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STUDY ON MICROHARDNESS AND WEAR PROPERTIES OF FRICTION STIR PROCESSED AL7075/SI_3N_4/BN SURFACE COMPOSITES

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Abstract

This investigation explores the potential of Friction Stir Processing (FSP) to enhance the mechanical, and tribological attributes of Aluminium Alloy 7075 (Al7075). By incorporating Silicon Nitride (Si_3N_4) and Boron Nitride (BN) as reinforcement agents, the study meticulously analyzes the resultant modifications in the alloy's hardness, and wear resistance. By varying filler ratios - 70% Si_3N_4 and 30% BN; 60% Si_3N_4 and 40% BN; and 50% Si_3N_4 and 50% BN - the research highlights the impact of these ceramics on the alloy's properties. Microstructural examinations of the developed surface composites were conducted using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) methods. From the microhardness and wear tests, it was revealed that the optimal composition (60% Si_3N_4, 40% BN) significantly reduced the wear loss by 32% compared to untreated Al7075, while the microhardness increased by 48.5%. This research underscores the effectiveness of FSP in tailoring the properties of Al7075 for advanced industrial applications, offering a comprehensive evaluation of its benefits and applicability in sectors demanding robust, high-performance materials.

Key words:
Friction Stir Process; Microhardness; Wear; Silicon Nitride; Boron Nitride.

1 Introduction

Aluminium alloys are pivotal in various engineering applications due to their excellent combination of light weight, high strength, and corrosion resistance [1-3]. Among these, Al7075 is recognized for its exceptional mechanical properties, making it a preferred material for aerospace and automotive applications [4-7].Enhancing its mechanical and tribological properties further enables Al7075 to potentially replace heavier traditional metals across various industries, contributing to weight reduction and improved performance in critical applications.

Friction Stir Processing (FSP) has emerged as a transformative approach for enhancing surface properties and microstructures of metallic materials. Originally developed from the principles of friction stir welding, FSP maintains the integrity and desired qualities of reinforcement particles while embedding them into the aluminum matrix effectively [8]. This process leads to a refined microstructure and improved distribution of reinforcing particles, thereby significantly boosting the material’s mechanical performance, including hardness, tensile strength, and wear resistance [9-11].

The introduction of ceramic particulates such as Silicon Carbide (SiC) [12, 13], Boron Carbide (B_4C) [14], Titanium Diboride (TiB_2) [15], and Aluminum Oxide (Al_2O_3) [16,17] as reinforcement materials in FSP has shown promising results in further enhancing the properties of aluminium alloys. Hybrid composites, which combine different types of ceramic particulates, offer the advantage of tailored material properties, allowing for a balanced improvement in mechanical characteristics and wear resistance. Specifically, the addition of $Si_3N_4$and BN has been reported to increase hardness and wear resistance due to their inherent material characteristics [18, 19]. The uniform dispersion of these ceramic particles within the aluminium matrix leads to significant improvements in material properties [20, 21].

Moustafaa et al. [22] explored the wear and microhardness behaviors of Al7075 alloy when reinforced with SiC and BN nanoparticles through FSP. They observed that the addition of SiC and BN nanoparticles increased wear resistance by 53-61% and microhardness by 45%.In the research conducted by Bharti et al. [23], FSP was employed to fabricate a surface composite using ZrO_2 as the reinforcement material and AluminiumAlloy 5052 (Al5052) as the substrate. Micro-hardness and wear tests were performed to evaluate the property enhancements of the treated composites. The incorporation of ZrO_2 ceramic particles resulted in a 32% increase in the average hardness of the FSP-treated specimens. Additionally, the ZrO_2-reinforced FSP samples exhibited reduced weight loss compared to the untreated Al5052 specimens.

Based on extensive literature reviews, it has been observed that while considerable research has been conducted on Al7075, the combined use of Si_3N_4 and BN as reinforcing agents has not been thoroughly explored. Therefore, this study aims to investigate the efficacy of FSP in enhancing the mechanical and tribological properties of Al7075 through the incorporation of Si_3N_4 and BN. By varying the ratios of these ceramic fillers, this research seeks to identify optimal conditions that maximize enhancements in material properties.

2 Materials and methods

2.1 Materials

Al7075, renowned for its exceptional mechanical strength, was selected as the base material for this study, targeting applications that demand high durability such as those in the aerospace and automotive industries. Table 1 shows the chemical composition of base alloy used in this study. The alloy's inherent properties make it an optimal candidate for testing enhancements through FSP. To further augment the mechanical properties of the alloy, ceramicnanoparticulates of Si_3N_4 and BN were incorporated.These ceramics are known for their hardness and thermal stability, properties that are expected to significantly improve the wear resistance and overall strength of the aluminium alloy when evenly distributed within the matrix [19].

Table 1: Chemical composition of Al7075

Elements	Zn	Mg	Cu	Cr	Si	Fe	Mn	Ti	Al
Weight %	5.3	2.43	1.52	0.23	0.15	0.42	0.15	0.12	Balance

2.2 Composite Fabrication

The Al7075 plates were prepared to specific dimensions of 100 mm in length, 50 mm in breadth, and 6 mm in thickness, and featured a machined slot measuring 100 mm by 1 mm by 2 mm to accommodate the filler materials. Si_3N_4 and BN fillers were mixed in varying ratios of 70:30, 60:40, and 50:50. The appropriate weight percentages for these fillers were calculated using the volume fraction approach and infused into the slot as detailed in Table 2.

Table 2: Weight Percentage of Filler materials

Sample	Si_3N_4 %	BN%
Sample 1	70	30
Sample 2	60	40
Sample 3	50	50

A high carbon, high chromium steel (HcHCr) tool with a hardness of 60 HRC was employed for the processing. The tool featured an 18 mm shoulder diameter and a 6 mm straight cylindrical threaded pin with a depth of 2.5 mm, facilitating effective matrix material flow within the treated region. The schematic diagram of the FSP tool with dimensions is depicted in Figure 1a, and the actual tool used in this study is illustrated in Figure 1b. To secure the fillers in the slot, a pinless FSP tool was initially used to partially seal the slot, preventing the escape of particulates. Subsequently, the threaded pin tool was applied to stir the packed groove thoroughly. FSP was conducted on a specialized friction stir welding machine, operating under controlled conditions with a tool rotational speed of 1100 RPM, a traverse speed of 30 mm/min, an axial force of 6 kN, and a tool tilt angle of 1.5 degrees. The FSP experimental setup used in this study is shown in Figure 1c.Finally, the processed plates were machined into standardized samples for subsequent metallographic, microhardness and wear tests.

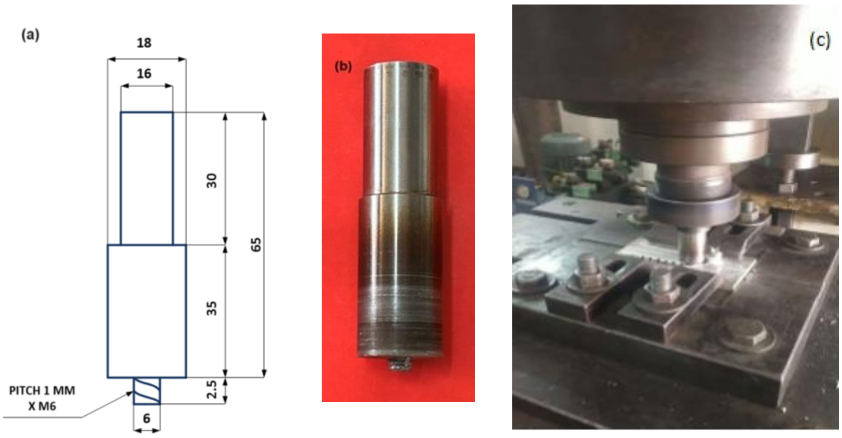


Fig 1 (a) Schematic diagram of FSP tool 3, (b) FSP tool used in this study, (c) FSP Experimental Setup

2.3 Microstructural Analysis

To examine the microstructure of developed composite materials, a detailed analysis was conducted using a scanning electron microscope (SEM), adhering to the ASTM D3039 standards. The process began with meticulous preparation of the specimens, which included polishing with emery sheets to achieve a smooth surface suitable for microscopy, followed by etching with Keller's etchant to reveal the microstructural features. This preparatory step is crucial as it enhances the visibility of the composite's internal structure, allowing for an accurate assessment of the distribution and integrity of the reinforcing particles within the matrix. EDS analysis was also employed alongside SEM to confirm the presence and distribution of elements within the composite material. This technique is essential for identifying the elemental composition of the samples, providing qualitative and quantitative data about the materials used, including the reinforcement particles.

2.4 Microhardness Test

Microhardness testing of the specimens was conducted using the Mitutoyo HM-210 B, adhering to the ASTM E384 standards. This machine as shown in Figure 3 features a Vickers indenter and is equipped with a 100 gf test force and a 50x optical lens. The automatic loading capability of the machine enhances the precision and reliability of the hardness measurements, ensuring accurate assessment of the specimen's microhardness. This methodology is particularly effective for detailed examination of material properties at microscale levels.

Fig 2 Microhardness Test Setup

2.5 Wear Study

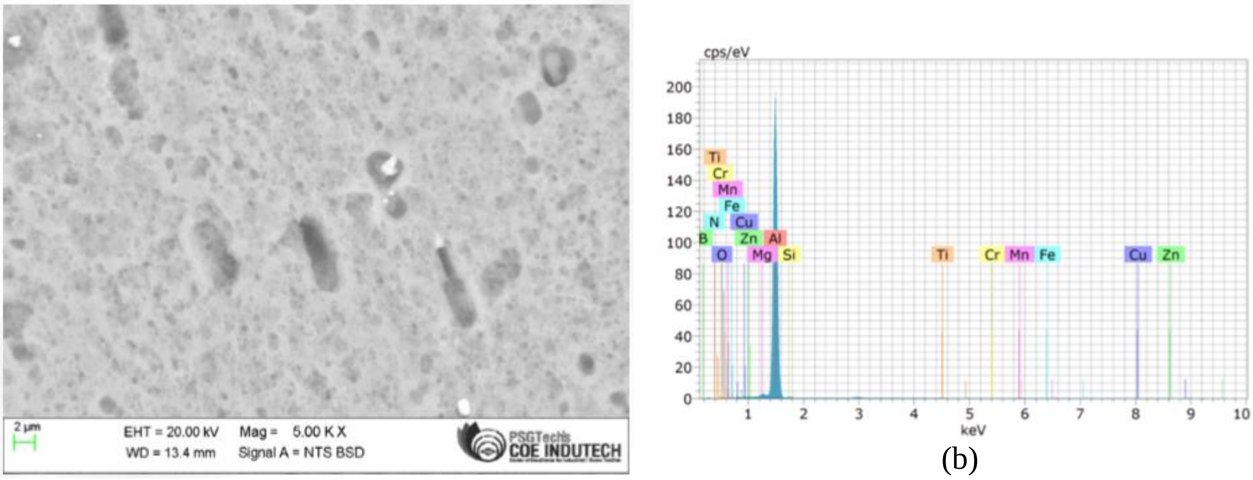
A wear experiment was conducted under dry sliding conditions using a pin-on-disc wear tester (Model: DUCOM TR-20LE-PHM 400-CHM 500) as shown in Figure 3, following the ASTM G99-95 standard guidelines. In this test, composite pin specimens measuring 6 mm×6 mm×30 mm were pressed against a rotating EN32 steel disc, which had a hardness of 62 HRC. The testing parameters included a sliding velocity of 1 m/s and a test duration of 1200 seconds, under a constant load of 15 N. The diameter of the wear track on the disc was set at 100mm. To assess wear performance, the weight loss of the specimens was precisely measured by weighing each specimen before and after the experiment using an electronic balance with a precision of 0.0001 g.

Fig 3 Wear Test Setup

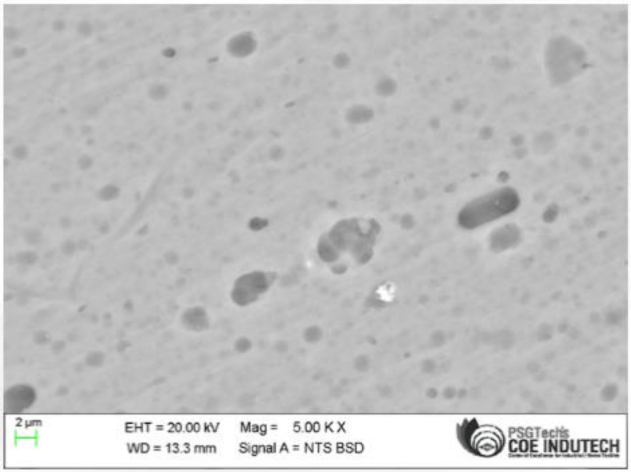
3 Result and Discussion

3.1 Microstructure

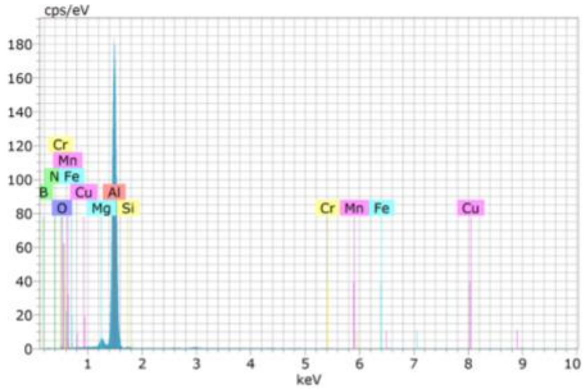
The characteristics of the fabricated composites are significantly influenced by the distribution of reinforcing particles within the matrix material [20]. Effective reinforcement is predicated on the homogeneous distribution of these particles throughout the matrix. In this study, the distribution of Si_3N_4 and BN particles was meticulously examined using SEM. The SEM analyses revealed a uniform dispersion of the reinforcement particles across the matrix. Importantly, the FSP zone was observed to be free from defects such as tunnels, pipe holes, and heat-affected zones. The particles within the reinforcement slot were consistently distributed throughout the FSP zone. Additionally, the formation of onion rings was noted, indicating a uniform material flow from the pin to the shoulder across the processed zone. EDS analysis further confirmed the uniform presence of silicon, nitrogen, and boron elements, validating the effective incorporation of the reinforcement particles in the composite material.Figure 4 presents the SEM and EDS images of the developed surface composites.



(a) (b)



(c)



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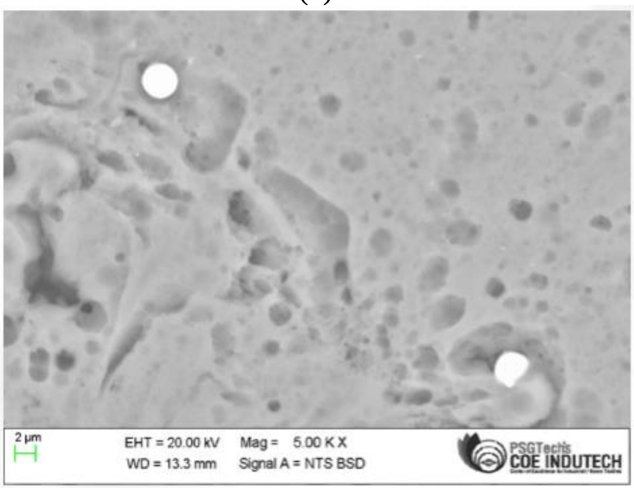

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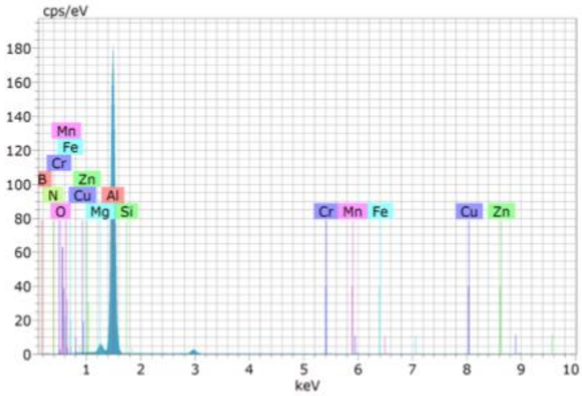

(f)

Fig 4(a) SEM image of Sample 1, (b) EDS image of Sample 1,(c) SEM image of Sample 2, (d) EDS image of Sample 2, (e) SEM image of Sample 3, (f) EDS image of Sample 3

3.2 Microhardness

The microhardness test results for the developed composite specimens, depicted in Figure 5, demonstrate a significant enhancement in hardness owing to the incorporation of Si_3N_4 and BN ceramic particles. The increased hardness of the matrix material is significantly attributed to the presence of harder ceramic particles and their uniform distribution [24, 25]. Among the tested samples, Sample 2, with a composition of 60% Si_3N_4 and 40% BN, exhibited the highest hardness of 101 HV. This represents a 48.5% increase compared to that of untreated Al7075, highlighting the optimal ratio of Si_3N_4 to BN for enhancing the microhardness of the composite.

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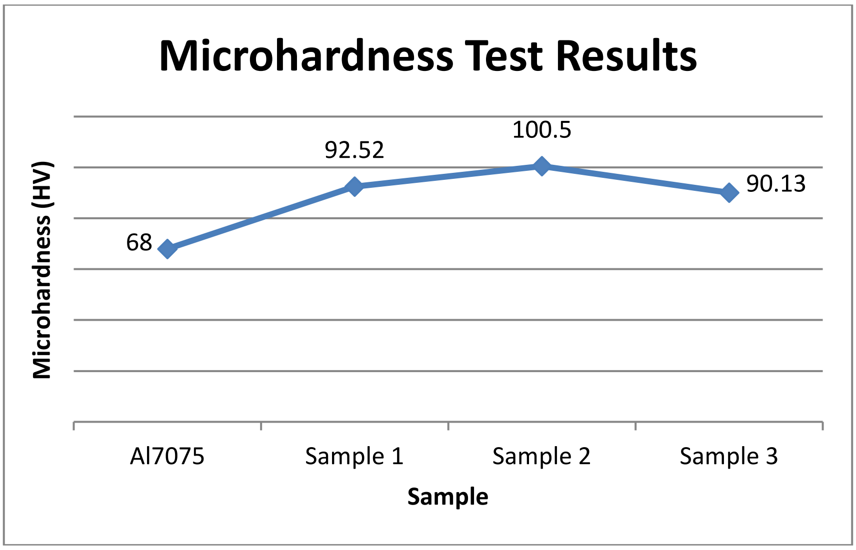

Fig 5Microhardness of the Samples

3.3 Wear Loss

The wear test results depicted in Figure 6 demonstrate a notable progression in wear resistance across the treated samples compared with untreated Al7075. The incorporation of Si_3N_4 and BN, which are known for their hardness and thermal stability, enhances wear resistance by altering the tribological properties of the base alloy. The ceramic particles in the matrix act as barriers to dislocation movement, which is a critical mechanism for enhancing the wear resistance [26, 27]. Additionally, the optimal distribution of these ceramic particulates ensures a uniform load distribution during wear, which minimises local stress concentrations and reduces wear propagation [28, 29]. Specifically, Sample 2, with a composition of 60% Si_3N_4 and 40% BN, showed the most pronounced reduction in wear lose, measured at 120 µm. This is a significant improvement, with a 32% decrease in wear lose compared to the 176 µm wear rate of the untreated alloy. This enhancement surpasses the wear rates observed in Sample 1 (142 µm) and Sample 3 (129 µm), indicating that a 60/40 ratio of Si_3N_4 to BN is optimal for wear resistance in this alloy system.This finding aligns with Archard's equation, which suggests that an increase in composite hardness correlates with enhanced wear resistance [30, 31].

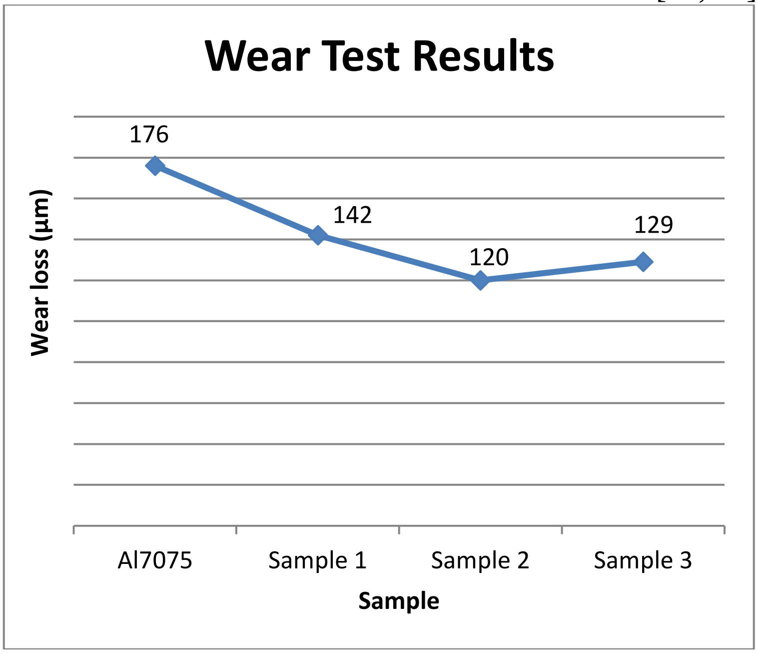

Fig 6 Wear loss of the Samples

4 Conclusion

Friction stir processing of Al7075 was performed with various compositions of added fillers, and the effect of these fillers on the surface composites was thoroughly investigated. The key findings from this study are as follows:

- Microstructural analysis revealed a uniform distribution of ceramic particles across the base alloy matrix, which is crucial for enhancing its mechanical properties.
- The addition of Si_3N_4 and BN ceramic particles to the Al7075 matrix significantly enhanced the microhardness and wear resistance of the composite.
- The optimal filler composition of 60% Si_3N_4 and 40% BNsignificantly enhanced the alloy's properties over other tested ratios and untreated Al7075, optimizing wear resistance and microhardness. This formulation resulted in a 32% reduction in wear loss and a 48.5% increase in microhardness compared to untreated Al7075.

These findings underscore the critical impact of precise filler composition on the enhancement of Al7075 through FSP, promising significant advancements in industrial applications that require materials with superior mechanical and wear-resistant properties. This investigation sets a foundation for future research on optimising composite formulations for specific performance criteria in surface composites.

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