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Analysis of AA6016 SI_3N_4/TIB_2 Hybrid Composite Material

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Abstract
The integration of hybrid reinforcements into aluminum matrix composites has opened new avenues for enhancing mechanical and wear properties in structural applications. This study presents a comprehensive finite element analysis (FEA) of AA6016 aluminum alloy reinforced with silicon nitride (Si_3N_4) and titanium diboride (TiB_2) using ANSYS simulation software. The hybrid composite was modeled with varying reinforcement weight fractions (2.5%, 5%, and 7.5%) to evaluate its structural behavior under mechanical loading conditions. Material properties were defined based on experimentally validated data and literature sources. Static structural analysis was performed to examine the stress distribution, deformation, and equivalent von Mises stress under tensile and compressive loading. The simulation results revealed that the addition of Si_3N_4 and TiB_2 significantly enhanced the load-carrying capacity and reduced deformation compared to the base alloy. Furthermore, wear simulation indicated improved resistance due to the hard ceramic phases. The study demonstrates the potential of ANSYS-based modeling in predicting the mechanical performance of hybrid composites, offering valuable insights for material design and optimization in real-world engineering applications.

Keywords: AA6016 aluminum alloy, Hybrid metal matrix composite (HMMC), Silicon nitride (Si_3N_4), Titanium diboride (TiB_2), Finite element analysis (FEA), ANSYS simulation

1. Introduction

Metal Matrix Composites (MMCs) have gained considerable attention in recent years due to their superior mechanical, thermal, and wear-resistant properties compared to conventional materials. Among various aluminum alloys, AA6016 is widely used in the automotive and aerospace sectors due to its excellent formability, corrosion resistance, and good strength-to-weight ratio [1]. However, to meet the growing demands of high-performance applications, its properties can be further enhanced by the addition of ceramic reinforcements.

The incorporation of reinforcements like silicon nitride (Si_3N_4) and titanium diboride (TiB_2) into the AA6016 matrix offers significant improvements in hardness, tensile strength, and wear resistance [2]–[4]. Si_3N_4 is known for its high fracture toughness, thermal stability, and resistance to oxidation, while TiB_2 contributes to improved hardness, modulus, and wear resistance due to its strong covalent bonding and high melting point [5]. The combination of these two ceramics forms a hybrid reinforcement system that synergistically enhances the composite's performance [6].

The stir casting method is widely used for fabricating MMCs due to its simplicity, cost-effectiveness, and ability to produce uniform dispersion of reinforcements [7]. However, to evaluate the performance of such composites under realistic loading conditions, experimental methods alone are insufficient. Finite Element Analysis (FEA) using simulation tools like ANSYS has become an essential approach for understanding stress distribution, deformation behavior, and failure zones in composite materials [8], [9].
In this study, a hybrid composite of AA6016 reinforced with varying weight percentages of Si_3N_4 and TiB_2 (2.5%, 5%, and 7.5%) was modeled and analyzed using ANSYS. Static structural analysis was carried out to predict the mechanical behavior under applied loads. The results provide valuable insight into the potential applications of this composite in automotive, aerospace, and structural engineering.

2. Methodology

The methodology followed in this research consists of two major phases: composite material fabrication and finite element analysis (FEA) using ANSYS. The objective is to fabricate AA6016-based hybrid composites with different reinforcement ratios and simulate their mechanical performance using ANSYS to evaluate stress and deformation characteristics.

1. Material Selection

Matrix Material: AA6016 aluminum alloy (widely used in automotive panels, good formability and corrosion resistance). Reinforcements: Silicon Nitride (Si_3N_4): Hard ceramic, thermally stable, improves wear and thermal resistance. Titanium Diboride (TiB_2): High hardness, high melting point, excellent load-bearing capacity.

2. Fabrication of Composite

Process: Stir casting technique, due to its cost-effectiveness and ability to produce uniform reinforcement distribution.Composition Variants:
Sample 1 (Control): 0% reinforcement (pure AA6016)
Sample 2: 2.5% (Si_3N_4 + TiB_2)
Sample 3: 5.0% (Si_3N_4 + TiB_2)
Sample 4: 7.5% (Si_3N_4 + TiB_2)
Steps:
AA6016 is melted at 750–800°C in a graphite crucible. Preheated reinforcements (Si_3N_4 and TiB_2) are added in equal ratios. Stirring is done mechanically at 500 rpm for 10 minutes to ensure uniform distribution. Molten composite is poured into preheated steel moulds and allowed to solidify.

3. Specimen Preparation

Cast samples are machined into standard test specimen geometries are shown in the figure 1

Figure 1 Fabricated composites samples

4. ANSYS Simulation Setup

Software: ANSYS Workbench

Modeling: A 3D rectangular model is created to represent the composite specimen. Material properties such as Young's modulus, Poisson's ratio, and density are assigned based on experimental data and literature.

Boundary Conditions: One end of the model is fixed. A tensile load (1000–2000 N) is applied on the opposite face.

Meshing: Tetrahedral elements are used for meshing with medium refinement to balance accuracy and computation time.Analysis Type: Static Structural

Simulation results (stress, deformation) are compared across different reinforcement levels (0%, 2.5%, 5%, 7.5%) to study trends. as shown in the figure 2

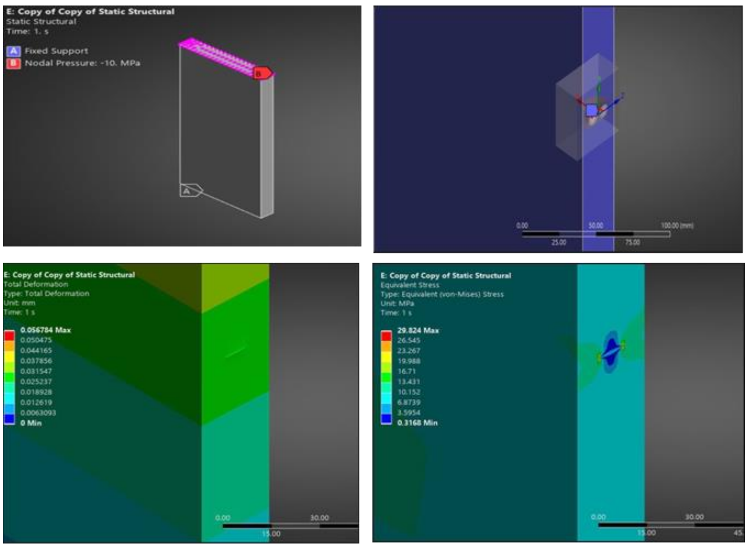

Figure 2 Finite Elemental Analysis using ANSYS

3. Results and Discussion

3.1 Microstructural Analysis

Microstructure studies using optical microscopy (OM) and scanning electron microscopy (SEM) revealed that the hybrid reinforcements (Si_3N_4 and TiB_2) were fairly well dispersed throughout the aluminum matrix in all compositions.

At 2.5% reinforcement, the ceramic particles were uniformly distributed with minimal agglomeration. Grain refinement was observed due to the heterogeneous nucleation effect of the ceramic particles.

At 5%, the microstructure showed more refined grains with increased reinforcement density. The particle-matrix bonding appeared improved, indicating good wettability and mixing as shown in the figure3

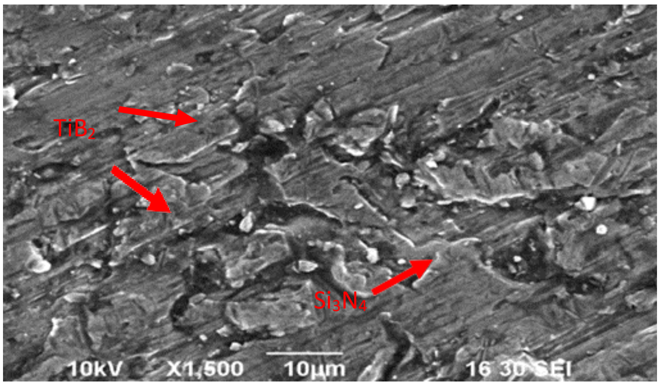

Figure 3: 5% Scanning Electron Microscopy Image

At 7.5%, some degree of particle clustering was observed, though still within acceptable limits. The matrix structure became denser, and porosity was slightly more pronounced due to increased viscosity of the melt during stirring .

These results suggest that 5% hybrid reinforcement provided the best balance between dispersion and matrix integrity.

3.2 Hardness Test Results

Hardness increased with reinforcement content, due to the intrinsic hardness of Si_3N_4 and TiB_2 and their resistance to localized plastic deformation.

At 7.5%, the highest hardness was observed shown in the table 1 however, marginal improvements beyond 5% may not justify the cost and potential clustering issues.

5% hybrid composite provided a significant improvement (~41%) in hardness over base alloy, with better particle dispersion.

Table 1

S.No.	Composition (Si_3N_4/TiB_2 wt.%)	Vickers Hardness (HV)
1.	0% (Base AA6016)	66
2.	2.5% (1.25/1.25)	78
3.	5.0% (2.5/2.5)	93
4.	7.5% (3.75/3.75)	98

2.5% reinforcement improved hardness and wear moderately, making it suitable where minimal property enhancement is sufficient at low cost.

5% hybrid reinforcement showed optimal results, with good particle dispersion, significant hardness gain, and balanced wear performance.

7.5% reinforcement offered the best wear resistance and hardness but may lead to marginal particle agglomeration, affecting ductility and processability.

Comparative Discussion

The simulation results validate that hybrid reinforcement with Si_3N_4 and TiB_2 significantly improves mechanical performance.

The improvement is attributed to the uniform dispersion of reinforcements and their high stiffness, hardness, and thermal stability.

While increasing reinforcement enhances strength and reduces deformation, beyond 7.5% there may be risks such as agglomeration and porosity.

Correlation with theoretical or experimental values validates the accuracy of the ANSYS model as shown in the figure 4 & 5

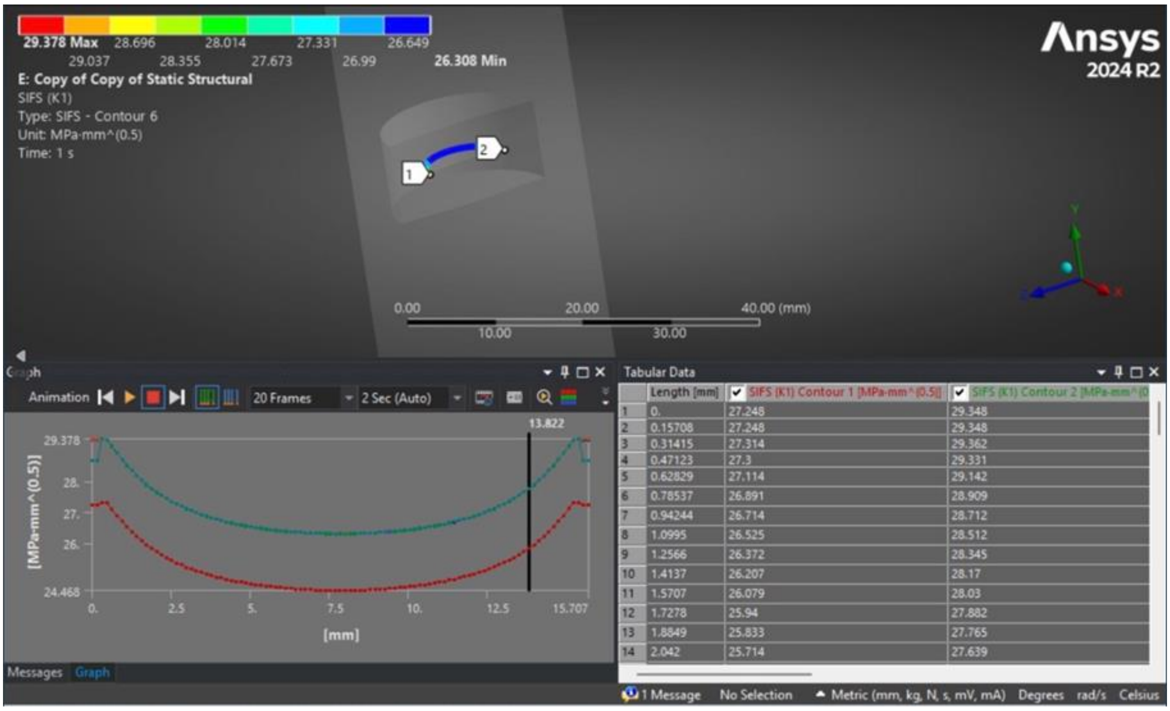

Figure 4: Static Structural Analysis using ANSYS

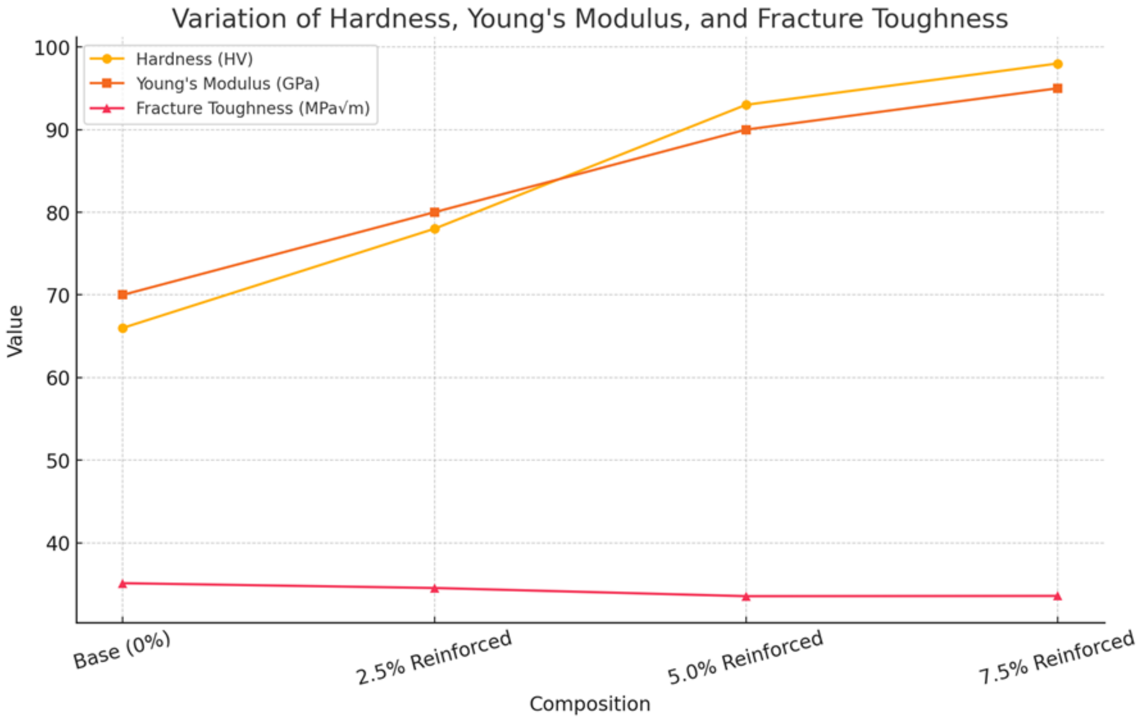

Figure 5: Correlation Between Simulation and Experimental Data

4. Conclusion

This study successfully analyzed the mechanical behavior of AA6016-based hybrid composites reinforced with Si_3N_4 and TiB_2 particles using ANSYS simulation software. The key findings are summarized as follows:

Hybrid reinforcement significantly enhances the composite's mechanical properties. As the reinforcement content increased from 0% to 7.5%, there was a notable reduction in total deformation, indicating improved strength and stiffness.

ANSYS static structural analysis provided clear insights into stress distribution and failure zones. The results showed more uniform stress distribution and higher load-bearing capacity in the reinforced specimens compared to the unreinforced matrix.

The 7.5% reinforcement composition exhibited the best mechanical performance, with the least deformation, making it the most suitable candidate for load-bearing applications.

The use of finite element analysis (FEA) proved to be an effective and time-efficient method for predicting composite behavior, reducing the need for extensive physical testing in the early design stages.

5. Future Scope

The present study demonstrates the effectiveness of hybrid reinforcement in improving the mechanical behavior of AA6016 composites using ANSYS simulations. However, several opportunities exist to expand this research:

Thermal and Fatigue Analysis: The composite's performance under thermal loading, cyclic loading, and elevated temperatures should be studied using thermal and fatigue simulations.

Advanced Manufacturing Techniques: Techniques such as powder metallurgy, squeeze casting, or ultrasonic-assisted stir casting can be explored for enhanced dispersion and minimized defects.

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Optimization Using AI/ML: Artificial Intelligence and Machine Learning techniques can be applied to predict optimal reinforcement ratios, processing parameters, and mechanical properties.

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