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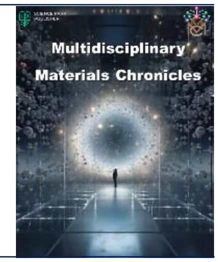

Multidisciplinary Materials Chronicles

The effect of single reinforcement nanoparticles on the AA3105 aluminum alloy fabricated by FSP: mechanical properties and wear behavior of composite matrix

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Abstract

This study investigates the impact of incorporating single reinforcement nanoparticles, namely Boron Nitride (BN), Graphene (G), and Carbon Nanotubes (CNT), on the mechanical properties (hardness) and wear behavior of AA3105 aluminum alloy fabricated using the Friction Stir Processing (FSP) method. The research focuses on enhancing the sliding wear resistance of AA3105 by reinforcing it with these nanoparticles. The novelty lies in reinforcing the aluminum substrate with solid lubricant ceramic particles like BN and enhancing the dispersibility of these nanoparticles in the aluminum melt through surface modification with salts. The study explores the potential for developing wear-resistant, self-lubricating aluminum 3105 bushings suitable for extreme environments such as bushings in aerospace and automotive industries, leveraging the alloy's ductility, formability, and corrosion resistance. The AA3105-CNT composite exhibited the most significant improvement, with microhardness increasing by 39.1% and wear resistance enhancing by 17% compared to the base alloy. The incorporation of BN nanoparticles resulted in a 16.2% increase in microhardness and a 36% enhancement in wear resistance.

Keywords: FSP; AMMC; nanoparticle reinforcement; wear resistance enhancement; microhardness enhancement

1. Introduction

Metal matrix composites (MMCs), particularly those with aluminum matrices, have gained significant attention due to their exceptional properties and diverse applications. These composites combine light metallic matrices with reinforcements like fibers, particles, or whiskers [1, 2]. Various processing methods, including solid-state and liquid-state fabrication techniques, produce MMCs with tailored properties [3]. The resulting composites exhibit improved mechanical, thermal, and specialized characteristics, making them suitable for aerospace, automotive, defense, and marine applications[2, 4]. Key factors influencing MMC properties include reinforcement type, morphology, volume fraction, matrix composition, and heat treatment [5]. Despite challenges such as, particle distribution and wettability, ongoing research focuses on optimizing process parameters to enhance MMC performance [6]. The unique combination of metallic and ceramic properties in MMCs continues to drive their development and application in various industries [7]. Aluminum metal matrix composites (AMMCs) combine the lightweight properties of aluminum with superior mechanical, thermal, and wear characteristics of reinforcing materials [8]. These composites are widely used in aerospace, automotive, and other industries due to their low density, high strength-to-weight ratio, and good corrosion resistance [9, 10]. Common reinforcements include ceramic particles like Al_2O_3, SiC, and ZrO_2, as well as other materials such as graphite and fly

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ash [11]. Various processing techniques are employed in AMMC fabrication, with the vortex method being the most popular due to its simplicity and cost-effectiveness wherein the vortex method involves creating a vortex in the molten metal by stirring, which helps in the uniform distribution of reinforcement particles within the matrix [12]. The addition of reinforcements significantly improves the aluminum matrix's mechanical properties, wear resistance, and thermal stability [13,14]. Ongoing research focuses on optimizing processing parameters, exploring new reinforcement combinations, and expanding the application range of AMMCs [15]. An SMMC is an advanced material that combines a metal or alloy base with a reinforcing material to enhance specific properties such as strength, thermal conductivity, and wear resistance. The base material in an MMC can vary widely, including metals such as aluminum, titanium, and copper, which are commonly used due to their desirable physical properties and compatibility with various reinforcing materials [16, 17]. For instance, aluminum or aluminum alloys serve as a popular choice for matrix materials due to their lightweight and excellent thermal properties. They can be reinforced with ceramic particles to create composites with an average particle size between 1.0μm and 0.5μm, significantly enhancing their mechanical properties [18]. Titanium, known for its high strength-to-weight ratio, can be combined with Al_3Ti alloy particles to form a composite with a continuous concentration transition, improving its overall performance [18, 19]. Copper, valued for its electrical conductivity, can also be used as a base in MMCs, often enhanced with carbon fibers or CNT to improve thermal conductivity and wear resistance[20]. Additionally, with its low density, magnesium can be incorporated into MMCs for applications requiring lightweight materials with good mechanical properties [21]. Reinforcement materials are essential for optimizing the performance of MMCs. SWCNT serves as a prime illustration of a reinforcement material that, upon incorporation into different metal matrices, notably augments the mechanical characteristics of the composite, including strength and resistance to abrasion [22]. Other reinforcing materials include fibers, whiskers, or particles, which can be tailored to meet specific application requirements [18, 23]. This work aims to improve the sliding wear resistance of aluminum 3105 by reinforcing it with BN, G, and CNT. Unlike the unreinforced, thermomechanically processed aluminum substrate, this approach is novel in two ways: 1) reinforcing the aluminum with solid lubricant ceramic particles like boron nitride, and 2) improving nanoparticle dispersion in the aluminum melt through surface modification with salts. Directly incorporating these solid lubricant nanoparticles into the aluminum substrate poses a dispersion challenge. This research explores the potential for wear-resistant, self-lubricating aluminum 3105 bushings for extreme environments, a novel application given the alloy's ductility, formability, and corrosion resistance. This study focuses on investigating the effect of single reinforcement nanoparticles (BN, G, and CNT) on the mechanical properties and wear behavior of AA3105 aluminum alloy fabricated using FSP. By enhancing the sliding wear resistance and microhardness of AA3105, this work aims to develop wear-resistant, self-lubricating AA3105 aluminum alloys suitable for demanding applications, such as bushings in extreme environments.

2. Materials and methods

2.1. Materials

Commercially available aluminum alloy 3105 (H24) (Al-Mg-0.5Mn) in the form of a solid sheet (10 mm thickness) was used as the matrix. The chemical compositions were Si (0.48), Fe (0.36), Cu (0.046), Mn (0.73), Mg (0.44), Cr (0.19), Zn (0.27), Ti (0.048), Al (97.69) expressed in wt.%. This study's reinforcing particles are single and divided into aluminum, boron nitride, graphite, and carbon nanotubes. Ultimately, composite materials with a 15 % volume fraction ratio of each of the reinforcing particles were used for each composite wherein the base metal is 85% for each composite. A milling machine performs friction stir processing, as shown in Figure 1. The high torque of approximately 23.5 Nm is achievable using a motor of 4.4 kW. The friction stir processing parameters were 900 rpm tool rotation speed, 30 mm/min tool traverse speed, and 3^{o} degree tilt angle.

2.2. Characterization and tests

Vickers microhardness testing was performed using a Vickers tester with a 100g load applied for 15 seconds. Six Vickers hardness measurements were taken at selected reinforcement locations in both the cross-section and the working surface. Samples prepared for nanoindentation were processed identically to those for Vickers microhardness testing. Nanoindentation hardness measurements were conducted using

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a nanoindentation tester with a 500 mN load applied for a 30-second dwell time.

Wear testing was conducted using a machine designed to simulate the desired wear conditions. This machine could be a pin-on-disc, pin-on-plate, or block-on-ring tester. The counter surface material was chosen based on its relevance to the intended application of the tested aluminum alloy; this could be another material or even the same aluminum alloy. Key wear test parameters included a load of 0.3 bar, a sliding speed of 265 rpm, and a dry run environment for duration of 5 minutes.

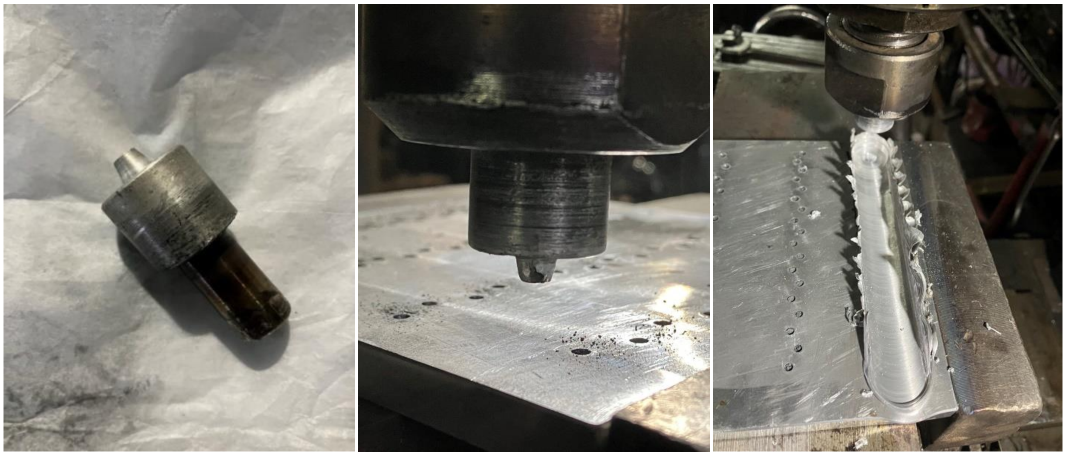

Figure 1. Schematic representation of the composite fabrication process using the milling machine for Friction Stir Processing.

3. Results and discussions

3.1. Microstructure observation

The AA3105 microstructure is characterized by elongated grains aligned along a specific direction, as illustrated in Figure 2. The grain size appears non-uniform, with some regions exhibiting finer grains and others showing coarser grains. The average grain length is approximately 700 µm, while the average grain width is around 500µm. This variation in grain size could be attributed to inhomogeneous deformation during processing or variations in local cooling rates. Overall, the Optical Polarization Microscope test results provide valuable information about the microstructure of the AA3105 base material. The distribution of elongated grains and non-uniform grain sizes are important characteristics that can influence the material's mechanical behavior.

Figure 3 visually represents the SEM microstructural characteristics and reinforcement particle distribution within the various AA3105 composites. The micrographs reveal significant differences in the dispersion quality of the different reinforcement types. AA3105/BN Composite: The SEM micrograph of the AA3105/BN composite (Figure 3a) shows a relatively fine dispersion of BN particles within the AA3105 matrix. While some minor agglomeration of BN particles is observed, the overall distribution is reasonably uniform. This suggests a good interfacial interaction between the BN particles and the AA3105 matrix, which is crucial for effective reinforcement. The AA3105/CNT composite (Figure 3b) exhibits significant agglomeration of CNTs. The CNTs appear to form tangled bundles and clusters, which are not uniformly distributed throughout the matrix. This agglomeration can hinder the effective reinforcement potential of the CNTs, as it reduces the surface area available for interaction with the matrix and can create stress concentration points. Improving the dispersion of CNTs is a significant challenge in composite fabrication and requires careful control of processing parameters. Similar to the CNT composite, the AA3105/Graphene composite (Figure 3c) also shows evidence of significant agglomeration. The graphene platelets appear to be stacked and clustered, forming larger aggregates. This restocking and agglomeration can limit the effective surface area of the Graphene and reduce its reinforcing efficiency. Achieving uniform dispersion of Graphene in metal matrices is a known challenge and requires specialized processing techniques.

3.2. Microhardness behavior

Figure 4 shows the microhardness profile of the investigated samples; hence, the graph also suggests that the distribution of

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the reinforcements might not be perfectly uniform, as evidenced by the fluctuations in microhardness values along the measured distance. To further quantify the fluctuation, the distance from -2 to +2 mm from the center corresponds to the following ranges of hardness [42.9,43.5], [48.8,50.3], [50.0,51.3], and [58.4,60.1] for AA310, AA3105-BN, AA3105-G, and AA3105-CNT respectively. Figure 5 illustrates a more explicit comparison of the mean microhardness values for the different composites. It visually emphasizes the superior microhardness of the AA3105-CNT composite compared to the other composites and the base alloy. The base alloy, AA3105, exhibits a microhardness of 42.95 HV. This value serves as the baseline for comparison with the reinforced composites. AA3105 is known for its good corrosion resistance and formability, but it possesses moderate strength and hardness. The addition of (BN) reinforcement results in an increase in microhardness to 49.89 HV.

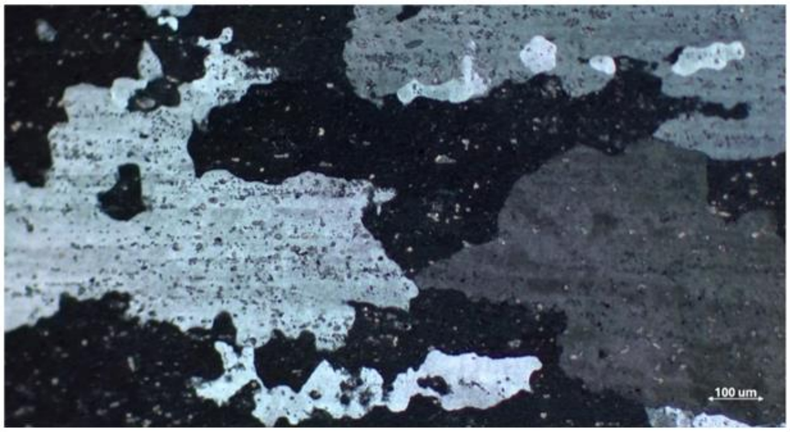

Figure 2. Base AA3105 aluminum wrought alloy (Optical Polarization Microscope results).

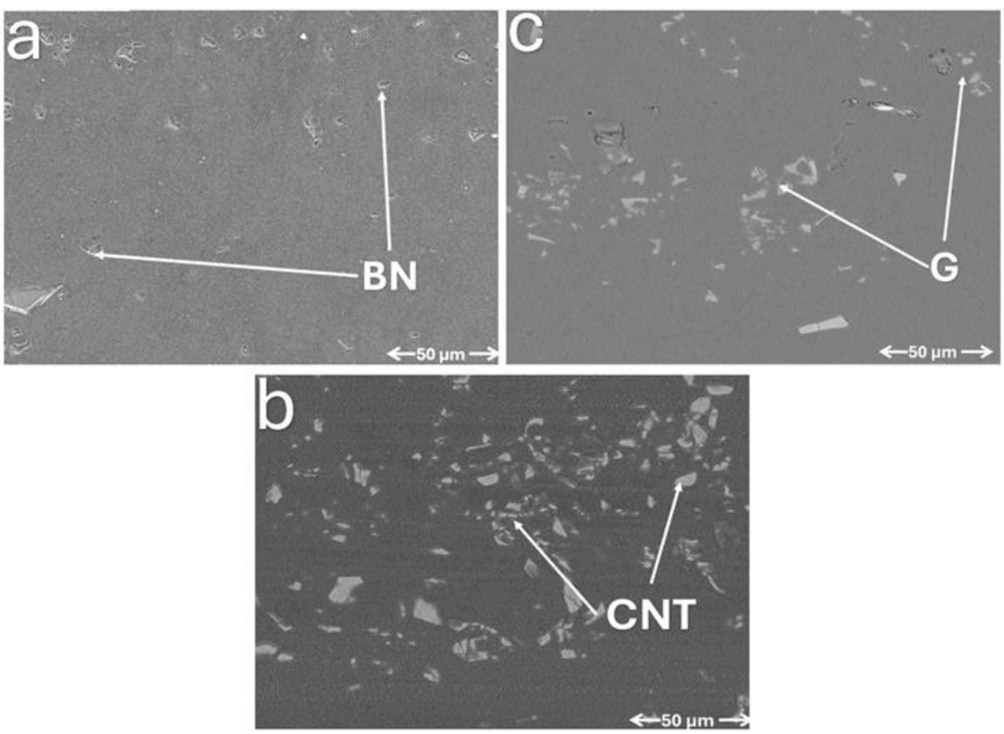

Figure 3. Scanning Electron Microscopy images of the single composite matrix for three materials: labeled a, b and c which are AA3105 reinforced with BN, CNT, and G respectively.

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This improvement can be attributed to BN particles' inherent hardness and ability to act as obstacles to dislocation movement within the AA3105 matrix. BN particles, being ceramic, possess high hardness and stiffness, thereby contributing to the overall strengthening of the composite. The relatively uniform distribution of BN particles (as suggested by the SEM analysis in the context image) also plays a crucial role in enhancing the microhardness. The AA3105-Graphene composite shows a microhardness value of 49.95 HV, which is nearly identical to that of the AA3105-BN composite. This indicates that despite being a two-dimensional material, Graphene provides comparable reinforcement to BN in terms of microhardness. Graphene's high strength and large surface area facilitate effective load transfer and restrict plastic deformation of the matrix. The similar microhardness values for AA3105-BN and AA3105-G suggest that when properly dispersed, both reinforcements can offer similar hardening levels to the AA3105 matrix under the tested conditions. The most significant improvement in microhardness is observed in the AA3105-CNT composite, with a value of 59.75 HV. This substantial increase highlights the exceptional reinforcing potential of carbon nanotubes. CNTs possess exceptionally high strength and stiffness along with a high aspect ratio. These characteristics enable them to constrain the deformation of the AA3105 matrix effectively. However, it's crucial to acknowledge that achieving uniform dispersion of CNTs within a metal matrix is challenging. The context image suggests significant agglomeration of CNTs, potentially limiting their effectiveness.

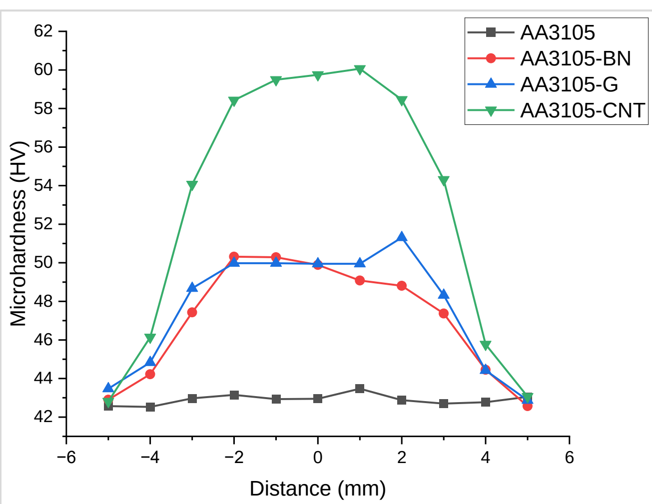

Figure 4. Microhardness profile.

Despite the agglomeration, the AA3105-CNT composite still exhibits the highest microhardness, indicating the potent reinforcing capability of CNTs when they are even partially dispersed within the matrix.

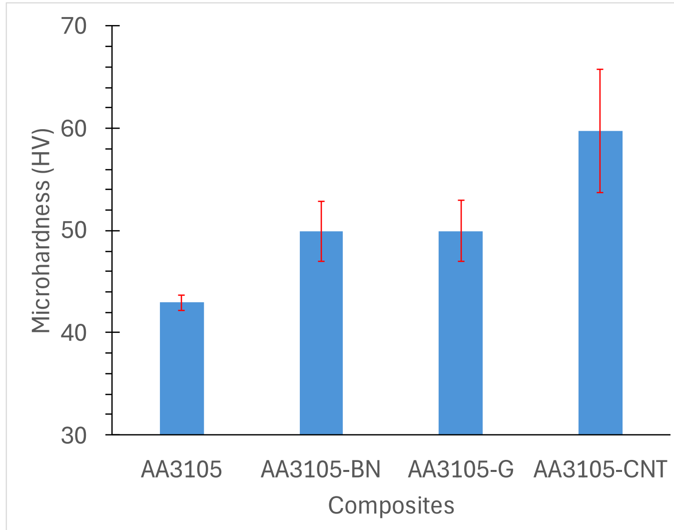

Figure 5. Mean value of the hardness in the stirred zone.

3.3. Wear behaviour

The results clearly demonstrate that the incorporation of G, CNT, and BN reinforcements into the AA3105 matrix via FSP significantly improves the wear resistance. The degree of improvement varies depending on the type of reinforcement, with BN providing the most substantial enhancement, followed by CNT and then G. These findings highlight the potential of FSP for fabricating high-performance metal matrix composites with tailored wear properties for various engineering applications. Further research could focus on optimizing the FSP parameters and exploring hybrid reinforcement strategies to further enhance the wear resistance of AA3105 composites.

Figure 6 represents the trend in wear rate for the different composites. The base alloy AA3105 shows the highest wear rate, depicted by the tallest bar. The wear rate progressively decreases with the addition of G, CNT, and BN reinforcements, as the progressively shorter bars show. The AA3105-BN composite exhibits the lowest wear rate, visually confirming the highest wear resistance among the tested materials. As expected, the base alloy AA3105 exhibits the highest wear rate of 0.06 g/min. This serves as the baseline for evaluating the improvement in wear resistance achieved by incorporating reinforcements. The addition of graphene reinforcement reduces the wear rate to

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0.0514 g/min, corresponding to a 14% enhancement in wear resistance. This improvement can be attributed to the unique properties of Graphene, such as its high strength, large surface area, and excellent lubrication properties. When dispersed adequately within the AA3105 matrix, graphene platelets can effectively hinder the material removal process during wear. The AA3105-CNT composite demonstrates a further reduction in wear rate to 0.04992 g/min, representing a 17% enhancement in wear resistance. Carbon nanotubes provide even more effective reinforcement than Graphene with their exceptional strength and stiffness. The tubular structure of CNTs allows for a stronger interaction with the matrix, leading to improved load transfer and resistance to deformation during sliding wear. The most significant improvement in wear resistance is observed in the AA3105-BN composite, which exhibits the lowest wear rate of 0.0386 g/min and a 36% enhancement. Boron nitride is a ceramic material known for its high hardness, chemical inertness, and excellent lubricity. Incorporating BN particles into the AA3105 matrix provides a substantial barrier to wear, effectively reducing material loss.

Table 1. Results of wear test.

Material	AA3105	AA3105-G	AA3105-CNT	AA3105-BN
Weight loss (g)	0.3	0.257	0.2496	0.193
Wear (g/min)	0.06	0.0514	0.04992	0.0386
Enhancement %	Reference	14%	17%	36%

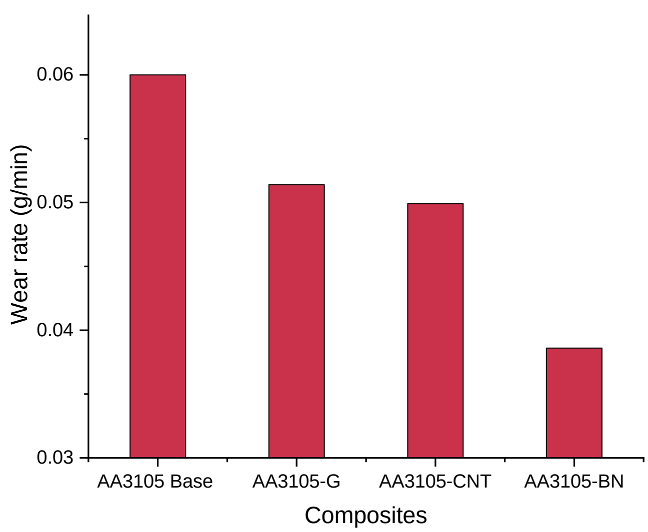

Figure 6. The wear rate behavior of the investigated samples.

4. Conclusion

- This study demonstrated significant improvements in microhardness and wear resistance of AA3105 aluminum alloy by incorporating single reinforcement nanoparticles (BN, G, and CNT) using the Friction Stir Processing (FSP) method.
- Microhardness increased by 16.16% for AA3105-BN, 16.31% for AA3105-G, and 39.14% for AA3105-CNT compared to the base AA3105 alloy.
- Wear resistance also saw enhancements: 14% for AA3105-G, 17% for AA3105-CNT, and 36% for AA3105-BN compared to the base alloy. These results highlight FSP's potential for fabricating high-performance metal matrix composites with tailored properties suitable for various engineering applications.
- Future research could explore the effects of hybrid reinforcement combinations and optimize processing parameters to further enhance the properties of AA3105 aluminum alloy composites.

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