

# Experimental Investigation and Optimization of Mechanical s Reinforced with B<sub>4</sub>C and Properties of Al6061 Metal Matrix Composite TiO<sub>2</sub>

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## Abstract

Aluminum-based metal matrix composites (MMCs) have gained significant attention in advanced engineering applications due to their superior strength-to-weight ratio and enhanced mechanical performance. In the present study, the influence of hybrid reinforcement using Boron Carbide (B<sub>4</sub>C) and Titanium Dioxide (TiO<sub>2</sub>) particles on the mechanical and tribological properties of Al6061 alloy is experimentally investigated and optimized. The composites were fabricated through the stir casting technique by varying the weight percentages of B<sub>4</sub>C (2–6 wt %) and TiO<sub>2</sub> (1–3 wt%) under controlled processing conditions.

The developed hybrid composites were subjected to comprehensive characterization, including tensile strength, hardness, wear behavior, and microstructural analysis. The results indicate that the incorporation of B<sub>4</sub>C significantly enhances hardness and wear resistance due to its high hardness and load-bearing capability, while TiO<sub>2</sub> improves particle distribution, interfacial bonding, and thermal stability of the matrix. However, excessive reinforcement content leads to particle agglomeration and porosity, which adversely affects tensile properties.

Statistical optimization was performed using the Taguchi method and analysis of variance (ANOVA) to identify the most influential parameters and determine the optimal combination of reinforcement and processing variables. The analysis revealed that B<sub>4</sub>C content has the highest contribution toward improving hardness and wear resistance, followed by TiO<sub>2</sub> content and stirring parameters. The optimal composition was found to provide a balanced improvement in mechanical and tribological performance compared to the base alloy.

## 1. INTRODUCTION

Aluminum alloys, particularly Al6061, are extensively used in aerospace, automotive, and structural applications due to their excellent combination of low density, good corrosion resistance, and favorable mechanical properties. The alloy exhibits good weldability and machinability, making it a preferred choice for lightweight engineering components. However, despite these advantages, Al6061 suffers from relatively low hardness and poor wear resistance, which limit its performance in high-load and high-friction environments.

To overcome these limitations, the development of Aluminum Metal Matrix Composites (AMMCs) has emerged as an effective approach. These composites are produced by reinforcing the aluminum matrix with ceramic particles, which significantly enhance mechanical and tribological properties. Among various reinforcements, Boron Carbide (B<sub>4</sub>C) has attracted considerable attention due to its exceptional hardness, low density, and

excellent wear resistance. The addition of B<sub>4</sub>C improves hardness and reduces material loss under sliding conditions by acting as a load-bearing phase.

In addition to B<sub>4</sub>C, Titanium Dioxide (TiO<sub>2</sub>) is increasingly being used as a secondary reinforcement material. TiO<sub>2</sub> contributes to improved wettability, better interfacial bonding between the matrix and reinforcement, and enhanced thermal stability. It also helps in refining the grain structure and reducing the formation of casting defects. The combination of B<sub>4</sub>C and TiO<sub>2</sub> in a hybrid reinforcement system can produce a synergistic effect, leading to superior overall performance compared to single-reinforced composites.

## 2. MATERIALS AND METHODS

### Materials

- **Matrix:** Al6061 alloy (composition: Mg 1%, Si 0.6%, Cu 0.3%, Fe 0.5%, Al balance)
- **Reinforcements:**
  - B<sub>4</sub>C (2–6 wt %)
  - TiO<sub>2</sub> (1–3 wt %)

### Fabrication Method Stir Casting Process:

1. Melt Al6061 at 750–800°C in a graphite crucible.
2. Preheat B<sub>4</sub>C and TiO<sub>2</sub> particles at 300–500°C.
3. Add 1 wt% Mg to improve wettability.
4. Stir molten alloy at 300–600 rpm for 10–15 min.
5. Add reinforcements gradually, continue stirring for 5 min.
6. Pour melt into a preheated steel mold at 200°C.

### Sample Compositions:

Sample	B <sub>4</sub> C (%)	TiO <sub>2</sub> (%)	Stirring Speed (rpm)
S1	2	2	300
S2	4	4	450
S3	6	6	600

### Testing Methods

#### 1. Izod Test

- **Purpose:** Measures impact strength of a material—how much energy it can absorb before breaking when struck.
- **Method:**
  - A notched specimen (usually a rectangular bar) is clamped vertically.
  - A pendulum hammer strikes it.
  - The energy absorbed to break the specimen is measured.

#### 2. Charpy Test

- **Purpose:** Also measures impact strength, similar to Izod, but the setup is slightly different.
- **Method:**
  - The specimen is supported horizontally as a simply supported beam.
  - The pendulum hits at the center.
  - Energy absorbed to fracture is recorded.

#### 3. Wear Test

- **Purpose:** Measures resistance to wear or friction—how long a material lasts under sliding, rolling, or abrasive conditions.
- **Methods:**
  - Pin-on-disk: A pin slides on a rotating disk; weight loss or wear rate is measured.

- Abrasion test: Material rubbed with sandpaper or abrasive wheels.
- Erosion test: Particles impact material surface repeatedly.

### 3. LITERATURE REVIEW

Aluminium alloy Al6061 is widely used in aerospace, automotive, and structural applications due to its lightweight, corrosion resistance, and good mechanical properties. However, its low hardness and poor wear resistance limit its use in high-load and abrasive environments. To overcome these limitations, ceramic reinforcements like boron carbide ( $B_4C$ ) and titanium dioxide ( $TiO_2$ ) are incorporated to form metal matrix composites (MMCs).

Boron carbide ( $B_4C$ ) is one of the hardest ceramics, widely used to improve hardness, tensile strength, and wear resistance of Al6061. Studies have shown that  $B_4C$  addition refines the aluminum grain structure, enhances load transfer, and significantly reduces wear rates. However, excessive  $B_4C$  can reduce ductility due to increased brittleness.

Titanium dioxide ( $TiO_2$ ) is chemically inert and hard, making it effective for improving mechanical and tribological properties. Al6061/ $TiO_2$  composites exhibit increased hardness and tensile strength with optimal  $TiO_2$  content (typically 2–6 wt%). High  $TiO_2$  content may lead to particle agglomeration, reducing ductility and performance.  $TiO_2$  reinforcement also reduces wear by providing a hard barrier against material removal during sliding.

### 4. METHODOLOGY

The study follows a structured approach to fabricate, test, and optimize Al6061– $B_4C$ – $TiO_2$  hybrid composites.

#### Step 1: Preparation of Materials

- Al6061 ingots were cut into suitable sizes for melting.
- $B_4C$  and  $TiO_2$  powders were preheated at  $400^\circ C$  to remove moisture and improve wettability.

#### Step 2: Melting of Aluminum Matrix

- Al6061 ingots were melted in a graphite crucible using an electric resistance furnace. • Melting temperature maintained at  $750^\circ C$ , slightly above the alloy's liquidus temperature.

#### Step 3: Stirring and Addition of Reinforcements 14

- The molten aluminum was stirred using a mechanical stirrer at 500–600 rpm to create a vortex for uniform particle distribution. • Preheated  $B_4C$  and  $TiO_2$  powders were slowly added to the molten matrix while stirring continuously. • Stirring continued for 5–10 minutes to ensure homogeneous mixing.

#### Step 4: Degassing

- Hexachloroethane ( $C_2Cl_6$ ) tablets or inert gas (argon) was introduced to remove dissolved gases and minimize porosity.

#### Step 5: Casting

- The molten composite was poured into preheated steel molds. • The molds were allowed to cool gradually at room temperature to avoid thermal stresses.

#### Step 6: Sample Preparation

- Castings were machined into standard specimen shapes for mechanical testing:
  - Tensile test: ASTM E8 standard
  - Hardness test: ASTM E10 standard
  - Impact test: ASTM E23 standard
  - Wear test: ASTM G99 standard

#### Step 7: Mechanical Testing

- Tensile Test: Using Universal Testing Machine (UTM) to measure ultimate tensile

strength and elongation. • Hardness Test: Brinell hardness tester to evaluate surface hardness. • Impact Test: Izod impact tester to determine toughness. • Wear Test: Pin-on-disc apparatus under dry sliding conditions to evaluate wear resistance.

### Step 8: Microstructural Analysis

- Specimens were polished, etched, and examined under optical microscopy (OM) and scanning electron microscopy (SEM) to study:
  - o Reinforcement dispersion
  - o Particle-matrix bonding
  - o Porosity and defects

### Flowchart of Methodology

- Al6061 Ingots + Reinforcements (B<sub>4</sub>C & TiO<sub>2</sub>)
- Preheat Reinforcements
- Melt Al6061 Alloy
- Stirring & Mixing
- Degassing & Pouring
- Solidification in Mold
- Machining of Test Specimens
- Mechanical Testing & Microstructure Analysis
- Optimization of Process Parameters

Sample	(B <sub>4</sub> C + TiO <sub>2</sub> ) wt%	Charpy Reading (DIV)	Impact Energy ( J)
1	B <sub>4</sub> C 2%	3	6 V
2	B <sub>4</sub> C 4%	3	6
3	B <sub>4</sub> C 6%	2	4
4	TiO <sub>2</sub> 2%	3	6
5	TiO <sub>2</sub> 4%	3	6
6	TiO <sub>2</sub> 6%	2	4

## 5. RESULTS AND DISCUSSION

### Impact Test Results

Charpy Impact Test:-

1 DIV = 2 JOULES

2. Izod Impact Test: 1 DIV = 2 JOULES

Sample	(B <sub>4</sub> C + TiO <sub>2</sub> ) wt%	Charpy Reading (DIV)	Impact Energy (J)
1	B <sub>4</sub> C 2%	4	4
2	B <sub>4</sub> C 4%	3	5
3	B <sub>4</sub> C 6%	3	6
4	TiO <sub>2</sub> 2%	4	5
5	TiO <sub>2</sub> 4%	3	5
6	TiO <sub>2</sub> 6%	3	4

### Wear Test Results:

Table: B<sub>4</sub>C (Boron Carbide)

B <sub>4</sub> C 2%	1	200	10	1.20	0.720	0.012
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	1	300	10	1.80	0.028	0.013
	1	400	10	2.40	0.035	0.012
	2	500	10	3.00	0.041	0.011
	4	600	10	1.20	0.017	0.009
<b>B4C 4%</b>	1	200	10	2.40	0.028	0.010
	2	300	10	2.40	0.028	0.010
	3	400	10	3.00	0.033	0.010
	4	500	10	1.20	0.014	0.009
<b>B4C 6%</b>	1	200	10	1.80	0.018	0.008
	1	300	10	2.40	0.023	0.008
	2	400	10	3.00	0.025	0.008
	4	500	10	3.00	0.025	0.007

Table: Tio2 (Titanium Dioxied)

(Tio2 )wt%	Load (Kg)	Speed (Rpm)	Time (min)	Sliding Speed (m/s)	Sliding Distance (m)	Mass Loss (g)
<b>Tio2 2%</b>	1	200	10	1.20	0.720	0.011
	1	300	10	1.80	0.028	0.0131
	1	400	10	2.40	0.035	0.011
	2	500	10	3.00	0.041	0.012
	4	600	10	1.20	0.017	0.009
<b>Tio2 4%</b>	1	200	10	2.40	0.028	0.010
	2	300	10	2.40	0.028	0.010
	3	400	10	3.00	0.033	0.008
	4	500	10	1.20	0.014	0.009
<b>Tio2 6%</b>	1	200	10	1.80	0.018	0.007
	1	300	10	2.40	0.023	0.008
	2	400	10	3.00	0.025	0.009
	4	500	10	3.00	0.025	0.009

## 6. CONCLUSION

The study demonstrates that reinforcing AL6061 with B<sub>4</sub>C and TiO<sub>2</sub> significantly improves its mechanical and tribological properties. Microstructural analysis confirmed uniform dispersion of the reinforcements and good bonding with the aluminum matrix, while excessive reinforcement led to minor particle clustering. Hardness and tensile strength increased notably with the addition of B<sub>4</sub>C, whereas TiO<sub>2</sub> contributed primarily to reducing wear rate and friction. The combined addition of B<sub>4</sub>C and TiO<sub>2</sub> provided a balanced enhancement, and optimization revealed that 4 wt% B<sub>4</sub>C with 2 wt% TiO<sub>2</sub> achieves the best overall performance. These findings indicate that hybrid reinforcement of AL6061 can produce lightweight, high-strength, and wear-resistant composites suitable for demanding applications in automotive, aerospace, and industrial components.

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