RESEARCH PAPER

Investigation of Thermal and Dynamic Mechanical Behaviour of Stir-Cast Al5083 Hybrid Composites Reinforced with Nano-ZrO_2 and Nano-SiC

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Abstract

The present investigation reports the development and comprehensive characterization of Al5083 hybrid nanocomposites reinforced with a fixed 5 wt.% of nano-zirconia (ZrO_2) and varying additions of nano-silicon carbide (SiC) at 5, 10 and 15 wt.%. The composites were fabricated through a stir-casting route, and their microstructural, mechanical, fracture, thermal and dynamic mechanical responses were systematically evaluated against the unreinforced alloy. Scanning electron microscopy revealed progressively refined matrix grains and a uniform dispersion of the dual ceramic phases, which acted as effective barriers to localized shear deformation. The hybrid composite containing the highest reinforcement content delivered the best overall performance, registering an improvement of approximately 53% in compressive yield strength and about 39% in ultimate compressive strength relative to the base alloy, together with a gain of nearly 20% in fracture toughness. Thermogravimetric analysis indicated a rise of roughly 15% in the oxidation onset temperature and a reduction of about 61% in high-temperature weight loss, confirming markedly enhanced oxidation resistance. Dynamic mechanical analysis further demonstrated an increase of around 34% in room-temperature storage modulus and nearly 45% in stiffness retention at elevated temperature, accompanied by a shift of the viscoelastic transition to higher temperatures and a 38% reduction in damping capacity. The findings establish the optimized hybrid nanocomposite as a strong candidate for high-load, elevated-temperature structural applications.

Keywords: Al5083; hybrid nanocomposite; nano-ZrO_2; nano-SiC; stir casting; compressive strength; fracture toughness; TGA/DTA; dynamic mechanical analysis.

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1. Introduction

Aluminium alloys of the 5xxx series, and Al5083 in particular, are widely employed in marine structures, transportation, cryogenic vessels and defence hardware owing to their attractive combination of moderate strength, excellent corrosion resistance, good weldability and low density. However, the relatively modest hardness, limited wear resistance and pronounced loss of stiffness at elevated temperatures restrict the use of the monolithic alloy in demanding structural applications. Metal matrix composites (MMCs), in which hard ceramic phases are dispersed within a ductile aluminium matrix, offer a well-established pathway to overcome these limitations while retaining the processing flexibility of aluminium.

Within this family, hybrid nanocomposites—matrices reinforced simultaneously with two or more nano-scale ceramic phases—have attracted particular attention because the constituent reinforcements can play complementary roles. Nano-ZrO_2 contributes high fracture toughness, thermal stability and transformation-related crack-shielding effects, whereas nano-SiC provides exceptional hardness, stiffness and thermal conductivity. When both are dispersed uniformly in Al5083, grain refinement, Orowan strengthening, load transfer and the mismatch in the coefficient of thermal expansion act together to elevate the mechanical response well beyond what either reinforcement can achieve alone. The present work therefore develops Al5083–5%ZrO_2 composites with progressive nano-SiC additions and characterizes their microstructure, compressive behaviour, fracture toughness, thermal stability and viscoelastic performance in a unified framework.

2. Literature Review

Research on particulate-reinforced aluminium matrix composites (AMCs) has matured over three decades, and the principal strengthening mechanisms, processing routes and property trade-offs are now well documented. Miracle [1] reviewed the state of the art in metal matrix composites and highlighted their penetration into aerospace, automotive and thermal-management applications, while Ibrahim et al. [2] provided an early but still authoritative account of particulate-reinforced AMC fabrication and mechanics. Among liquid-state routes, stir casting remains the most economical and scalable technique; Hashim et al. [3] examined its viability and identified particle wetting, settling and porosity as the central processing challenges. Kok [4] produced Al2024–Al_2O_3 composites by vortex stir casting and showed that strength and hardness rise with particle content and decreasing particle size, and Sajjadi et al. [5] compared micro- and nano-Al_2O_3 reinforced A356 composites, demonstrating that nano-scale additions deliver disproportionately large gains at low volume fractions.

The transition from micro- to nano-reinforcement has been a decisive development. Casati and Vedani [6] surveyed aluminium nanocomposites and attributed their superior strength to Orowan looping, enhanced dislocation density from thermal mismatch and Hall–Petch grain refinement. Ultrasonic and semi-solid processing have been advanced to counteract nanoparticle agglomeration: Yang et al. [7] dispersed nano-SiC in molten A356 using ultrasonic cavitation, and Ezatpour et al. [8] reported simultaneous improvement of strength and ductility in stir-cast Al6061 nano-Al_2O_3 composites after extrusion. Concerning SiC-bearing systems specifically, Ozden et al. [9] investigated the impact behaviour of SiC-particle reinforced AMCs, while Ravindran et al. [10] showed that hybrid additions of SiC and graphite to Al5083 markedly improve tribological performance. Rana et al. [11] characterized Al5083 nano-SiC composites fabricated through ultrasonic-assisted stir casting and recorded significant hardness and tensile gains at low nanoparticle loadings.

Zirconia and zirconium-bearing reinforcements have likewise proven effective. Abdizadeh et al. [12] fabricated A356–ZrO_2 composites by both powder metallurgy and stir casting and observed strengthening that depended strongly on processing temperature. Kumar et al. [13] studied AA6061–ZrO_2 composites and reported systematic improvements in hardness and ultimate tensile strength with reinforcement content, and Gurusamy and co-workers [14] examined the influence of processing temperature on the mechanical response of ZrO_2-reinforced aluminium castings. Hybridization strategies, in which two ceramics act synergistically, are increasingly favoured: Suresh et al. [15] reviewed hybrid AMCs and catalogued the property envelopes attainable with dual reinforcements; Umanath et al. [16] analysed the dry sliding wear of Al6061–SiC–Al_2O_3 hybrid composites; Alaneme and Olubambi [17] evaluated the corrosion and wear of alumina–rice-husk-ash hybrid composites; and Radhika and Raghu [18] investigated three-body abrasive wear in Al–Si/Al_2O_3/graphite systems, all confirming that hybrid architectures broaden the balance between strength, toughness and wear resistance.

Studies devoted to the thermal and viscoelastic behaviour of AMCs are comparatively scarce but instructive. Uju and Oguocha [19] examined the thermal expansion and thermogravimetric response of AA2618 composites containing fly ash and alumina, showing that ceramic phases retard oxidative mass change, while Lakshmipathy and Kulendran [20] and related dynamic mechanical studies established that ceramic nano-reinforcements raise the storage modulus and shift the viscoelastic transition of aluminium matrices to higher temperatures. Prasad and Krishna [21] reported the tribological and mechanical gains achievable in Al–SiC systems with process optimization, and Bodunrin et al. [22] critically reviewed hybrid AMCs with an emphasis on the interplay between mechanical, corrosion and tribological behaviour, identifying the paucity of combined thermo-mechanical datasets on 5xxx-series hybrid nanocomposites as a clear research gap.

Novelty of the present work

The surveyed literature shows that (i) most stir-cast investigations address single micro- or nano-reinforcements, (ii) ZrO_2–SiC dual nano-reinforcement of the marine-grade alloy Al5083 has received little systematic attention, and (iii) very few studies couple compressive response, plane-strain fracture toughness (ASTM E399), TGA/DTA oxidation behaviour and dynamic mechanical analysis for the same composite series. The novelty of the present research therefore lies in the development of stir-cast Al5083 hybrid nanocomposites with a fixed 5 wt.% nano-ZrO_2 and graded nano-SiC additions (5–15 wt.%), and in their unified microstructural, mechanical, fracture, thermal and viscoelastic characterization, which together identify an optimized composition (Al5083–5%ZrO_2–15%SiC) offering simultaneous gains in strength, toughness, oxidation resistance and high-temperature stiffness retention.

3. Materials and Methodology

3.1 Materials and composite compositions

Commercially available Al5083 alloy was selected as the matrix in view of its established marine and structural pedigree. Nano-zirconia (ZrO_2) was held constant at 5 wt.% in all reinforced compositions, while nano-silicon carbide (SiC) was introduced at 5, 10 and 15 wt.% to generate a graded hybrid series. Five compositions, designated Sample 1 through Sample 5, were prepared as summarized in Table 1.

Table 1. Composition and designation of Al5083 hybrid nanocomposites

S. No	Sample ID	Composite	Al (wt. %)	ZrO_2 (wt. %)	SiC (wt. %)
1	Sample 1	Pure Al5083	100	–	–
2	Sample 2	Al5083–5%ZrO_2	95	5	–
3	Sample 3	Al5083–5%ZrO_2–5%SiC	90	5	5
4	Sample 4	Al5083–5%ZrO_2–10%SiC	85	5	10
5	Sample 5	Al5083–5%ZrO_2–15%SiC	80	5	15

3.2 Fabrication route

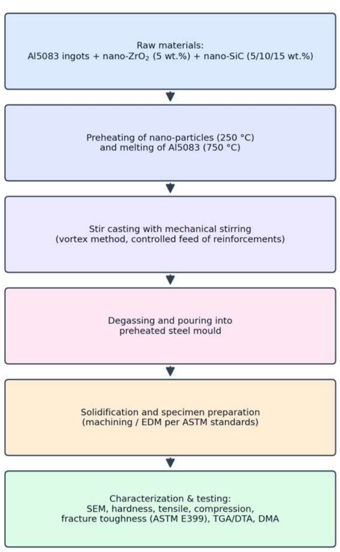

Figure 1. Experimental flowchart for fabrication and characterization of Al5083 hybrid nanocomposites

The composites were produced by the stir-casting (vortex) technique. The nano-reinforcements were preheated to remove adsorbed moisture and improve wettability before being fed progressively into the molten Al5083 maintained above its liquidus. Mechanical stirring generated a stable vortex that entrained and dispersed the ceramic particles through the melt; the slurry was then degassed and poured into a preheated steel mould. Cast billets were machined into standard test coupons, with fracture-toughness notches introduced by electrical discharge machining (EDM). Figure 1 presents the overall experimental flowchart adopted in this study.

3.3 Characterization and testing

Microstructural examination of polished and fractured surfaces was carried out using scanning electron microscopy (SEM). Compression tests were conducted on a universal testing machine to obtain compressive stress–strain curves, compressive yield strength (CYS) and ultimate compressive strength (UCS). Plane-strain fracture toughness was measured on single-edge notched bend (SENB) specimens of 60 mm × 12 mm × 6 mm with a 6 mm EDM notch and fatigue pre-crack, tested in three-point bending over a 48 mm span at 10 mm/min in accordance with ASTM E399-20; K_IC was evaluated from $K_IC = (P_{max}S)/(BW^{(3/2)}) \cdot f(a/W)$. Thermal stability was assessed by simultaneous TGA/DTA (TA Instruments SDT Q600) from ambient to 800 °C at 10 °C/min under nitrogen (100 mL/min) using 10–15 mg samples in alumina crucibles. Dynamic mechanical analysis (TA Instruments DMA Q800) was performed in three-point bending on 35 mm × 10 mm × 3 mm bars from 30 °C to 300 °C at 5 °C/min, 1 Hz frequency and 0.1% strain amplitude, recording storage modulus (E′), loss modulus (E″) and loss tangent (tan δ).

4. Results and Discussion

4.1 Microstructural analysis

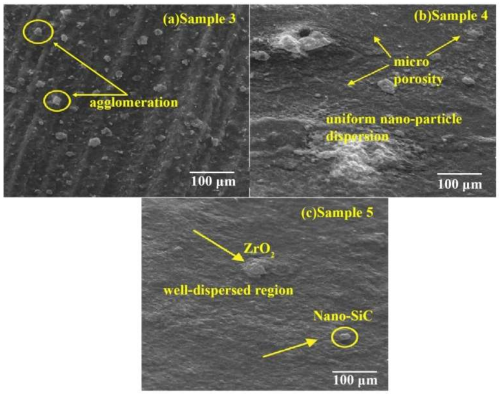

Figure 2. SEM micrograph of Al5083 alloy reinforced with nano-scale ZrO_2 and SiC

SEM examination confirms that the dual nano-reinforcements are distributed uniformly through the Al5083 matrix with progressively refined grains as the SiC content rises; the hybrid compositions exhibit average grain sizes reduced to approximately 35–45 µm relative to the coarse as-cast structure of the base alloy. The refined, well-bonded particle–matrix interfaces visible in Figure 2 underpin the mechanical and thermal gains discussed below.

4.2 Compressive behaviour

The compressive stress–strain curves (Figure 3) show a systematic elevation of both flow stress and stiffness with increasing nano-reinforcement content. Although higher ceramic loading ordinarily depresses ductility, Sample 5 deforms stably without premature failure, indicating an effective balance between strength and structural integrity under compression. Table 2 lists the measured properties: the base alloy exhibits a CYS of 165 MPa and a UCS of 428 MPa, both of which rise monotonically through the series, with the peak composition delivering improvements of approximately 53% in yield strength and 39% in ultimate strength over pure Al5083. These trends correlate directly with the refined microstructure and enhanced densification, and arise from load transfer to the stiff ceramic phases, Orowan strengthening by the nano-particles and dislocation generation from thermal-expansion mismatch. The comparative bar representation in Figure 4 summarizes the CYS and UCS evolution across all compositions.

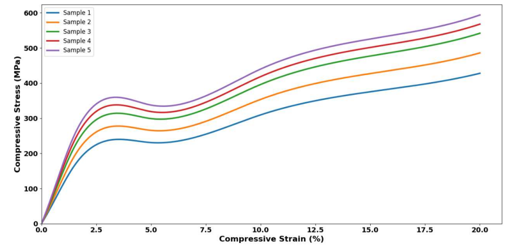

Figure 3. Compressive stress–strain curves of Al5083 hybrid nanocomposites

Table 2. Compressive properties of Al5083 nanocomposites

Sample ID	Compressive Yield Strength (MPa)	Ultimate Compressive Strength (MPa)
Sample 1	165 ± 6	428 ± 12
Sample 2	192 ± 7	486 ± 15
Sample 3	218 ± 8	542 ± 17
Sample 4	228 ± 9	554 ± 18
Sample 5	236 ± 10	568 ± 19

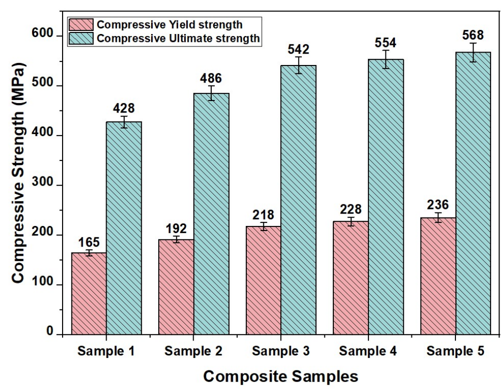

Figure 4. Compressive yield strength and ultimate compressive strength of Al5083 nanocomposites

4.3 Compressive fracture surface study

Post-test SEM observation reveals a clear evolution of deformation mode with reinforcement content (Figures 5 and 6). Pure Al5083 fails in a classically ductile manner: pronounced barreling, shear bands inclined at roughly 45° to the loading axis, extensive plastic flow with fine slip lines, and large dimples on the fracture surface. With 5% nano-ZrO_2 (Sample 2), barreling diminishes and shear bands become more numerous but individually weaker, the dispersed nano-particles acting as barriers that arrest localized shear propagation. The hybrid compositions continue this progression: Sample 3 develops multiple intersecting shear bands with well-bonded particle–matrix interfaces;

Sample 4 exhibits highly distributed deformation with only isolated interfacial micro-cracking in regions of high local strain; and Sample 5 shows the most homogeneous deformation field with negligible barreling and numerous fine shear bands spread across the entire compressed area, evidencing excellent load distribution throughout the composite.

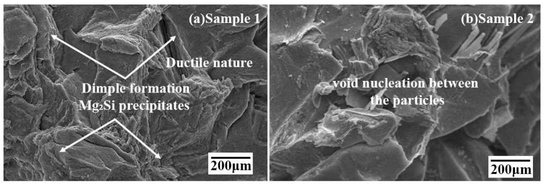

Figure 5. SEM images of compression specimen surfaces showing deformation patterns and shear bands: (a) Sample 1 – Pure Al5083, (b) Sample 2 – Al5083–5%ZrO_2

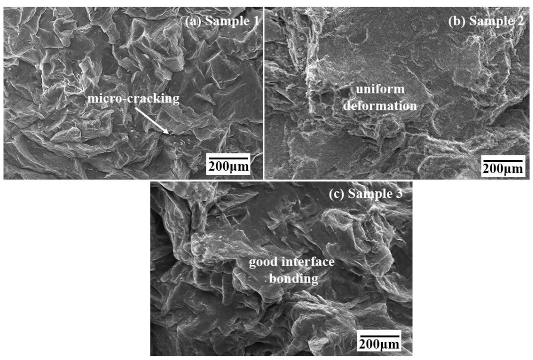

Figure 6. SEM images of compression specimen surfaces: (a) Sample 3, (b) Sample 4, (c) Sample 5

4.4 Fracture toughness

The SENB results are collected in Table 3 and plotted in Figure 7. The as-cast base alloy records a K_1C of 29.4 MPa√m, typical of aluminium alloys in this condition. Adding 5 wt.% nano-ZrO_2 raises the toughness by about 11%, and the hybrid series improves progressively thereafter, culminating in a value of 35.2 MPa√m for Sample 5—an overall gain of roughly 20% relative to pure Al5083. All reinforced compositions retain K_1C above 32 MPa√m, confirming excellent resistance to crack propagation. The improvement is attributed to crack deflection and bridging at the nano-particle interfaces together with the transformation-toughening contribution of ZrO_2, mechanisms that offset the intrinsic brittleness usually introduced by high ceramic loadings.

Table 3. Fracture toughness of Al5083 nanocomposites

Sample ID	Composition	Fracture Toughness K_1C (MPa√m)
Sample 1	Pure Al5083	29.4 ± 1.8
Sample 2	Al5083–5%ZrO_2	32.6 ± 1.9
Sample 3	Al5083–5%ZrO_2–5%SiC	33.8 ± 2.0
Sample 4	Al5083–5%ZrO_2–10%SiC	34.5 ± 2.1
Sample 5	Al5083–5%ZrO_2–15%SiC	35.2 ± 2.2

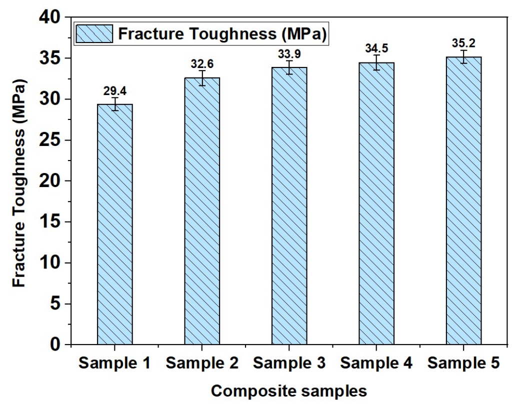

Figure 7. Variation of fracture toughness with nano-reinforcement content

Taken together, the mechanical programme identifies Sample 5 (Al5083–5% nano-ZrO_2–15% nano-SiC) as the best overall performer, combining maximum hardness (122.3 BHN), the highest tensile strength (408 MPa), maximum compressive strength and superior fracture toughness while retaining an acceptable ductility of 6.5% elongation.

4.5 Thermogravimetric and differential thermal analysis

The TGA/DTA results (Table 4, Figures 8 and 9) demonstrate a progressive enhancement of thermal stability with nano-reinforcement content. The oxidation onset of the base alloy at 458 °C shifts upward through the series to 528 °C for Sample 5—an increase of 70 °C (≈15%)—while the weight loss at 800 °C falls from 2.3% to 0.9%, a reduction of about 61%. Correspondingly, the peak exothermic temperature in the DTA traces rises from 612 °C to 668 °C and the residual mass at 800 °C climbs from 97.7% to 99.1%. The refractory character of the two ceramic phases (melting points near 2715 °C for ZrO_2 and 2730 °C for SiC) allows them to act as thermal barriers that retard oxidation kinetics and stabilize the matrix at elevated temperature.

Table 4. Thermal decomposition characteristics of Al5083 hybrid nanocomposites

Sample ID	Onset Oxidation Temp. (°C)	Weight Loss at 800 °C (%)	Peak Exothermic Temp. (°C)	Residual Mass at 800 °C (%)
Sample 1	458	2.3	612	97.7
Sample 2	482	1.9	628	98.1
Sample 3	498	1.5	641	98.5
Sample 4	512	1.2	653	98.8
Sample 5	528	0.9	668	99.1

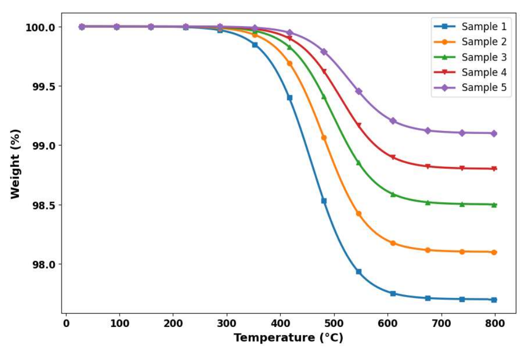

Figure 8. TGA curves showing weight loss (%) versus temperature (25–800 °C) for all Al5083 hybrid nanocomposites

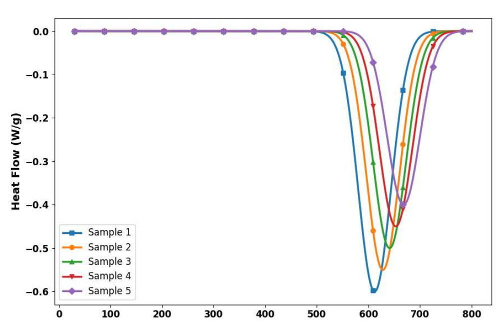

Figure 9. DTA curves showing heat flow (W/g) versus temperature for all compositions, displaying exothermic peaks and delayed oxidation

4.6 Dynamic mechanical analysis

The viscoelastic response (Table 5, Figures 10 and 11) mirrors the quasi-static findings. The storage modulus of pure Al5083 falls from 68.5 GPa at 30 °C to 52.3 GPa at 200 °C (a 24% loss), whereas the hybrid composites both start stiffer and retain stiffness better: Sample 5 reaches 91.6 GPa at room temperature and 75.8 GPa at 200 °C, improvements of approximately 34% and 45% respectively over the base alloy. The loss modulus at 30 °C declines from 3.42 GPa to 2.43 GPa across the series, indicating reduced energy dissipation and a more elastic response. The tan δ peak—marking the transition from predominantly elastic to viscous behaviour—shifts from 185 °C for the base alloy to 212 °C for Sample 5, a 27 °C elevation, while the peak height drops from 0.052 to 0.032, a 38% reduction in damping capacity. These changes reflect the restriction of matrix mobility by the densely dispersed ceramic phases, which suppress internal-friction mechanisms and preserve stiffness at temperature.

Table 5. Dynamic mechanical properties of Al5083 hybrid nanocomposites

Sample ID	E′ at 30 °C (GPa)	E′ at 200 °C (GPa)	E″ at 30 °C (GPa)	tan δ Peak Temp. (°C)	tan δ Peak Height
Sample 1	68.5	52.3	3.42	185	0.052
Sample 2	73.2	58.6	3.15	192	0.046
Sample 3	79.8	64.2	2.88	198	0.041
Sample 4	85.4	69.8	2.65	205	0.036
Sample 5	91.6	75.8	2.43	212	0.032

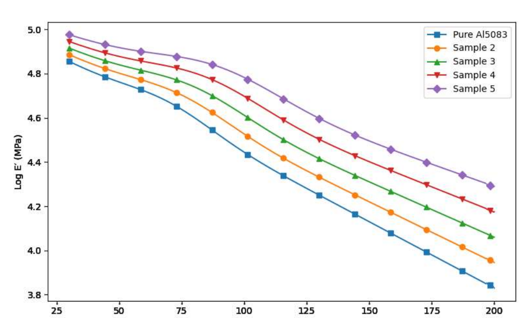

Figure 10. Storage modulus (E′) versus temperature (30–300 °C) for all Al5083 hybrid nanocomposites

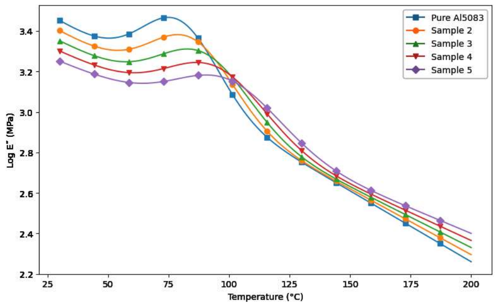

Figure 11. Loss tangent (tan δ) versus temperature showing the transition-temperature shift and reduced damping with nano-reinforcement addition

The combined thermal and dynamic mechanical evidence confirms that the highest-loading hybrid composition possesses superior thermal stability and elevated-temperature mechanical integrity, making it particularly suitable for components required to sustain mechanical performance under prolonged thermal exposure.

5. Conclusion

Al5083 hybrid nanocomposites containing a fixed 5 wt.% nano-ZrO_2 and graded nano-SiC additions of 5–15 wt.% were successfully fabricated by stir casting and subjected to an integrated programme of microstructural, compressive, fracture, thermal and dynamic mechanical characterization. The dual ceramic nano-reinforcements acted synergistically—refining the matrix grains, homogenizing plastic deformation and shielding the alloy from oxidation—so that every property examined improved monotonically with SiC content. The principal outcomes of the investigation are:

- SEM analysis confirmed uniform dispersion of nano-ZrO_2 and nano-SiC with matrix grain refinement to approximately 35–45 µm and well-bonded particle–matrix interfaces.
- Compressive yield strength and ultimate compressive strength improved by about 53% and 39% respectively over pure Al5083, with the highest-loading composite deforming stably without premature failure.
- Fracture surfaces evolved from pronounced barreling and dominant 45° shear bands in the base alloy to a highly homogeneous deformation field in the hybrid composites, the nano-particles acting as barriers to localized shear.
- Plane-strain fracture toughness rose by nearly 20% to 35.2 MPa√m, with all reinforced compositions exceeding 32 MPa√m, confirming excellent crack-propagation resistance.
- TGA/DTA revealed a 70 °C (≈15%) increase in oxidation onset temperature, a 61% reduction in weight loss at 800 °C and a rise in residual mass to 99.1%, demonstrating markedly enhanced oxidation resistance.
- DMA showed a 34% gain in room-temperature storage modulus, 45% better stiffness retention at 200 °C, a 27 °C upward shift of the viscoelastic transition and a 38% reduction in damping capacity.
- Overall, Al5083–5%ZrO_2–15%SiC (Sample 5) emerged as the optimal composition, recommended for high-load structural and elevated-temperature engineering applications.

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