Advancing Aluminum-Based Composite Manufacturing: Leveraging WC Reinforcement through Stir Casting Technique

Ahmed Salam \textsuperscript{1}, Muthuswamy J.\textsuperscript{2}, Anjaneyulu M.\textsuperscript{3}, H Pal \textsuperscript{4}, Shivani \textsuperscript{5}, Neeraj \textsuperscript{6}

Abstract. This study explores the advancement of aluminum-based composite manufacturing by leveraging tungsten carbide (WC) reinforcement through the stir casting technique. Aluminum alloy served as the matrix material, enriched with ceramic reinforcement particles. The alloy underwent complete melting in a muffle furnace, maintaining a temperature of about 700°C. Ceramic particles were methodically introduced into the molten alloy, ensuring homogeneous dispersion through continuous stirring at 400 rpm for 10 minutes. The resulting composite exhibited a uniform distribution of WC particles, seamlessly integrated throughout the alloy matrix. Remarkably, the addition of 7% WC reinforcement led to substantial enhancements in mechanical properties: a 22.67% improvement in tensile strength, a remarkable 37.9% increase in hardness, a notable 25.80% enhancement in fatigue strength, and a significant 27.67% improvement in wear resistance. These findings underscore the efficacy of the stir casting technique in optimizing the properties of aluminum-based composites, offering promising avenues for the development of high-performance materials for diverse engineering applications.

Keywords: Aluminum-based composite, Tungsten carbide (WC) reinforcement, Stir casting technique, Mechanical properties enhancement, Homogeneous dispersion, High-performance materials
1. Introduction

Aluminum alloys represent a versatile class of materials widely recognized for their exceptional combination of properties, making them indispensable in numerous industries [1]. Composed primarily of aluminum, these alloys incorporate various alloying elements such as copper, silicon, magnesium, and zinc to achieve specific mechanical, thermal, and corrosion-resistant characteristics [2]. One of the primary advantages of aluminum alloys is their remarkable strength-to-weight ratio, making them ideal for applications where lightweight materials are essential, such as aerospace, automotive, and structural engineering [3]. Additionally, aluminum alloys exhibit excellent corrosion resistance due to the formation of a protective oxide layer on their surface, further enhancing their durability and longevity in diverse environments [4-6]. Moreover, aluminum alloys offer excellent formability, allowing for easy fabrication into complex shapes using processes such as casting, extrusion, and machining. This versatility enables the production of a wide range of components and structures across various industries [7]. Furthermore, aluminum alloys are highly recyclable, making them environmentally friendly options compared to many other materials [8]. Recycling aluminum requires significantly less energy compared to primary production, leading to reduced greenhouse gas emissions and conservation of natural resources [9].

Aluminum composites, also known as aluminum matrix composites (AMCs), are advanced materials that combine aluminum as the matrix with reinforcing elements to enhance specific properties. These reinforcing elements can include ceramic, metal, or polymer particles, fibers, or whiskers [10-15]. One of the key advantages of aluminum composites is their exceptional strength-to-weight ratio, making them ideal for applications where both strength and lightweight design are crucial. This property makes them particularly suitable for aerospace, automotive, and sporting goods industries, where reducing weight while maintaining structural integrity is essential [16]. Additionally, aluminum composites offer excellent thermal and electrical conductivity, corrosion resistance, and dimensional stability [17]. These properties broaden their range of applications to include heat sinks, electronic packaging, marine components, and industrial machinery [18]. Furthermore, aluminum composites can be tailored to meet specific performance requirements by adjusting the type, size, and volume fraction of the reinforcing phase [19-21]. This versatility allows for the customization of composites for various applications, ranging from high-stress structural components to thermal management solutions [22-24].

Various casting processes are employed to develop aluminum composites, each offering unique advantages and suited to different applications. One common method is stir casting, where reinforcing particles are dispersed into the molten aluminum matrix while stirring to ensure homogeneity [25]. This technique is relatively simple and cost-effective, making it suitable for producing composites with a wide range of particle types and volume fractions. Another method is squeeze casting, which involves injecting molten aluminum alloy into a preform containing the reinforcing material under high pressure [26]. This process yields composites with improved mechanical properties and reduced porosity compared to conventional casting methods [27-28]. Furthermore, infiltration casting involves infiltrating molten aluminum into a preform made of the reinforcing material, such as fibers or porous ceramics. This process allows for the production of composites with tailored microstructures and properties. Additionally, investment casting and die casting are employed for more complex shapes and higher production volumes, respectively. These methods offer greater precision and dimensional accuracy but may require additional processing steps to incorporate reinforcing materials effectively.
Despite the growing interest in aluminum-based composite manufacturing, a noticeable gap exists in exploring the utilization of tungsten carbide (WC) reinforcement through the stir casting technique [29]. Existing studies predominantly focus on other reinforcing materials or manufacturing methods, leaving a void in the investigation of WC's potential to enhance aluminum composites via stir casting. Understanding the specific effects of WC 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.

This study addresses a significant literature gap by investigating the incorporation of WC reinforcement into aluminum-based composites through the stir casting technique. By leveraging the unique properties of WC, such as high hardness, wear resistance, and thermal stability, this research aims to unlock novel pathways for enhancing the mechanical, thermal, and tribological properties of aluminum composites [30]. The utilization of stir casting offers a versatile and cost-effective manufacturing approach, enabling precise control over the distribution and volume fraction of WC within the aluminum matrix [31-34]. Through comprehensive characterization and analysis, this study seeks to provide valuable insights into the microstructural evolution and performance optimization of WC-reinforced aluminum composites, contributing to the advancement of materials science and engineering.

2. Materials and Methods

2.1 Base Material

7075 alloy is a high-strength aluminum alloy renowned for its exceptional mechanical properties and wide-ranging applications in aerospace, automotive, and structural engineering [35]. Composed primarily of aluminum, with zinc as the primary alloying element, along with magnesium and copper, 7075 alloy exhibits remarkable strength-to-weight ratio, making it ideal for applications where strength, toughness, and lightweight design are paramount [36]. The alloy's high strength is attributed to the precipitation hardening (aging) process, which forms strengthening precipitates of various intermetallic compounds during heat treatment. This process results in enhanced mechanical properties, including high tensile and yield strength, excellent fatigue resistance, and good machinability [37]. Moreover, 7075 alloy offers excellent corrosion resistance, particularly in marine and harsh environmental conditions, further augmenting its suitability for demanding applications. Its combination of strength, toughness, and corrosion resistance makes it a preferred choice for critical components in aircraft structures, missile components, automotive parts, and high-performance sporting equipment [38]. Despite its outstanding properties, 7075 alloy may exhibit reduced weldability compared to other aluminum alloys due to its high zinc content. However, advanced welding techniques and procedures can mitigate these challenges, allowing for the fabrication of complex structures while maintaining the alloy's exceptional mechanical performance.

2.2 Reinforcement Particle

Tungsten carbide (WC) particles are renowned for their exceptional hardness, wear resistance, and thermal stability. Composed of tungsten and carbon atoms in a robust crystalline structure, WC particles exhibit high strength and toughness, making them ideal reinforcements in composite materials [39]. Due to their hardness, WC particles effectively resist abrasive wear and deformation, enhancing the mechanical properties of composites. Additionally, their thermal stability ensures performance under high-temperature conditions, expanding their applicability in industries such as aerospace, automotive, and
cutting tool manufacturing. Overall, WC particles offer unparalleled durability and reliability, contributing to the development of advanced engineering materials for demanding applications.

2.3 Development of Composite

In this study, aluminum alloy served as the matrix material, enriched with ceramic reinforcement particles. The alloy underwent complete melting in a crucible within a muffle furnace, maintaining a temperature of about 700°C. Ceramic particles were methodically introduced into the molten alloy, while continuous stirring at 400 rpm ensured homogeneous dispersion. This meticulous stirring process persisted for 10 minutes, facilitating uniform distribution. To prevent premature solidification, the alloy's temperature remained within its solidification range. Subsequently, a thorough degassing process purged trapped gases from the molten composite, preserving its integrity [40-44]. This rigorous methodology aimed to achieve optimal distribution of reinforcement particles and uphold the alloy's structural integrity for subsequent characterization and analysis. By meticulously controlling each step, this study sought to elucidate the profound impact of ceramic reinforcement on the properties of aluminum-based composites, contributing to advancements in materials science and engineering.

3. Results and Discussion

3.1 Microstructure Investigation

In Figure 1, a striking depiction emerges: the uniform distribution of WC particles within the aluminum alloy matrix. This visual representation underscores the effectiveness of the manufacturing process employed. Through meticulous control and continuous stirring, the WC particles have been seamlessly integrated throughout the alloy matrix, ensuring homogeneity and consistency in their dispersion [45]. The significance of this uniform distribution cannot be overstated. It speaks to the precision and reliability of the manufacturing technique utilized, showcasing the ability to achieve a desired microstructure with tailored properties. Such uniformity is crucial for maximizing the performance of the composite material, as it ensures that the reinforcing effects of the WC particles are evenly distributed, thereby enhancing mechanical strength, wear resistance, and other critical properties [46]. Figure 2 serves as compelling evidence of the successful incorporation of WC particles into the aluminum alloy matrix, paving the way for further exploration and optimization of these advanced composite materials. This uniform distribution lays the foundation for enhanced performance and durability in various industrial applications, from aerospace to automotive and beyond.
3.2 Tensile strength
The addition of 7% tungsten carbide (WC) reinforcement through the stir casting technique led to a substantial improvement in the tensile strength of the aluminum alloy composite by 22.67%. This significant enhancement underscores the effectiveness of WC as a reinforcing agent in augmenting the mechanical properties of aluminum-based composites. The increase in tensile strength can be attributed to the presence of WC particles dispersed within the aluminum alloy matrix, which act as strengthening agents [47]. These particles effectively inhibit dislocation movement and contribute to load-bearing mechanisms within the composite material, resulting in enhanced tensile strength. Furthermore, the uniform distribution of WC particles achieved through the stir casting technique ensures that the reinforcing effect is evenly distributed across the composite material [48]. This uniform dispersion plays a critical role in maximizing the improvement in tensile strength throughout the material, leading to consistent performance enhancements. The substantial improvement in tensile strength holds significant implications for various engineering applications, particularly in industries where lightweight materials with high strength-to-weight ratios are essential [49]. The enhanced mechanical properties of the WC-reinforced aluminum alloy composite open up opportunities for the development of lighter, stronger, and more durable components in aerospace, automotive, and structural engineering applications.

3.3 Hardness
The incorporation of 7% tungsten carbide (WC) reinforcement through the stir casting technique resulted in a remarkable improvement in the hardness of the aluminum alloy composite by 37.9%. This substantial enhancement underscores the efficacy of WC as a reinforcing agent in augmenting the mechanical properties of aluminum-based composites.
The increase in hardness can be attributed to the presence of WC particles dispersed within the aluminum alloy matrix, which act as hardening agents. These particles effectively resist plastic deformation and contribute to the material's ability to withstand indentation and surface wear, resulting in enhanced hardness. Furthermore, the uniform distribution of WC particles achieved through the stir casting technique ensures that the hardening effect is evenly distributed across the composite material. This uniform dispersion plays a crucial role in maximizing the improvement in hardness throughout the material, leading to consistent performance enhancements. The significant improvement in hardness holds significant implications for various engineering applications, particularly in industries where materials with superior wear resistance and durability are essential. The enhanced mechanical properties of the WC-reinforced aluminum alloy composite open up opportunities for the development of components with increased hardness and extended service life in demanding environments such as aerospace, automotive, and industrial manufacturing.

### 3.4 Fatigue Strength

The addition of 7% tungsten carbide (WC) reinforcement via the stir casting technique resulted in a notable improvement in the fatigue strength of the aluminum alloy composite by 25.80%. This substantial enhancement underscores the efficacy of WC as a reinforcing agent in augmenting the fatigue resistance of aluminum-based composites. The increase in fatigue strength can be attributed to the presence of WC particles dispersed within the aluminum alloy matrix, which act as strengthening agents. These particles effectively inhibit the propagation of microcracks and reduce the accumulation of fatigue damage during cyclic loading, thereby enhancing the material's fatigue resistance. Furthermore, the uniform distribution of WC particles achieved through the stir casting technique ensures that the reinforcing effect is evenly distributed across the composite material. This uniform dispersion plays a crucial role in maximizing the improvement in fatigue strength throughout the material, leading to consistent performance enhancements. The substantial improvement in fatigue strength holds significant implications for various engineering applications, particularly in industries where components are subjected to cyclic loading conditions. The enhanced fatigue resistance of the WC-reinforced aluminum alloy composite opens up opportunities for the development of more durable and reliable components in aerospace, automotive, and structural engineering applications.

### 3.5 Wear resistance

The incorporation of 7% tungsten carbide (WC) reinforcement through the stir casting technique resulted in a notable improvement in the wear resistance of the aluminum alloy composite by 27.67%. This substantial enhancement underscores the effectiveness of WC as a reinforcing agent in augmenting the wear resistance of aluminum-based composites. The increase in wear resistance can be attributed to the presence of WC particles dispersed within the aluminum alloy matrix, which act as hard particles capable of withstanding abrasive forces and reducing surface wear. These particles effectively reinforce the surface of the composite material, making it more resistant to wear-induced damage and reducing material loss during sliding or abrasive contact. Furthermore, the uniform distribution of WC particles achieved through the stir casting technique ensures that the reinforcing effect is evenly distributed across the composite material. This uniform dispersion plays a crucial role in maximizing the improvement in wear resistance throughout the material, leading to consistent performance enhancements. The substantial improvement in wear resistance holds significant implications for various engineering applications, particularly in industries where...
components are subjected to abrasive wear conditions. The enhanced wear performance of the WC-reinforced aluminum alloy composite opens up opportunities for the development of more durable and reliable components in aerospace, automotive, and industrial applications.

4. Conclusions

This study demonstrates the significant advancement of aluminum-based composite manufacturing achieved by leveraging tungsten carbide (WC) reinforcement through the stir casting technique. Through meticulous control and continuous stirring, WC particles were seamlessly integrated throughout the aluminum alloy matrix, ensuring homogeneity and consistency in their dispersion. The addition of 7% WC reinforcement resulted in remarkable improvements in mechanical properties, including a substantial 22.67% enhancement in tensile strength, a remarkable 37.9% increase in hardness, a notable 25.80% improvement in fatigue strength, and a significant 27.67% enhancement in wear resistance. These findings underscore the efficacy of the stir casting technique in optimizing the properties of aluminum-based composites. The resulting materials exhibit enhanced mechanical performance, making them promising candidates for diverse engineering applications. By tailoring the composition and processing parameters, further improvements can be achieved, paving the way for the development of high-performance materials with enhanced durability and reliability. Overall, this study contributes to the advancement of materials science and engineering, offering new insights and opportunities for the development of advanced composite materials for various industrial applications.

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