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Investigation of the Independent and Combined Roles of Gr and ZrO_2 on Strengthening Behaviour of Al-7075 Composites

Sampath Kumar R.[1,*], H. C. Chittappa[2], Praveena Bindiganavile Anand[3], Manjunath Vatnalmath[4], Madeva Nagaral[5]

Abstract

This study investigates the effect of individual and hybrid reinforcements on the mechanical and microstructural behaviour of Al7075 composite fabricated using the 2-step stir-casting technique. Four compositions were made with the base Al-7075, Al-7075 3 weight % ZrO2, and Al-7075 3 weight % Gr as well as a hybrid composite Al7075 with 3 wt.% Gr, 3 wt.% ZrO2. 2-step stir-casting was used to increase the wettability of the particles, decrease agglomeration and to maintain even distribution of the reinforcement particles. The homogenous dispersion of the particulates was observed and the strength of interfaces bonding was ensured by SEM and the success of the incorporations of the reinforcements was confirmed by EDS. Mechanical analysis revealed that the hybrid composite exhibited the highest enhancement in most of the evaluated properties. The yield strength shows a directly improved by +51 Mpa, increasing from 182 MPa to 233 MPa. Relative to the base alloy, hardness, compressive strength, and impact strength exhibit enhancements of 11.8%, 18.1%, and 16.2%, respectively. These enhancements result from the synergistic strengthening and toughening mechanisms activated by the combined addition of Gr and ZrO2 added together. +The originality of the study is a direct comparison of single and hybrid reinforcement strategies under identical processing conditions, supported by SEM–EDS analysis to clarify the relationship between microstructural features and resulting mechanical performance. The resulting Al7075 hybrid composite is especially suitable for aerospace and automotive component, along with wear resistant, where an optimized balance of strength, toughness and reliability is essential.

Keywords: Al7075, Stir casting, hybrid composites, ZrO2, graphite, mechanical properties, microstructure

INTRODUCTION

Metal matrix composites consist of a tough metallic matrix, such as aluminium, titanium or copper, with rigid ceramic reinforcements in forms like particles, fibres, or whiskers that possess superior strength and modulus. This synergy merges the matrix's high toughness and ductility with the reinforcement's exceptional hardness and stiffness. The outcome is markedly superior mechanical properties over the unreinforced metal alone [1, 2]. AMC's have gained popularity as materials for load-bearing structures in the aerospace, automotive, and other manufacturing

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because of their high specific strength, low density, and enhanced wear and thermal performance, which enable designers to satisfy contemporary lightweight engineering requirements [3]. Numerous liquid-state, solid-state, and in situ processing methods can be used to produce MMCs. In solid-state processing, the mixed powders are compacted during consolidation and subsequently bonded through diffusion mechanisms is more costly and challenging to control the interface reaction than liquid-state techniques like stir casting [3, 4, 5]. Stir casting are better suited for producing near-shaped final products among the various MMCs production techniques mentioned. Stir casting stands out as a straightforward, adaptable, and economical technique for producing metal matrix composites [6, 7]. Achieving superior properties in metal matrix composites hinges on accomplishing uniform dispersion of ceramic reinforcements throughout the matrix metal and establishing robust interfacial bonding between the matrix and reinforcements [8].

In stir casting of MMCs, factors like melt temperature, rotor speed and duration, particle addition rate, and mould preheat level critically control clustering, porosity, interface reactions, and evenness of reinforcement spread. Fine-tuning them promotes good wetting, cuts defects, and yields a sound microstructure with reliable properties [9, 10]. Preheating the ceramic particles, adding surface modifiers like magnesium, etching or coating particle surfaces, choosing high-purity raw materials, and degassing the melt are some additional steps that work well to improve wetting and uniform dispersion of reinforcements within the metal matrix [11, 12].

Aluminium metal matrix composites (AMCs) are unique because of their minimal density, good machinability, corrosion resistance, and balanced strength and ductility. Ceramic reinforcements like Al_2O_3, SiC, B_2C, and ZrO_2 and solid lubricant graphite are frequently used to improve strength,wear performance, stiffness, and hardness etc. [13, 14]. Composites with a hard ceramic and soft carbon based reinforcers have been developed, referred to as hybrid composites, as a feasible approach in meeting a synergistic balance of mechanical and tribological behavior [15]. Al-6061/ZrO_2 composites having 3 wt.% of ZrO_2 were found to have a uniform network structure of the particles, fine grain structure, and significant increase in hardness, wear and corrosion resistance. Particle aggregation and grain enlargement were apparent when the reinforcement level surpassed 6 wt.% with reduced mechanical performance consequentially. As a result, ZrO_2 3 wt.% was found to be the most appropriate percentage to provide an equal balance between mechanical strength and stability in corrosion [16]. The researchers have employed various types of reinforcing particles to alter the characteristics of the aluminium composites. Among them is graphite, which has a reputation for being an efficient reinforcement that enhances the matrix material's tribological performance [17].

Research on Al7075/SiC/Gr hybrids was able to find that 2 wt.% graphite gave the best hardness and wear resistance with the hybrids, with higher additions decreasing the hardness because the smaller additions caused lubrication. In general, the 2 wt.% graphite composite provided optimum strength/damping behaviour balance [18]. Two-step stir casting has shown considerable promise in improving dispersion of particles, agglomeration reduction, and improved interfacial bonding thus achieving the full potential of hybrid composite potential [19]. A 2-step stir-casting method was used to create Al7075 composites reinforced with 3 weight percent ZrO_2, 3 weight percent Gr, and their blend of hybrids. SEM and EDS analyses verified a homogeneous dispersion of the reinforcing particles. Although the Al7075–Gr composite exhibited slightly lower hardness, it showed superior wear resistance. Among all the compositions, the hybrid Al7075–Gr–ZrO_2 composite demonstrated the most favorable wear performance [20].

The paper explores four Al7075-based composites, namely unreinforced Al7075, Al7075+3wt.%ZrO_2, Al7075+3wt.%Gr and a hybrid of Al7075+3wt.%ZrO_2+3wt.%Gr all prepared by means of a 2-step stir casting procedure. To determine the effects of reinforcement, microstructural (SEM, EDS) and mechanical (yield strength, impact strength, compressive, flexural strength and

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hardness) analyses were performed. The uniqueness lies in directly comparing single and hybrid reinforcements under identical processing conditions, with the hybrid composite showing a synergistic enhancement in mechanical strength and toughness, making it appropriate for wear-resistant, automotive, and aerospace applications.

EXPERIMENTAL DETAILS

Material and Composite Preparation

Al7075 ingots (Perfec Metal Works, Bengaluru, India) were chosen as a matrix material because of their great strength material which finds a lot of application in aerospace and structural. The reinforcement phases graphite (Gr, 30-40µm) and zirconia (ZrO_2, 20-30µm) were obtained from Speed-Fam (India) Pvt. Ltd. Chennai. Table 1 and Table 2 display the primary physical attributes and chemical compositions of the matrix and reinforcement particle. SEM and EDS were used in the investigation of the reinforcements morphology and elemental distribution (Figures 1–3) and confirmed that they are composed of uniformly sized, shaped and composed particles, therefore, establishing their suitability for incorporated into Al7075-based composites.

Figure 2–3 EDS spectra of reinforcements showing zirconium dioxide (zirconium 67.31 wt.%, oxygen 32.69 wt.%), and graphite (carbon 100 wt.%).

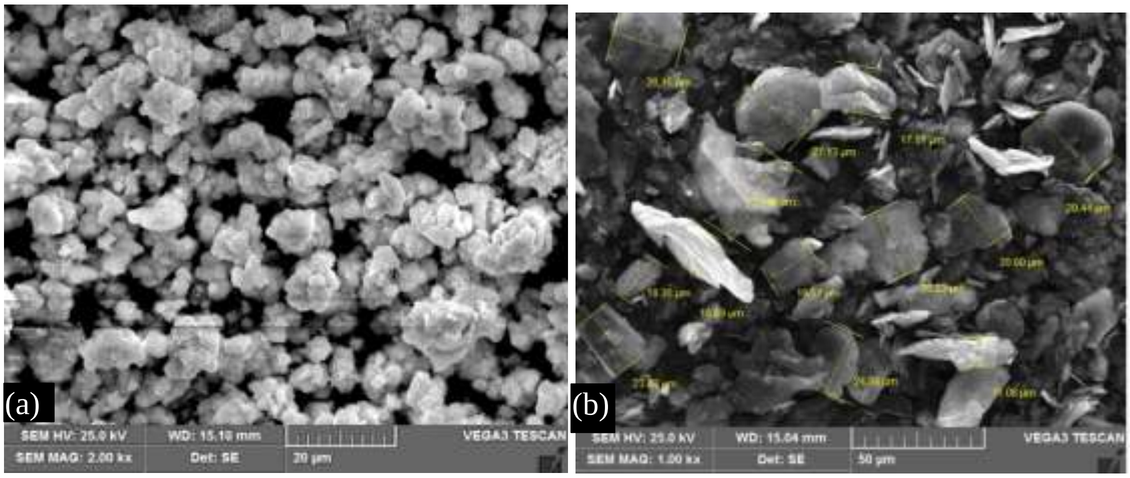


Figure 1. (a, b)SEM Morphology of ZrO_2 and Gr reinforcements.

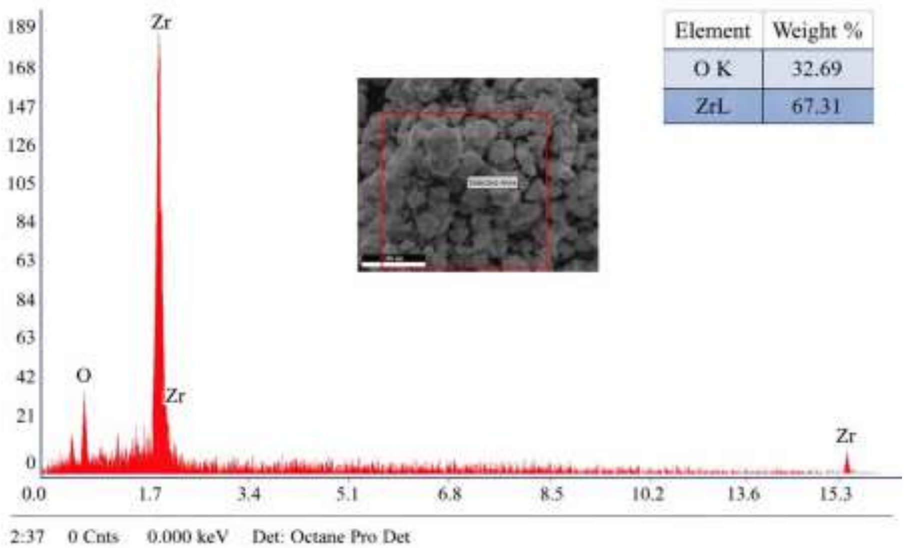


Figure 2. EDS spectrum of ZrO_2 particles.

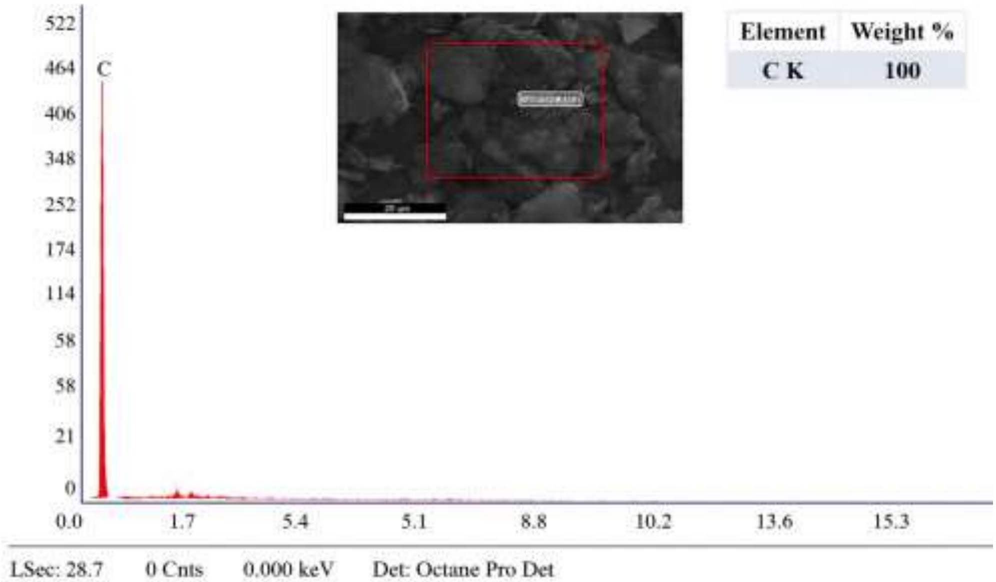


Figure 3. EDS spectrum of graphite particles.

Table 1. Characteristics of the boron carbide, graphite, ZrO_2 particles and Al7075 alloy

Material	Hardness (BHN)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (gm/cm^3)
Al7075	65	205	70	2.80
Graphite	1.3*	200	16	2.2
ZrO_2	1300	1800 (C)**	380	5.68

*Mohs Hardness
**Compression Strength

Table 2. Composition of Al7075 Alloy in Weight Percent

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

The matrix material was aluminium alloy Al7075, and the reinforcing phases were graphite (Gr) and zirconia (ZrO_2). All the reinforcements were added at 3 wt.% in order to create a balance between mechanical reinforcement and the dispersion of the particles in the matrix. The resulting composites were classified as Sample 1 (Al7075 + ZrO_2), Sample 2 (Al7075 + Gr) and Sample 3 the hybrid composite (Al7075+3 wt.%ZrO_2 +3wt.%Gr) to evaluate the reinforcements' synergistic effect on microstructural and mechanical behavior.

The two-stage stir casting technology, a reliable liquid metallurgy technique for incorporating particle reinforcements into aluminium matrices, was employed to produce Al7075-based AMCs. First, high-purity, commercial-grade Al7075 Ingots were placed in a crucible made of graphite and fully melted at 650–680°C. Thermocouples were used to continually monitor the melt temperature in order to preserve thermal stability and avoid localised overheating. In order to reduce porosity and improve the structural integrity of the cast alloy, solid hexachloroethane tablets were used for degassing in order to release dissolved gases and trapped air [11, 2].

The graphite and ZrO_2 reinforcements were heated to 300–350 °C before being added in order to eliminate any remaining moisture and improve wettability with the aluminium melt. K_2TiF_4 flux was added to the molten Al-7075 matrix to encourage interfacial bonding and prevent particle agglomeration. This was followed by mechanical stirring at 300 rpm for 5 to 10 minutes to make sure uniform dispersion and avoid particle clustering or sedimentation. Effective compatibility between the reinforcements and the matrix was achieved by the two-step stir-casting process in conjunction with thermal conditioning and interfacial activation. While graphite's wettability was greatly increased, ZrO_2 remained chemically stable in the molten aluminium, leading to uniform particle incorporation and stable matrix-reinforcement interfaces.

After the particles were evenly incorporated, the composite melt was superheated to 720–740°C and then transferred into a graphite mould that had been pre-heated to 200–250 °C. Thermal gradients were reduced and favourable microstructural development was encouraged by this regulated thermal management. The resultant cylindrical specimens were suitable for further mechanical testing as they measured 15 mm in dia and length of 120 mm. The Al7075 composites enhanced mechanical performance and reliability were made possible by the regulated two-stage processing, which successfully guaranteed consistent particle integration, strong matrix–particle adhesion with minimum casting flaws.

Figure 4 demonstrates the stir-casting apparatus that will be used in the production of the Al7075-based composites, and Figure 5 depicts cast specimens with the reinforced with ZrO_2 and graphite. Samples were prepared to be analyzed using a microstructural technique in a systematic manner through metallography preparation. The specimens were first ground gradually with silicon carbide abrasive papers of 200, 400, 600 and 800 roughness to create an even surface and free of the scratch. This was then polished with a fine polishing on a soft velvet cloth making use of a suitable polishing chemical to produce a reflecting mirror-like polish.

Figure 4. The composites were made using a stir casting setup.

Figure 5. Al 7075 alloy reinforced with, ZrO_2, Gr and hybrid composites.

The polished specimens were etched in a reagent containing a specific ratio of nitric acid, hydrofluoric acid and hydrochloric acid also known as Keller reagent which was used to reveal the underlying microstructure. Etching exposed critical properties such as grain boundaries, reinforcement particle distribution, and interface areas between the matrix and particulates. The etch and residual debris were vigorously washed with distilled water. A VEGA3 TESCAN-(Figure 6) scanning electron microscope (SEM) was used to conduct microstructural observations that enabled the high-resolution determination of the particle homogeneity, matrix-reinforcement bonding, and morphological features that are important to relate microstructure to the mechanical performance of the composites.

The specimens' Brinell hardness had been determined using ASTM E10 [22]. The samples were well prepared, such that they smooth and flat surface, free from burr or scratches, which would lead to errors in the indentation. A 250 kg-f load weight was imposed by means of an indenter made of steel ball having a diameter of 5 mm. Three different points were made on each specimen with a well-spaced point to consistently, and the representative hardness, which was determined by recording the average value. This approach allowed exact and reproducible assessment of hardness for all composite types.

To examine the tensile performance of the Al7075 as-cast and its composites with 3 weight percent reinforcement, individually and in hybrid forms, tensile testing specimens were made in alignment with ASTM E8 [23]. As seen in Figure 7, specimens were put through uniaxial tension using a computer-assisted universal testing apparatus. Each test sample had a gauge diameter of 9 mm and 45 mm length. Each specimen's load-bearing capacity was precisely measured by the tensile test, allowing for a direct correlation with its mechanical behaviour and microstructure.

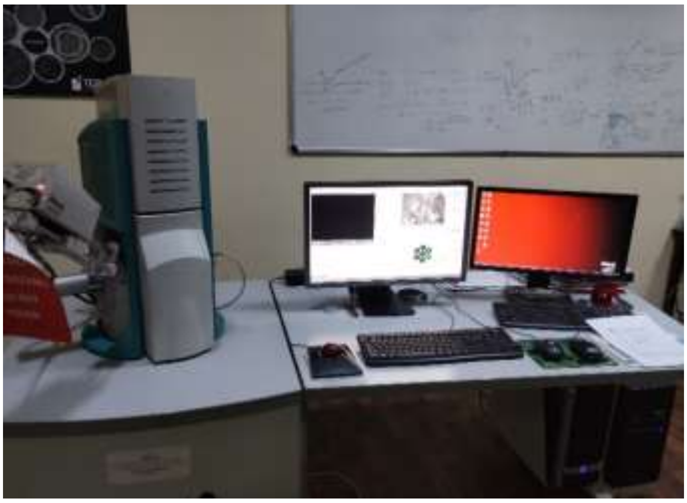


Figure 6. SEM/EDAX (VEGA3 TESCAN)

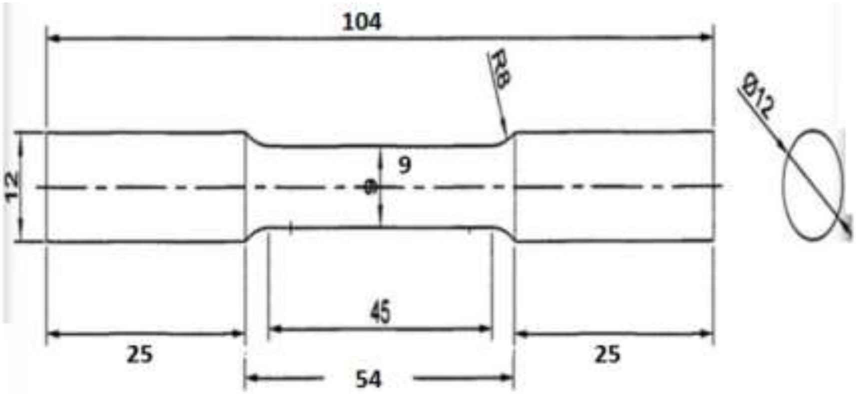


Figure 7. Tensile Specimen Dimensions in Compliance with ASTM E8.

As shown in Figure 8, the Al7075 alloy and its composites' compression behaviour was evaluated in accordance with ASTM E9. Cylindrical samples with a height-to-diameter ratio of 2:1 were subjected to uniaxial compressive loading. The investigation included both the hybrid combination and specimens reinforced with 3 weight percent of individual particles. This method made it possible to assess how particle dispersion and hybridisation affected overall compressive performance, deformation processes, and load-bearing capacity.

Figure-9 depicts the Charpy impact testing sample sketch used in accordance with ASTM E23 to assess the fracture toughness of the Al7075 alloy and its particulate-reinforced composites. A single-blow loading was applied to standard V-notched specimens, and the energy absorbed during fracture was noted as the material's impact strength, indicating its ability to withstand abrupt loading. The three-point bending setup sample used for flexural evaluation in accordance with ASTM D790 is shown in figure-10. Rectangular specimens were loaded in the middle and supported at both ends until they failed. The maximum bending stress encountered prior to fracture was defined as the flexural strength. The maximum bending stress measured just prior to fracture was regarded as the flexural strength, and failure was induced under increasing load.

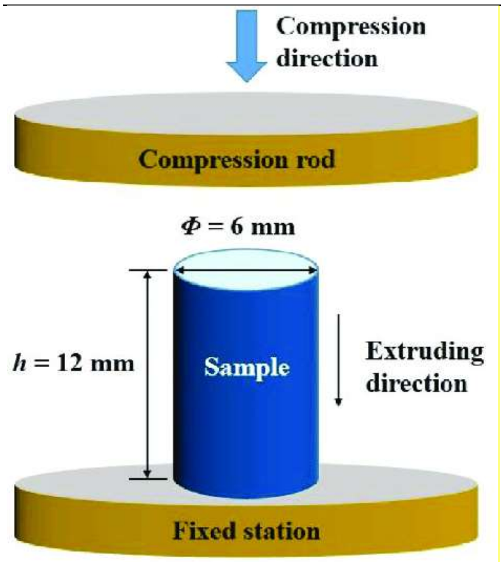


Figure 8. Compression Test Specimen Geometry (ASTM E9).

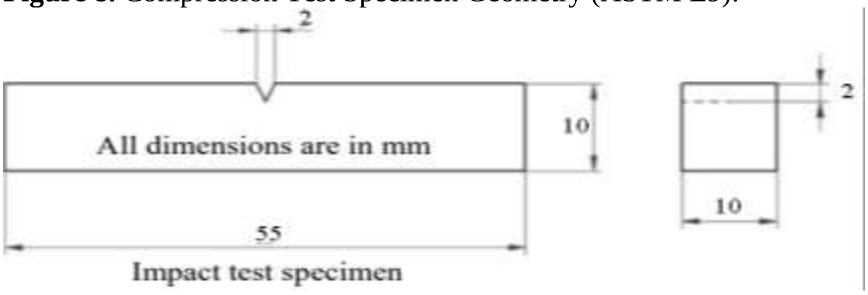
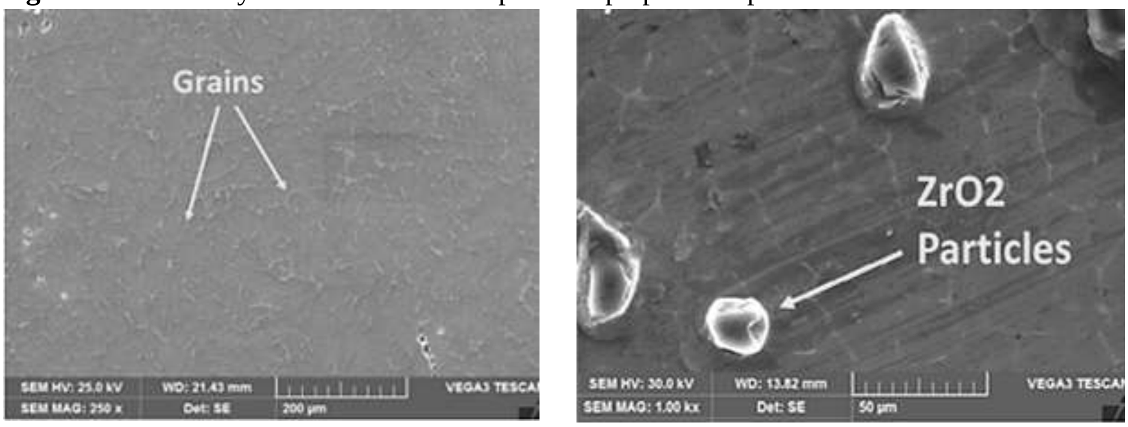


Figure 9. Charpy-Impact test specimen geometry in accordance with ASTM.

Figure 10. Geometry of the Flexural test specimen prepared as per ASTM.



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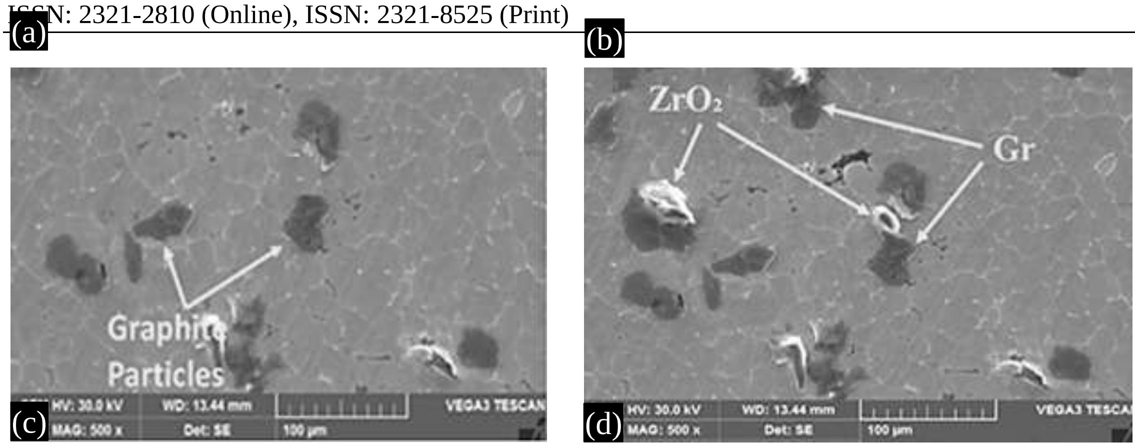


Figure 11. SEM of (a) As-cast Al7075 (b) Al7075 +3%ZrO_2 (c)Al7075+3% Gr and (d) Al7075+3% Gr+3%ZrO_2 composites.

EXPERIMENTAL ANALYSIS AND RESULTS

Microstructural Analysis

Figure 11(a) illustrate the morphology of the unreinforced Al7075 alloy, and Figures 11(b–d) correspond to the composites containing 3 wt.% ZrO_2, the composites containing 3 wt.% Gr, and the hybrid mixture containing 3 wt.% Gr + 3 wt.% ZrO_2. The SEM analyses verify that the reinforcement particles are uniformly distributed, with very little porosity or agglomeration. Improved wettability was encouraged by the two-step stir-casting process, which was aided by particle preheating.

This allowed the particulates to be uniformly assimilated into the molten alloy. Effective wettability, stable interfacial bonding, and successful reinforcement incorporation are verified by the SEM micrographs, which show a uniform dispersion of ZrO_2 and graphite particles with little clustering and clean matrix–reinforcement interfaces. These findings are directly related to the enhanced mechanical performance of the composites.

The EDS spectrum of the alloy Al7075 is illustrated in Figure 12 and indicates the elemental composition of the alloy. It is observed that there are well defined peaks of Si, Cu, Mn, Ti, Mg, Fe and Zn, with the most prominent peak that is attributed to Zn, highlighting its essential role in the chemistry of the alloy and its impact on improving mechanical performance.

Figure 13 displays the EDS spectrum of Al7075composites (a) 3% ZrO_2, (b) 3% Gr, and (c) hybrid composite with 3% ZrO_2 and 3% Gr. The EDS analysis verifies the presence of ZrO_2 and graphite across the Al7075 matrix, with no detectable signs of interfacial deterioration. This confirms that the processing conditions adopted in the present study were effective in ensuring sound matrix–reinforcement bonding and uniform particle distribution.

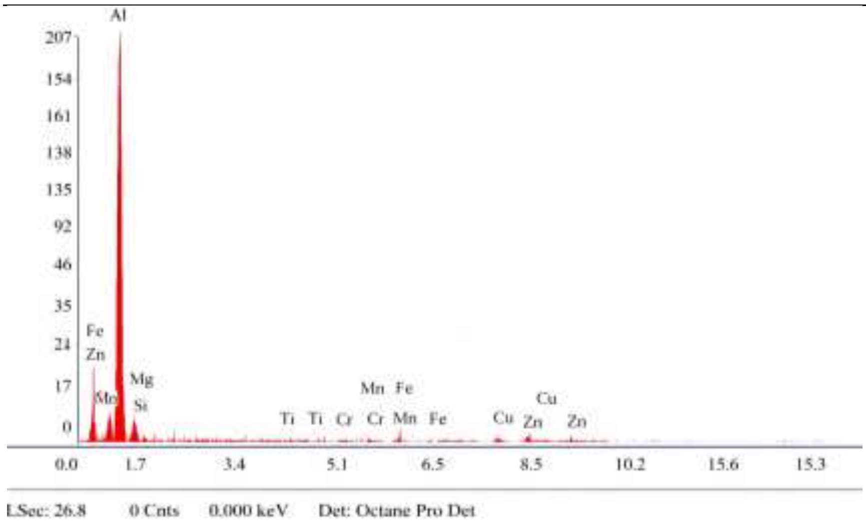
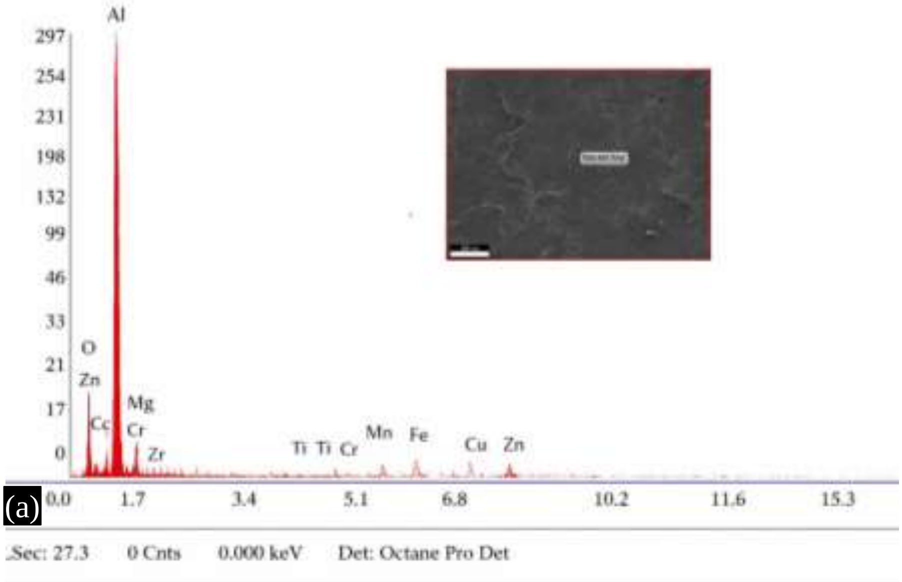


Figure 12. As-cast Al-7075 alloy's EDS spectrum.



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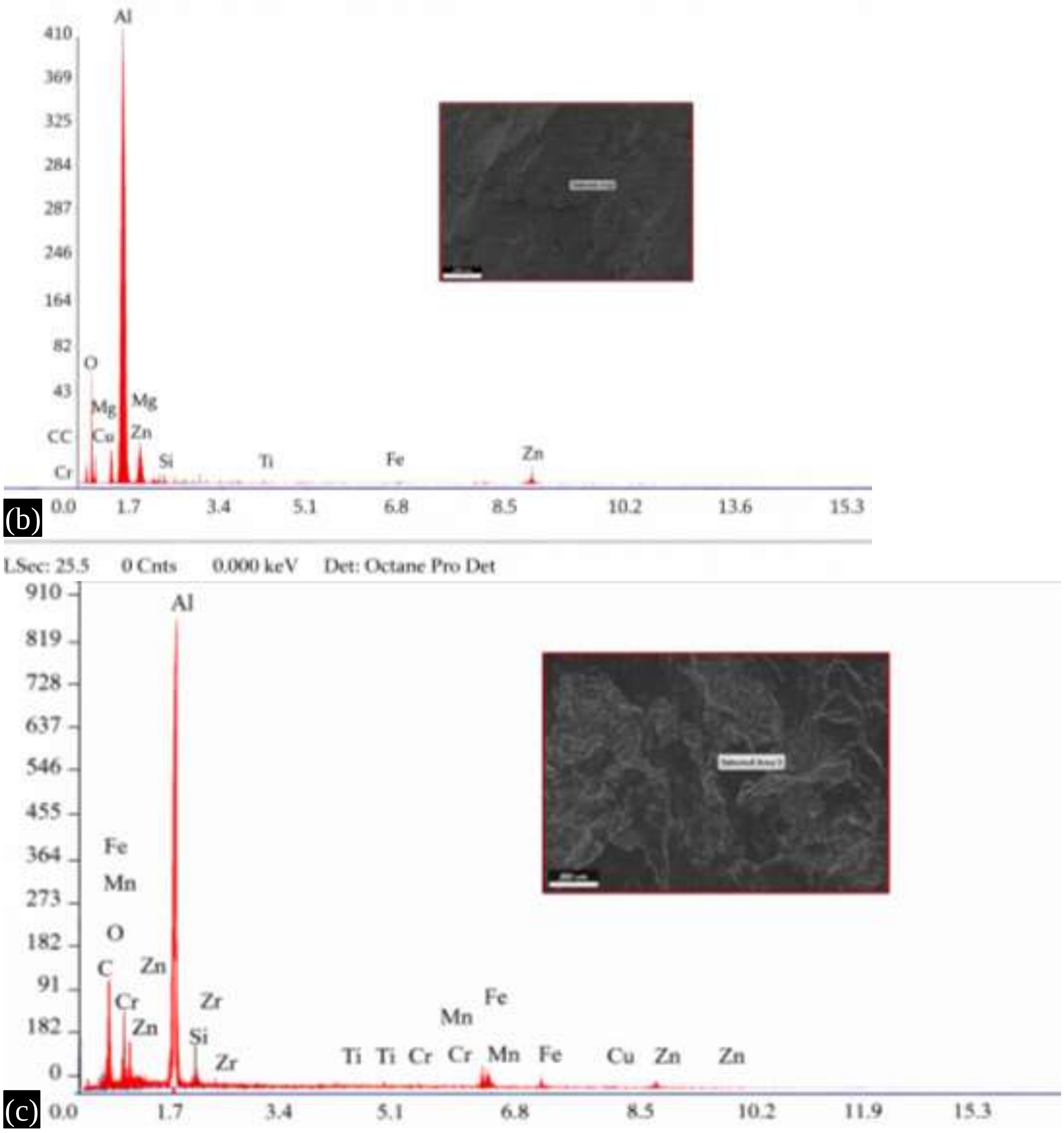

Figure 13. (a–c) EDS spectrum of Al7075 composites reinforced with (a) 3%ZrO_2, (b) 3%Gr, and (c) 3%Gr & 3%ZrO_2

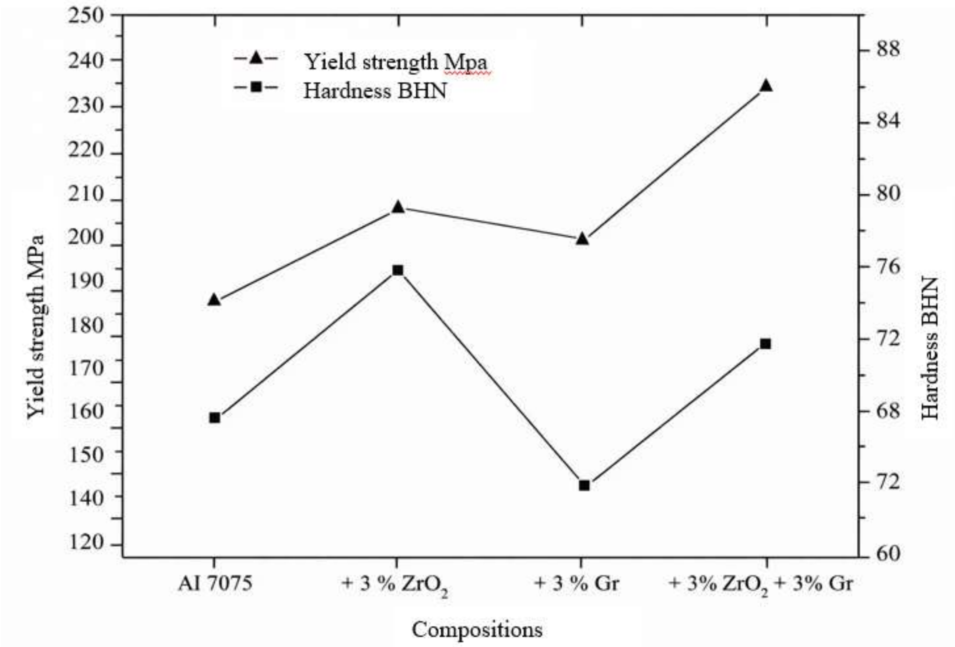

Figure 14. Alterations in Al7075's Yield strength & Hardness of with ZrO_2, and Gr reinforcement Additions.

Hardness

The hardness behaviour of the composites of Al7075 is depicted in figure-14, which clearly demonstrates the impact of the additional reinforcements. Because the hard ceramic particles prevent dislocation movement and improve the microstructure, the base alloy records 68 BHN, which rises to 76 BHN with 3 weight percent ZrO_2. This represents an 11.8% improvement. On the other hand, when 3 wt. % of graphite is added, the hardness drops to 64 BHN because Gr soft, lubricating properties make it less resistant to indentation. The hybrid composite achieves 72 BHN, suggesting a balanced effect in which graphite somewhat moderates hardness while ZrO_2 increases it. Overall, the combined contributions of particle rigidity, dispersion quality, and interfacial bonding are correlated with the trend ZrO_2 > Hybrid > Base > Gr. [24, 25].

The Tensile Characteristics

The yield strength of the Al7075 composites in Figure 14 illustrates how each reinforcement contributes differently to the alloy's ability to withstand the onset of plastic deformation. Because the strong ceramic particles serve as obstacles to the motion of dislocation and improve grain refinement, the base alloy's yield strength of 182 MPa increases to 205 MPa with 3 wt. % of ZrO_2. The graphite-reinforced composite shows a moderate increase to 194 MPa because graphite enhances load transfer but its soft nature limits the amount of strengthening. With a yield strength of 233 MPa, the hybrid composite outperforms the base alloy by a substantial +51 MPa. The synergistic effect of ZrO_2 and Gr, where ZrO_2 strongly hinders dislocations while graphite enhances stress transfer and decreases localised strain accumulation, is responsible for this superior performance [25]. The refined, well-bonded microstructure created by the combined reinforcement increases the alloy's ability to withstand applied loads before yielding.

Compressive Strength

Figure 15 illustrates how the addition of both individual and hybrid reinforcements, backed by the corresponding microstructural changes, significantly improves the compressive strength of the Al7075 composites. With 3 weight percent ZrO_2, the base alloy's strength rises to 625 MPa from 568 MPa. According to SEM observations that demonstrate uniform particle anchoring and decreased microvoid

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formation, this improvement is ascribed to the presence of hard ceramic particles that successfully obstruct plastic flow, refine the grain morphology, and produce a more compact matrix. Because graphite can more evenly distribute stresses and suppress localised deformation, the composite reinforced with 3 weight percent graphite records 593 MPa, a moderate increase. Gr is relatively soft, but by smoothing the stress path at the particle–matrix interface, its lamellar structure helps to delaying the initiation of microcracks.

Because of the synergistic interaction between ZrO_2 and graphite, the hybrid composite exhibits the highest compressive strength of 671 MPa. Superior mechanical stability under compressive loading is a result of improved particle dispersion, refined grains, and decreased porosity, all of which are revealed by microstructural analysis. While graphite helps to reduce stress concentration and stabilise the microstructure during progressive compression, ZrO_2 offers high rigidity and resistance to deformation. Higher compressive stresses can be withstood by the material because of the hybrid architecture that results, which creates a densely packed and well-bonded matrix. Consequently, the observed trend is Hybrid > ZrO_2 > Gr > Base correlates directly with the microstructural refinement and enhanced load-transfer capabilities imparted by the reinforcements.

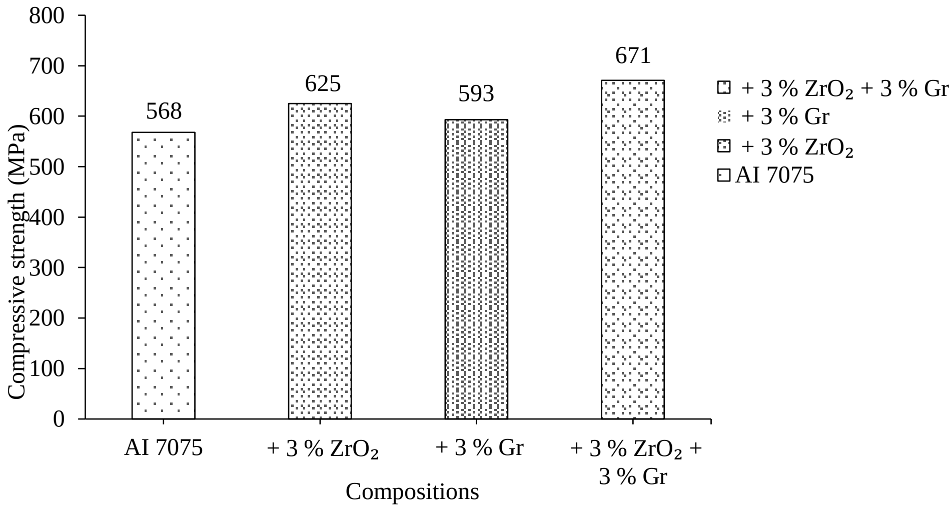

Figure 15. Influence of ZrO_2 and graphite reinforcements on the compressive strength of Al7075.

Impact Strength

The impact behaviour of as-cast alloy Al7075 and its reinforced composites is shown in Figure 16, clearly improving with the addition of graphite, ZrO_2, and their hybrid combination. An impact energy of 1.813 J is recorded for the base alloy. The value rises to 1.953 J with 3 weight percent ZrO_2, which is in line with microstructural observations where the fine ceramic particles are evenly distributed and function as efficient barriers to crack movement. The presence of graphite flakes within the matrix, which help relieve stress concentration and stop crack growth, is responsible for the composite containing 3 weight percent graphite reaching 2.023 J.

The hybrid composite yields the highest value of 2.107 J. This specimen's microstructure demonstrates that both ZrO_2 and graphite are evenly distributed throughout the matrix, resulting in a combined effect where ZrO_2 limits the propagation of cracks and graphite helps with energy absorption and crack deflection. The consistent increase in impact energy is due to combined microstructural behaviour, which also demonstrates that hybrid reinforcement provides greater toughness than individual additions.

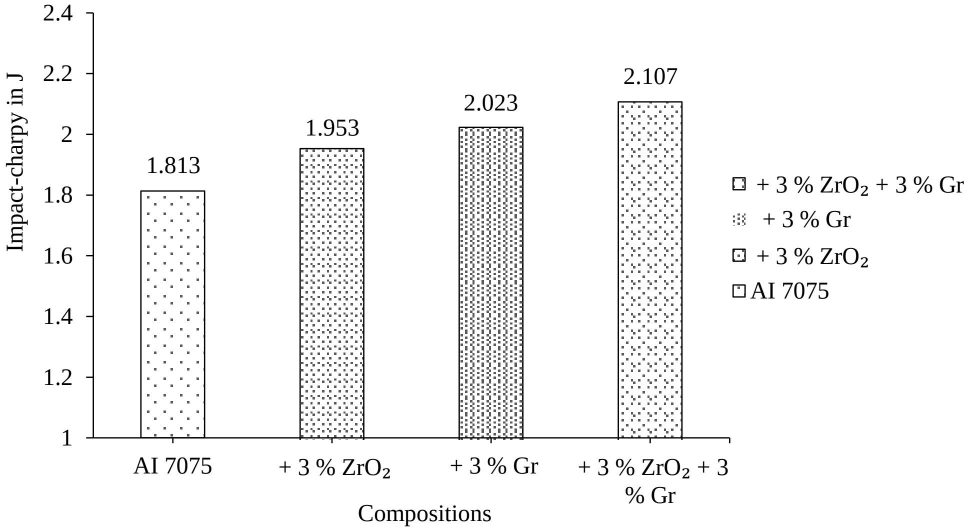

Figure 16. Influence of ZrO_2 and Gr Reinforcements on the Impact Strength of Al7075

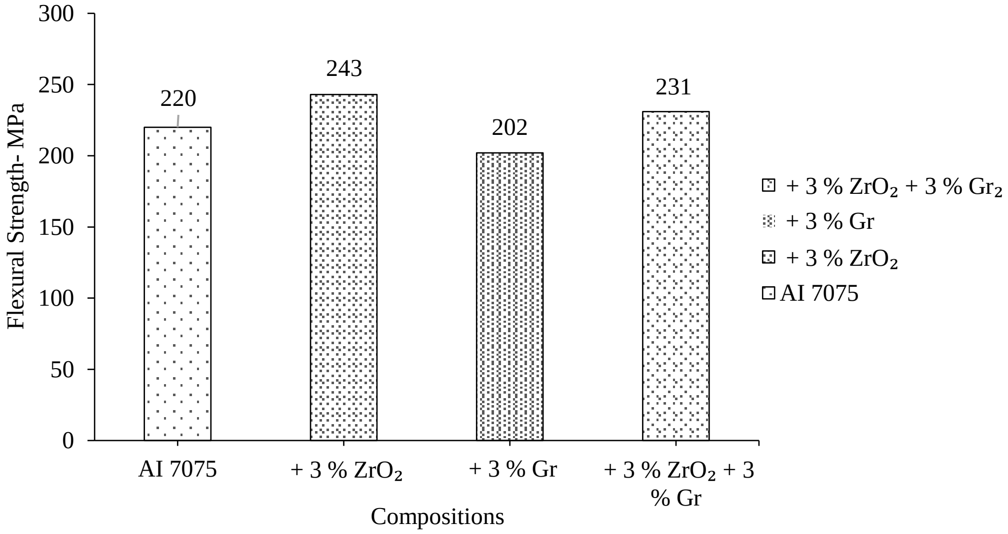

Figure 17. Influence of ZrO_2 and Gr Reinforcements on the Flexural Strength of Al7075.

Flexural Strength

Flexural performance was assessed using a standard three-point bending setup, in which rectangular specimens were supported at both ends and loaded centrally using a universal testing machine until fracture. According to Figure 17 flexural strength values for all compositions, the base Al7075 alloy has a strength of 220 MPa, which increases to 243 MPa when 3 weight percent ZrO_2 is added. Among the single-reinforcement composites, the stiff ceramic particles have the highest flexural enhancement because they serve as micro-load carriers, prevent matrix deformation, and successfully stop crack initiation. The Al7075 + 3 wt. % of Gr composite, on the other hand, shows a decreased flexural strength of 202 Mpa where soft graphite flakes create weak interfaces and make it easier for cracks to propagate along the matrix graphite boundary

The hybrid composite with 3 weight percent of Gr and 3 weight percent ZrO_2 has a flexural strength of 231 Mpa. In this case, Gr helps with controlled crack blunting and crack deflection, while the stiff ZrO_2 particles enhance rigidity and load transfer. Flexural behaviour improves somewhat but steadily as a result of this balanced reinforcement effect. Overall, the findings unequivocally demonstrate that

ZrO_2 primarily contributes to flexural strengthening, while graphite increases ductility but decreases bending rigidity. The combination of these two elements results in a well-balanced microstructure that is more effective at preventing flexural fracture.

Compressive Fractography

The SEM fracture morphologies shown in Figures 18(a–d) illustrate the impact of particle–matrix interactions, interfacial integrity, and microstructural constraint on the deformation and failure mechanisms of Al7075 and its reinforced composites under compressive loading.

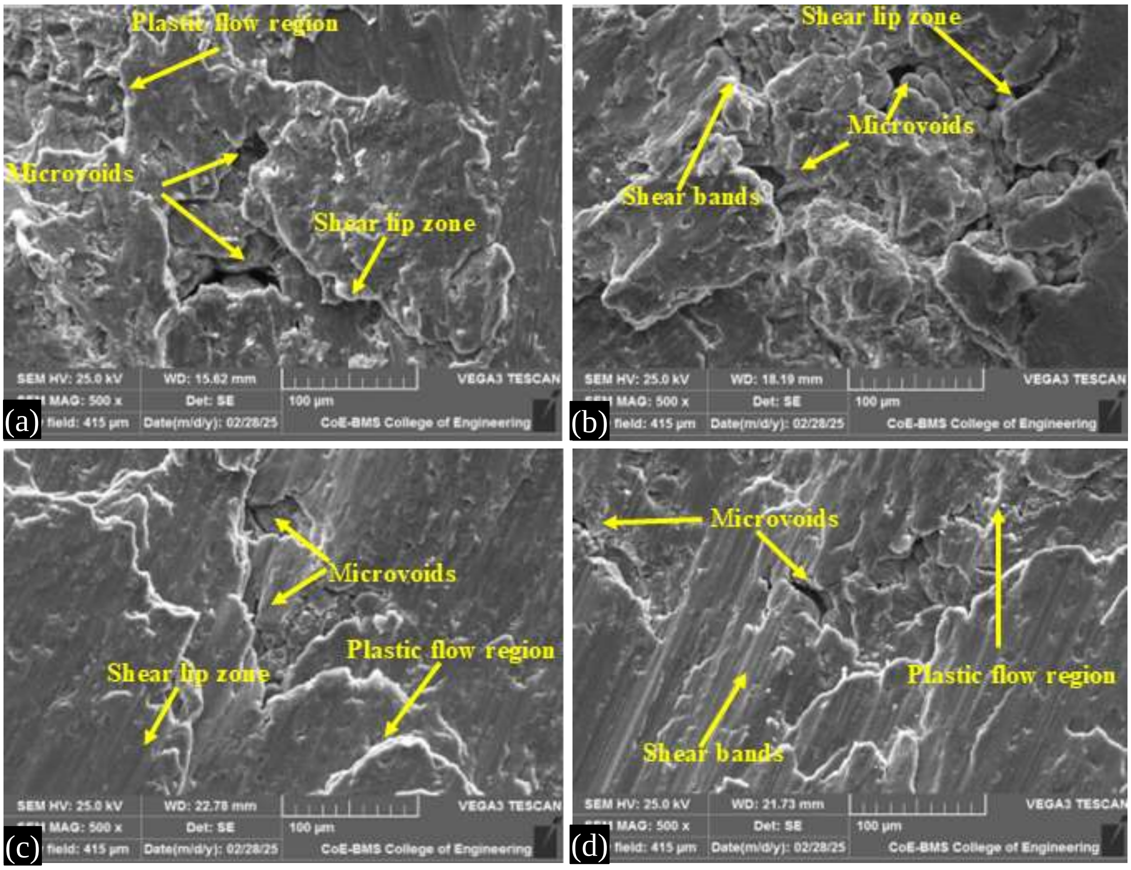

Figure18. SEM images of compressive fractured surfaces (a) Alloy Al7075, (b) Al7075+3%ZrO_2, (c) Al7075+3%Gr and (d)Al7075+3%ZrO_2 +3%Gr.

The as-cast Al7075 alloy is depicted in figure (18a), which shows a highly heterogeneous fracture surface with microvoids, shallow transgranular cracks, and tearing ridges. These features indicate dominant ductile flow along with localised shear banding; the lack of reinforcement permits unrestricted plastic deformation, which correlates with its lower compressive strength. ZrO_2 induced grain-boundary pinning and matrix hardening are reflected in figure (18b) Al7075 + 3 weight percent ZrO_2 composite, which has a denser, more interlocked morphology with decreased crack continuity. Nevertheless, isolated particle matrix debonding continues due to localized strain accumulation around rigid ceramic inclusions.

The Al7075 + 3 weight percent Gr composite in figure (18c) exhibits smeared lamellar features and intergranular shear traces, which are indicative of lubricant-assisted plasticity resulting from graphite's solid lubricant behaviour. This reduces frictional resistance and slows the propagation of cracks but restricts load-bearing capacity when compared to ceramic reinforcement. With minimal interfacial discontinuities and suppressed microcrack density, the hybrid composite in figure (18d) exhibits the most refined and homogeneous fracture topology, demonstrating a synergistic strengthening mechanism wherein ZrO_2 improves rigidity and load transfer while graphite facilitates uniform strain accommodation; this interaction fosters a quasi-ductile fracture response that balances strength and deformability. The fractographic signatures taken as a whole verify that reinforcement, particularly hybridisation, maximises crack arresting effectiveness and enhances energy absorption under compressive deformation, which is consistent with the noted increases in compressive strength values.

CONCLUSIONS

Stir casting was successfully employed to fabricate Al7075 composites reinforced with ZrO_2 and graphite and observed synergistic strengthening is confirmed through direct experimental comparison of single-reinforced and hybrid composites processed under the same conditions.

- Graphite and ZrO_2 reinforcements were equally spread throughout the Al7075 matrix,
- according to SEM analysis, suggesting good bonding and little clustering in all composites.
- Graphite and ZrO_2 were successfully incorporated into the Al7075 matrix, demonstrating chemical consistency and successful reinforcement embedding, according to EDS spectra.
- Among all the compositions, 3 weight percent ZrO_2 produced the greatest hardness improvement of 11.7%, rising from 68 BHN to 76 BHN.
- Compressive strength improved substantially with reinforcement, with the hybrid composite obtaining the highest value (671 MPa), demonstrating the synergistic strengthening effect of ZrO_2 and graphite.
- In response to improved stress transfer and synergistic grain-boundary pinning, the hybrid composite's yield strength improved by 28%, from 182 MPa in the base alloy to 233 MPa.
- The hybrid composite's impact strength showed the biggest improvement, rising from 1.813 J to 2.107 J, or 16.2%, as a result of the combined energy absorption (Gr) and crack-deflection (ZrO_2) mechanisms.
- Improved resistance to compressive failure was confirmed by compressive fractography, which revealed more controlled and refined fracture features in the reinforced composites. The hybrid specimen displayed restricted shear bands and crack deflection.

Overall, ZrO_2 alone produced the maximum hardness and flexural strength, the hybrid composite (3 weight percent ZrO_2 + 3 weight percent Gr) produced the greatest improvements in yield strength, compressive strength, and impact toughness. Therefore, the hybrid composite is the best-performing Al7075 material for demanding lightweight and long-lasting engineering applications because it provides the best balance of strength, stiffness, and toughness.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings are included within the manuscript itself.

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