

Thermal Conductivity and Thermal Expansion of Recycled Aluminium–Graphite Composites Produced Using Recovered MnO₂–Carbon Melt Treatment

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Abstract

High relative density and low porosity are crucial for optimizing the thermal performance of aluminium–graphite (Al–Gr) composites for high-reliability thermal management applications in the automotive and electronics industries. This study investigated the influence of MnO₂-carbon powder melt treatment on the microstructure, relative density, porosity, and thermal properties of aluminium-graphite composites produced via stir casting method at 700 °C with a stirring time of 3 min. Despite extensive research on aluminium melt-treatment with fluoride salts (NaF, CaF₂, AlF₃ and MgF₂) reinforced synthetic carbon fiber, little is known about the combined thermal behavior of recycled aluminium–graphite composites treated with MnO₂–carbon powder. Recovered MnO₂–carbon powder was introduced into recycled aluminum melt, treated and reinforced with 3, 6 and 9 wt.% graphite nanoparticles. Electrical conductivity of the produced composites was measured at room temperature using an FP-001 four-point probe conductivity Tester, and the thermal conductivity (TC) was estimated using the Wiedemann–Franz law, while coefficient of linear thermal expansion (CLTE) was evaluated from the change in specimen length with temperature. Scanning electron microscopy (SEM) revealed a fine and relatively homogeneous distribution of graphite nanoparticles within the aluminium matrix with reduced particle agglomeration. The highest TC of 239.50 W/m·K was obtained at Al+3 wt.% nm-Gr, representing a 27.56% improvement over the control sample of TC 173.50 W/m·K, whereas the lowest CLTE of $24.55 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ was obtained at Al+9 wt.% nm-Gr represented a 19.67% reduction relative to the control sample of CLTE $30.56 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. The composite samples exhibited lower percentage porosity values of 0.67%, 0.78% and 1.21% compared with the control sample having percentage porosity values of 1.33%. This study, therefore, demonstrated that MnO₂–carbon powder melt treatment of recycled aluminium reinforced graphite nanoparticles enhanced thermal conductivity and lowered thermal expansion of Al-Gr-based composites which have promising applications in industries especially for thermal management.

Keywords: Composite, aluminium-graphite, MnO₂-carbon, Thermal conductivity, Thermal expansion.

Introduction

Aluminium-matrix composites (AMCs) are widely used in thermal management applications, including automotive engine components, heat sinks, and electronic packaging, due to their low density, good corrosion resistance, and high thermal conductivity (Yadav *et al.*, 2024; Lewis *et al.*, 2024). AMCs are extensively utilized in wear-resistant applications, such as friction linings, brake components, structural wear components and other rotating parts, because of their favourable combination of high specific strength, moderate ductility, and low weight (Sharma *et al.*, 2026; Mohamed *et al.*, 2026). Such materials require adequate mechanical strength, good corrosion resistance, high thermal conductivity and low coefficient of thermal expansion (CTE)

to enhance performance while maintaining a high strength-to-weight ratio and reducing production costs (Zhou *et al.*, 2024; Pooja *et al.*, 2025). Additionally, Al–SiC_p composites have been used extensively for thermal management applications (Du *et al.*, 2023; Zapata-Valencia *et al.*, 2025; Mathebula *et al.*, 2026). However, the mismatch in the coefficients of thermal expansion between the aluminium matrix and SiC particles results in thermal stresses that can limit their performance and long-term reliability (Lattanzi and Jarfors, 2025; Qi *et al.*, 2026). To overcome this limitation, researcher incorporated high thermal conductivity materials into aluminium to further enhanced thermal conductivity and reduced thermal expansion for advanced thermal management applications (Sreekumar and Saravantan, 2023). Different ceramic reinforcements, including B₄C, Al₂O₃, TiC, TiB₂, ZrO₂, BN, TiC, and SiC, have been incorporated into aluminium matrices to improve their mechanical properties.

Similarly, carbon-based materials, such as graphite, carbon black, activated carbon (Beldar *et al.*, 2025; Banoth *et al.*, 2025; Liu *et al.*, 2025; Bellucci, 2026) and diamond particles or fibres (Fu *et al.*, 2024; Sang *et al.*, 2025) have been incorporated as secondary phases to enhance the thermal properties of aluminium composites. These materials generally exhibit higher thermal conductivity (TC) and lower coefficients of thermal expansion (CTE) than unreinforced aluminium alloys. Among them, diamond-reinforced aluminium composites have achieved thermal conductivities of above 700 W m⁻¹ K⁻¹ (Fu *et al.*, 2024; Sang *et al.*, 2025; Zhang *et al.*, 2025). The high cost of diamond and the processing challenges associated with production of diamond–aluminium composites have limited its application. However, graphite particles form a more uniform dispersion in aluminium matrix, making it an alternative reinforcement in aluminium matrix composites (Taiwo *et al.*, 2025; Ravi *et al.*, 2025). The wettability between the graphite and aluminium is a significant challenge in achieving an optimal combination of strength-thermal conductivity (Velliangiri *et al.*, 2023; Lin *et al.*, 2025). This has to be to be overcome to improve thermal conductivity pathways. Therefore, process optimization through stir casting method (Anand *et al.*, 2025; Yekinni *et al.*, 2025) could mitigate such a drawback, which aims at reducing the interfacial defect and improving the performance of aluminium-graphite (Al-Gr) composites. Different techniques have been adopted in modifying the interfacial bond in Al-Gr composites to mitigate the negative effect of incompatibility. Surface treatment of carbon phase, carbide coating with Ni and Cr₇C₃ by salt bath or electroless deposition, Ni-P using electroless coating process, and the effects of transition metals (Cu, Ni, Co) on the bonding properties at the graphite/aluminium interface have been systematically investigated (Hunag *et al.*, 2022; Luo *et al.*, 2023; Nough *et al.*, 2026; Du *et al.*, 2026), aimed at improving the wettability and promote the interfacial bonding strength between the Al matrix and Gr reinforcement.

Furthermore, the traditional methods for purifying aluminium melts involve the use of commercial fluxing agent such as the chloride (e.g., KCl, NaCl, MgCl₂) or fluoride (e.g., NaF, CaF₂, AlF₃ and MgF₂) based salt (Wan *et al.*, 2020; Cai *et al.*, 2024), and is usually combined with gas purging technique to aid inclusion flotation. These materials are more expensive, and often generate toxic and harmful by-products which cause environmental and ecological challenges (Arianpour *et al.*, 2021). For example, Na₂SiF₆ can partially decompose during melting process and release SiF₄ gas which is harmful to the environment and the surrounding organisms (Arianpour *et al.*, 2021; Zhang *et al.*, 2023). Therefore, the present study investigates the recovery of MnO₂-carbon powder from waste Zn-C battery as an economical alternative melt-treatment in recycled aluminium cans. The carbon component present in the recovered MnO₂-carbon powder may take part in oxidation reaction and the manganese oxide (MnO₂) may interact with non-metallic inclusions, thereby

facilitate their removal. Unlike conventional melt-treatment process, the current study expands on earlier research by assessing the recovered MnO₂–carbon powder as melt-treatment for recycled aluminum can and reinforced with 3, 6 and 9 wt.% graphite nanoparticles. Changes in microstructure, relative density, porosity, thermal conductivity, and coefficient of linear thermal expansion in comparison to the control sample were evaluated.

Materials and Methods

Two kilograms of waste aluminium cans (WACs) were collected from local scrap yards and used as the raw material for aluminium ingot preparation. The WACs were gradually heated to remove surface paints and coatings, thereby improving melting efficiency. Discarded zinc-carbon (Zn-C) dry-cell batteries were manually dismantled to recover the MnO₂-carbon mixture and graphite rods. Approximately 100 g of the recovered MnO₂-carbon mixture was dried and subsequently used as a melt-treatment agent for the recycled aluminium can. Following the experimental procedure of Milani *et al.*, (2023), 10 wt.% MnO₂-carbon powder was used as melt-treatment in 90 wt.% recycled aluminium can. Approximately 1 kg of recovered graphite rods was milled in a horizontal ball mill at 350 rpm for 10 h using a ball-to-powder ratio of 3:1. Ethanol was added as a process control agent, to prevent excessive cold welding, minimize particle agglomeration and improve milling efficiency (Mancillas-Salas *et al.*, 2020; Huang *et al.*, 2022). Graphite nanoparticles (GNPs) with an average particle size of 5.06 ± 2.87 nm were obtained. The milled GNPs were stored in airtight containers following the procedure described by dos Santos *et al.* (2022). The recovered aluminium ingots were charged into a graphite crucible and melted in an electric resistance furnace at 700 ± 5 °C, while the temperature was monitored using a 12-channel thermocouple. Preheated GNPs were incorporated into the molten aluminium at reinforcement levels of 0, 3, 6, and 9 wt.%, and at a constant feeding rate. A vortex was generated using a steel impeller rotating at 250 rpm, immersed to approximately 60% of the melt depth in a graphite crucible measuring 100 mm in diameter and 120 mm in height to facilitate uniform particle dispersion. Stirring was maintained for 3 min before the melt was poured into a prepared sand mould to produce cylindrical composite rods measuring 12 mm in diameter and 150 mm in length. The morphology and particle size of the MnO₂-carbon powder and graphite nanoparticles were characterized using transmission electron microscopy (TEM, JEM ARM200F-G). The microstructure and elemental composition of the composite samples were examined using scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (SEM/EDS, JEOL JSM-6400 with Oxford X-Max detector).

Testing Method

Density and porosity evaluation

The density and porosity of the samples were evaluated as an indicator of their physical properties. The measured density and porosity values were reported as the arithmetic mean of three different measurements taken from the same sample (Westphal and Seitz, 2025). The density and porosity were calculated using Equation 1.

$$\rho_c = \left(\frac{M_a}{M_w} \right) \rho_w \quad (1a)$$

$$P(\%) = \left[\frac{\rho_{th} - \rho_{exp}}{\rho_{th}} \right] \times 100 \quad (1b)$$

Characteristics of thermal properties

The electrical conductivity of the samples was measured at room temperature using an FP-001 Four-point probe conductivity Tester for Metals (Bowler and Huan, 2005). Samples with a Ø10 mm and a thickness of 5 mm were used for the electrical conductivity test. Wiedemann-Franz Law $k = \sigma L T$ (where k is the thermal conductivity (W/mK), σ is electrical conductivity (S/m), L is the Lorenz number, which equals 2.45×10^{-8} (W.Ω/K²), and T is the temperature in Kelvin), was used to determine the thermal conductivity of composites using electrical conductivity measurements. The reported thermal conductivity values were estimated from the electrical conductivity tests, which is the average of three measurements taken from the same sample. This method was adopted as an approximation because aluminium is primarily a metallic material and the electrical conductor is generally associated with charge carriers that aid in heat transport mechanism. The Wiedemann-Franz relationship may not fully characterise the heterogeneous behaviour of aluminum-graphite composite. As a result, the thermal conductivity values are considered estimate, and direct measurement would provide adequate thermal conductivity values of the composites. To evaluate the statistically significant of the estimated thermal conductivity values, the analysis of variance (ANOVA) was performed in Microsoft excel 2021 version. Furthermore, the coefficient of linear expansion (CLE) of both the composite and control samples were determined using a PASCO Model TD-8558A thermal expansion apparatus. Al–Gr specimens were prepared into a thin cylindrical shape of 5 mm in diameter and 100 mm length, and carefully mounted on the expansion base of the apparatus. Before the experiment, the initial length of each specimen was recorded at room temperature. Steam was introduced uniformly into the apparatus and the linear expansion of the specimen was monitored using the built-in dial gauge with a resolution of 0.01 mm, while the temperature was measured at intervals of 5 °C using a thermistor positioned at the center of the tube. The experiment was conducted at the Materials Science Laboratory, Kwara State University, Nigeria. The change in length (ΔL), with respect to the change in temperature (ΔT) was calculated using $\Delta L = L_f - L_o$, for which the coefficient of thermal expansion (α) was evaluated: $\alpha = \Delta L / L_o \Delta T 10^{-6} \text{ } ^\circ\text{C}^{-1}$ (Khina *et al.*, 2025), where L_o and L_f are the original and final length of the sample, ΔT is the change in temperature from T_o to T_f . Since the temperature data represent discrete points, α was then calculated accordingly;

$$\Delta T_i = T_{i+1} - T_i \quad (2a)$$

$$\Delta L_i = L_{i+1} - L_i \quad (2b)$$

$$\alpha_i = \Delta L_i / L_o \Delta T_i \quad (2c)$$

For each Al-Gr composite and control sample, the mean coefficient of linear thermal expansion (α_{mean}), standard deviation (σ), intercept, and R-square values were evaluated.

Results and Discussion

Morphology of the powders and composite samples

The morphology of the waste MnO₂-carbon powder is presented in Figure 1. The micrograph reveals clusters and porous aggregates of micrometre-sized particles, suggesting a heterogeneous microstructure. The observed features are characteristic of spent Zn–C battery materials and may facilitate interaction with the molten aluminium during melt treatment owing to their relatively high specific surface area (Ran *et al.*, 2025). The brighter regions observed in the SEM micrograph correspond to areas enriched in Mn and O, as confirmed by EDS analysis, suggesting the presence of MnO₂-rich particles. EDS analysis showed that Mn and Zn were the predominant elements, with trace amounts of O, Cl, C, K, and Fe. These findings are consistent with those reported by Ge *et al.* (2023), Sadawy *et al.* (2024) and Ran *et al.* (2025), who also identified Mn and Zn as the

principal constituents of spent Zn–C battery materials. The variations in elemental composition of the waste Zn–C battery studied by different researchers have been attributed to differences in battery composition and manufacturing technologies (Maisel *et al.*, 2026).

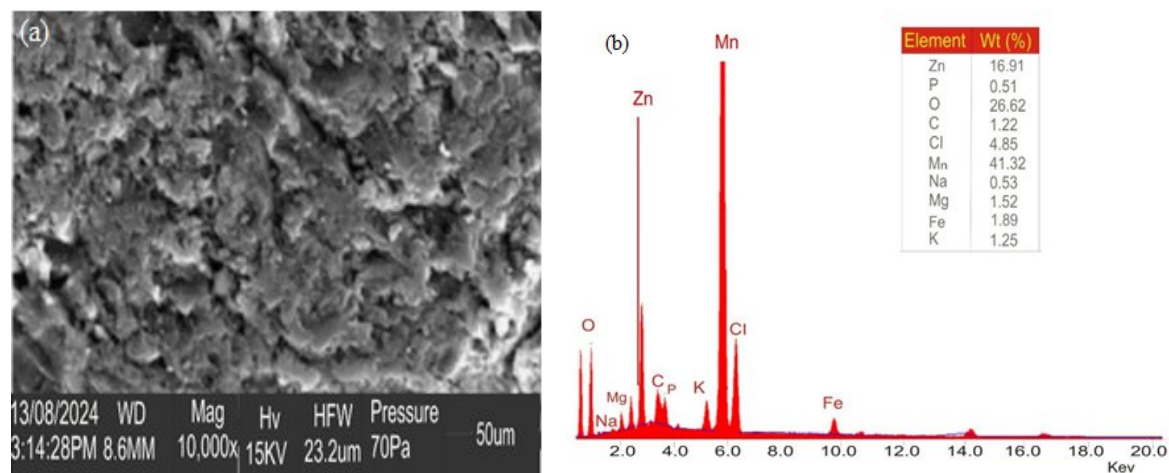


Figure 1: (a) SEM and (b) EDS micrograph of the MnO₂-carbon powder

The morphology of the as-milled graphite powder is presented in Figure 2. Figure 2a shows the SEM micrograph of graphite nanoparticles (GNPs) with a few spherical, elongated, and leaf-like structures with interconnected networks. These features may enhance the interaction between the graphite particles and the molten aluminium during composite processing. Additionally, the brighter regions observed in the SEM micrograph (Figure 2a) are likely associated with variations in particle topography and sizes (Festusa *et al.*, 2022). Figure 2b presents the TEM image of the milled graphite nanoparticles, showing particle sizes ranging from approximately 1.47 to 10.02 nm with an average particle size of 5.01 ± 3.15 nm, indicating a predominantly nanoscale distribution with relatively uniform dispersion and slight agglomeration.

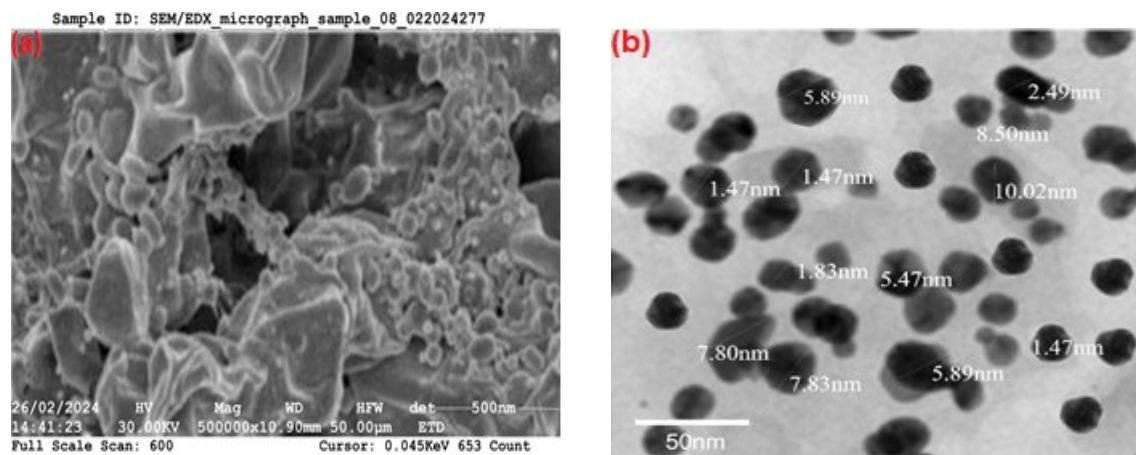


Figure 2: SEM Micrograph of 5.01 nm graphite powder (a) SEM and (b) TEM

Figure 3 presents the SEM micrographs of the aluminium ingot (a) before and (b) after treatment with the MnO₂-carbon powder. The untreated aluminium sample (Figure 3a) consists primarily of α -Al matrix together with eutectic Si, irregular clustered features, and several voids. The clustered features may be attributed to non-metallic inclusions or oxide-rich regions commonly observed in

recycled aluminium alloys (Kolparambath *et al.*, 2026), although their exact composition was not determined in this study. The presence of numerous voids suggests gas porosity and/or solidification shrinkage, resulting in a relatively heterogeneous microstructure (Kolparambath *et al.*, 2026). Figure 3b shows the aluminium ingot treated with MnO₂–carbon powder, exhibited a cleaner and more uniform structure with fewer pores compared with the untreated sample. Dispersed carbon particles were observed within the α -Al matrix, with no evidence of pronounced agglomeration in the analysed region, suggesting relatively uniform particle distribution (Rosdi and Hatta, 2026). Furthermore, the clustered features observed in the untreated sample appear less pronounced after treatment with MnO₂–carbon powder, suggesting improved microstructural uniformity. Collectively, these observations suggest that the MnO₂–carbon powder treatment promoted more uniform solidification of the molten aluminium, leading to a more homogeneous microstructure.

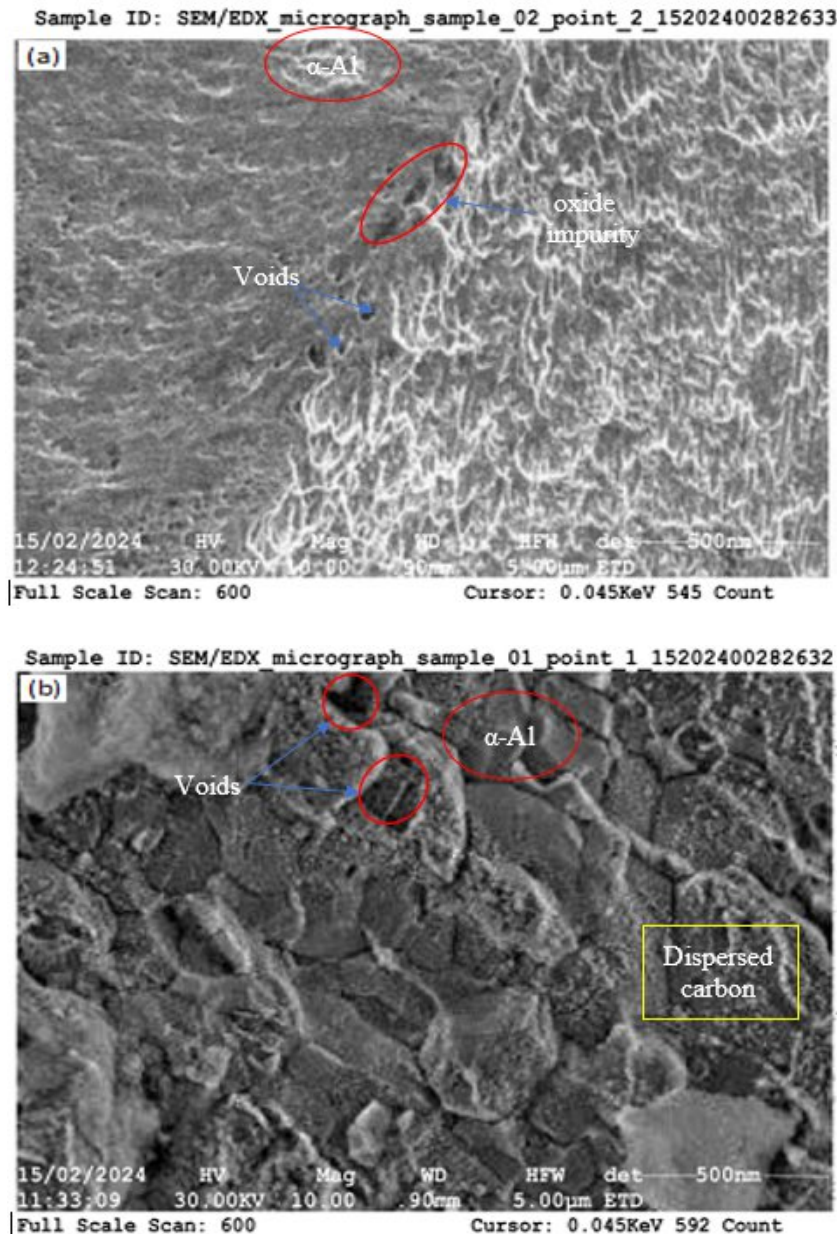
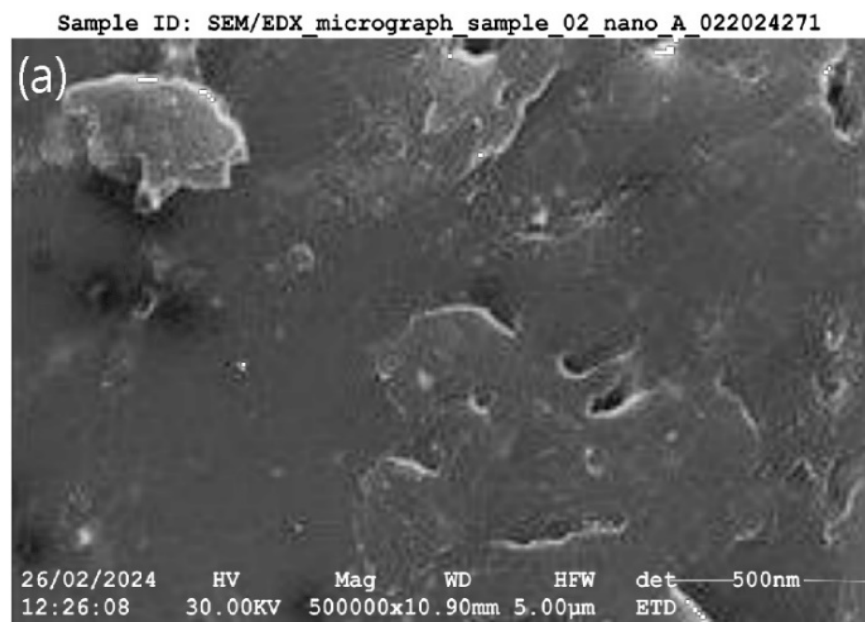


Figure 3: SEM Micrograph of aluminium ingot (a) without (b) with MnO₂-carbon powder

The SEM micrographs of aluminium matrix composites reinforced with 3, 6, and 9 wt.% graphite nanoparticles are presented in Figure 4. The brighter regions show the aluminium phases due to rapid solidification process, while the darker regions correspond to graphite particles. A relatively continuous matrix-graphite particle interface with no apparent interfacial gaps were observed in Al+3 wt.% nm-Gr (Figure 4a) and Al+6 wt.% nm-Gr (Figure 4b). At this reinforcement level, the graphite particles appear to be relatively well dispersed, with minimal agglomeration. Furthermore, the observed elongated, flake-like graphite structures observed in the Al+6 wt.% nm-Gr composite (Figure 4b) suggests a relatively uniform distribution of graphite reinforcement within the aluminium matrix (Ravi *et al.*, 2025). Such a morphology is expected to enhance the continuity of the matrix–reinforcement interface and facilitate efficient heat transfer, thereby contributing to the improved thermal performance of the composite (Durowoju *et al.*, 2020; Lin *et al.*, 2025).



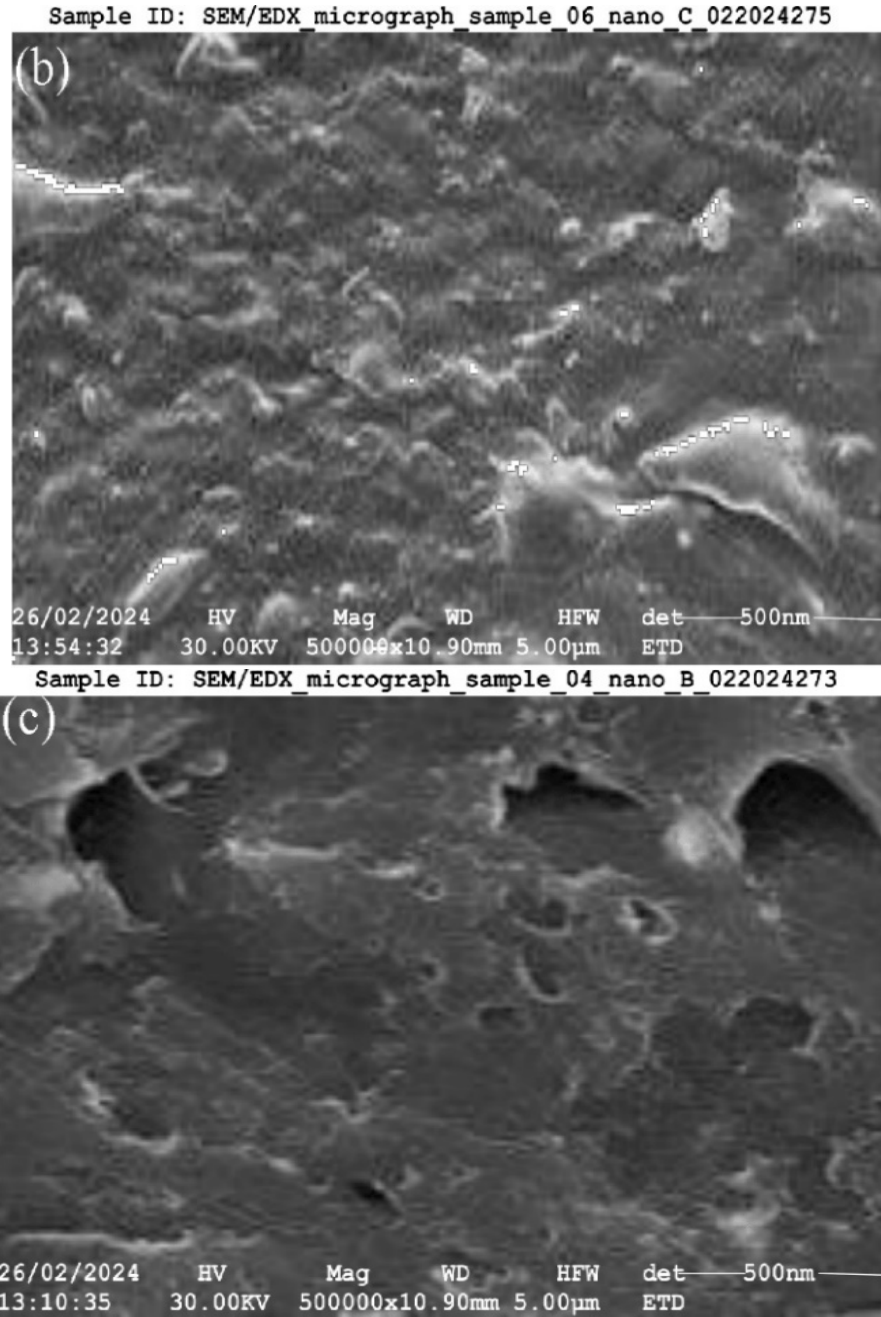


Figure 4: SEM images of (a) Al-3 wt.% nm-Gr (b) Al-6 wt.% nm-Gr (c) Al-9 wt.% nm-Gr sample

In contrast, the SEM micrograph of Al+9 wt.% nm-Gr composite (Figure 4c) reveals localized agglomeration of the graphite particles and microvoids dispersed within the aluminium matrix. These microstructural features may disrupt the continuity of the matrix–reinforcement interface, reduce the effectiveness of particle dispersion and disrupt the heat transfer mechanism across the composite. Excessive graphite addition in aluminium–graphite composites often resulted in particle agglomeration and porosity, lowering the yield strength and fatigue resistance of the composites as reported by Du *et al.*, (2023), Zhou *et al.*, (2024), Kolparambath *et al.*, (2026).

Relative density and porosity of the samples

Figure 5 illustrates the variation in relative density (R.D.) and porosity of the produced composites. Increase in relative density with graphite nanoparticles (GNPs) addition up to 6 wt.% was observed, followed by a slight decrease at 9 wt.% GNPs. The noticeable improvement in relative density at lower reinforcement levels may be attributed to fairly uniform distribution of GNPs, reduced porosity, and improved solidification behaviour, as supported by the SEM micrographs in Figures 4a and 4b. However, the porosity of the Al+3 wt.% and Al+ 6 wt.% nm-Gr composites is lower than that of the control sample and the Al+9 wt.% nm-Gr composites. The small reduction in relative density and likewise increase in porosity at 9 wt.% graphite addition can be justified by low density of graphite relative to aluminium matrix, the presence of microvoid and localized particle agglomeration, as evident in Figure 4c. These observations suggest that lower graphite nanoparticle additions in aluminium matrix composite promoted a more uniform microstructure, with improved relative density and lower porosity, which may have contributed to the improved thermal conductivity and reduced coefficient of linear thermal expansion observed in the produced composites. The study conducted by Rosdi and Hatta (2026) and Vijaya *et al.* (2026) on graphite-reinforced recycled AA6061 and LM26 aluminium with SiC, reported improvement in composite performance with the additions of low graphite content, whereas excessive graphite causes increased porosity, graphite particle agglomeration, and reduced effective relative density.

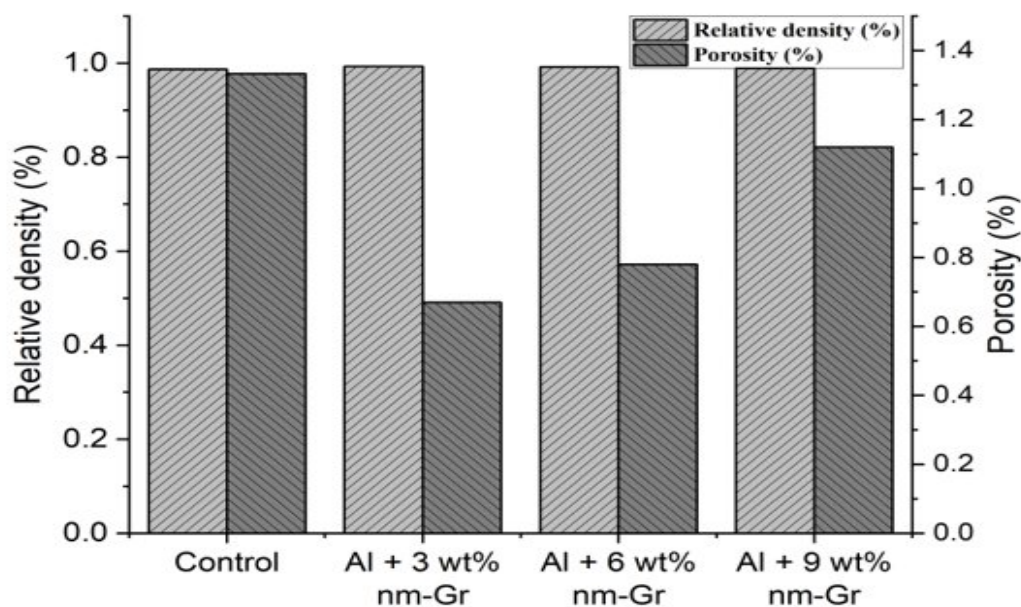


Figure 5: Variation in relative density and porosity as a function of graphite nanoparticles content

Thermal conductivity of the samples

The estimated thermal conductivity (TC) of the produced aluminium–graphite (Al-Gr) composites are shown in Figure 6. The control sample has a TC of $173.50 \text{ W m}^{-1} \text{ K}^{-1}$. It is obvious that the addition of graphite nanoparticle increases the TC of the composites. It can be seen that Al+3 wt.% nm-Gr composite has the highest thermal conductivity of $239.50 \text{ W m}^{-1} \text{ K}^{-1}$ above which there is a gradual decrease in the TC values of the composites. This improvement may be attributed to the high thermal conductivity of graphite ($\sim 800 - 2000 \text{ W m}^{-1} \text{ K}^{-1}$) relative to aluminium ($237 \text{ W m}^{-1} \text{ K}^{-1}$), its uniform dispersion within the aluminium matrix, and reduced porosity observed in the

microstructure (Figure 4a). These effects may facilitate heat conduction through the composite (Durowoju *et al.*, 2020; Kumar *et al.*, 2022). However, increase in graphite nanoparticles (GNPs) content up to 9 wt.% in aluminium matrix decreases the thermal conductivity of the composite material, rather than increasing it. This effect can likely be ascribed to increase in porosity content and agglomeration of GNPs, which may generate weakly bonded interface, restrict localized plastic flow, and hinder continuous heat transfer pathways within the Al-Gr composite (Durowoju *et al.*, 2020; Kumar *et al.*, 2022; Chi *et al.*, 2024). The results showed that the addition of low graphite nanoparticle in aluminium matrix improved the thermal conductivity of Al+3 wt.% nm-Gr composite more than Al+6 wt.% nm-Gr and Al+9 wt.% nm-Gr composites. Nevertheless, the thermal conductivity of the produced composites remained higher than the control sample, suggesting that the aluminium matrix thermal transport properties were improved by the addition of graphite nanoparticles. It can be seen that Al+3 wt.% nm-Gr composite achieved an optimum balance between graphite dispersion and porosity reduction, making it a promising candidate for lightweight components and thermal management applications requiring efficient heat dissipation. Additionally, the results of average thermal conductivity (TC) values were recorded in Table 1a. Al+3 wt.% nm-Gr composite had the highest average TC value of 239.50 ± 0.84 W/m.K, compared with the Al+6 wt.% nm-Gr, Al+9 wt.% nm-Gr composites and control sample having average TC values of 216.50 ± 0.99 , 192.50 ± 0.91 and 173.50 ± 0.09 W/m.K respectively. From Table 1b, since $F(\text{cal.}) = 3903.29 > F(\text{crit.}) = 4.0662$, and $p < 0.05$, there is statistically significant difference in thermal conductivity among the composites and the control samples. This indicates that the addition of graphite nanoparticles and its weight percent significantly influence the thermal conductivity of the aluminium matrix.

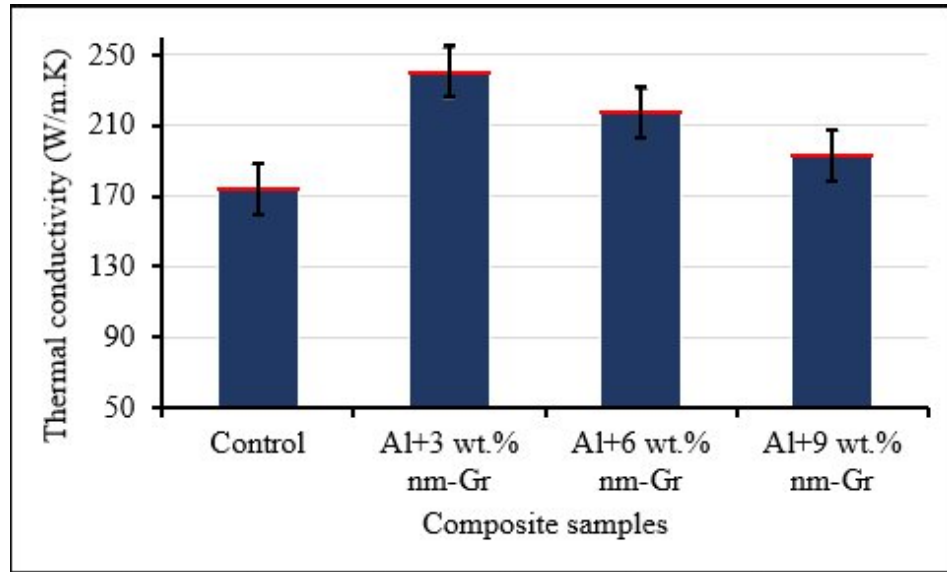


Figure 6: Variation in thermal conductivity as a function of graphite nanoparticles content

Table 1a: Variations in mean thermal conductivity values

Sample	Count	Sum (W/m.K)	Average (W/m.K)	Variance	Standard deviation (SD)
Control	3	520.50	173.50	0.0097	0.0985
Al+3 wt.% nm-Gr	3	718.50	239.50	0.7059	0.8402
Al+6 wt.% nm-Gr	3	649.50	216.50	0.9948	0.9974

Al+9 wt.% nm-Gr	3	577.50	192.50	0.8208	0.9059
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Table 1b: ANOVA test result comparing the relationship between and within the thermal conductivity values

Source of Variation	Sum of Square (SS)	Degree of Freedom (DF)	Mean Square (MS)	F(cal.)	P-value	F(crit.)
Between Groups	7410	3	2470	3903.29	5.35E-13	4.0662
Within Groups	5.0624	8	0.6328			
Total	7415.06	11				

Linear thermal expansion of the sample

Figure 7 presents the mean coefficient of linear thermal expansion (α_{mean}) of the prepared Al–Gr composites and the control sample. Although all samples exhibited similar thermal expansion trends, noticeable differences in the magnitude of expansion were observed. The control sample exhibited the highest coefficient of linear thermal expansion, whereas the graphite-reinforced aluminium matrix composites showed lower linear thermal expansion throughout the experimental temperature range.

Al+3 wt.% nm-Gr, Al+6 wt.% nm-Gr, and Al+9 wt.% nm-Gr composites showed comparatively stable thermal expansion behavior at approximately 180 °C, 182 °C, and 170 °C, respectively. These results indicate that increasing the graphite nanoparticle content gradually reduced the linear thermal expansion of the aluminium matrix, thereby restricting matrix deformation during heating process. This discrepancy in thermal expansion behaviour may be attributed to the thermally induced stresses generated due to a mismatch in the coefficients of thermal expansion between the aluminium matrix and graphite particles which may have further limited matrix expansion (Matvienko *et al.*, 2021). Additionally, higher coefficient of thermal expansion was observed in Al+3 wt.% nm-Gr and Al+6 wt.% nm-Gr composites, compared with Al+9 wt.% nm-Gr composite which exhibit the lowest thermal expansion behaviour. This may be attributed to the combined effect of graphite nanoparticle reinforcement and possible interfacial constraint effect arisen from the dispersed MnO₂-carbon powder. Chi *et al.* (2024) attributed the reduced thermal expansion to the low coefficient of thermal expansion of the reinforcement and the constraint imposed on the aluminium matrix during heating. Consequently, such materials with moderate linear thermal expansion behaviour may be considered for lightweight component applications operating at elevated temperatures where dimensional stability is essential. Collectively, the experimental findings show that the main factors contributing to reduce thermal expansion of the produced composites are the reinforcement's low coefficient of thermal expansion, its strong interfacial bonding with the aluminium matrix, and the possible constraint effect imposed by the reinforcement on matrix deformation during heating process.

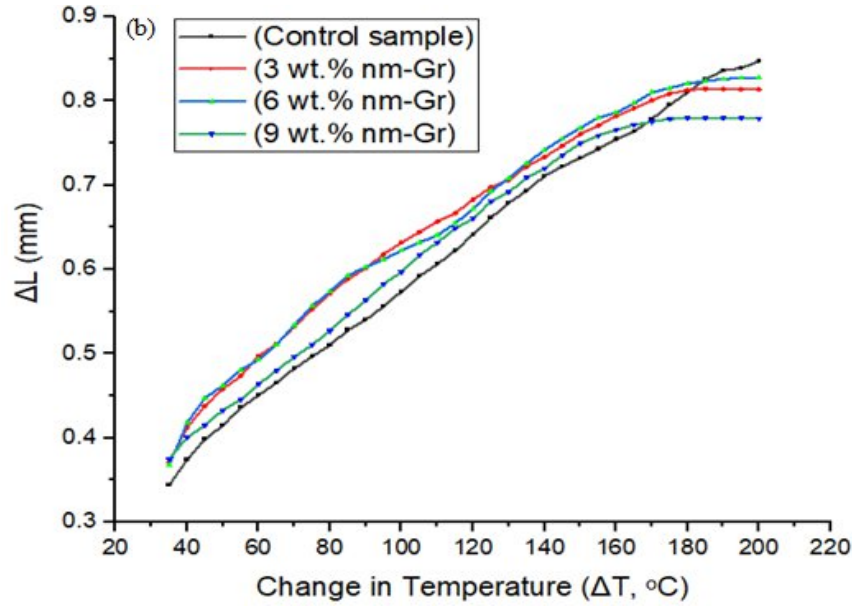


Figure 7: Variations in linear thermal expansion

Table 2 summarizes the statistical analysis of the mean coefficient of linear thermal expansion (CLTE) of the produced Al–Gr composites. A progressive reduction in CLTE was observed with increasing graphite nanoparticle content. The Al+9 wt.% nm-Gr composite had the lowest CLTE, indicating that higher graphite nanoparticle additions effectively suppressed the thermal expansion and improved the dimensional stability of the composite. This behavior could be explained by the different in coefficients of thermal expansion of graphite nanoparticles and aluminium matrix, which may generate interfacial constraints that restrict matrix expansion during heating (Matvienko *et al.*, 2021; Alsamawi *et al.*, 2025). Compared to the control sample, the Al-Gr composite samples exhibited higher regression intercepts, reflecting variations in the extrapolated linear thermal expansion at 0 °C. Additionally, for all samples, the coefficients of determination (R^2) were close to unity, indicating a good linear relationship between the temperature and linear thermal expansion.

Table 2: Statistical analysis of the linear thermal expansion of composite samples

Sample	$\alpha (\times 10^{-6}/^{\circ}\text{C})$	Standard deviation $\alpha (\times 10^{-6}/^{\circ}\text{C})$	Intercept	R-square
Control	30.56	9.85	0.2489	0.9954
Al+3 wt.% nm-Gr	29.96	10.99	0.3540	0.9922
Al+6 wt.% nm-Gr	27.87	18.71	0.3376	0.9732
Al+9 wt.% nm-Gr	24.55	14.14	0.3176	0.9594

Conclusion

Aluminium matrix composite reinforced with graphite nanoparticles were successfully produced by the stir casting process. The addition of graphite nanoparticles reduced porosity and increased the relative density of the composites compared with the control sample. The Al+3 wt.% nm-Gr composite exhibited the highest thermal conductivity of $239.50 \text{ W m}^{-1} \text{ K}^{-1}$, whereas the Al+9 wt.% nm-Gr composite recorded the lowest coefficient of linear thermal expansion (CLTE) of

$24.55 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. The improved thermal performance was associated with reduced porosity, and a more uniform distribution of graphite nanoparticles within the aluminium matrix. These results show that the graphite nanoparticle is a useful reinforcement for modifying the thermal characteristics of aluminum matrix composites, which make the material developed viable options for lightweight heat-dissipation components and other applications requiring high thermal conductivity and improved dimensional stability.

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