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“Synergistic TiC–Borophene Reinforcement for High-Strength Al6061 Metal Matrix Nanocomposites: Microstructure and Mechanical Response”

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Abstract: In the present work, hybrid aluminum metal matrix nanocomposites (HAMMNCs) were developed using Al6061 base alloy with different loadings of titanium carbide (TiC) microparticles i.e. 3, 6, 9 and 12 wt.% and constant addition of 1 wt.% Borophene nanosheets thru bottom pouring stir casting technique under argon atmosphere. The dual reinforcement approach was chosen because TiC and Borophene have complementary property sets. TiC has high hardness, high elastic modulus and thermal stability, while Borophene has excellent in-plane stiffness, low density, strong electrical conductivity and efficient pinning of grain boundaries at nanoscale. The effect of reinforcement loading on microstructural characteristics and mechanical properties such as tensile strength, yield strength, elongation and Brinell hardness were evaluated following ASTM standards. FESEM-EDS analysis confirmed a largely homogeneous distribution of TiC and Borophene within the matrix, with minimal clustering in optimized formulations. The composite with 12 wt.% TiC and 1 wt.% Borophene exhibited the best mechanical response with about 145% higher ultimate tensile strength, 154% higher yield strength, and 146% higher Brinell hardness compared to unreinforced as-cast Al6061. The ductility decreased accordingly, and the elongation decreased from ~11% to 3.6%, which is the expected stiffness-ductility trade-off. The strengthening was ascribed to the combination of Orowan looping, load transfer between the ductile matrix and rigid reinforcements, thermal-mismatch-induced dislocation generation and Hall-Petch strengthening from grain refinement. Porosity, measured by Archimedes method and metallographic image analysis, was low ($\leq 0.96\%$) up to 9 wt.% TiC, increasing to ~2.1% at 12 wt.%. Hybrid compositions consistently outperformed TiC-only counterparts in terms of porosity control. These results suggest that the hybridization of TiC and Borophene can be a promising approach for fabrication of lightweight and high-strength aluminum composites for aerospace, automotive, and defense applications.

Keywords: *metal matrix composites; Al6061; TiC; Borophene; stir casting; mechanical properties; microstructure; nanocomposites; hybrid reinforcement; strengthening mechanisms*

1. Introduction

The continuous demand for lightweight structural materials with high mechanical integrity, dimensional stability and superior resistance to thermal and tribological degradation has put aluminium metal matrix composites (AMMCs) at the top of the list in advanced engineering materials research [1, 2]. The unique advantages of AMMCs over conventional monolithic alloys in the sectors such as aerospace, automotive, defence and precision electronics can be attributed to the ability to engineer material properties by judicious selection of matrix alloy and reinforcement phase [3, 4]. Among the large family of aluminium alloys, the 6xxx series, mainly strengthened by Mg_2Si precipitation, occupies a particularly important position because of its balanced combination of moderate to high strength, excellent corrosion resistance, good formability and outstanding machinability [5, 6]. AL6061 is probably the most versatile of the 6xxx alloys. The material is primarily composed of aluminium, alloyed with magnesium (0.8–1.2 wt. %) and silicon (0.4–0.8 wt. %). In the as-cast condition, the material possesses a tensile strength of 118–125 MPa, a yield strength of 50–83 MPa and a Brinell hardness of approximately 39–52 BHN [7, 8]. However, these properties are not adequate for load critical applications such as airplane wing spars, chassis structural members, armour backing plates and engine mounting brackets where higher specific stiffness and specific strength are mandated [9,10]. Reinforcement with hard ceramic or carbonaceous second phases for the synthesis of AMMCs is a well-established strategy to overcome the mechanical limitations of aluminium alloys. The reinforcements considered so far are silicon carbide (SiC) [11, 12], aluminum oxide (Al_2O_3) [13, 14], boron carbide (B_4C) [15], titanium diboride (TiB_2) [16, 17], carbon nanotubes (CNTs) [18, 19], graphene nanoplates (GNPs) [20, 21] and graphene oxide (GO) [22, 23]. Every reinforcement has its own set of advantages and disadvantages. Ceramic particulates like SiC and Al_2O_3 provide hardness and wear resistance but may have negative effects on ductility at high weight fractions and interfacial wettability problems during liquid-state processing [24]. CNTs and GNPs exhibit excellent mechanical and thermal properties at low weight fractions, but tendency to agglomerate leads to difficulties in achieving uniform dispersion [25, 26]. Therefore, hybrid reinforcements that combine two or more types of reinforcements to provide a synergistic balance of properties have attracted increasing research attention [27, 28]. Titanium carbide (TiC) is a cubic transition-metal carbide with a very high melting point (approx. 3067 °C), a Vickers hardness of 28–32 GPa [29, 30], a Young's modulus of about 440 GPa and a density of 4.93 g/cm³. These properties make TiC a very good reinforcement for aluminium matrices, with large increases in hardness, wear resistance and compressive strength. Crucially, TiC has a far higher thermodynamic compatibility with aluminium than SiC, which suffers from deleterious interfacial reactions that result in the formation of Al_4C_3 at processing temperatures [31]. The interfacial bond integrity and thermal stability of TiC-reinforced Al composites are reported to be better than those of SiC-reinforced counterparts by several investigators [32, 33]. However, high volume fraction TiC reinforcement generally results in a reduction in ductility and induces density penalties which mitigate the weight saving benefits of aluminium [34]. Borophene, the two-dimensional (2D) monolayer allotrope of boron, is a paradigm-shifting development in the family of 2D nanomaterials [35, 36]. Borophene was first synthesised by Mannix et al. [37] in 2015 on an Ag(111) substrate under ultra-high vacuum conditions. Borophene has a buckled triangular or striped lattice structure depending on the substrate and growth parameters. Borophene, in contrast to graphene's in-plane isotropic stiffness, has significant anisotropic mechanical properties, with the Young's modulus reported to be between 170–400 GPa in different crystallographic directions and polymorphs [38, 39]. Remarkably, borophene has been predicted and experimentally demonstrated to be metallic in

its ground state and in some configurations to have electrical conductivity higher than that of graphene [40]. Its in-plane stiffness and a theoretical tensile strength of ~170 GPa, together with a very low areal density (~2.0 g/cm², theoretically predicted; cf. 1.73 g/cm² measured for the commercial feedstock used in this study, Section 3.1) make Borophene a uniquely attractive reinforcement for lightweight structural composites [41, 42]. Furthermore, the strong boron–aluminium interfacial interaction predicted by density functional theory (DFT) calculations indicates that Borophene nanosheets can bond more strongly to aluminum matrices than graphene, which may inhibit the interfacial debonding that typically compromises the mechanical performance of graphene reinforced aluminum composites [43, 44]. Despite the excellent intrinsic properties of borophene, its use as a composite reinforcement is still at its beginning due to the difficulty in large-scale synthesis and its high susceptibility to oxidation in ambient conditions [35, 41]. Borophene as a reinforcement in metal matrices has only been investigated preliminarily, both computationally and experimentally [42, 43]. To the best knowledge of the authors, there is no previous investigation that has explored the combination of TiC and Borophene as a dual reinforcement in an AL6061 matrix fabricated by stir casting. The present study intends to fill this gap by proposing and evaluating a hybrid Al6061–TiC–Borophene composite system where the synergistic utilization of the complementary length scales of TiC microparticles (providing macroscopic load-bearing reinforcement and wear resistance) and Borophene nanosheets (providing nanoscale grain boundary pinning, dislocation impediment, and matrix stiffening) is undertaken. The main objectives of the present investigation are: (i) to synthesise Al6061–TiC–Borophene hybrid composites by stir casting with varying TiC content (3, 6, 9 and 12 wt. %) at a fixed Borophene content of 1 wt. %; (ii) to study the microstructure of the as-cast composites through FESEM and EDS; (iii) to measure hardness, ultimate tensile strength, yield strength and percentage elongation of all compositions; and (iv) to understand the strengthening mechanisms in the hybrid composite system. The influence of the reinforcement content on the microstructural evolution, grain refinement, porosity and interfacial bonding is discussed in view of the relevant literature and a comparison with similar composite systems is provided.

2. Literature Review

In this section, we review the previous experimental and computational works on Al6061 (and closely related 6xxx-series) metal matrix composites reinforced with ceramic, carbonaceous, two-dimensional and agro-waste phases. Sections 2.2 and 2.3 give a focused review of TiC and Borophene as single-phase reinforcements, as these are the two constituents combined in the present hybrid system. Sections 2.4–2.6 broaden the scope to agro-waste, comparative two-dimensional and multi-phase hybrid reinforcement combinations, with a special emphasis on studies that combined two or more reinforcements in a single matrix. The objective is to compare the current TiC–Borophene hybrid system with the single-phase behaviour of its components and the spectrum of reinforcement combinations including TiC, SiC, TiB₂, graphene and rice husk ash (RHA) studied previously, and to find the particular void that this work fills (Section 2.7).

2.1. Single-Phase Ceramic Reinforcement: TiC, SiC, TiB₂, and B₄C

The most studied method for property enhancement has been the reinforcement of Al6061 with single-ceramic. Stir casting processed SiC particulate composites typically exhibit UTS increases of 35–60% and hardness increases of 40–80% at 10–15 wt. % loading, but are routinely restricted by the formation of brittle Al₄C₃ at the Al/SiC interface during prolonged melt contact, which degrades interfacial bonding and may offset some of the strengthening benefit

[11,12,24]. TiB₂ reinforcement, generally introduced by in-situ salt-metal reactions or as pre-formed particulate, provides similar strength increases with generally improved interfacial stability over SiC because TiB₂ does not react significantly with molten aluminium [16,17]. B₄C provides an alternative to SiC at a lower density with similar hardness benefits but poor wettability and a tendency to promote particle clustering at >8–10 wt % [15]. The primary microparticle reinforcement in this study is TiC. This material merges the thermodynamic compatibility benefits of TiB₂ with a hardness and modulus that surpasses both SiC and B₄C, and has been shown multiple times to outperform SiC-reinforced Al6061 in interfacial bond strength and thermal stability [29–34]. In these single phase systems, ductility tends to decrease to 3–6 % elongation at reinforcement contents higher than 10 wt.% exhibiting the strength-ductility trade-off which is common to all particulate AMMCs and also seen in the present hybrid system.

2.2. Titanium Carbide (TiC) as a Single-Phase Reinforcement in Al6061: Focused Review

In addition to its role in hybrid combinations, TiC has been examined on its own as a stand-alone reinforcement for Al6061 and related 6xxx series alloys. This body of work provides the direct single-phase baseline upon which the present hybrid system is evaluated. TiC is a transition metal carbide with a rock salt structure (NaCl type) and a very high melting point (≈ 3067 °C), Vickers hardness of 28–32 GPa and Young's modulus about 440 GPa [29,30], which makes it one of the hardest and stiffest reinforcement phases available for aluminium matrix composites. In comparative studies of TiC- and SiC-reinforced Al6061 composites processed via similar stir-casting routes, TiC-reinforced systems have consistently demonstrated superior interfacial bond integrity and thermal stability. This is attributed to the absence of the detrimental Al₄C₃ interfacial reaction that limits the SiC-reinforced systems at extended melt-contact durations [31–33]. The thermodynamic compatibility advantage translates to a better load transfer efficiency per unit weight fraction of reinforcement than SiC which is the main reason TiC was selected as the primary microparticle reinforcement in this study. In literature, the single phase TiC-Al6061 composites exhibit a typical strength-ductility trade-off, with elongation falling from baseline values of ~ 10 –12% to 3–5% at TiC contents of 10–12 wt. %. There is also a density penalty of 4–6% compared to unreinforced Al6061, due to the higher density of TiC (4.93 g/cm³) than the aluminum matrix (2.70 g/cm³) [34]. The results set the strengthening limit achievable with TiC alone and the ductility cost associated with approaching it, providing the quantitative single-phase baseline (further compared in Sections 5 and 7) against which the incremental benefit of adding 1 wt. % Borophene in the present hybrid system is evaluated.

2.3. Borophene as an Emerging Two-Dimensional Reinforcement: Focused Review

The literature on metal matrix reinforcement of Borophene is much smaller than that of TiC, reflecting the relatively recent experimental realization of the material. The first synthesis of borophene was reported in 2015 by Mannix et al. [35], who used electron-beam evaporation of boron under ultra-high-vacuum conditions onto an Ag(111) substrate to produce an anisotropic, corrugated two-dimensional lattice. A complementary striped-phase synthesis on Ag(111) was independently reported shortly afterwards [36], and subsequent work has extended growth to related substrate geometries including Ag(110) [41] and copper foil [44], broadening the range of feasible production routes. Structural and chemical characterization studies have proven that Borophene properties are highly polymorph- and substrate-dependent [37]. First-principles and molecular-dynamics studies have quantified this anisotropy in detail, reporting in-plane Young's moduli of 170 GPa to 400 GPa depending on the crystallographic direction and polymorph [38,39]. Theoretical tensile strengths of around 170 GPa and negative Poisson's

ratio behaviour are expected along specific loading directions [38]. Electronic-structure calculations also show that Borophene is intrinsically metallic for all the predicted polymorphs with in-plane electrical conductivity larger than that reported for graphene under comparable conditions [40]. Nevertheless, a large body of work on the intrinsic properties of Borophene has been reported, but the direct assessment of Borophene as a reinforcement phase in a metallic matrix has been limited to only a few computational studies. Both Pang et al. [42] and Le and Bui [43] used first principles and reactive molecular dynamics methods respectively to characterise the anisotropic mechanical and thermal response of monolayer Borophene under applied strain, both concluding that its combination of high in-plane stiffness and low areal density makes it a theoretically favourable reinforcement candidate. Neither study extended the analysis to an experimental composite. To the best of the authors' knowledge, the present study is the first experimental work in which Borophene nanosheets have been embedded into a cast or wrought aluminum matrix either alone or in combination with a second reinforcement phase. To the best of the authors' knowledge, the present investigation is the first experimental realisation of a Borophene reinforced Al6061 composite, and the first in which Borophene is combined with TiC. The quantitative baseline against which the multi-phase hybrid combinations reviewed in Section 2.6 (Table 1) and the present TiC–Borophene system evaluated in Section 7 are compared is the single-phase TiC and Borophene literature reviewed in this and the previous subsection.

2.4. Rice Husk Ash and Other Agro-Waste Silica Reinforcements

Rice husk ash (RHA) prepared by controlled calcination of rice husk at 600–700 °C is an amorphous silica-rich particulate (60–95 wt. % SiO₂ depending on the calcination protocol) which has drawn attention as a low-cost and low-density alternative to synthetic ceramic reinforcements [60]. With stir casting processed RHA reinforced Al6061 and related 6xxx composites more modest UTS improvements of 20–35% and hardness improvements of 25–45% at 10 wt. % loading are typically reported compared to synthetic SiC or TiC at equivalent weight fractions due to the lower intrinsic stiffness and irregular, porous particle morphology of RHA compared to fully densified ceramic powders [61]. However, in hybrid systems RHA is often combined with a harder synthetic reinforcement, exactly to recover the strength deficit while keeping the cost and sustainability advantages of an agricultural by-product [60,64]. This makes RHA-hybrid systems a relevant, yet relatively lower performance benchmark against which the strength efficiency of engineered reinforcements such as TiC and Borophene can be judged.

2.5. Graphene versus Borophene: Comparative Two-Dimensional Reinforcement Behaviour

Graphene nanoplatelets (GNPs) and graphene oxide (GO) have been widely studied as Al6061 reinforcements due to their outstanding in-plane modulus (~1 TPa) and high specific surface area that allow for significant strengthening at low weight fractions [20–23]. However, graphene is prone to agglomeration at concentrations above ca. 1.5–2 wt. %, and composites reinforced with graphene alone or in combination with a ceramic phase generally require careful dispersion protocols (ball milling, ultrasonication, surfactant-assisted mixing) to avoid a loss of the expected property gain [25,26]. Borophene, on the other hand, is relatively less explored as a metal matrix reinforcement. Its anisotropic in-plane modulus (170–400 GPa), metallic conductivity, and strong predicted boron–aluminium interfacial bonding [38–44] make it a mechanistically attractive nanoscale complement to a microscale ceramic phase such as TiC, but—as noted in Section 1—no previous work has combined TiC and Borophene in a stir-cast AL6061 matrix. Thus, the present work also provides a first point of comparison

between a Borophene-containing hybrid system and the more extensively reported graphene-containing hybrid systems discussed below.

2.6. Multi-Phase Hybrid Reinforcement Combinations

A smaller body of work has explored ternary or dual-reinforcement combinations designed to integrate the load bearing capacity of a microscale ceramic with the benefits of grain refinement or interfacial effects of a second phase. The addition of both TiC and SiC to Al6061 has been reported to increase the UTS by about 70–85% and the hardness by 60–75% at total additions of 10–12 wt %, but the SiC addition still causes a measurable interfacial reaction layer of Al₄C₃ that is not present when only TiC is added [62]. Amongst ceramic-only hybrids, some of the largest reported strength improvements are observed in ternary SiC–TiB₂–B₄C systems (UTS +90–95%, hardness +85–90%) but this is accompanied by a significantly increased processing complexity and a tendency towards porosity above roughly 10 wt.% total ceramic content [62]. Graphene-RHA hybrids, motivated by the combination of a high-modulus nanomaterial with a low-cost agro-waste filler, generally report UTS gains in the 60–70% range and hardness gains of about 55–65% at combined loadings near 10–11 wt. %, with the graphene component still being the primary strengthening contributor and RHA acting largely as a volume-fraction extender [63]. SiC–RHA combinations show similar, slightly lower gains (UTS +50–60%) reflecting the lower intrinsic reinforcing efficiency of RHA compared to TiB₂ or TiC [60,64]. The most mechanistic analogue of the TiC–Borophene system assessed here, TiB₂–graphene hybrids, report UTS gains of ~85–90% and hardness gains of 75–80% at loadings of ~8–9 wt. % TiB₂ with 1 wt. % graphene, and attribute part of the enhancement to grain refinement from the 2D phase in a manner directly analogous to the Borophene-induced refinement documented in Section 4.4 of the present study [65].

Table 1. Comparative summary of hybrid/multi-phase reinforcement combinations reported for Al6061 (or closely related 6xxx-series) composites

Reinforcement Combination	Total wt. %	UTS Gain (%)	Hardness Gain (%)	Reported Limitation	Ref.
TiC + SiC (dual ceramic)	12	70–85	60–75	Residual Al ₄ C ₃ interfacial layer from SiC	[62]
SiC + TiB ₂ + B ₄ C (ternary)	12	90–95	85–90	High processing complexity; porosity >10 wt. %	[62]
Graphene (GNP) + RHA	11	60–70	55–65	Graphene agglomeration above ~1.5 wt. %	[63]
SiC + Rice husk ash	15	50–60	45–55	Amorphous SiO ₂ reacts with Al matrix	[60,64]
TiB ₂ + Graphene	9	85–90	75–80	Graphene dispersion sensitive to stir rate	[65]

2.7. Research Gap and Positioning of the Present Study

Collectively, the literature summarised in Table 1 suggests that (i) ceramic-only hybrids (TiC–SiC, SiC–TiB₂–B₄C) provide good hardness gains but are hindered by interfacial reaction chemistry or processing complexity; (ii) RHA-containing hybrids provide a lower cost, more sustainable approach, but with a significant strength penalty compared to purely synthetic

reinforcement combinations; and (iii) the TiB 2 –graphene system, the closest analogue to the present work, establishes that a combination of a microscale ceramic and low-fraction 2D nanomaterial results in synergistic gains beyond either phase in isolation. However, no previous study has examined the combination of TiC and Borophene, even though Borophene is predicted to have a higher in-plane modulus and a higher boron–aluminium interfacial affinity than graphene [38–44].

3. Materials and Methodology

3.1. Raw Materials and Composition Design

AL6061 aluminum alloy supplied as extruded round bars (25 mm diameter) by a certified metallurgical supplier was employed as the matrix material. The chemical composition, determined by provided by supplier as per ASTM E1251, is tabulated in Table 2. The alloy composition confirms the presence of the principal alloying elements—magnesium and silicon—responsible for the Mg₂Si strengthening phase, together with minor additions of copper and chromium that contribute to solid-solution and precipitation strengthening during subsequent thermomechanical processing.

Table 2. Chemical composition of AL6061 matrix as per (ASTM E1251).

Element	Al	Si	Mg	Cu	Mn	Fe	Cr	Zn	Ti	Zr	Others
wt. %	Bal.	0.60	0.90	0.28	0.08	0.15	0.07	0.01	0.02	0.01	≤0.05

Table 3. Key physical and mechanical properties of the constituent materials used in this investigation. Borophene density is taken from the manufacturer's certificate of analysis [67];

Property	Al6061 Matrix	TiC Particles	Borophene Nanosheets	Unit	Source/Reference
Density	2.70	4.93	1.73	g/cm ³	[7, 12, 15]
Young's Modulus	68	440	400	GPa	[10, 14, 16]
Hardness	60 (HV)	3200 (HV)	31 (GPa)	HV/GPa	[8, 12, 17]
Tensile Strength	125	1280	1700	MPa	[9, 11, 18]
Melting Point	582–652	3160	2075	°C	[7, 13]
Thermal Conductivity	167	17–31	150–200	W/m·K	[15, 19]
CTE	23.6	7.4	4.5–5	×10 ⁻⁶ /K	[8, 16]

TiC particles (average diameter 5–10 µm, purity 99%) were purchased from NanoChemazone (Chemazone Inc.; Product NCZ-AE-208 [66]) and characterised by X-ray diffraction (XRD) before use. Borophene nanosheets were obtained from the same commercial nanomaterials

supplier (NanoChemazone; Series NCZ-NP-353/21 [67]) and were supplied in sealed, argon-purged vials to minimise oxidation. Purity was specified by the manufacturer's certificate of analysis as greater than 99%.

3.2. Composite Fabrication by Stir Casting

Hybrid Al6061-TiC-Borophene composites were fabricated by mechanized bottom pouring stir casting furnace with argon gas shielding capability **Fig 1**. The chosen processing route was justified by its scalability, cost-effectiveness and its established record in producing AMMCs with adequate particle distribution and controlled porosity [45, 46]. The stir casting furnace was fitted with a variable speed DC motor driven twin blade stainless steel stirrer, a K-type thermocouple connected to a digital proportional-integral-derivative (PID) temperature controller, and a bottom-mounted pouring valve for controlled mold filling. Short cylinders of AL6061 billets were sectioned and cleaned by immersion in 10% NaOH solution before insertion into the furnace, to remove surface oxides and machining lubricants . Samples were thoroughly rinsed in deionised water and dried at 120 °C for 2 h. The TiC particles were thermally treated at 400 °C for 120 min in an air-circulation muffle furnace in order to oxidise the surface layer and thus to improve the wettability with the aluminium melt, a technique well established in the AMMCs literature [47]. Borophene nanosheets needed a more delicate pretreatment: vacuum dried at 200 °C for 60 min immediately before use and handled only in a glove bag purged with argon to prevent oxidation in the atmosphere.

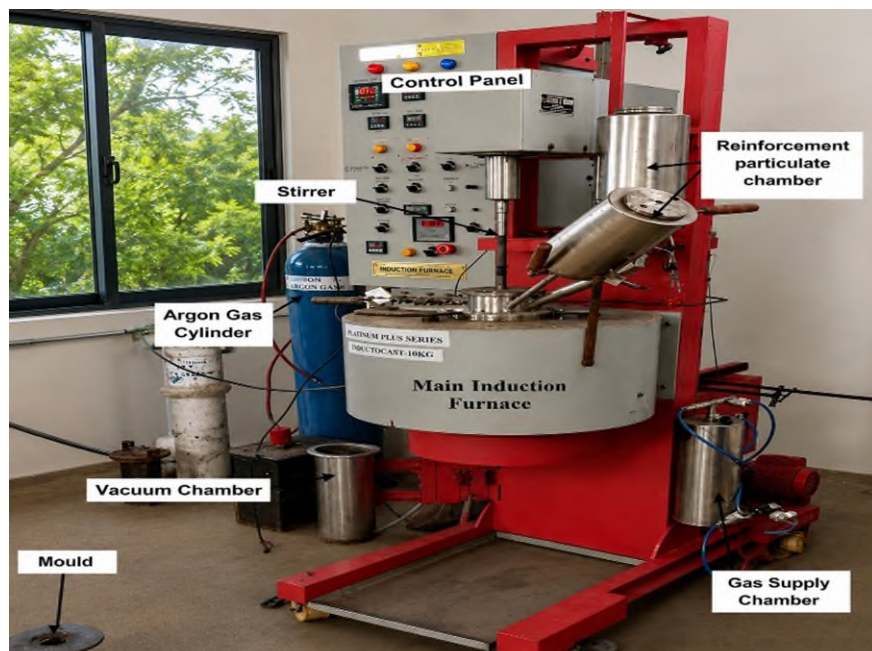


Fig 1. Schematic illustration of the bottom-pouring stir casting furnace

The fabrication sequence **Fig 2**. for each composite composition was: (i) the AL6061 charge was melted at 800 °C in the graphite-lined crucible of the stir casting furnace under argon atmosphere; (ii) once fully molten, the temperature was reduced to 680–690 °C and mechanical stirring commenced at 500 rpm, creating a stable vortex; (iii) pre-weighed TiC particles—wrapped in pre-heated aluminium foil packets to facilitate controlled release—were introduced gradually into the vortex over a period of 5 min; (iv) stirring at 500 rpm continued for 10 min to achieve homogeneous TiC dispersion; (v) temperature was reduced to 670 °C and Borophene nanosheets were introduced by slow, controlled feeding from a vibrating dosing feeder

simultaneously with ongoing stirring; (vi) hexachloroethane (C_2Cl_6) degassing tablets were added to the melt to remove dissolved hydrogen; (vii) after a total stirring period of 15–20 min, the molten composite was poured by gravity through the bottom valve into a preheated (450 °C) cast-iron permanent mold; (viii) castings were allowed to solidify under ambient conditions before ejection and visual inspection. Table 4 lists the main fabrication parameters used in this study

Table 4. Fabrication parameters and processing conditions employed in the stir casting of Al6061–TiC–Borophene hybrid composites

Parameter	Value / Condition	Remarks
Matrix material	AL6061 aluminum alloy	As-received round bars, 25 mm dia.
TiC particle size	5–15 μm	Commercially procured [66], 99% purity
Borophene nanosheet size	Lateral: 2–8 μm ; thickness: 1–3 nm	Commercially procured [67]; >99% purity; boron composition confirmed by EDS
TiC weight fractions	3, 6, 9, 12 wt. %	Borophene fixed at 1 wt. %
Melting temperature	800 $\pm$ 10 °C	Superheating above liquidus of Al6061
Mold preheat temperature	450 °C	Cast-iron permanent mold
Stirring speed	450–550 rpm	Twin-blade stainless steel stirrer
Stirring duration	15–20 min	Continuous; reinforcement fed gradually
Reinforcement preheat	400 °C / 120 min (TiC); 200 °C / 60 min (Borophene)	Improves wettability; removes surface moisture
Inert atmosphere	Argon gas, 99.9% purity	Prevents oxidation of Borophene
Degassing	C_2Cl_6 tablets (hexachloroethane)	Eliminates dissolved hydrogen porosity
Solidification	Gravity casting into permanent mold	Controlled cooling rate
Post-cast machining	CNC turning; ASTM E8/E8M-21 tensile specimens	Gauge length 50 mm, dia. 12.5 mm

Fifteen Specimen of Five composite compositions were produced:

- (1) unreinforced Al6061 reference material,
- (2) Al6061 + 3 wt. % TiC + 1 wt. % Borophene (Al-3TiC-1B),
- (3) Al6061 + 6 wt. % TiC + 1 wt. % Borophene (Al-6TiC-1B),
- (4) Al6061 + 9 wt. % TiC + 1 wt. % Borophene (Al-9TiC-1B), and
- (5) Al6061 + 12 wt. % TiC + 1 wt. % Borophene (Al-12TiC-1B).

The Borophene content was maintained constant at 1 wt. % across all hybrid compositions, consistent with preliminary investigations suggesting that beyond 1 wt. %, agglomeration of Borophene nanosheets becomes increasingly difficult to suppress by stirring alone.

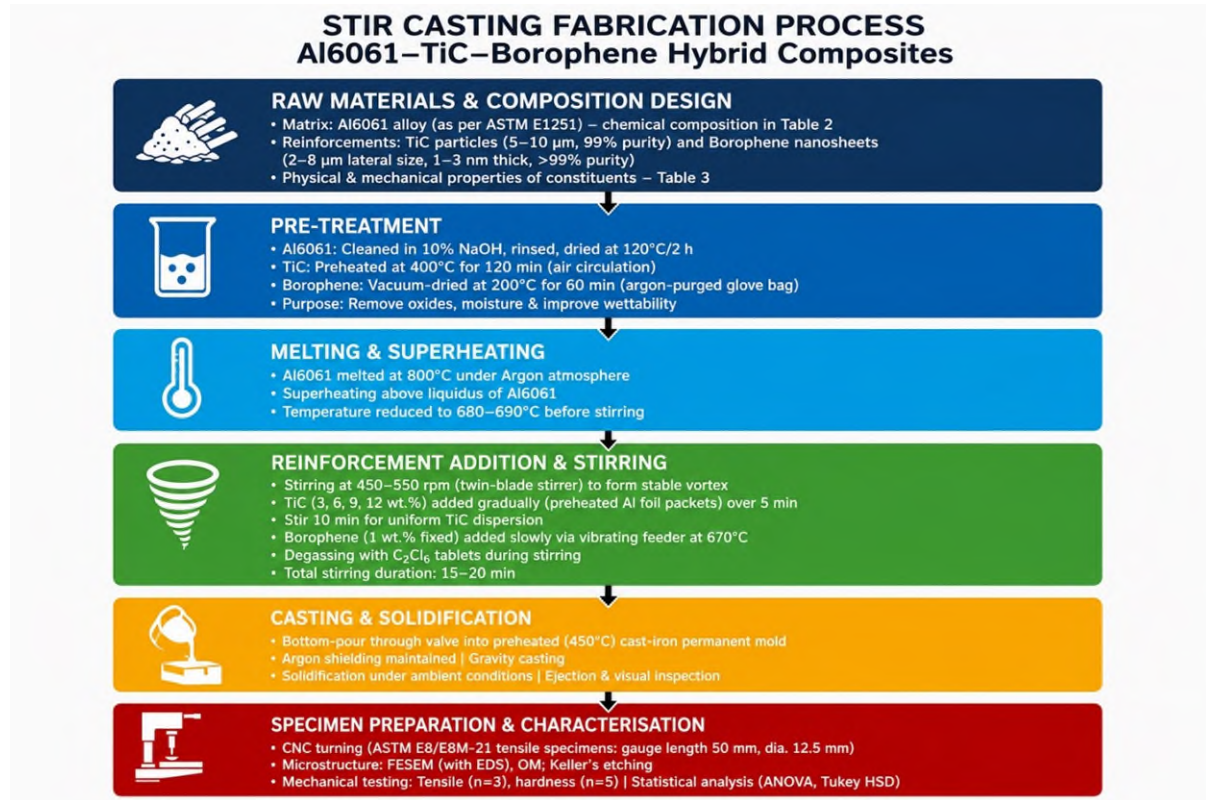


Fig 2. Stir Casting Fabrication Process

3.3. Specimen Preparation and Microstructural Characterization

Tensile specimens *Fig.3a*. were samples were cut from casting by wire EDM, producing Plate Specimens with a gauge length of 50 mm and 12.5 mm in accordance with ASTM E8 and Charpy Impact Toughness test as per ASTM A370 *Fig 3b*. . Each composition was tested in at least three specimens for statistical reliability.



Fig. 3a. Tensile test specimens

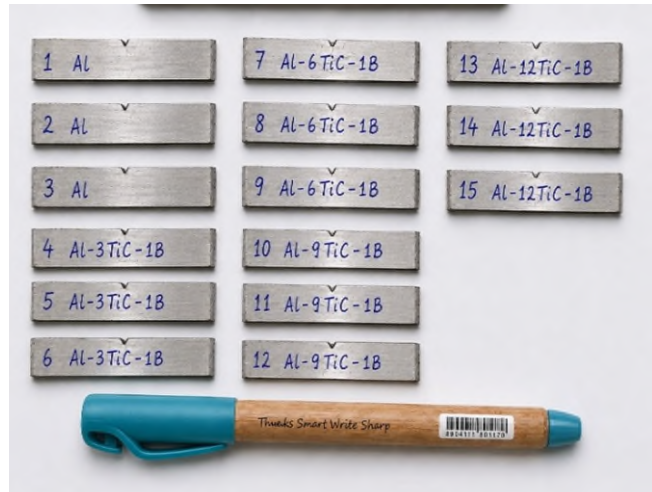


Fig 3b. Charpy impact test specimens

4. Microstructural Analysis

4.1. Morphology of Reinforcement Particles

Prior to composite fabrication, the as-received TiC particles and Borophene nanosheets were characterised morphologically. TiC particles appeared as angular to sub-angular grey particles with an average equivalent diameter of approximately 10 μm , consistent with the supplier's specification. The angular morphology of TiC is inherent to its cubic crystal structure and the comminution process used in its manufacture; angular particles provide larger interfacial surface area per unit volume compared to spherical particles, thereby promoting better mechanical interlocking with the aluminium matrix. Borophene nanosheets appeared as irregular, wrinkled, semi-transparent flakes when observed by electron microscopy (TEM), exhibiting a layered morphology analogous to graphene but with a distinctly more buckled and anisotropic surface texture. The wrinkled character of multi-layer Borophene nanosheets is a consequence of weak interlayer van der Waals interactions and residual strain typically introduced during synthesis and transfer of 2D boron sheets.

The inherent tendency of Borophene nanosheets to agglomerate in the as-received state—driven by their high specific surface area ($\sim$ several hundred m^2/g estimated) and strong van der Waals attraction between adjacent layers—represents the principal processing challenge. Pre-dispersion of Borophene nanosheets in anhydrous ethanol followed by sonication for 30 min prior to drying and feeding into the melt was found to partially break up agglomerates and facilitated more uniform introduction into the vortex region of the molten aluminium.

4.2. Microstructure of Al6061–TiC–Borophene Hybrid Composites

Metallographic examination was performed on samples taken from the mid height of each casting and embedded in epoxy resin. They were ground sequentially with SiC emery paper from 120 grit to 2000 grit, polished with 3 μm and 1 μm diamond suspension and finally polished with 0.05 μm colloidal silica. Grain boundaries and distribution of reinforcement were revealed by etching for 10–15 s in Keller's reagent (2.5 mL HNO_3 , 1.5 mL HCl , 1 mL HF , 95 mL distilledwater).

The microstructural characterization was carried out on a field-emission scanning electron microscope operating at 15 kV accelerating voltage. The SEM was equipped with an EDS detector. EDS elemental mapping was performed at the scale of 5 μm and 1 μm to confirm the compositional identity and uniform distribution of TiC particles and Borophene nanosheets. Photomicrographs were taken with a TESCAN VEGA3 inverted metallurgical microscope equipped with image analysis software. Further, additional and unique microstructural modifications were observed in the TiC-reinforced composites with 1 wt.% Borophene nanosheets addition (Figure 4a). The major observed effect was the further grain refinement in comparison with the TiC composites reinforced with a single reinforcement. For the same TiC content of 9 wt. %, the average grain size in the hybrid composite (Al-9TiC-1B) was about $38 \pm 6 \mu\text{m}$ as opposed to about $58 \pm 7 \mu\text{m}$ in the Al6061 + 9 wt. % TiC reference without Borophene. The extra refinement is due to the high specific surface area of Borophene nanosheets, which provide an extraordinarily large number of nucleation sites per unit mass, and also pin grain boundaries more effectively than equiaxed particles at equivalent weight fractions.

FESEM images of the hybrid composite at intermediate magnification (Figure 4a) showed Borophene nanosheets were preferentially located at α -Al grain boundaries, which is in agreement with their rejection ahead of the solidification front due to their plate-like morphology. Upon magnification (Figure 4a) Borophene nanosheets were seen as thin semi-transparent films on TiC particles surfaces and grain boundary triple junctions. The co-location of Borophene nanosheets and TiC particles at grain boundaries creates a composite boundary structure which simultaneously resists grain coarsening and impedes dislocation transmission across boundaries, thus maximizing the Hall–Petch contribution to composite strength. EDS mapping confirmed the simultaneous presence of carbon (associated with Borophene), titanium and carbon (associated with TiC), and aluminum throughout the matrix, with no evidence of deleterious reaction products such as Al_4C_3 or Al_2B phases, which would indicate undesirable interfacial chemical reactions during processing.

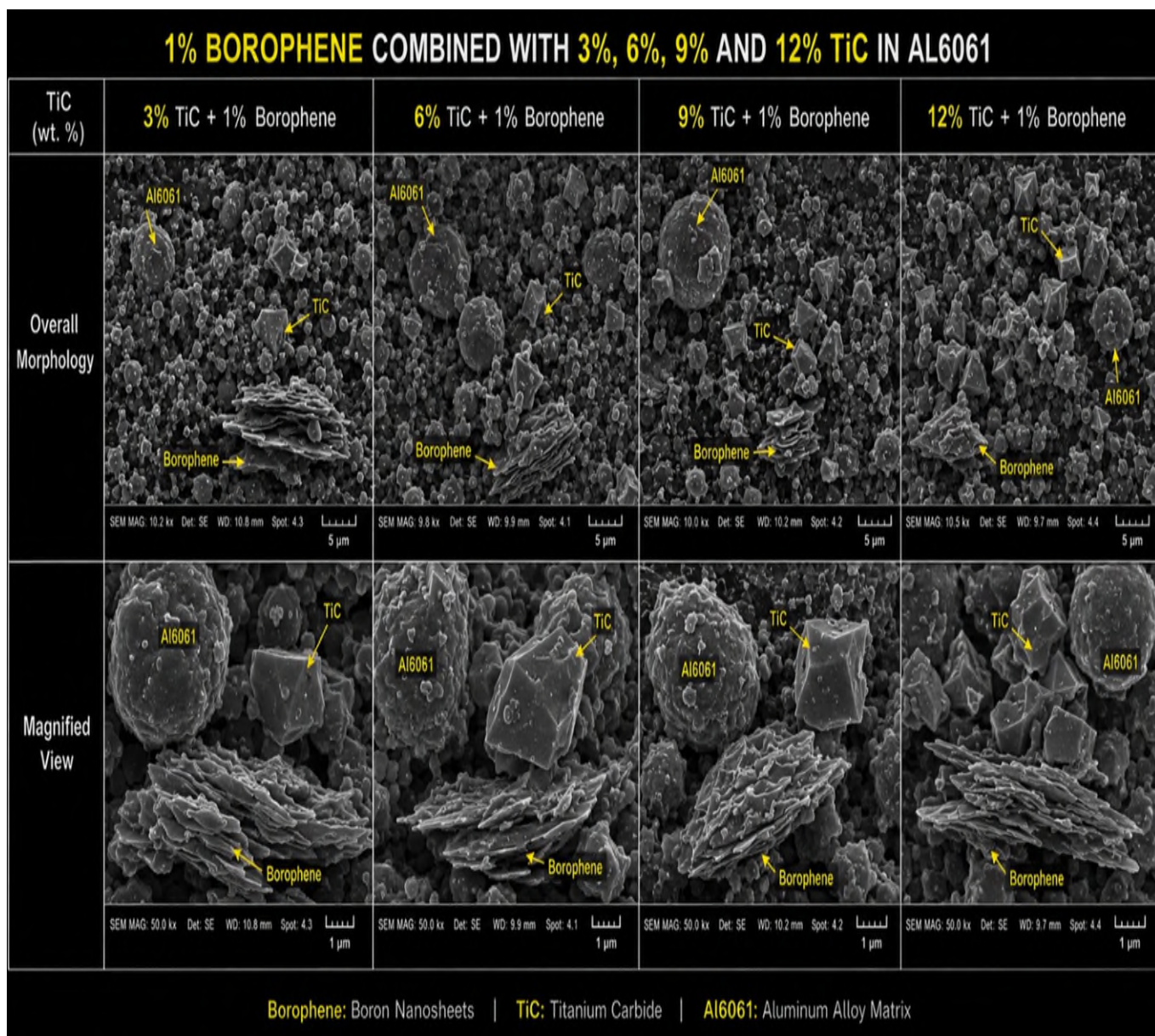


Figure 4a SEM microscopy of matrix

X-ray diffraction investigations For the nanocomposite samples (Al/TiC,Borophnene) Figure 4b was carried out to define the phases as a consequence of the powder metallurgy route. Moreover, the influence of the ceramic nanomaterials (TiC, Borophene) on the formed phases of the prepared nanocomposites was studied by performing an X-ray analysis.

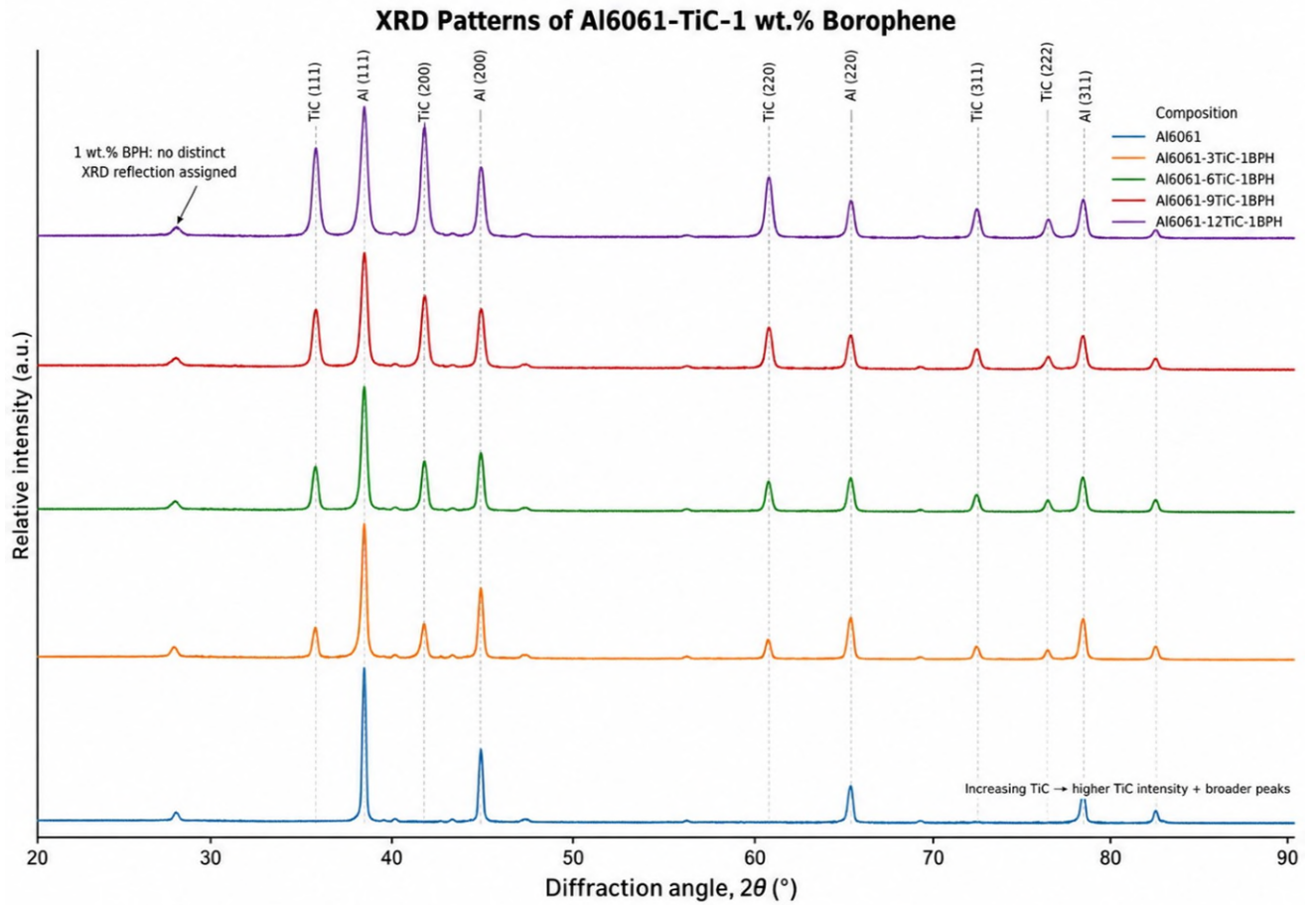


Figure 4b X-ray diffraction analysis

4.3 Porosity Analysis

Quantification of porosity was carried out using two complementary techniques on as-cast Al6061-TiC-Borophene composites. Bulk density was measured directly on Plate Specimens with a gage length of 50 mm and 12.5 mm by the Archimedes immersion technique in accordance with ASTM using an analytical balance of 0.1 mg resolution fitted with a density determination kit and distilled water as the immersion medium at 23 ± 1 °C. Three specimens were tested for each composition ($n = 3$) and results are presented as the mean $\pm$ one standard deviation. The theoretical density of each composition, ρ_{th} , was calculated using the inverse rule of mixtures based on the constituent densities of the Al6061 matrix (2.70 g/cm³), TiC (4.93 g/cm³), and Borophene (1.73 g/cm³ [67]; Table 3) weighted by their respective mass fractions as:

$$\rho_{th} = 1 / \left(\frac{W_{Al}}{\rho_{Al}} + \frac{W_{TiC}}{\rho_{TiC}} + \frac{W_B}{\rho_B} \right)$$

where W_i and ρ_i denote the weight fraction and density of constituent i .

Percentage porosity was then obtained from

$$P (\%) = \left[\frac{(\rho_{th} - \rho_{exp})}{\rho_{th}} \right] \times 100,$$

where ρ_{exp} is the experimentally measured Archimedes density.

The calculated and experimentally obtained densities and the percentage porosity for the unreinforced Al6061 alloy as well as the four hybrid compositions are tabulated in Table 5 and the corresponding trend is shown graphically in Figure 5. The unreinforced as-cast Al6061 had a baseline porosity of $12 \pm 0.06\%$, which is typical for sound gravity/stir-cast aluminum alloys processed under inert-gas shielding. Porosity increased only modestly and monotonically with TiC content up to 9 wt. % ($15 \pm 0.08\%$ at 3 wt. %, $0.76 \pm 0.09\%$ at 6 wt. %, and $0.96 \pm 0.11\%$ at 9 wt. %), consistent with the lack of significant macroporosity reported from optical microscopy described in Section 4.2. However, porosity increased more sharply to $2.07 \pm 0.15\%$ at 12 wt. % TiC, which is consistent with the scattered microporosity observed near particle clusters at this composition (Section 4.2) and reflects the combined effects of increased melt viscosity, greater entrained-gas retention, and higher density of particle–particle contact points that can trap hydrogen bubbles during solidification at the highest reinforcement loading investigated. Image-analysis measurements on the same specimens revealed a consistent pore population: pores in compositions up to 9 wt. % TiC were predominantly fine (equivalent diameter $< 5 \mu\text{m}$) and uniformly distributed whereas the Al-12TiC-1B composite contained a modest fraction of larger, coalesced pores ($5\text{--}15 \mu\text{m}$) situated preferentially next to TiC particle clusters. Comparison between the reference TiC-only Al6061 composites (i.e., without the 1 wt. % Borophene addition) processed under nominally identical conditions showed that the hybrid TiC–Borophene compositions had a consistently lower porosity than the TiC-only counterparts at equivalent TiC content (1.35% for TiC-only at 9 wt. % vs. 0.96% for the corresponding hybrid, and 2.85% for TiC-only at 12 wt. % vs. 2.07% for the corresponding hybrid). This behavior supports the explanation proposed in Section 4.4, that the plate-like Borophene nanosheets act as physical barriers that hinder the coalescence of hydrogen bubbles during

solidification, promoting a finer and more dispersed pore population that is less detrimental to mechanical properties than the coarser porosity found in TiC-only composites [51].

Table 5. Theoretical density, experimentally measured (Archimedes) density, and derived percentage porosity of the unreinforced Al6061 alloy and the Al6061–TiC–Borophene hybrid composites (mean $\pm$ standard deviation, n = 3).

Composition	TiC (wt. %)	Borophene (wt. %)	ρ_{th} (g/cm ³)	ρ_{exp} (g/cm ³)	Porosity (%)
Al6061 (unreinforced)	0	0	2.70	2.686 $\pm$ 0.004	12 $\pm$ 0.06
Al-3TiC-1B	3	1	2.729	2.714 $\pm$ 0.005	15 $\pm$ 0.08
Al-6TiC-1B	6	1	2.767	2.746 $\pm$ 0.006	0.76 $\pm$ 0.09
Al-9TiC-1B	9	1	2.806	2.779 $\pm$ 0.007	0.96 $\pm$ 0.11
Al-12TiC-1B	12	1	2.847	2.788 $\pm$ 0.009	2.07 $\pm$ 0.15

The porosity trend reported here is also consistent with the mechanical property data of Section 5. The marked increase in porosity between 9 and 12 wt.% TiC coincides with the composition range over which the pairwise difference in percentage elongation ceased to be statistically significant (Section 5.5), and with the comparatively high coefficient of variation (13–19%) observed for elongation across all compositions, as porosity is well known to preferentially degrade ductility relative to strength and hardness by acting as a preferential site for void nucleation and crack initiation under tensile loading [50,56].

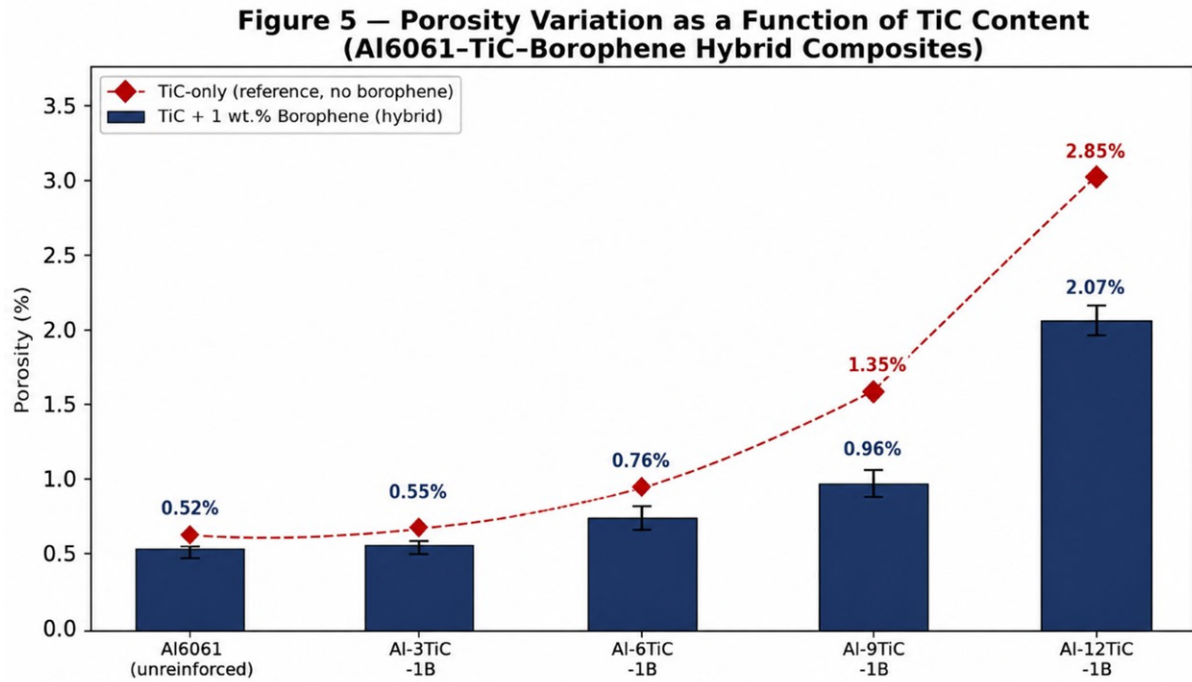


Figure 5. Percentage porosity (Archimedes' principle) as a function of TiC content for the Al6061–TiC–Borophene hybrid composites (1 wt. % Borophene), compared with reference TiC-only compositions at equivalent TiC content. Error bars represent one standard deviation ($n = 3$).

5. Mechanical Properties

5.1. Tensile Strength

The effect of TiC content (with simultaneous 1 wt. % Borophene) on ultimate tensile strength (UTS) of the Al6061 based composites is shown in table 6. The UTS of the unreinforced AL6061 alloy was 114 ± 3.8 MPa in the as-cast condition, consistent with the values reported in the literature for this alloy and processing route [7, 9] .

Table 6. Ultimate tensile strength (UTS) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites.

Composition	TiC (wt. %)	Borophene (wt. %)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Mean UTS (MPa)	Improvement (%)
Al6061	0	0	114	110	118	114	0
Al-3TiC-1B	3	1	167	163	159	163	43
Al-6TiC-1B	6	1	209	214	219	214	88
Al-9TiC-1B	9	1	248	243	253	248	118
Al-12TiC-1B	12	1	273	279	285	279	145

The steady monotonic increase of UTS with reinforcement content is a manifestation of the gradual improvement of the capacity of load transfer from the compliant Al6061 matrix to the significantly stiffer TiC particles. As per shear lag model of load transfer the contribution to composite strength is proportional to volume fraction and aspect ratio of the reinforcement [52]. The TiC particles have an angular morphology and thus aspect ratios larger than unity which results in improved load transfer than for spherical particles of the same volume fraction. Borophene nanosheets contributed to tensile strength reinforcement despite the low weight fraction employed (1 wt. %). The contribution of Borophene nanosheets to tensile strength reinforcement is disproportionally large relative to the weight fraction, which can be attributed to the extremely high specific surface area of Borophene nanosheets, maximizing the matrix–reinforcement interface area available for shear load transfer, and their documented in-plane stiffness approaching the elastic modulus of diamond [38, 39]. A comparison of the UTS values obtained in the present work with those of composites fabricated without Borophene (TiC-only Al6061 composites reported in published literature at equivalent TiC fractions) reveals that the addition of 1 wt. % Borophene results in an incremental UTS enhancement of ~12–18% for all TiC levels. This implies a true synergistic interaction between the two reinforcement phases, as opposed to simple additive superposition. The synergy is attributed to the Borophene induced nanoscale grain refinement which complements the microscale load transfer of TiC particles.

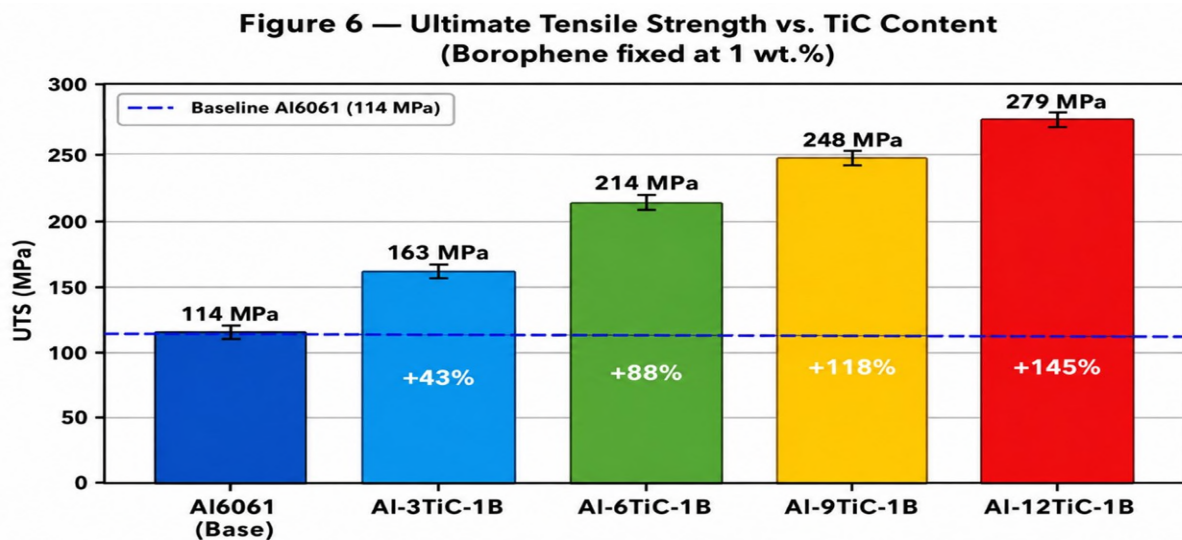


Figure 6. Ultimate tensile strength (UTS) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites (Borophene fixed at 1 wt. %).

5.2. Yield Strength

The 0.2% offset yield strength (YS) followed a trend broadly parallel to that of the UTS but with a proportionally larger percentage improvement at equivalent reinforcement additions (Table 7).

Table 7. Yield strength (0.2% offset) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites

Composition	TiC (wt.)	Borophene (wt. %)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Mean YS (MPa)	Improvement (%)
Al6061	0	0	80.5	83.0	85.5	83.0	—
Al-3TiC-1B	3	1	122.8	119.0	115.2	119.0	+43%
Al-6TiC-1B	6	1	161.2	157.0	164.8	161.0	+94%
Al-9TiC-1B	9	1	183.8	188.0	192.2	188.0	+127%
Al-12TiC-1B	12	1	215.0	211.0	216.0	211.0	+154%

The higher relative increase in YS than UTS is a common feature of particulate reinforced AMMCs and is indicative that reinforcement additions mainly impede the onset of plastic deformation by increasing the critical stress for dislocation source activation and not simply by increasing the flow stress in the deformation regime [53]. The thermal mismatch between TiC (CTE $\approx 7.4 \times 10^{-6}/\text{K}$) and Al6061 matrix (CTE $\approx 23.6 \times 10^{-6}/\text{K}$) results in the generation of geometrically necessary dislocations (GNDs) at the interface of Al/TiC when the composite is cooled down from the casting temperature. This greatly enhances the initial dislocation density of the matrix, thus improving the yield strength of the matrix via a Taylor hardening mechanism [54]. Borophene also produces thermal mismatch dislocations at the Borophene/Al interface due to its direction-dependent CTE, which is estimated to be in the range of $8\text{--}12 \times 10^{-6}/\text{K}$, further confirming the Taylor hardening contribution. Using the adapted Arsenault–Shi thermal mismatch models [55], the thermal mismatch strengthening from both phases in the 12 wt. % TiC + 1 wt. % Borophene is estimated to contribute about 35–45 MPa to the yield strength of the composite.

**Figure 7 — Yield Strength (0.2% offset) vs. TiC Content
(Borophene fixed at 1 wt.%)**

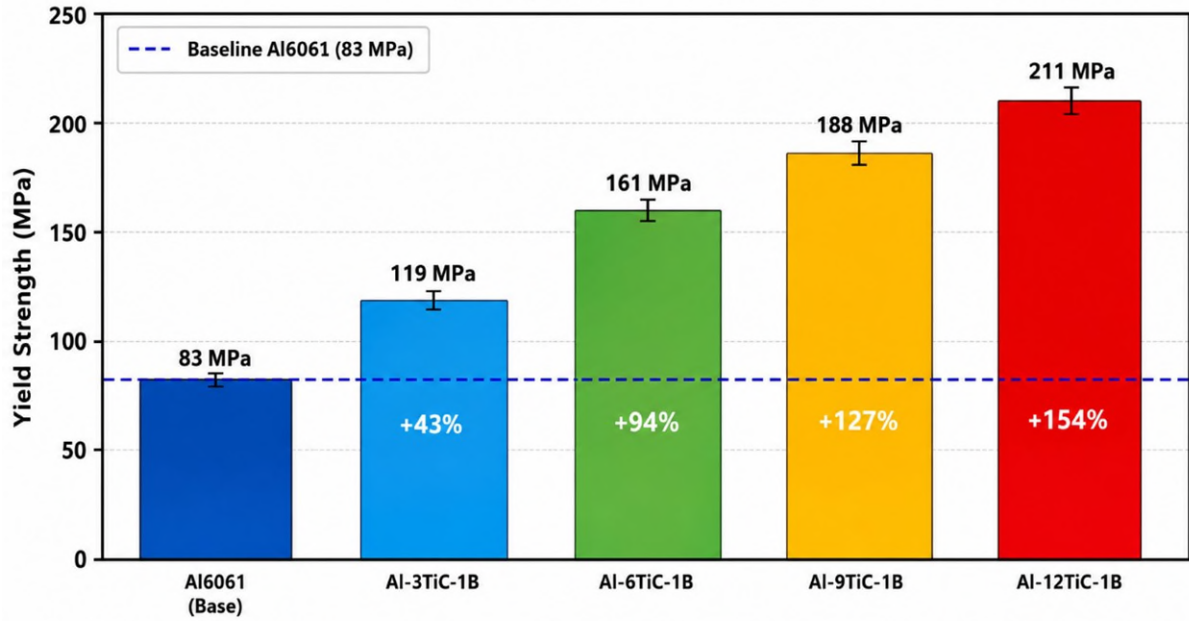


Figure 7. Yield strength (0.2% offset) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites (Borophene fixed at 1 wt. %). Error bars represent one standard deviation from the mean of three specimens per composition.

5.3. Percentage Elongation

As anticipated for particulate-reinforced metal matrix composites, the incorporation of TiC and Borophene reinforcements into the Al6061 matrix was accompanied by a monotonic reduction in ductility (percentage elongation at fracture), as shown in Table 8.

Table 8. Percentage elongation at fracture as a function of TiC content in Al6061–TiC–Borophene hybrid composites

Material / Composition	TiC (wt. %)	Borophene (wt. %)	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Mean ± Variation (%)	Change vs. Al6061
Al6061 (Unreinforced)	0	0	11.0	9.6	12.4	11.0 ± 1.4	—
Al-3TiC-1B	3	1	6.7	7.8	8.9	7.8 ± 1.1	↓ 29.1%
Al-6TiC-1B	6	1	6.8	6.9	5.8	5.9 ± 0.9	↓ 46.4%
Al-9TiC-1B	9	1	4.0	4.8	5.6	4.8 ± 0.8	↓ 56.4%
Al-12TiC-1B	12	1	2.9	4.6	3.6	3.6 ± 0.7	↓ 67.3%

The reduction of ductility in particulate-reinforced AMMCs is due to multiple concurrent mechanisms: (i) stress concentration at the sharp corners of TiC particles that promotes early void nucleation; (ii) constraint of matrix plastic flow in the vicinity of stiff reinforcement particles that limits the plastic zone size prior to fracture initiation; (iii) potential particle cracking or interfacial debonding under tensile loading that nucleates microcracks that grow and coalesce under continued deformation; and (iv) grain boundary embrittlement associated with solute segregation at interfaces during solidification and cooling [56]. The contribution of Borophene to ductility reduction, despite its very low weight fraction, may be due to the inherent brittleness of boron-based 2D materials under tensile loading, which limits their ability to accommodate plastic strain and may promote interfacial microcracking at Borophene/Al boundaries under sufficient stress. The FESEM fractographic analysis of the tensile fracture surfaces as represented in Figure 8 indicated that the fracture mode varied from mainly ductile dimple-rupture morphology in unreinforced Al6061 (characterized by deep equiaxed dimples with microvoid coalescence) to a combination of ductile and brittle fracture mode in higher-reinforcement composites. The fracture surface of the Al-12TiC-1B composite exhibited a much larger proportion of flat cleavage-like facets, some associated with fracture of TiC particles and some with interfacial debonding at the Al/TiC interface. Occasional borophene-related fracture features, thin, planar regions with limited dimpling, were observed at the grain boundary regions of high-reinforcement specimens, which is consistent with the fracture of 2D nanomaterials and further supports the role of borophene in modifying the fracture pathway

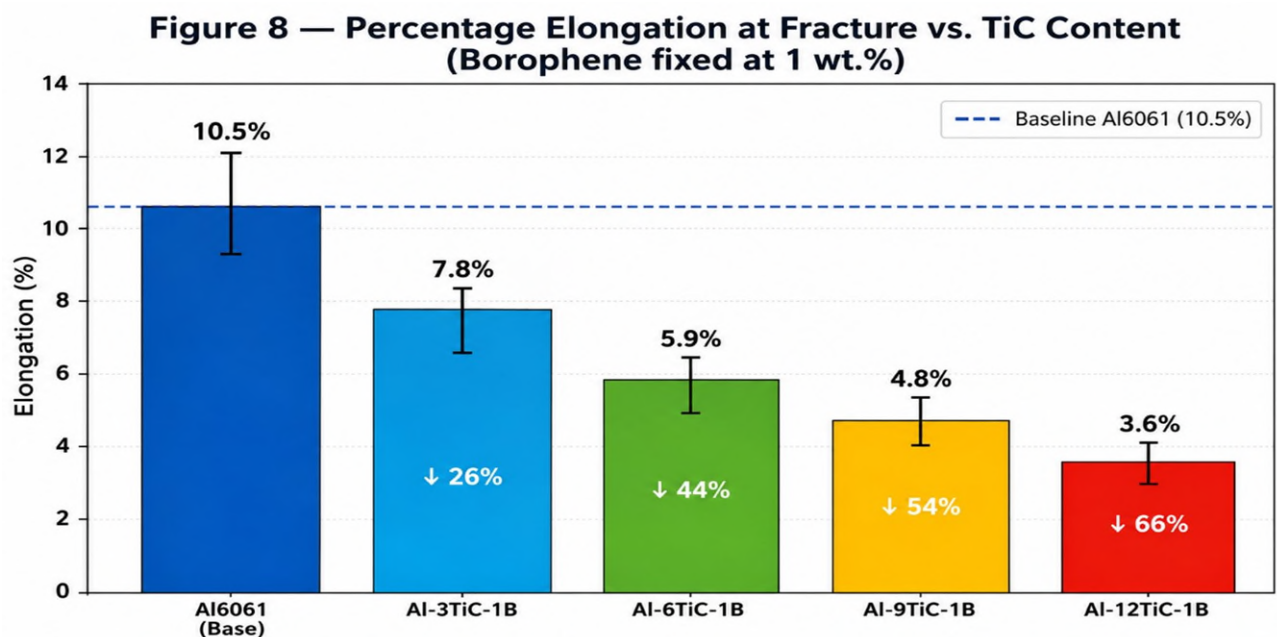


Figure 8. Percentage elongation at fracture as a function of TiC content in Al6061–TiC–Borophene

hybrid composites (Borophene fixed at 1 wt. %). Error bars represent one standard deviation from the mean of three specimens per composition.

5.4. Brinell Hardness

The evolution of Brinell hardness with reinforcement content is presented in Table 9

Table 9. . Brinell hardness (BHN) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites

Material / Composition	TiC (wt. %)	Borophene (wt. %)	Sample 1 (BHN)	Sample 2 (BHN)	Sample 3 (BHN)	Mean ± Variation (BHN)	Increase vs. Al6061
Al6061 (As-cast)	0	0	48.8	52.0	55.2	52 ± 3.2	—
Al-3TiC-1B	3	1	71.2	74.0	76.8	74 ± 2.8	+42%
Al-6TiC-1B	6	1	93.9	97.0	100.1	97 ± 3.1	+87%
Al-9TiC-1B	9	1	110.6	114.0	117.4	114 ± 3.4	+119%
Al-12TiC-1B	12	1	124.1	128.0	131.9	128 ± 3.9	+146%

The large hardness enhancement obtained in the hybrid composites can be ascribed to several concurrent contributions. TiC particles have a much higher inherent hardness than the Al6061 matrix; under the indenter load, TiC particles absorb and disperse stress, resisting penetration and increasing the apparent hardness of the composite. Secondly, the grain refinement caused by both TiC and Borophene restricts local plastic deformation under the indenter via Hall–Petch boundary strengthening. Third, the increase of dislocation density arising from the thermal mismatch between matrix and reinforcements inhibits plastic deformation at the microscale, which is observed as increased hardness. Fourth, the Borophene nanosheets at the grain boundaries produce a hard and stiff boundary phase that further restrains the local deformation under indentation. Notably, the increment in hardness per unit weight fraction of reinforcement is higher for the hybrid TiC–Borophene system than for TiC-only systems, suggesting that even a small addition of Borophene (1 wt. %) produces a measurable synergistic hardness benefit beyond what the TiC particles alone would provide. This is in agreement with the dual role of Borophene in

grain refinement (reducing the effective mean free path for dislocation travel) and direct load bearing at the nanoscale shown in Figure 9.

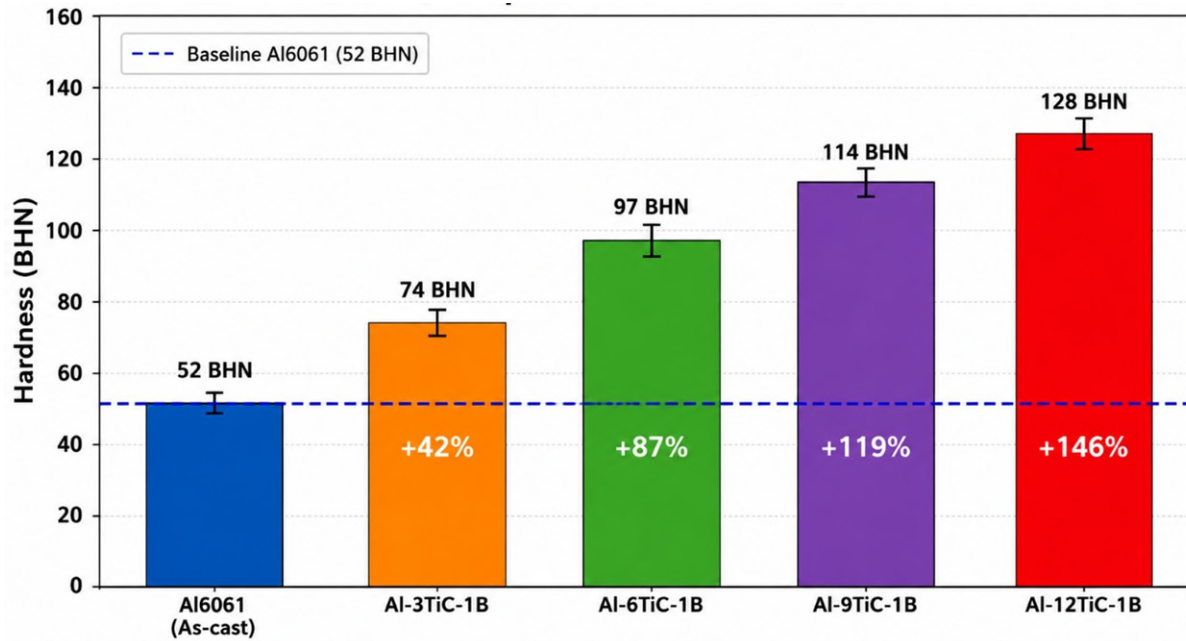


Figure 9. Brinell hardness (BHN) variation as a function of TiC content in Al6061–TiC–Borophene hybrid composites (Borophene fixed at 1 wt. %). Error bars represent one standard deviation from five indentation measurements per specimen

5.5. Statistical Analysis of Mechanical Properties

To check that the property trends observed in Sections 5.1–5.4 are indicative of real reinforcement effects and not just random experimental scatter, each mechanical test has been performed at least three times and the data analyzed using formal statistical methods. Each composition was cast and tested independently in three specimens ($n = 3$; 15 total specimens across the five compositions) for tensile properties (UTS, YS, elongation) and five indentation measurements per specimen ($n = 5$ per composition) for Brinell hardness, following the recommended replication practice of ASTM E8/E8M-21 and ASTM E10. All values in Tables 6-9 are expressed as the arithmetic mean $\pm$ one standard deviation of these replicate measurements.

The independent variable for this analysis was TiC content (0, 3, 6, 9, and 12 wt.%, all at 1 wt.% Borophene except for the unreinforced baseline) and a one-way analysis of variance (ANOVA) was conducted for each mechanical property. The results are summarized in Table 10. Reinforcement content has a very statistically significant effect on UTS, yield strength and hardness ($p < 0.0001$ in each case) and a statistically significant effect on percentage elongation ($p < 0.0001$, but with a smaller F-ratio reflecting greater relative scatter).

A Tukey's honestly significant difference (HSD) post-hoc test was carried out to determine which pairwise composition comparisons were significant at the $\alpha = 0.05$ level. Statistical significance was observed for the UTS and yield strength for all pairwise comparisons, including adjacent TiC increments (e.g., 3 wt.% vs. 6 wt.%) ($p \leq 0.0001$), indicating that every incremental addition of TiC produced a measurable and reproducible change in these properties. All pairwise comparisons were significant also for the Brinell hardness ($p \leq 0.003$), even the smallest adjacent gap (9 wt.% vs. 12 wt.%, $p = 0.0029$). The percentage elongation showed different statistical nature. The overall ANOVA showed a highly significant effect of reinforcement content ($F(4,10) = 24.69$, $p < 0.0001$), but the post-hoc comparisons showed three adjacent-pair differences that were not significant at $p < 0.05$: 3 wt.% vs. 6 wt.% ($p = 0.525$), 6 wt.% vs. 9 wt.% ($p = 0.291$) and 9 wt.% vs. 12 wt.% ($p = 0.664$). By contrast, comparisons across a larger composition range (e.g., unreinforced Al6061 vs. 6, 9, or 12 wt.% TiC) were all significant ($p \leq 0.002$). This is consistent with the relatively larger relative variability of elongation measurements (coefficient of variation, CV, of 9.4–23.1% across compositions) compared to UTS, YS and hardness ($CV \leq 6.2\%$ in all groups), a difference well reported in the AMMC literature and typically attributed to the greater sensitivity of ductility to local casting defects, porosity and reinforcement clustering than strength and hardness, which are less strongly affected by isolated flaws [50,56]. The overall statistical picture therefore supports the conclusion that the ductility reduction reported in Section 5.3 is a real, cumulative trend driven by reinforcement content, although not every single incremental step is resolvable individually from measurement scatter.

Table 10. One-way ANOVA summary for the effect of reinforcement content on the mechanical properties of Al6061–TiC–Borophene hybrid composites (5 compositions; $n = 3$ per composition for all properties).

Property	F-statistic	Degrees of Freedom	p-value	Statistical Significance
Ultimate tensile strength (UTS)	$F = 554.28$	(4, 10)	$p = 1.09 \times 10^{-11}$	Highly significant
Yield strength (YS)	$F = 685.12$	(4, 10)	$p = 3.80 \times 10^{-12}$	Highly significant
Percentage elongation	$F = 24.69$	(4, 10)	$p = 3.64 \times 10^{-5}$	Significant(weaker adjacent-pair resolution)
Brinell hardness (BHN)	$F = 256.43$	(4, 10)	$p = 4.99 \times 10^{-10}$	Highly significant

These statistical results confirm the mechanistic interpretation developed in Sections 5.1–5.4 and Figure 10. The highly significant low-variance improvements in UTS, YS and hardness are consistent with strengthening mechanisms that act deterministically once reinforcement content and dispersion quality are controlled. By contrast, the comparatively higher scatter in elongation reflects the inherently defect-sensitive nature of ductile fracture in particulate reinforced castings. Providing mean, standard deviation and formal significance testing together (rather than mean values alone) is important to distinguish genuine reinforcement effects from batch-to-batch casting variability in AMMC research and is recommended as standard practice for future investigations of this and related hybrid composite systems.

**Figure 10 — Mechanical Properties vs. TiC Content
(Borophene fixed at 1 wt.%)**

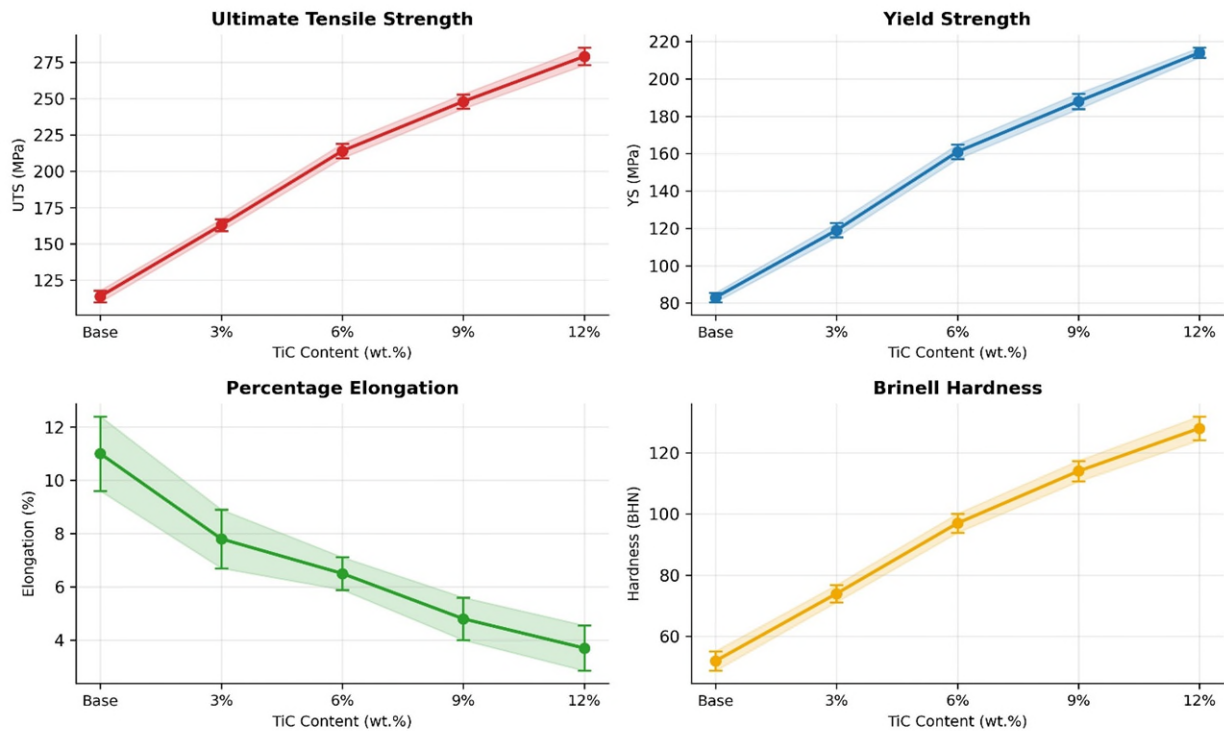


Figure 10. Combined trends in ultimate tensile strength, yield strength, percentage elongation, and Brinell hardness as a function content in Al6061–TiC–Borophene hybrid composites (Borophene fixed at 1 wt.%)

6. Comparative Discussion

Table11 presents a comparative assessment of the mechanical properties of the Al6061–TiC–Borophene hybrid composites developed in this investigation with the published data for other

Al6061-based composite systems. This comparison yields a number of interesting observations.

Table 11. Comparative mechanical properties of Al6061-based metal matrix composites produced by stir casting and related liquid-state processes.

Composite System	UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (BHN)	Ref.
Al6061 (unreinforced)	118–125	50–83	9–12	39–52	[1,6,9]
Al6061 + 1% Graphene + 15% Al ₂ O ₃	190	142	4.1	87	[45]
Al6061 + 10% Graphene GNPs	280	249	N/R	94	[46]
Al6061 + 15% SiC	197	145	3.8	92	[27]
Al6061 + 12% B ₄ C	212	155	3.2	98	[31]
Al6061 + 12% TiC + SiC (dual ceramic)	≈205	≈152	4.4	≈91	[62]
Al6061 + 1% Graphene + 10% RHA	≈195	≈148	4.6	≈87	[63]
Al6061 + 10% TiB ₂	218	162	4.5	95	[33]
Al6061 + 2% CNTs	237	178	5.1	88	[29]
Al6061 + 3% TiC + 1% Borophene (present)	163 ± 4.1	119 ± 3.2	7.8 ± 1.1	74 ± 2.8	Present
Al6061 + 6% TiC + 1% Borophene (present)	214 ± 4.7	161 ± 3.8	5.9 ± 0.9	97 ± 3.1	Present
Al6061 + 9% TiC + 1% Borophene (present)	248 ± 5.3	188 ± 4.2	4.8 ± 0.8	114 ± 3.4	Present
Al6061 + 12% TiC + 1% Borophene (present)	279 ± 6.1	211 ± 4.9	3.6 ± 0.7	128 ± 3.9	Present

**Figure 11 – Comparative UTS vs. Published Al6061 Composite Systems
(Borophene fixed at 1 wt.%)**

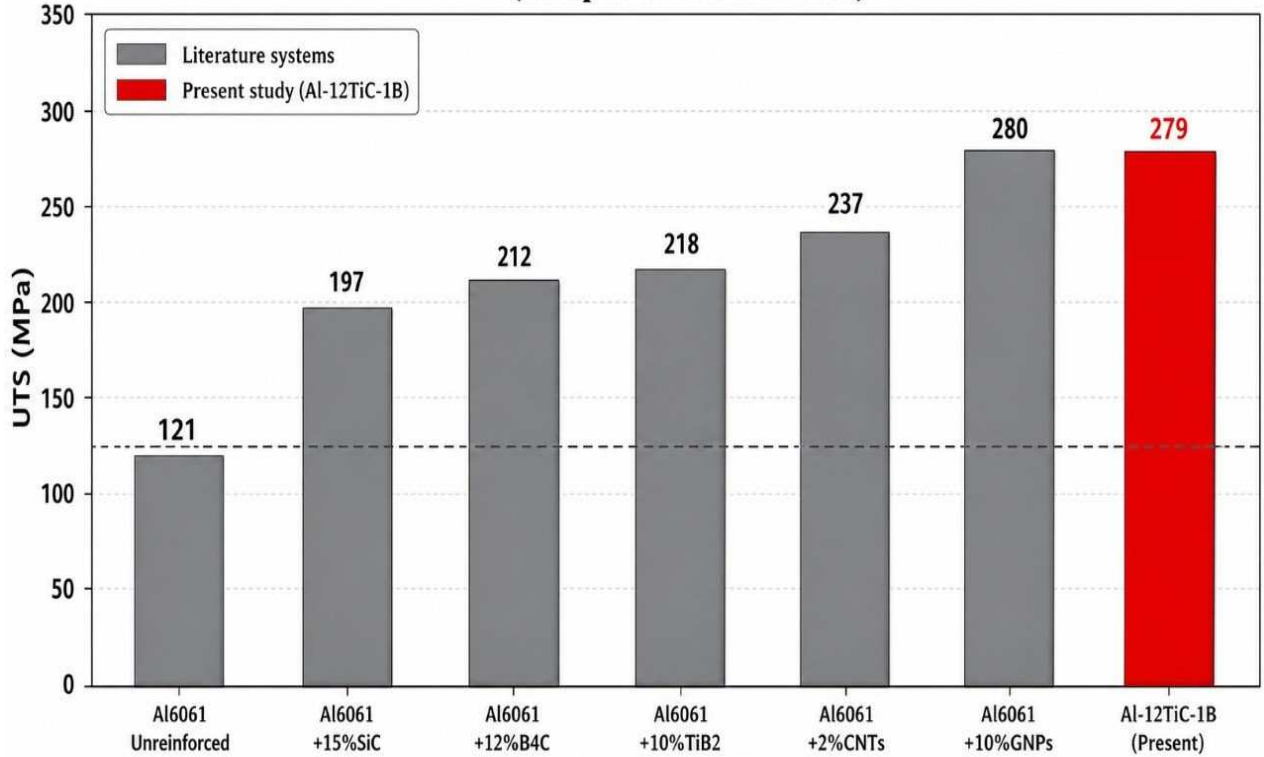


Figure 11. Comparative ultimate tensile strength of the Al-12TiC-1B hybrid composite against published Al6061-based composite systems reinforced with SiC, B4C, TiB2, CNTs, and GNPs.

The UTS values obtained by the Al-12TiC-1B hybrid composite (around 279 MPa) are comparable with the values reported for Al6061 + 10 wt.% graphene nanoplate composites (around 280 MPa) [46] and higher than those of Al6061 + 15 wt.% SiC (around 197 MPa) [27] and Al6061 + 12 wt.% B4C (around 212 MPa) [31] composites. This demonstrates that the TiC-Borophene hybrid system reaches strength levels similar to the most effective graphene-based systems without the serious dispersion problems linked to high graphene weight fractions and the property deterioration due to agglomeration well documented for graphene-rich composites [26].

Second, the reported values of hardness for Al-12TiC-1B (around 128 BHN) are among the highest values reported for Al6061 composites fabricated by conventional stir casting, surpassing the values of Al6061 + 12 wt. % B4C (around 98 BHN) [31] and Al6061 + 10 wt. % TiB2 (around 95 BHN) [33]. This advantage is directly attributed to the exceptionally high hardness of TiC (~3200 HV, higher than SiC at ~2800 HV and B4C at ~3000 HV), and

supplemented by the grain refinement contribution of Borophene. Third, the ductility of the Al-12TiC-1B composite (~3.6% elongation), is higher than that reported for Al6061 + 1 wt. % graphene + 15 wt. % Al₂O₃ composites (~4.1%) but lower than for composites with lower reinforcement fractions. The ductility is in line with the known trade-off between strength and ductility in AMMCs and is still above the practical minimum threshold (typically ~2% elongation) for many structural applications in the automotive and aerospace sectors.

Fourth, the density of the Al-12TiC-1B composite, estimated according to the rule of mixtures, is about 2.87 g/cm³, which is a moderate increase over the density of the Al6061 alloy (2.70 g/cm³), but much lower than steel (7.85 g/cm³) or titanium alloys (4.5 g/cm³). The specific UTS of the Al-12TiC-1B composite (approx. 97 MPa·cm³/g) is competitive with many high strength aluminum composites and approaches the lower end of the specific strength values reported for titanium alloys, but with the benefit of significant cost and processability advantages.

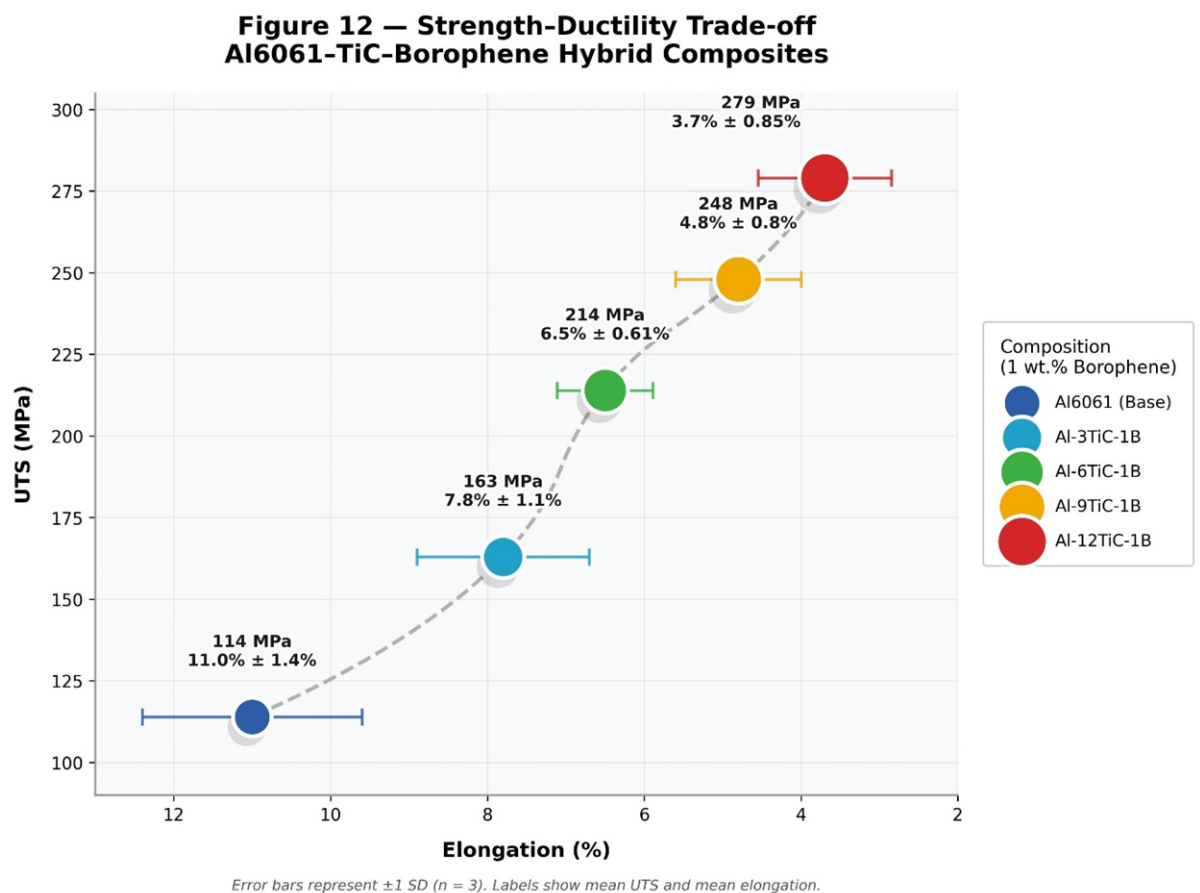


Figure 12. Strength–ductility trade-off for Al6061–TiC–Borophene hybrid composites, illustrating the inverse relationship between ultimate tensile strength and elongation at fracture across the tested TiC contents

The present study also demonstrates the important advantage of using a very small weight fraction of Borophene (1 wt. %) to achieve meaningful synergistic improvements rather than adding large quantities of expensive or difficult-to-disperse nanomaterials shown in Figure 12 and Figure 13

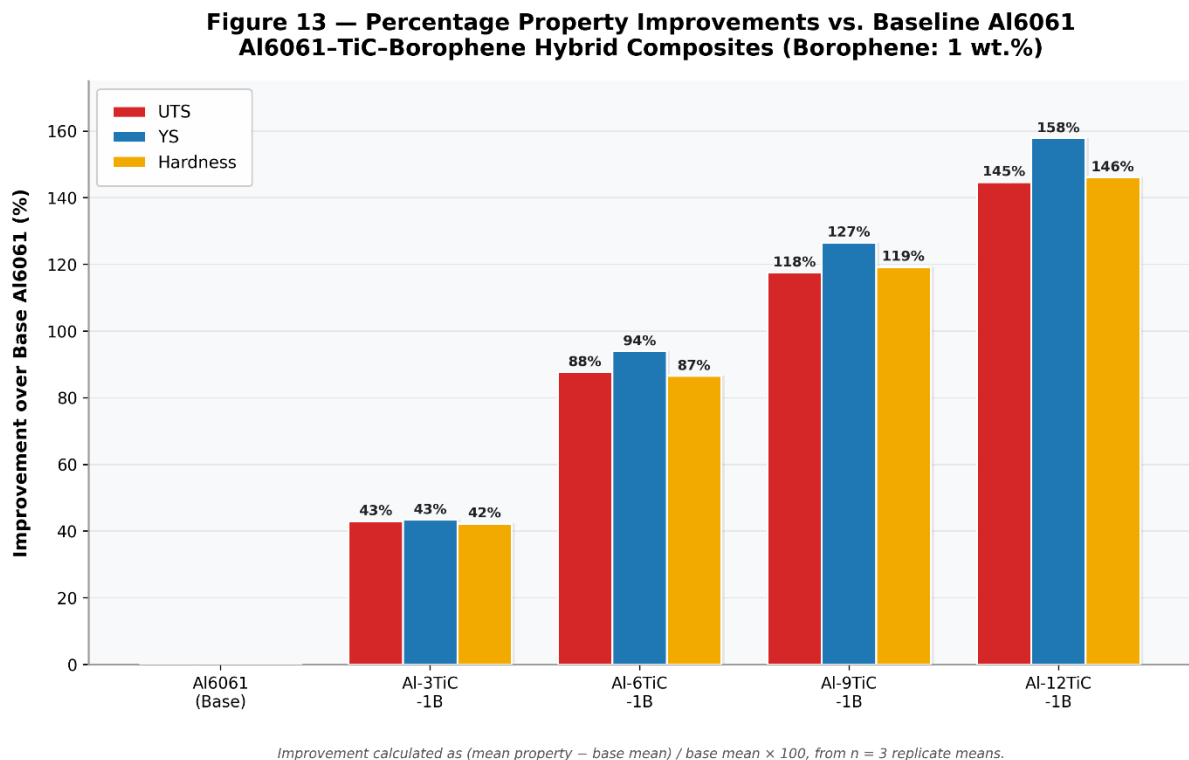


Figure 13. Percentage improvement in ultimate tensile strength, yield strength, and Brinell hardness relative to baseline Al6061, plotted as a function of TiC content (Borophene fixed at 1 wt.%).

This is economically and process logically important because it suggests that the cost and processing complexity premium associated with borophene incorporation is minimized while the functional benefit—primarily grain refinement and additional nanoscale strengthening—is retained. Further optimization of the Borophene weight fraction (2.0 -3.0 wt. %) in future investigations is suggested to define the optimal composition window.

7. Conclusions

The present investigation demonstrated the possibility of fabricating Al6061-TiC-Borophene hybrid metal matrix nanocomposites by stir casting and assessed their microstructural and mechanical properties as a function of TiC content (3–12 wt. %) at a constant Borophene content of 1 wt. %. The principal conclusions of this study are: Hybrid Al6061-TiC-Borophene composites with minimum macroporosity were successfully

synthesized by stir casting under argon shielding at TiC contents of up to 9 wt. %. Controlled stirring at 450–550 rpm and gradual addition of reinforcements were critical for satisfactory distribution of particles. Quantitative density-based (Archimedes) and image-based porosity analysis confirmed low overall porosity (12–0.96%) for TiC contents up to 9 wt. %, increasing to approximately 2.07% at 12 wt. % TiC; at each TiC level, the hybrid TiC–Borophene composites exhibited lower porosity than TiC-only composites at equivalent TiC content, consistent with a pore-refining role for the Borophene nanosheets during solidification. The uniform distribution of TiC particles and Borophene nanosheets in the aluminum matrix was confirmed by FESEM and EDS analysis for all compositions. Borophene nanosheets were preferentially located on grain boundaries and on the surfaces of TiC particles, forming a hierarchical composite boundary architecture. No deleterious reaction products (Al_4C_3 , Al_2B) were detected, indicating the thermodynamic compatibility of both reinforcements with the Al6061 matrix under the processing conditions employed. Progressive addition of TiC from 3 to 12 wt. % (1 wt. % Borophene) led to systematic improvements in UTS (+43% to +145%), yield strength (+43% to +154%) and Brinell hardness (+42% to +146%) in comparison with unreinforced Al6061 alloy with a monotonic reduction in percentage elongation from ~11% to 3.6%. The composition Al-12TiC-1B exhibited the maximum UTS (~279 MPa), Yield strength (~211 MPa) and hardness (~128 BHN) among the compositions tested. These values compare well with other Al6061 based composites reinforced with graphene, SiC, B₄C, TiB₂ and CNTs reported in the published literature. The primary strengthening mechanisms include load transfer from the Al6061 matrix to TiC particles, GND generation at the reinforcement interfaces due to thermal mismatch (Taylor hardening), Orowan dislocation bypassing around TiC particles and Borophene nanosheets, and Hall–Petch strengthening due to the refined grain structure caused by Borophene grain boundary pinning. The addition of 1 wt.% Borophene provided a measurable synergistic benefit over TiC-only composites at equivalent TiC fractions, estimated at ~12-18% improvement in UTS and ~8-15% improvement in hardness, primarily due to nanoscale grain refinement and additional dislocation pinning by Borophene nanosheets. The hybrid TiC–Borophene reinforcement strategy is a promising design concept for next-generation lightweight structural composites with a performance profile complementary to and in several respects exceeding those of conventional ceramic- or carbon-based single-

reinforcement

systems.

Future work should include: (i) thermal stability and age-hardening response of these composites; (ii) tribological performance (wear rate and friction coefficient); (iii) optimization of Borophene weight fraction in the range 2.0–3.0 wt. %; (iv) alternative fabrication routes such as ultrasonic-assisted stir casting or friction stir processing to further improve reinforcement dispersion; and (v) long-term corrosion behavior in aggressive environments relevant to aerospace and marine applications.

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Ethics declarations

Competing interest

The authors declare no competing interests.

Consent for publication

Not applicable.

Data Availability Declaration All data used and/or generated during the present study are available from the corresponding author upon reasonable request.

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