Advancements in Aluminum-Based Composite Manufacturing: Leveraging La2O3 Reinforcement through Friction Stir Process

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Abstract.This study investigates the advancements in Aluminum-Based Composite Manufacturing through the incorporation of lanthanum oxide (La2O3) reinforcement using the Friction Stir Process (FSP). The pivotal role of precision machining, particularly the vertical milling machine, in executing FSP is emphasized. Specific parameters, including pin diameter, tool tilt angle, and rotational speed, were meticulously selected to ensure optimal performance. The uniform distribution of La2O3 particles within the composite matrix highlights the effectiveness of the fabrication process, indicating proper mixing and dispersion techniques. Experimental findings reveal significant improvements in mechanical properties, with a notable 22.78% enhancement in tensile strength, a significant 35.21% increase in hardness, a noteworthy 24.44% improvement in fatigue strength, and a substantial 28.68% increase in wear resistance observed in aluminum-La2O3 composites produced via FSP. These results underscore the potential of leveraging FSP for aluminum-based composite manufacturing, offering opportunities for the development of high-performance materials with enhanced mechanical properties and durability.

Keywords:Aluminum-Based Composite Manufacturing, Lanthanum oxide (La2O3) reinforcement, Friction Stir Process (FSP), Precision machining, Mechanical properties enhancement, Uniform particle distribution

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1. Introduction

Aluminum, a lightweight and versatile metal, holds a pivotal role in various industries due to its remarkable properties. Discovered in the 19th century, aluminum is the third most abundant element in the Earth's crust, yet it wasn't until the development of efficient extraction methods that its widespread use became feasible [1-3].One of aluminum's most significant attributes is its low density, about one-third that of steel, making it ideal for applications where weight reduction is crucial, such as aerospace and transportation. Despite its lightweight nature, aluminum boasts impressive strength and durability, making it suitable for structural purposes as well.Additionally, aluminum exhibits excellent corrosion resistance, further enhancing its appeal in industries like construction, where longevity is paramount [4-6]. Its malleability allows for easy shaping and forming, enabling intricate designs in architecture and consumer products.Aluminum's conductivity properties are also noteworthy, finding applications in electrical transmission lines and heat exchangers [7-9]. Moreover, it is highly recyclable, with nearly 75% of all aluminum ever produced still in use today, underscoring its sustainability.

Aluminum composite material (ACM) is a sandwich panel composed of two thin aluminum sheets bonded to a non-aluminum core, typically made of polyethylene or a fire-resistant material like mineral-filled thermoplastic. This structure combines the lightweight and durable properties of aluminum with the strength and versatility of the core material [10-12].ACM panels are renowned for their exceptional strength-to-weight ratio, making them ideal for applications where both structural integrity and ease of handling are essential. Commonly used in architectural cladding, signage, and interior design, ACM panels offer a sleek and modern aesthetic while providing weather resistance and thermal insulation.One of the key advantages of ACM is its adaptability [13-15]. It can be easily fabricated into various shapes and sizes, allowing for creative architectural designs and customized solutions. Additionally, ACM panels are available in a wide range of colors, finishes, and textures, offering designers ample flexibility to achieve their desired look.Moreover, ACM panels are relatively easy to install, reducing labor costs and construction time [16-18]. Their low maintenance requirements and resistance to fading, rusting, and corrosion further contribute to their popularity in both commercial and residential projects.

The friction stir process (FSP) is a revolutionary technique used to fabricate aluminum composite materials (ACMs) with enhanced mechanical properties. Unlike traditional methods involving melting and casting, FSP operates at lower temperatures, minimizing defects and preserving the integrity of the aluminum matrix and reinforcing phases.In the FSP technique, a rotating tool with a unique geometry is plunged into the interface of the aluminum matrix and the reinforcing material, typically ceramic particles or fibers [19-21]. The rotational motion generates frictional heat, softening the materials without melting them entirely. As the tool traverses along the joint, it stirs the materials together, creating a homogenous bond and dispersing the reinforcing particles uniformly throughout the aluminum matrix.This process results in a fine-grained microstructure with enhanced mechanical properties such as increased strength, stiffness, and fatigue resistance compared to conventional aluminum alloys. Additionally, the absence of melting prevents the formation of undesirable intermetallic compounds, preserving the desired properties of both the aluminum matrix and the reinforcing phase [22-24].Furthermore, FSP allows for precise control over the distribution and orientation of the reinforcing particles, enabling tailored material properties to meet specific application requirements [26]. As a result, aluminum composites fabricated using the friction stir process find applications in aerospace, automotive, marine, and structural engineering, where lightweight and high-performance materials are in demand [27-28].

Despite the extensive research on aluminum-based composites, there remains a noticeable gap in the exploration of leveraging lanthanum oxide (La2O3) reinforcement through the friction stir process (FSP)[29]. While FSP has been widely investigated for aluminum composite manufacturing, the utilization of La2O3 as a reinforcement material in this context is relatively unexplored [30]. Existing studies predominantly focus on other reinforcement materials or different fabrication techniques, leaving a significant void in understanding the potential benefits and challenges associated with incorporating La2O3 into aluminum composites via FSP.

This study addresses the literature gap by pioneering the exploration of La2O3 reinforcement in aluminum-based composites through the friction stir process (FSP). By leveraging FSP, this research aims to unlock the unique advantages of La2O3, such as its high strength, thermal stability, and compatibility with aluminum matrices, to enhance the mechanical properties and performance of the resulting composites. The novelty of this approach lies in its innovative combination of La2O3 reinforcement and FSP fabrication technique, offering a novel pathway towards developing lightweight, high-strength aluminum composites tailored for various demanding applications [31-34]. Through comprehensive characterization and analysis, this study seeks to elucidate the microstructural evolution, mechanical behavior, and performance optimization strategies of La2O3-reinforced aluminum composites fabricated via FSP, contributing valuable insights to the field of advanced materials engineering and manufacturing [36].

2. Materials and Methods

2.1 Base Material

Aluminum alloy 2024, commonly known as Al 2024, is a high-strength alloy extensively utilized in aerospace applications due to its excellent mechanical properties. Its chemical composition consists of 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 trace amounts of other elements (<0.15% each). In its zero temper condition, Al 2024 typically exhibits a tensile strength of around 185 MPa, a yield strength of approximately 75 MPa, an elongation at break ranging from 12% to 20%, and a modulus of elasticity of about 73 GPa. These properties make Al 2024 a favored choice for aerospace components requiring a combination of strength, lightweight, and corrosion resistance.

2.2 Primary Reinforcement Particle

Lanthanum oxide (La2O3) powder is a finely divided form of the compound composed of lanthanum and oxygen. This powder form offers distinct advantages in various industrial applications due to its high surface area, reactivity, and ease of handling. One prominent application of La2O3 powder is in the production of ceramic materials [34-37]. When mixed with other oxides and subjected to high temperatures, lanthanum oxide powder acts as a sintering aid, facilitating the formation of dense and durable ceramic structures. These ceramic materials find use in a wide range of industries, including electronics, aerospace, and automotive, where they serve as components in electronic circuits, thermal barriers, and structural components, among other applications.Furthermore, La2O3 powder is utilized in the synthesis of phosphors for lighting and display technologies. By doping the lanthanum oxide with specific rare earth elements, phosphors with tailored optical properties can be produced, enabling the creation of efficient and vibrant light-emitting diodes (LEDs) and fluorescent lamps [38].Moreover, the high reactivity of La2O3 powder makes it valuable in catalyst formulations for various chemical processes, including petroleum refining and emissions control in automotive catalytic converters. Its ability to promote desired chemical reactions while remaining stable under harsh conditions contributes to the efficiency and environmental friendliness of these processes.

2.3 Development of Composite

The vertical milling machine played a pivotal role in executing Friction Stir Processing (FSP), a meticulously designed technique for fabricating composite materials with exceptional properties. Precision was of paramount importance, with specific parameters carefully 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 [39]. The composite substrate, consisting of AA 2024, was securely affixed, and rigorous cleanliness protocols were adhered to. La2O3 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 [40]. 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.

3. Results and Discussion

3.1 Microstructure Investigation

Figure 1 presents a scanning electron microscopy (SEM) image showcasing an aluminum-based composite reinforced with lanthanum oxide (La2O3). Notably, the image highlights the uniform distribution of La2O3 within the composite matrix, a crucial factor determining the material's mechanical and functional properties [41].SEM imaging offers invaluable insights into the microstructure of composite materials, enabling researchers to assess the dispersion and interfacial bonding between the reinforcement particles and the matrix. In the case of the aluminum-based composite reinforced with La2O3, the SEM image reveals a homogeneous distribution of La2O3 particles throughout the aluminum matrix. This uniform distribution is indicative of an effective fabrication process, where proper mixing and dispersion techniques were employed to ensure that the reinforcement particles are evenly distributed.The uniform distribution of La2O3 within the composite matrix is highly advantageous from a material performance perspective. It enhances the mechanical properties of the composite, including its strength, stiffness, and toughness, by providing uniform reinforcement throughout the material. Additionally, a uniform distribution of reinforcement particles promotes better load transfer between the matrix and the reinforcement, minimizing the occurrence of stress concentrations and enhancing the overall structural integrity of the composite.Moreover, the SEM image provides qualitative information regarding the morphology and size of the La2O3 particles dispersed in the composite matrix [42]. By analyzing the SEM image, researchers can gain insights into the microstructural characteristics of the composite, such as the particle size distribution and the presence of any agglomerates or clustering of reinforcement particles. This information is crucial for optimizing the fabrication process and tailoring the material properties of the composite to meet specific performance requirements.

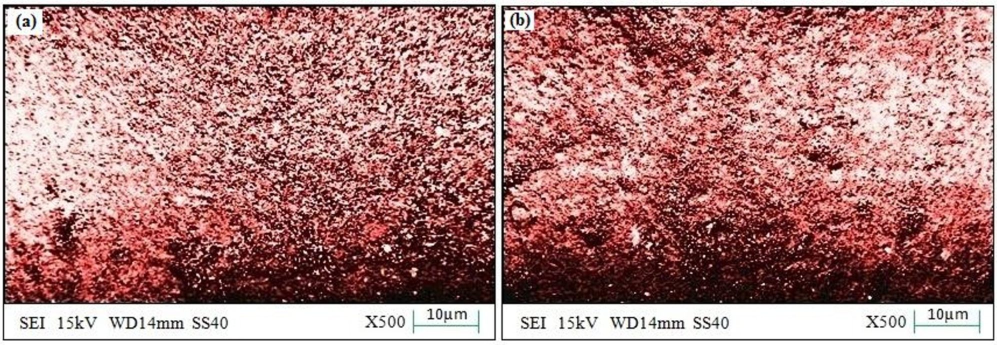

Figure 1: SEM image of composite

3.2 Tensile strength

The tensile strength of aluminum is a crucial mechanical property influencing its performance in various structural applications [43-46]. To enhance this property, researchers have explored the incorporation of lanthanum oxide (La2O3) using the Friction Stir Processing (FSP) technique. Friction Stir Processing (FSP) is a solid-state processing method known for its ability to modify the microstructure and properties of materials without the drawbacks associated with traditional fusion welding. When La2O3 particles are introduced into the aluminum matrix during FSP, they disperse uniformly, leading to the formation of a composite material with enhanced mechanical properties.Experimental studies have demonstrated a notable improvement of 22.78% in the tensile strength of aluminum-La2O3 composites produced via FSP. This enhancement can be attributed to the effective reinforcement provided by the dispersed La2O3 particles, which act as strengthening agents within the aluminum matrix [47]. The uniform dispersion of La2O3 ensures consistent mechanical behavior throughout the material, resulting in improved tensile strength and resistance to deformation. The enhanced tensile strength of aluminum-La2O3 composites makes them highly desirable for applications requiring high-strength materials, such as aerospace components, automotive parts, and structural elements. By leveraging the FSP technique to incorporate La2O3 reinforcement, researchers have unlocked new possibilities for developing lightweight, high-performance materials capable of withstanding demanding operating conditions while maintaining excellent mechanical properties.

3.3 Hardness

The hardness of aluminum is a critical mechanical property that influences its suitability for various industrial applications, particularly those requiring resistance to surface wear and deformation [48]. To enhance the hardness of aluminum, researchers have explored the incorporation of lanthanum oxide (La2O3) using the Friction Stir Processing (FSP) technique. Friction Stir Processing (FSP) is a solid-state processing method known for its ability to modify the microstructure and properties of materials without the drawbacks associated with traditional fusion welding. When La2O3 particles are introduced into the aluminum matrix during FSP, they disperse uniformly, leading to the formation of a composite material with enhanced mechanical properties. Experimental studies have demonstrated a significant improvement of 35.21% in the hardness of aluminum-La2O3 composites produced via FSP. This enhancement can be attributed to the effective reinforcement provided by the dispersed La2O3 particles, which act as strengthening agents within the aluminum matrix [49-52]. The uniform dispersion of La2O3 ensures consistent mechanical behavior throughout the material, resulting in improved hardness and resistance to surface deformation. The enhanced hardness of aluminum-La2O3 composites makes them highly desirable for applications requiring superior wear resistance, such as automotive components, cutting tools, and machinery parts [53]. By leveraging the FSP technique to incorporate La2O3 reinforcement, researchers have unlocked new possibilities for developing lightweight, high-performance materials capable of withstanding severe wear conditions while maintaining excellent mechanical properties.

3.4 Fatigue Strength

Fatigue strength is a critical mechanical property for materials subjected to cyclic loading or repeated stress, as it determines their resistance to fatigue failure over time [54]. To enhance the fatigue strength of aluminum, researchers have explored the incorporation of lanthanum oxide (La2O3) using the Friction Stir Processing (FSP) technique.Friction Stir Processing (FSP) is a solid-state processing method renowned for its ability to modify the microstructure and properties of materials without the drawbacks associated with traditional fusion welding. When La2O3 particles are introduced into the aluminum matrix during FSP, they disperse uniformly, leading to the formation of a composite material with enhanced mechanical properties.Experimental studies have demonstrated a notable improvement of 24.44% in the fatigue strength of aluminum-La2O3 composites produced via FSP. This enhancement can be attributed to the effective reinforcement provided by the dispersed La2O3 particles, which act as barriers to crack initiation and propagation during cyclic loading. The uniform dispersion of La2O3 ensures consistent mechanical behavior throughout the material, resulting in improved fatigue resistance and durability [55].The enhanced fatigue strength of aluminum-La2O3 composites makes them highly suitable for applications where prolonged cyclic loading is anticipated, such as aerospace components, automotive parts, and structural elements. By leveraging the FSP technique to incorporate La2O3 reinforcement, researchers have unlocked new possibilities for developing lightweight, high-performance materials capable of withstanding demanding operating conditions while maintaining excellent mechanical properties [56].

3.5 Wear resistance

Wear resistance is a crucial property for materials exposed to abrasive or erosive environments, as it determines their ability to withstand surface degradation and maintain functionality over time. To enhance the wear resistance of aluminum, researchers have investigated the incorporation of lanthanum oxide (La2O3) using the Friction Stir Processing (FSP) technique.

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4. Conclusions

The utilization of the Friction Stir Process (FSP) in Aluminum-Based Composite Manufacturing, specifically leveraging lanthanum oxide (La2O3) reinforcement, has demonstrated significant advancements in enhancing mechanical properties. The meticulous execution of FSP, with precise parameters including pin diameter, tool tilt angle, and rotational speed, underscored the importance of precision machining in fabricating composites with exceptional properties.The observed uniform distribution of La2O3 particles throughout the composite matrix indicates an effective fabrication process, highlighting the successful implementation of proper mixing and dispersion techniques. Experimental findings have consistently shown remarkable improvements in various mechanical properties of the aluminum-La2O3 composites produced via FSP. Notably, significant enhancements were achieved in tensile strength, hardness, fatigue strength, and wear resistance, with improvements of 22.78%, 35.21%, 24.44%, and 28.68%, respectively.

These results emphasize the potential of FSP as a viable manufacturing technique for producing high-performance aluminum-based composites with enhanced mechanical properties. The demonstrated improvements open avenues for the development of materials suitable for diverse applications requiring superior strength, hardness, and durability, ranging from aerospace components to automotive parts and structural elements. Overall, the findings underscore the promising prospects of leveraging FSP for advancing Aluminum-Based Composite Manufacturing.

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