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# EXPERIMENTAL ANALYSIS OF FRICTION STIR PROCESSED AL6082 HYBRID SURFACE COMPOSITES

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## ABSTRACT

This study focuses on enhancing the surface properties of AA6082 using Friction Stir Processing with Silicon Nitride ($Si_3N_4$) and Boron Nitride (BN) as reinforcement materials. A high-carbon, high-chromium steel (HcHCr) tool with a straight cylindrical threaded profile was used under specific parameters: spindle speed of 1100 rpm, traverse speed of 30 mm/min, axial force of 6 kN, and a tool tilt angle of 1.5°. The reinforcement materials, $Si_3N_4$ and BN, were added to surface slots in the base material in varying weight ratios: 80:20, 65:35, and 50:50, respectively. The friction stir-processed aluminum alloy was then evaluated for its microstructural and mechanical characteristics. Microstructural analysis was performed using Scanning Electron Microscopy and Energy Dispersive Spectroscopy. The results demonstrated a significant 18.33% increase in microhardness and a 5.2% improvement in tensile strength for the 65:35 composition. This study demonstrates the potential of hybrid reinforcement combinations in producing high-performance aluminum surface composites through FSP.

**Keywords**:
Friction Stir Process; Al6082; Silicon Nitride; Boron Nitride.

## 1. Introduction

Aluminum alloys, renowned for their lightweight and corrosion-resistant properties, are extensively used in the automotive, aerospace, and construction industries due to their excellent strength-to-weight ratio and machinability [1–3]. Among these, aluminum alloy 6082 is particularly notable for its high strength, superior corrosion resistance, and lightweight characteristics, making it an ideal choice for structural components in aircraft, automobiles, and other engineering applications [4–6]. To further enhance the properties of aluminum alloys, numerous studies on metal matrix composites (MMCs) have explored the incorporation of reinforcement particles into their matrix [7–10].

The addition of reinforcement particles has been shown to significantly improve the mechanical properties of aluminum alloys compared to their unreinforced counterparts [11–14]. Friction stir processing (FSP) is a promising technique for creating surface composites. During FSP, a non-consumable rotating and translating tool with a shoulder and pin is inserted into the metal surface along a groove. This process ensures adequate plasticization and uniform mixing of materials, allowing for the even distribution of reinforcement particles across the treated zone, which enhances the material's mechanical properties [15, 16].

Hybrid aluminum composites, which integrate multiple reinforcements within a single matrix, exhibit superior physical and mechanical characteristics compared to those with single reinforcement [17]. Among the materials used for developing MMCs, silicon nitride ($Si_3N_4$) stands out as a preferred reinforcement due to its exceptional mechanical, thermal, and chemical properties, including excellent resistance to oxidation, corrosion, and wear [18]. Similarly, boron nitride (BN) is recognized as a promising reinforcement material, valued for its remarkable chemical stability and mechanical strength [19].

Kaya et al. [20] employed FSP to fabricate a surface composite using SiC as the reinforcement material and Al5083–H111 as the substrate. Micro-hardness, tensile, and wear tests were conducted to evaluate property enhancements. The composite specimen exhibited a 38% increase in hardness, a 42% improvement in wear resistance, and 97% of the tensile strength of the base material. Singh et al. [21] utilized FSP to enhance aluminum-based composites by incorporating $Si_3N_4$ reinforcement into an AA2024 substrate. Precise parameters, including pin diameter, tool tilt angle, and tool profile, were applied to achieve uniform dispersion of $Si_3N_4$ particles in the aluminum matrix. This resulted in a 36.9% increase in hardness, a 21.45% improvement in tensile strength, a 24.12% boost in fatigue strength, and a 30.44% enhancement in wear resistance compared to the base material.

While significant research has been conducted on AA6082, there has been limited investigation into the use of twin nitride combinations, such as $Si_3N_4$ and BN, as reinforcing agents. In this study, $Si_3N_4$ and BN nanoparticles are incorporated into the aluminum alloy matrix as reinforcements. The primary objective is to evaluate how the addition of these nanoparticles, combined with FSP, influences the microstructural and mechanical characteristics of the Aluminium based MMCs.

## 2. Materials and Experimental Procedure

The Al6082 aluminum alloy plates were prepared with dimensions of 100 mm × 50 mm × 6 mm and featured a machined slot (100 mm × 1 mm × 2 mm) to accommodate reinforcement materials. The chemical composition of the base material, AA6082, is provided in Table 1. $Si_3N_4$ and BN were used as fillers, mixed in ratios of 80:20, 65:35, and 50:50, with weight percentages calculated using the volume fraction approach, as detailed in Table 2.

Table 1: Chemical composition of Al6082

| Elements | Si | Cr | Mg | Mn | Fe | Cu | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| Weight % | 1.0 | 0.06 | 0.81 | 0.53 | 0.28 | 0.02 | 0.1 | 0.03 | Balance |

To produce surface composites, Friction Stir Processing was carried out using a high carbon, high chromium steel tool with a hardness of 60 HRC. The tool featured an 18 mm shoulder diameter and a threaded cylindrical pin with a 6 mm diameter and 2.5 mm depth, designed to ensure effective material flow and uniform distribution of reinforcements. The FSP employed in this experimental study is given in Figure 1.

Table 2: Weight Percentage of reinforcement materials

| Reinforcement Material | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| $Si_3N_4$ (% by weight) | 80 | 65 | 50 |
| BN (% by weight) | 20 | 35 | 50 |

Figure 1: FSP Tool

The process began with partial sealing of the slot using a pinless tool to prevent the escape of filler particles, followed by stirring with the threaded pin tool. 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°. The experimental setup used in this study is shown in Figure 2.

Figure 2: FSP Experimental Setup

The processed plates underwent comprehensive characterization to evaluate their microstructural properties. Scanning Electron Microscopy (SEM) was used for high-resolution imaging of the surface and internal structure. The specimens were polished with emery sheets to create a smooth surface, followed by etching with Keller's reagent to reveal detailed microstructural features. This process allowed for the examination of the distribution and uniformity of reinforcement particles within the aluminum matrix. The SEM images provided valuable insights into the composite's structure. Additionally, Energy Dispersive X-ray Spectroscopy (EDS) was conducted in conjunction with SEM to verify the presence and distribution of elements within the composite material. EDS provided crucial qualitative and quantitative data, enabling a deeper understanding of the elemental composition, including the reinforcement particles.

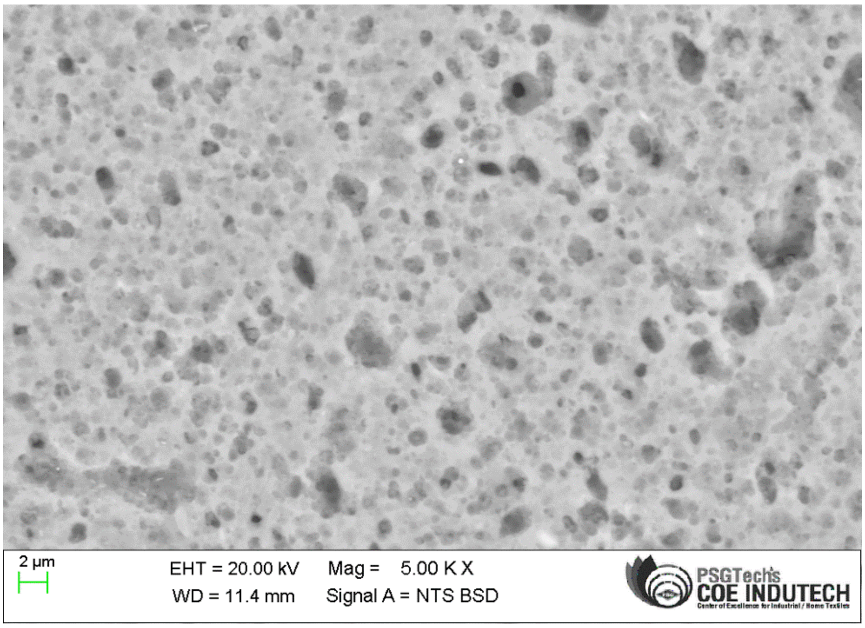
Microhardness testing was performed following ASTM E3-11 standards using a Mitutoyo Vickers microhardness tester to evaluate the hardness of the material in the friction stir zone. The test involved creating precise indentations along the processed zone using a 100 gf load applied for 10 seconds at each measurement point. Multiple indentations were made across the zone to ensure consistency, and the average microhardness values were calculated. These measurements provided a detailed assessment of the localized mechanical properties in the stir zone.

Tensile testing was conducted in accordance with ASTM E8M standards using a computer-controlled universal testing machine (Fine Spavy Associates, M100). During the test, a uniaxial tensile force was applied steadily through both ends of the composite specimens, inducing elongation until failure. The machine continuously recorded data such as the applied force and the corresponding displacement. This experimental data was used to calculate the tensile strength of the material under tensile loading conditions.

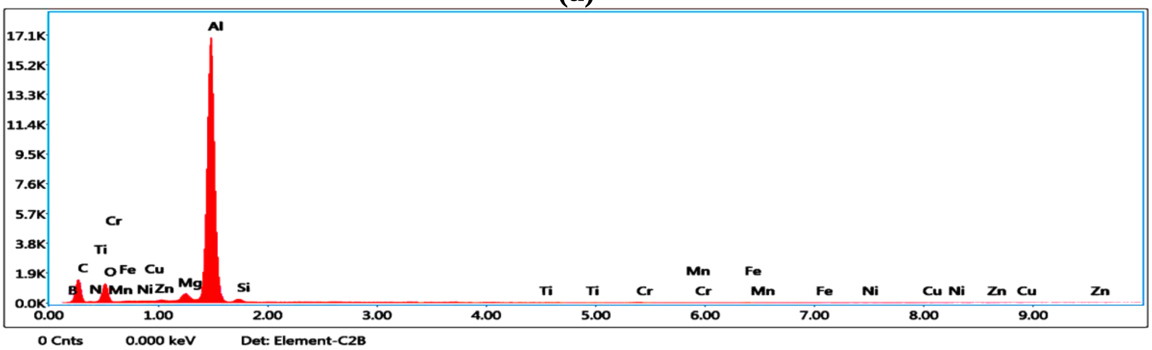
## 3. Result and Discussion

### 3.1 Microstructure

The characteristics of the fabricated composites were found to depend heavily on the uniform distribution of reinforcing particles within the matrix material. SEM analysis confirmed a homogeneous dispersion of $Si_3N_4$ and BN particles across the FSP zone, with no defects such as tunnels, pipe holes, or heat-affected zones. Energy Dispersive Spectroscopy (EDS) analysis further confirmed the successful integration of the reinforcing elements, with clear evidence of silicon, nitrogen, and boron uniformly distributed throughout the matrix. These findings validate the effectiveness of the processing parameters and the reinforcement technique employed in this study. Figure 3 illustrates the SEM and EDS images of Sample 2.




**(a)**




**(b)**

Figure 3: (a)SEM image of Sample 2 (b)EDS image of Sample 2

### 3.2 Microhardness

The microhardness test results for the developed composite specimens, shown in Figure 4, indicate a significant increase in hardness due to the incorporation of $Si_3N_4$ and BN ceramic particles. This increase in hardness can be attributed to the presence of these harder ceramic particles and their uniform distribution within the matrix material [22, 23]. Among the tested samples, Sample 2, which contains 65% $Si_3N_4$ and 35% BN, exhibited the highest microhardness of 142 HV. This represents a 18.33% increase in microhardness compared to the base alloy Al6082, which had a microhardness of 120 HV. These results highlight the effectiveness of the 65:35 $Si_3N_4$ to BN ratio in significantly enhancing the microhardness of the composite material.

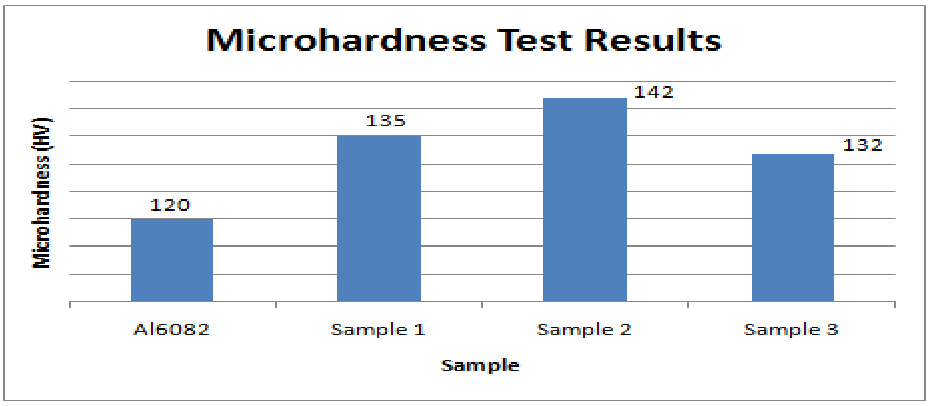



Figure 4: Microhardness test results

### 3.3 Tensile Strength

The tensile test results for the developed composite specimens, presented in Figure 5, show a significant improvement in tensile strength due to the incorporation of $Si_3N_4$ and BN ceramic particles. The enhancement in tensile strength can be attributed to the reinforcing effect of these harder ceramic particles within the matrix. Among the samples, Sample 2, with a composition of 65% $Si_3N_4$ and 35% BN, exhibited the highest tensile strength of 282 MPa. This represents a 5.2% increase in tensile strength compared to the base Al6082, which had a tensile strength of 268 MPa. These results demonstrate that the 65:35 $Si_3N_4$ to BN ratio provides the most significant improvement in tensile strength, making it the optimal reinforcement combination for this composite.

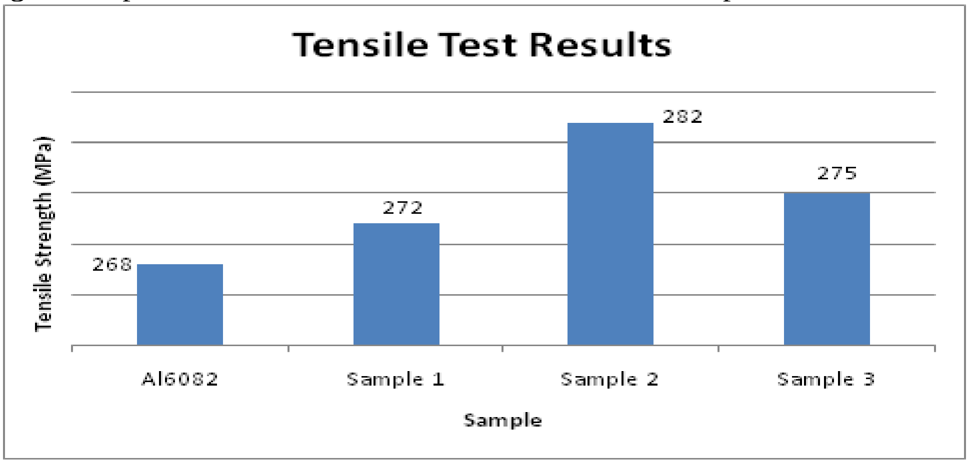



Figure 5: Tensile test results

## 4. Conclusion

The experimental investigation on Friction Stir Processing of Al6082 alloy with varying compositions of $Si_3N_4$ and BN fillers has yielded significant insights into the enhancement of surface composite properties. The primary conclusions drawn from this study are summarized below:

- The processed composites exhibited a uniform distribution of $Si_3N_4$ and BN particles, achieved through optimized FSP parameters. This homogeneity was critical in minimizing defects and enhancing the matrix's integrity.
- Among the tested reinforcement ratios, the 65:35 composition of $Si_3N_4$ to BN demonstrated the most remarkable improvement, achieving an 18.33% increase in microhardness and a 5.2% enhancement in tensile strength compared to the base alloy.
- The hybrid reinforcement of 65% $Si_3N_4$ and 35% BN provided a balance of strength and hardness, making it the most effective formulation for enhancing the performance of Al6082 alloy.

These findings underscore the potential of using hybrid ceramic fillers in friction stir processing to achieve superior mechanical properties in aluminum alloys. The results pave the way for future research to explore tailored composite formulations for specific engineering applications, including aerospace and automotive industries, where material performance is critical.

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