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Tribo-Mechanical Analysis Of Aluminum Metal Matrix Composites With Tio2 Reinforcement

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Abstract

The demand for lightweight, high-strength, and wear-resistant materials in industries such as automotive, aerospace, and defense has driven the development of aluminum metal matrix composites (AMMCs). This study focuses on the fabrication and tribo-mechanical analysis of Al6061 reinforced with titanium dioxide (TiO2) particles using the powder metallurgy technique. Composites with 0%, 2%, 4%, and 6% TiO2 weight fractions were synthesized and evaluated for tensile strength, compressive strength, hardness, and sliding wear behavior. The results indicate that the addition of 4% TiO2 significantly enhances mechanical properties, including a 19% increase in tensile strength, 25% increase in compressive strength, and 36% increase in hardness compared to pure Al6061. Sliding wear tests conducted using a pin-on-disc tester revealed that the 4% TiO2 composite exhibited the lowest wear rate and a high coefficient of friction (COF) of 0.35–0.45, outperforming existing brake pad materials by approximately 26% in wear resistance and 21% in COF. Finite element analysis (FEA) corroborated experimental findings, validating the structural integrity of the composites. The study highlights the potential of Al6061-TiO2 composites for high-temperature wear-resistant applications, such as automotive brake pads.

Keywords: Aluminum Metal Matrix Composites, TiO2 Reinforcement, Powder Metallurgy, Tribo-Mechanical Properties, Brake Pads

I. Introduction

The pursuit of advanced materials with superior mechanical and tribological properties is critical for modern engineering applications. Aluminum metal matrix composites (AMMCs) have emerged as promising candidates due to their high strength-to-weight ratio, low density, and excellent wear resistance. These properties make AMMCs suitable for demanding applications in automotive, aerospace, and defense industries, where components must withstand high temperatures, stresses, and wear [1].

Tribology, the science of interacting surfaces in relative motion, plays a pivotal role in optimizing material performance by minimizing friction and wear. Studies indicate that tribological advancements can reduce global energy consumption by 18–40% over 8–15 years, translating to significant economic and environmental benefits [2]. Aluminum alloys, particularly Al6061, are widely used as matrix materials due to their excellent corrosion resistance, machinability, and thermal stability. Reinforcing Al6061 with hard ceramic particles, such as titanium dioxide (TiO2), enhances its tribo-mechanical properties, making it ideal for applications like brake pads, pistons, and structural components [3].

This research aims to develop and characterize Al6061-TiO2 composites fabricated via powder metallurgy, focusing on their mechanical and tribological performance under varying conditions. The study addresses the research gap in evaluating sliding wear behavior at elevated temperatures, a critical parameter for automotive brake pad applications.

II. Materials and Methods

2.1 Materials Selection

The matrix material selected was Al6061 alloy due to its favorable mechanical and thermal properties, as shown in Tables 1 and 2. TiO2 was chosen as the reinforcement material for its high hardness, wear resistance, and thermal stability (Table 3). The chemical composition of Al6061 and the properties of TiO2 are detailed below.

Table 1: Chemical Composition of Al6061 Alloy

Elements	Si	Fe	Cu	Mg	Ni	Mn	Zn	Ti	Pb	Cr	Remaining
Content (wt.%)	0.7	0.5	0.15	0.5	0.15	0.55	0.5	0.1	0.15	0.35	Al

Table 2: Thermal and Mechanical Properties of Al6061

Properties	Values
Hardness (Rockwell)	55
Ultimate Tensile Strength (MPa)	320
Yield Tensile Strength (MPa)	280
Break Elongation (%)	12.0
Modulus of Elasticity (MPa)	68.5×10^3
Specific Heat (J/g-°C)	0.896
Thermal Conductivity (W/m-K)	165
Coefficient of Thermal Expansion (µm/m-°C)	25.2

Table 3: Properties of TiO2

Property	Values
Crystal Structure	Tetrahedral Close Packed
Density (g/cm³)	3.2
Hardness (kg/mm²)	2800
Tensile Strength (MPa)	310
Elastic Modulus (GPa)	476
Melting Point (°C)	2850
Thermal Conductivity (W/m-K)	41
Compressive Strength (MPa)	1750–2500

2.2 Fabrication of Composites

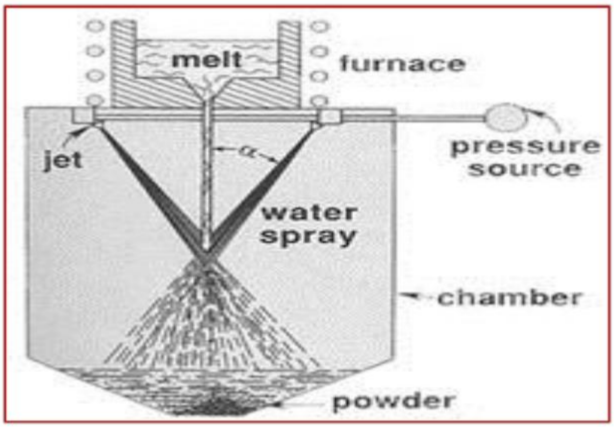

Figure 1: Schematic Diagram of Powder Metallurgy Technique

Al6061-TiO_2 composites with 0%, 2%, 4%, and 6% TiO_2 weight fractions were fabricated using the powder metallurgy technique. The process involved the following steps:

1. **Powder Blending**: Al6061 and TiO_2 powders were mixed using a horizontal attritor ball mill to ensure uniform dispersion.
2. **Compaction**: The blended powders were compacted into green compacts using a 13 kbar vertical hydraulic press.
3. **Sintering**: The green compacts were sintered at 550°C in a controlled environment to achieve densification.
4. **Hot Extrusion**: The sintered compacts were extruded to produce fully dense materials.

2.3 Experimental Testing

2.3.1 Tensile Testing

Tensile tests were conducted on dog-bone-shaped specimens (ASTM E8/E8M) using a Unitech-Instron 4001 series UTM. A progressive load of 1.5 N was applied to measure yield strength, ultimate tensile strength, and elongation.

Fig.2.1. Conduction of Tension Test of Al6061 on UTM

2.3.2 Hardness Testing

Hardness was measured using a Model B 3000 Brinell hardness tester (ASTM E10) with a 5 mm ball indenter at 32°C and 75 bar pressure. Three measurements were averaged for each sample.

Fig.2.2. Conduction of Hardness Test Al6061 on BHT

2.3.3 Sliding Wear Testing

Dry sliding wear tests were performed using a pin-on-disc tester (ASTM G-99-95a) with a grey cast-iron disc (50 HRC, Ra = 1.57 μm). Test parameters included:

- Loads: 20 N, 70 N, 120 N, 170 N
- Temperatures: 50°C, 100°C, 150°C, 200°C
- TiO2 Weight Fractions: 0%, 2%, 4%, 6%
- Sliding Velocities: 2–8 m/s
- Sliding Distance: 1500 m

Wear rate was calculated using the weight loss method, and COF was determined from load cell sensor readings.

2.3.4 Finite Element Analysis (FEA)

FEA was conducted using ANSYS with a triangular mesh to simulate tensile and impact strength. Material properties (Young's modulus, Poisson's ratio) were applied consistent with experimental conditions.

III. Results and Discussion

3.1 Mechanical Properties

3.1.1 Tensile Strength

The tensile strength and elongation of Al6061-TiO2 composites are presented in Table 4 and Figure 2. The addition of TiO2 significantly improved tensile strength, with the 6% TiO2 composite exhibiting a strength of 349 MPa, a 19% increase over pure Al6061 (309 MPa). Elongation also increased, with the 6% TiO2 composite showing a 7.4% elongation, 20% higher than pure Al6061.

Table 4: Tensile Strength and Elongation of Samples

Compositions of Pins	Tensile Strength (MPa)	Elongation (%)
AL6061 + 0% TiO2	309	5.4
AL6061 + 2% TiO2	316	6.6
AL6061 + 4% TiO2	334	6.9
AL6061 + 6% TiO2	349	7.4

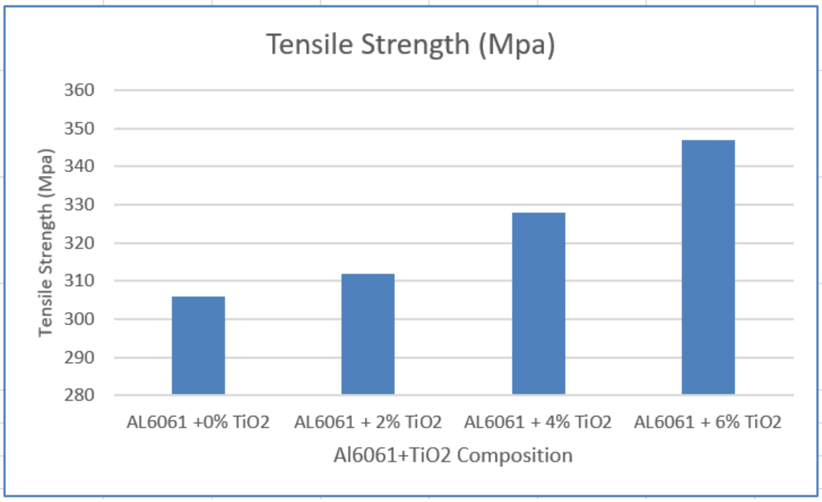

Figure 2: Tensile Strength of TiO2 Compositions

3.1.2 Hardness

Hardness results (Table 5, Figure 3) show a progressive increase with TiO2 content. The 6% TiO2 composite achieved a hardness of 129.42 BHN, approximately 36% higher than pure Al6061 (81.12 BHN). This enhancement is attributed to the high hardness of TiO2 particles.

Table 5: Hardness of Samples

Compositions of Pins	Hardness (BHN)
AL6061 + 0% TiO2	81.12
AL6061 + 2% TiO2	111.45
AL6061 + 4% TiO2	114.64
AL6061 + 6% TiO2	129.42

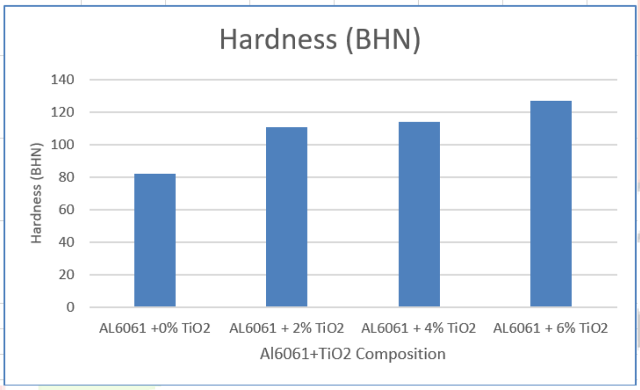

Figure 3: Hardness (BHN) of TiO2 Compositions

3.1.3 Compressive Strength

Compressive strength results (Table 6, Figure 4) indicate a significant improvement with TiO2 reinforcement. The 6% TiO2 composite exhibited a compressive strength of 189.20 MPa, a 25% increase over pure Al6061 (102.9 MPa).

Table 6: Compressive Strength of Samples

Compositions of Pins	Compressive Strength (MPa)
AL6061 + 0% TiO2	102.9
AL6061 + 2% TiO2	109.75
AL6061 + 4% TiO2	140.10
AL6061 + 6% TiO2	189.20

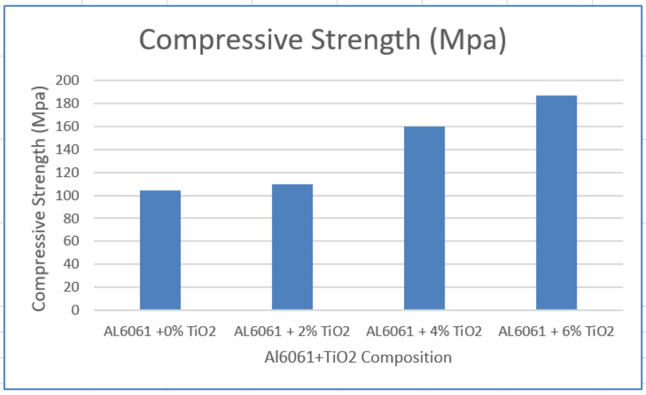

Figure 4: Compressive Strength of TiO2 Compositions

3.2 Sliding Wear Behavior

Sliding wear tests revealed that the 4% TiO_2 composite exhibited the lowest wear rate and a high COF (0.35–0.45), as shown in Table 7 and Figures 5–6. Compared to existing brake pad materials (COF: 0.30–0.35), the proposed composite demonstrated 26% lower wear and 21% higher COF, indicating superior performance for brake pad applications.

Table 7: Sliding Wear Rate and COF Results

Sr. No	Load (N)	Wear (Micron)	Coefficient of Friction (COF)								
		Al	Mg	Zn	Cu	Al6061	Al	Mg	Zn	Cu	Al6061
1	20	102.6	92.4	97.6	78.8	74.2	0.36	0.42	0.39	0.33	0.35
2	20	168.6	122.4	130.6	94.8	82.2	0.48	0.49	0.53	0.47	0.42
3	20	280.6	154.4	206.6	146.8	103.2	0.61	0.54	0.66	0.49	0.45
4	40	160.6	145.4	152.6	132.8	98.2	0.51	0.51	0.51	0.44	0.41
5	40	259.6	166.4	197.6	162.8	123.2	0.55	0.61	0.52	0.53	0.46
6	60	319.6	263.4	297.6	195.8	162.6	0.72	0.61	0.63	0.53	0.47
7	60	322.6	299.4	284.6	184.8	147.2	0.50	0.48	0.76	0.42	0.44
8	60	345.6	302.4	324.6	200.8	164.2	0.60	0.55	0.84	0.63	0.51
9	60	453.6	359.4	403.6	298.8	206.2	0.76	0.71	0.90	0.63	0.53

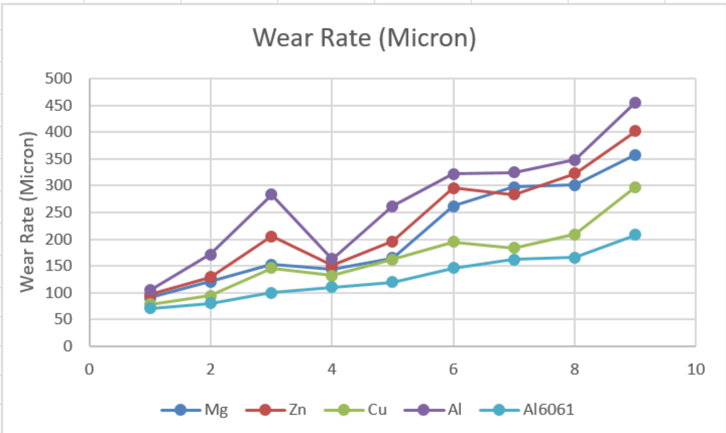

Figure 5: Wear Rate of Different Materials

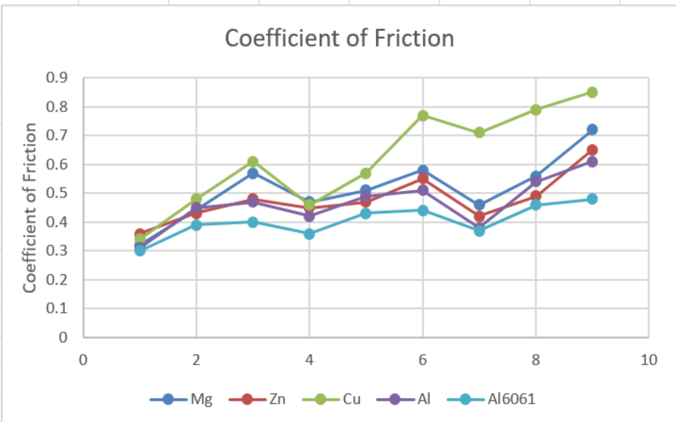

Figure 6: COF of Different Materials

3.3 Finite Element Analysis

As shown in Fig.7 as we increase tensile load of specimen the Al6061 with 0%TiO_2 The maximum von Mises stress was 371MPa at the fixed end, which is below the yield strength, resulting in a elongation of 1.575.

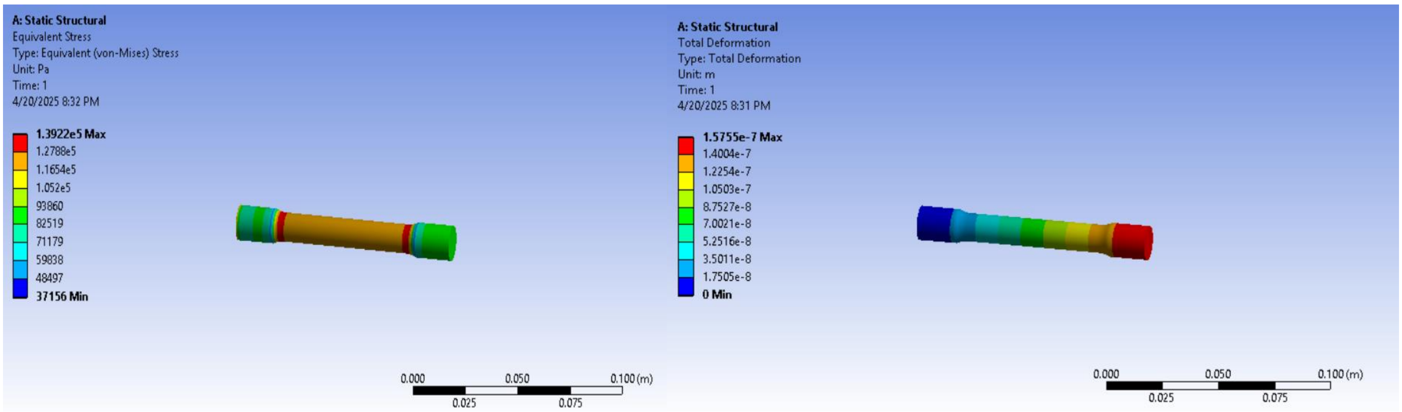

Figure 7: FEA Results for AL6061 + 0% TiO_2

As shown in Fig.8 as we increase tensile load of specimen the Al6061 with 4%TiO_2 The maximum von Mises stress was 371
MPa at the fixed end, which is below the yield strength, resulting in a elongation of 1.447.

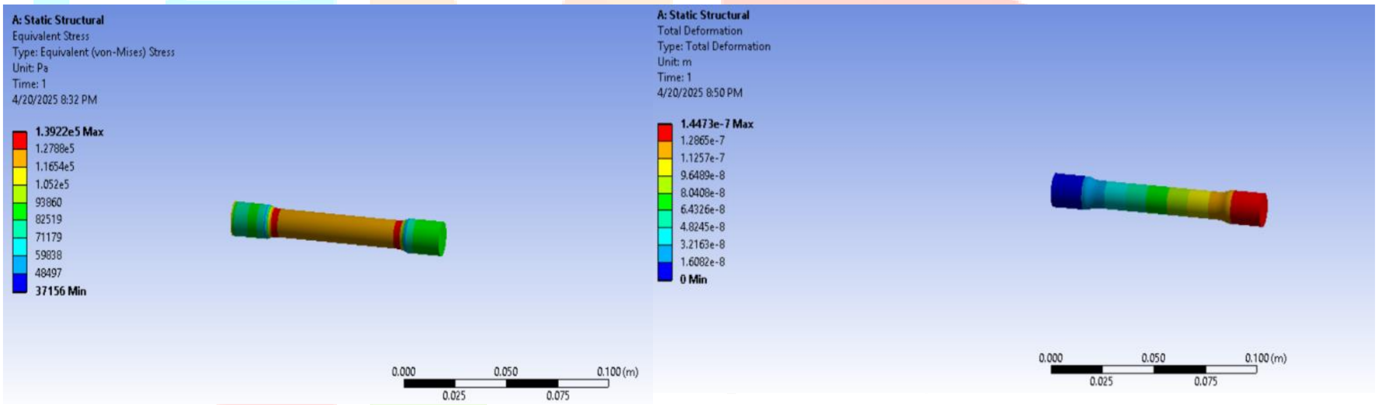

Figure 8: FEA Results for AL6061 + 4% TiO_2

As shown in Fig.9 as we increase tensile load of specimen the Al6061 with 6%TiO_2 The maximum von Mises stress was 371MPa at the fixed end, which is below the yield strength, resulting in a elongation of 1.277.

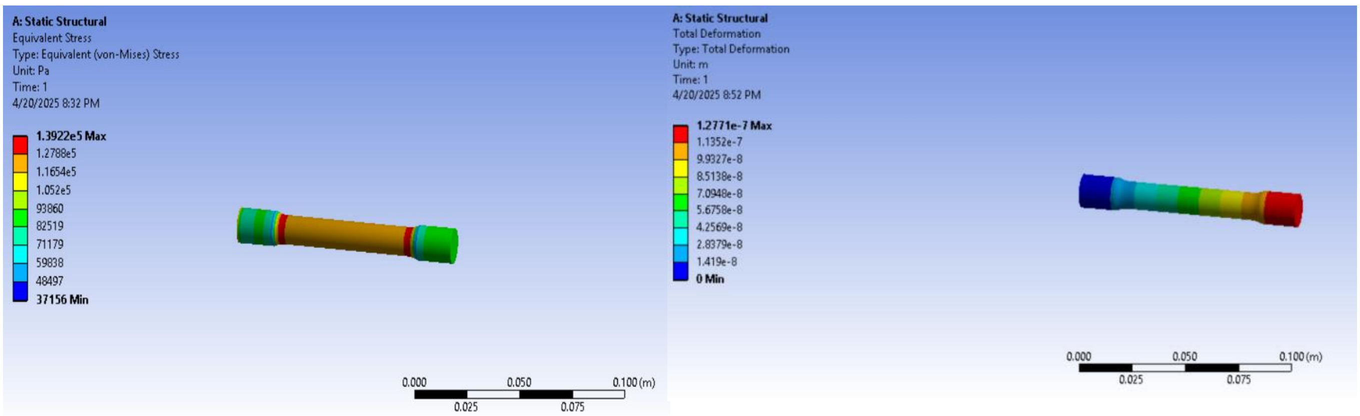

Figure 9: FEA Results for AL6061 + 6% TiO_2

FEA results for Al6061 with 0%, 4%, and 6% TiO2 (Figures 7–9) confirmed the experimental findings, showing increased tensile and impact strength with TiO2 reinforcement. The stress distribution and deformation patterns indicated improved structural integrity for the 4% TiO2 composite.

IV. Conclusions

Al6061-TiO2 composites were successfully fabricated using the powder metallurgy technique, with 4% TiO2 exhibiting optimal mechanical and tribological properties. The addition of TiO2 increased tensile strength by 19%, compressive strength by 25%, and hardness by 36% compared to pure Al6061.The 4% TiO2 composite demonstrated superior wear resistance (26% lower wear) and a higher COF (0.35–0.45) compared to existing brake pad materials.FEA validated the experimental results, confirming the enhanced structural performance of the composites. The Al6061-TiO2 composite with 4% TiO2 is a promising candidate for automotive brake pad applications due to its high wear resistance and mechanical strength.

V. Future Scope

1. Investigate advanced nano-ceramic fillers to further enhance the coefficient of friction and wear resistance.
2. Explore cost-effective filler materials to reduce the overall cost of AMMCs.
3. Study thermal management techniques to mitigate overheating in high-temperature applications.
4. Evaluate the mechanical properties of AMMCs at elevated temperatures using alternative manufacturing processes, such as liquid metallurgy.

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