

Influence of B₄C, Gr, and ZrO₂ Reinforcement Additions on the Mechanical Properties of Al-7075 Composites

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Abstract - This study examines the effect of 3 wt.% additions of boron carbide (B₄C), graphite (Gr), and zirconia (ZrO₂) on the mechanical performance of Al-7075 metal matrix composites fabricated through a two-step stir-casting method. Three individual composite systems Al7075+3wt.%B₄C, Al7075+3wt.% Gr, and Al7075+3wt.%ZrO₂ were produced to evaluate the distinct strengthening mechanisms associated with each reinforcement. Microstructural characterization using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) confirmed uniform particle distribution and sound interfacial bonding within the composites. The fabricated samples were subjected to tensile, compressive, hardness, impact, and flexural tests to compare their mechanical responses. The results showed that the B₄C-reinforced composite achieved the highest ultimate tensile strength of 245 MPa, indicating superior load-carrying capability. The graphite-reinforced composite exhibited the greatest improvement in toughness, showing an 11.5% increase in impact strength due to the crack-arresting and solid-lubricating characteristics of Gr particles. B₄C addition further enhanced compressive and flexural behaviour, achieving a maximum compressive strength of 649 MPa and a 15.9% improvement in flexural strength, attributed to refined microstructure and efficient stress transfer from the matrix to hard ceramic particles. The novelty of this work lies in directly comparing B₄C, Gr, and ZrO₂ reinforcements at the same 3 wt.% level, allowing clear identification of their individual effects on Al-7075. The findings support the selection of suitable reinforcements for aerospace, automotive, defence, and other lightweight load-bearing applications.

Keywords: Al-7075, Metal Matrix Composite, Boron Carbide, Graphite, Zirconia, Mechanical Properties, Stir Casting, Microstructure.

I. INTRODUCTION

Metal matrix composites (MMCs) represent an advanced group of engineered materials known for their broad industrial

applicability. The incorporation of hard ceramic particles into a metallic matrix significantly elevates the material's overall performance, contributing to improved specific strength and stiffness, enhanced wear and corrosion resistance, and a higher elastic modulus [1]. Aluminium metal matrix composites have gained remarkable prominence in the automotive, aerospace, and shipbuilding sectors. Their increasing adoption is driven by their distinctive combination of high specific strength, favourable thermal conductivity, superior resistance to wear and corrosion, and balanced mechanical and electrical characteristics [2-4]. Aluminium alloys are widely used as matrix materials for MMCs due to their broad industrial relevance, and significant efforts have focused on developing cost-effective aluminium-based composites reinforced with SiC, Al₂O₃, ZrO₂, B₄C, mica, and graphite. Graphite, available in both fibre and particulate form, is valued for its low density, solid-lubricant behaviour, and ability to enhance wear resistance and strength. Aluminium-graphite composites produced through solidification methods offer tailored properties and are commonly employed in automotive components, bushes, and bearings [5-6].

Extensive studies on aluminium alloys reinforced with SiC, B₄C, TiB₂, ZrO₂, Gr and MoS₂ particles have been reported by various researchers, and their results consistently show that incorporating these particulates leads to notable enhancements in the alloy's physical and mechanical properties [7-10]. The stir casting technique offers several notable advantages for producing metal matrix composites; however, achieving consistently high-quality particle reinforcement remains a significant challenge due to issues such as particle clustering, poor wettability, and non-uniform distribution of reinforcements [11-12]. Stir casting is widely recognized as a simple, flexible, and cost-effective method for fabricating metal matrix composites [13-14]. Achieving enhanced properties in metal matrix composites largely depends on attaining a uniform distribution of ceramic particles within the matrix and ensuring strong interfacial bonding between the reinforcements and the metallic phase [15].

Studies on the compressive and tensile behaviour of stir-cast Al6061 MMCs reinforced with B₄C have shown that incorporating 9 wt.% B₄C significantly improves the mechanical properties of the composite[16]. Aluminium metal matrix composites consist of a base alloy combined with one or more reinforcement particulates. These particulates, introduced in relatively small proportions, significantly enhance the mechanical and tribological performance of the base metal within the matrix. Such improvements arise from the effective interaction between the matrix and the dispersed reinforcements [17-18]. Aluminium reinforced with boron carbide (B₄C) exhibits higher load-bearing capability, and its enhanced wear resistance largely results from the compact, stabilized surface layer that develops during sliding contact [19]. The mechanical and tribological performance of Al 7075 incorporated with graphite demonstrates that higher graphite content contributes to improved surface hardness, bending resistance, and reduced material loss during sliding [20].

Despite these advances, direct comparative studies of B₄C, Gr, and ZrO₂ at the same weight fraction in Al-7075 are limited. Most research focuses on hybrid systems or single reinforcements at varying contents. To address this gap, the present study fabricates Al-7075 composites reinforced individually with 3 wt.% B₄C, 3 wt.% Gr, and 3 wt.% ZrO₂, using a two-step stir-casting process. Microstructural characterization using SEM and EDS, along with a comprehensive suite of mechanical tests (tensile, compressive, hardness, impact, and flexural), is conducted to elucidate the distinct strengthening mechanisms of each reinforcement. The novelty lies in the direct side-by-side comparison at identical reinforcement level, providing clear insights into which addition best tailors specific mechanical attributes. The findings aim to guide the design of lightweight, high-performance MMCs for aerospace, automotive, defence, and other load-bearing applications.

II. EXPERIMENTAL DETAILS

2.1 Preparation of Materials and Composites

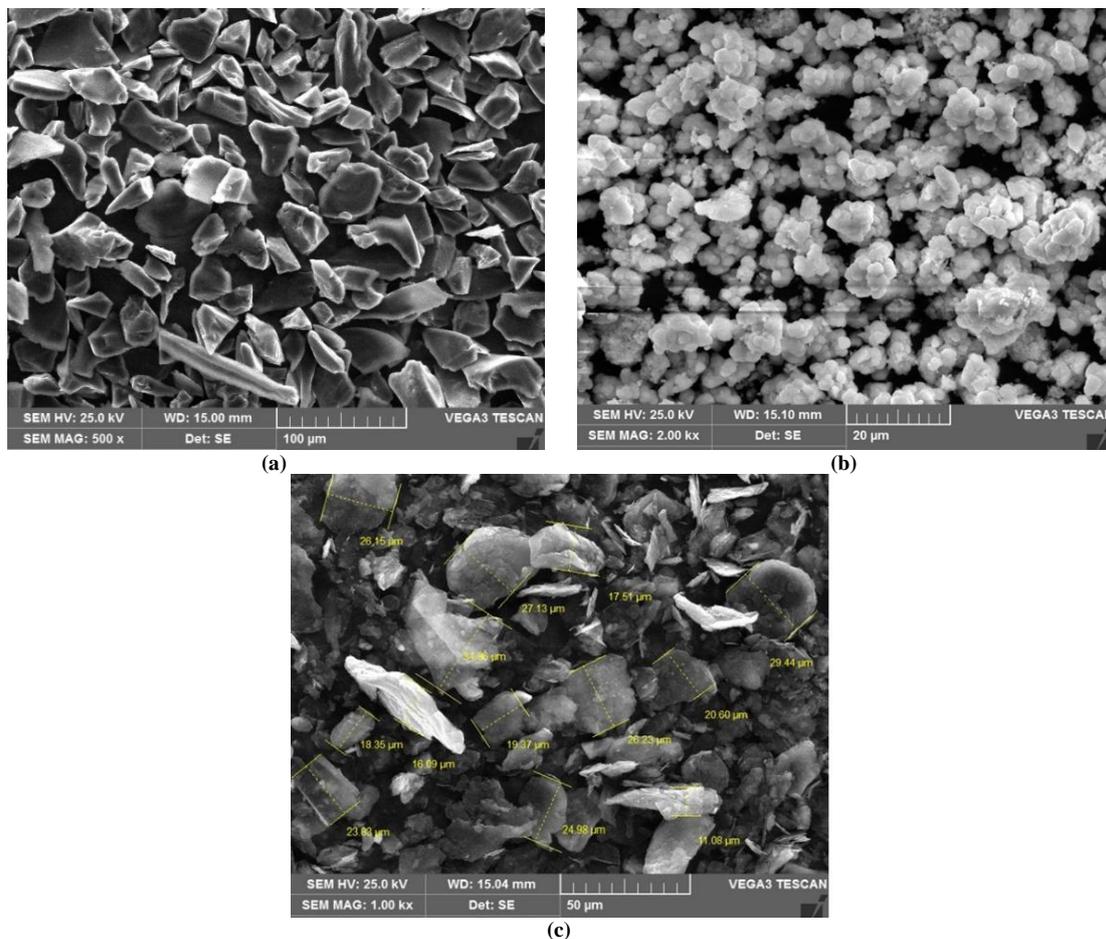


Figure 1: SEM micrographs of particles (a) B₄C, (b) ZrO₂, (c) Graphite

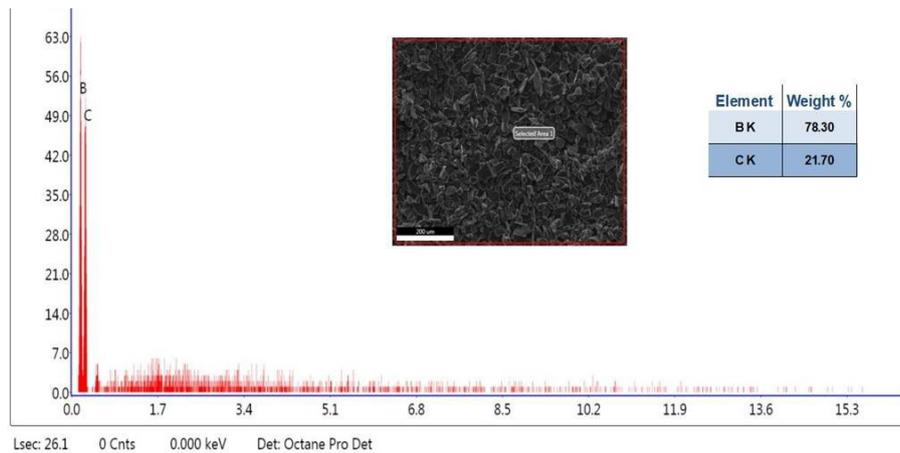


Figure 2: EDS spectrum of Boron Carbide particles

The matrix material used was Al-7075 ingots (Perfec Metal Works, Bengaluru, India), a high-strength Al–Zn–Mg–Cu alloy suitable for aerospace and structural applications. The reinforcements were boron carbide (B_4C , 20–35 μm), graphite (Gr, 30–40 μm), and zirconia (ZrO_2 , 20–30 μm), supplied by Speedfam (India) Pvt. Ltd., Chennai. The chemical and physical properties of the matrix and reinforcements are listed in Tables 1 and 2. The morphology and elemental composition of the reinforcement particles were characterized using SEM and EDS, as shown in Figures 1–4. These analyses confirmed appropriate particle size, shape, and composition, ensuring suitability for composite fabrication.

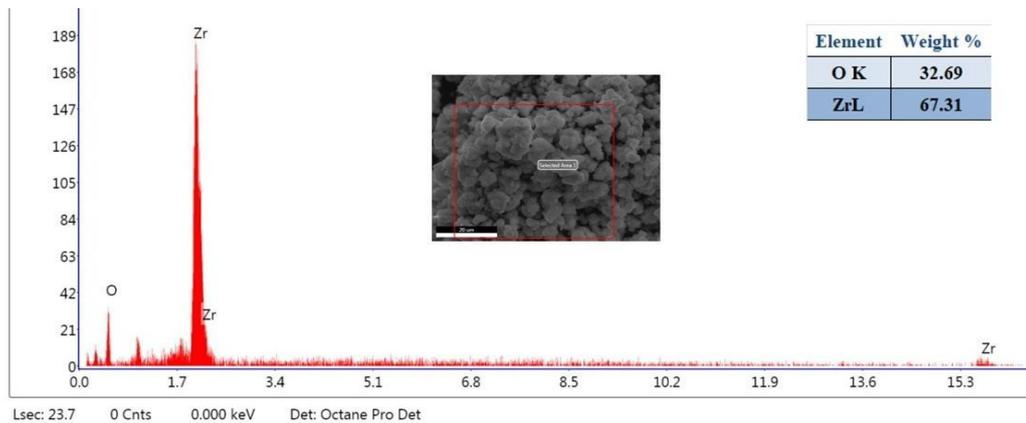


Figure 3: EDS spectrum of ZrO_2 particles

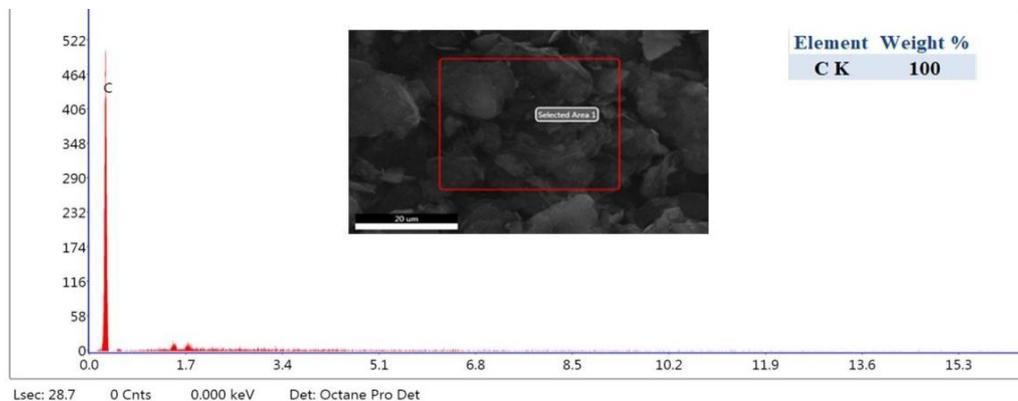


Figure 4: Graphite particle EDS spectrum

Figure 2–4 shows EDS spectra of reinforcements showing boron carbide (carbon 21.69 wt.%, boron 78.31 wt.%), zirconium dioxide (zirconium 67.28 wt.%, oxygen 32.72 wt.%), and graphite (carbon 100 wt.%).

Table 1: Composition of Al7075 Alloy in Weight Percent

Cu	Si	Mg	Cr	Fe	Zn	Mn	Ti	Al
1.95	0.40	2.89	0.22	0.49	6.03	0.26	0.20	Balance

Aluminium alloy Al 7075 was used as the matrix, with graphite, boron carbide, and zirconia as reinforcements. Composites were prepared by adding 3 wt.% of each reinforcement, chosen to balance improved properties with good particle dispersion. The composites were designated as sample 1 (Al 7075 + B₄C), sample 2 (Al 7075 + Gr), and sample 3 (Al 7075 + ZrO₂).

Table 2: Characteristics of the boron carbide, graphite, ZrO₂ particles and Al7075 alloy

Material	Hardness (BHN)	Tensile Strength (MPa)	Density (gm/cm ³)	Elastic Modulus (GPa)
Al7075	65	205	2.80	70
Graphite	1.3*	200	2.2	16
ZrO ₂	1300	1800 (C)**	5.68	380
Boron Carbide	2900	350	2.52	460

*Mohs Hardness **Compression Strength

The metal matrix composites were fabricated using a two-step stir casting technique, a widely adopted liquid metallurgy route for producing particulate-reinforced aluminium alloys. In the first step, the required amount of commercial-grade Al 7075 alloy was charged into a graphite crucible and melted at 650–680 °C. The melt temperature was continuously monitored and controlled using thermocouples to ensure complete melting without overheating. Degassing was then performed using solid hexachloroethane to eliminate dissolved and entrapped gases, thereby minimizing porosity [21].

In the second step, the ceramic reinforcements were preheated to 300–350 °C to remove moisture and enhance their wettability with the molten aluminium. The particles were introduced into the melt through a controlled two-stage addition procedure, accompanied by K₂TiF₆ flux to improve matrix–particle interfacial bonding and promote uniform dispersion. Continuous stirring at 300 rpm for 5 to 10 minutes was employed to prevent particle agglomeration and ensure homogeneous distribution.

After thorough mixing, the composite melt was heated to a controlled pouring temperature of 720–740°C and then transferred into a preheated cast iron die maintained at 200–250°C to reduce thermal shock and improve solidification quality. The cast composites were allowed to cool under ambient conditions. The resulting cylindrical samples measured 15 mm in diameter and 120 mm in length, suitable for mechanical testing. This carefully controlled two-step casting procedure ensured uniform reinforcement distribution, strong interfacial bonding, and minimal casting defects.



Figure 5a: Stir casting setup used for fabrication of the composites



Figure 5b: Al 7075 alloy reinforced with boron carbide, zirconia, and graphite composites

Figure-5a shows the stir-casting apparatus used for the fabrication of the composite specimens, while figure-5b displays the cast samples of Al7075 reinforced with B₄C, ZrO₂, and Gr particles. The specimens intended for microstructural analysis were prepared following a standard metallographic procedure. Initially, the samples were subjected to sequential grinding using silicon-carbide abrasive papers of 200, 400, 600, and 800 grit to achieve a uniform, scratch-free surface. This was followed by polishing on a velvet cloth using a suitable polishing medium to obtain a mirror-like finish. After polishing, the specimens were etched using Keller's reagent (a controlled mixture of HNO₃, HF, and HCl) to reveal the microstructural features such as grain boundaries, particle distribution, and matrix–reinforcement interfaces. The etched surfaces were thoroughly rinsed with distilled water to remove any residual chemicals or debris. Microstructural characterization of the Al7075 composite specimens was performed using a VEGA3 TESCAN (Figure-6) scanning electron microscope (SEM). The SEM analysis enabled detailed observation of reinforcement dispersion, particle–matrix bonding quality, and morphological characteristics relevant to the composite's structural behavior.

The hardness test specimens were prepared in accordance with ASTM E10 [22]. Brinell hardness measurements were carried out using a standard hardness testing machine. The test surfaces were carefully finished to ensure smooth, burr-free surfaces without any roughness that could influence indentation accuracy. A load of 250 kg-f was applied using a 5 mm diameter steel ball indenter. Three indentations were made at suitably spaced locations on each specimen, and the average of these readings was taken as the representative Brinell hardness value.



Figure 6: SEM/EDAX (VEGA3 TESCAN)

Tensile specimens were prepared in accordance with ASTM E8 standard [23] to characterize the mechanical response of the as-cast Al7075 alloy and its composites reinforced with 3 wt.% particulates. The uniaxial tensile tests were performed to determine the ultimate tensile strength and to analyze how the uniform distribution of reinforcement influences the alloy's deformation behaviour. Each test specimen was machined to an overall length of 104 mm, with a gauge length of 45 mm and a gauge diameter of 9 mm, as mandated by the standard as shown in figure 7. The tensile loading enabled the extraction of key strength parameters and provided a clear understanding of the composite's structural performance.

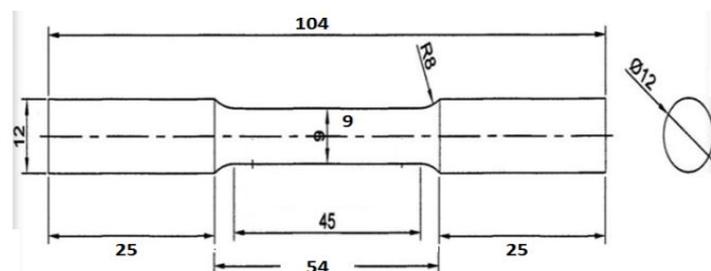


Figure 7: Tensile Specimen Geometry as per ASTM

Compression testing was performed as per ASTM E9 standards as shown in figure 8. Cylindrical specimens with a 2:1 height-to-diameter ratio were machined and tested under uniaxial compression to determine the compressive strength and deformation behaviour of Al7075 and its 3 wt.% reinforced composites. The test helped evaluate the effect of particle dispersion on the material's load-bearing capability.

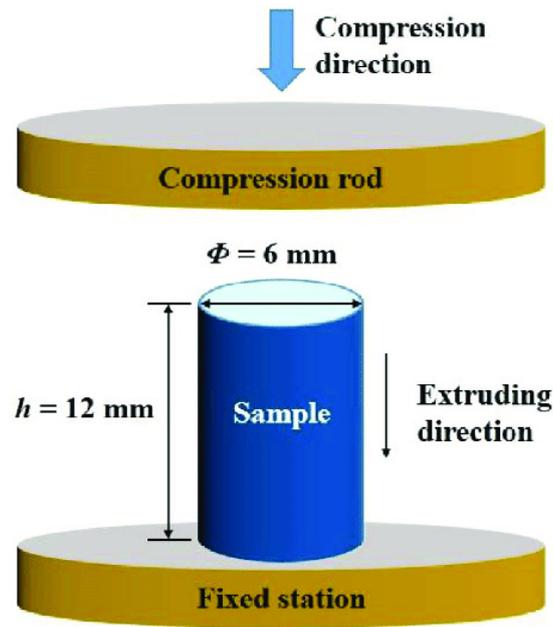


Figure 8: Compression Specimen Geometry as per ASTM

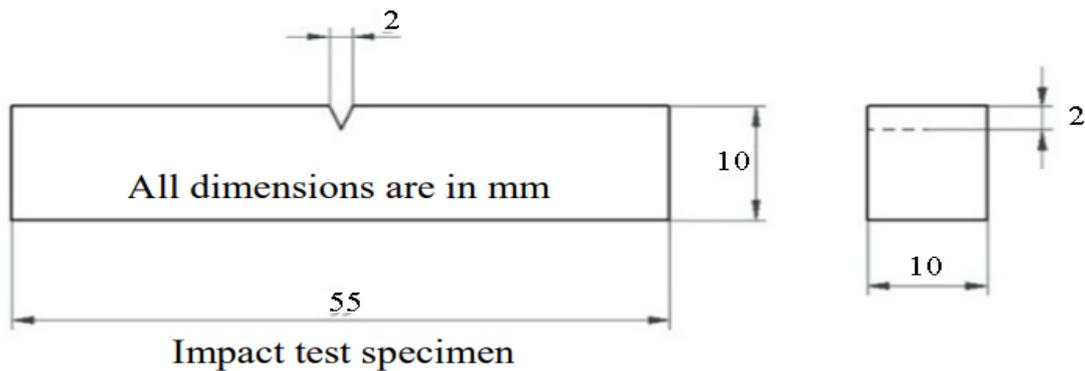


Figure 9: Charpy-Impact Specimen Geometry as per ASTM

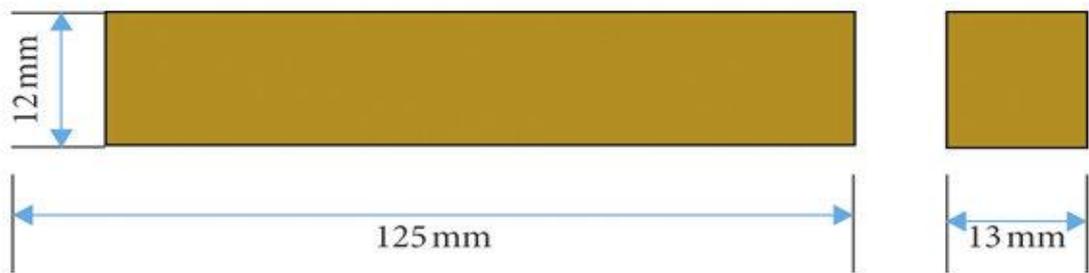


Figure 10: Flexural Specimen Geometry as per ASTM

Figure-9 shows the impact testing setup used to evaluate the toughness of Al7075 and its reinforced composites in accordance with ASTM E23. Standard notched Charpy specimens were tested, and the energy absorbed during fracture was recorded as the impact strength. Figure-10 illustrates the flexural (three-point bending) test arrangement performed as per ASTM D790, where rectangular specimens were loaded at the midpoint until failure. The maximum bending stress sustained before fracture was taken as the flexural strength. These tests collectively provided insight into the composites' ability to withstand sudden impact loads and their resistance to bending deformation.

III. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Microstructural Analysis

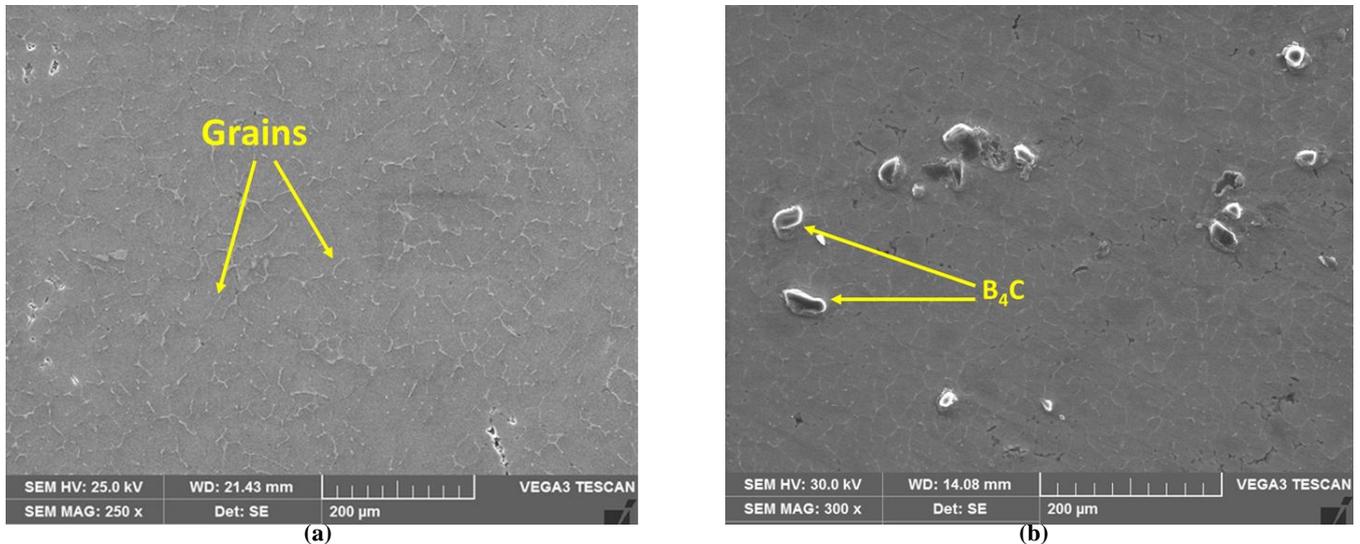


Figure 11: SEM of (a) Al7075 as-cast alloy and (b) Al7075+3wt.% B₄C composites

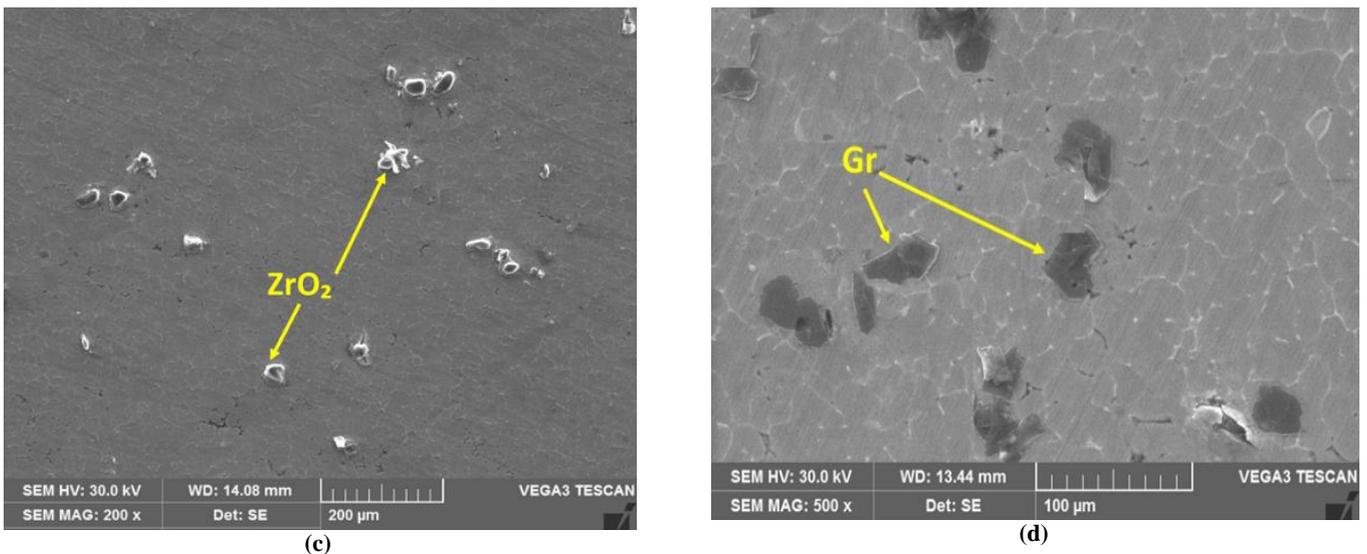


Figure 11: SEM of (c) Al7075+3wt.%ZrO₂ and (d) Al7075+3wt.% Gr composites

Figure 11a shows the microstructure of the base Al7075 alloy, whereas figures 11(b–d) present the composites reinforced with 3 wt.% B₄C, ZrO₂, and graphite, respectively. The SEM images reveal a uniform distribution of the reinforcement particles, with no observable pores or voids. All composites were fabricated using a two-step stir-casting technique, and the reinforcements were preheated to improve wettability and dispersion. The micrographs confirm good interfacial bonding between the Al7075 matrix and the added particulates, indicating effective incorporation of B₄C, ZrO₂, and graphite into the alloy.

Figure-12 displays the EDS spectrum of the Al7075 alloy, validating its elemental signature. Distinct peaks corresponding to Si, Cu, Mn, Ti, Mg, Fe, and Zn are observed, with Zn exhibiting the highest intensity, consistent with its major contribution to the alloy chemistry.

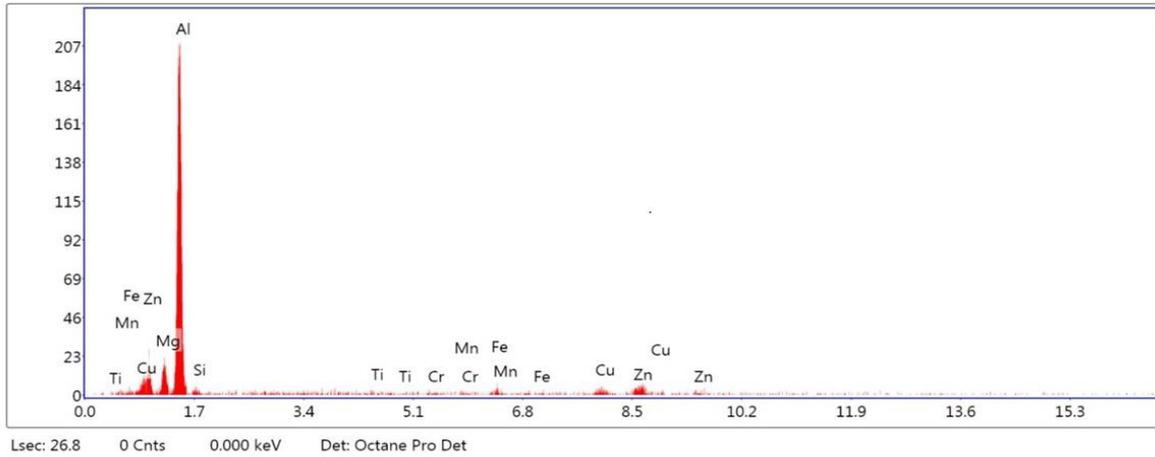


Figure 12: As-cast Al-7075 alloy's EDS spectrum

Figure 13(a–c) presents the EDS spectra of the Al7075 composites containing 3 wt.% B₄C, ZrO₂, and Gr reinforcements, respectively. Zinc remains the dominant peak in all spectra, consistent with its role as the primary alloying element in Al7075. The composites show additional peaks corresponding to the respective reinforcements: B and C for B₄C (Fig. 13a), Zr and O for ZrO₂ (Fig. 13b), and C for graphite (Fig. 13c). These elemental signatures confirm the effective incorporation of each reinforcement into the Al7075 matrix.

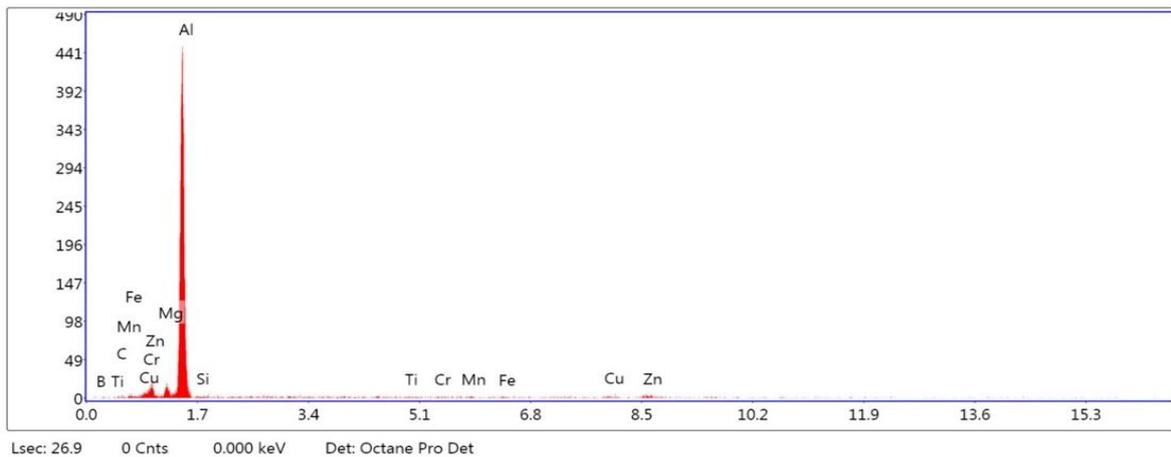


Figure: 13a

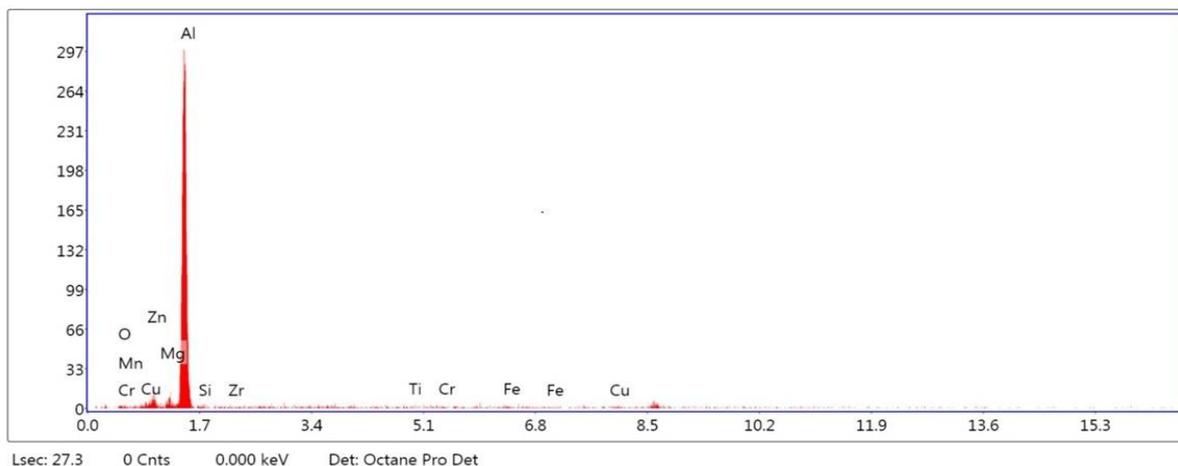


Figure: 13b

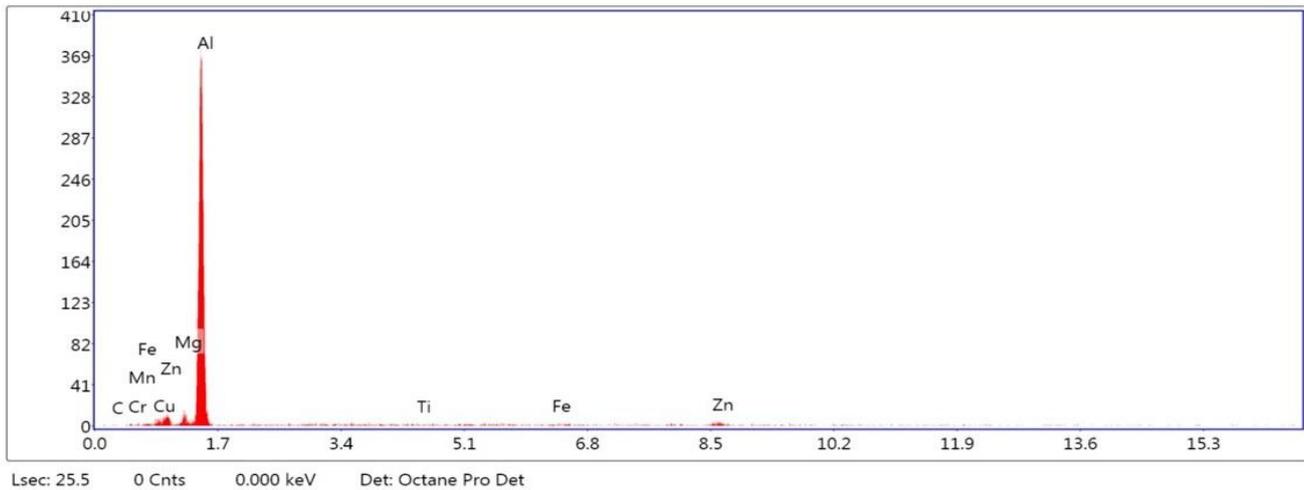


Figure: 13c

Figure 13: EDS spectra of Al7075 composites reinforced with (a) 3wt.% B₄C, (b) 3wt.% ZrO₂, and (c) 3wt.% graphite (Gr)

3.2 Hardness

Hardness measurements were carried out using a ball indenter under a 250-kgf load and a 30-second dwell time to evaluate Al7075 and its composites containing 3 wt.% Gr, ZrO₂, and B₄C, as illustrated in figure-14. When 3 wt.% graphite was incorporated, the hardness of Al7075 decreased from **68.7 BHN** to **64.0 BHN**. This reduction arises from the soft, lubricating characteristics of graphite, which lacks the stiffness required to effectively impede dislocation movement in the matrix. Instead, graphite functions more as a solid lubricant, enhancing ductility rather than contributing to strengthening, an effect consistent with trends reported in earlier material studies [24].

The hardness of Al7075 increases from 68.7 BHN in the base alloy by about 11% with the addition of 3 wt.% ZrO₂. This improvement is attributed to microstructural refinement, where ZrO₂ particles act as heterogeneous nucleation sites and promote finer grain formation. The hard ceramic particles also impede dislocation motion, increasing dislocation density through thermal mismatch and Orowan strengthening. Additionally, their uniform distribution enhances particle–matrix interfacial bonding and reduces porosity, collectively contributing to the observed hardness increase.

The hardness of the Al7075 with 3 wt.% B₄C composite increases from 68.7 BHN in the base alloy to 79.3 BHN, showing an improvement of approximately 15.4%. This rise in hardness is primarily due to the presence of hard B₄C particles, which effectively hinder dislocation motion and strengthen the matrix [25]. The stir-casting process ensures uniform dispersion and strong interfacial bonding, enabling efficient load transfer from the matrix to the reinforcements. Acting as rigid, load-bearing particles, B₄C significantly enhances the composite’s resistance to indentation and wear, making the 3wt.% B₄C reinforcement the most influential in improving hardness among the studied composites. In summary, graphite reduces the hardness of Al7075 due to its soft, lubricating behaviour, whereas ZrO₂ and B₄C significantly enhance hardness through grain refinement and strong particle–matrix interactions. Among all reinforcements, B₄C yields the highest hardness improvement.

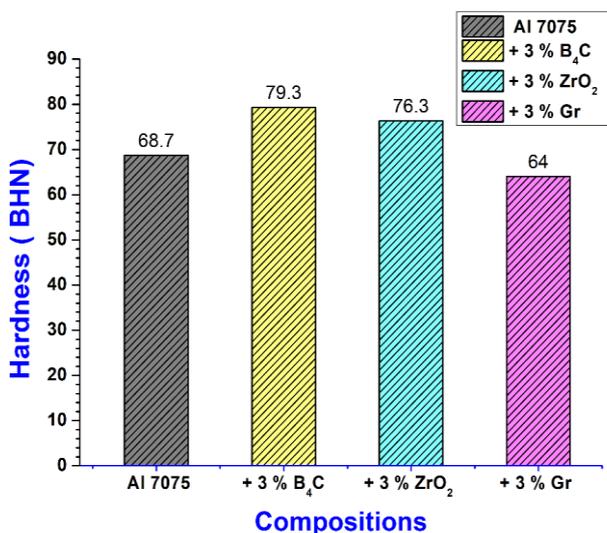


Figure 14: Variation in Hardness of Al7075 with B₄C, ZrO₂, and Graphite Additions

3.3 Tensile Properties

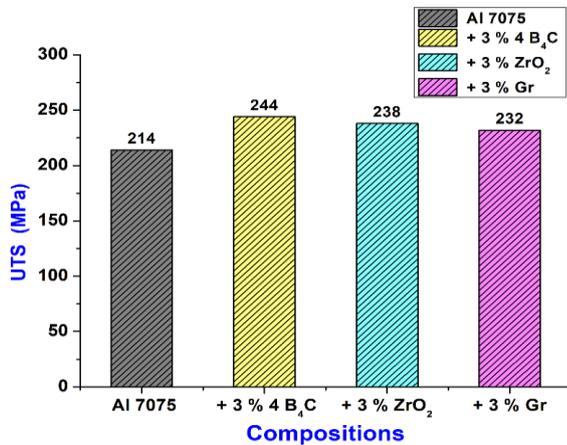


Figure 15: UTS of Al7075 with B₄C, ZrO₂, and graphite particles

Figure-15 shows the tensile performance of the Al7075 composites shows a clear dependence on the type of reinforcement introduced. The graphite-added composite offers only a slight rise in strength, as the soft, layered structure of Gr primarily assists in crack deflection rather than significantly hindering dislocation motion. With ZrO₂ reinforcement, the alloy exhibits better improvement due to the particle-induced grain refinement, which produces a denser and more uniform microstructure. The most notable enhancement is observed in the B₄C-reinforced composite, where the UTS reaches 244 MPa, corresponding to an improvement of approximately 13.4% over the base alloy. This increase is strongly linked to microstructural refinement, uniform distribution of hard B₄C particles, and strong particle–matrix bonding, all of which support efficient load transfer and restrict plastic deformation [26]. Because of these strengthened microstructural characteristics, the B₄C-reinforced Al7075 composite is highly suitable for aerospace joints, automotive structural components, defence armour systems, and other lightweight applications that demand superior strength and reliability.

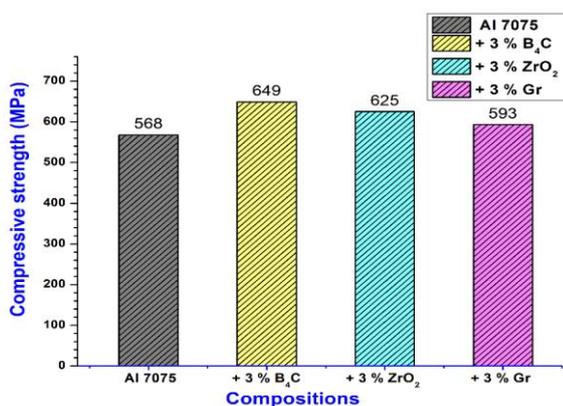


Figure 16: Compressive strength of Al7075 with B₄C, ZrO₂ and graphite particles

Figure-16 shows the compressive strength values for the Al7075 alloy and its composites containing 3wt.% B₄C, ZrO₂, and graphite. The unreinforced alloy exhibits a compressive strength of 568 MPa. When B₄C is added, the strength increases markedly to 649 MPa (about 14.2% improvement). This enhancement is mainly due to the presence of hard B₄C particles that are uniformly distributed within the matrix, allowing them to carry a portion of the applied load and restrict dislocation motion. The composite reinforced with ZrO₂ reaches a strength of 625 MPa (roughly 10% increase), which can be linked to grain refinement and stronger particle–matrix bonding that improves resistance to deformation. The addition of graphite results in a moderate increase to 593 MPa (around 4.4%), where graphite’s soft, lubricating nature helps in distributing stress more evenly while still contributing to limited load transfer. Microstructural observations support these trends, showing well-dispersed reinforcements and minimal porosity across all composites. The hard ceramic particles (B₄C and ZrO₂) form strong interfaces with the matrix, while graphite produces a smoother, more compliant interface that helps reduce local stress concentrations. Overall, the order of improvement B₄C > ZrO₂ > Graphite reflects the combined influence of reinforcement hardness, interfacial integrity, and grain refinement on the compressive behaviour of the composites, making them suitable for demanding structural applications.

3.5 Impact strength

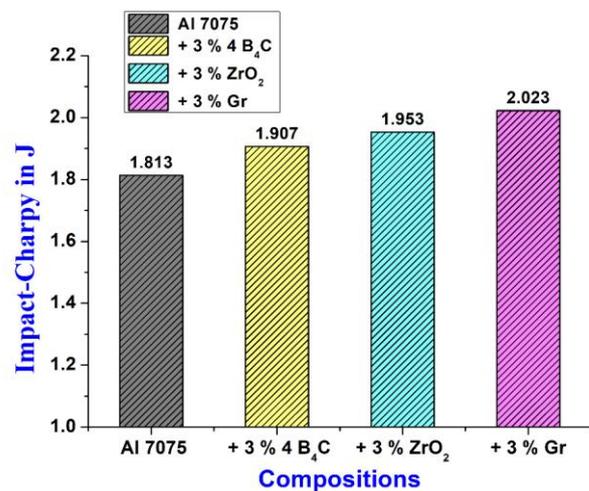


Figure 17: Compressive strength of Al7075 with B₄C, ZrO₂, and graphite particles

Figure-17 shows the impact strength results show that adding reinforcements significantly improves the energy-absorbing capability of Al7075. The base alloy registers an impact strength of 1.813 J, which increases to 1.907 J with 3wt.% B₄C and 3wt.%ZrO₂, representing identical improvements of 5.19%. These moderate gains result from the

uniform dispersion of ceramic particles that enhance load transfer and minimize local stress concentration, even though the particles themselves are brittle. The highest improvement is achieved by the 3 wt.% graphite-reinforced composite, which records 2.023 J—an 11.57% increase over the unreinforced alloy. This superior performance stems from graphite’s ductile, layered structure, which promotes crack deflection, enhances energy absorption, and reduces internal stresses during impact. Overall, the trend Graphite > ZrO₂ ≈ B₄C > Al7075 indicates that impact toughness is strongly influenced by the compliance and energy-dissipating behaviour of the reinforcement, with graphite providing the most significant benefit for components subjected to dynamic or sudden loading.

flexural strength improves when stiff ceramic particles are used, while the more compliant graphite phase lowers resistance to flexural deformation.

IV. CONCLUSIONS

Composites of Al7075 reinforced with graphite, ZrO₂, and B₄C were successfully fabricated through the stir casting route, and the study's findings included the following conclusions:

- SEM characterization verified a fairly consistent distribution of reinforcement particles within the aluminium matrix of Al7075 and its composites containing 3wt.% B₄C, 3wt.% ZrO₂, and 3wt.% graphite, indicating good particle-matrix bonding.
- The successful incorporation of the reinforcements was supported by the fact that EDS spectra helped confirm the presence of graphite, ZrO₂, and B₄C in the produced Al7075 composites.
- Incorporating 3wt.% graphite into the Al7075 matrix caused a marginal decline in hardness (6.8%), while the B₄C-reinforced composite demonstrated the greatest enhancement, showing a 15.42% rise over the base alloy.
- The ultimate tensile strength (UTS) of Al7075 improved most significantly with the addition of 3wt.% B₄C, achieving a UTS of 245 MPa, which represents a 13.44% increase over the base alloy.
- The compressive and flexural strength of Al7075 improved most significantly with the addition of 3wt.% B₄C, achieving increases of 14% and 15.9%, respectively, over the base alloy, due to uniform particle distribution, grain refinement, and enhanced load transfer from the matrix to the hard B₄C particles.
- Impact testing of Al7075 showed the most significant improvement with the addition of 3wt.% graphite, achieving an increase of 11.8% over the base alloy, due to the ductile nature of graphite particles, which absorbed energy and slowed crack propagation within the matrix.

In overall, Al7075 composites reinforced with 3wt.% B₄C exhibited the highest improvements in hardness, tensile, compressive, and flexural strength due to grain refinement and effective load transfer. Graphite enhanced impact strength and toughness through energy absorption, while ZrO₂ provided moderate improvements across all mechanical properties.

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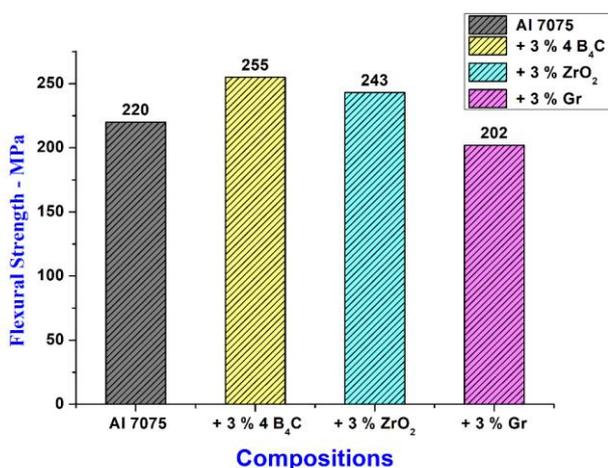


Figure 18: Flexural strength of Al7075 with B₄C, ZrO₂ and graphite particles

Figure-18 presents the flexural strength of Al7075 and its reinforced composites, showing clear differences in bending performance depending on the type of reinforcement added. The base alloy records a flexural strength of 220 MPa. When 3 wt.% B₄C is introduced, the strength rises to 255 MPa, giving a 15.9% improvement. This increase is mainly due to the high rigidity and strong load-supporting ability of B₄C particles, which help the matrix resist bending stresses and delay crack formation. The composite reinforced with 3wt.% ZrO₂ also shows a noticeable improvement, reaching 243 MPa, which corresponds to a 10.45% increase. This enhancement is linked to grain refinement and better adhesion between ZrO₂ particles and the matrix, allowing stresses to be distributed more evenly during flexural loading. In contrast, the composite containing 3 wt.% graphite shows a flexural strength of 202 MPa, an 8.18% reduction compared to the base alloy. The drop in performance is due to the soft and lubricating characteristics of graphite, which reduce the overall stiffness of the composite and limit its ability to withstand bending. Overall, the order B₄C > ZrO₂ > Al7075 > Graphite indicates that

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