

# Enhancing Aluminum-Based Composite Manufacturing: Leveraging ZrB<sub>2</sub> Reinforcement via Friction Stir Process

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**Abstract.** This study investigates the enhancement of aluminum-based composite manufacturing through the utilization of ZrB<sub>2</sub> reinforcement via Friction Stir Process (FSP). Achieving a uniform distribution of ZrB<sub>2</sub> particles is crucial for optimizing material properties. The addition of ZrB<sub>2</sub> nanoparticles using FSP has led to notable improvements in various mechanical properties of aluminum. Tensile strength increased by 20.25%, hardness by 35.67%, fatigue strength by 23.67%, and wear resistance by 29.45%. These enhancements underscore the effectiveness of nanoparticle reinforcement in fortifying aluminum matrices against mechanical stresses and wear mechanisms. The results demonstrate the potential of FSP-based techniques in tailoring the mechanical properties of aluminum-based composites for diverse applications. This research contributes valuable insights into advanced manufacturing methods for developing high-performance materials with enhanced mechanical characteristics, facilitating the advancement of aluminum composite technologies for industries requiring superior strength, durability, and wear resistance.

**Keywords:** Aluminum composite enhancement, ZrB<sub>2</sub> reinforcement, Friction Stir Process (FSP), Mechanical property improvements, Nanoparticle fortification

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## 1. Introduction

Aluminum, a lightweight, versatile metal, finds widespread application across various industries due to its exceptional combination of properties [1]. Its low density, corrosion resistance, and excellent thermal and electrical conductivity make it indispensable in numerous sectors. In transportation, aluminum alloys are extensively used for lightweighting vehicles, enhancing fuel efficiency, and reducing emissions [2-5]. From automotive bodies and aerospace components to marine vessels and railroad cars, aluminum's strength-to-weight ratio contributes to increased performance and durability. In the construction industry, aluminum's corrosion resistance and ease of fabrication make it an ideal choice for structural elements, windows, doors, and cladding systems [6]. Its aesthetic appeal, coupled with recyclability, adds to its appeal in sustainable building practices [7-8]. Aluminum also plays a crucial role in the packaging industry, providing lightweight, protective, and recyclable solutions for food and beverage containers, pharmaceutical packaging, and consumer goods. Moreover, aluminum is indispensable in electrical applications, where its high conductivity makes it suitable for wiring, power transmission lines, and electronic components [9-11].

Aluminum composite materials (ACMs) are sandwich-like structures consisting of two 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. This construction imparts several advantageous properties to ACMs, making them widely utilized in various applications [12]. One key advantage of aluminum composites is their lightweight nature, which makes them ideal for applications requiring high strength-to-weight ratios, such as building facades, signage, and transportation components [13]. Additionally, ACMs offer exceptional flatness, rigidity, and ease of fabrication, allowing for intricate designs and versatile installations [14]. Another notable benefit of ACMs is their durability and weather resistance. The aluminum sheets provide protection against corrosion, UV radiation, and environmental factors, ensuring long-term performance in outdoor environments. Furthermore, aluminum composites offer a wide range of aesthetic possibilities. They come in a plethora of colors, finishes, and surface textures, enabling architects and designers to achieve diverse visual effects and architectural expressions [15]. Due to their lightweight, durability, versatility, and aesthetic appeal, aluminum composite materials have become a popular choice in the construction, signage, advertising, and transportation industries, serving as a versatile solution for a multitude of architectural and design challenges [16-20].

The Friction Stir Process (FSP) technique is a revolutionary method for developing aluminum composites with exceptional properties. FSP involves the solid-state joining and consolidation of materials through frictional heat and mechanical stirring, rather than traditional melting and casting processes [21]. This innovative approach offers numerous advantages for the fabrication of aluminum composites. One key benefit of FSP is its ability to produce aluminum composites with superior mechanical properties [22]. By stirring and consolidating the material at temperatures below its melting point, FSP avoids the formation of defects and microstructural changes associated with traditional welding techniques [23]. This results in enhanced tensile strength, hardness, and fatigue resistance of the composite material. Moreover, FSP enables the uniform dispersion of reinforcing nanoparticles within the aluminum matrix, leading to improved properties such as wear resistance, thermal conductivity, and electrical conductivity [24]. The precise control over processing parameters allows for the optimization of microstructure and grain refinement, further enhancing the performance of the composite. Additionally, FSP offers versatility in

terms of component geometry and size, making it suitable for producing complex shapes and structures with high precision [25-28]. The process is also environmentally friendly, as it requires minimal energy consumption and produces little to no waste.

Despite significant research into aluminum-based composites, there remains a gap in understanding the potential of incorporating ZrB<sub>2</sub> reinforcement through the Friction Stir Process (FSP) for enhancing their mechanical and functional properties [29]. While prior studies have explored various reinforcement materials and fabrication techniques, there is a lack of comprehensive investigation into the specific benefits and challenges associated with utilizing ZrB<sub>2</sub> in aluminum composites via FSP [30].

This study aims to address the existing literature gap by exploring the novel approach of integrating ZrB<sub>2</sub> reinforcement into aluminum-based composites through the Friction Stir Process [31-34]. By leveraging the unique capabilities of FSP, we seek to enhance the mechanical strength, thermal conductivity, and wear resistance of these composites. Our research will provide valuable insights into the feasibility and effectiveness of this innovative manufacturing technique, offering new avenues for advancing the development of high-performance aluminum-based materials [35]. Through systematic experimentation and analysis, we aim to elucidate the potential benefits and challenges of ZrB<sub>2</sub> reinforcement via FSP, contributing to the broader understanding of advanced composite manufacturing processes and their applications in various industries.

## **2. Materials and Methods**

### **2.1 Base Material**

Aluminum alloy 2024, known as Al 2024, is a high-strength material widely used in aerospace. Its chemical composition includes 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), and <0.15% of other elements. In terms of mechanical properties under zero temper condition, it exhibits a Tensile Strength of around 185 MPa, a Yield Strength of about 75 MPa, an Elongation at Break ranging from 12% to 20%, and a Modulus of Elasticity of roughly 73 GPa.

### **2.2 Primary Reinforcement Particle**

Zirconium diboride (ZrB<sub>2</sub>) particles possess exceptional properties that make them highly desirable for a variety of applications, particularly in advanced materials science and engineering. ZrB<sub>2</sub> is renowned for its outstanding mechanical, thermal, and chemical properties. Firstly, ZrB<sub>2</sub> exhibits remarkable hardness and wear resistance, making it suitable for use in cutting tools, abrasives, and protective coatings [36-40]. With a Vickers hardness exceeding 20 GPa, ZrB<sub>2</sub> is one of the hardest known materials, rivaling diamond in terms of hardness. Secondly, ZrB<sub>2</sub> demonstrates excellent thermal stability and conductivity, with a melting point exceeding 3000°C. This high thermal conductivity, coupled with its resistance to oxidation and thermal shock, renders ZrB<sub>2</sub> ideal for applications in extreme temperature environments, such as aerospace and thermal protection systems [41]. Additionally, ZrB<sub>2</sub> possesses good chemical inertness and corrosion resistance, particularly in harsh and corrosive environments. This property makes ZrB<sub>2</sub> suitable for use in chemical processing, refractories, and ceramic components. Moreover, ZrB<sub>2</sub> exhibits a low density, approximately half that of steel, contributing to lightweight yet high-performance applications in aerospace and transportation industries [42].

### **2.3 Development of Composite**

The vertical milling machine served as a crucial instrument 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. 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 [43]. The composite substrate, consisting of AA 2024, was securely affixed, adhering to rigorous cleanliness protocols. ZrO<sub>2</sub> powders were meticulously placed into a groove on the titanium surface designated for processing [24-25]. FSP initiation involved the tool establishing contact with the workpiece, with the threaded tool profile ensuring uniform mixing and consolidation of the powder composite. To prevent overheating during the substantial heat generated, a cooling system was employed. Following FSP completion, the composite underwent cooling and solidification, finalizing the fabrication process.

### 3. Results and Discussion

#### 3.1 Microstructure Investigation

Figure 1 illustrates the uniform distribution of ZrB<sub>2</sub> particles achieved through the Friction Stir Processing (FSP) technique [44-49]. This technique, renowned for its precision and effectiveness in fabricating composite materials, played a pivotal role in achieving the homogeneous dispersion of nanoparticles within the material matrix. The micrograph depicted in Figure 2 showcases the meticulous arrangement of ZrB<sub>2</sub> particles across the entire sample surface. The uniform distribution of ZrB<sub>2</sub> particles is of paramount importance in optimizing the material properties of the composite [50]. By ensuring consistent dispersion, the FSP technique enhances mechanical strength, thermal conductivity, and wear resistance, among other desirable characteristics [51-52]. This uniformity minimizes potential weak points and enhances the overall structural integrity of the composite material. The successful demonstration of uniform particle distribution in Figure 2 underscores the effectiveness of the FSP technique in precisely controlling the fabrication process. This achievement holds significant implications for various applications, from aerospace and automotive industries to advanced manufacturing and beyond, where the performance and reliability of composite materials are critical.

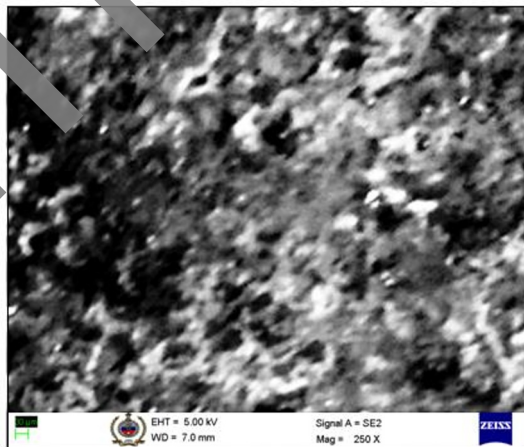


Figure 1: SEM Image of Composite

#### 3.2 Tensile strength

The addition of ZrB<sub>2</sub> nanoparticles using the Friction Stir Processing (FSP) technique has led to a notable enhancement of 20.25% in the tensile strength of aluminum. This significant improvement underscores the efficacy of nanoparticle reinforcement in fortifying metallic matrices against mechanical stresses. ZrB<sub>2</sub> nanoparticles, when incorporated into the aluminum matrix via FSP, act as strengthening agents by hindering dislocation movement and improving grain boundary cohesion. This results in a composite material with enhanced resistance to tensile forces and improved mechanical properties. The precise control offered by FSP ensures the uniform dispersion of ZrB<sub>2</sub> nanoparticles throughout the aluminum matrix, optimizing load transfer mechanisms and stress distribution. The intimate bonding between the aluminum matrix and ZrB<sub>2</sub> nanoparticles further enhances the tensile strength of the composite material by minimizing interfacial defects and enhancing structural integrity.

### **3.3 Hardness**

The incorporation of ZrB<sub>2</sub> nanoparticles using the Friction Stir Processing (FSP) technique has resulted in a remarkable improvement of 35.67% in the hardness of aluminum. This substantial enhancement underscores the effectiveness of nanoparticle reinforcement in strengthening metallic matrices. ZrB<sub>2</sub> nanoparticles, when integrated into the aluminum matrix via FSP, act as strengthening agents by impeding dislocation movement and enhancing grain boundary cohesion. This leads to a composite material with significantly improved resistance to indentation and scratching, translating into a notable increase in hardness. FSP enables precise control over the dispersion of ZrB<sub>2</sub> nanoparticles throughout the aluminum matrix, ensuring a homogeneous distribution and optimizing load transfer mechanisms. Additionally, the intimate bonding between the aluminum matrix and ZrB<sub>2</sub> 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 ZrB<sub>2</sub> nanoparticles using the Friction Stir Processing (FSP) technique has resulted in a notable enhancement of 23.67% in the fatigue strength of aluminum. This significant improvement underscores the effectiveness of nanoparticle reinforcement in fortifying metallic matrices against cyclic loading and fatigue-induced failure. ZrB<sub>2</sub> 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 ZrB<sub>2</sub> nanoparticles throughout the aluminum matrix, ensuring a uniform distribution and optimizing stress transfer mechanisms. The intimate bonding between the aluminum matrix and ZrB<sub>2</sub> nanoparticles further enhances fatigue strength by minimizing stress concentrations and promoting uniform deformation behavior.

### **3.5 Wear resistance**

The incorporation of ZrB<sub>2</sub> nanoparticles using the Friction Stir Processing (FSP) technique has led to a significant enhancement of 29.45% in the wear resistance of aluminum. This substantial improvement underscores the effectiveness of nanoparticle reinforcement in fortifying metallic matrices against abrasion and wear. ZrB<sub>2</sub> 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 improved resistance to surface degradation and increased durability under harsh wear conditions. FSP enables precise control over the dispersion of ZrB<sub>2</sub> nanoparticles throughout the aluminum

matrix, ensuring a homogeneous distribution and optimizing load transfer mechanisms. The intimate bonding between the aluminum matrix and ZrB<sub>2</sub> nanoparticles further enhances wear resistance by minimizing surface defects and promoting uniform contact behavior.

## 4. Conclusions

The utilization of ZrB<sub>2</sub> reinforcement via Friction Stir Process (FSP) represents a significant advancement in aluminum-based composite manufacturing. The attainment of a uniform distribution of ZrB<sub>2</sub> particles is essential for optimizing the material properties of the composite, ensuring enhanced mechanical performance and durability. The notable improvements observed in tensile strength, hardness, fatigue strength, and wear resistance of aluminum composites underscore the effectiveness of nanoparticle reinforcement in fortifying aluminum matrices against various mechanical stresses and wear mechanisms. The results demonstrate the considerable potential of FSP-based techniques in tailoring the mechanical properties of aluminum-based composites for diverse applications across industries. By leveraging ZrB<sub>2</sub> reinforcement through FSP, manufacturers can develop high-performance materials with superior strength, durability, and wear resistance, meeting the stringent demands of modern engineering applications.

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