Effect of B_4C variation on the mechanical, fractographic and tribological performance of hybrid composites $Al7075/Gr/ZrO_2$

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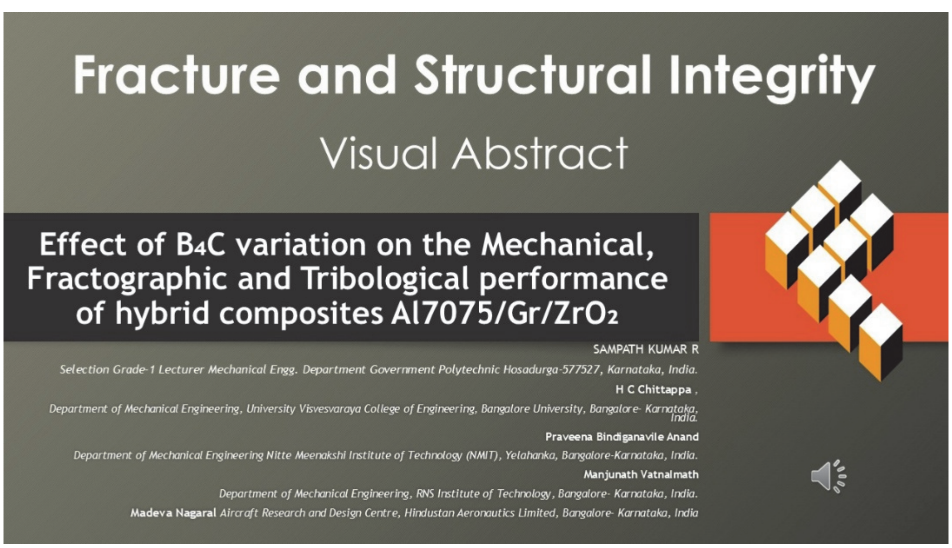

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INTRODUCTION

Aluminium 7075 is a common alloy used in the automotive and aerospace industries because it has a high toughness, ratio of strength to weight, and resistance to fatigue. It is well suited for high-stress structural elements like load-bearing components, automobile chassis, and aircraft frames because of its dependable mechanical performance [1]. Al7075 composites containing 3 wt.% ZrO_2, 3 wt.% graphite (Gr), and a combination of the two were created using two-step stir casting. The particles uniform dispersion was confirmed by SEM and EDS. Despite having a slightly lower hardness, Al7075-Gr demonstrated improved wear resistance and tensile strength in mechanical tests. The composites made of hybrid Al7075-Gr-ZrO_2 showed the best wear performance[2]. In Al7075/B_4C composites, low B_4C content promoted good densification and matrix-reinforcement bonding, while higher amounts led to particle agglomeration. Bending strength, hardness, compressive, and yield strength improved with addition of B_4C content, peaking at 7.5 wt.% before declining due to clustering[3]. Although wear increased with increasing load and sliding speed, Al7010/B_4C composites' wear resistance was improved by the addition of B_4C. Out of all the formulations, the one with 12 wt.% B_4C had the least wear loss [4]. Yield, hardness, and tensile strength were enhanced in Al-7025 composites reinforced with 6 wt.% B_4C, while ductility and density were slightly reduced. Additionally, B_4C improved wear resistance and decreased thermal expansion [5]. Al7075 composites prepared using K_2TiF_6 flux showed improved wear resistance and lower friction with increasing B_4C, achieving optimum performance at 10 vol% due to a protective tribolayer formation [6]. Graphite-reinforced Al7075 composites demonstrated maximum strength and hardness at 3% Gr, while hardness decreased by 6.12% at 6% Gr. Taguchi analysis confirmed better overall properties in comparison to earlier reports, indicating optimal wear performance at 40 N load and 1500 rpm[7]. ZrO_2 particles were typically observed around grain boundaries in AA6061/ZrO_2 composites; higher contents led to agglomeration. Although wear rate rose at greater loads, ZrO_2 addition improved hardness and wear resistance. At 5 wt.% ZrO_2, there was mild wear, but at 15 wt.%, there was significant wear with grooves and delamination[8].

At 3 wt.% of ZrO_2, Al-6061/ZrO_2 composites demonstrated uniform dispersion, grain improvement, and improved hardness, wear, and corrosion resistance. Agglomeration and coarse grains decreased performance above 6 wt.%. The optimum mechanical and corrosion-resistant qualities were thus provided by 3 wt.% ZrO_2 [9]. Al7075/Al_2O_3/graphite hybrid composites were fabricated via stir casting and tested for dry sliding wear by making use of a pin-on-disk tribometer. Al_2O_3 acted as load-bearing particles to improve wear resistance, while graphite provided solid lubrication. Wear behaviour was primarily influenced by Al_2O_3 content and applied load, with sliding distance and graphite having minor effects. The combined reinforcement significantly enhanced the tribological performance[10]. Al7075/graphite (Gr)/TiB_2 hybrid composites exhibited uniform particle distribution with minimal clustering. Graphite acted as a solid lubricant, reducing friction, while the reinforcements increased hardness. Ultimate tensile strength (UTS) improved by 68% for 8 wt.% Gr and 5 wt.% TiB_2, with a slight 4.8% decrease in ductility. The combined effect of graphite and TiB_2 enhanced both mechanical and tribological performance [11]. Because of the coupled hard phases, Al-7075/Al_2O_3/B_4C hybrid composites with 3 wt.% B_4C and varied Al_2O_3 (3–15 wt.%) demonstrated enhanced wear resistance. Al_2O_3 composition, load, and sliding speed all affected performance, and SEM showed uniform dispersion and important wear mechanisms[12]. Particle distribution inside the matrix was homogeneous in Al7075 hybrid composites supplemented with 2 wt.% fly ash and varied B_4C (2–8 wt.%). Compared to unreinforced composites, the hardness increased gradually with the addiotion of B_4C, to the point that a 37 % improvement was obtained with 8 wt.% B_4C, which indicated that B_4C plays a critical role in structural integrity and strength enhancement [13].

Mechanical behaviour of the Al7075 hybrid composites of 2-4 wt.% graphite and 5 wt.% SiC was varied. The sample of 2 wt.% graphite was much harder and had high wear resistance whereas the graphite in excess suppressed the hardness through lubrication. On the whole, the best damping properties and strength were achieved with 2 wt.% graphite [14]. The hybrid composites of Al7075 reinforced with B_4C and SiC (10-10 wt.% of the total) had the even particle distribution in the matrix. B_4C content increased tensile behavior, and 1 wt.% SiC and 9 wt.% B_4C gave the highest UTS (59 MPa) and yield strength(50 MPa). These findings confirm the dominant role of B_4C in enhancing strength of composite [15]. In A380 aluminium composites that were reinforced with different levels of B_4C and ZrO_2, the wear rate significantly reduced as a result of synergistic effect of the two reinforcements. The composite with the total reinforcement of 3 wt.% had the maximum wear resistance, and this confirms the process of synergistic strengthening between ZrO_2 and B_4C [16]. Mono (Al2219/B_4C) and hybrid (Al2219/B_4C/Gr) composites based on Al2219 had a greater resistance to wear compared to the mono-composite. The graphite made it more lubricated and B_4C made it harder and increased the load bearing capacity. Their joint effect contributed to a great extent of wear performance[17]. Al7020 alloy with 0-8 wt.% of B_4C was analyzed in terms of tensile, compressive, hardness and fracture toughness. The inclusion of B_4C enhanced strength and hardness greatly with 8 wt.% composite demonstrating tensile and compressive strength increase by 52.8 and 50.29 percentages respectively. These gains signify that it can be used in lightweight aerospace structures [18]. Incorporating 3 wt.% graphite into aluminium composites enhances sliding performance by introducing a solid lubrication mechanism that effectively reduces friction and wear. The composite is suitable for wear-resistant parts in automotive and aerospace systems since it maintains adequate strength while presenting improved durability when combined with ceramic reinforcements[19].

While several studies have examined the individual or binary reinforcement effects of B_4C, Gr, and ZrO_2 in aluminium alloys, comprehensive investigations addressing their combined influence in Al7075 matrices remain limited. By methodically assessing the synergistic effects of Gr, ZrO_2, and different B_4C contents (2–4wt.%) on the microstructural evolution, mechanical performance, and wear behaviour of Al7075 composites, the current work fills this gap. The B_4C content was limited to 2-4 wt.% because higher additions typically result in reduced ductility, poor wettability, and particle agglomeration, while lower additions offer insufficient strengthening. This approach enables effective optimization of hybrid reinforcement systems for high-performance structural applications.

EXPERIMENTAL DETAILS

Aluminium alloy ingots of Al7075 were purchased from PMC, Bengaluru, India and graphite (25-40 μm) boron carbide (30-40 μm) and zirconia (ZrO_2, 20-25 μm) were purchased at Bio-aid Industries Ltd., Bengaluru. Tab. 1 and 2 respectively provide the Al7075 alloy precise chemical configuration and the physical and mechanical behaviour of the matrix and reinforcements respectively. SEM micrographs illustrating the morphology of graphite, ZrO_2, and B_4C particles are presented respectively in the Figs. 1(a-c). The elemental compositions identified through EDS analyses are shown respectively in the Figs. 2(a-c). Aluminium 7075 hybrid composites are fabricated by keeping the Gr & ZrO_2 reinforcement constant while varying the B_4C particles at 2 wt.% and 4 wt.%.

Fig. 2(a) illustrates the EDS spectrum of graphite particles, confirming that the reinforcement consists entirely of carbon. Fig. 2(b) presents the EDS spectrum of ZrO_2 particles, indicating the presence of zirconium (Zr) and oxygen (O) elements. Fig. 2(c) shows the EDS spectrum of B_4C content, verifying that the reinforcement is composed of boron (B) and carbon (C)

Si	Mn	Mg	Ti	Cu	Cr	Zn	Fe	Al
0.41	0.29	2.92	0.21	1.98	0.16	6.20	0.45	balance

Table 1: Elemental Configuration of Aluminum 7075 Alloy in wt.%.

Material	Density (g/cm^3)	Hardness (BHN)	Tensile Strength (MPa)	Elastic Modulus (GPa)
Al7075	2.80	66	205	71
Gr	2.21	1.30*	200	16
ZrO_2	5.67	1300	1800 (C)**	382
B_4C	2.52	2900	350	460

Table 2: Properties of Al7075 matrix and reinforcement constituents (*Mohs Hardness **Compression Strength).

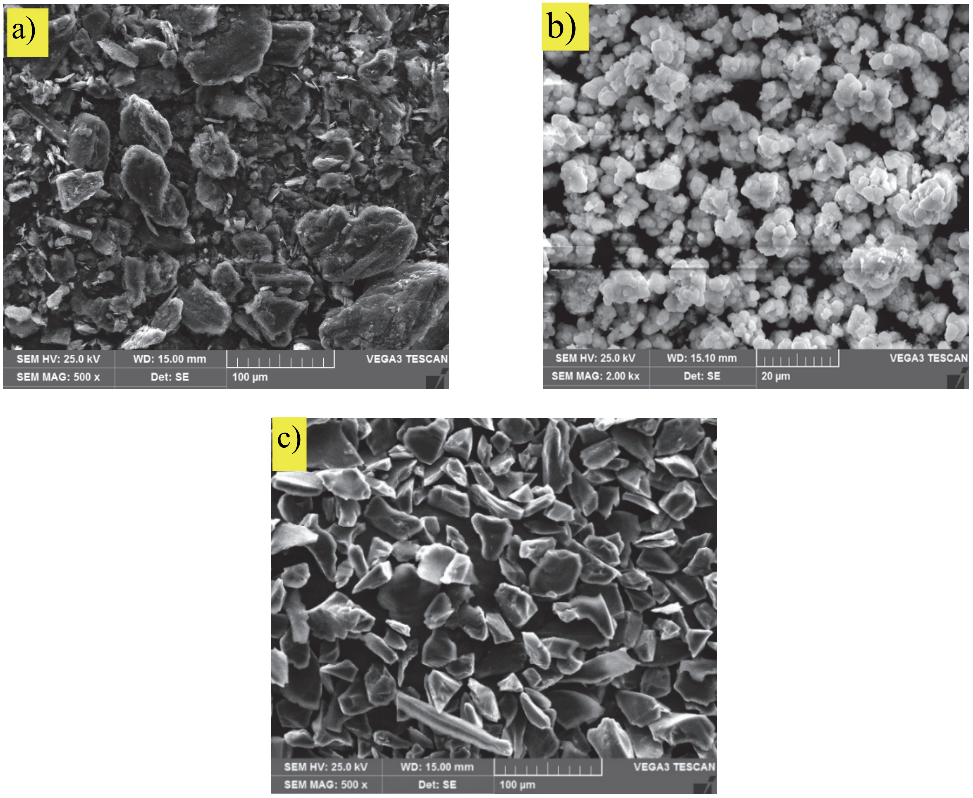

Figure 1: Reinforced particle SEM micrographs of (a) Gr (b) ZrO_2 (c) B_4C.

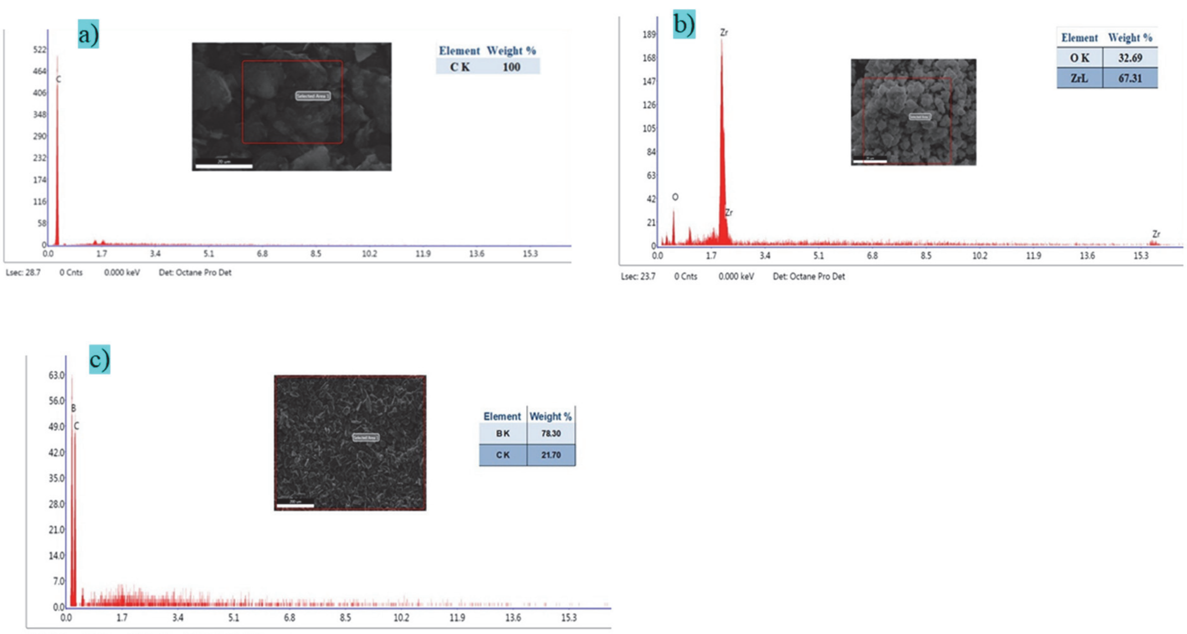

Figure 2: EDS Spectrographs of particles (a) Gr (b) ZrO_2, and (c) B_4C.

A liquid metallurgy approach was embraced for fabricating the metal matrix composites, because of its economical nature and ease of operation. The Al7075 alloy and reinforcement Gr, ZrO_2 and B_4C was processed into a hybrid composite using a liquid metallurgy technique. To ensure a clean and gas-free melt, hexachloroethane was used as a degassing agent during the melting stage and a coverall flux was employed to separate and remove the slag accumulated on the molten metal surface [20]. A tiny amount of magnesium chips was added into the molten metal to enhance the degree of wettability among the reinforcement particles and the matrix. Continuous stirring of the aluminium molten metal was done with a zirconium-covered bladed fan-type steel rotor mechanical stirrer. Approximately molten metal filled 65% of the crucible, and the zirconium-coated stirrer was immersed into the melt and rotates at about 300 revolutions per minute to generate a vortex, facilitating the uniform incorporation of reinforcements. To improve wettability and eliminate moisture, the reinforcement particles were preheated to approximately 400 °C. Then, in two stages, particles of preheated Gr, ZrO_2, and B_4C were added to the molten Al7075 alloy. To ensure uniform dispersion of the reinforcing particles all over the matrix, stirring was done continuously for about 8 to 10 minutes. The molten Al7075 composites was cast into preheated moulds and cooled at room temperature to get cylindrical samples of 120 mm in length and 15 mm in diameter.

Fig. 3 presents the laboratory setup implemented for producing Al7075 composites with Gr, ZrO_2, and B_4C reinforcements through the stir casting technique. Gr and ZrO_2 were fixed at 3 wt.% , while B_4C(2–4 wt.%) was varied; for uniform dispersion during stir casting, stirring was controlled to ensure strong interfacial bonding and optimal composite properties. Fig. 4 presents the Al7075 matrix composites with different reinforced particles of Gr, ZrO_2 and B_4C . The fabricated composite specimens were polished sequentially with 200, 400, 600, and 800 grit emery papers, followed by cleaning with a velvet cloth and etching in Keller's reagent containing HNO_3, HF, and HCl to expose the microstructural features. Finally, the samples were rinsed with distilled water to ensure the removal of any remaining dust or debris after polishing [21].

Scanning electronic microscopes [Tescan Vega 3LMU] was used to examine the microstructure of Al7075 alloy composites strengthened with B_4C, Gr, and ZrO_2 particles, to view particle distribution and interfacial bonding, the samples measuring length of 10 mm and diameter 12 mm were polished using 240, 600, and 800 grit emery papers, after which a final rinse with distilled water to take away any last impurities or surface particles [21].

Figure 3: Set-up of Stir casting.

Figure 4: Al7075 alloy with Gr/ZrO_2/ B_4C composite.

The samples for hardness evaluation were prepared following the ASTM E10 standard [22]. The Brinell hardness evaluation were carried out by means of a standard testing apparatus on specimens with a finely polished surface finish. A load of 250-kg was usable through a 5mm diameter steel ball indenter, and the final hardness value was obtained by averaging three individual indentation readings. The Al7075 matrix as-cast and its composites containing distinct weight fractions of Gr, ZrO_2 and B_4C reinforcements were made in compliance with the ASTM E-8 guidelines [23] for tensile examination. The specimens were subjected to uniaxial tension using a computer-assisted universal testing apparatus, as shown in Fig. 5. Each test sample possessed a gauge length of 45 mm and gauge diameter of 9 mm.

The dry sliding wear performance of the Al7075 as-cast and Al7075 hybrid composites strengthened with varying proportions of Gr, ZrO_2, and B_4C particles was investigated at room temperature utilising a pin-on-disc wear setup, in compliance with the ASTM G99 standard. Cylindrical samples (fig. 6) measuring 30 mm long and 8 mm in diameter were prepared for the tests. During the first set of experiments, a 40 N continuous load and a 3000m sliding distance were maintained, while the rotational sliding speed was changed at intervals of 100 rpm between 100 and 400 rpm. In the subsequent tests, the composites were evaluated under identical conditions with a sliding distance of 3000 m and a fixed speed of 400 revolution per minute, while the applied load was differed from 10N to 40N in increments of 10N. Three samples were tested for each load/speed condition, and the extent of wear was evaluated based on the decrease in specimen height, recorded in micrometers.

Figure 5: Tensile sample as per ASTM.

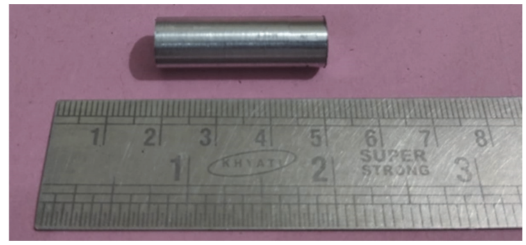

Figure 6: Specimen for wear test.

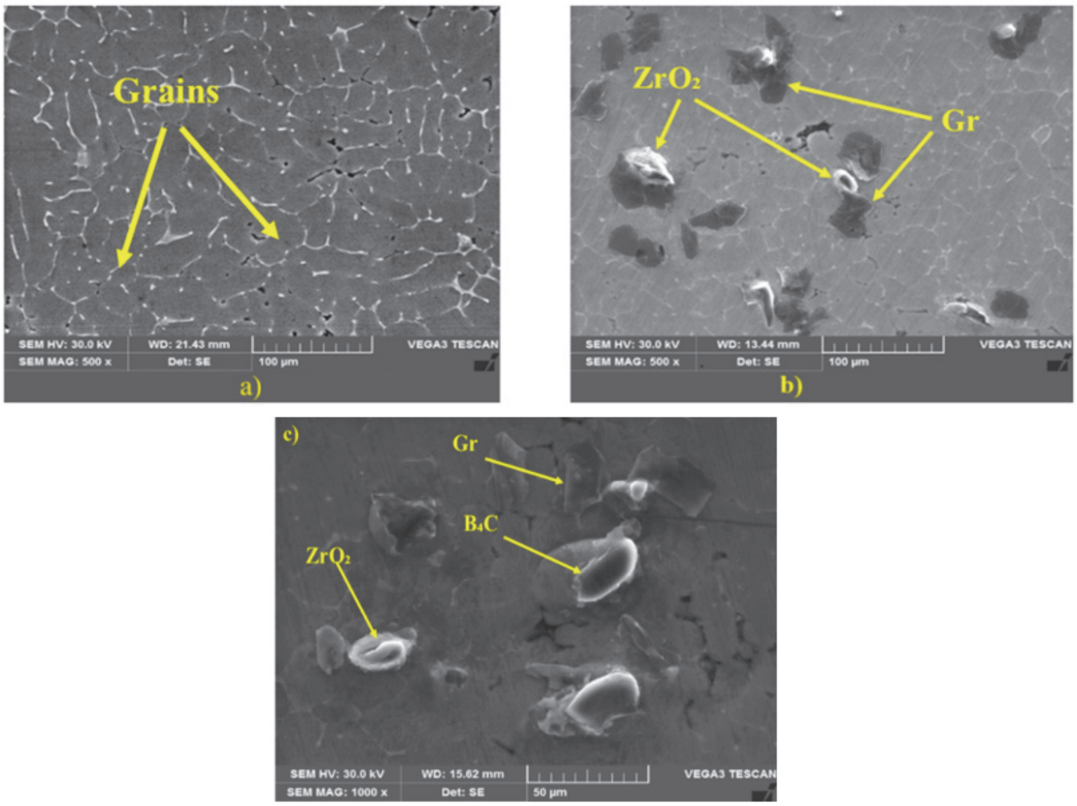

Figure 7: SEM image (a)Al7075 as-cast alloy (b and c) Al7075 hybrid composites.

RESULTS AND DISCUSSION

Analysis of microstructures

Fig. 7 (a-c) displays the SEM pictures of the hybrid composite reinforced with Gr, ZrO_2, and B_4C, as well as the basic Al7075 alloy. The shape, quantity and distribution of the reinforced particles in the aluminium matrix are brought into focus through SEM examination as they indicate that the reinforcing particles are uniformly scattered and bonded well. In this work micro-sized graphite, ZrO_2, and B_4C particles were dispersed in Al7075 alloy with the help of a two-step stir casting method in order to facilitate the unvarying mixing of the elements and enhance the strength of the composite structure.

When the reinforcement particles are preheated before they added to molten Al7075 alloy, this will improve their wettability and ensure that they are dispersed evenly throughout the matrix. The base Al7075 SEM pictures reveal a normal grain structure free of foreign inclusions. The uniform distribution of Gr and ZrO_2 at 3 wt.% each in the composites improves load transfer and matrix stability by appearing both within and along grain boundaries. Additionally, B_4C, which ranges from 2 to 8 wt.%, is uniformly embedded. Strong interfacial bonding and uniform particle distribution are generally confirmed by the micrographs, which directly contribute to the composites' enhanced mechanical and tribological behaviour.

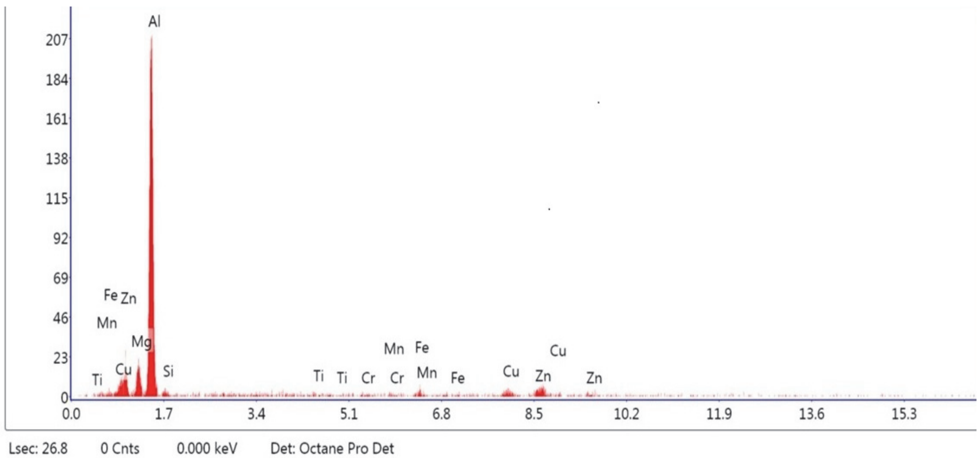

Figure 8: Al7075 Base alloy's EDS spectrum.

Fig. 8 shows the EDS spectrum of Al7075 matrix and showing its element composition. The spectrum identifies zinc (Zn) as the major alloying element with some traces of copper-Cu, manganese-Mn, magnesium-Mg, iron-Fe, titanium-Ti and silicon-Si. The EDS analysis confirms the typical chemical makeup of the Al7075 alloy, indicating the presence of both the primary and the auxiliary elements that play a crucial role in determine its mechanical and metallurgical characteristics.

Fig. 9(a-b) depicts the hybrid composites EDS spectra, confirming the presence of the constituent elements in the fabricated materials. In both spectra, zinc (Zn) appears as the primary element from the Al7075 matrix. Fig. 9(a), the spectrum reveals clear carbon (C), zirconium (Zr) and oxygen (O) peaks, hence the inclusion of 3 wt.% graphite and 3 wt.% ZrO_2 reinforcements were successful. Likewise, Fig. 9(b) reveals additional peaks corresponding to boron (B) and carbon (C), verifying the presence of B_4C particles in addition to other reinforcement elements. These findings confirm the effective incorporation and uniform distribution of all reinforcement phases within the aluminium matrix.

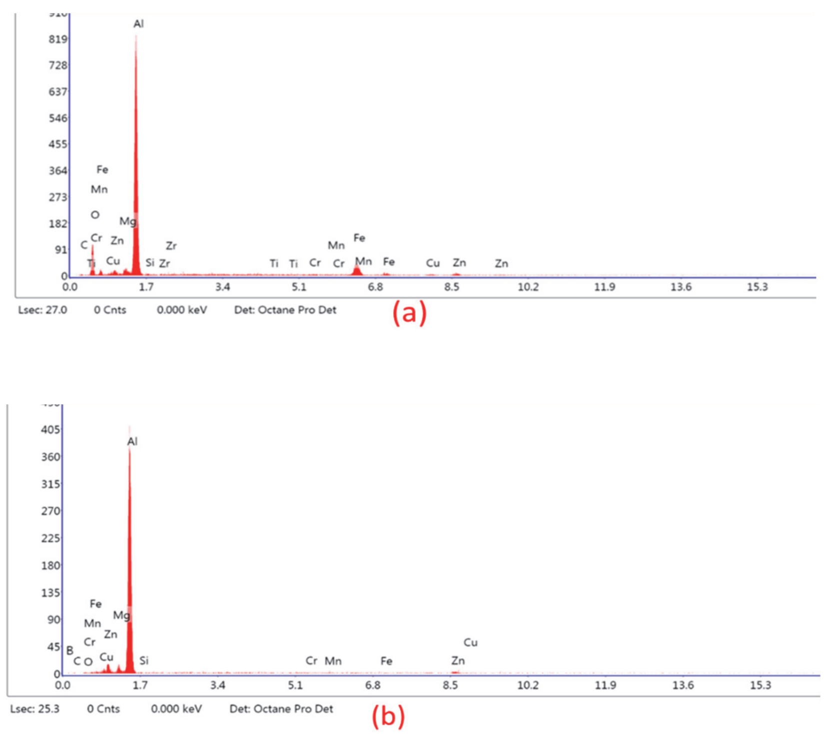

Figure 9: Hybrid composites EDS spectrum (a) Al7075-Gr-ZrO_2 (b) Al7075-Gr-ZrO_2-B_4C.

Hardness

As illustrated in Fig. 10, the hardness of unreinforced Al7075 alloy and its hybrid reinforced composites with Gr, ZrO_2, and B_4C particles was determined by utilising a ball indenter with a 250 kg applied load and a 30-second dwell time. The Brinell hardness number (BHN) variation for the unreinforced Al7075 matrix and its hybrid reinforced composites with 3 wt.% zirconia (ZrO_2), 3 wt.% graphite (Gr) with varying amounts of boron-carbide (B_4C) particles. The augmentation in hardness of the hybrid composites is mainly ascribed to the existence of hard ceramic particles within the aluminium matrix. When Gr and ZrO_2 reinforcements were added, the hardness of Al7075 as-cast matrix increased slightly to 71 BHN from 68 BHN. The uniform distribution of Gr and the presence of hard ZrO_2 particles, which improve interfacial bonding and limit matrix deformation, are the primary causes of the increase in hardness[2]. For 2 wt.% B_4C addition, the hardness further increases to 77 BHN, while 4 wt.% B_4C reached the highest rate of 87 BHN, marking a 28% enhancement over the base as-cast alloy. The hard ceramic reinforcements (B_4C and ZrO_2) act as obstacles to plastic deformation, while graphite contributes to keeping structural integrity during solidification. The increase in hardness with increased B_4C content is primarily because of the barrier to dislocation and grain refining. The even distribution of hard particles and transfer of active loads between the matrix and reinforcements further strengthen the material, thereby improving the composite's overall resistance to deformation [24].

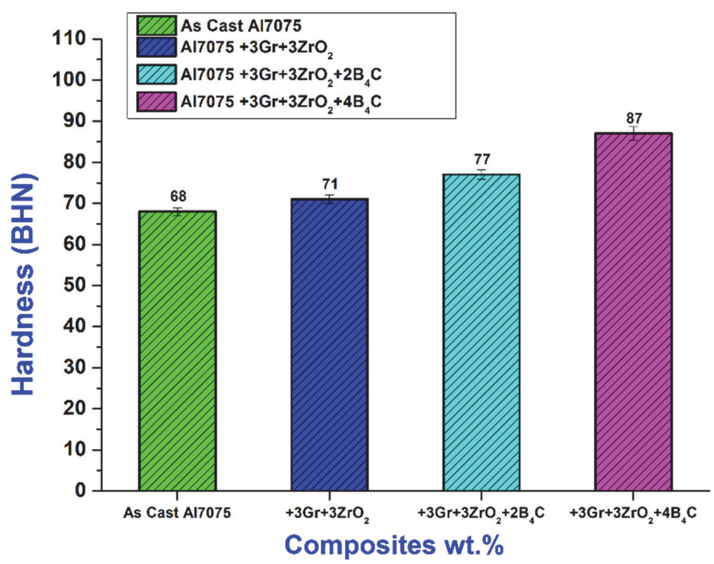

Figure 10: Hardness variation of Al7075 hybrid reinforced composites.

Tensile properties

Fig. 11 shows the UTS of Al7075 base alloy and Al7075 hybrid composites strengthened with Gr, ZrO_2 and B_4C particles. Al7075 hybrid composites shows the improvements in the UTS as compare to the unreinforced Al7075 alloy. The collective adding of graphite (Gr) and zirconia (ZrO_2) to the Al7075 matrix remarkably improves the UTS in relation the Al7075 alloy. The layered structure of Gr improves load-bearing ability under tension and enhances to ductility, while the hard ZrO_2 particles reinforce the matrix by impeding the movement of dislocation and endorsing higher dislocation density throughout solidification[2]. The UTS improved to 277 MPa when 2 wt.% B_4C was added, and the maximum UTS of 293 MPa was attained with 4 wt.% B_4C, signifying a 37% enhancement over the base alloy. This growth is due to lubricating effect of graphite and the synergistic strengthening from the hard B_4C and ZrO_2 particles, which results in better interfacial connection and a refined microstructure. The pinning effect of the graphite and oxide reinforcements that impedes the movement of dislocations during deformation is the major reason behind the enhancement in UTS[25].

Fig. 12 presents the yield strength of unreinforced alloy Al7075 and Al7075 hybrid composites reinforced with Gr, ZrO_2 as well as B_4C particles. The Al7075 hybrid composites have a notable growth in the yield strength relative to the unreinforced Al7075 alloy. The addition of two reinforcements graphite and zirconia to the Al7075 base matrix enhances the yield strength from 182 MPa (base alloy) to 232 MPa that is an improvement of 27.5 %.

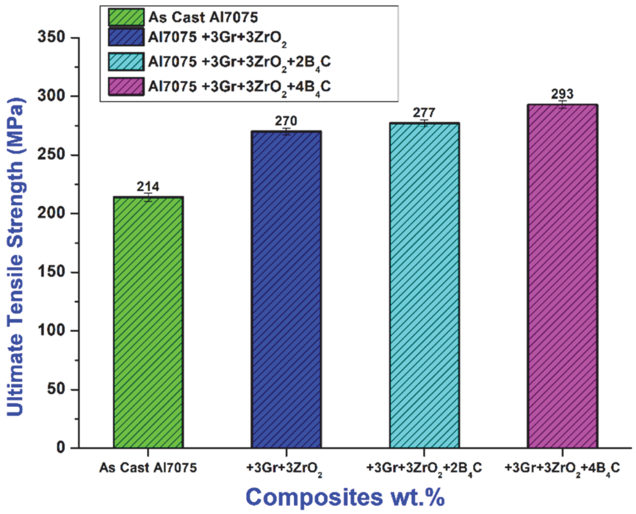

Figure 11: UTS of Al7075 hybrid reinforced composites.

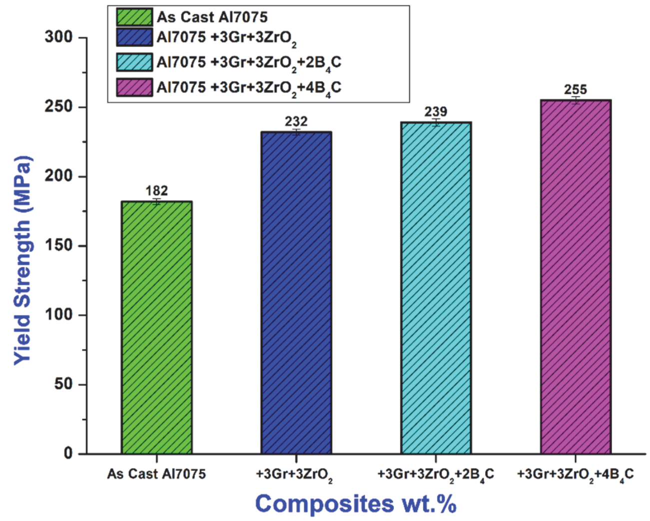

Figure 12: YS of Al-7075 hybrid reinforced composites.

The hard ZrO_2 particles impede the dislocation movement and enhance the density of dislocations whereas, even stress transfer in the layered graphite is confirmed. Together, they improve matrix stability and mechanical properties [2]. The yield strength improved to 239 MPa and 255 MPa for composites containing 2 wt.% and 4 wt.% B_4C, showing an overall 40% development over the base alloy. Analysis of SEM confirmed a even spreading of Gr, ZrO_2, and B_4C particles with strong interfacial bonding. The existence of hard reinforcements improves the load transfer and dislocation strengthening, while grain refinement produced a microstructure that was dense. These mutual effects significantly enhanced the mechanical integrity of Al7075 hybrid reinforced composites. The elongation percentages for the unreinforced Al7075 alloy and its hybrid reinforced composites with Gr, ZrO_2, and B_4C is shown in Fig. 13. After adding 3 wt.% of Gr and 3 wt.% of ZrO_2, the base alloy elongation dropped marginally from 14.2 % to 13.4 %. With additional reinforcement of 2 wt.% and 4 wt.% of B_4C, the elongation dropped to 12.9% and 12.2%, respectively. The hard ceramic particles (B_4C and ZrO_2) limit the matrix's plastic flow by blocking dislocation motion, which results in decreased deformability and a slow decrease in ductility.

Overall, the mechanical strength was increased by the addition of Gr, ZrO_2, and B_4C. Graphite decreased friction, while ZrO_2 and B_4C increased load-bearing capacity. In line with earlier research [2,7,10], these findings support the synergistic effect of hybrid reinforcements in maximizing the strength performance of Al7075-based composites.

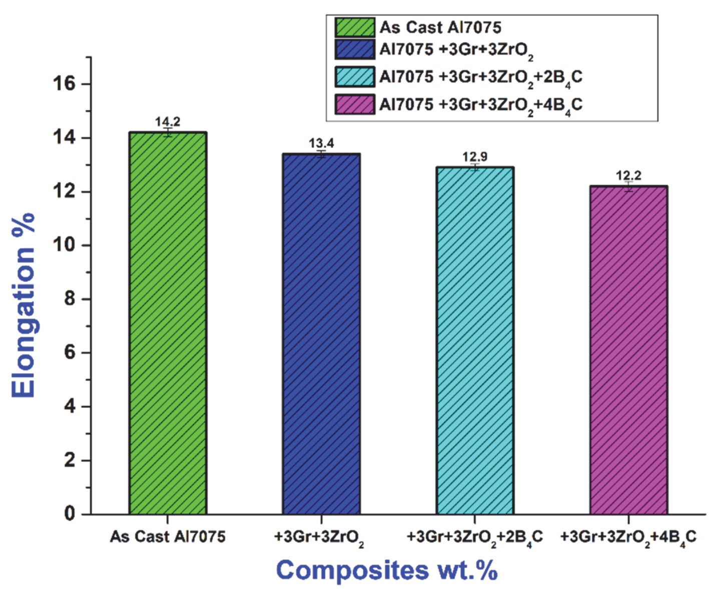

Figure 13: Elongation % of Al7075 hybrid reinforced composites.

Tensile fractography

The tensile fracture morphologies of unreinforced Al7075 alloy and its hybrid composites are revealed in the SEM micrographs in Fig. 14(a–d), which highlight how the reinforcement content affects fracture behaviour. The base alloy (Fig. 14a) shows deep, equiaxed dimples that reflect a predominantly ductile fracture. Addition of 3 wt.% of Gr and 3 wt.% of ZrO2 (Fig. 14b), the surface exhibits a mix of dimples and cleavage facets, which signifying a change to semi-brittle behavior because of hard ZrO_2 grains, as well as lower plasticity because of Gr. Adding 2 wt.% of B_4C (Fig. 14c) leads to finer and more evenly distributed dimples implying stronger performance and better interfacial bonding. The fracture surface of the composite with 4 wt.% of B_4C (Fig. 14d) is denser and has more shallow dimples with small traces of cleavage, which is conducive to the fact that the composite is more brittle and possesses greater hardness. Overall, the reinforcement of B_4C, Gr, and ZrO_2 refines the microstructure, strengthens the matrix, and shifts the fracture mode from ductile to quasi-brittle with superior load-bearing capacity.

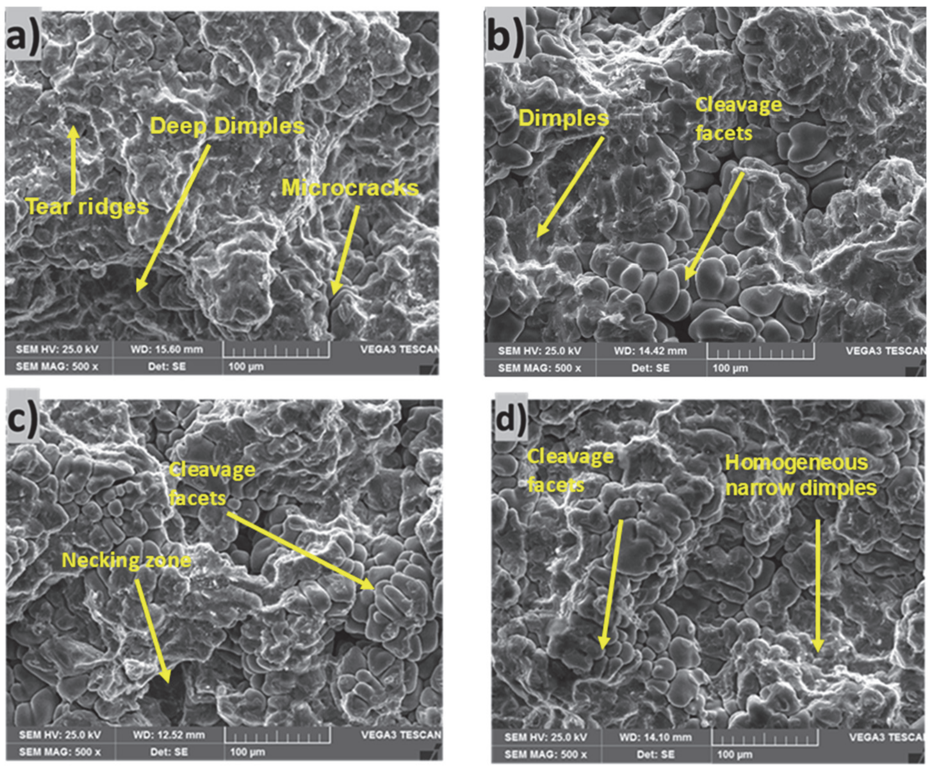

Figure 14: SEM images of surfaces with tensile fractures (a) Alloy Al-7075, (b) Al7075+ 3 wt.% ZrO_2, + 3 wt.% Gr (c) + 2 wt.% B_4C and (d) + 4 wt.% B_4C.

Wear properties

Fig. 15 shows the wear performance of the unreinforced Al7075 alloy and its hybrid composites reinforced with Gr, ZrO_2, and different proportions of B_4C was assessed using a pin-on-disc test device for wear adhering to ASTM G99. The experiments were executed under varying test conditions to estimate the effect of sliding speed and load on material wear. With a constant 400 revaluation per minutes sliding speed and a 3000m sliding distance, loads of 10-40 in a step of 10 N were applied. Similarly, further tests were conducted under a fixed load of 40 N for the same distance at 100–400 rpm sliding speeds in 100 rpm increments. The wear of each specimen was identified based on the height loss measured in micrometers (µm), which served as a reliable indicator of the material's wear resistance and surface durability under various operational conditions. Wear loss during sliding contact is greatly impacted by the load that is applied. The wear rate of aluminium alloys is directly impacted by increasing the normal load by varying the contact pressure, frictional heat, and wear mechanism, according to several studies. The hybrid composites revealed significantly reduce the wear loss compared to the Al7075 base alloy. The as-cast Al7075 showed the greatest wear loss, ranging from 778 µm at 10 N to 987 µm at 40 N, whereas the hybrid reinforced composite with 4 wt.% B_4C recorded the lowest wear loss of 563 µm at 10 N and 763 µm at 40 N. The composite with 2 wt.% B_4C reinforcement also demonstrated intermediate wear loss values (610 µm at 10 N and

803 μm at 40 N). At the highest load 40 N, the wear loss was reduced by roughly 27.6% for the 2 wt.% of B_4C composite and 34.8% for the 4 wt.% of B_4C composite when related to the unreinforced alloy.

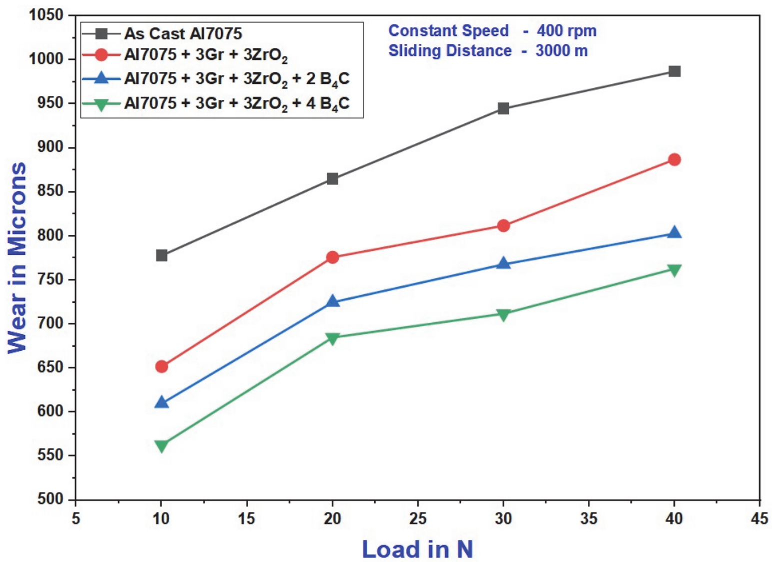

Figure 15: Variation in wearing patterns of alloy Al7075 and hybrid composites under different loads at a steady speed of sliding.

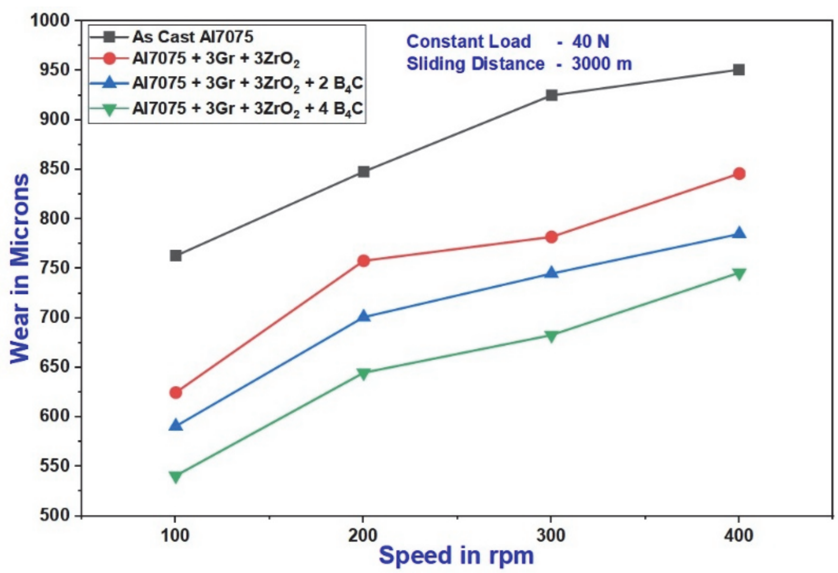

Figure 16: Variation in wearing patterns of alloy Al7075 and hybrid composites under different rotational speed at a constant load.

Fig. 16 shows the variation in wear patterns of alloy Al7075 and hybrid composites under different rotational speed at a constant load. Wear loss increases with increasing the speed of sliding for all materials due to higher frictional heat and surface softening, which accelerate material removal. However, the hybrid composites show significantly less wear loss than the unreinforced alloy, confirming the positive effect of the reinforcements on enhancing resistance to wear. At a speed of 100 rpm, the Al7075 as-cast alloy wear loss was 763 μm, which increased to 951 μm at 400 rpm. In contrast, the composite that has 4 wt.% of B_4C exhibited the lowest wear loss, increasing from 541 μm to 746 μm across the same speed range. The composite with 2 wt.% B_4C showed intermediate values (591 μm at 100 rpm and 785 μm at 400 rpm). Thus, the presence of 4 wt.% of B_4C resulted in an approximate 21.5% decrease in wear loss associated to the as-cast Al7075 alloy at the highest speed tested. The decrease in wear loss with increasing B_4C content is due to the hard ceramic reinforcements (B_4C and ZrO_2), which increase load-bearing capacity and resist plastic deformation of the Al matrix. Furthermore, Graphite functions as a solid lubricant, forming a protective film that decreases the friction and adhesive wear. Hence, adding B_4C significantly improves wear resistance, with the 4 wt.% B_4C composite demonstrating optimal under all load conditions.

The worn surface morphologies are shown in Fig. 17 (a–d) obtained from tribological tests carried out on the Al7075 alloy and its hybrid composites reinforced with a combination of Gr, ZrO_2, and B_4C particle. The unreinforced Al7075 alloy (Fig. 17a) shows significant surface damage with delamination and deep grooves, due to extreme adhesive wear. When 3 wt.% Gr and 3 wt.% ZrO_2 are added (Fig. 17b), the roughness of the surface diminishes as ZrO_2 improves surface hardness and Gr reduces friction by creating a thin lubricating layer. When 2 wt.% B_4C is added (Fig. 17c), the wear tracks get finer, indicating that the hard B_4C particles limit the plastic flow and improve structural homogeneity. The hybrid composite containing 4 wt.% B_4C (Fig. 17d) shows a much smoother worn surface with minimal grooves, indicating a high load-bearing capacity and refined grain structure. The combined presence of Gr, ZrO_2, and B_4C improves matrix strength, refines the microstructure, and reduces deterioration of the surface. Overall, the hybrid reinforcements significantly expand wear resistance compared with the base Al7075 alloy.
In accordance with earlier research [2,6,7], the enhanced wear resistance observed in the present work is the combined effect of graphite's lubricating action and the load-bearing reinforcement offered by ZrO_2 and B_4C, which together reduce friction, limit material removal, and enhance surface stability.

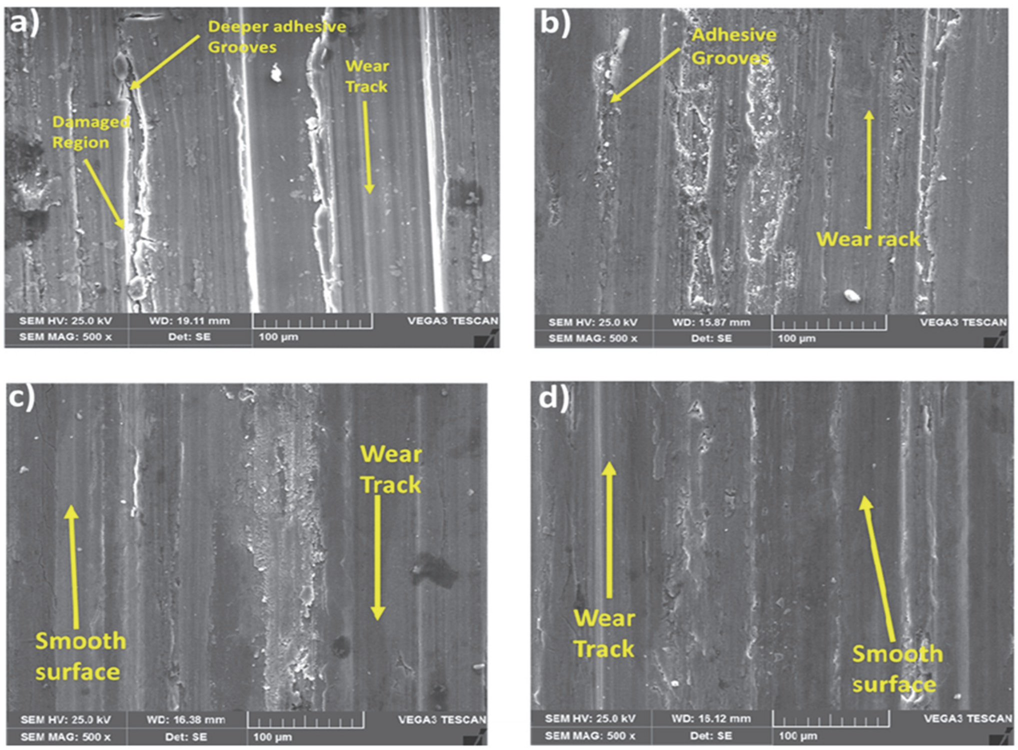

Figure 17: SEM microphotographs of surface wear of alloy Al7075 and hybrid composites (a) Base alloy Al7075, (b) Al7075+3 wt.% Gr + 3 wt.% ZrO_2 (c) +2 wt.% of B_4C (d) + 4 wt.% of B_4C.

Conclusions

Alloy Al7075 and its hybrid composites were made with a two-step stir casting process, and their mechanical properties, microstructure and wear behavior were systematically evaluated.

- SEM analysis reveals that Gr, ZrO_2, and B_4C particles are homogeneously dispersed within the Al7075 hybrid composite matrix, indicating strong bonding and effective mixing during fabrication. EDS spectra further verify the existence of these reinforcement units in the composites.
- The hardness of Al7075 hybrid composites increased with reinforcement content, reaching 87 BHN for 4 wt. % of B_4C. It is attributed by the existence of hard ceramic reinforcement (B_4C and ZrO_2) that enhance the strength of the matrix and deformation resistance.
- Including B_4C in addition to Gr and ZrO_2 to Al7075, UTS has increased by 37 % (214 to 293 MPa) and yield strength by 40 % (182 to 255 MPa) and elongation is reduced by 14 % (14.2 to 12.2 %). The enhancements are

ascribed to the hard ceramic character of B_4C, uniform distribution of particles, which characteristically smooth microstructure and improve the strength of the matrix, as well as limit the movement of dislocations.

- Al7075 exhibits ductile fracture surface with deep dimple, while Gr, ZrO_2 and B_4C refine microstructure producing finer dimples and minor cleavage which enhances hardness and fracture becomes quasi-brittle.
- Al7075 hybrid composites significantly increases its wear resistance by the addition of B_4C, Gr, and ZrO_2 with the 4 wt.% B_4C composite exhibiting the lowest wear at all loads and speeds. The hard ceramic reinforcements improve the load bearing capacity and Gr act as a solid lubricant that minimizes friction as well as material loss.
- In summary, study demonstrates that the mechanical and tribological performance of Al7075 composites is significantly enhanced through hybrid reinforcement with B_4C, Gr, and ZrO_2. The results also highlight the dominance of abrasive wear and the absence of delamination or mechanically mixed layer (MML) formation under the investigated testing conditions.
- These results offer direction for the design of Al7075-based composites for light structural, automotive, and aerospace applications.

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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.

Ethical considerations

The authors confirm that all the research meets ethical guidelines and adheres to the legal requirements of the study country.

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