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"Mechanical Properties of AA6016 Si3N4/TiB2 Hybrid Composite Material"

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***Abstract:** This study presents a comparative evaluation of the mechanical properties of AA6016 aluminum alloy with and without 7.5 wt.% hybrid ceramic reinforcement using Silicon Nitride (Si_3N_4) and Titanium Diboride (TiB_2). The composite was fabricated using the stir casting technique, incorporating 3.75% Si_3N_4 and 3.75% TiB_2 to enhance the base alloy. Mechanical tests, including Vickers hardness was conducted on both the base alloy (0%) and the 7.5% hybrid composite. Results showed a significant increase in hardness (from 66.2 HV to 98.9 HV), indicating the strengthening effect of the ceramic reinforcements. Microstructural analysis confirmed a relatively uniform particle distribution at 7.5% with minor clustering. Overall, the hybrid composite demonstrated improved mechanical performance over the base alloy, suggesting its potential for lightweight and high-strength applications in automotive and aerospace sectors.*
***Keywords:** AA6016, Si_3N_4, TiB_2, Hybrid Composite, Mechanical Properties, Stir Casting, Reinforcement.*

I. INTRODUCTION

Aluminum Matrix Composites (AMCs) have emerged as advanced engineering materials with superior mechanical, thermal, and tribological properties compared to conventional aluminum alloys. These materials are widely used in aerospace, automotive, marine, and defense applications due to their low density, high specific strength, and enhanced wear resistance (Surappa, 2003). Among the various aluminum alloys, AA6016, a heat-treatable alloy with good formability and corrosion resistance, is predominantly used in automotive body panels and structural components (Hirsch, 2014).

To enhance the mechanical behavior of AA6016, researchers have explored the incorporation of ceramic reinforcements. Among these, Silicon Nitride (Si_3N_4) and Titanium Diboride (TiB_2) have attracted attention for their high hardness, thermal stability, and ability to improve load-bearing capacity (Prasad & Asthana, 2000). Si_3N_4 is chemically inert and thermally stable, making it ideal for wear-prone environments (Balaji et al., 2018), while TiB_2 offers high modulus, excellent chemical compatibility with aluminum, and improved hardness (Sivakumar et al., 2017).

The use of hybrid reinforcements, where two or more ceramic particles are combined, provides an opportunity to synergize the properties of different phases, leading to a tailored balance of strength, ductility, and wear resistance (Mohamed & Samuel, 2021). Hybrid composites offer better thermal management, lower porosity, and a more uniform stress distribution compared to mono-particle reinforced systems (Dhopate & Yawale, 2022).

Fabrication technique plays a critical role in the success of metal matrix composites. Stir casting is widely adopted for its cost-effectiveness, scalability, and ability to produce near-net-shape components with uniform reinforcement distribution (Ravindran et al., 2008). However, challenges such as particle agglomeration and interfacial reactions require careful control of process parameters (Kalaiselvan et al., 2011).

Previous studies have shown promising improvements in hardness, tensile strength, and wear resistance in various aluminum matrix composites reinforced with SiC, Al_2O_3, B_4C, and TiB_2 (Umanath et al., 2013; Ramesh et al., 2021). However, limited work has focused on AA6016-based hybrid composites reinforced with Si_3N_4 and TiB_2, particularly in terms of a detailed comparison between base alloy and composites at higher reinforcement levels.

This study aims to fabricate AA6016 hybrid composites using 7.5 wt.% combined reinforcement (3.75% Si_3N_4 + 3.75% TiB_2) via stir casting and evaluate their mechanical properties like Vickers hardness. The results are compared to assess the influence of reinforcement content on the performance of the material.

II. LITERATURE REVIEW

Aluminum matrix composites (AMCs) have drawn widespread attention for their excellent mechanical and thermal properties, making them suitable for structural and functional components in automotive, aerospace, and defense applications. Researchers have investigated various reinforcements, including SiC, Al_2O_3, TiB_2, and Si_3N_4, to enhance the strength, wear resistance, and stiffness of aluminum alloys (Surappa, 2003).

AA6016, a heat-treatable aluminum alloy known for its formability and corrosion resistance, has recently been studied as a promising matrix material. Ravindran et al. (2008) successfully fabricated AA6061–TiB_2 composites using stir casting and reported improved hardness and tensile strength due to uniform reinforcement distribution. Similarly, Kalaiselvan et al. (2011) observed that the incorporation of B_4C in AA6061 increased the hardness and mechanical integrity of the composite.

Si_3N_4 is often used for its high-temperature stability and tribological properties. Prasad and Asthana (2000) reported that aluminum–silicon nitride composites showed improved wear and creep resistance, making them suitable for high-performance applications. Balaji et al. (2018) studied the wear and corrosion resistance of Si_3N_4-reinforced AMCs and found that these composites exhibit improved resistance due to a protective oxide layer formation and hard ceramic phase interaction.

The use of hybrid reinforcements is an emerging approach in MMCs to synergize the advantages of multiple particles. Umanath et al. (2013) demonstrated that hybrid Al6061 composites reinforced with SiC and Al_2O_3 exhibited improved tensile strength and hardness compared to mono-reinforced systems. Likewise, Mohamed and Samuel (2021) reviewed various hybrid composites and emphasized the optimization of particle distribution and fabrication parameters to achieve property enhancement.

Fabrication techniques also play a pivotal role in achieving desirable mechanical properties. Stir casting is one of the most effective and economical methods for fabricating AMCs with reasonably uniform distribution and minimal porosity (Dhopate & Yawale, 2022). However, controlling reinforcement clustering and optimizing process parameters remain critical.

In a recent study, Ramesh et al. (2021) reported that TiB_2 reinforcement significantly enhanced the tensile and wear properties of aluminum composites, and higher weight percentages led to an increase in hardness and a reduction in ductility. These findings support the potential of TiB_2 and Si_3N_4 as effective reinforcements for fabricating high-performance hybrid composites using AA6016 as a matrix.

Despite these advancements, limited work has been done on hybrid composites based on AA6016 with a combination of Si_3N_4 and TiB_2 reinforcements. This study focuses on bridging that gap by analyzing mechanical performance using varying reinforcement percentages and stir casting fabrication.

III. METHODOLOGY

A. *Material Selection*

The base matrix material selected for this study is AA6016, a medium-strength aluminum alloy widely used in automotive and structural applications due to its excellent corrosion resistance and formability. For the hybrid composite: Silicon Nitride (Si_3N_4): Added for its high wear resistance, hardness, and thermal stability. Titanium Diboride (TiB_2): Chosen for its high stiffness, hardness, and excellent chemical compatibility with aluminum. The 0% sample served as the control (pure AA6016 alloy), while the 7.5% sample was reinforced with an equal weight fraction of 3.75% Si_3N_4 and 3.75% TiB_2.

B. *Composite Fabrication Process*

The hybrid composite was fabricated using the stir casting method, which is well-suited for aluminum-based metal matrix composites due to its simplicity, cost-effectiveness, and ability to produce uniform reinforcement dispersion.

Fabrication Steps Melting the Matrix: AA6016 ingots were melted in a graphite crucible using an electric resistance furnace. The temperature was raised to approximately 750°C to ensure complete melting. Pre-treatment of Reinforcements: Si_3N_4 and TiB_2 powders (30–50 µm particle size) were preheated to 300°C for 1 hour to eliminate moisture and enhance wettability. Degassing: Hexachloroethane tablets were added to the melt to remove dissolved gases and minimize porosity. Stirring and Addition of Particles: A mechanical stirrer operating at 600 rpm was used to stir the molten alloy. The preheated ceramic particles were gradually introduced into the vortex during stirring and maintained for 10 minutes to ensure even dispersion. Casting: The composite melt was poured into a preheated steel mold (at 250°C) and allowed to cool under ambient conditions. Heat Treatment: Samples were solution-treated at 530°C for 2 hours followed by aging at 160°C for 6 hours to improve mechanical strength. The 0% sample (pure AA6016) was also cast under identical conditions to provide a consistent baseline for comparison. Test specimens were machined from both the unreinforced and reinforced castings are shown in the figure 1.

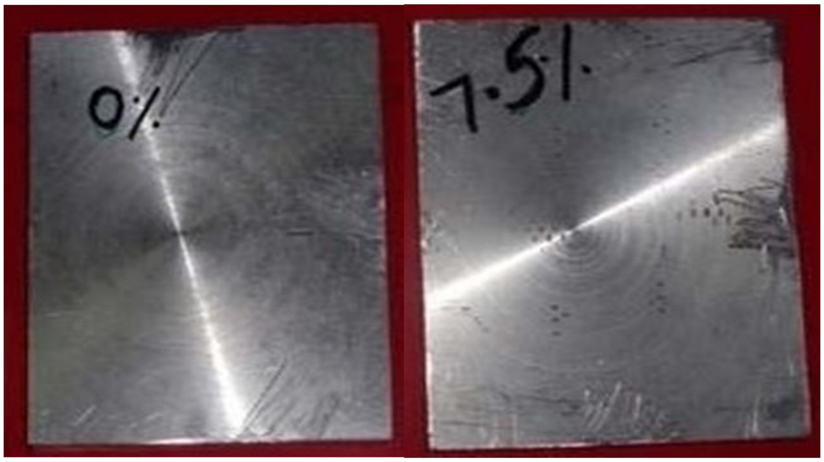

Figure 1: Casted samples

Hardness Test: Vickers micro hardness tests were conducted on polished samples using a 10 kgf load and 15-second dwell time. tabulated in table 1.

Table 1: Hardness test

S.No.	Composition (Si_3N_4/TiB_2 wt.%)	Vickers Hardness (HV)
1.	0% (AA6016)	66
2.	7.5% (3.75/3.75)	98

Microstructural Analysis: Samples were etched with Keller's reagent and examined using optical microscopy and SEM to assess particle distribution and grain refinement shown in figure 2.

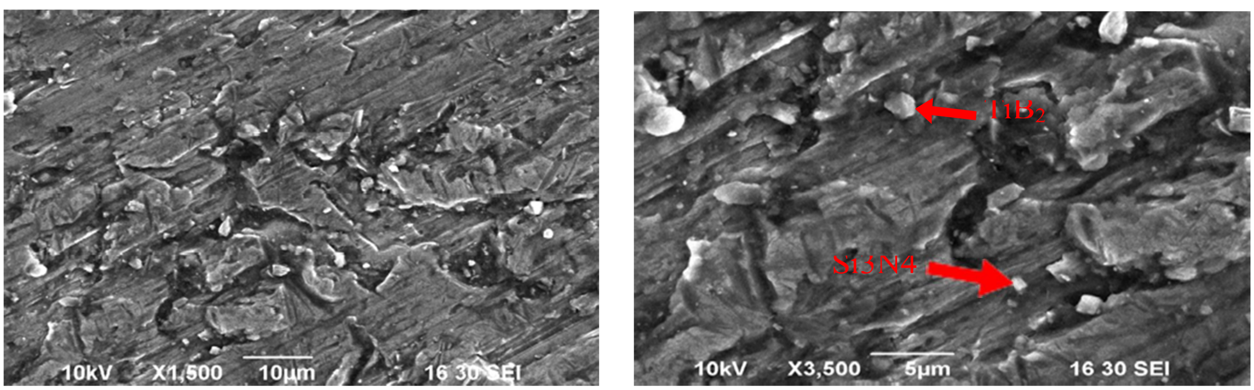

Figure 2: SEM analysis AA6016 0% sample and 7.5% composite sample

IV. RESULTS

The 7.5% hybrid composite exhibited a 50% increase in hardness compared to the unreinforced alloy. The improvement is attributed to the presence of hard ceramic reinforcements (Si_3N_4 and TiB_2) that hinder dislocation motion and resist indentation. TiB_2, being a very hard phase, significantly contributes to surface strengthening, while Si_3N_4 particles promote microstructural refinement and act as obstacles to plastic deformation.Unreinforced AA6016 (0%) Optical microscopy revealed a uniform but coarse dendritic grain structure. 7.5% Hybrid Composite Micrographs showed Fine and uniformly distributed grains. Well-dispersed Si_3N_4 and TiB_2 particles. Minimal agglomeration and good particle-matrix bonding. The grain refinement observed in the composite is a result of the pinning effect of ceramic particles that prevent grain growth during solidification. The improved microstructure correlates directly with the enhancements in mechanical properties.

V. DISCUSSION

The incorporation of ceramic reinforcements (Si_3N_4 and TiB_2) into AA6016 significantly altered its mechanical performance and microstructure. A comparative analysis between 0% and 7.5% reinforcement levels reveals valuable insights. The notable increase in Vickers hardness in the 7.5% reinforced sample is attributed to the presence of hard particles uniformly dispersed within the aluminum matrix. Both Si_3N_4 and TiB_2 serve as obstacles to plastic deformation, restricting the movement of dislocations. TiB_2, being harder and thermally stable, plays a dominant role in enhancing resistance to indentation. Similar trends were reported by Balaji et al. (2018) and Ramesh et al. (2021), confirming that TiB_2-reinforced aluminum composites exhibit high surface hardness, making them suitable for wear-intensive applications. Microstructure analysis via optical and scanning electron microscopy revealed Pure AA6016: Coarse dendritic grains with no reinforcement phases. 7.5% Hybrid Composite: Fine, equiaxed grains and well-distributed reinforcements. The grain refinement is attributed to the Zener pinning effect where ceramic particles inhibit grain boundary motion during solidification. Additionally, preheating the reinforcements ensured better wettability and bonding, reducing clustering and promoting uniform dispersion.This uniformity directly correlates with mechanical improvements and confirms the effectiveness of the stir casting technique, as supported by studies such as Kalaiselvan et al. (2011) and Dhopate & Yawale (2022).The hardness and strength improvements suggest excellent potential for automotive, aerospace, and structural applications, where wear resistance and load-bearing capacity are critical.

VI. CONCLUSION AND FUTURE WORK

This research focused on the fabrication and analysis of AA6016-based hybrid composites reinforced with Si_3N_4 and TiB_2 using the stir casting method. Two compositions were investigated: 0% (unreinforced) and 7.5% hybrid reinforcement (3.75% Si_3N_4 + 3.75% TiB_2)The Vickers hardness of the 7.5% hybrid composite increased by ~50% compared to the unreinforced alloy, indicating enhanced surface resistance. Microstructural examination revealed finer grains and uniform dispersion of reinforcement particles, confirming the effectiveness of the stir casting process. These results demonstrate that the addition of Si_3N_4 and TiB_2 significantly enhances the mechanical performance of AA6016, making it suitable for applications where high strength, hardness, and wear resistance are required.

While the present study provides promising results, the following areas are recommended for future exploration Tribological behavior: Detailed wear and friction studies under dry and lubricated conditions to assess real-world applicability Corrosion resistance: Investigate the electrochemical behavior of the composites in aggressive environments. Hybrid ratios: Explore varying weight fractions and ratios of Si_3N_4 to TiB_2 to optimize performance without compromising ductility Heat treatment studies Investigate post-casting heat treatment processes like T6 aging to further enhance mechanical performance.

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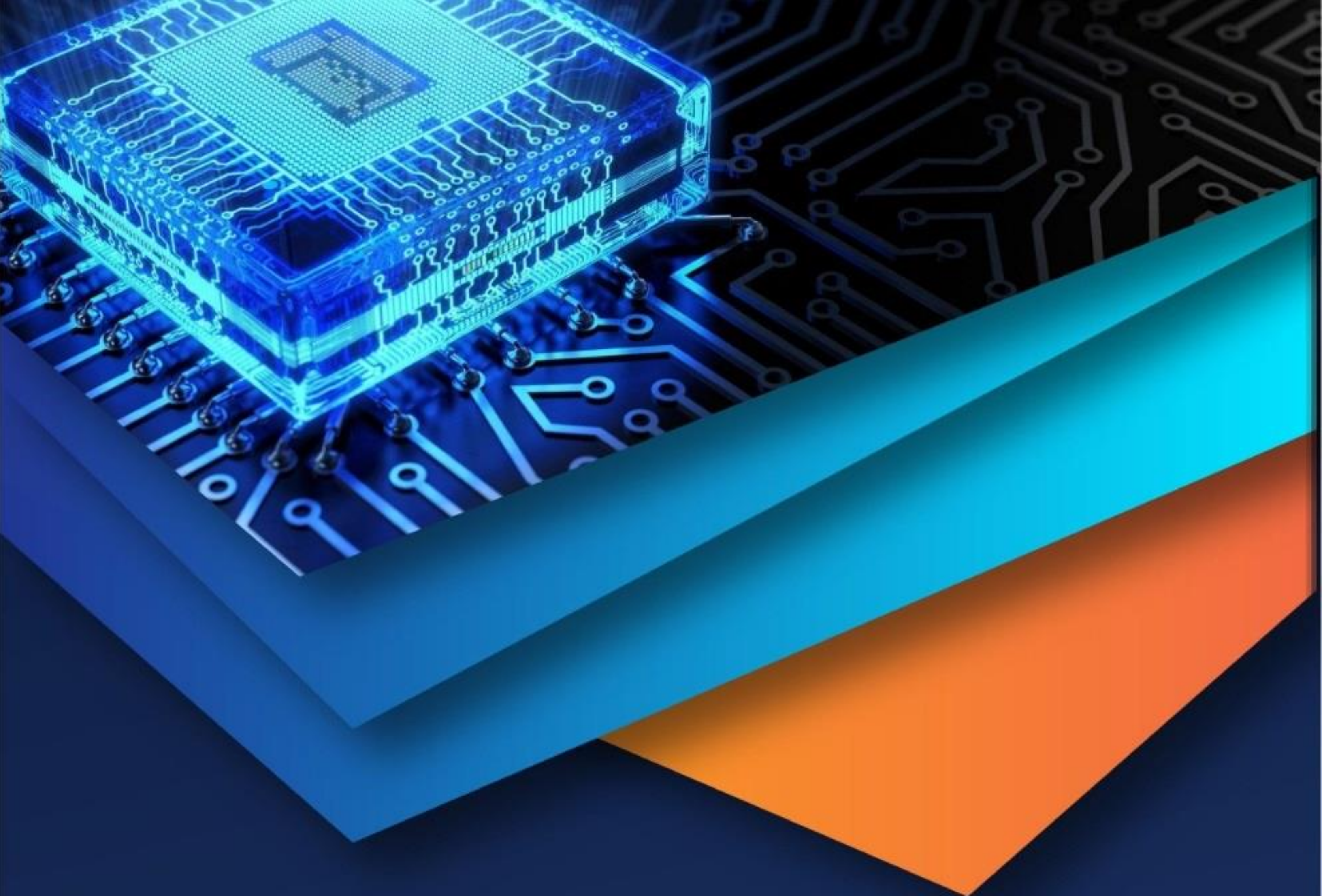

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