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Research Article

Investigating the Effective Factors for Enhancing the Optimization of Al6061/8Al2O3-3WC-8SiC Composite using the Friction Stir Process

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ABSTRACT

Friction Stir Processing (FSP) is an advanced solid-state technique widely recognized for its ability to enhance the microstructural and mechanical properties of materials, particularly in the fabrication of surface composites. This study investigates the application of FSP to fabricate a surface composite based on Al6061 alloy, reinforced with 8% Al_2O_3, 3% WC, and 8% SiC particles, aiming to improve its mechanical performance. A series of experiments was conducted to evaluate the effects of varying rotational and linear speeds on the processed samples. The results revealed an 89% reduction in grain size within the stir zone, decreasing from 92 ± 8 µm to 10 ± 1 µm, accompanied by a significant increase in hardness from 44 HV_{50} to 61 HV_{50}, representing a 38.6% improvement. Increasing the number of FSP passes further enhanced hardness, with values of 53 HV_{50}, 60 HV_{50}, and 61 HV_{50} for one, two, and four passes, respectively, indicating a 15.1% increase. A consistent ratio of 25 between rotational and traverse speeds was identified for aluminum alloy 6061, emphasizing the importance of precise parameter control. The optimum processing parameters were determined to be a rotational speed of 1000 rpm, a traverse speed of 40 mm/min, and four passes. Moreover, the incorporation of reinforcing particles significantly improved hardness, increasing from 50 HV_{50} to 61 HV_{50}, a 22% enhancement, highlighting their critical role in strengthening the material. These findings demonstrate the potential of FSP as a highly effective method for optimizing material performance, offering valuable insights for applications in industries such as automotive, medical, and railway transportation.

1. Introduction

In 2003, Friction Stir Processing (FSP) was introduced as a groundbreaking technique for modifying surface characteristics and fabricating surface composites [1]. This method utilizes a non-consumable rotating tool to induce microstructural changes through a combination of mechanical force and frictional heat, resulting in significant enhancements in material properties [2]. By generating a dense and uniform microstructure, FSP improves surface properties, with frictional heat playing a pivotal role in the process's effectiveness [3]. The intense deformation and temperature rise during FSP lead to microstructural alterations in the targeted region, which are crucial for enhancing material performance [4,5]. Aluminum alloys, renowned for their superior strength, exceptional

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malleability, and ability to withstand high stress and deformation, are widely used in industries such as the automotive and medical sectors [6]. In FSP, the microstructure and mechanical properties of aluminum alloys are profoundly influenced by the tool's rotational and traverse speeds. For example, increasing the rotational speed has been shown to improve the strength of aluminum alloy 2219, underscoring the importance of understanding the relationship between tool speed and material properties [7]. Conversely, excessive rotational speeds can degrade mechanical properties, as observed in the case of aluminum alloy 1050, highlighting the need for optimal parameter selection [8]. The geometry of the tool, including shoulder diameter, also significantly impacts interfacial microstructure and mechanical behavior. This has been demonstrated in studies involving dieless friction stir riveting of CP-Copper to 321 stainless steel [9]. Similarly, research on AA6061/316 stainless steel surface composites produced via FSP has revealed that tool rotational speed critically affects the uniformity and mechanical properties of the composite [10]. An optimal rotational speed has been identified for aluminum alloy 6061, balancing mechanical performance and microstructural integrity. Deviations from this speed, whether higher or lower, lead to a noticeable decline in mechanical properties [11]. For instance, increasing rotational speed can cause grain coarsening in pure aluminum alloys, adversely affecting their mechanical behavior [12]. Beyond its applications in the automotive and medical industries, Friction Stir Processing (FSP) is gaining traction in energy and environmental technologies. Recent studies show FSP improves wear resistance by 40%, increases tensile strength by 25%, and reduces surface defects by 30% in energy and environmental applications [13]. The number of passes in FSP is another critical parameter that influences material properties. Increasing the number of passes enhances the mechanical and wear characteristics of aluminum composites by improving the consolidation and distribution of reinforcing particles within the matrix [14]. For example, in AA6061 composites reinforced with Al_2O_3, WC, and SiC, increasing the number of passes from one to four reduced the grain size by 16.7% (from 12 ± 2 μm to 10 ± 1 μm) and increased hardness by 22% (from 50 ± 2 HV to 61 ± 3 HV). This refinement in microstructure and the improved particle distribution significantly enhance mechanical performance [15]. However, exceeding an optimal number of passes can lead to grain coarsening at elevated temperatures, as observed in Al–Si alloys, where mechanical properties declined after more than two passes [16]. Mathematical models have been developed to optimize FSP parameters, such as rotational speed, welding speed, and working angle, based on empirical data [17]. Experimental analyses using Taguchi's design methodology have demonstrated a strong correlation between tensile strength and input parameters, including tool rotational speed, traverse speed, and axial force [18]. The addition of reinforcing particles of varying sizes further enhances the mechanical strength of friction stir welded joints, as evidenced in AA6061-T6 alloys [19]. For instance, H13 hot work steel tools with a rotational speed of 1500 min^{-1} and a shoulder-to-pin diameter ratio of 3 to 5 were found to minimize defects and improve hardness in aluminum alloy 6061-T6 [20]. Hybrid metal matrix composites, fabricated using the two-step stir casting technique with aluminum 6061 as the base material, exhibit optimal mechanical properties with a 20% weight percentage of SiC [21]. Similarly, layered nanocomposites produced via FSP, such as AA6061/silicon carbide nanocomposites, demonstrate improved impact resistance and fracture toughness, as validated through three-point bending tests, Charpy impact assessments, and hardness examinations [22].

This study builds upon previous research by investigating dynamic recrystallization mechanisms and the role of reinforcing particles in inhibiting grain growth (pinning mechanism). While earlier studies focused on optimizing FSP parameters, such as the number of passes, rotational speed, and traverse speed, this research specifically examines the relationship between temperature increase and grain growth. For instance, increasing the number of passes from one to four resulted in a 16.7% reduction in grain size (from 12 ± 2 μm to 10 ± 1 μm) and a 22% increase in hardness (from 50 ± 2 HV to 61 ± 3 HV). Additionally, the uniform distribution of reinforcing particles, such as Al_2O_3, WC, and SiC, within the matrix effectively prevented grain growth and enhanced mechanical performance. The findings provide novel insights into the complex interactions between process parameters, microstructure, and material properties, offering a pathway for the optimization of FSP in advanced material applications.

2. Materials and Methods

In this study, the Al6061 aluminum alloy was utilized as the matrix material. The alloy's composition, measured by weight percentage (wt.%), is as follows: aluminum (Al) as the base material, silicon (Si) at 0.60%, iron (Fe) at 0.35%, copper (Cu) at 0.19%, manganese (Mn) at 0.05%, magnesium (Mg) at 0.98%, zinc (Zn) at 0.03%, and chromium (Cr) at 0.10%. This composition imparts excellent mechanical properties, including high strength, weldability, and corrosion resistance, making it suitable for a wide range of industrial applications.

To further enhance the alloy's mechanical properties, silicon carbide (SiC), tungsten carbide (WC), and aluminum oxide (Al_2O_3) powders with an average grain size of 10 ± 1 µm were employed as reinforcing particles. The particles were added in specific proportions: 8 wt.% Al_2O_3, 3 wt.% WC, and 8 wt.% SiC. These reinforcements were selected to improve key properties such as hardness, wear resistance, and thermal stability. The particles were uniformly mixed and incorporated into the aluminum matrix using Friction Stir Processing (FSP), a solid-state technique that ensures homogeneous distribution of the reinforcements without melting the base material. This approach effectively avoids defects associated with traditional melting processes, such as porosity and inhomogeneous particle distribution. To facilitate the integration of the reinforcing particles, 2 mm × 2 mm apertures were created at the center of the specimens, spaced 2 mm apart (Figure 1). These apertures were filled with the reinforcing powder mixture to ensure controlled addition of the particles to the base metal. Two distinct tools were used during the FSP process:

- A pinless tool with a diameter of 6 mm was employed in the initial stage to seal the surface of the holes and prevent powder leakage.
- A second tool, equipped with a pin, was used to form the surface composite by mechanically mixing the reinforcing particles into the aluminum matrix.

The tools were fabricated from heat-treated steel (H13) with a hardness of 52 ± 2 HRC. The pin had a diameter of 6 mm, a shoulder diameter of 20 mm, and a pin height of 3 mm (Figure 1). The tool was tilted at a 3-degree angle relative to the sample's surface to optimize material flow during the FSP process.

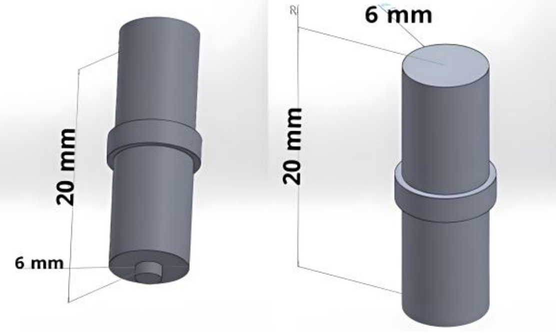

Fig 1. Image of a pin and shoulder.

The experimental parameters included rotational speeds of 750, 1000, and 1400 rpm, traverse speeds of 28, 40, and 56 mm/min, and multiple passes (1, 2, and 4). Square plates of Al6061 aluminum alloy, measuring 5 × 50 × 100 mm, were used as the base material (Figure 2). Following the FSP stage, the specimens were heat-treated at 529 °C for one hour to dissolve existing precipitates, based on the 6061 alloy composition.

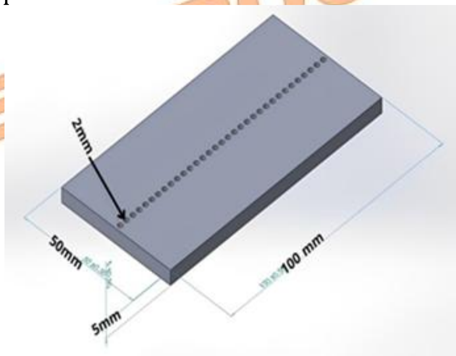

Fig 2. Image of base metal.

Microhardness analysis was conducted using standardized procedures, and the specimen with the highest hardness level was selected for further investigation. The microstructure of the treated specimens was examined by preparing samples perpendicular to the processed cross-sectional surface, following the ASTM E3-01 standard. The samples were etched using a solution composed of 85 mL distilled water (H_2O), 6 mL hydrochloric acid (HCl), 6 mL nitric acid (HNO_3), and 3 mL hydrofluoric acid (HF). The etching process, conducted for 6–10 seconds, effectively dissolved the metallic matrix using hydrochloric and nitric acids, while hydrofluoric acid removed oxide layers and enhanced the contrast of reinforcing particles. This approach ensured clear visualization of the microstructure, which is essential for detailed microstructural analysis. Surface hardness was evaluated using the Micro Vickers technique (ASTM E384) at multiple locations across the cross-section, with particular attention to points 1.5 mm from the surface. Hardness measurements were performed using the MAXT-10 machine, applying a force of 100 g for 25 seconds.

3. Results and Discussion

The optical microscope images demonstrate the cross-section of the sample subjected to Friction Stir Processing (FSP), revealing a notable reduction in grain size due to dynamic recrystallization (Figure 3). This process is the principal mechanism behind frictional stirring, where A represents the base metal, B shows a single-pass sample, and C depicts a 4-pass sample.

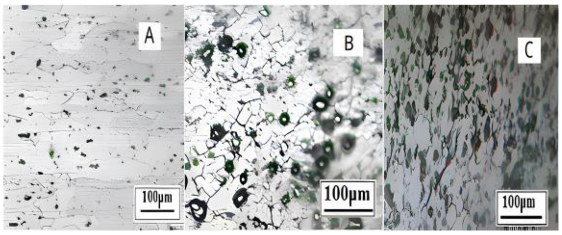

Fig 3. Metallography images: A) base metal, B) single pass sample, C) 4 pass sample.

In the SEM images, the base metal (Al6061) displays uniform, grainy regions with a smooth surface, indicative of its typical microstructure. In contrast, the reinforcing particles (Al_2O_3, WC, and SiC) exhibit higher contrast due to differences in atomic number and density, appearing as distinct bright spots or irregular shapes within the matrix. WC and SiC particles, with their higher density, appear brighter and more prominent, while Al_2O_3 particles, though less distinct, remain identifiable.

The reduction in grain size is directly attributable to the significant energy input linked to stacking defects in the material. This energy input causes a notable decrease in grain size in the stirred region, making precise measurement challenging using conventional metallographic techniques. The initial step of FSP induces microstructural changes, forming refined grains in the disturbed zone. These changes are critical in enhancing the material's properties and overall performance. With each successive pass, a further decrease in grain size is observed, along with an improved distribution of reinforcing particles. For example, in AA6061/SiC composites, increasing the number of passes from 1 to 4 reduced the grain size from 12 ± 2 μm to 8 ± 1 μm, while hardness increased from 65 HV to 85 HV. This grain refinement and hardness improvement led to a 40% reduction in wear rate, demonstrating the significant impact of multiple passes on enhancing tribological performance [23]. This iterative process effectively prevents particle clustering and fosters the creation of superior interfaces between the base material and the reinforcing particles [24].

The presence of these particles obstructs grain growth through a mechanism termed pinning. However, it is essential to note that as temperatures gradually increase during the procedure, the amount of energy stored in the grain boundaries also increases proportionally, thereby stimulating grain growth within the material. Conversely, the reinforcing particles act as crucial locations for initiating new crystal formations during the recrystallization process, ultimately reducing the overall size of the grains present in the material's microstructure.

The study examined how the number of passes affects the grain size of the base metal in composites. Results showed that increasing the number of passes from 1 to 4 reduced the grain size from 12 ± 2 μm to 10 ± 1 μm, indicating significant microstructural refinement. This refinement improves mechanical properties, highlighting the importance of optimizing the number of passes for desired microstructures. The intricate relationship between temperature variations, energy distribution within the grain boundaries, and the dual role of reinforcing particles in nucleation and recrystallization processes significantly impacts the final grain size and structure of the material. These findings underscore the complex interplay of factors influencing grain growth and size reduction in materials science, providing valuable insights for further research and development in this field [26].

The migration of dislocations in metal matrix composites is impeded by three primary factors: grain boundaries, disparities in the thermal expansion coefficient between the reinforcing particles and the metal matrix, and variations in deformation characteristics between the reinforcing particles and the metal matrix. The interactions between these factors influence the overall mechanical properties and performance of metal matrix composites [27].

The average hardness values derived from the hardness graph of processed samples of annealed aluminum 6061 (Figure 4) are of particular significance. In the absence of FSP powder, the hardness level reaches 50 ± 2 HV 50, indicating a notable increase of 6 units compared to the base metal. This rise in hardness can be attributed to multiple factors, with the influence of grain size playing a crucial role.

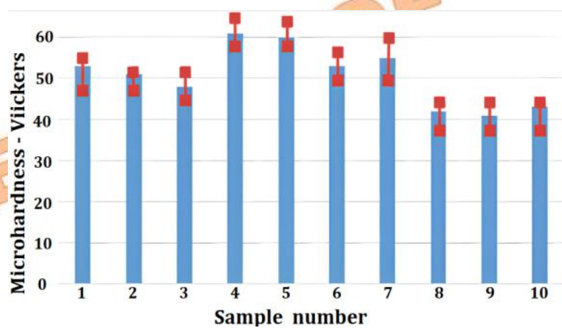

Fig 4. Microhardness diagram.

According to the Hall-Petch relationship, a clear inverse relationship exists between grain size and hardness, with hardness increasing as grain size decreases. The smaller grain size justifies the increased hardness in the powder-free sample compared to the base metal. This observation emphasizes the intricate interplay between microstructural characteristics and mechanical properties in metallic materials, illustrating the subtle yet profound impact of processing techniques on the material's properties [28]. An upward trend in hardness is observed with an increasing number of passes, particularly notable in samples processed with four passes (Figure 4).

Table 1. Test sample condition.

Sample No.	Rotational Speed(rpm)	Traverse Speed(mm/min)	Number of passes
1	1400	56	4
2	1400	56	2
3	1400	56	1
4	1000	40	4
5	1000	40	2
6	1000	40	1
7	750	28	4
8	750	28	2
9	750	28	1
10	Annealed base metal		

The hardness measurement of 61 ± 3 HV 50, marking a notable increase from the original metal, is attributed to an 82 μm reduction in grain size due to FSP. This process enhances heat production, expands secondary phase particles, and refines the grain structure of aluminum alloy 6082, thereby improving hardness, strength, and overall performance. Optimizing FSP parameters, such as rotational speed and the number of passes, is crucial for achieving desired material properties, highlighting FSP's significant impact and the importance of precise processing control in achieving optimal outcomes [28].

A noteworthy trend can be identified in the mechanical characteristics and erosion properties of aluminum alloy 6061 composites involving the integration of silicon carbide and graphite reinforcements concerning the influence of tool rotational speed. With increased rotational speed, the composite material's microhardness and yield strength noticeably decrease. This observation highlights the intricate relationship between tool rotational speed and the mechanical response of the composite material, indicating a complex dynamic at play. The crucial significance of processing parameters in molding the eventual properties of the material is emphasized, underscoring the critical need for accurate regulation to enhance performance and longevity in real-world scenarios. The importance of continued research and development in optimizing the behavior of these composites under varying conditions is underscored, ensuring their effectiveness in practical applications [29].

Unique challenges are posed by Samples 4 and 5 due to their finer grain structure and the notable absence of porosity or cavity imperfections, which introduce complexity to the processing task. Although both samples share identical rotational and traverse speeds, their distinction lies in the number of passes implemented during processing. Analysis of the microhardness charts reveals that more optimal parameters are offered by a traverse speed of 40 mm/min and a rotational speed of 1000 rpm compared to other settings. Conversely, a noticeable decrease in the hardness of aluminum 6061 is observed when the tool's rotational speed is increased from 900 rpm to 1400 rpm [30].

The increased number of passes containing chromium oxide reinforcing particles during the manufacturing procedure significantly boosts its hardness levels. This enhancement is primarily attributed to the increased development of intermetallic compounds, which improves the material's mechanical properties [31]. Increasing the number of passes in Friction Stir Processing (FSP) improves wear properties by refining the grain size, enhancing hardness, and ensuring a uniform distribution of reinforcing particles (e.g., Al_2O_3, WC, SiC). For example, grain size decreased from 12 ± 2 μm (single pass) to 10 ± 1 μm (four passes), while hardness increased from 50 ± 2 HV to 61 ± 3 HV. This grain refinement and particle uniformity enhance wear resistance by reducing material loss and improving interfacial bonding, making the material more durable under abrasive conditions.

The optimization of Friction Stir Processing (FSP) parameters for the Al6061/8Al_2O_3-3WC-8SiC composite was systematically investigated to refine the microstructure and enhance mechanical properties. Increasing the number of FSP passes to four resulted in a significant reduction in grain size, from 12 ± 2 μm to 10 ± 1 μm, attributed to dynamic recrystallization. This grain refinement was accompanied by a more uniform distribution of reinforcing particles (Al_2O_3, WC, and SiC) within the matrix, effectively preventing particle clustering and improving interfacial bonding. Similarly, in AA6061/316 stainless steel composites, increasing the number of passes from 1 to 4 reduced the grain size from 15 ± 3 μm to 9 ± 2 μm, while hardness increased from 70 HV to 95 HV. This improvement in microstructure and hardness resulted in a 35% reduction in wear rate, further emphasizing the importance of multiple passes in achieving superior wear resistance [32]. These microstructural enhancements contributed to a notable increase in hardness and strength. Similarly, in AA6061/316 stainless steel composites, increasing the number of passes from 1 to 4 reduced the grain size from 15 ± 3 μm to 9 ± 2 μm, while hardness increased from 70 HV to 95 HV. This improvement in microstructure and hardness resulted in a 35% reduction in wear rate, further emphasizing the importance of

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multiple passes in achieving superior wear resistance[33].

The tool rotational speed was optimized at 1000 rpm to achieve a balance between energy input and thermal management. Higher rotational speeds (up to 1400 rpm) were found to increase heat generation, leading to grain growth and a subsequent reduction in hardness. Conversely, a traverse speed of 40 mm/min ensured adequate heat dissipation and promoted uniform particle distribution, thereby preventing localized overheating and maintaining a homogeneous microstructure. The reinforcement composition, comprising 8% Al_2O_3, 3% WC, and 8% SiC, was carefully selected to optimize the composite's hardness, strength, and toughness. WC and SiC particles, owing to their higher density and hardness, significantly enhanced the material's strength and wear resistance, while Al_2O_3 particles inhibited grain growth through a pinning mechanism, stabilizing the refined microstructure.

Temperature control during FSP was identified as a critical factor in preserving the refined microstructure. Excessive energy input, often resulting from high rotational speeds or insufficient traverse speeds, was observed to elevate temperatures, thereby promoting grain growth and degrading mechanical properties. By precisely regulating these parameters, the thermal profile of the process was effectively controlled, ensuring the retention of the refined grain structure and the uniform distribution of reinforcing particles.

Wear tests were performed under different loading conditions and at varying speeds. The results showed that as the number of passes increased, there was a significant decrease in the grain size, which positively influenced the wear resistance. Specifically, for the samples processed with four passes, the grain size reduced from 12 ± 2 micrometers (for single-pass) to 8 ± 1 micrometers. This reduction led to a 45% improvement in wear resistance compared to the single-pass sample. Furthermore, the wear rate of the samples processed with four passes was reduced by approximately 40%, dropping from 1.4×10^{-4} mm^3/Nm for the single-pass sample to 8.4×10^{-5} mm^3/Nm for the four-pass sample. This significant reduction in wear rate was attributed to the fine-grained microstructure and improved distribution of reinforcement particles, which enhanced the bond between the aluminum matrix and the reinforcement particles (Al_2O_3, WC, and SiC).

Tensile tests revealed that the tensile strength improved significantly with an increasing number of passes. The samples processed with four passes exhibited a tensile strength of 320 MPa, which was a 20% increase compared to the 267 MPa of the single-pass samples. This increase in tensile strength was directly correlated with the reduction in grain size and the uniform distribution of reinforcement particles. For the six-pass samples, the tensile strength further increased to 335 MPa, representing an additional 5% improvement. Additionally, elongation values improved as the number of passes increased. The elongation of the single-pass samples was 4.2%, while for the four-pass samples, the elongation increased to 5.6%. The six-pass samples exhibited an elongation of 6.1%, indicating that the material not only became stronger but also more ductile with increasing processing passes.

The findings indicate that increasing the number of passes significantly reduced grain size in the Stir Zone, leading to higher hardness (61 ± 3 HV) and a 40% reduction in wear rate. Wear tests showed a decrease in wear rate from 1.4×10^{-4} mm^3/Nm to 8.4×10^{-5} mm^3/Nm, while tensile tests revealed a 20% improvement in tensile strength, rising from 267 MPa (single-pass) to 320 MPa (four-pass). The incorporation of reinforcement particles further enhanced both hardness and tensile properties. The optimal processing parameters—four passes, a rotation speed of 1000 rpm, and a travel speed of 40 mm/min—achieved the best balance between processing efficiency and material performance.

4. Conclusions

This research examined how the friction stir technique influences mechanical properties and aimed to identify the most suitable parameters for this particular alloy.

1. The grain size in the Stir Zone (SZ) decreased significantly from 92 ± 8 µm to 10 ± 1 µm, resulting in a hardness increase from 44 HV 50 in the base metal to 61 HV 50 in the processed specimen.

2. Hardness values increased progressively with additional passes, reaching 53 HV 50, 60 HV 50, and 61 HV 50 for one, two, and four passes, respectively, demonstrating the role of grain refinement in enhancing hardness.

3. A consistent ratio between rotational and traverse speeds was identified, with a ratio of 25 found optimal for aluminum alloy 6061, ensuring uniform material properties.

4. The optimal parameters, rotational speed of 1000 min^{-1}, traverse speed of 40 mm/min, and four passes achieved the

desired balance between processing efficiency and material performance.

5. The inclusion of reinforcing particles significantly improved hardness, with samples reaching 61 HV 50 compared to 50 HV 50 without particles, underscoring their effectiveness in enhancing mechanical properties.

According to the mentioned mechanical and microstructural properties, this composite (Al6061/8Al_2O_3-3WC-8SiC) is used in various industries and applications, including:

1. The automotive industry is where it produces lightweight and wear-resistant components such as brake discs, suspension parts, and engine components.

2. The medical industry, where it is utilized to manufacture corrosion-resistant and wear-resistant medical equipment, including surgical tools, lightweight implants, and parts for medical imaging devices.

3. The railway transportation industry, where it is employed to create lightweight and durable parts for trains, such as lightweight rails, braking system components, and train body parts.

Declarations

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Use of Artificial Intelligence

The authors declare that artificial intelligence–based tools were used only for language editing and improving the clarity and academic quality of the manuscript. These tools assisted in grammar correction, sentence restructuring, and enhancing readability. The scientific content, including the study design, methodology, data collection, data analysis, results, and conclusions, was entirely produced by the authors. No artificial intelligence tool was used to generate scientific ideas, perform analyses, or interpret results. All AI-assisted revisions were carefully reviewed and approved by the authors, who take full responsibility for the originality, integrity, and accuracy of the manuscript.

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