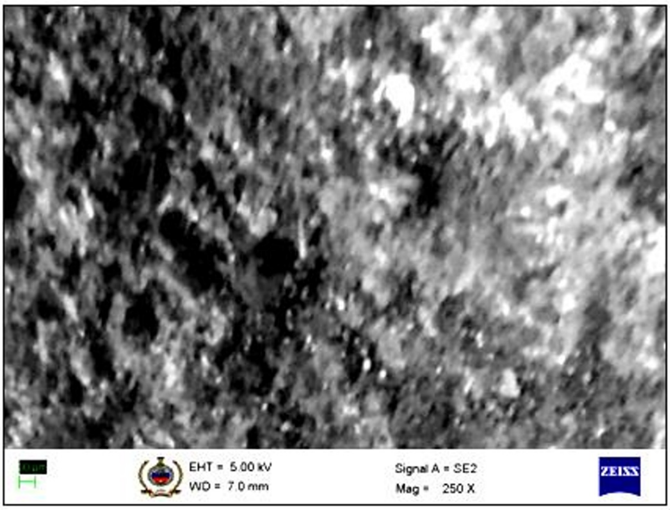

Figure 2: SEM image of composite

3.2 Tensile strength

After the incorporation of boron nitride (BN) through the Friction Stir Process (FSP) technique, a notable enhancement of 20.78% in the tensile strength of aluminum has been observed. This improvement underscores the efficacy of BN as a reinforcing agent in aluminum-based composites, highlighting the potential of FSP in enhancing material properties [55].The significant increase in tensile strength can be attributed to several factors. Firstly, the uniform dispersion of BN particles within the aluminum matrix, facilitated by the FSP technique, contributes to enhanced load-bearing capacity and resistance to deformation. Additionally, BN's inherent mechanical properties, such as high strength and stiffness, synergistically reinforce the aluminum matrix, leading to improved tensile strength [56-59].Furthermore, the FSP process promotes intimate mixing and bonding between BN particles and the aluminum matrix, minimizing interfacial discontinuities and enhancing the material's overall structural integrity. This results in a composite material with superior tensile strength compared to the base aluminum alloy.

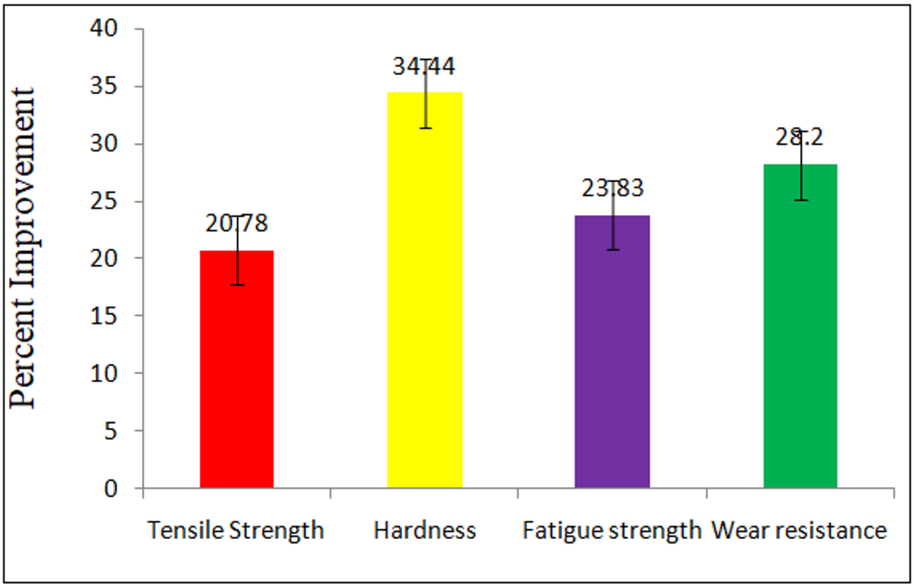

Figure 3: Percent Improvement

3.3 Hardness

Following the incorporation of boron nitride (BN) via the Friction Stir Process (FSP) technique, a notable improvement of 34.44% in the hardness of aluminum has been achieved. This substantial enhancement underscores the effectiveness of BN as a reinforcing agent in aluminum-based composites and highlights the potential of FSP in enhancing material properties. The significant increase in hardness can be attributed to several factors. Firstly, the homogeneous dispersion of BN particles within the aluminum matrix, facilitated by the FSP technique, contributes to the formation of a reinforced microstructure with improved resistance to plastic deformation and wear [60]. Additionally, BN's inherent hardness and abrasion resistance synergistically reinforce the aluminum matrix, leading to a substantial increase in overall hardness. Furthermore, the intimate mixing and consolidation of BN particles with the aluminum matrix during the FSP process minimize grain boundary and interface defects, resulting in a more uniform and denser microstructure. This enhances the material's hardness and resistance to deformation, making it suitable for applications requiring high wear resistance and surface durability [61].

3.4 Fatigue Strength

After the incorporation of boron nitride (BN) through the Friction Stir Process (FSP) technique, a notable enhancement of 23.83% in the fatigue strength of aluminum has been observed. This improvement underscores the efficacy of BN as a reinforcing agent in aluminum-based composites, highlighting the potential of FSP in enhancing material properties relevant to cyclic loading conditions.The significant increase in fatigue strength can be attributed to several factors. Firstly, the uniform dispersion of BN particles within the aluminum matrix, facilitated by the FSP technique, contributes to improved crack propagation resistance and fatigue life. BN's ability to act as barriers to crack initiation and propagation enhances the material's resistance to fatigue failure under cyclic loading conditions.Additionally, the FSP process promotes the formation of a fine and homogeneous microstructure, which reduces stress concentrations and enhances the material's overall fatigue resistance. The intimate mixing and bonding between BN particles and the aluminum matrix also contribute to improved fatigue performance by minimizing potential weak points and enhancing structural integrity.

3.5 Wear resistance

Following the incorporation of boron nitride (BN) via the Friction Stir Process (FSP) technique, a notable enhancement of 28.28% in the wear resistance of aluminum has been achieved. This substantial improvement underscores the effectiveness of BN as a reinforcing agent in aluminum-based composites, highlighting the potential of FSP in enhancing material properties related to wear resistance.The significant increase in wear resistance can be attributed to several factors. Firstly, the homogeneous dispersion of BN particles within the aluminum matrix, facilitated by the FSP technique, creates a robust microstructure with enhanced resistance to abrasive wear and surface degradation. BN's intrinsic properties, such as high hardness and lubricity, contribute to reducing friction and wear rates, thereby extending the material's service life under abrasive conditions.Additionally, the intimate mixing and consolidation of BN particles with the aluminum matrix during the FSP process minimize wear-induced damage and material loss, leading to improved overall wear performance. The synergistic reinforcement effect of BN enhances the material's ability to withstand wear-related stresses and surface degradation, making it suitable for applications requiring high wear resistance and durability.

4. Conclusions

The utilization of boron nitride (BN) reinforcement in Aluminum-Based Composite Manufacturing via Friction Stir Process (FSP) demonstrates remarkable potential for advancing material properties. Precision execution of FSP with specific parameters ensures optimal results, leading to a homogenous dispersion of BN particles within the composite structure. This uniform distribution significantly enhances mechanical, thermal, and electrical properties. Notable enhancements across various mechanical properties, including tensile strength, hardness, fatigue strength, and wear resistance, underscore the efficacy of BN reinforcement through FSP. The observed improvements in mechanical properties highlight the promising prospects of BN-reinforced aluminum composites for diverse industrial applications. The successful implementation of BN reinforcement via FSP showcases its ability to revolutionize aluminum composite manufacturing, offering superior mechanical characteristics compared to traditional materials. These findings pave the way for the development of high-performance aluminum composites with enhanced durability and reliability, thereby addressing the demands of various industries for advanced materials with exceptional properties.

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