
EFFECT OF HEAT TREATMENT AND QUENCHING MEDIA ON THE MECHANICAL, TRIBOLOGICAL, AND MICROSTRUCTURAL BEHAVIOUR OF A6082-SNSA/MWCNT HYBRID COMPOSITES

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ABSTRACT

The effect of heat treatment and different quenching media on the mechanical, tribological, and microstructural behaviour of A6082–SNSA/MWCNT hybrid composites were studied. The fabricated composites were subjected to heat treatment and quenched in tap water (TW), ice block (IB), and SAE40 engine oil (SEO), and their properties were compared with untreated hybrid composites and the base matrix alloy. The result of the mechanical properties revealed that all heat-treated samples exhibited significant improvements in hardness, compressive strength, and impact strength relative to the untreated composite. The IB quenched sample recorded the highest hardness of 155.33 Hv, representing 15% increment, while the TW quenched sample exhibited superior compressive and impact strengths of 1567.1 MPa representing 64.30% and 3.0J respectively. Tribological analysis showed that the SEO quenched composite possessed the lowest coefficient of friction of 0.166, which represents 16.27% improvement, whereas the TW quenched composite demonstrated the most favourable wear performance among the treated samples. Optical microstructural analysis revealed that rapid quenching (IB) produced the finest and most compact dendritic network, while oil quenching resulted in coarse, elongated dendrites with increased segregation and micro-voids. Scanning electron microscope (SEM) analysis of the worn surfaces confirmed dominance of abrasive and delamination wear mechanisms, with reduced surface damage observed in heat-treated samples. The results demonstrate that quenching medium significantly influences the mechanical, tribological, and microstructural behaviour of the hybrid composites.

Keywords: A6082 aluminium alloy; Hybrid metal matrix composites; Heat treatment; Quenching; Microstructure

1. INTRODUCTION

Aluminium matrix composites (AMCs) have attracted considerable interest for lightweight engineering applications because of their high strength-to-weight ratio, wear resistance, and thermal stability. A6082 aluminium alloy is particularly attractive as a matrix material, while the incorporation of suitable reinforcements can further improve its mechanical and tribological performance (Jiang *et al.*, 2021; Ononiwu *et al.*, 2021; Kumar *et al.*, 2025).

MWCNTs are attractive reinforcements because of their high strength, stiffness, and nanoscale load-transfer capability, while shea nutshell ash (SNSA) provides a low-cost and environmentally sustainable agro-waste reinforcement. Previous studies have demonstrated the potential of SNSA and carbon-based reinforcements for improving the properties of polymeric and aluminium composites (Haruna *et al.*, 2019; Zubairu *et al.*, 2021; Abdullahi *et al.*, 2025).

Heat treatment can modify precipitation behaviour, grain structure, matrix–reinforcement interaction, and consequently the mechanical and tribological properties of aluminium composites. Previous studies have reported improvements in hardness, strength and wear resistance following appropriate heat-treatment schedules, although the response depends strongly on alloy composition, reinforcement characteristics and quenching conditions (Gandhi *et al.*, 2019; Huang *et al.*, 2024; Kuczek *et al.*, 2025; Ravikumar *et al.*, 2021).

Despite the substantial progress reported in the literature, most existing studies have focused on single or conventional reinforcement systems, with relatively few investigations considering hybrid reinforcement combinations. Furthermore, majority of the reported works evaluated only selected mechanical or tribological properties, while limited attention has been given to understanding the combined effects of heat treatment on the microstructure, mechanical properties, and wear behaviour of hybrid AMCs reinforced simultaneously with agro-waste and carbon nanotubes. Addressing this gap is essential for developing lightweight, high-performance, and sustainable AMCs for advanced engineering applications. Therefore, the present study investigates the effect of heat treatment on the mechanical and wear behaviour of A6082–SNSA/MWCNT hybrid composites.

2. METHODOLOGY

In this study, A6082 metal matrix with length x width x thickness of 350 mm x 25 mm x 25 mm was used. The content of the components of the A6082 alloy is presented in Table 1. Shea nut shell ash (SNSA) particles and Multiwalled carbon nanotubes, comprising 6wt% and 2 wt% particles were used as reinforcements. Stir casting method was employed to fabricate the hybrid composites. The details of the synthesis and characterization of the reinforcements could be found in our previous studies (Abdullahi *et al.*, 2025). While A6082 provides excellent strength-to-weight ratio, corrosion resistance, and good castability, SNSA offers a sustainable and low-cost reinforcement source, whereas MWCNTs contribute exceptional strength, stiffness, and load-transfer capability at the nanoscale. The combination of these reinforcement materials is therefore expected to produce hybrid composites with improved mechanical and tribological performance while promoting sustainable utilization of agricultural waste (Abdullahi *et al.*, 2025).

Table 1: Compositions of AA6082 Alloy

Element	Al	Si	Ti	Fe	Mn	Zn	Mg	Cu	Cr	Ni
Wt. %	96.22	1.26	0.07	0.47	0.11	0.28	1.30	0.18	0.09	0.02

2.1 Hybrid Composites Fabrication

The hybrid composite was produced by heating about 550g of AA6082 to 680 °C using a graphite crucible in a charcoal fired furnace. Coated MWCNT (Abdullahi *et al.*, 2025) and the SNSA were introduced into the molten AA6082 alloy and stirred using a mechanical stirrer equipped with a stainless-steel tip, operating at 450 rpm for 4.5 min. To ensure effective wetting of the reinforcement phase by the matrix, the reinforcements were heated to 250 °C and introduced into the molten AA6082. The molten mixture was poured into a square pre-heated steel mould of 350 mm in length 25 mm height and 25 mm thickness. The fabrication parameters were adopted from the optimized procedure reported by Abdullahi *et al.* (2025).

2.2 Heat Treatment

Heat treatment was performed on the cast samples using a Box-Resistance Furnace Model No 2392. Samples were solution-treated at 540 °C for 4 h, quenched separately in tap water (TW), ice block (IB) and SAE 40 engine oil (SEO), aged at 160 °C for 8 h, and subsequently cooled at room temperature (Rotella *et al.*, 2018).

2.3 Mechanical Properties Tests

Hardness test was performed according to ASTM E384. The compressive strength of the hybrid composites was tested using a computerized universal testing machine. The specimens were prepared as per the ASTM E-8. The tensile strength specimen was machined as per ASTM E8 with 10 mm diameter and 15 mm length specimens. Impact test of the samples was conducted as per ASTM Standard E 602. V-notches of 0.5mm depth was made on the samples and the impact strength was carried out using Charpy Impact testing machine, serial no. 412-07-152619 with capacity of 155-300J. Table 2 show samples designations and the heat treatment carried out.

Table 2: Samples Nomenclature and Heat Treatment Process carried out

S/N	Heat treatment sample	Designation
1	A6082	Matrix
2	Un-treated hybrid composite	HBC
3	Water quenched	TW
4	Ice block quenched	IB
5	SAE 40 oil quenched	SEO

2.4 Tribological Test

A standard Tribometer/Version 6.1.19 (ball-on-disc) apparatus was employed to conduct the wear tests in accordance with ASTM G99. Test was conducted by applying 10N load at 10 cm/s speed for 30 m sliding distance. Hardened steel (65 HRC) counter disc of 10 mm track diameter and 8 mm thick was used. Specimens of 20 mm diameter and 40 mm height were prepared and the ball surface was polished by emery paper. The tests were conducted at 29 °C room temperature and 55 % relative humidity for 30 minutes (Ahmer *et al.*, 2016). The variation of friction coefficient with time and sliding distance was recorded continuously during the tests. Wear rate and coefficient of friction for samples were measured using Equations 1 and 2 as earlier used by Bhaumik and Kamaraj, (2021).

$$\text{Wear rate, } WR = \Delta W/s \quad (1)$$

$$\Delta W = W_1 - W_2 \quad (2a)$$

$$s = 2\pi Ndt \quad (2b)$$

Where WR is the wear rate (mg/min), ΔW is the weight loss, W_1 and W_2 is the weight before and after abrasion (mg), S is the sliding distance (m), N is the machine speed, d is the disc diameter, and t is the time for each sample to undergo abrasion.

2.5 Scanning Electron Microscope (SEM) and Metallography

The microstructures and worn surfaces were examined by optical microscopy and SEM/EDS following standard metallographic preparation and Kroll's etching (Shuvo *et al.*, 2025; Jaber *et al.*, 2023; Motyka *et al.*, 2014).

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties

Figure 1a-c shows average variation of mechanical properties of the samples after different heat treatment processes. It can be seen from Figure 1a that all heat-treated composite samples exhibited superior hardness compared to the untreated samples. The IB block quenched sample recorded the highest hardness of 155.33 HV (a 15% increase relative to the untreated control), followed by the sample quenched in SEO at 134 HV (an 8.45% increase). This enhancement in hardness is attributed to precipitation hardening, grain refinement, a more homogeneous microstructure, and the stabilization of hard intermetallic phases during solution treatment and artificial aging (Rmadan *et al.*, 2024). The variation across quenching media underlines the critical role of cooling rate in dictating precipitation kinetics, with ice-block quenching yielding the most favourable hardening response. Heat treatment proved more effective in enhancing the hardness of the composite specimens than that of the unreinforced matrix alloy (Ravikumar *et al.*, 2021; Abishkenov *et al.*, 2024; Rmadan *et al.*, 2024).

Figure 1b shows average compressive strength of the treated hybrid composite samples. It can be seen that heat treatment significantly enhanced the compressive strength across all samples compared to the HBC. The sample quenched in TW achieved the highest compressive strength of 1567.1 MPa (a 64.30% increase), followed by the IB-quenched sample at 828.8 MPa (a 36.25%

increase). These strength improvements stem from matrix-reinforcement diffusion mechanisms, composition of the reinforcements, grain refinement, and strengthened matrix–reinforcement interfacial bonding (Nagaraja *et al.*, 2021). The variation in compressive strength among the quenching media also demonstrates that cooling rate significantly influences distribution of strengthening precipitates required for maximum load-bearing capability. (Şenel and Mahmutoğlu, 2022; Nagaraja *et al.*, 2021).

Figure 1c shows the mean effect of heat treatment on Impact strength of the hybrid composite of all samples. Both treated and untreated hybrid composites demonstrated higher impact energy absorption than the unreinforced matrix sample. The TW-quenched sample exhibited the highest impact strength at 3.0 J, demonstrating superior toughness and resistance to dynamic load deformation. Conversely, the IB-quenched sample recorded lower impact energy values. The improved impact resistance in TW quenching suggests that a balanced cooling rate promoted a uniform distribution of fine precipitates, achieving an optimal trade-off between strength and toughness without inducing excessive brittleness. Improved impact resistance could be due to an increased number of fine precipitates that were uniformly distributed after the heat treatment of the composite samples (Mahan *et al.*, 2023). This finding demonstrates that the choice of quenching medium has a significant influence on the dynamic mechanical behaviour of the hybrid composites (Mahan *et al.*, 2023; Zubairu *et al.*, 2021).

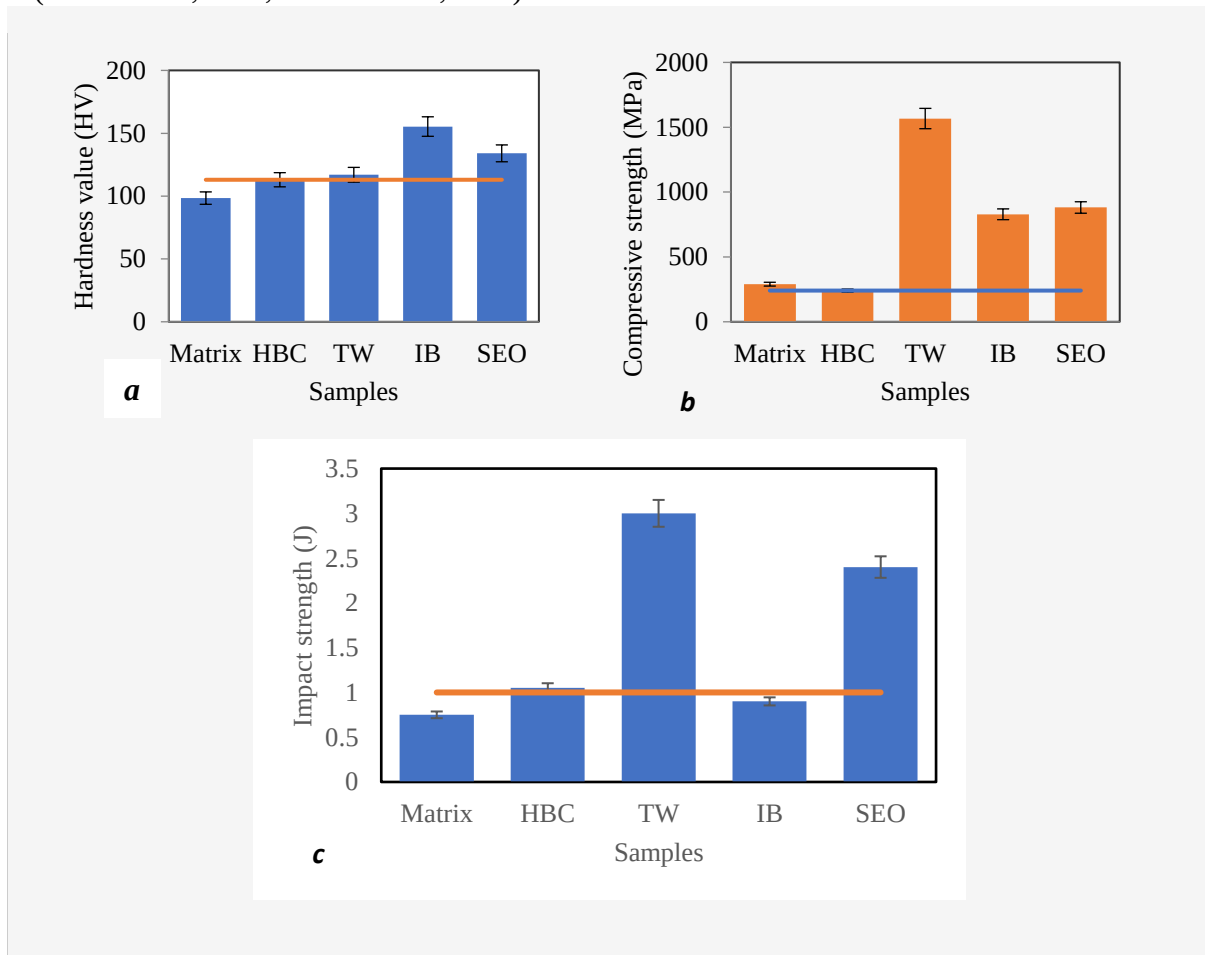


Figure 1: Variation Mechanical properties of A6082-SNSA/MWCNT composites after different heat-treatment conditions: (a) hardness, (b) compressive strength, and (c) impact strength

3.2 Tribological Properties

Tribological properties, including the coefficient of friction (CoF) and specific wear rate (SWR), were determined for the samples, and the results are presented in Figure 2a–b. Figure 2a shows the mean variation in CoF under the different heat-treatment conditions. The sample quenched

in SEO exhibited the lowest CoF of 0.166, representing a 16.6% reduction relative to the untreated HBC, which recorded a CoF of 0.199. In comparison, higher CoF values were obtained for the untreated AA6082 matrix (0.221), TW-quenched sample (0.217), and IB-quenched sample (0.211). The lower friction exhibited by the SEO-quenched sample may be attributed to the relatively mild cooling rate associated with oil quenching, which can promote a more favourable microstructural condition and enhance the stability of the surface tribo layer during sliding contact. This behaviour suggests that heat treatment influences not only the bulk mechanical properties of the composite but also the surface characteristics and interfacial interactions that govern its frictional response (Paladugu *et al.*, 2022; Baghel and Krishna, 2023).

Figure 2b presents the mean specific wear rate (SWR) of the AA6082 hybrid composite samples subjected to different heat-treatment conditions. The untreated HBC exhibited the lowest specific wear rate, whereas heat treatment resulted in increased material loss for the samples quenched in TW, IB, and SEO. The increase in wear rate following heat treatment may be associated with changes in matrix hardness, precipitate distribution, residual stresses, and matrix–reinforcement interfacial integrity. Such microstructural modifications can increase the susceptibility of the matrix to plastic deformation and facilitate the detachment of wear debris during sliding. Similar observations have been associated with thermal treatment and ageing-induced changes in aluminium alloys (Anuar *et al.*, 2023). Although severe quenching, such as ice quenching, has been reported to promote favourable precipitation and dislocation-pinning effects in alloys such as AA7075, thereby improving wear resistance (Ravikumar *et al.*, 2021), the present results demonstrate that the tribological response is strongly dependent on alloy composition, reinforcement characteristics, heat-treatment condition, and cooling rate. Therefore, the higher wear rates observed after quenching in the present AA6082-SNSA/MWCNT hybrid composite indicate that the applied heat-treatment conditions did not produce sufficient strengthening to offset the microstructural changes that promoted material removal during sliding.

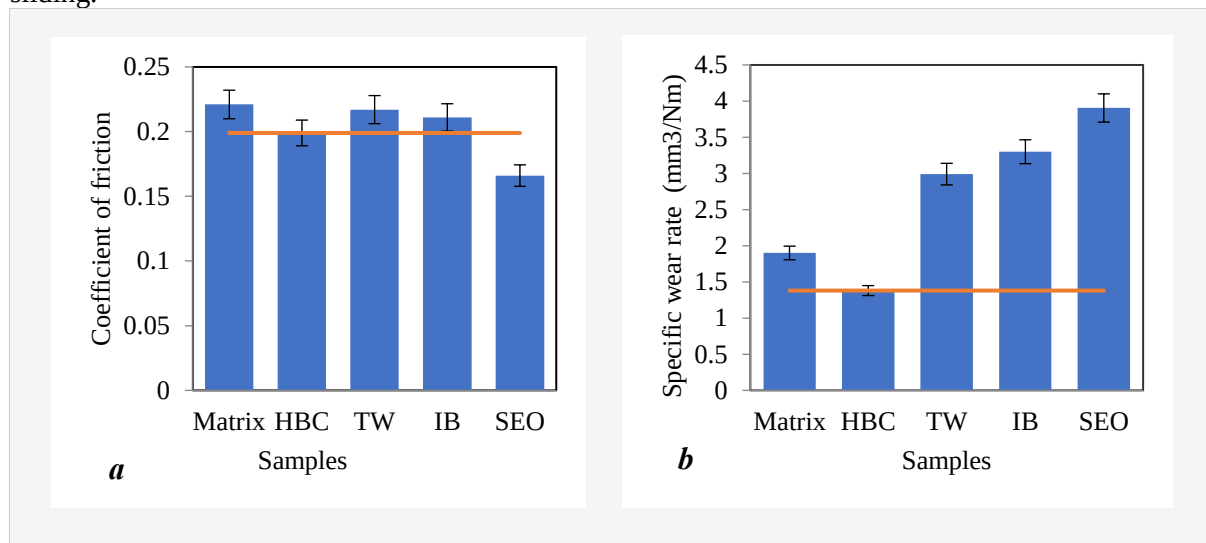


Figure 2: Variation of Tribological behaviour of A6082-SNSA/MWCNT composites: (a) coefficient of friction and (b) specific wear rate

3.3 Microstructure and wear surface characterization

3.3.1 Optical microstructure

The microstructure of the as-cast AA6082 matrix shown in Figure 6a reveals elongated dendritic structures of primary α -Al grains (bright regions) and Al–Mg₂Si eutectic phases (dark regions), which are characteristic of cast aluminium alloys (Yuan *et al.*, 2021; Brodova *et al.*, 2022). Figure 6b presents the microstructure of the untreated HBC, characterized by relatively coarse dendrites and localized clustering of reinforcement particles within the matrix. Figures 6c–e shows the microstructures of the composite subjected to different quenching media. The TW-quenched sample (Figure 6c) exhibits moderately refined and more equiaxed grains, with shorter dendritic arms and

narrower inter dendritic regions compared with the untreated HBC. The IB-quenched sample (Figure 6d) displays the finest and most compact dendritic structure, with relatively uniform grain morphology and reduced inter dendritic regions. This refinement can be attributed to the higher cooling rate of ice-block quenching, which restricts dendritic growth and limits coarsening. Ramirez-Vidaurre *et al.* (2022) similarly reported that increasing cooling rate reduces secondary dendrite arm spacing and suppresses dendritic coarsening. In contrast, the SEO-quenched sample (Figure 6e) exhibits comparatively coarser dendritic features, suggesting that the slower cooling rate of SEO permits greater dendritic growth and localized segregation. The micrographs demonstrate that the quenching medium significantly influences the grain morphology and dendritic structure of the A6082–SNSA/MWCNT hybrid composites. Rapid cooling in the IB medium produced greater grain refinement, whereas slower cooling in SEO promoted relatively coarser structures. These microstructural differences are consistent with the observed mechanical behaviour, as grain refinement and a more compact microstructure can restrict dislocation movement and improve matrix–reinforcement interaction, thereby contributing to increased hardness and compressive strength (Ramirez-Vidaurre *et al.*, 2022; Odinachi *et al.*, 2017).

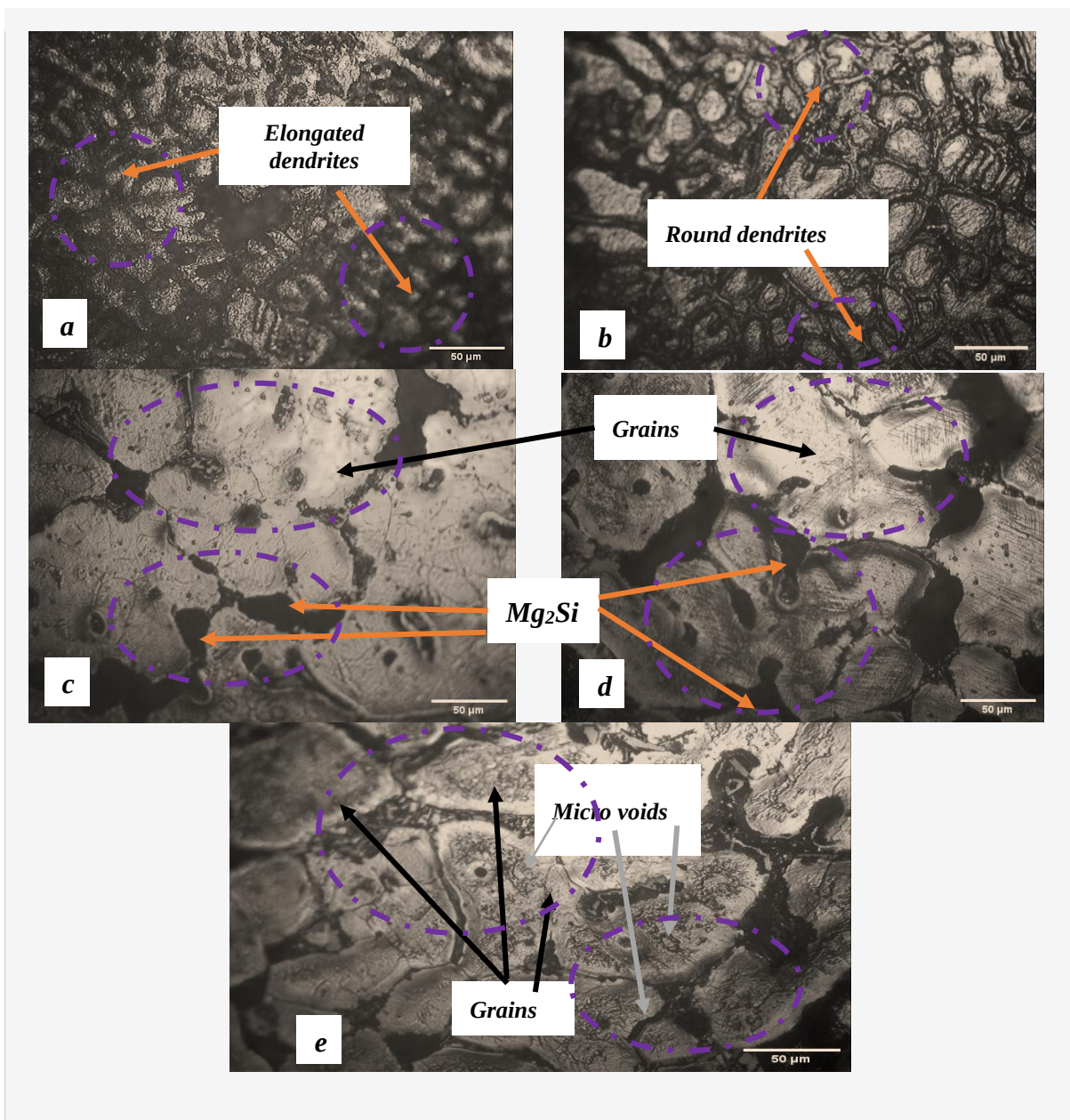


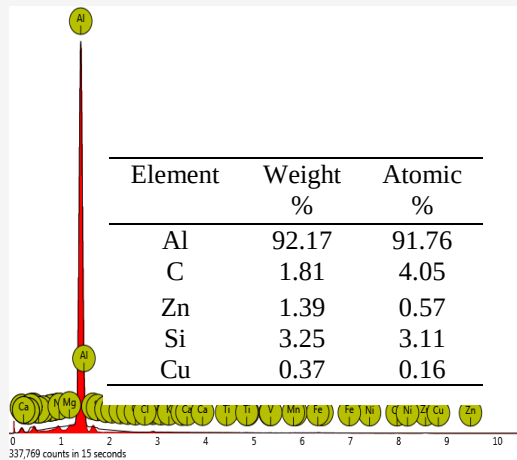
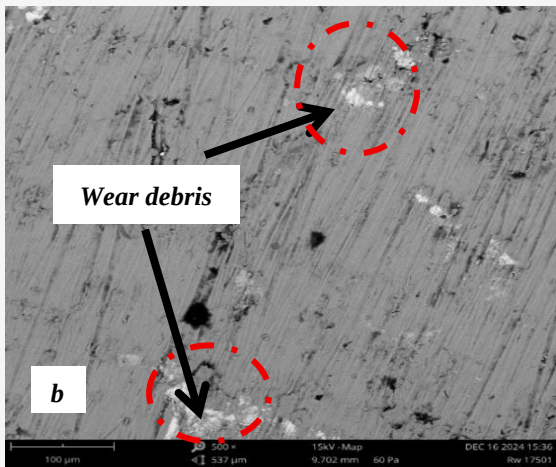
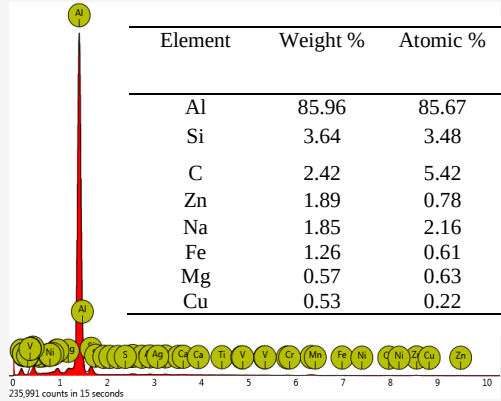
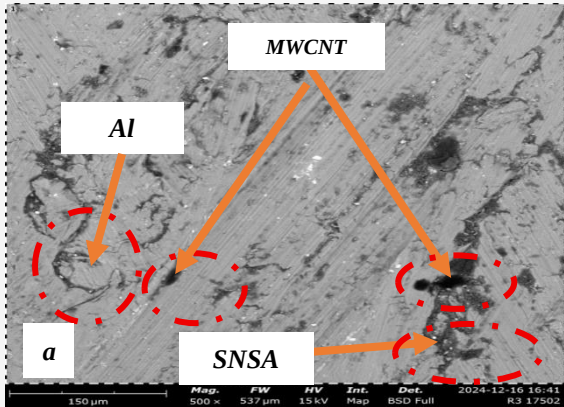
Figure 6: Optical Micrograph of: (a) Matrix (b) HBC, (c) TW treated, (d) IB treated, and (e) SEO treated A6082-SNSA/MWCNT Hybrid Composites at Magnifications of X100

3.3.1 SEM/EDS analysis

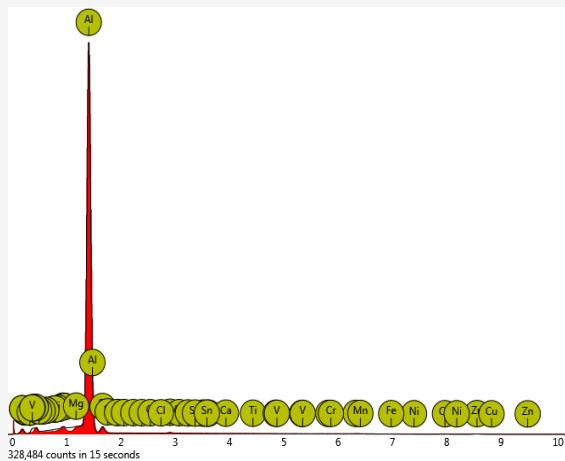
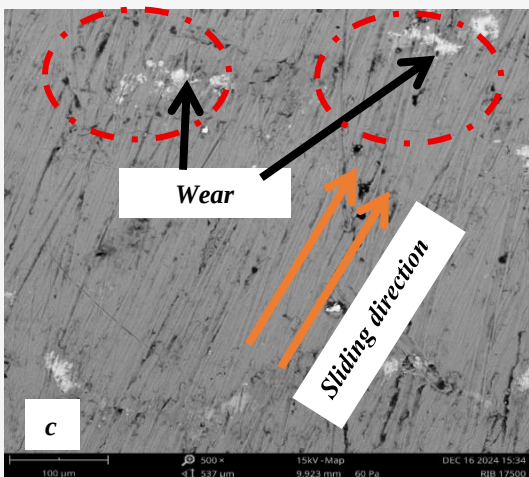
The microstructure studies of worn surfaces of the samples were studied using SEM/EDS and the micrographs are presented in Figure 7a-d. The worn surfaces of the A6082-SNSA/MWCNT hybrid composites were examined using SEM/EDS, and the resulting micrographs are presented in Figure 7a-d. The worn surfaces exhibited characteristic features associated with abrasion, delamination, adhesion, and, in some cases, reinforcement particle pull-out. The untreated HBC (Figure 7a) showed pronounced grooves parallel to the sliding direction, together with delaminated regions. These features indicate that abrasive and delamination wear were the dominant mechanisms. The formation of grooves along the wear track is commonly associated with the ploughing action of hard reinforcement particles or detached wear debris (Erappa Rajj *et al.*, 2024; Turan *et al.*, 2020). The TW-quenched sample (Figure 7b) exhibited fewer and shallower grooves, reduced delamination, and a comparatively uniform worn surface, suggesting less severe surface damage. This observation is consistent with the findings of Suchendra *et al.* (2023), who associated smoother worn surfaces with improved resistance to material removal. The IB-quenched sample (Figure 7c) contained a small amount of scattered wear debris, which may have resulted from micro-fracture, delamination, or reinforcement particle pull-out during sliding. Similar wear debris and micro-fracture features have been reported for reinforced aluminium composites (Ramadoss *et al.*, 2020). In contrast, the SEO-quenched sample (Figure 7d) displayed relatively large delaminated or particle pull-out regions and prominent grooves, but comparatively little loose wear debris. The limited accumulation of debris suggests that detached material was readily removed from the contact surface, consistent with its relatively low coefficient of friction. Similar combinations of grooves, delamination, ploughing, and particle pull-out have been identified as characteristic wear features in aluminium-based composites under sliding conditions (Radhika *et al.*, 2024; Yadav *et al.*, 2024).

The EDS results presented alongside the SEM micrographs in Figure 7 further confirm the elemental composition of the worn surfaces. Aluminium was the dominant element in all samples, ranging from 85.96 to 94.29 wt.%, while Si and C were detected in the ranges of 0.41–3.64 wt.% and 1.81–2.98 wt.%, respectively. The presence of these elements indicates the involvement of both the AA6082 matrix and reinforcement-containing regions during sliding. The TW-quenched sample recorded the highest Al content (94.29 wt.%) and exhibited a relatively uniform worn morphology, whereas the untreated HBC showed more pronounced grooves and delamination. The SEM/EDS observations demonstrate that heat treatment altered the severity and dominant modes of surface damage, with the nature of the wear response being dependent on the quenching medium and the resulting microstructural condition.

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Element	Weight %	Atomic %
Al	94.29	93.99
C	1.94	0.62
Zn	1.52	0.62
Si	0.41	0.39
Cu	0.33	0.14
Ni	0.13	0.06



Element	Weight	Atomic
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Figure 7: SEM/EDS analysis of worn surfaces: (a) HBC, (b) TW, (c) IB, and (d) SEO samples

4. CONCLUSION

This study investigated the effects of heat treatment and quenching media on the mechanical, tribological, and microstructural behaviour of A6082–SNSA/MWCNT hybrid composites. The results demonstrate that the heat-treatment significantly influenced the overall performance of the composites, with the response varying according to the quenching medium.

Among the investigated conditions, ice-block (IB) quenching produced the highest hardness of 155.33 HV, representing an improvement of approximately 15% over the untreated HBC. Tap-water (TW) quenching resulted in the highest compressive strength of 1567.1 MPa, corresponding to a 64.30% improvement, as well as the highest impact strength of 3.0 J. The SEO-quenched sample exhibited the lowest coefficient of friction (CoF) of 0.166, while the untreated HBC recorded the lowest specific wear rate (SWR) of 1.38 mm³/Nm.

Microstructural examination further revealed that IB quenching produced the finest and most compact dendritic structure, whereas SEO quenching resulted in relatively coarser dendrites accompanied by micro voids. SEM/EDS analysis of the worn surfaces identified abrasion and delamination as the predominant wear mechanisms. The dominance of aluminium, together with the detection of Si and C, confirmed the involvement of the A6082 matrix and reinforcement-containing phases during sliding. Overall, the findings establish that appropriate selection of the quenching medium can be used to tailor the mechanical, tribological, and microstructural characteristics of A6082–SNSA/MWCNT hybrid composites for potential engineering applications.

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