

# Influence of Tib2 Wt. % on the Microstructural and Mechanical Properties of In-Situ Processed Stir-Cast Metal Matrix Composite of Al-6061

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## Abstract

Currently, there is an increasing trend in the automotive and aerospace industries towards the adoption of lighter and stronger materials to reduce weight and enhance fuel efficiency. Metal matrix composites must be developed in order to increase the overall performance of automobiles and aircraft as a result of this transition. Among the various composite materials employed, Aluminium Matrix Composites (AMCs) are frequently utilised to meet stringent industrial requirements. The purpose of this study is to gain a better understanding of the mechanical characteristics and microstructure of an in-situ processed stir-cast metal matrix composite of Al-6061/x weight percent TiB<sub>2</sub>. The material under investigation is an in-situ composite made of aluminum in which the reinforcement, TiB<sub>2</sub>, is produced in the molten alloy by a salt reaction between K<sub>2</sub>TiF<sub>6</sub> and KBF<sub>4</sub>. The optical microstructure study of the 2.5 wt% composites revealed a uniform distribution of reinforcements throughout the matrix. Moreover, the formation of reinforcement clusters within the matrix is seen when the weight proportion of the reinforcements grows. These occurrences are attributed to additional obstructions formed during stirring, which restrict the fluidity of the TiB<sub>2</sub> particles inside the matrix. Along with microstructure homogeneity, increasing the weight percentage of in-situ TiB<sub>2</sub> particles up to 2.5% enhanced the composite's tensile strength without significantly reducing elongation. Additionally, when the weight percentage of TiB<sub>2</sub> particles is increased to 2.5%, the hardness of the cast materials rises by 42%.

**Keywords:** Al-6061-TiB<sub>2</sub>, metal matrix composite, stir casting, microstructure; mechanical properties

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## INTRODUCTION

Metal matrix composites (MMCs) have evolved as a significant material class with unique characteristics that make them valuable for structural, thermal, and wear applications [1]. Several manufacturing techniques produce Al-metal matrix composites (AMCs), including powder metallurgy, semi-solid, and liquid-state methods [2]. Stir casting is a common liquid-state process for fabricating composite materials in which reinforcement particles are homogeneously incorporated into a liquid matrix metal via mechanical stirring [3]. The stir casting process, known for its ease of manufacture and cost-effectiveness, remains a widely studied technology for producing AMCs. It effectively combines the metallurgical qualities of the matrix and reinforcements, making it suitable for applications like liners for cylinders, gear components, pistons, roller skates, brakes, frames of bicycles, baseball shafts, etc. [3].

The reinforcement of ceramic particulates with aluminium alloys can assist with strengthening processes like grain refinement, higher dislocation density due to thermal instabilities between the matrix and reinforcements, and load transmission from the aluminium to the reinforcements [4-6]. The most generally used ceramic particle reinforcements in AMCs include titanium carbide, boron carbide, titanium diboride, aluminium oxide, and silicon carbide [7]. However, titanium diboride offers several advantages over other ceramic particles [8]. For instance, silicon carbide reacts with the aluminium matrix, forming a brittle metallic phase at the interface known as aluminium carbide. This reaction detrimentally affects the mechanical properties of aluminium matrix composites, particularly at elevated temperatures [9].

Similarly, the magnesium within the matrix reacts with aluminium oxide to form aluminium magnesium oxide [10]. In contrast, titanium diboride is thermodynamically stable in molten aluminium, allowing the fabrication of aluminium-titanium diboride composites using both solid-state and liquid-state techniques [4]. The combination of titanium diboride's excellent material properties have led to its widespread use in high-temperature structural and functional applications for the aeronautics, automobiles, and other industries. Furthermore, the external addition of reinforcement particles to molten metal, known as ex-situ processing, often leads to the clustering of particulates within the matrix, significantly reducing the mechanical properties of the resulting composites. The primary underlying factor for the reinforcement's non-uniform distribution is an insufficient wetting agent between the ceramic particulates and the matrix [11]. This issue can be addressed by the in-situ formation of the reinforcement within the matrix, which decreases surface tension and interfacial forces. Researchers have explored various in-situ synthesis methods, such as reactions involving halide salts of  $K_2TiF_6$  and  $KBF_4$  [7], master alloy addition method [12], and exothermic reactions [12]. These in-situ composites have demonstrated superior mechanical properties compared to base alloys.

This study aims to produce in-situ  $TiB_2$  particles by adding inorganic salts of  $K_2TiF_6$  and  $KBF_4$  salts to a pure Al matrix. The stir casting process is used to manufacture Al- $TiB_2$  in-situ composites by varying weight percentages of  $TiB_2$  (0, 2.5, 5 wt.%) were evaluated for their microstructural and mechanical properties. The novelty lies in utilising economically available halide salts and exploring the potential for industrial applications.

## MATERIAL AND METHODS

Al-6061 aluminium alloy has been selected for the fabrication of metal matrix composite. Al-6061 alloy consists of major alloying elements like magnesium and silicon and small traces of zinc, copper, chromium, nickel and iron. The chemical composition of the alloy, as obtained through spectroscopic analysis, is furnished in Table 1. Additionally, the salts of  $K_2TiF_6$  and  $KBF_4$  are tabulated in Table 2.

**Table 1.** Chemical composition of Al-6061.

Elements	Mg	Si	Cr	Mn	Ti	Cu	Fe	Zn	Ni	Al
Wt.%	0.9	0.4	0.2	0.15	0.15	0.25	0.7	0.25	0.05	96.95

**Table 2.** Calculated weight of the salts for various percentages of  $TiB_2$  formation.

Wt%	2.5	5
$K_2TiF_6$ (g)	181	362
$KBF_4$ (g)	173	345

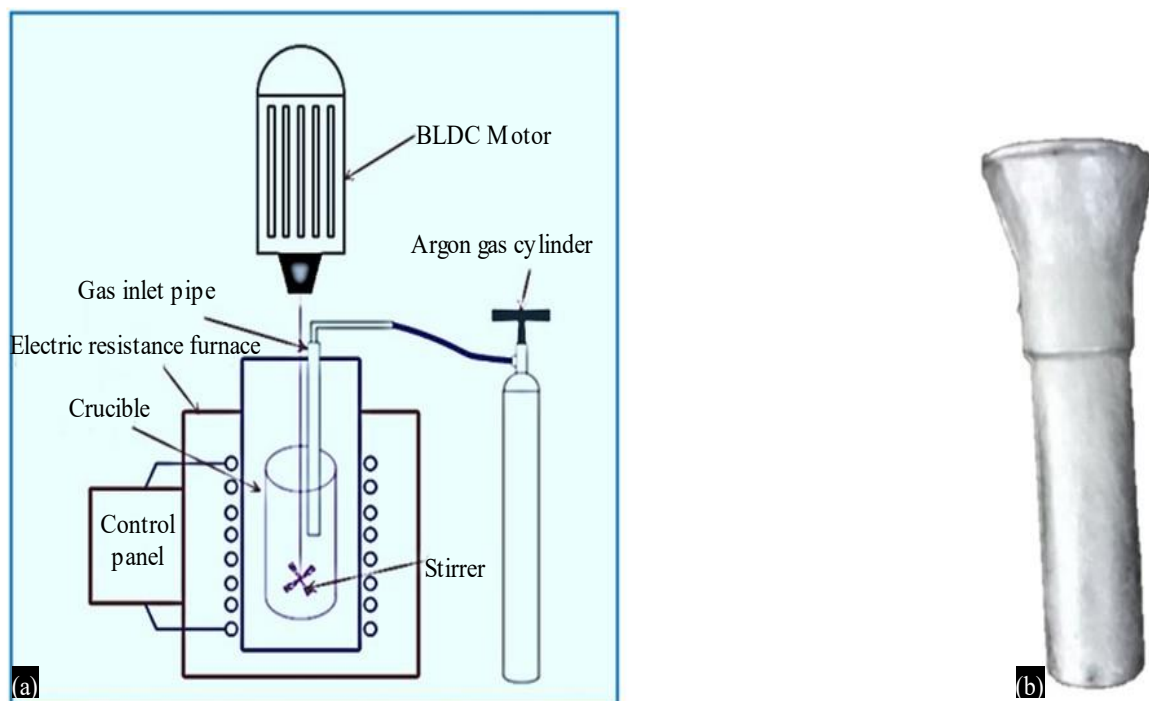
The matrix material, i.e., aluminium alloy Al-6061 (2Kg), was melted at 750°C using an electric resistance furnace in a graphite crucible, as shown in Figure 1(a). A suitable material covered the setup to avoid the absorption of gases into the melt. The melt was then held isothermally for 20 minutes for melt homogenization. The ready-mixed halide inorganic salts of  $K_2TiF_6$  and  $KBF_4$ , stoichiometrically calculated to form X amount of  $TiB_2$ , were preheated in an aluminium foil at 200°C temperature for an hour to remove the moisture.

After the melt homogenization, preheated reinforced particles were added to molten metal and stirred intermittently with the help of a four-blade stainless steel mechanical stirrer for 60 minutes for the in-situ reaction to occur and to distribute the reinforcement particles throughout the matrix. To enhance the wettability, 1% by weight of pure magnesium was added to the molten Al-6061 matrix. Adding magnesium improved the reinforcement's wettability by reducing the molten metal's surface tension. Further, the addition of magnesium beyond 1% to the melt altered its viscosity, affecting its material properties and preventing improper dispersion [4]. Degassing tablets of hexachloroethane ( $C_2Cl_6$ ) were added to the molten metal to degas the melt. The process of creating in-situ endogenous  $TiB_2$  particles involves inducing a chemical reaction in the melt of inorganic salts and can be expressed as:



The composite melt was poured into a cast iron mould, which was preheated at  $250^\circ C$  after removing the slag. The cast iron mould's dimensions are  $(170 \times 80 \times 80)$  mm. To ensure reproducibility, the experiment was performed three times for each run, yielding three cylindrical cast billets of  $60 \text{ mm} \times 120 \text{ mm}$  (see Figure 1(b)). A similar method was utilized for comparative analysis to obtain an as-cast billet of Al-6061 aluminium alloy.

The samples were prepared metallographically from the cast billets for microstructural investigation per the standard metallographic technique as per ASTM E3-95 standards, i.e., processing with various grades of SiC emery papers with grit sizes ranging from 180 to 2000. Further processing of the samples was done using a double disc polishing machine (Meta-Tech). Mirror polish was obtained with the help of diamond paste ( $3\text{-}0.5 \mu\text{m}$ ), polishing velvet cloth, and polishing lubricant. Finally, using Keller's reagent (1 vol.% HF, 15 vol.% HCl, 2.5 vol.%  $HNO_3$ , and distilled water), the acetone-washed specimens were etched.



**Figure 1.** (a) Schematic diagram of stir casting setup, (b) Cast billet.

## SAMPLE CHARACTERIZATION

Metallographic observations were conducted using an optical microscope (Zeiss, Axio Imager model). Hardness tests were performed with a Vickers microhardness tester (Metatech) using a 50N load and a 15-second dwell time for indentation. For every sample, ten measurements were obtained, and the mean values were reported. In accordance with ASTM E8 standards, three tensile samples were obtained from each cast billet, and the tensile tests were done using a universal testing machine with a 0.5 mm/min strain rate. Figure 2 displays the tensile specimens' dimensions.

## RESULTS AND DISCUSSION

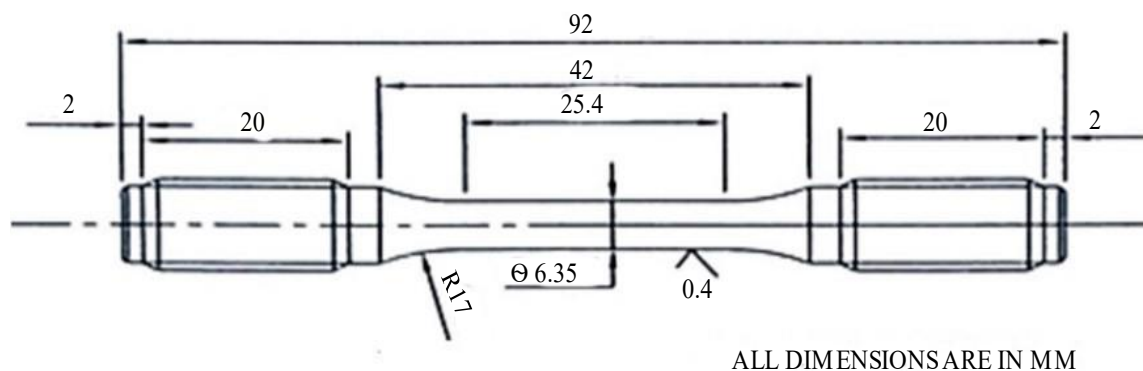
### Effect of Wt.% of Tib2 on The Microstructural Characteristics of The Cast Composite

Figure 3 shows the optical microstructure of the as-cast aluminium alloy and the Al-TiB<sub>2</sub> composite with varying wt.%. The parameters of stir casting were optimized as previous work of the same groups of authors [13]. Figure 3(a) illustrates the as-cast microstructure of the Al-6061 alloy employed as the matrix material. The optical microstructure comprises a coarser primary phase, and needle and elongated Al-Mg-Si ternary eutectic phases dispersed in  $\alpha$ -phase boundaries. Furthermore, in some areas within the primary grains of aluminium alloy and at the primary grains' boundaries, Mg<sub>2</sub>Si precipitates are observed. These Mg and Si-rich intermetallic phases induce stress concentration, which deteriorates the mechanical properties [14]. Figure 3(b)-(c) show the microstructures of stir-cast composites with varying weight percentages of TiB<sub>2</sub> reinforcement. Micrographs show TiB<sub>2</sub> particles as black spots surrounded by a white  $\alpha$  matrix. The microstructure reveals that in the case of 2.5 wt.% of TiB<sub>2</sub>, the reinforcement particles are well distributed throughout the matrix. The aluminium matrix of the reinforced cast composite exhibits a finer grain size than the as-cast aluminium alloy. This is attributed to the kinetics involved in the formation of TiB<sub>2</sub> within the matrix during solidification

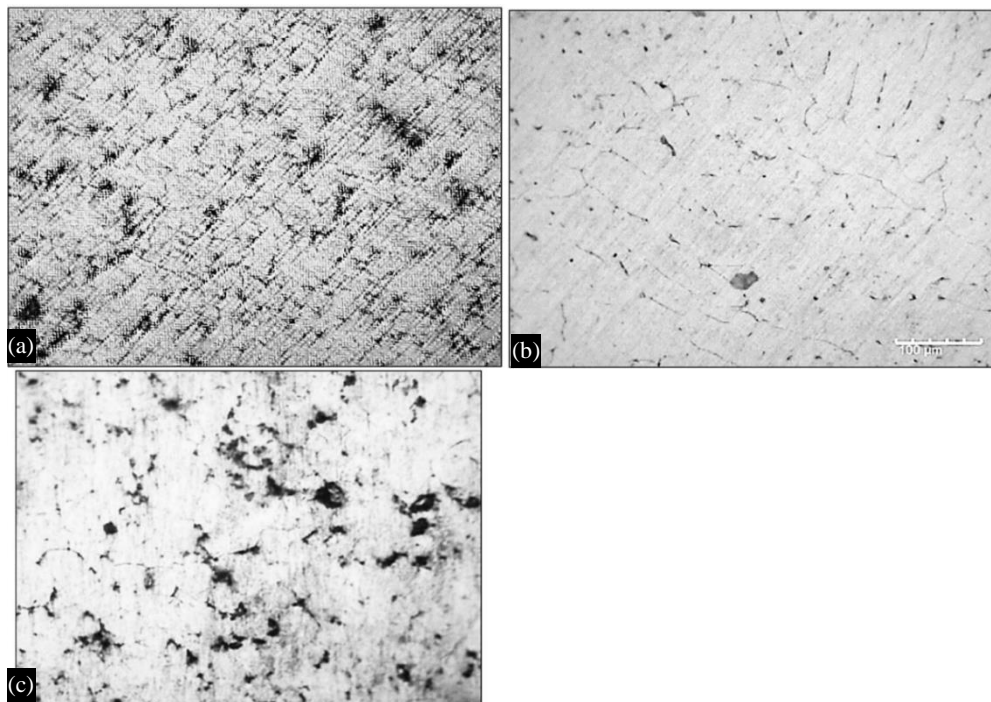
Further, in the case of 2.5 wt.% of the reinforcement, the quantity of observable TiB<sub>2</sub> particles in the matrix is less, and the grain size of the aluminium matrix remains relatively fine compared to that of 5 wt.% reinforced composites. Additionally, some regions in the 5 wt.% reinforced composite displays clustering and agglomeration of TiB<sub>2</sub> particles.

### Effect of Wt.% of Reinforcement on The Tensile Properties of The Composite

Figure 4 illustrates the mechanical properties of as-cast aluminum alloy 6061 and Al-6061-TiB<sub>2</sub> cast composites with varying wt.% of TiB<sub>2</sub>. The findings reveal that increasing TiB<sub>2</sub> content enhances the ultimate tensile strength (UTS) but reduces ductility. The as-cast aluminum alloy 6061 exhibits a low UTS of 190 MPa and high ductility of 4.64%. For composites with 2.5 and 5 wt.% TiB<sub>2</sub>, the UTS values show respective improvements of 22% and 20%, alongside a reduction in ductility of 15% and 23% compared to the base alloy. The 2.5 wt.% TiB<sub>2</sub> composite demonstrates the highest UTS output of 232 MPa, though with reduced ductility of 3.6%. This increase in UTS is attributed to the load-bearing capacity of the reinforcement particles, which enhance resistance to crack propagation.

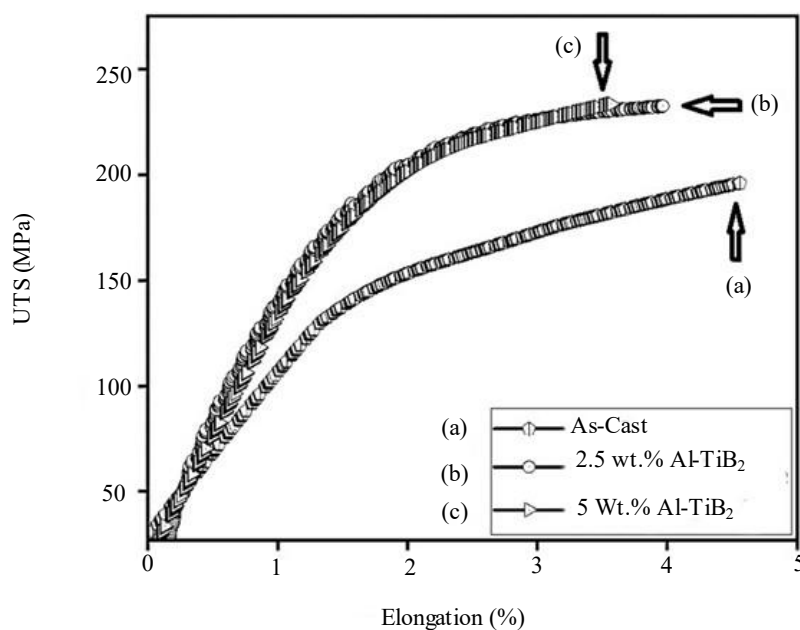


**Figure 2.** Dimensions of the tensile specimen as per ASTM E8.

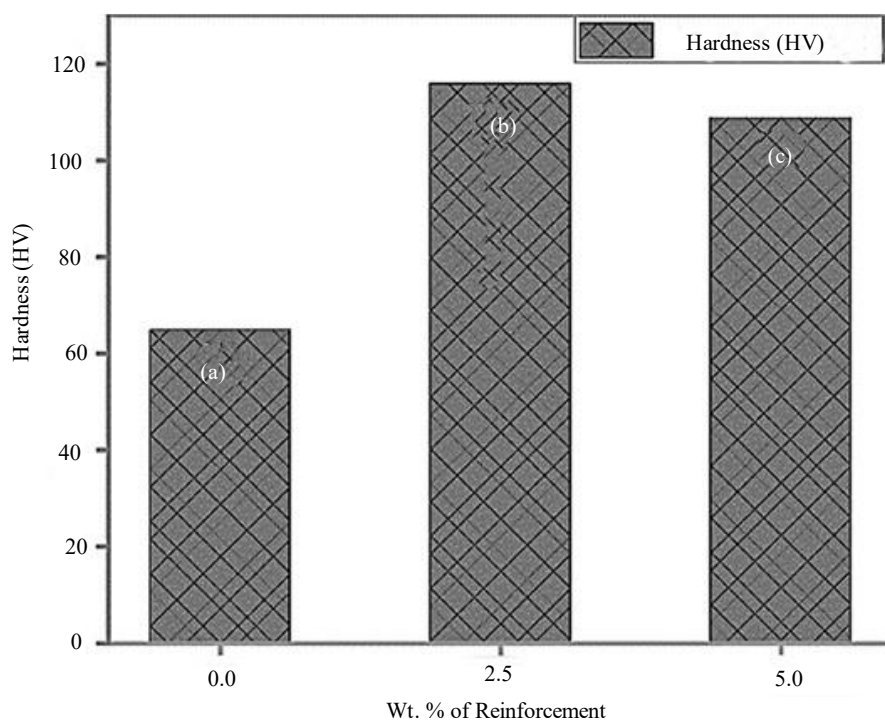


**Figure 3.** Microstructural evaluation of (a) As-cast aluminium alloy, (b) 2.5 wt.% reinforced Al-TiB<sub>2</sub> composite, (c) 5 wt.% reinforced Al-TiB<sub>2</sub> composites.

The rise in tensile strength primarily results from the reinforcement particles that impede dislocation motion and reduce plastic deformation. Higher particle concentrations lead to increased dislocation density, limiting plastic flow in the matrix under applied load. These hard particulates accumulate dislocations, which interact with the reinforcement and grain boundaries, thereby strengthening the alloy. The shear-lag theory explains the higher strength of composites compared to the unreinforced matrix due to the transfer of load from the matrix to reinforcement particles at composite surfaces. The reinforcing phase, TiB<sub>2</sub>, plays a crucial role as a load-bearing component in the matrix, facilitating efficient load transmission.



**Figure 4.** Tensile properties of (a) As-cast aluminium alloy, (b) 2.5 wt.% reinforced Al-TiB<sub>2</sub> composite, (c) 5 wt.% reinforced Al-TiB<sub>2</sub> composites.



**Figure 5.** Hardness of (a) As-cast aluminium alloy, (b) 2.5 wt.% reinforced Al-TiB<sub>2</sub> composite, (c) 5 wt.% reinforced Al-TiB<sub>2</sub> composites

#### Effect of Wt.% of Reinforcement on The Hardness of The Composite

Figure 5 illustrates Vickers' hardness values for aluminium (Al) and aluminium-titanium di-boride (Al-TiB<sub>2</sub>) in-situ composites. A substantial enhancement in hardness is observed, with improvements of 78% and 70% achieved when incorporating 2.5 wt.% and 5 wt.% TiB<sub>2</sub> in-situ composites, respectively. This increased hardness results from hard particles being incorporated into a flexible matrix to generate composite materials with high hardness levels. The inclusion of hard TiB<sub>2</sub> enhances the matrix material's resistance to deformation [15]. Additionally, the uniform distribution of in-situ TiB<sub>2</sub> particles in the Al matrix and the particulate strengthening effect contribute to an increase in hardness. [14].

#### CONCLUSIONS

The study synthesized an Al-6061-TiB<sub>2</sub> composite with varying TiB<sub>2</sub> percentages using inorganic halide salts of KBF<sub>4</sub> and K<sub>2</sub>TiF<sub>6</sub> with Al-6061 alloys. The research examined the impact of TiB<sub>2</sub> content on the composites' microstructures and mechanical properties like hardness and ultimate tensile strength. The following inferences can be acquired from this investigation.

1. The microstructural investigation of the composite shows the formation of very fine TiB<sub>2</sub> particles.
2. TiB<sub>2</sub> particles are evenly dispersed across grain boundaries and throughout the  $\alpha$ -Al matrix grains. Moreover, particles with a higher TiB<sub>2</sub> level have a tendency to cluster.
3. Introducing TiB<sub>2</sub> particles as a reinforcement material into the matrix, i.e., Al-6061 aluminium alloy, enhances the microhardness compared to the base matrix alloy by up to 78%.
4. The tensile properties show that the fabricated composite's tensile strength increased by 22%. Additionally, the elongation percentage decreases marginally with the increased percentage of TiB<sub>2</sub> particulates.

#### DISCLOSURE STATEMENT

The authors reported no financial or non-financial conflict of interest.

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