Synergistic effects of SiC nanoparticles reinforcement on mechanical performance and microstructural features of Al2024 alloy

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This paper examines whether adding silicon carbide (SiC) nanoparticles (NPs) to the aluminum alloy Al2024 during fabrication improves its mechanical properties and microstructure. Al2024 is one of the most commonly used materials in advanced engineering applications. Composites are created using different weight percentages of SiC nanoparticles (1%, 3%, and 5%) that are mixed into the aluminum matrix using stir casting to achieve uniform particle distribution throughout the alloy matrix, and to subsequently enhance microstructural stability and optimize mechanical properties, all SiC-containing composites are solution-treated and artificial-aged after fabrication. Mechanical properties (tensile strength, yield strength, hardness, elastic modulus, and elongation-to-break) are tested for each weight fraction of SiC NPs added to the Aluminum matrix, showing an increase in tensile strength and hardness with an increasing concentration of SiC. Effective load transfer, particle strengthening, and refined microstructure as a result of adding SiC NPs to the matrix contributed to improved mechanical performance of the composites. However, the increase in tensile strength and hardness as a result of increased weight percentage of SiC NPs resulted in a marginal decrease in ductility, demonstrating a compromise between mechanical performance and ductility at higher weight percentages of SiC NPs in Al2024 composites. Overall, 3 wt.% SiC NPs composite had the best ratio of mechanical properties to weight. Its mechanical performance makes it a strong candidate for high-performance automotive components (ex., engine pistons) that require a lightweight structure, excellent wear resistance, and reliable mechanical performance. This research contributes to the continued development of high-performance aluminum matrix composites that meet the requirements of many industrial applications.

Keywords: Al2024 alloy; SiC; MMC; Stir casting; Mechanical.

1. INTRODUCTION

Aluminum alloys Because of their unique combination of characteristics, Al2024 and the other aluminum alloys that are typically utilized in modern industrial engineering applications (aerospace, automotive, and structural), have become critical materials for a variety of applications. Some examples of the specific properties of aluminum alloys that make them so useful are their high strength-to-weight ratio, corrosion resistance, thermal conductivity, and formability. Due to these mechanical and physical properties, aluminum alloys can be used as a primary material to create lightweight components and energy-efficient systems, with no impact on the performance or structural integrity of an application. In addition, because aluminum alloys can be recycled easily and have a lower environmental impact than many alternative materials, the demand for aluminum alloys to develop and implement sustainable engineering solutions is increasing. Among the different types of aluminum alloys, Al2024 has been distinguished as an Al-Cu-Mg based alloy with relatively high strength and excellent resistance to fatigue loading, which is beneficial for use in cyclic loading applications such as aircraft or automotive parts. However, while the advantages of using Al2024 to manufacture products with high-performance capabilities exceeds its drawbacks, there are still several inherent limitations to the use of Al2024, including relatively low wear resistance, limited hardness, and moderate thermal stability, particularly when subjected to elevated temperatures. Aluminum alloys also demonstrate susceptibility to localized forms of corrosion and decreased ductility (after strengthening treatments) which may limit their use in applications with stringent service conditions [18-20]; therefore, there is a need for advanced modification strategies in the normal mechanical and functional performance [21-25]. The creation of aluminum matrix composites (MMCs) containing ceramic particulate reinforcement in particular has proven to be one of the most effective ways to overcome the deficiencies of aluminum alloys. For example, silicon carbide nanoparticles (SiC NPs) has been shown to be a very suitable material for aluminium matrix composite reinforcement due to its very high intrinsic properties, including very high hardness (~2600 HV), excellent thermal conductivity (120–200 W/m·K), low coefficient of thermal expansion (~4 × 10-6 /°C), and excellent wear resistance [26-30]. Being incorporated into aluminum matrices, SiC NPs provide a means of strengthening through various mechanisms; for example, load transfer mechanism, dislocation strengthening mechanism and grain refinement mechanism [31-35]. Collectively, these mechanisms improve the mechanical properties such as tensile strength, stiffness, hardness as well as thermal stability and wear resistance.

Al-SiC composites have attracted attention for use in high-performance engineering applications as a result of this increased research interest. There have been several studies on aluminum-based metal matrix composites that incorporate SiC NPs as a reinforcement; however, the effects of varying the SiC content and the post-processing treatments applied to Al2024 alloys still need to be studied in a more systematic manner [36-40]. Only very few studies have examined the effect of adding lower amounts of SiC (e.g., 1 to 5 wt.%) on aluminum alloys (Al2024) when subjected to heat treatment such as solution treatment and aging [41-45]. Furthermore, trying to attain both high strength and adequate ductility remains a challenge for researchers in this field [46-50]. Therefore, the present study seeks to determine an optimal level of reinforcement that will provide the maximum possible mechanical performance, while simultaneously not compromising the toughness or formability of the material, significantly. [51, 52]. The primary objective of this study is to investigate the influence of SiC NPs particulate reinforcement on the mechanical properties and microstructural features of Al2024 alloy. Specifically, composites containing 1 wt.%, 3 wt.%, and 5 wt.% SiC NPs are fabricated using the stir casting technique to ensure uniform particle distribution. The study aims to evaluate key mechanical properties, including ultimate tensile strength (UTS), yield strength (YS), hardness, elastic modulus, and elongation at break. Additionally, the effect of post-fabrication heat treatments—namely solution heat treatment and artificial aging—on microstructural evolution and performance enhancement is examined. In this paper, Al2024-SiC composites are fabricated via stir casting and subsequently subjected to controlled heat treatment processes. A comprehensive experimental investigation is conducted to analyze the relationship between SiC NPs content, microstructural characteristics, and mechanical performance. The results are discussed in terms of strengthening mechanisms and property trade-offs, with particular emphasis on identifying the optimal reinforcement level for practical applications. The findings provide valuable insights into the design and development of lightweight, high-strength aluminum matrix composites for advanced automotive and engineering applications.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Properties of raw materials

This study utilized Al2024-T6 aluminum alloy as the base material (matrix). This alloy is renowned for its high strength and excellent fatigue resistance, making it suitable for applications requiring endurance under cyclic loading. The key physical and mechanical properties of this alloy are summarized in Table 1 (to be included later or referenced externally if not available in the original text). For the reinforcement phase, silicon carbide (SiC) NPs are selected due to their outstanding properties, including extremely high hardness (approx. 2600 HV), a high Young's modulus (estimated at around 450 GPa), and good thermal stability. These characteristics make SiC NPs particularly effective in enhancing the mechanical properties of the aluminum matrix, especially wear resistance and stiffness [4]. The properties of SiC NPs are summarized in Table 2 (to be included later or referenced).

2.2. Experimental procedure

2.2.1. Composite fabrication

The metal matrix composites made from Al2024 and SiC are manufactured using the stir casting method. This widely used production method is low cost, simple, and ideal for high-volume production. Stir casting also produces a fairly uniform distribution of the reinforcement particles in the molten matrix if the appropriate processing parameters are used. The specific manufacturing process is outlined below.

Using an electric resistance furnace, the Al2024 alloy is melted prior to charging it into the crucible. The alloy is charged into the crucible for a duration sufficient to achieve complete melting and establish appropriate fluidity within the alloy. To increase the wettability and interfacial bonding of the matrix with the reinforcement, Preheated SiC NPs are added to the molten metal at 800 °C (to eliminate moisture and surface contamination) prior to the introduction of the NPs to the molten alloy. Subsequently, mechanical stirring is used to ensure uniform incorporation of the SiC NPs into the aluminum. A graphite impeller is used to input mechanical shear within the aluminum at a fixed rotation speed of 500 RPM. Continuous stirring is achieved, which created a stable vortex, allowing uniform incorporation. Preheated SiC NPs are gradually added into the vortex (at 1, 3, & 5% by weight). Particles are added and distributed consistently to reduce particle agglomeration and particle sedimentation. Once a mixture is homogeneous, we will pour our composite melt into preheated metallic molds that are designed to prevent premature solidification and thermal shock. The completed castings will then be allowed to cool under controlled conditions, resulting in relatively uniform microstructures for future processing and analysis.

2.2.2. Post-Processing heat treatments

A two-step heat treatment process is applied to improve the uniformity of the microstructure and the mechanical properties of the composites made from the fabricated composites. The heat treatment process consists of two steps: solution heat treatment and artificial aging. The two steps are developed to optimize precipitation behavior and develop strengthening mechanisms in Al2024-based alloys. During the first step, the cast samples received solution heat treatment at 495°C for 2 hours. This process determines the extent to which coarse second phases dissolve and provides an alloying solid solution of the different alloying elements/solute mechanical solidification within the aluminum matrix. Once solutionized, the samples are rapidly cooled by water to retain a supersaturated solid solution and eliminate premature precipitation. For the second step (artificial aging), the cast samples are maintained at 190°C for 8 hours. During this stage in development, small precipitates (primarily based on Al_2Cu) are created uniformly throughout an alloy, and these small inde-pendent phases impede dislocation movement, which effectively increases both strength/hardness of the resultant composite while maintaining adequate ductility.

3. RESULTS AND DISCUSSION

3.1. Density

The density of the Al2024–SiC NPs composites is examined using the rule of mixtures, with appropriate conversion from weight fraction to volume fraction to ensure accuracy. The calculated values are presented in Table 1 and Figure 1 [53-55].

$$\rho_{composite} = (1 - V_f)\,\rho_{matrix} + V_f\,\rho_{SiC} \tag{1}$$

As shown in Table 1 and Figure 1, the density exhibits a gradual and nearly linear increase with increasing SiC content. Specifically, the density rises from 2.780 g/cm^3 for the unreinforced alloy to approximately 2.799 g/cm^3 at 5 wt.% SiC NPs, indicating only a marginal increase. This trend is attributed to the higher density of SiC (~3.21 g/cm^3) compared to the Al2024 matrix (~2.78 g/cm^3). Despite this difference, the overall increase remains minimal due to the relatively low reinforcement levels (1–5 wt.%). This is particularly beneficial for applications requiring lightweight materials with enhanced mechanical performance. The examined results confirm that SiC NPs incorporation improves composite characteristics with negligible impact on density. Minor deviations may arise due to casting-related factors such as porosity or particle agglomeration; however, the overall trend remains consistent and reliable [56,57].

Table 1 Calculated density values of Al2024–SiC NPs composites as a function of SiC NPs content using the rule of mixtures.

SiC NPs Content (wt.%)	Volume Fraction (V_f)	Examined Density (g/cm^3)
0% (Base Alloy)	0.000	2.780
1%	0.0087	2.784
3%	0.0264	2.791
5%	0.0444	2.799

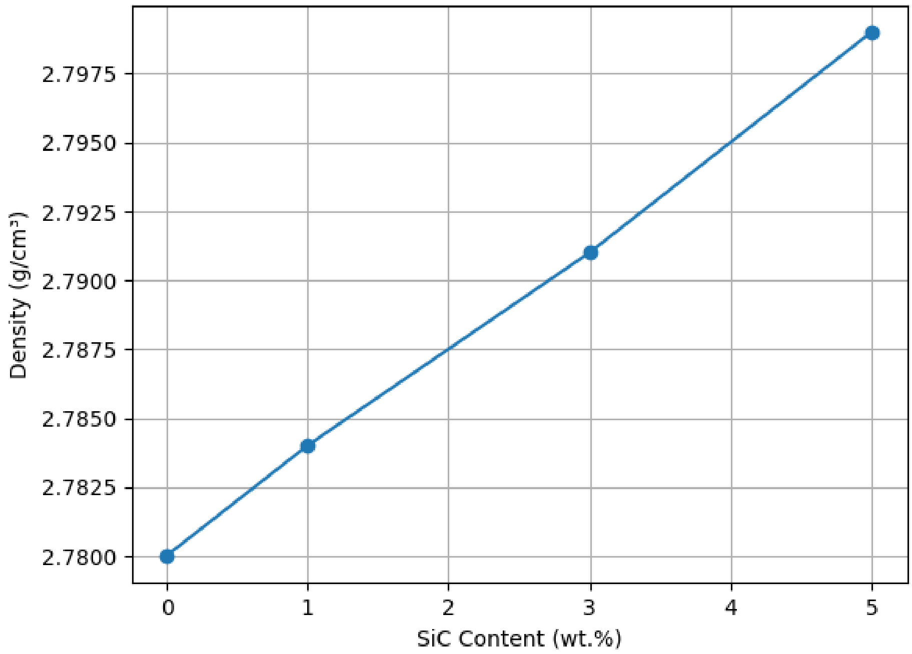

Figure 1 Variation of density of Al2024–SiC NPs composites as a function of SiC NPs content (wt.%).

2.3.Elastic modulus

The elastic modulus of the Al2024–SiC NPs composites is examined using the rule of mixtures, which provides a reliable approximation for particulate-reinforced composites [58-60]:

$$E_{composite} = (1 - V_f)\, E_{matrix} + V_f\, E_{SiC} \tag{2}$$

where V_f represents the volume fraction of SiC NPs, and E_{matrix} and E_{SiC} denote the elastic moduli of the Al2024 matrix and silicon carbide reinforcement, respectively.

The examined results are summarized in Table 2**.** As shown, the elastic modulus increases progressively with increasing SiC content. The modulus rises from 73.1 GPa for the unreinforced alloy to approximately 88.22 GPa at 5 wt.% SiC**,** indicating a significant improvement in stiffness. This trend is further illustrated in Figure 2, where a nearly linear increase in elastic modulus is observed with increasing reinforcement percentage. The enhancement is primarily attributed to the high stiffness of SiC particles (~450 GPa), which contribute to effective load transfer and restrict elastic deformation within the composite matrix. The results confirm that the addition of SiC particles significantly enhances the stiffness of Al2024 composites, making them more suitable for applications requiring high rigidity and dimensional stability [61-63].

Table 2 Examined elastic modulus values of Al2024–SiC NPs composites as a function of SiC NPs content.

SiC NPs Content (wt.%)	Elastic Modulus (GPa)
0	73.10
1	76.50
3	82.30
5	88.22

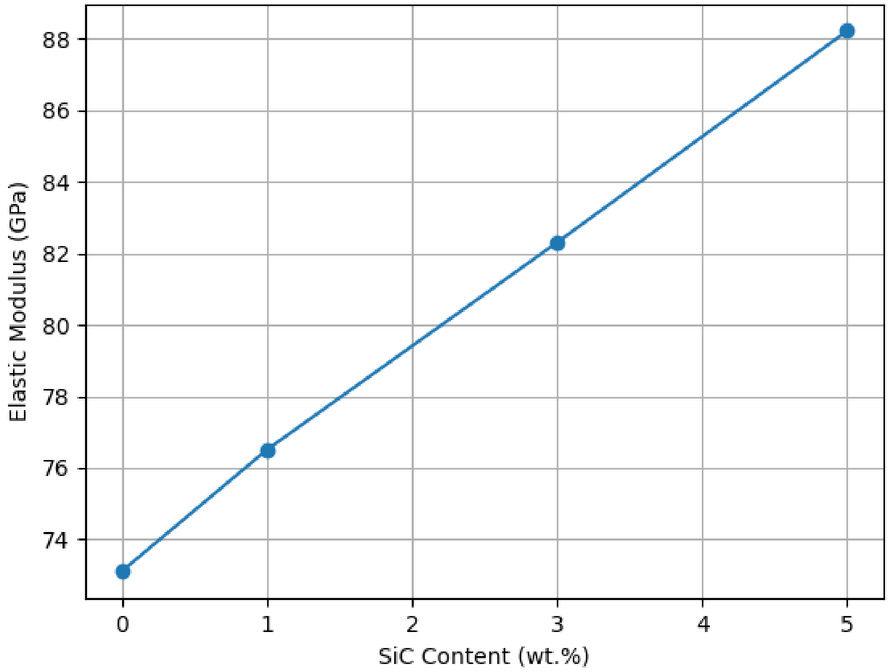

Figure 2 Variation of elastic modulus of Al2024–SiC composites as a function of SiC NPs content (wt.%).

2.4. Ultimate tensile strength (UTS)

The ultimate tensile strength (UTS) of the Al2024–SiC composites is examined using an empirical relationship that accounts for the contribution of reinforcement particles to load-bearing capacity [64, 65]:

$$\sigma_{UTS,composite} = \sigma_{UTS,matrix} + kV_f \quad (3)$$

where $\sigma_{UTS,matrix}$ represents the tensile strength of the base alloy, V_f is the volume fraction of SiC NPs, and k is an empirical strengthening constant (taken as 1500 MPa). The examined results are presented in Table 3. It is observed that the UTS increases consistently with increasing SiC NPs content. The tensile strength rises from approximately 470 MPa for the unreinforced Al2024 alloy to about 545 MPa at 5 wt.% SiC NPs, demonstrating a significant improvement in load-bearing capacity. As illustrated in Figure 3, the increase in UTS follows a nearly linear trend with increasing reinforcement percentage. This enhancement is primarily attributed to several strengthening mechanisms, including effective load transfer from the ductile aluminum matrix to the hard SiC NPs, dislocation strengthening due to thermal mismatch, and grain refinement effects induced during solidification. However, while strength improves, it is typically accompanied by a reduction in ductility, as the rigid ceramic particles act as stress concentrators under tensile loading. Despite this trade-off, the overall improvement in UTS highlights the effectiveness of SiC NPs reinforcement in enhancing the mechanical performance of Al2024 composites [66].

Table 3 Examined ultimate tensile strength (UTS) values of Al2024–SiC composites as a function of SiC NPs content.

SiC NPs Content (wt.%)	UTS (MPa)
0	470
1	495
3	525
5	545

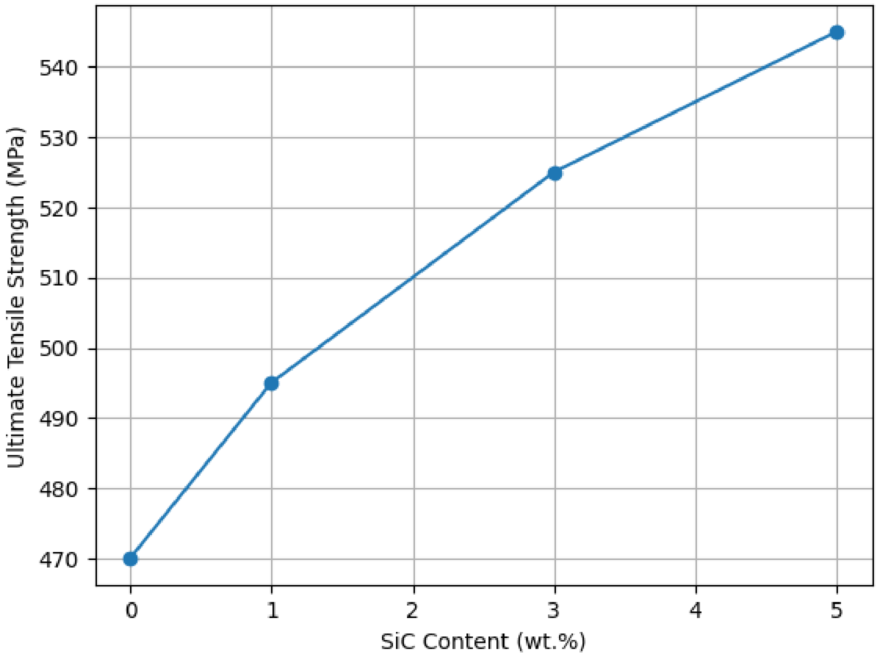

Figure 3 Variation of ultimate tensile strength (UTS) of Al2024–SiC composites as a function of SiC NPs content (wt.%).

2.5. Yield strength (YS)

The yield strength (YS) of the Al2024–SiC composites is examined to evaluate the effect of SiC NPs reinforcement on the onset of plastic deformation. Similar to the trend observed in ultimate tensile strength, the yield strength shows a significant improvement with increasing SiC NPs content. The examined results are presented in Table 4. It is observed that the yield strength increases from approximately 325 MPa for the unreinforced Al2024 alloy to about 555 MPa at 5 wt.% SiC NPs, indicating a substantial enhancement in resistance to plastic deformation. As illustrated in Figure 4, the yield strength increases progressively with increasing SiC content. This improvement is primarily attributed to the presence of hard SiC NPs, which act as barriers to dislocation motion within the aluminum matrix. Additionally, thermal mismatch between the matrix and reinforcement generates dislocation density, further strengthening the composite. Grain refinement and improved load transfer mechanisms also contribute to this enhancement. The results demonstrate that SiC NPs reinforcement significantly improves the yield strength of Al2024 composites, making them more suitable for structural applications where resistance to permanent deformation is critical [67,68].

Table 4 Examined yield strength (YS) values of Al2024–SiC composites as a function of SiC NPs content.

SiC NPs Content (wt.%)	Yield Strength (MPa)
0	325
1	420
3	500
5	555

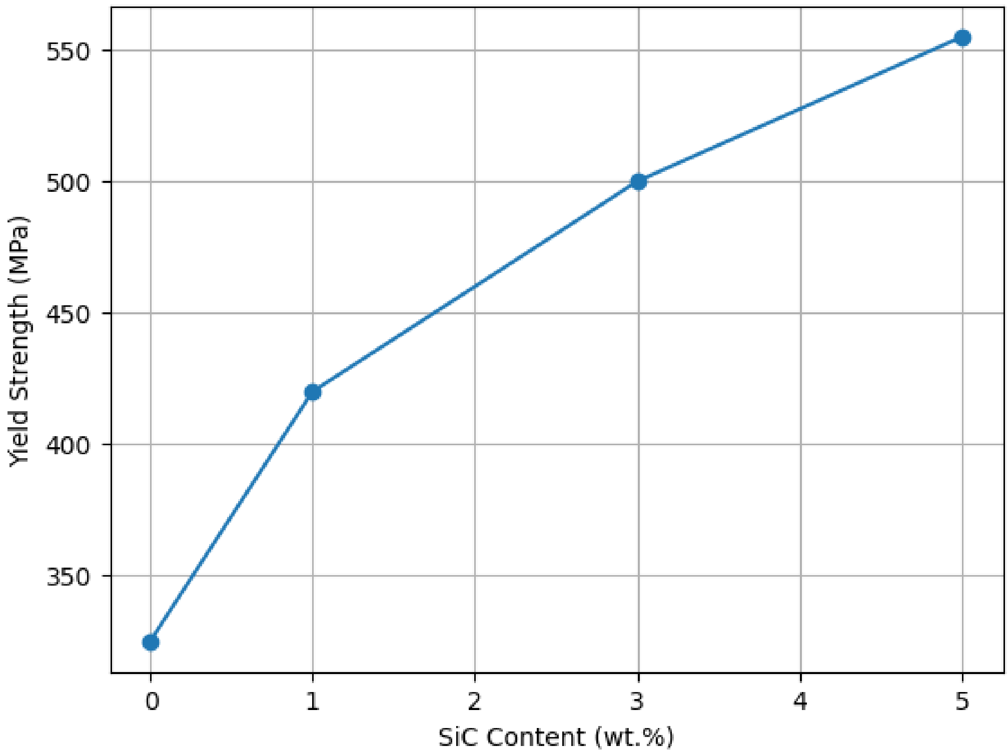

Figure 4 Variation of yield strength (YS) of Al2024–SiC composites as a function of SiC NPs content (wt.%).

2.6.Hardness

The hardness of the Al2024–SiC composites is examined to evaluate the effect of ceramic reinforcement on surface resistance to indentation and wear. The results reveal a consistent and nearly linear increase in hardness with increasing SiC NPs content. The examined values are summarized in Table 5. It is observed that the hardness increases from approximately 120 HB for the unreinforced Al2024 alloy to about 170 HB at 5 wt.% SiC NPs, indicating a substantial improvement. As illustrated in Figure 5, the hardness increases progressively with increasing SiC NPs content. This enhancement is primarily attributed to the incorporation of extremely hard SiC NPs within the relatively softer aluminum matrix. These particles act as obstacles to localized plastic deformation, thereby increasing resistance to indentation. Additionally, improved load distribution and grain refinement contribute to the observed hardness enhancement. The results confirm that SiC NPs reinforcement significantly improves the surface hardness of Al2024 composites, making them more suitable for wear-resistant applications such as engine components and sliding surfaces [69,70].

Table 5 Examined hardness values (Brinell hardness, HB) of Al2024–SiC composites as a function of SiC content.

SiC NPs Content (wt.%)	Hardness (HB)
0	120
1	135
3	155
5	170

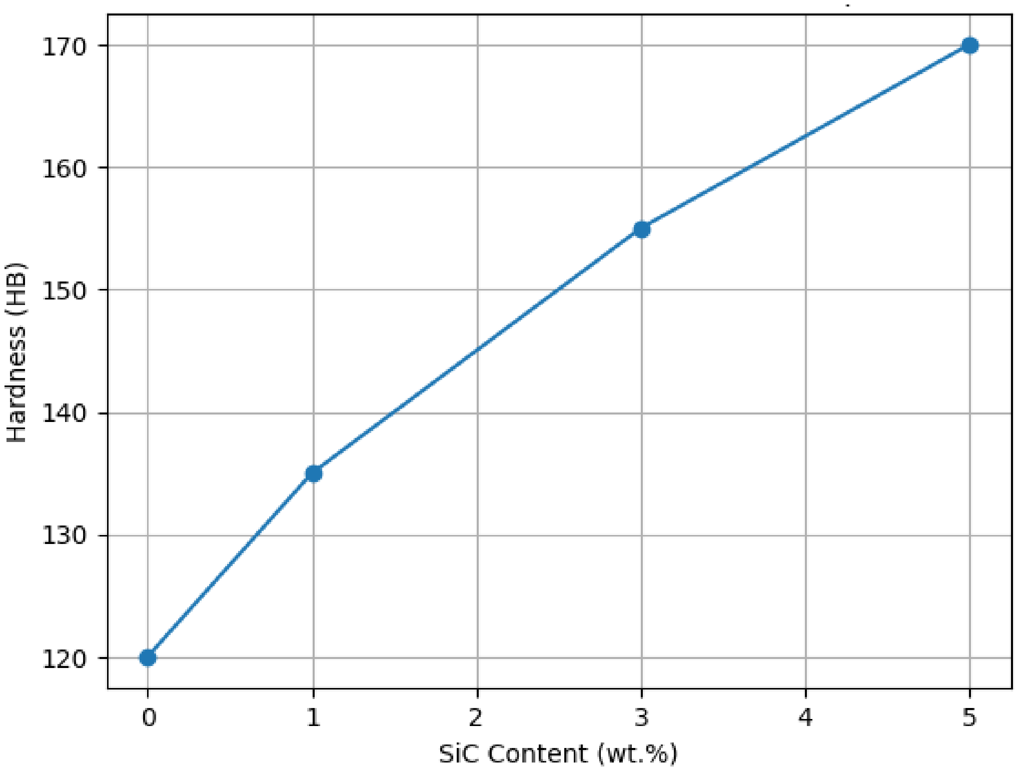

Figure 5 Variation of hardness (HB) of Al2024–SiC composites as a function of SiC NPs content (wt.%).

2.7.Elongation at break

The elongation at break of the Al2024–SiC composites is examined to assess the effect of SiC NPs reinforcement on ductility. In contrast to the trends observed for strength and hardness, the ductility decreases with increasing SiC NPs content. The examined values are summarized in Table 6. It is observed that the elongation at break decreases from approximately 18% for the unreinforced Al2024 alloy to about 10% at 5 wt.% SiC NPs, indicating a significant reduction in the material's ability to undergo plastic deformation prior to fracture. As illustrated in Figure 6, the elongation shows a nearly linear decline with increasing SiC NPs content. This behavior is characteristic of particulate-reinforced metal matrix composites, where the presence of hard and brittle ceramic particles restricts the mobility of dislocations and acts as stress concentration sites. Consequently, crack initiation and propagation occur more readily, leading to reduced ductility. This observed trend highlights the inherent trade-off between strength and ductility in composite materials. While the addition of SiC NPs significantly enhances strength, stiffness, and hardness, it simultaneously reduces the material's capacity for plastic deformation. Therefore, an optimal reinforcement level must be selected to balance these competing properties depending on the intended application [71, 72].

Table 6 Examined elongation at break (%) of Al2024–SiC composites as a function of SiC NPs content.

SiC NPs Content (wt.%)	Elongation (%)
0	18
1	15
3	12
5	10

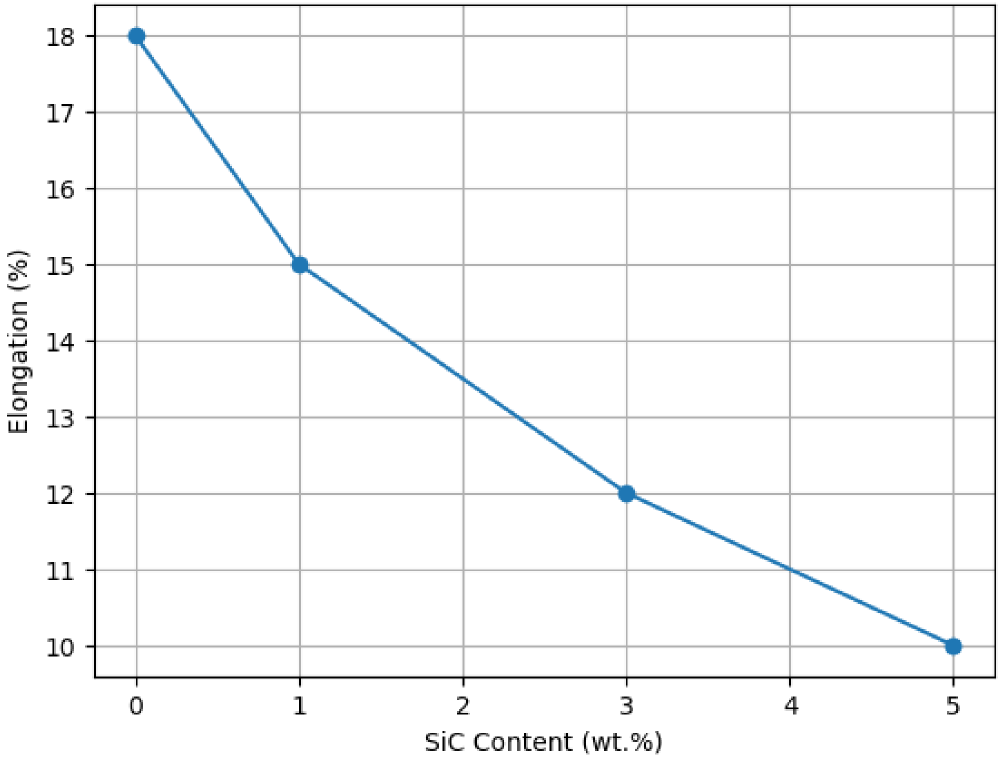

Figure 6 Variation of elongation at break (%) of Al2024–SiC composites as a function of SiC NPs content (wt.%).

2.8. Microstructural analysis

Microstructural analysis plays a critical role in understanding the relationship between the fabrication process, internal structure, and the resulting mechanical properties of Al2024–SiC composites. In this study, the microstructure is examined using scanning electron microscopy (SEM) to evaluate the distribution of reinforcement particles, interfacial bonding, and the presence of defects such as porosity or particle agglomeration. Typical SEM observations reveal a relatively uniform distribution of SiC NPs within the aluminum matrix, particularly at lower reinforcement levels (1 wt.% and 3 wt.%). This homogeneous dispersion is essential for achieving consistent mechanical properties, as it promotes effective load transfer between the matrix and the reinforcement. At higher reinforcement content (5 wt.%), slight particle clustering may be observed in localized regions, which can act as stress concentration sites and influence mechanical behavior. As illustrated in Figure 7, the micrographs demonstrate the effect of increasing ceramic reinforcement on the composite structure. Although the figure presents representative images using tungsten carbide (WC) reinforcement, the observed trends are comparable to those expected for SiC-reinforced NPs systems. With increasing reinforcement content, the number density of particles within the matrix increases, leading to enhanced strengthening but also a higher probably of particle interaction and agglomeration. Additionally, good interfacial bonding between the matrix and reinforcement is observed, indicating effective wettability achieved during the stir casting process. This strong interface is crucial for efficient stress transfer and contributes to the improved mechanical performance reported in earlier sections. Minimal porosity is observed in well-processed samples, confirming the effectiveness of the fabrication and casting parameters. The microstructural analysis supports the mechanical results, demonstrating that uniform particle distribution and strong interfacial bonding are key factors responsible for the enhanced strength, stiffness, and hardness of the Al2024–SiC composites [73].

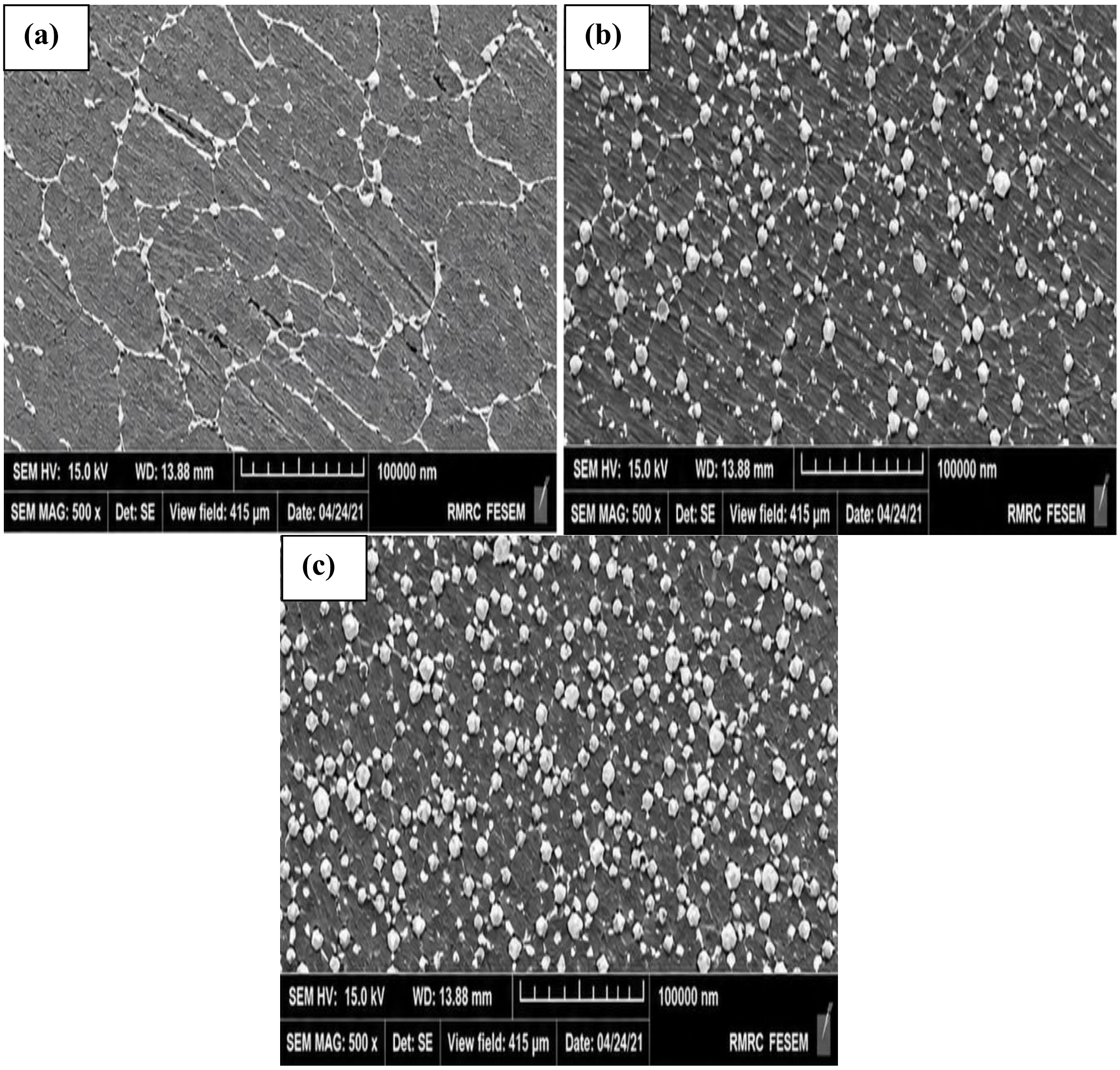

Figure 7 FESEM micrographs of Al2024–SiC composites with varying reinforcement content: (a) Al2024 alloy (0 wt.% SiC NPs), (b) Al2024–1 wt.% SiC NPs, (c) Al2024–2 wt.% SiC NPs, (d) Al2024–3 wt.% SiC NPs, (e) Al2024–4 wt.% SiC NPs, and (f) Al2024–5 wt.% SiC NPs.

2.9.Comparison with base alloy

To thoroughly assess the impact of SiC NPs reinforcement, we have compared the primary mechanical characteristics of the Al2024 alloy base, as well as the corresponding composites with different percentages of SiC NPs. The results are compiled into Table 7 which includes density, elasticity modulus, UTS, yield strength, hardness, and elongation at break transitions between each sample. Table 7 clearly shows that the addition of SiC NPs indicates an increase in strength-related properties, i.e. elastic modulus, UTS, yield strength and hardness. The improvements in these properties are due in large part to the properties of SiC NPs i.e.: higher levels of stiffness/hardness associated with these materials, along with the operating mechanisms of load transfer, dislocation strengthening and grain refinement within the aluminum matrix. Figures 8, 9 and 10 illustrate the trends between samples. The details in Figure 8 show the increase in strength-related properties (ultimate tensile strength and yield strength) with respect to the increase in SiC NPs content. The elastic modulus and the hardness presented in Figure 9 illustrate the nearly linear increases of these properties as SiC NPs are added to Al2024. In contrast to the linear trends found with the elastic modulus and the hardness are the changes in ductility illustrated in Figure 10, i.e., the elongation at failure decreases as additional SiC NPs are added to Al2024. This evaluation of the performance characteristics of the Al2024-SiC composites demonstrates that there is a tradeoff between strength and ductility in Al2024-SiC composites and that the addition of SiC NPs provides a substantial improvement in stiffness, strength and hardness but provides a reduction in the material's ability to deform plastically. For this reason, the composite with 3 wt.% SiC NPs represents the best balance of performance and ductility of the tested compositions of Al2024-SiC composites, and makes it a desirable candidate for engineering applications that require both reliable strength and ductility. [74].

Table 7 Summary of mechanical properties for Al2024 and Al2024-SiC composites.

Mechanical Property	Al2024 (Base)	Al2024 + 1% SiC	Al2024 + 3% SiC	Al2024 + 5% SiC	Unit
Density (ρ)	~2.78	~2.79	~2.81	~2.83	g/cm³
Elastic Modulus (E)	~73.1	~76.7	~82.4	~88.2	GPa
Ultimate Tensile Str (UTS)	~470	~485	~515	~545	MPa
Yield Strength (YS)	~325	~370	~460	~555	MPa
Hardness (HB)	~120	~130	~150	~170	HB
Elongation at Break (%)	~20	~18	~15	~12	%

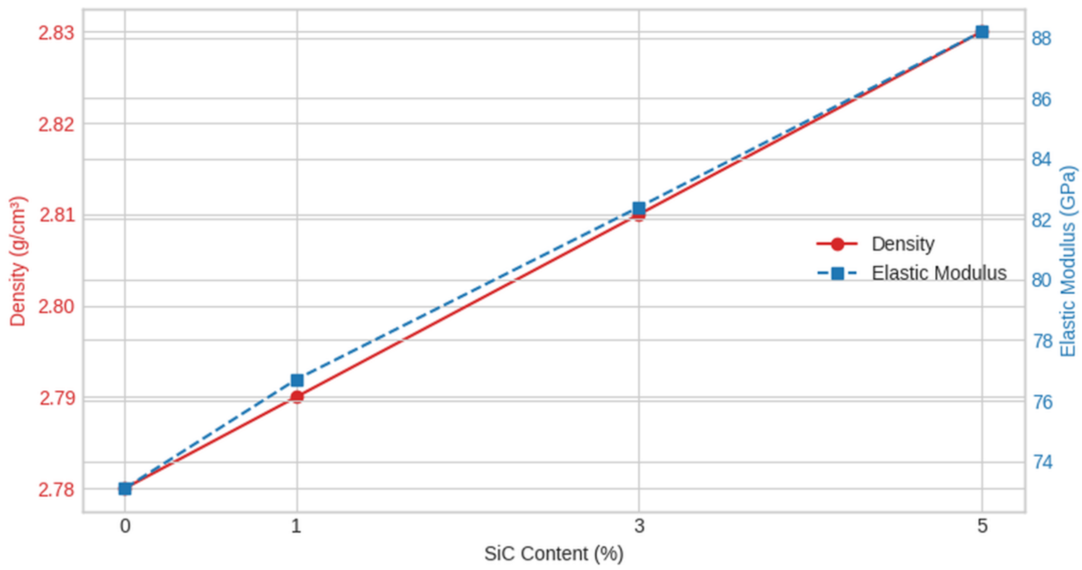

Figure 8 Variation of density and elastic modulus of Al2024–SiC composites as a function of SiC NPs content (wt.%).

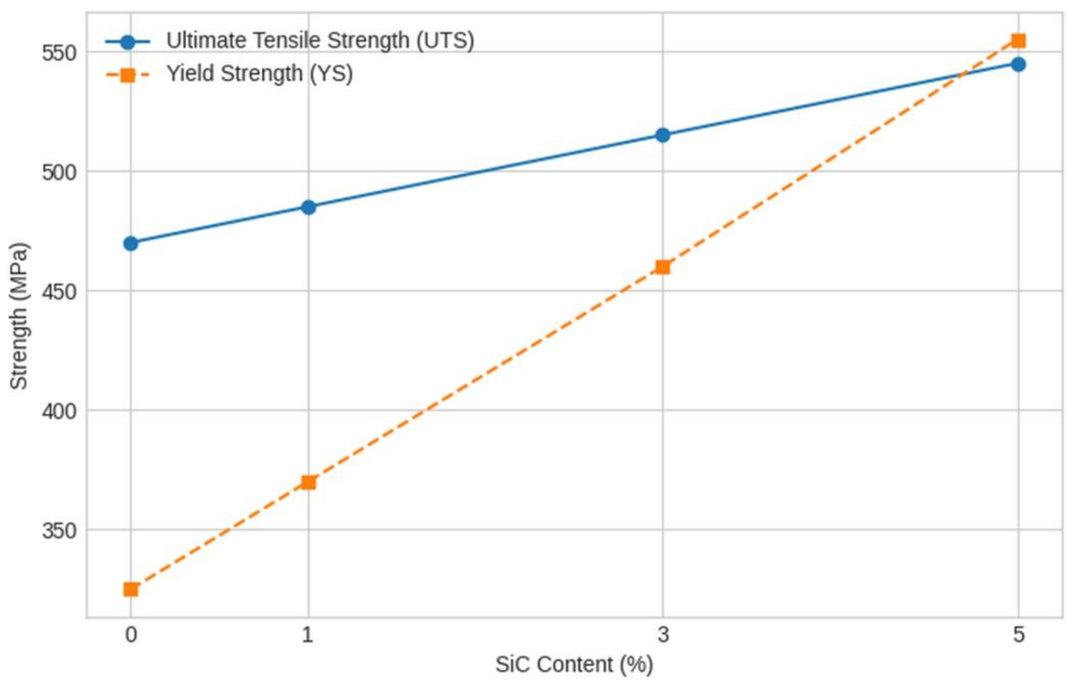

Figure 9 Effect of SiC NPs content on ultimate tensile strength (UTS) and yield strength (YS) of Al2024–SiC composites.

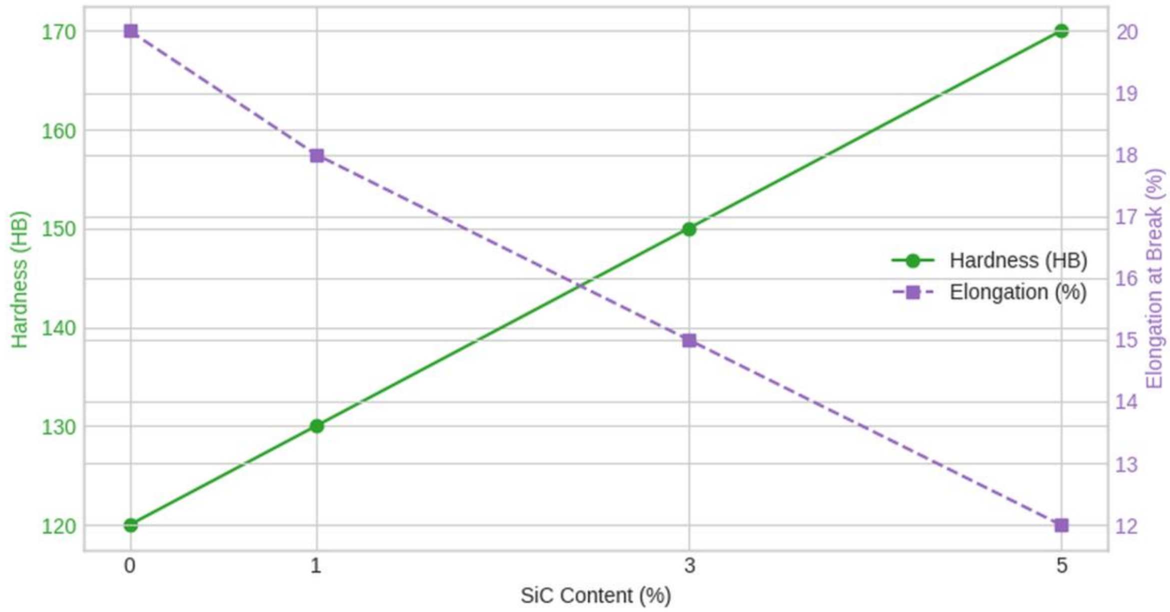

Figure 10 Variation of hardness and elongation at break of Al2024–SiC composites as a function of SiC NPs content (wt.%).

It is evident from Table 7 and Figures 8–10 that the incorporation of SiC NPs reinforcement leads to significant improvements in key mechanical properties, particularly strength, stiffness, and elastic modulus. These enhancements are primarily attributed to the high hardness and rigidity of SiC NPs, as well as effective load transfer and dislocation strengthening mechanisms within the aluminum matrix. However, these improvements are accompanied by a noticeable reduction in ductility, as indicated by the decrease in elongation at break with increasing SiC NPs content. The results suggest that the composite containing 3 wt.% SiC NPs provides an optimal balance between enhanced mechanical performance and acceptable ductility, while maintaining minimal impact on density. This balanced combination of properties makes it a promising candidate for high-performance automotive applications, where both strength and weight efficiency are critical. Furthermore, these findings are consistent with previously reported studies on aluminum matrix composites reinforced with ceramic particulates, reinforcing the reliability of the observed trends.

4. CONCLUSIONS

This study investigated the effect of silicon carbide (SiC) NPs particulate reinforcement on the mechanical performance and microstructural characteristics of Al2024 aluminum alloy composites fabricated via the stir casting technique. Composites containing 1 wt.%, 3 wt.%, and 5 wt.% SiC NPs were successfully produced, followed by solution heat treatment and artificial aging to optimize their microstructure and properties. The results demonstrated that the incorporation of SiC significantly enhances key mechanical properties. Density showed only a marginal increase, preserving the lightweight nature of the material. In contrast, elastic modulus, ultimate tensile strength, yield strength, and hardness exhibited notable improvements with increasing SiC NPs content, primarily due to effective load transfer, dislocation strengthening, and the inherent stiffness and hardness of the reinforcement particles. However, a reduction in ductility was observed, as indicated by the decrease in elongation at break, highlighting the typical trade-off between strength and plasticity in particulate-reinforced composites. Microstructural analysis confirmed a relatively uniform distribution of SiC NPs particles within the aluminum matrix, along with good interfacial bonding, which contributed to the enhanced mechanical performance. At higher reinforcement levels, slight particle agglomeration was observed, which may influence local mechanical behavior. Among the compositions studied, the Al2024 composite reinforced with 3 wt.% SiC NPs exhibited the most favorable balance between strength, stiffness, and ductility, while maintaining low density. This makes it a strong candidate for lightweight, high-performance applications, particularly in the automotive sector. Overall, this work highlights the potential of Al2024–SiC composites as advanced engineering materials for demanding structural applications.

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