



Influence of hybrid nano $\text{Al}_2\text{O}_3\text{--ZrO}_2$ reinforcements on microstructure, fracture toughness and fractographic behaviour of Al6061 alloy

Annapoorna Krishnappa

*Dept. of Mechanical Eng., RNS Institute of Technology, Visvesvaraya Technological University, India
annapoorna.apk@gmail.com, <http://orcid.org/0000-0003-2543-4801>*

Shobha Ramesh

*Dept. of Industrial Eng. and Management, Ramaiah Institute of Technology, Bengaluru, Karnataka, India
shobhamtech@gmail.com, <http://orcid.org/0000-0003-0210-3540>*

Rajanna Siddagangappa

*Dept. of Mechanical Eng., Government Engineering College, Mosale Hosaballi, Karnataka, India
rajanna.cit@gmail.com, <http://orcid.org/0000-0001-9209-5104>*

Srimadhu Ashokkumar

*Trelleborg Sealing Solutions, Bengaluru, Karnataka, India
srimadhua@gmail.com, <http://orcid.org/0009-0002-7671-2381>*

Manjunath Vatnalmath

*Dept. of Mechanical Engineering, RNS Institute of Technology, Visvesvaraya Technological University, India,
vmanjunathsit@gmail.com <http://orcid.org/0000-0003-3138-9453>*

Virupaxi Auradi

*Dept. of Mechanical Engineering, Siddaganga Institute of Technology, Tumakuru-572103, Karnataka, India
vsauradi@gmail.com <http://orcid.org/0000-0001-6549-6340>*

Madeva Nagara

*Aircraft Research and Design Centre, Hindustan Aeronautics Limited, Bangalore-560037, Karnataka, India,
madev.nagara@gmail.com <http://orcid.org/0000-0002-8248-7603>*



Fracture and Structural Integrity

Visual Abstract

Influence of Hybrid Nano Al₂O₃-ZrO₂ Reinforcements on Microstructure, Fracture Toughness and Fractographic Behaviour of Al6061 Alloy



Dr. Annapoorna K
Department of Mechanical Engineering, RNS Institute of Technology, VTU, India.

Dr. Shobha R
Dept. of Industrial Eng. and Management, Ramaiah Institute of Technology, VTU, India

Dr. Rajanna S
Dept. of Mechanical Eng., Government Engineering College, Mosale Hosahalli, Karnataka, India

Dr. Madeva Nagral
Aircraft Research and Design Centre, Hindustan Aeronautics Limited, India

Mr. Srimadhu Ashokkumar
Trelleborg Sealing Solutions, Bengaluru, Karnataka, India

Dr. Manjunath Vatnalmath
Department of Mechanical Engineering, RNS Institute of Technology, VTU, India.

Dr. Virupaxi Auradi
Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumakuru Karnataka, India

Citation: Krishnappa, A., Ramesh, S., Siddagangappa, R., Ashokkumar, S., Vatnalmath, M., Auradi, V., Nagral, M., Influence of hybrid nano Al₂O₃-ZrO₂ reinforcements on microstructure, fracture toughness and fractographic behaviour of Al6061 alloy, *Fracture and Structural Integrity*, 76 (2026) 223-237.

Received: 22.11.2025

Accepted: 03.03.2026

Published: 04.03.2026

Issue: 04.2026

Copyright: © 2026 This is an open access article under the terms of the CC-BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

KEYWORDS. Al6061, Stir casting, Nano- Al₂O₃, ZrO₂, SEM, Fracture toughness.

INTRODUCTION

Composites are a significant class of materials that can meet the growing requirements of contemporary technology. They surpass the limitations of traditional monolithic materials by attaining optimal combinations of strength, hardness and density among other attributes. Sustainable nano-composites provide automotive, biotechnology, electronics and aerospace industries new economic and technological opportunities [1, 2]. To enhance the mechanical performance and wear resistance of Metal Matrix Composites (MMCs), hard ceramic particles are incorporated into the matrix. Hybrid Metal Matrix Composites (HMMCs) demonstrate better wear resistance, specific modulus, damping capacity and superior specific strength when compared to pure alloys [3]. As a result, on-going inquiry is aimed on the development of advanced composites and improvement of current materials to achieve tailored properties for specific applications.

The practical applications of aluminum alloys are limited by their degree of softness and reduced wear resistance. Common applications for Al6061 include the automotive, defense, and marine industries. Its remarkable strength, low weight and resistance to corrosion are the main reasons for its extensive use [4, 5]. The addition of hard ceramic reinforcement particles to aluminum and its alloys creates a matrix composite with localized strengthening and nearly homogenous properties [6]. Al₂O₃ (alumina) is a widely employed reinforcement due to its remarkable hardness and excellent thermal stability. Zirconium oxide possesses different range of properties (excellent fracture toughness, good resistance to crack propagation, high thermal endurance and reduced thermal conductivity) at elevated temperature. These properties make zirconium di oxide very strong like other ceramics [7-8].

Mixing zirconia (ZrO₂) with alumina (Al₂O₃) nanoparticles makes composites even stronger. Now a day's most of the researches are going on Hybrid Metal Matrix Composites (HMMCs) due to its better mechanical and tribological properties. HMMCs can be synthesized by squeeze casting, stir casting, spray atomization casting, powder metallurgy, and plasma spraying technique. Among these stir-casting/ liquid stirring technique is widely used especially for synthesizing discontinuous reinforcing aluminium alloy MMCs [9] also this process is economical compare to other techniques as mentioned above. The difficulty in this process is that particles don't mix evenly; they tend to float which leads to wettability issues and segregation of the reinforcing particulates. Hence, to overcome this problem Yong Yang and his team [10] used an ultrasonic cavitation technique to mix nanoparticles into aluminium, while it solidifies and making the particles spread out evenly. For metal matrix composites fracture toughness is an important property which determines their ability against the crack growth and failure due to applied stress.

Past studies reveals that nano graphene and zirconium oxide improves the fracture toughness by enhancing the load bearing capacity and bridging in the matrix [11, 12]. Also, increasing the content of ZrO_2 in Al6061- ZrO_2 composites improves the fracture toughness by using SENB and FEA test [13]. Research on HMMCs reinforced with nano particles (Alumina and ZrO_2)-Al6061 is limited and most prior work focus on single reinforcement systems also lack of systematic fracture toughness optimization at low nano wt.%. Present study shows the use of novel ultrasonic-assisted stir casting is a key contribution, as it minimizes nanoparticle agglomeration and ensures improved dispersion within the aluminum matrix. Meanwhile the study thoroughly optimizes the reinforcement ratio and identifies the optimum composition for maximum fracture resistance for potential engineering applications.

EXPERIMENTAL DETAILS

In the present study Al6061 alloy and nano Al_2O_3 and nano ZrO_2 used as matrix and reinforcements respectively. Chemical composition was determined by using Energy Dispersive Spectroscopy (EDS). Tab. 1 depicts the properties of matrix material and reinforcement. SEM and EDAX analysis reveal peaks that align with the base alloy, nano Al_2O_3 , and ZrO_2 in Fig (1-6).

Material	Density (gm/cc)	Melting point (°C)	Modulus of Elasticity (GPa)	Brinell Hardness	Poissons Ratio	Tensile Strength (MPa)
Al6061	2.7	585	68.9	30-33	0.33	110-182
Al_2O_3	3.98	2072	370	1900	0.21	650-660
ZrO_2	5.68	2715	94.5	1150	0.34	300-330

Table 1: Characteristics of matrix and reinforcement materials.

Mg	Si	Ti	Cr	Mn	Fe	Cu	Zn	Al
0.80	0.62	0.10	0.13	0.12	0.35	0.2	0.11	Balance

Table 2: Composition analysis of Al6061 alloy.

The synthesis of hybrid nano-composite employed Al6061 Alloy as the matrix, with its elemental composition outlined in Tab. 1. Nano-sized alumina (Al_2O_3) and zirconia (ZrO_2) particles, with diameters ranging from 50 to 90 nanometers, functioned as reinforcement agents. The Al6061/ Al_2O_3 / ZrO_2 composite was synthesized using ultrasonic-assisted stir casting technique by varying wt % of Al_2O_3 and ZrO_2 (0.5, 0.75, 1, and 1.25 wt% for each reinforcement). Fig. 7 presents an illustration of the experimental apparatus utilized in this method (manufacturer: SwamEquip). The equipment provided with a graphite crucible, an ultrasonic vibrator, stirring system, digital timer, thermocouples, weighing scale and resistance furnace.

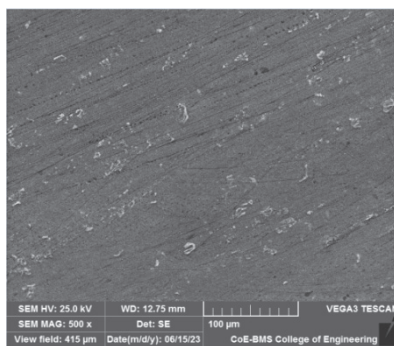


Figure 1: SEM image of Al6061.

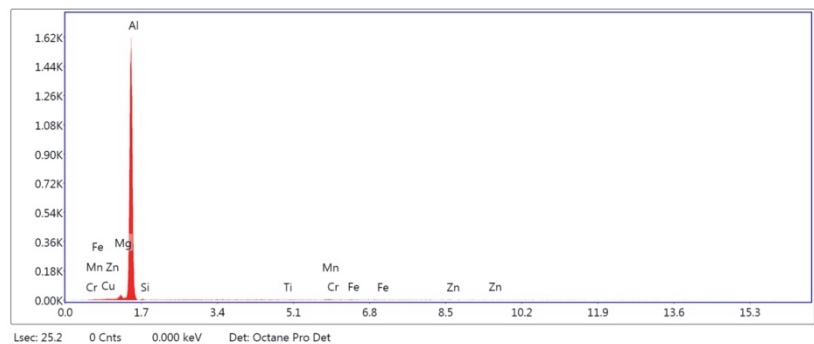


Figure 2: EDS Spectrum of Al6061

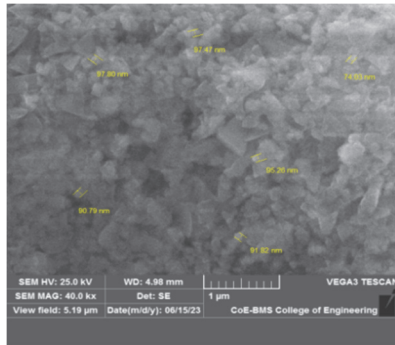


Figure 3: SEM image of Al₂O₃.

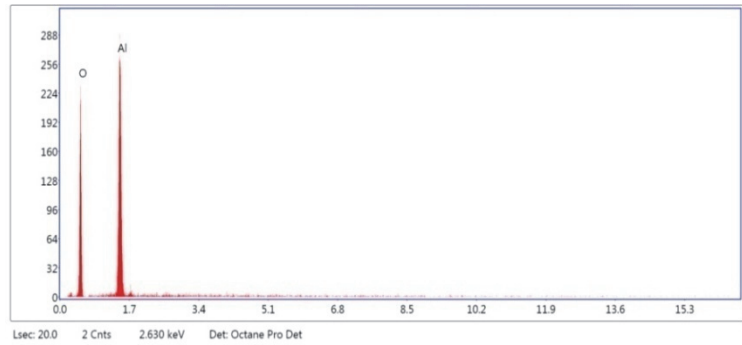


Figure 4: EDS Spectrum of Al₂O₃.

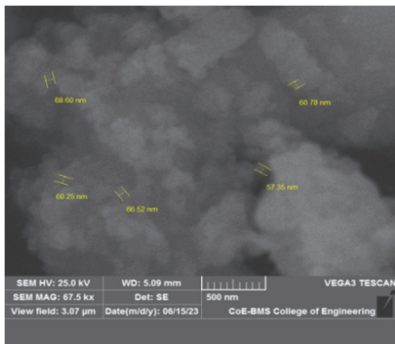


Figure 5: SEM image of ZrO₂.

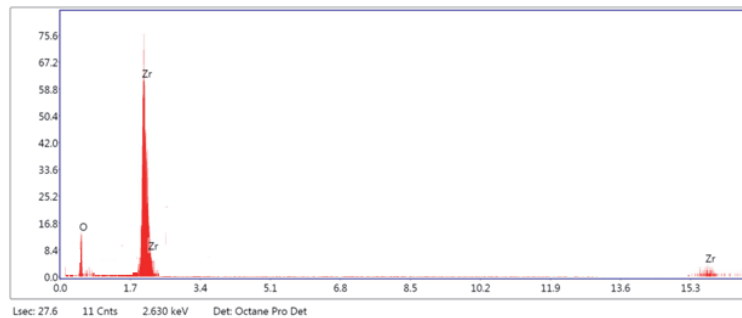


Figure 6: EDS Spectrum of ZrO₂.



Figure 7: Experimental set up of stir casting equipment.

A weighed amount of Al6061 is placed in an electrical resistance furnace and heated to a temperature of 750°C until it reaches to melting. Once this temperature is attained a solid hexachloroethane are introduced into the melt which act as an effective degasser stirred vigorously until the clear vortex is formed using an ultrasonic stirrer. Meanwhile, preheated (250°C) nano-sized ZrO₂ and Al₂O₃ particulates are introduced into the molten alloy, in a two-steps rather than adding at once to improve the dispersion of the particulates in the molten alloy and stirred at a speed of 500 rpm for duration of ten minutes which generate the vortex and helps dispersion of nanoparticles within the melt [14]. Due to high surface area and agglomeration of the reinforcing particulates mechanical stirring is difficult which leads to wettability issues. Hence an ultrasonic-stirring was used to overcome this problem. After 10 minutes of mechanical stirring action is done, an ultrasonic probe is used to disperse ceramic nanoparticles in the metal pool, creating a homogenous combination (High-energy vibrations from the probe three-quarters deep in the liquid created many cavitation bubbles in the molten pool. Due to pressure differentials, bubbles at high temperatures and pressures burst quickly, disintegrating clusters and

distributing nanoparticles evenly in the liquid metal). Later the mixed molten metals are poured (750°C) into the prepared mould for complete solidification for few minutes and after complete solidification samples are withdrawn from the mold and it was it was taken off for further testing. The composites were subjected to microstructural examination through SEM, in conjunction with an assessment of fracture toughness. To reduce measurement errors in each trial three specimens were assessed and their mean values were documented.

Sample No.	Matrix	Al ₂ O ₃	ZrO ₂	Parameters
1.		-	-	
2.		1	0.5	
3.		1	0.75	
4.	Al6061	1	1	Temperature: 750 °C Speed: 500 RPM Duration: 10 minutes
5.		1	1.25	
6.		0.5	1	
7.		0.75	1	
8.		1.25	1	

Table 3: wt.% of matrix and reinforcement.

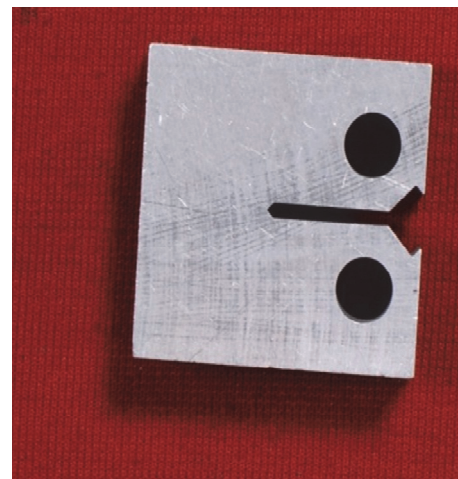
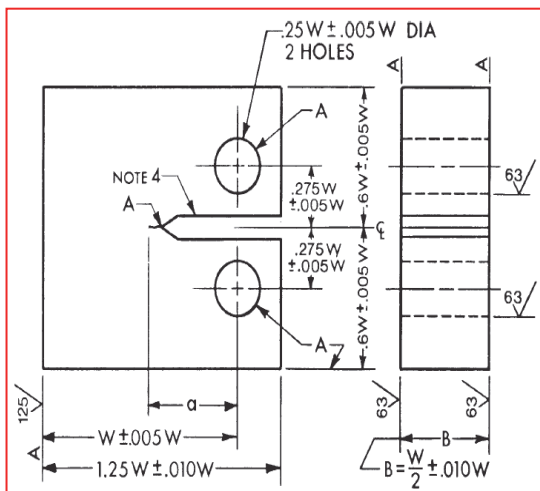


Figure 8: Fracture Toughness Specimen Specifications.

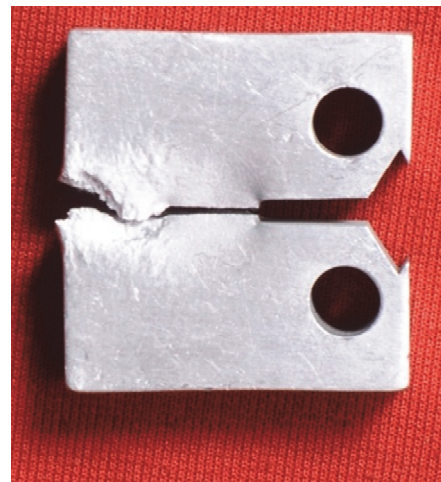


Figure 9: Testing using a servo-hydraulic universal testing machine.

Microstructural analyses were performed utilizing a SEM (Model: Tescan Vega 3) to assess the dispersion of reinforced particulates (Al_2O_3 and ZrO_2) + Al6061 matrix). To evaluate the fracture toughness of the Al6061-based hybrid composite reinforced with nano-scale Al_2O_3 and ZrO_2 particles, compact tension (CT) specimens were fabricated in accordance with ASTM E399 criteria. [16]. As shown in fig.8 during the experiments samples were machined to a thickness (B) of 20.0 mm with notches and pre-cracks for controlled crack growth [17,18]. Using servo-hydraulic universal testing machine (BISS model) fitted with a 25 kN load cell and a displacement transducer for measuring Crack Opening Displacement (COD) fracture toughness test was conducted. Preliminary pre-cracking was conducted to attain an a/w ratio of 0.5. During testing, to calculate fracture toughness (K_{IC}) the critical load was used for the prepared samples which are loaded at 0.55 MPa $\sqrt{\text{m/s}}$ until failure [19]. SEM fractography was also conducted.

RESULTS AND ANALYSIS

SEM characterization of Al6061- Al_2O_3 - ZrO_2 hybrid nano-composite at different weight fractions

SEM pictures reveal the microstructure of Al6061 reinforced with different percentages of Al_2O_3 and ZrO_2 composites, as depicted in Fig. 10 (a–h). The examination via EDS ensures the chemical composition of the analyzed regions corresponded with the designated sample formulation. Fig. 11 presents the EDS results for Al6061 reinforced with 1% Al_2O_3 and 1% ZrO_2 , indicating successful integration of the reinforcements inside the aluminum matrix.

Fig.10 (a-h) demonstrates the SEM images of the synthesized composites for weight fraction of nano alumina- ZrO_2 particulates. EDS confirms the chemical composition of the studied regions as intended.

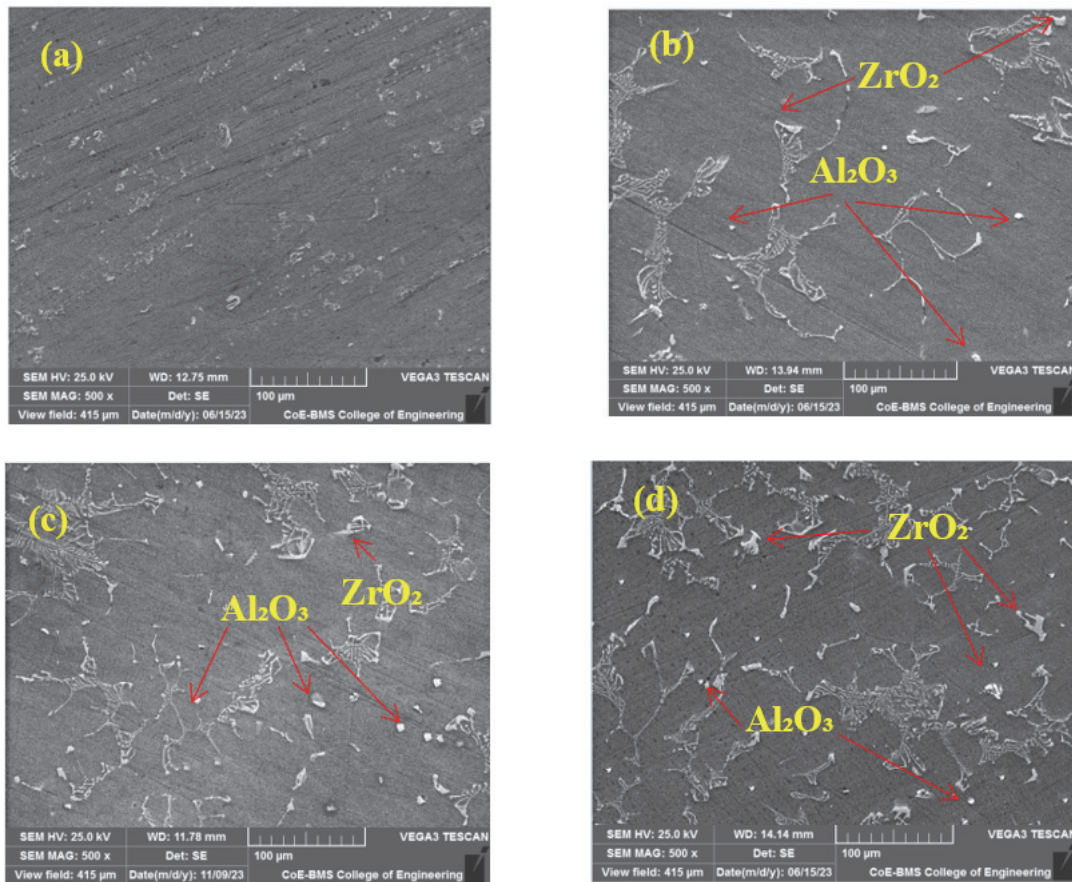


Figure 10 (a-d): SEM images of (a) Al6061, (b) Al6061-1% Al_2O_3 -0.5% ZrO_2 , (c) Al6061-1% Al_2O_3 -0.75% ZrO_2 , (d) Al6061-1% Al_2O_3 -1% ZrO_2

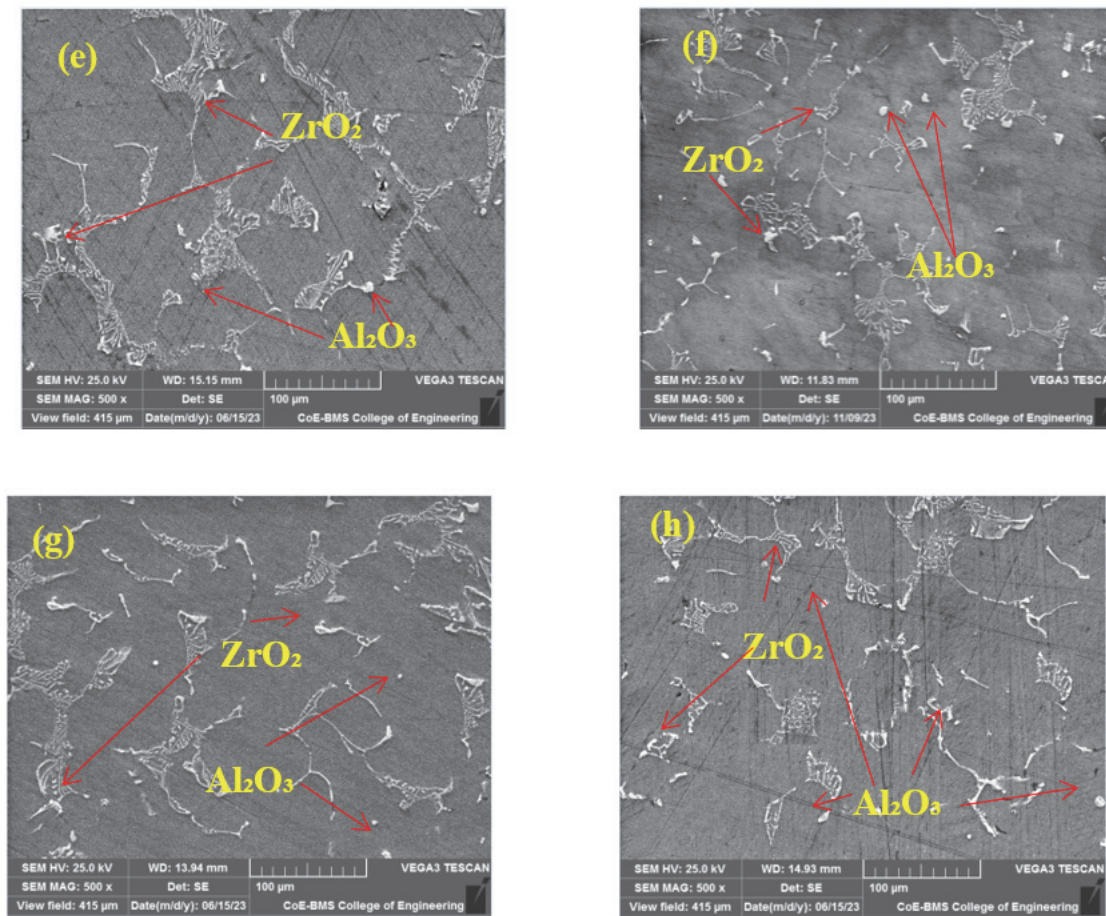


Figure 10(c-h): SEM images of (e) Al6061-1% Al₂O₃-1.25% ZrO₂, (f) Al6061-0.5% Al₂O₃-1% ZrO₂, (g) Al6061-0.75% Al₂O₃-1% ZrO₂ and (h) Al6061-1.25% Al₂O₃-1% ZrO₂

Fig. 10(a) SEM image of as cast Al6061 matrix shows the uniformly distributed grains with smooth surface. Fig.10 (b) shows the uniform dissemination of the reinforced particulates (1 wt. % of alumina and 0.5 wt.% of ZrO₂) in Al6061 matrix indicates the incorporation of hard ceramic nano particles contributing to grain refinement. Fig. 10(c) shows the compact arrangements of 1 wt. % Al₂O₃ and 0.75 wt. % ZrO₂ particles reinforced to Al6061. Agglomeration is seen but dissemination of the particles remains effective; though cluster may leads to stress concentration. Fig.10 (d) composites with 1% Al₂O₃-Al6061 and 1% ZrO₂-Al6061 depict the uniform and refined particles dissemination which leads to improve mechanical properties by hindering dislocation movement. Al6061 reinforced with 1.25% ZrO₂ and 1.25% Al₂O₃ (Fig. 10e) shows the increase in agglomeration of the reinforced particulates, possibly creating stress concentrations which reduces the fracture toughness. Composite reinforced with 0.5% Al₂O₃ and 1% ZrO₂ (Fig. 10(f)) demonstrates a moderate particle dissemination with clustering, due to the lower content of alumina which affecting uniform dissemination. Fig. 10(g) demonstrates variation in weight fraction of alumina content (0.75%) with of 1% ZrO₂ enhances dissemination and decreases the agglomeration and balances the reinforcement. Al6061 reinforced with 1.25% Al₂O₃ and 1% ZrO₂ (Fig. 10h) depicts the concentrated reinforcement particles with increased spacing between them. Higher ZrO₂ levels lead to more clustering, which results in diminishing wear resistance and fracture toughness. Among the produced composites with different composition, Al6061 reinforced with 1% alumina and 1% Zirconium dioxide shows more uniform dissemination of the reinforcing particles with small amount of clustering which suggest better potential for enhanced mechanical properties.

EDS analysis of elemental composition

Fig. 11 shows the EDS spectra of Al6061- 1% Al₂O₃ and 1% ZrO₂ which confirms the existence of elements such as oxygen (O), zirconium (Zr), silicon (Si), magnesium (Mg), and chromium (Cr) and also depicts the other elements. Presence of O and Zr indicates that the reinforcing phases were well integrated to base matrix Al6061, while a summary

table displays the elemental breakdown of all samples for different composition. This method eliminates EDS spectra redundancy by revealing how reinforcements affect composite chemical composition. Elemental analysis for composite samples comparing Al6061 alloy with different reinforcement combinations is shown in Tab. 4. Quantifying elements like Zr, O, Zn, Mn, Fe, Si, Cr, Ti and Mg reveals how Al₂O₃ and ZrO₂ reinforcements affect the alloy's composition. The results show that matrix reinforcement type and quantity directly affect oxygen and zirconium levels.

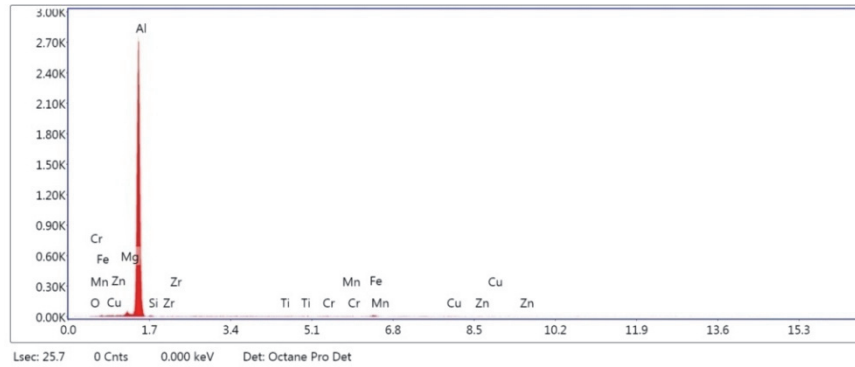


Figure 11: EDS Spectrum of 1 wt% Al₂O₃ and 1wt% ZrO₂.

Element	Al6061 Range	Sample- 1	Sample-2 (1+0.5)	Sample-3 (1+0.75)	Sample -4 (1+1)	Sample -5 (1+1.25)	Sample-6 (0.5+1)	Sample -7 (0.75+1)	Sample - 8(1.25+1)
Al	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal	Bal
Mg	0.8-1.2	0.86	0.85	0.89	0.84	0.86	0.85	0.83	0.88
Si	0.4-0.8	0.68	0.68	0.64	0.72	0.65	0.66	0.71	0.7
Ti	0.15max	0.1	0.09	0.11	0.12	0.1	0.08	0.1	0.13
Cr	0.04-0.35	0.19	0.23	0.22	0.2	0.21	0.18	0.25	0.21
Mn	0.15max	0.11	0.12	0.1	0.09	0.11	0.1	0.08	0.12
Fe	0.7max	0.35	0.32	0.36	0.34	0.37	0.32	0.36	0.38
Cu	0.15-0.4	0.24	0.24	0.22	0.3	0.26	0.21	0.3	0.28
Zn	0.25max	0.12	0.14	0.2	0.16	0.18	0.19	0.21	0.18
O	-	-	0.49	0.53	0.52	0.57	0.3	0.41	0.66
Zr	-	-	0.45	0.7	0.91	1.1	0.92	0.93	0.91

Table 4: Chemical Composition of Al6061- with various wt% of nano Alumina and Zirconium dioxide reinforcing particles.

Phase analysis through X-ray diffraction (XRD)

XRD studies were performed to determine the different phases/crystalline formed in the Al6061 matrix and the nano-sized reinforcements, namely Al₂O₃ and ZrO₂. For examining the crystallographic structure of materials XRD is a valuable technique which allows the detection of phase transitions, the distribution of reinforcements, and the presence of any secondary phases formed in stir casting process. The Al6061 alloy shows clear diffraction peaks at 2θ values of 38.47° (111), 44.73° (200), 65.13° (220), 78.22° (311), and 82.55° (222), each corresponding to the face-centered cubic (FCC) structure of aluminium as per JCPDS NO 04-0787. For α-alumina (Al₂O₃), reference peaks are observed at 25.58° (012), 35.15° (104), 37.77° (110), 43.39° (113), 52.61° (024), 57.50° (116), 66.51° (018), 68.24° (214), and 77.03° (300) in accordance with JCPDS NO 46-1212. Meanwhile, monoclinic ZrO₂ presents characteristic peaks at 28.19° (011), 31.48° (111), 34.13° (002), 35.24° (112), 50.31° (022), 59.68° (013), 62.80° (222), and 74.39° (023) as given by JCPDS NO 37-1484.

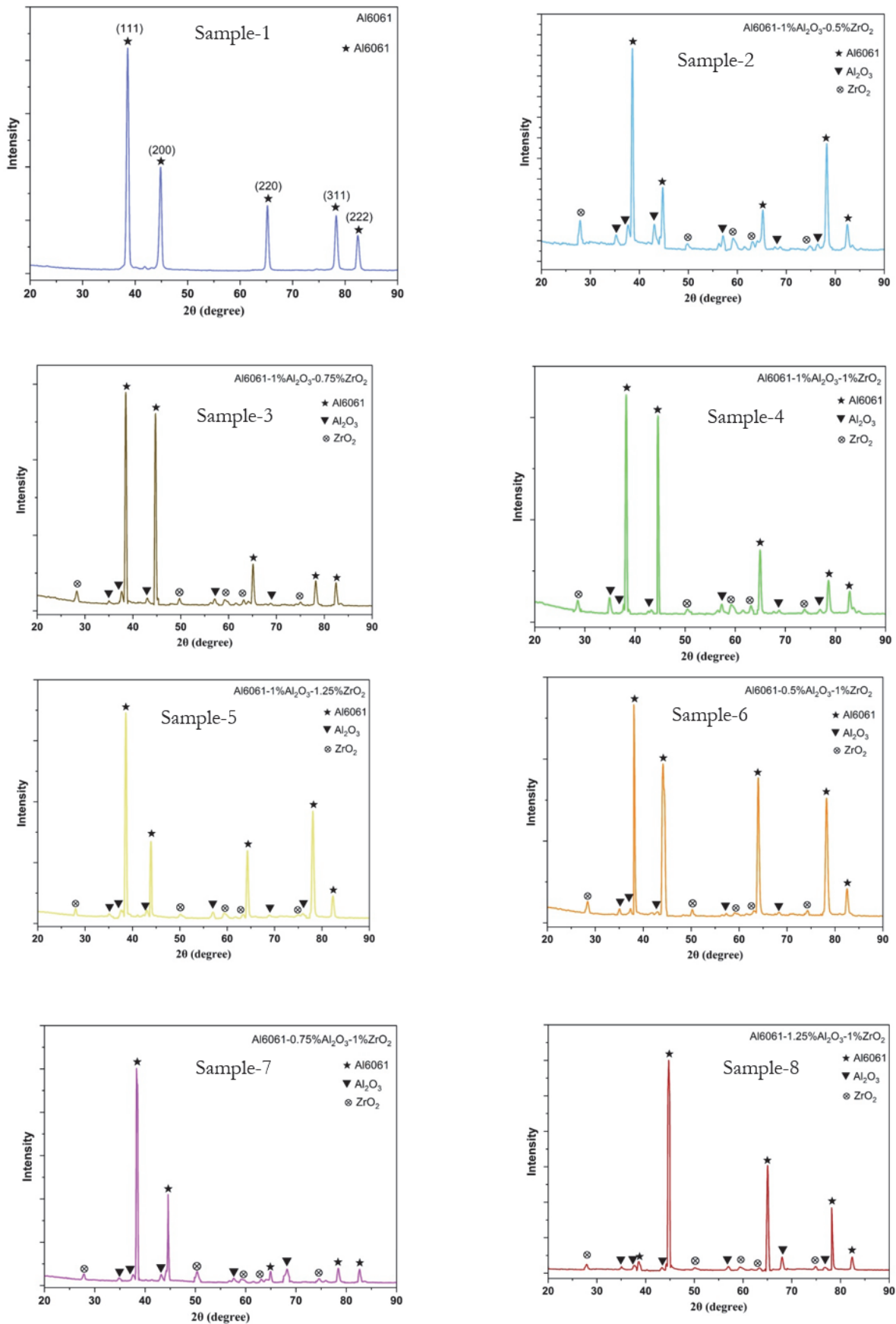


Figure 12: Stacked plot of X-ray diffraction patterns of Al6061 reinforced -varying wt. % of alumina and zirconium dioxide.



XRD study of Al6061-based composites shows the crystalline structure and phase composition of nano alumina (Al_2O_3) and zirconia (ZrO_2) in various quantities. As-cast Al6061 alloy has clear peaks at specific 2θ points, indicating a crystalline aluminum phase. 1% Al_2O_3 and 0.5% ZrO_2 add new peaks alongside Al peaks, showing successful incorporation. With 0.75% ZrO_2 , ZrO_2 peaks intensify, Al_2O_3 peaks persist, and Al matrix dominates. Separate peaks for Al_2O_3 and ZrO_2 at 1% each, indicating strong reinforcement presence. With 1.25% ZrO_2 , ZrO_2 peaks intensify, Al_2O_3 peaks stable, and Al matrix dominates. In 0.5% Al_2O_3 + 1% ZrO_2 , lower Al_2O_3 concentration reduces its peak intensity, while ZrO_2 peak intensifies. With 0.75% Al_2O_3 + 1% ZrO_2 , clear phases and dominant Al peaks coexist. The 1.25% Al_2O_3 + 1% ZrO_2 sample shows stronger Al_2O_3 pattern and distinct ZrO_2 peaks, indicating good nano-reinforcement integration in Al6061 matrix. Produced composites with different compositions show Al_2O_3 and ZrO_2 phases alongside the dominant Al phase, which indicating the Al6061 structure is preserved. A similar trend was observed by Nagaral M et.al. [20] Confirms the incorporation of reinforcing particulates by maintaining the minimal phase change. The obtained result indicates nano reinforcements are well disseminated within the matrix which is expected to enhance the mechanical strength and wear resistance of the produced composites.

Fracture toughness

Evaluation of the fracture toughness is essential to evaluate the ability of a material to endure the crack initiation and growth, when it is subjected to stress [21]. The study employed the fracture toughness test to assess the influence of Al_2O_3 and ZrO_2 reinforcements in the matrix of Al6061. It is evident from the analysis of the results that the optimal reinforcement blend of Al_2O_3 and ZrO_2 would be obtained, which further enhances the composite's resistance to crack propagation and overall mechanical properties.

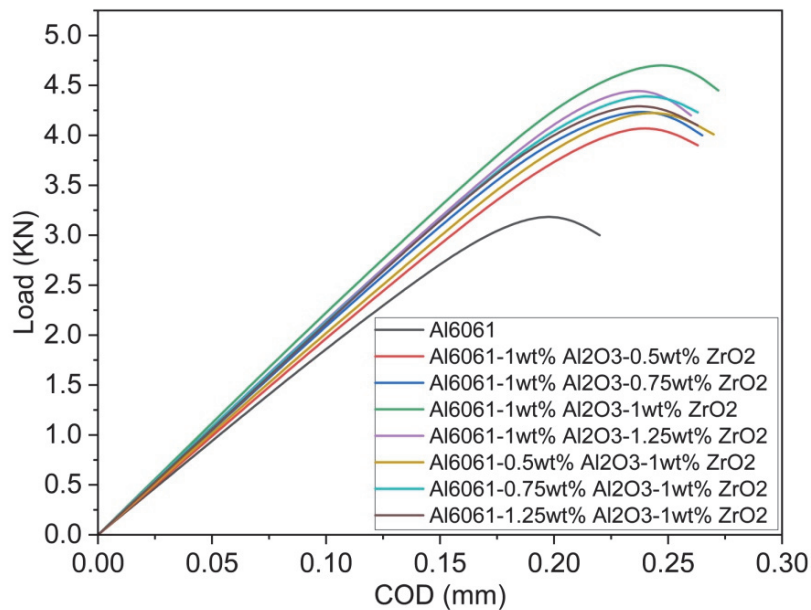


Figure 13: Load versus COD of Al6061 alloy reinforced with different wt.% of nano alumina and zirconium dioxide reinforcements.

Fig. 13 shows the load-crack opening displacement (COD) curve. The graph shows the variation in the fracture toughness of Al6061 with different reinforcement proportions. Also, it is evident that the load required increases with an increase in COD, which is attributed to the resistance of the aluminium composites to crack propagation under the stress. As-cast Al6061 samples exhibited a lower load capacity and failed well before the Al_2O_3 and ZrO_2 reinforced Al6061 samples. The incorporation of Al_2O_3 and ZrO_2 nano particles enhanced the load bearing capacity and it is evident from the curves (Fig. 13). The Al6061 composite with 1% Al_2O_3 and 1% ZrO_2 shows the highest load capacity and greater improvement in the fracture toughness Al6061 with 0.75% and 1.25% ZrO_2 with 1% Al_2O_3 are envisaged to enhance load tolerance. The reinforcement of nano Al_2O_3 and ZrO_2 particles has a significant effect on the fracture toughness. To evaluate the fracture toughness K_{IC} the following equation is used



$$K_{IC} = \frac{P_q \times f\left(\frac{a}{w}\right)}{B \times \sqrt{W}} \tag{1}$$

The critical load P_q , the beginning of unstable crack growth, which is prominently identified at the peak, where a significant change in slope is observed. B is the thickness of the specimen, W is the width of the specimen and $f(a/w)$ indicates the ratio of crack length to the specimen width. The 95% secant line method uses a reference line (which is drawn at 95% of the initial elastic slope) intersecting with the actual load-COD curve mainly to detect the critical transition from linear to nonlinear behaviour and the unstable fracture propagation.

Sample	Composition	Thickness (m)	P_q (kN)	P_{max} (kN)	P_{max}/P_q	$2.5(K_q/YS)^2$ (m)	$K_q = K_{IC}$ (MPa√m)	Percentage increase in K_{IC} relative to as-cast Al6061
1	Al6061	0.020	3.02	3.27	1.081	0.0199	7.28	-
2	Al6061-1%Al ₂ O ₃ -0.5%ZrO ₂	0.020	3.83	4.17	1.089	0.0194	9.23	26.78%
3	Al6061-1%Al ₂ O ₃ -0.75%ZrO ₂	0.020	4.04	4.34	1.073	0.0195	9.75	33.92%
4	Al6061-1%Al ₂ O ₃ -1%ZrO ₂	0.020	4.43	4.83	1.091	0.0199	10.73	47.39%
5	Al6061-1%Al ₂ O ₃ -1.25%ZrO ₂	0.020	4.26	4.55	1.068	0.0190	10.28	41.20 %
6	Al6061-0.5%Al ₂ O ₃ -1%ZrO ₂	0.020	3.97	4.34	1.092	0.0197	9.61	32.00%
7	Al6061-0.75%Al ₂ O ₃ -1 %ZrO ₂	0.020	4.14	4.49	1.084	0.0197	10.01	37.5 %
8	Al6061-1.25%Al ₂ O ₃ -1%ZrO ₂	0.020	4.09	4.39	1.074	0.0183	9.86	35.43%

Table 5: Fracture Toughness of Al6061 alloy reinforced with different weight fractions of nano alumina and zirconium dioxide reinforcing particulate.

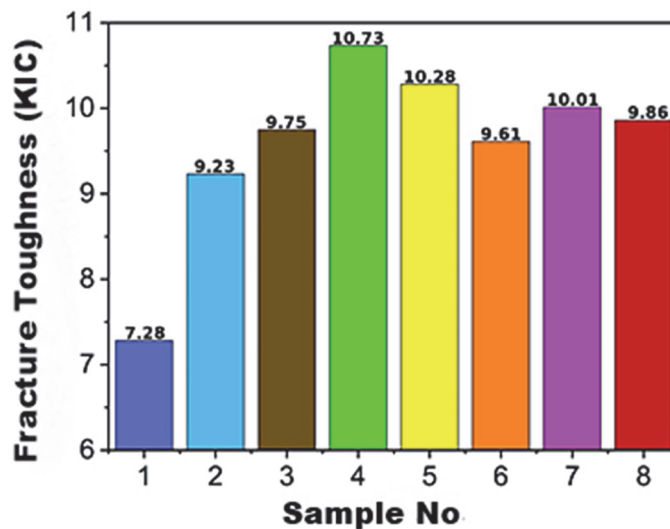


Figure 14: Fracture Toughness of 6061Al reinforced with different weight fractions of nano alumina and Zirconium dioxide reinforcing particulates

The fracture toughness assessment of the Al6061 alloy indicates that the crack resistance of the alloy is greatly improved with the addition of nano-sized Al_2O_3 and ZrO_2 particles. As cast Al6061 exhibits a fracture toughness of $7.28K_{IC}$. With the addition of 1% alumina and 0.50 ZrO_2 , toughness increased significantly to $9.23K_{IC}$, which highlights the beneficial influence of the synergistic reinforcement. The addition of more ZrO_2 to 0.75 and keeping the Al_2O_3 at 1 gave a toughness value of $9.75 K_{IC}$ and this means that the higher the content of ZrO_2 , the higher the resistance that will be offered to the fracture propagation. The highest fracture toughness value of $10.73 K_{IC}$ was observed in the specimen containing 1% Al_2O_3 and 1% ZrO_2 , indicating that the combination of the two nano-reinforcements significantly improved the resistance of the alloy to crack propagation. Nevertheless, a slight decrease in fracture toughness to $10.28 K_{IC}$ is observed with an increase in ZrO_2 content to 1.25%. This reduction can be explained by particle clustering or a change in the interaction between the matrix reinforcement at such high concentrations.

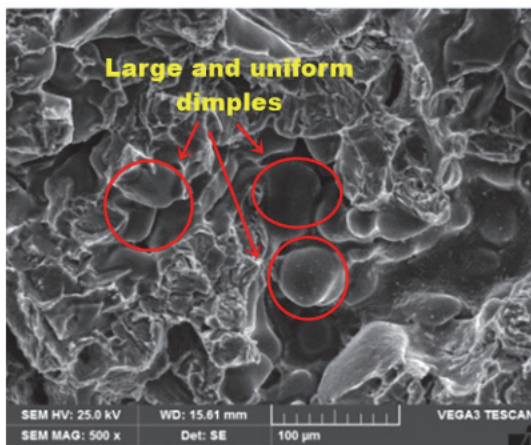
Al6061 with 0.5% Al_2O_3 and 1% ZrO_2 , and Al6061 with 0.75% Al_2O_3 and 1% ZrO_2 have shown the increased values of fracture toughness of $9.61 K_{IC}$ and $10.01 K_{IC}$, respectively, which are greater than that of the as cast Al6061 alloy. These data indicate that the 1% Al_2O_3 - ZrO_2 mixture results in the most significant increase in fracture toughness. Beyond this reinforcement content level, though, there is no proportional benefit of an increase in the reinforcement content since the gains level off. The same tendencies have been detected by previous studies [22, 23]. It is essential to optimize the ratio of Al_2O_3 to ZrO_2 to maximize the fracture toughness of the alloy.

Fractography analysis

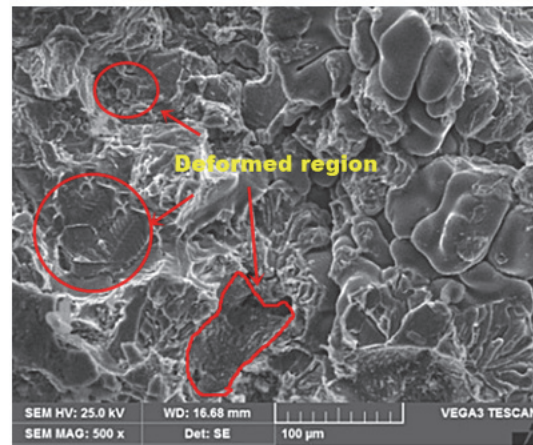
Fig.15 depicts the SEM images of the fracture toughness of the tested samples which reveal failure mechanisms in the synthesized composites at different weight fractions. Fig.15 (a) depicts the fracture surface of the as-cast Al6061 indicates the ductile nature behaviour which are marked with large and uniform dimples which demonstrate the micro void coalescence.

Fig. 15 presents images of the cracked surface, illustrating the various shapes associated with each composite configuration of the Al6061 alloy, reinforced with differing amounts of nano- Al_2O_3 and ZrO_2 . The fracture surface of the unreinforced base alloy (Fig. 15a) exhibits large dimples and significant plastic deformation, indicative of ductile fracture. The images illustrate a trend toward smaller dimples and the development of mixed ductile-brittle properties as the amount of reinforcement rises (Fig. 15b–h). Increased levels of reinforcement lead to more distinct river patterns and crack deflection points, signifying a shift towards brittle fracture behavior. The specimen containing 1% alumina and 1% zirconium dioxide (Fig. 15d) demonstrates balanced fracture morphology, featuring both micro void formation and trans-granular fracture characteristics, which suggests enhanced toughness attributed to the effective dispersion of nanoparticles.

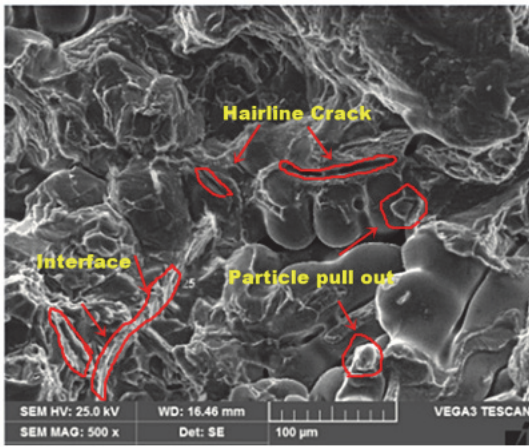
In contrast, samples with excessive reinforcement demonstrate increased particle aggregation and a tendency for brittle fracture, underscoring the necessity to optimize nano-reinforcement levels to improve mechanical performance in the alloy system.



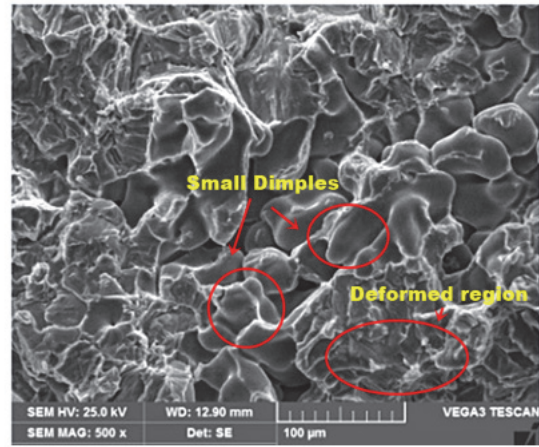
(a)



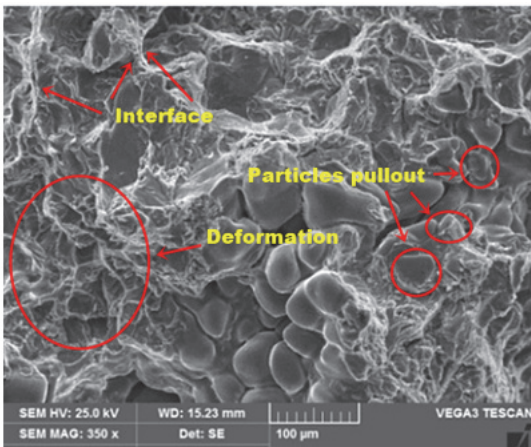
(b)



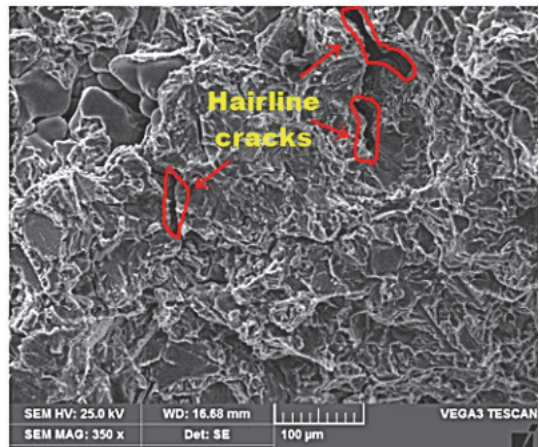
(c)



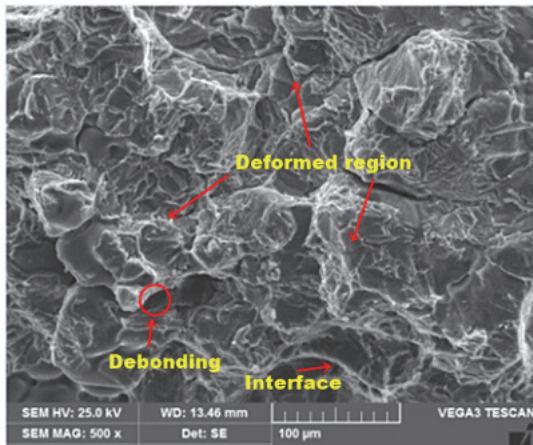
(d)



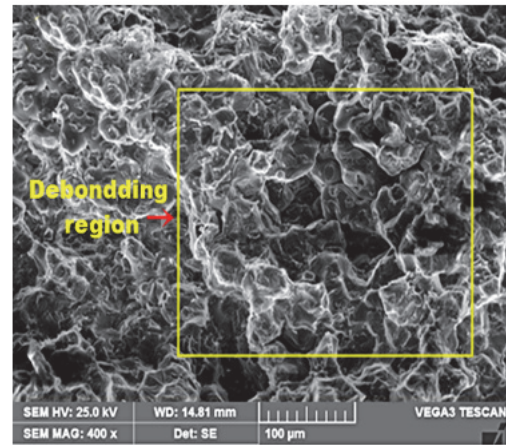
(e)



(f)



(g)



(h)

Figure 15(a-h): Fractography of (a) Al6061, (b) Al6061-1% Al₂O₃-0.5% ZrO₂, (c) Al6061-1% Al₂O₃-0.75% ZrO₂, (d) Al6061-1% Al₂O₃-1% ZrO₂, (e) Al6061-1% Al₂O₃-1.25% ZrO₂, (f) Al6061-0.5%Al₂O₃-1%ZrO₂, (g) Al6061-0.75% Al₂O₃-1% ZrO₂, (h) Al6061-1.25% Al₂O₃-1% ZrO₂.



CONCLUSION

Present research studies demonstrate a novel approach of ultrasonic-assisted stir-casting to examine the impact of nano- Al_2O_3 and nano- ZrO_2 reinforcing particulates on the fracture toughness of Al6061 alloy-based hybrid MMCs.

Microstructural studies shows uniform dissemination of nano reinforced particulates at ideal compositions, showing small amount of agglomeration. While, XRD and EDS confirms the presence or existence of the reinforcing particulates in the base matrix Al6061 alloy.

Fracture toughness testing demonstrates a significant enhancement in fracture toughness for all the nano particulates reinforced HMMCs as contrasted as-cast Al6061 matrix. Among the produced composites Al6061 alloy reinforced with 1% alumina and 1% zirconium dioxide achieving the highest fracture toughness.

The fractographic examination revealed a transition from ductile to mixed-mode fracture, with nanoparticles adequately disseminated to impede crack propagation and improve energy absorption. However, an excess of reinforcing material led to particle aggregation, increased brittleness, and a subsequent deterioration in fracture performance. The results indicate that a precisely balanced hybrid nano-reinforcement in Al6061 alloys can markedly improve fracture resistance, making these materials viable candidates for advanced engineering applications requiring high strength and toughness.

REFERENCES

- [1] Surappa, M. K. (2003). Aluminium matrix composites: Challenges and opportunities. *Sadhana*, 28(1), pp. 319-334.
- [2] Prasad, S. V. and Asthana, R. (2004). Aluminum metal-matrix composites for automotive applications: tribological considerations. *Tribology letters*, 17(3), pp. 445-453.
- [3] Annapoorna, K., Ananda, R., Deshpande, V. and Shobha, R. (2024, April). Nano reinforced aluminium based Metal Matrix Hybrid Composites-an overview. In *Journal of Physics: Conference Series* 2748(1), 012007.
- [4] Mieczkowski, G., Szymczak, T., Szpica, D. and Borawski, A. (2023). Probabilistic modelling of fracture toughness of composites with discontinuous reinforcement. *Materials*, 16(8), 2962.
- [5] Soliman, E. S. M. M. (2025). A study of fracture mechanics for compact tensile specimen of Al6061-SiC metal matrix composite. *Scientific Reports*, 15(1), 5763.
- [6] Chandel, R., Sharma, N. and Bansal, S. A. (2021). A review on recent developments of aluminum-based hybrid composites for automotive applications. *Emergent Materials*, 4(5), pp. 1243-1257.
- [7] Hassan, H. A., Hellier, A. K., Crosky, A. G. and Lewandowski, J. J. (2020). Fracture toughness of cast and extruded Al6061/15% Al_2O_3 metal matrix composites. *Australian Journal of Mechanical Engineering*.
- [8] Coleman, N. J., Bishop, A. H., Booth, S. E. and Nicholson, J. W. (2009). Ag⁺-and Zn²⁺-exchange kinetics and antimicrobial properties of 11 Å tobermorites. *Journal of the European Ceramic Society*, 29(6), pp. 1109-1117.
- [9] Hashim, J., Looney, L. and Hashmi, M. S. J. (1999). Metal matrix composites: production by the stir casting method. *Journal of materials processing technology*, 92, pp. 1-7.
- [10] Munro, C. and Walczyk, D. (2007). Reconfigurable pin-type tooling: A survey of prior art and reduction to practice. *Journal of Manufacturing Science and Engineering*, 129(3), pp. 497-501.
- [11] Shil, A., Roy, S., Balaji, P. S., Kumar Katiyar, J., Pramanik, S. and Kumar Sharma, A. (2019, November). Experimental analysis of mechanical properties of stir casted aluminium-graphene nanocomposites. In *IOP Conference Series: Materials Science and Engineering* 653(1), . 012021.
- [12] Balakumar, G. (2013). Tensile and wear characterization of aluminium alloy reinforced with nano- ZrO_2 metal matrix composites (NMMCs). *Int. J. Nano Sci. Nanotechnol*, 4(1), pp. 121-129.
- [13] Shekhawat, D., Agarwal, P., Patnaik, T. K., Singh, A. and Patnaik, A. (2023). Fracture toughness of nano-zirconia filled aluminum matrix composites: an experimental and numerical analysis. *Engineering Research Express*, 5(1), 015012.
- [14] Krishnappa, A., Ramesh, S., Bharath, V. M., Siddagangappa, R., Ashokkumar, S., Nagaral, M. and Auradi, V. (2025). Effect of hybrid nano particle reinforcements on fractographic, mechanical and wear behavior of Al6061 alloy composites developed by ultrasonic assisted stir casting technique. *Fracture and Structural Integrity*, 19(71), pp. 285-301.
- [15] Annapoorna, K., Shobha, R., Bharath, V., Rajanna, S., Nagaral, M.M.V., Auradi, V., Shivaprasad, C.G. (2025). Optimization of stir casting parameters for the tensile behavior of nano Al_2O_3 and ZrO_2 reinforced Al-Mg-Si alloy



- metal composites. *Research on Engineering Structures and Materials*. 11(2), pp. 631-646
- [16] ASTM standard E399- Standard Test Method for Plane strain Fracture Toughness of Metallic Materials.
- [17] Shil, A., Roy, S., Balaji, P. S., Kumar Katiyar, J., Pramanik, S. and Kumar Sharma, A. (2019, November). Experimental analysis of mechanical properties of stir casted aluminium-graphene nanocomposites. In *IOP Conference Series: Materials Science and Engineering* 653(1), 012021.
- [18] Hareesha, G., Chikkanna, N. and Doddamani, S. (2021, February). Finite element simulation of fracture toughness of Al6061 reinforced with silicon carbide. In *IOP Conference Series: Materials Science and Engineering* 1065(1), 012036.
- [19] Hegde, R., Sivaram, N. M., Ajaykumar, B. S., Kirthan L. J. (2017). Evaluation of Heat treatment Effect on Fracture Behavior of Aluminum Silicon Carbide Graphite Hybrid Composite, *International Journal of Applied Engineering Research*, 12(5), pp. 605-610)
- [20] Nagral, M., Bharath, V. and Auradi, V. (2013). Effect of Al₂O₃ particles on mechanical and wear properties of 6061Al alloy metal matrix composites. *J. Mater. Sci. Eng*, 2(120), pp. 2169-0022.
- [21] Doddamani, S. and Kaleemulla, M. (2015). Review of experimental fracture toughness (K_{IC}) of aluminium alloy and aluminium MMCs. *International Journal of Fracture and Damage Mechanics*, 1(1), pp. 1-15.
- [22] Owaid, A. J. (2018). Characterization of AA 6061–alloy composites reinforced by Al₂O₃ nano particles obtained by stir casting. *Engineering and Technology Journal*, 36(7 Part A).
- [23] Kushvaha, V. and Tippur, H. (2014). Effect of filler shape, volume fraction and loading rate on dynamic fracture behavior of glass-filled epoxy. *Composites Part B: Engineering*, 64, pp. 126-137.