

Microstructure and nanomechanical properties of heat treated AlCu composites reinforced with SiC and stainless steel particles

Samuel Ranti Oke^{a,b,*}, Gabriel Elojo Ugwu^b, Nthabiseng Maledi^{a,c}, Oluwasegun Eso Falodun^a

^a School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment University of the Witwatersrand, Johannesburg, South Africa

^b Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

^c DSI-NRF Centre of Excellence in Strong Materials, University of the Witwatersrand, Johannesburg, South Africa

HIGHLIGHTS

- The study examines the effect of SiC and SS reinforcements and heat treatment on improve AlCu.
- Heat treatment refines microstructure and enhances particle-matrix bonding.
- SiC-reinforced composites show superior hardness and wear resistance.
- Mechanical properties are linked to microstructural changes from SEM analysis.
- Nanoindentation highlights improved deformation behavior post-heat treatment.

ARTICLE INFO

Keywords:

Al
Cu
Composite
Microstructure
Nano-indentation

ABSTRACT

AlCu-based hybrid composites are increasingly utilized in engineering applications due to their excellent mechanical and thermal properties, which can be optimized through reinforcement and heat treatment. This study investigates the microstructural evolution and nanomechanical properties of heat-treated AlCu composites reinforced with silicon carbide (SiC) and stainless steel (SS) particles fabricated via stir casting. The composites were heat-treated to study the influence of thermal exposure on particle-matrix interaction, and nanomechanical behavior. Scanning Electron Microscopy (SEM) and nanoindentation techniques were employed to assess the microstructure and mechanical properties of the composites. Microstructural analysis revealed significant refinement post-heat treatment, forming fine precipitates and improved particle-matrix bonding. Heat treatment enhanced the load-carrying capacity, hardness, anti-wear resistance (H/E_r), and yield pressure of all composites, as indicated by lower indentation depths and increased values in nanoindentation tests, particularly for SiC-reinforced composites. The elastic modulus showed a complex response to reinforcement and heat treatment, with initial increases in the as-cast state for SiC-reinforced composites but varied results post-heat treatment due to residual stresses and microstructural changes. The plasticity index decreased across all samples after heat treatment, reflecting improved resistance to plastic deformation. The study demonstrates the effectiveness of reinforcement and heat treatment in enhancing the mechanical performance of AlCu composites, providing valuable insights for applications in structural and thermal management domains.

1. Introduction

The aluminum-copper (AlCu) alloy, resulting from the fusion of aluminum and copper, presents a unique blend of properties highly desirable in contemporary engineering domains. Influenced by the integration of copper, the alloy's intricate atomic structure and crystal

lattice arrangement contribute to its diverse utility across various industries [1–3]. With its face-centered cubic (FCC) crystal structure akin to pure aluminum, bolstered by copper atoms, the alloy embodies notable strength, ductility, and corrosion resistance, enabling its seamless integration into different manufacturing processes such as casting, extrusion, and machining [4–6]. Due to its lightweight yet durable

* Corresponding author. School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment University of the Witwatersrand, Johannesburg, South Africa.

E-mail address: samuel.oke@wits.ac.za (S.R. Oke).

<https://doi.org/10.1016/j.matchemphys.2025.130451>

Received 13 September 2024; Received in revised form 11 January 2025; Accepted 21 January 2025

Available online 23 January 2025

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nature, AlCu alloy finds application in high-stakes industries like aerospace, where it is used for aircraft components, and in automotive and marine sectors for lightweight structural elements [7,8]. Additionally, its conductivity and mechanical prowess find significance in electrical engineering applications, while its effective heat dissipation capabilities are well-suited for thermal management in electronics. Moreover, the alloy's versatility extends to meeting diverse needs in consumer goods and packaging materials, further solidifying its integral role across various industrial sectors [9].

Aluminum-based hybrid composites, reinforced with ceramic and metallic particles, have garnered significant interest due to their potential to enhance mechanical properties and corrosion resistance in various industrial applications. However, a comprehensive understanding of the intricate relationship between microstructural characteristics, heat treatment parameters, and multifaceted performance attributes remains a critical research gap [10–12]. The existing literature offers fragmented insights into the effects of heat treatment on the microstructural evolution and mechanical behavior of these hybrid composites. While some studies have investigated the individual contributions of ceramic and metallic particles to the overall performance, a systematic examination integrating both reinforcements and their synergistic effects is lacking. Additionally, the influence of different heat treatment regimens on these particles' interfacial bonding, dispersal, and distribution within the aluminum-copper (AlCu) matrix remains insufficiently explored [13,14].

Research on AMCs and hybrid composites (HCs) has highlighted improvements in mechanical, thermal, and tribological properties through various reinforcement strategies. Incorporating ceramic reinforcements such as TiO_2 , and SiC enhances tensile strength, impact resistance, and tribological performance due to uniform particle distribution and strong interfacial bonding [15–17]. Reinforcements like Al_2O_3 , TiC, and ZrB_2 have also been reported to enhance strength via mechanisms such as grain refinement and Orowan strengthening [18, 19]. However, challenges such as particle clustering, porosity, and reductions in hardness with specific reinforcements like graphite have been identified [20]. Preheating reinforcements and optimizing their proportions have proven effective for enhancing wettability and mechanical responses [21]. While substantial progress has been made with individual reinforcements, understanding the synergistic effects of combining metallic and ceramic reinforcements to achieve balanced properties remains limited [22].

While conventional macroscopic mechanical testing provides valuable insights into composite bulk properties, nanomechanical properties like hardness and elastic modulus at the nanoscale remain largely unexplored. Nanomechanical characterization techniques, such as nanoindentation, have emerged as powerful tools to probe material properties at small length scales, offering critical insights into hardness, elastic modulus, and deformation mechanisms at the nanoscale [23,24]. Despite their significance, applying these techniques to AlCu-based hybrid composites, mainly to study the impact of reinforcement content and heat treatment parameters on nanoscale mechanical behavior, is scarce [25–27]. Existing research predominantly focuses on macroscopic testing, leaving a gap in understanding nanoscale mechanical properties. Nanoindentation studies provide key information on elastic-plastic deformation, creep resistance, and strengthening mechanisms, as highlighted by previous research on AlCu alloys. Pan et al. [28] studied the nanoindentation creep behaviour of AlCu alloys and reported enhanced strength and plasticity of the hypoeutectic AlCu solidified under high pressure. Liu et al. [29] evaluated the nanoindentation properties of AlCu diffusion couples. They identified the $\zeta_2(\text{Al}_9\text{Cu}_{11.5})$ phase as the hardest (11.94 GPa) and $\gamma_1(\text{Al}_4\text{Cu}_9)$ as having the highest Young's modulus (254.69 GPa) and lowest creep tendency. Small-scale mechanical testing of AlCu intermetallics has also been reported by Ref. [30].

This study aims to bridge these knowledge gaps by investigating the impact of reinforcing AlCu alloy with SiC and SS particles, followed by

heat treatment, on both microstructural evolution and mechanical properties. Specifically, we synthesized AlCu composites using the stir casting technique and employed nanoindentation to assess their elastic-plastic deformation behavior and nanoscale mechanical properties. The novelty of this work lies in its integration of hybrid reinforcements and systematic evaluation of the synergistic effects of reinforcement content and heat treatment on nanoscale mechanical behavior. Additionally, this study emphasizes the interplay between microstructural changes and mechanical performance, advancing the understanding of hybrid composite materials.

Despite its comprehensive approach, the study acknowledges certain limitations. For instance, the potential variability in particle distribution during stir casting and its influence on localized mechanical properties warrants further investigation. Similarly, the role of reinforcement volume fractions in dictating the heat treatment response remains a potential avenue for future research. By addressing these limitations and systematically exploring the influence of hybrid reinforcements and heat treatment, this work advances aluminum-based hybrid composites, offering insights into their design and optimization for engineering applications.

2. Materials and methods

2.1. Materials

The base materials for the investigation are Aluminium 6063, Copper (99.9 % purity), with Silicon carbide powder (APS 50 μm ; 99.9 % purity) and Stainless-Steel powder (APS 25 μm ; 99.8 % purity) as reinforcements. Copper (5 wt%) was added to the aluminium to form the AlCu alloy through solid solution strengthening and precipitation hardening mechanisms [31]. With the AlCu alloy as the base matrix, 5 wt% of single reinforcements, each SiC and stainless steel (SS) powder were added separately to produce SiC and SS reinforced composites. Additionally, a hybrid reinforcement of 2.5 wt% for each SiC and SS was incorporated to create a fourth sample. Nigalex, Nigeria supplied the Aluminium 6063, and the Stainless-Steel powder was supplied by Sandvik Osprey Ltd, UK, and their chemical compositions presented in Tables 1 and 2 are as received from the suppliers.

2.2. Experimental procedure

The stir casting process for an AlCu alloy reinforced with SiC and SS particles involves several key steps. First, the calculated amount of Al alloy is charged into a crucible furnace and melted at a temperature of 680 °C exceeding its melting point. Copper (5 wt%) is melted separately and then added to the molten aluminum at 680 °C, followed by stirring to achieve a homogeneous mixture. The selected temperature and stirring process parameters are based on established practices in the literature to ensure the proper dissolution of copper and uniform alloy formation [11,32]. The melt mixture was cooled to semi-solid state at 600 °C. Simultaneously, the SiC and SS particles are preheated in a separate furnace at 250 °C for 45 min to improve their bonding with the molten metal. The molten AlCu alloy is then likely stirred and degassed to remove impurities. Next, the preheated SiC and SS particles are gradually added to the vigorously stirred melt to achieve a uniform dispersion. After this addition, the mixture undergoes superheating at 750 °C, stirred mechanically at 400 rpm for 10 min to allow for complete mixing and remove any trapped air or bubbles. Finally, the molten composite slurry is poured into a preheated sand mold for solidification. The solidified casting was machined for a good surface finish.

The AlCu alloy undergoes solution heat treatment at 550 °C for 2 h, followed by water quenching and artificial aging at 170 °C for 6 h. These time intervals for solutionizing and aging are selected based on literature recommendations to achieve peak aging conditions [33].

The microstructure and elemental composition of the cast AlCu + SiC + SS composites were characterized using a JEOL 7001F Scanning

Table 1

Chemical composition of aluminium 6063 alloy.

Elements	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
Composition (wt%)	0.45	0.22	0.02	0.03	0.5	0.02	0.03	0.02	Bal

Table 2

Chemical composition of the stainless steel particle SAF 2205.

Elements	C	Si	Mn	P	S	Cr	Ni	Mo	N	Fe
Composition (wt%)	≤0.03	≤1.0	≤2.0	≤0.03	≤0.015	22	5	3.2	0.18	Bal

Electron Microscope (SEM) equipped with Energy Dispersive X-ray Spectroscopy (EDS). The AlCu and composites were sectioned, mounted, surface grinded and polished to prepare the surface for microstructural analysis. Secondary electron imaging was used to examine the morphology and distribution of SiC and SS particles within the AlCu matrix. EDS analysis afforded elemental composition at specific points and elemental maps, allowing for identification and assessment of elemental distribution.

Nanoindentation tests were used to measure the mechanical characteristics of the composite. The nanoindentation technique (Antor Paar, Switzerland) was used with a Berkovich indenter comprising a three-sided pyramid tip. A load–displacement curve was plotted for each indentation and the corresponding hardness and elastic modulus values were evaluated using [34]. The maximum load applied, holding time, and loading rate were 100 mN, 5 s, and 40 mN/S, respectively. The composite's resistance to localized plastic deformation (Hardness H) is quantified by the size of indentation left by the hard indenter under 100 mN load and expressed in equation (1).

$$H = \frac{P}{A_c} \quad (1)$$

where P is the applied load and A_c is the contact area of the indentation. The reduced elastic modulus E_r is determined from the slope of the unloading curve (stiffness S) during the indentation process as expressed in equation (2).

$$E_r = \frac{\sqrt{\pi}}{2} \frac{1}{\beta} \frac{S}{\sqrt{A}} \quad (2)$$

where S is the stiffness of the material, obtained from the initial unloading slope. The variable β is a geometric constant that depends on the indenter's shape which typically ranges from 1 to 1.05. In this work, β is taken as 1. The effective elastic modulus, E_r , is thus given by:

$$E_r = \left(\frac{1 - \nu_i^2}{E_i} + \frac{1 - \nu^2}{E} \right)^{-1} \quad (3)$$

where, ν_i and ν represent the Poisson's ratios while E_i and E denote the elastic moduli of the indenter and the composite samples, respectively.

The plasticity index φ is used to quantify the extent of plastic deformation in the composite relative to its total deformation (both elastic and plastic). Mathematically, it is expressed as:

$$\varphi = \frac{W_p}{W_t} \quad (4)$$

W_t is the total work, which is the sum of the plastic work W_p and the elastic work W_e (the work done in elastically deforming the material) as expressed in equation (4).

$$W_t = W_e + W_p \quad (5)$$

To ensure the accuracy of the measurements, the frame stiffness of the nanoindenter was also assessed. The measured frame stiffness was found to be 85 N/m, which is higher than the elastic contact stiffness of

the composites, ensuring minimal influence from the machine's compliance. Peak stiffness was used to extrapolate frame stiffness, considering a value of 110 N/m at maximum load. The frame stiffness was not extrapolated beyond this range to avoid inaccuracies in the data. A total of 10 indentations were performed on each sample to ensure statistical reliability. The physical dimensions of the indentation arrays were set to $10 \times 10 \mu\text{m}$, allowing for sufficient spacing to prevent interaction between indentations.

To accurately determine the stiffness, 50 % of the unloading data were used, focusing on the initial portion of the unloading curve where elastic recovery dominates. Thermal drift was accounted for by conducting a hold segment at 90 % of the maximum load for 30 s prior to unloading, allowing the instrument to adjust for any thermal expansion or contraction. This correction was applied to all data to ensure that the measured mechanical properties accurately reflect the inherent characteristics of the composites rather than artifacts from the testing environment.

3. Result and discussion

3.1. Microstructure of AlCu and composite

The microstructure of the as-cast AlCu alloy, as depicted in Fig. 1, presents vital insights into its structural characteristics and elemental composition. The AlCu alloy typically exhibits a dendritic microstructure in its as-cast state, indicating its solidification process. This dendritic structure comprises primary dendrites rich in aluminum, showcasing a face-centered cubic (FCC) crystal structure [35]. Dispersed copper intermetallic phases are observed within the dendritic matrix, primarily accumulating in the interdendritic regions between the primary dendrites, leading to the formation of intermetallic phases such as Al_2Cu or $\theta\text{-Al}_2\text{Cu}$, which are notably enriched in copper content. This segregation phenomenon results from the differential solidification rates experienced by various regions within the alloy during the cooling process [36–38]. The observed dendritic structure not only reflects the thermal history of the solidification process but also significantly influences the mechanical behavior of the AlCu alloy. The interdendritic regions, enriched in copper-based intermetallic phases, contribute to localized strengthening but may also serve as sites for potential stress concentration under mechanical loading. Such regions are susceptible to microvoid formation or cracking under stress [39,40], particularly in the as-cast state where homogeneity is limited. This highlights the importance of post-processing techniques, such as heat treatment, to homogenize these phases' distribution and mitigate potential microstructure weaknesses.

As presented in Fig. 1b, the EDS analysis provides quantitative data on the elemental composition of the as-cast AlCu alloy. The study reveals the predominant presence of Al, constituting approximately 80 wt% of the alloy composition. Si is detected at approximately 14.8 wt%, followed by Cu at 4.3 wt%, and Mg at 0.1 wt%. The EDS mapping presented in Fig. 1c visually illustrates the spatial distribution of the detected elements within the alloy microstructure. Each element is depicted in distinct colors, representing its distribution and concentration across the

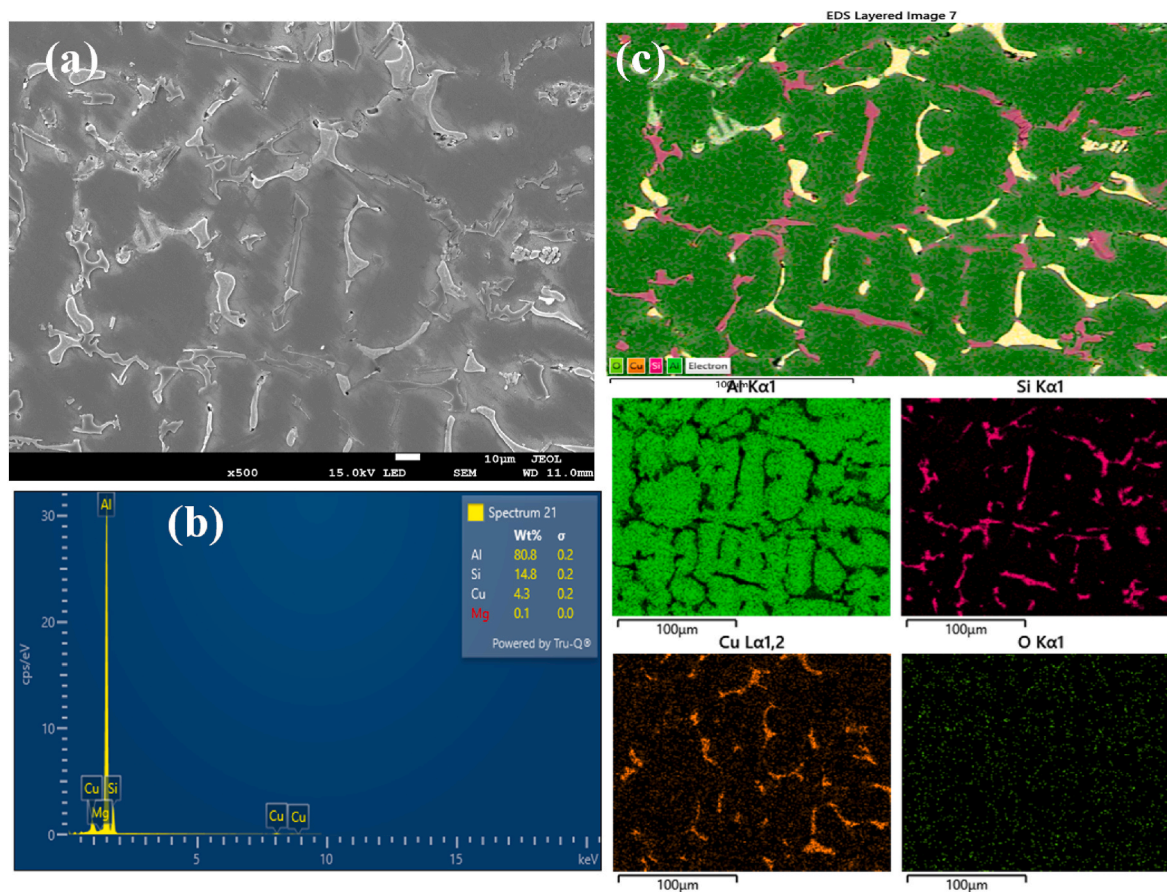


Fig. 1. Microstructure of as-cast AlCu (a) SE image (b) EDS showing elemental composition and (c) EDS mapping showing elemental distribution.

sample surface. This mapping identifies elemental segregation or clustering phenomena within specific alloy regions, characterizing its microstructural features and compositional heterogeneity. The EDS mapping highlights the segregation behavior of alloying elements, which is an intrinsic outcome of the non-equilibrium solidification process in the as-cast state. Aluminum dominates the microstructure, forming the continuous matrix, while Si and Cu show clustering tendencies in specific regions, likely due to their limited solubility in the aluminum matrix at room temperature. This clustering further underscores the role of heat treatment in promoting elemental diffusion and equilibrium phase distribution, which can enhance the composite's overall mechanical performance and corrosion resistance.

The microstructures depicted in Fig. 2 illustrates the effect of incorporating SiC particles into the AlCu alloy matrix. With the addition of SiC, notable changes in the microstructural morphology and distribution of phases are observed. In the micrograph, SiC particles are dispersed throughout the AlCu matrix, primarily at the grain boundaries, forming a heterogeneous structure. These particles act as strengthening agents within the alloy, effectively hindering dislocation movement and enhancing its mechanical strength and hardness [41]. The distribution of SiC particles at grain boundaries enhances the load transfer between the matrix and the reinforcement and plays a critical role in grain boundary pinning. This pinning effect restricts grain growth during high-temperature processing, leading to a more refined grain structure, which improves strength and ductility. Additionally, the presence of SiC particles introduces mismatch stresses at the particle-matrix interface, which can further impede dislocation motion and contribute to strain hardening under mechanical loading.

The EDS analysis, as shown in Fig. 2b, provides quantitative data on the elemental composition of the SiC-reinforced AlCu composite. The study reveals the predominant presence of Al, constituting

approximately 75.3 wt% of the composite composition. Si is detected at approximately 12.5 wt%, indicating the presence of SiC particles within the matrix. Carbon (C) is also detected at 8.9 wt%, attributed to the SiC particles' carbon content. Other elements such as zinc (Zn), copper (Cu), and oxygen (O) are detected, likely originating from impurities or alloying elements present in the composite material [35,42]. The mapping (Fig. 4.2c) confirms the uniform dispersion of SiC particles throughout the AlCu matrix, highlighting their role as reinforcing agents.

Microstructural analysis using SEM provided valuable insights into the distribution and morphology of stainless steel (SS) particles within the AlCu matrix (Fig. 3a). The micrograph revealed a uniform dispersion of SS particles throughout the matrix, indicating effective incorporation during fabrication. Importantly, no agglomeration of SS particles was observed, ensuring homogeneity and integrity within the composite material. EDS analysis (Fig. 3b) complemented the SEM observations by confirming the composite's elemental composition of both phases. The AlCu phase exhibited characteristic peaks corresponding to Al and Cu, while the SS phase showed peaks associated with Fe, Ni, and Mn. This analysis provided crucial information regarding the presence of alloying elements in each phase, contributing to a comprehensive understanding of the composite's composition. EDS mapping (Fig. 3b) revealed Cu distribution within the AlCu matrix and provided insights into inter-diffusion phenomena occurring at the interface between the AlCu matrix and SS particles. Interdiffusion at this interface can significantly influence the mechanical properties of the composite, including its strength, ductility, and corrosion resistance.

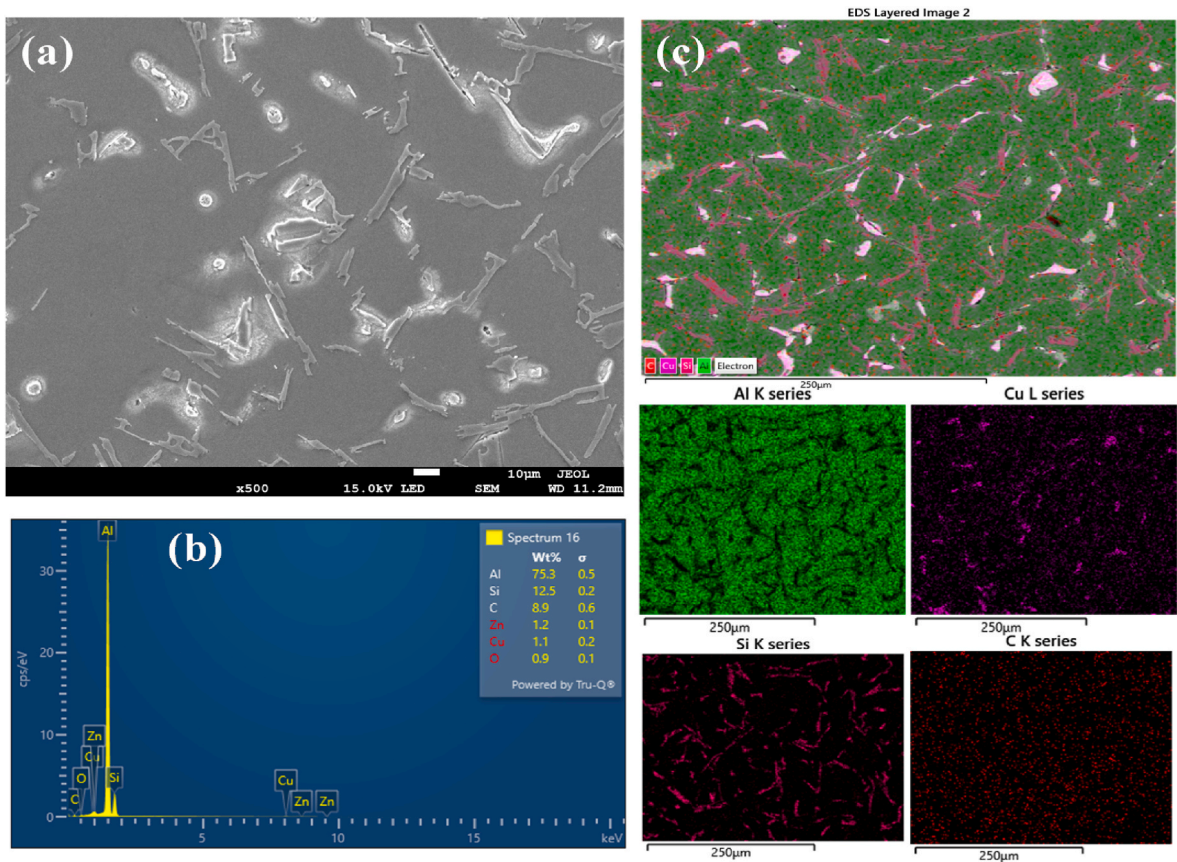


Fig. 2. Microstructure of as-cast AlCu reinforced with SiC (a) SE image (b) EDS showing elemental composition and (c) EDS mapping showing elemental distribution.

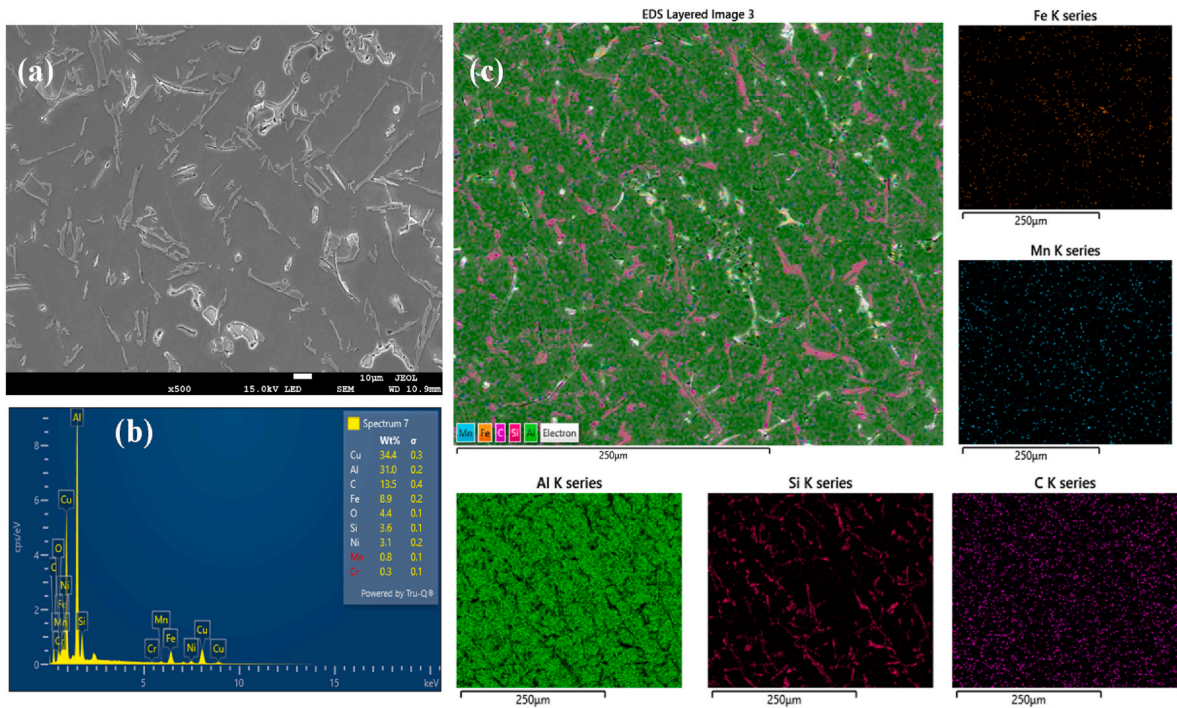


Fig. 3. Microstructure of as-cast AlCu reinforced with Stainless steel (a) SE image (b) EDS showing elemental composition and (c) EDS mapping showing elemental distribution.

3.2. Effect of heat treatment on the microstructure of the SiC, SS reinforced AlCu

Heat treatment was employed to refine the microstructure and enhance the mechanical properties of the AlCu alloy. Fig. 4 provides SEM micrographs and corresponding EDS analyses to elucidate the effects of heat treatment on the AlCu microstructure. Comparing the as-cast (Fig. 4a) and heat-treated (Fig. 4b) specimens reveals notable differences. The as-cast sample exhibits a dendritic microstructure, characteristic of as-cast alloys, with dispersed copper intermetallic phases. Conversely, the heat-treated sample displays potentially larger grains and fine precipitates within the aluminum matrix. The formation of these precipitates during heat treatment is crucial for microstructural evolution. As the alloy undergoes heating to elevated temperatures, the intermetallic phases dissolve, resulting in a supersaturated aluminum solid solution. Upon cooling, excess solute atoms precipitate out of the solution, forming fine precipitates dispersed throughout the AlCu matrix [43]. These precipitates act as strengthening agents, impeding dislocation movement and enhancing mechanical properties. Moreover, the heat treatment influences the grain structure, with the as-cast sample typically exhibiting a finer grain structure due to rapid solidification during casting [9]. In the EDS analysis, the as-cast sample (Fig. 4a1) primarily shows Al, Si, Cu, and Mg. However, the heat-treated sample (Fig. 4b1) also detects C and O. The presence of carbon may be due to carbide precipitates formed during heating or environmental contamination. Oxygen is likely introduced through oxide formation on the alloy surface during heat treatment, which contributes to the overall elemental composition observed in the EDS analysis.

Fig. 5 illustrates the impact of heat treatment on the microstructure of AlCu composites reinforced with SiC, as shown through SEM and EDS analyses. Heat treatment enhances microstructural refinement and precipitates strengthening phases in the AlCu matrix. Specifically, recrystallization during solutionizing exposes SiC particles previously located at grain boundaries, increasing their surface area and interaction

with the matrix. This results in a refined microstructure with dispersed Al_2Cu precipitates and uniformly distributed SiC particles, which improve strength, toughness, and thermal stability by hindering dislocation movement [44]. EDS analyses (Fig. 5a1 & a2) reveal that in the as-cast state, the composition is approximately 75.3 % aluminum, 1.1 % copper, 12.5 % silicon, and 8.9 % carbon. After heat treatment, aluminum decreases to 73.2 %, copper to 1 %, silicon increases to 13.2 %, and carbon rises to 10.7 %. These changes reflect dynamic transformations during heat treatment, with reduced aluminum indicating its role in forming intermetallic phases and carbides, while increased silicon and carbon suggest their involvement in precipitate formation, contributing to enhanced mechanical properties.

In the as-cast state (Fig. 6a), the microstructure displays coarse stainless steel particles dispersed within the AlCu matrix. The EDS analysis (Fig. 6a1) shows elements such as Al, Cu, Si, and Fe, with Al and Cu being predominant. Carbon (13.5 wt%) and oxygen (6.1 wt%) indicate some contamination or initial oxide formation. Upon heat treatment (Fig. 6b), the microstructure reveals significant refinement, with the stainless steel particles appearing more uniformly distributed and better integrated into the matrix. The heat treatment likely involved solutionizing, which dissolves intermetallic phases and promotes the formation of a homogeneous solid solution, followed by controlled cooling that leads to the reprecipitation of phases [45]. This process enhances the interaction between the stainless steel particles and the aluminum matrix, promoting better mechanical properties. The EDS analysis of the heat-treated sample (Fig. 6b1) shows an increase in aluminum content to 48.4 wt%, a decrease in copper to 15.4 wt%, and adjustments in other elements like Si and Fe. The reduction in copper content and changes in other elements reflect diffusion processes and phase transformations during heat treatment.

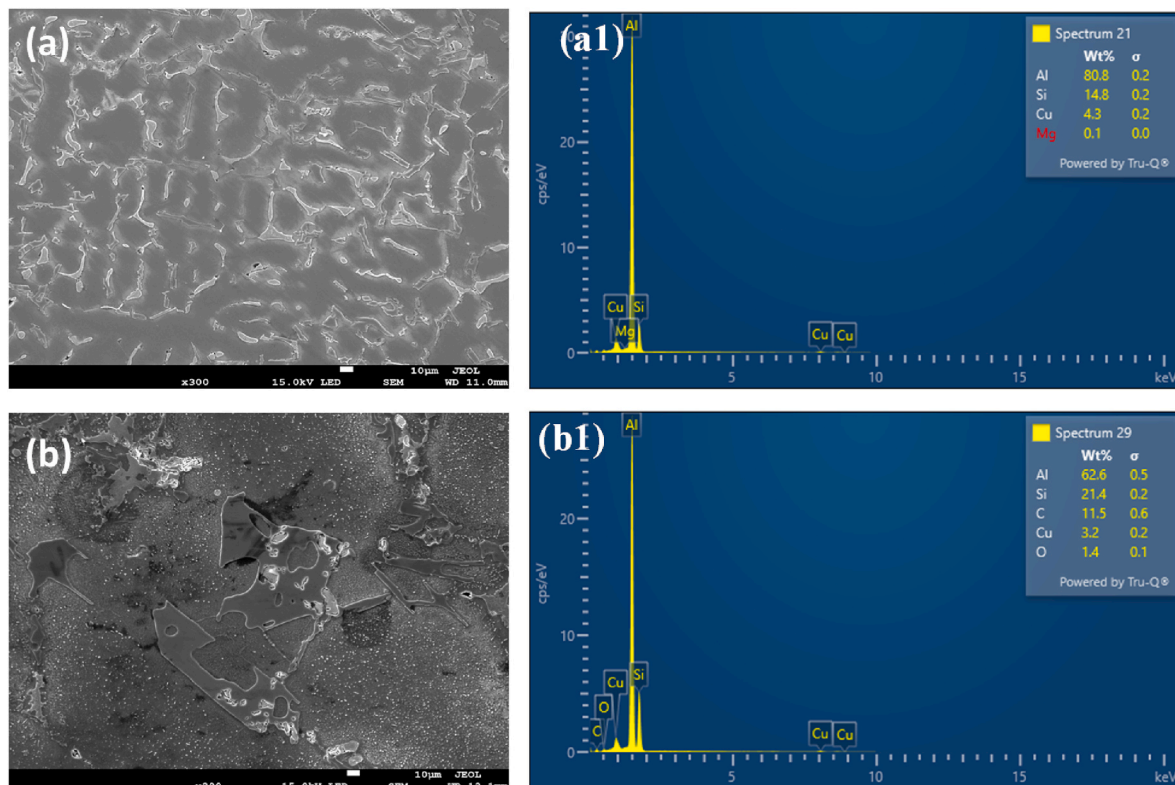


Fig. 4. SEM micrographs paired with corresponding EDS analyses depicting the microstructural evolution of (a) as-cast and (b) heat-treated Al-Cu specimens.

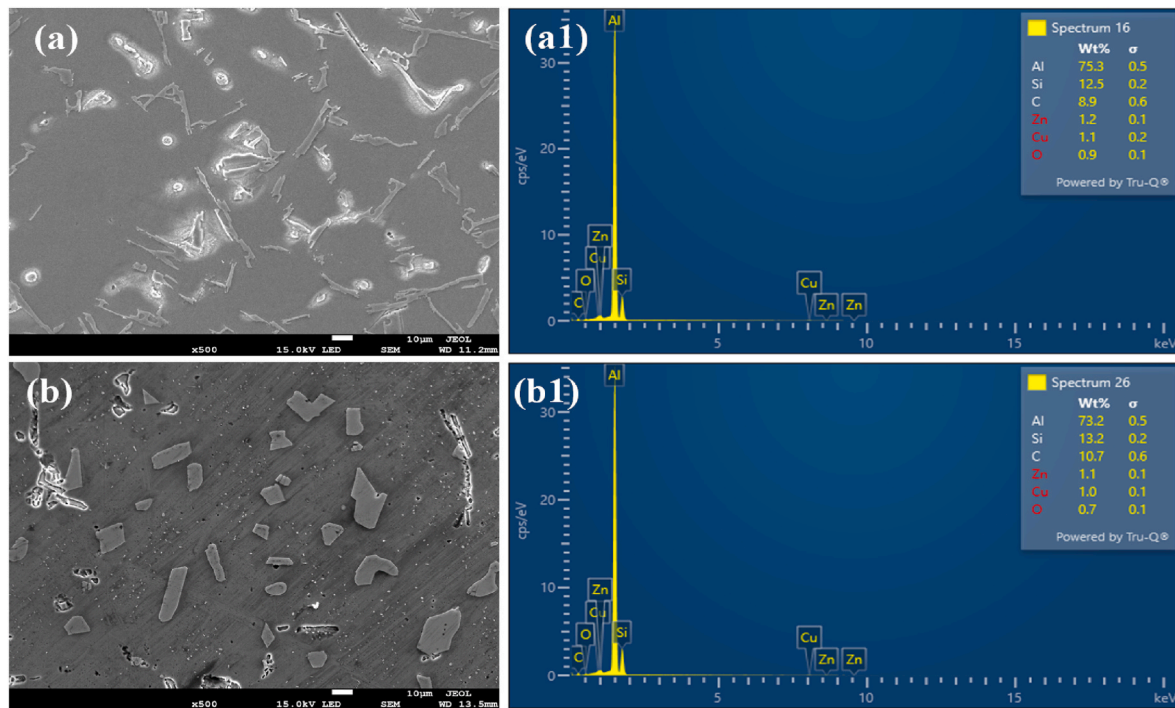


Fig. 5. SEM micrographs paired with corresponding EDS analyses depicting the microstructural evolution of (a) as-cast and (b) heat-treated Al-Cu-SiC specimens.

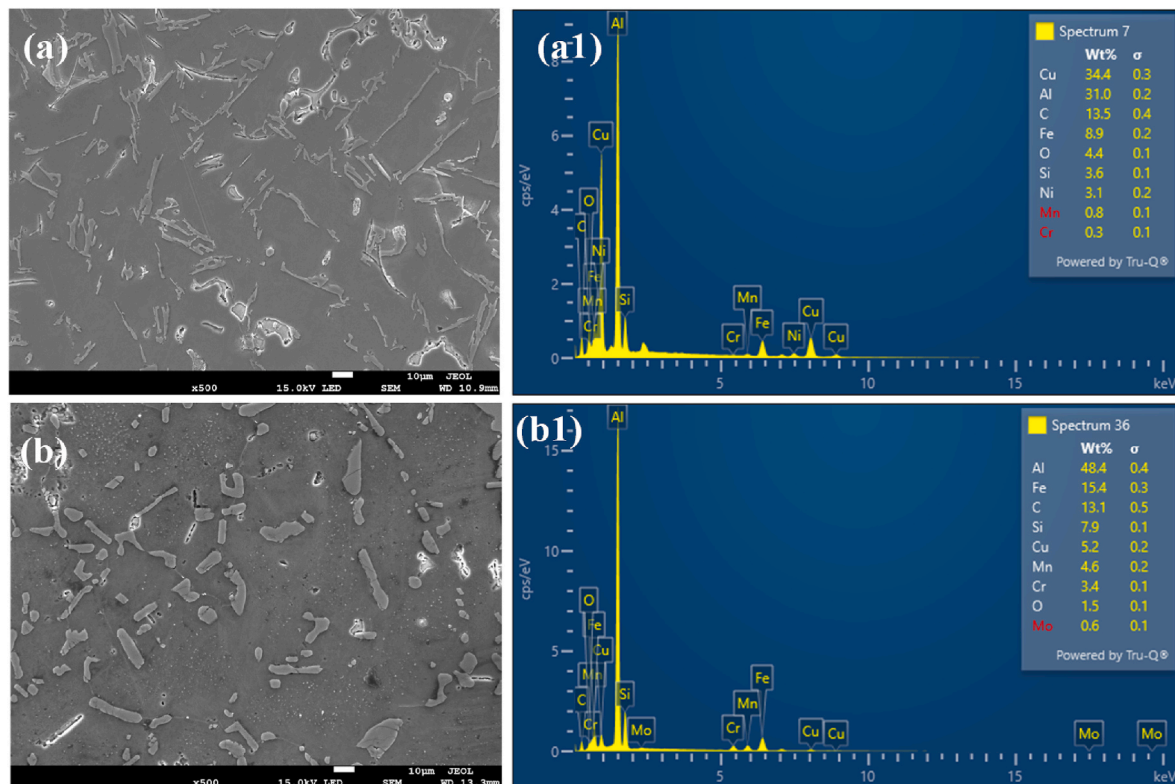


Fig. 6. SEM micrographs paired with corresponding EDS analyses, depicting the microstructural evolution of (a) as-cast and (b) heat-treated Al-Cu-SS specimens.

3.3. Effect of SiC, stainless-steel addition, and heat treatment on load-carrying capacity of AlCu

Fig. 7 presents the nanoindentation profiles of as-cast (a) and heat-treated (b) AlCu, AlCuSS, AlCuSiC, and AlCuSiCSS composites. The

loading and unloading curves highlight the effect of single and combined additions of SiC and SS particles on the mechanical properties of these materials. In the as-cast state (Fig. 7a), adding SiC and SS particles significantly affects the loading and unloading behavior. AlCuSiC and AlCuSiCSS composites show steeper loading curves than the AlCu and

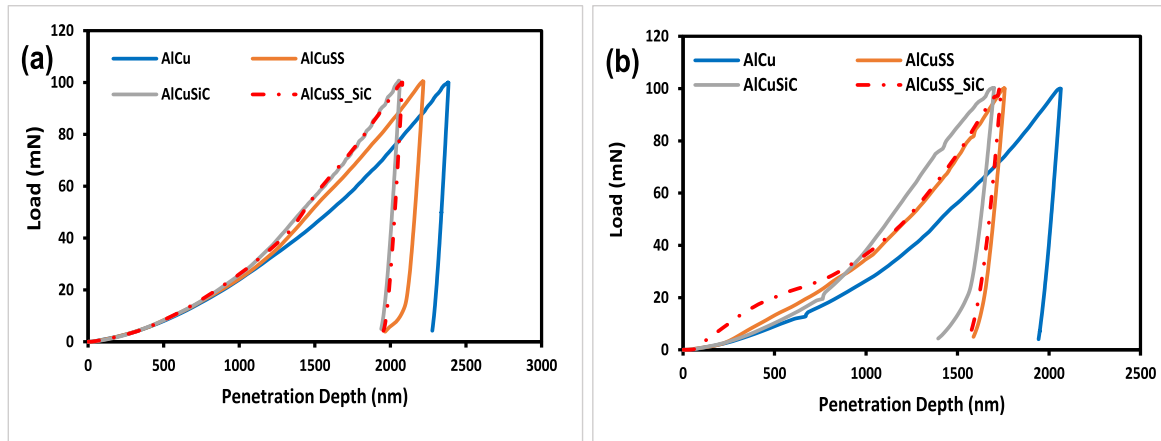


Fig. 7. The nanoindentation profile of (a) as cast and (b) heat treated AlCu, AlCuSS, AlCuSiC, and AlCuSiCSS.

AlCuSS, indicating higher resistance to deformation and superior load-carrying capacity. The SiC particles, being hard and stiff, enhance the material's hardness by impeding dislocation movement. SS particles also contribute to this effect but to a lesser extent due to their relatively softer nature compared to SiC. Upon unloading, the curves for AlCuSiC and AlCuSiCSS composites exhibit less elastic recovery compared to AlCu and AlCuSS, suggesting a more pronounced plastic deformation in the reinforced composites. This indicates that the single and combined addition of SiC and SS enhances the hardness and load-carrying capacity but also influences the material's ability to recover elastically after deformation [28].

The heat-treated state (Fig. 7b) reveals further changes. Heat treatment enhances the mechanical properties of all composites, but the effect is more pronounced in those containing SiC and SS. The loading

curves for AlCuSiC and AlCuSiCSS are even steeper than in the as-cast state, reflecting further increased hardness and load-carrying capacity. The heat treatment promotes the dissolution and subsequent precipitation of strengthening phases, refining the microstructure and enhancing the interaction between the reinforcing particles and the matrix. For AlCuSS, the heat treatment results in a noticeable increase in load-carrying capacity, likely due to the formation of fine precipitates and improved particle-matrix bonding. The combined addition of SiC and SS in AlCuSiCSS shows the most significant improvement, with the steepest loading curve and highest load-carrying capacity among all composites.

Fig. 8 illustrates the nanoindentation profiles of as-cast and heat-treated AlCu, AlCuSS, AlCuSiC, and AlCuSiCSS composites, revealing the mechanical property enhancements post-heat treatment. Across all samples, heat-treated specimens show lower indentation depths,

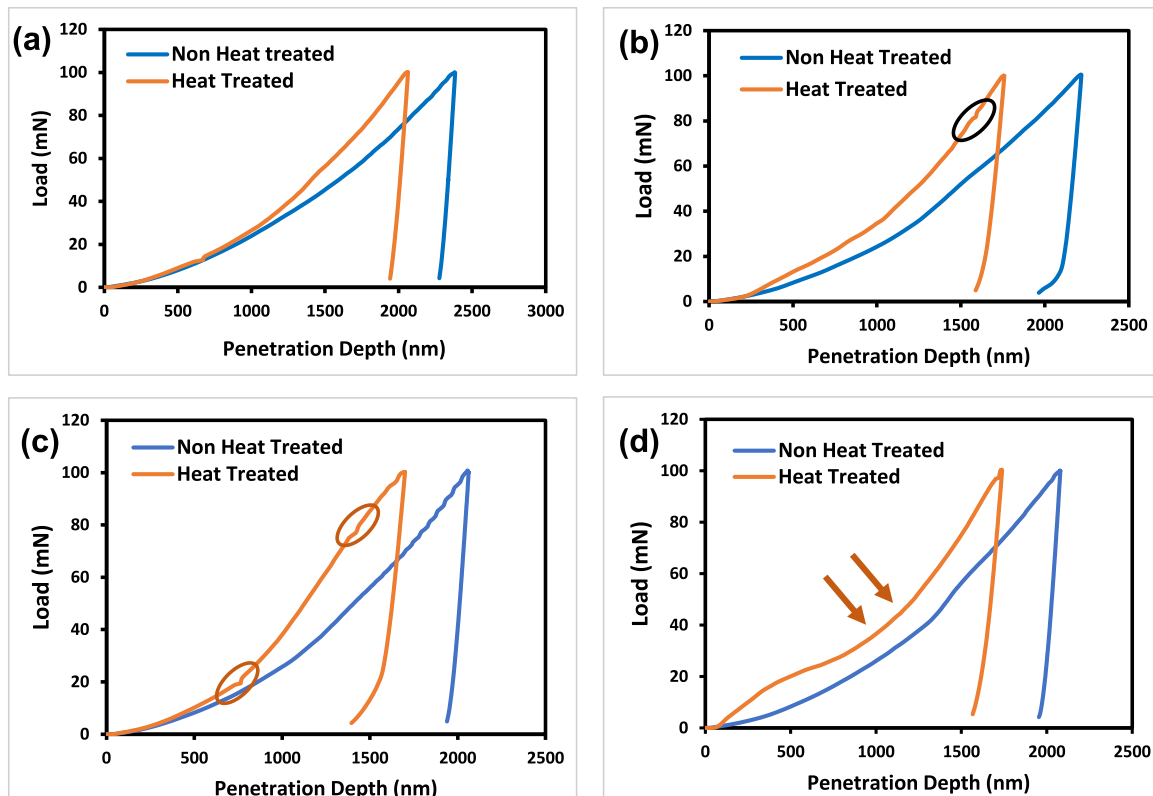


Fig. 8. Variation of Loading and unloading curves for as cast and heat treated of the (a) AlCu (b) AlCuSS (c) AlCuSiC (d) AlCuSSSiC.

indicating improved load-carrying capacity. Specifically, the indentation depth for AlCu decreases from 2230.45 nm (as-cast) to 1900.18 nm (heat-treated). Similar trends are observed for AlCuSS, AlCuSiC, and AlCuSSSiC, with each composite exhibiting reduced indentation depths after heat treatment. The reduction in indentation depth post-heat treatment is due to several factors. Heat treatment refines the microstructure and promotes the precipitation of strengthening phases within the aluminum matrix, enhancing resistance to plastic deformation. Additionally, heat treatment mitigates casting defects and impurities, resulting in a more homogeneous microstructure with fewer structural discontinuities. These changes collectively improve the composites' mechanical properties and load-carrying capacity [29,46].

3.4. Effect of reinforcement and heat treatment on hardness and elastic modulus of AlCu

The hardness analysis (Fig. 9a) reveals the significant impact of SiC and SS reinforcements and heat treatment on AlCu composites. In the as-cast state, AlCuSiC demonstrates the highest hardness (1.51 GPa), attributed to the hard, dispersed SiC particles that impede dislocation movement and grain growth within the AlCu matrix. AlCuSS shows a moderate increase in hardness compared to the base AlCu alloy, due to the hindrance of dislocation movement by stainless steel particles. Upon heat treatment, AlCuSiC maintains its position as the hardest material, underscoring the effectiveness of SiC particles in enhancing hardness. AlCuSS, however, exhibits a more pronounced increase in hardness post-heat treatment, likely due to the formation of strengthening precipitates at the interface between the AlCu matrix and stainless steel particles [47]. The base AlCu alloy also shows a slight increase in hardness after heat treatment, attributed to work hardening during casting and potential strain aging effects. The mechanisms responsible for the significant hardness increase in heat-treated AlCuSiC include solution strengthening and recrystallization, where SiC particles partially dissolve into the AlCu matrix, forming a supersaturated solid solution and precipitating upon cooling as finer dispersoids that fortify the matrix [48]. Thus, adding SiC particles emerges as the most effective strategy for enhancing the hardness of AlCu composites, with heat treatment further augmenting this effect, particularly in AlCuSS.

The analysis of the reduced elastic modulus E_r (Fig. 9b) highlights the influence of SiC and SS additions and heat treatment on AlCu composites in both as-cast and heat-treated conditions. In the as-cast state, the presence of SiC in AlCuSiC and AlCuSSSiC significantly increases the E_r , with AlCuSSSiC showing the highest value (92.18 GPa). This enhancement is due to the stiff and incompressible nature of SiC particles, which effectively restrict the elastic deformation of the AlCu matrix by acting as obstacles to dislocation movement, thereby enhancing the overall stiffness of the composite. However, after heat treatment, the trend in E_r becomes less straightforward. While AlCuSS shows the highest E_r (88.25

GPa) post-heat treatment, AlCuSiC and AlCuSSSiC exhibit a decrease in E_r compared to their as-cast counterparts. This reduction could be attributed to thermal expansion mismatch between the SiC particles and the AlCu matrix, leading to residual stresses, reduced stiffness, and possible microstructural changes such as grain growth or interfacial reactions. In contrast, AlCu and AlCuSS experience an increase in E_r after heat treatment, suggesting that beneficial effects like grain refinement or precipitation hardening outweigh any potential drawbacks. This indicates that while SiC reinforcement initially enhances stiffness in the as-cast state, the effects of heat treatment on microstructure and interfacial interactions can lead to variations in E_r among different composite formulations.

Fig. 10a illustrates the ratio of E/H for AlCu composites in both the as-cast and heat-treated conditions, providing insights into the elastic-to-plastic deformation characteristics of these materials. A higher E/H ratio indicates that a material can sustain more elastic deformation relative to plastic deformation, which is desirable for applications requiring high toughness and resilience. The as-cast AlCu composite shows the highest E/H ratio at approximately 112.48 GPa, indicating its superior ability to undergo elastic deformation. This is followed by AlCu reinforced with stainless steel (SS) particles at about 89.19 GPa, AlCu with silicon carbide (SiC) particles at 89.74 GPa, and AlCu with a combination of SS and SiC particles at 94.80 GPa. After heat treatment, the E/H ratio decreases for all composites, with the most significant reduction observed in the AlCuSiC composite, where the ratio drops to around 53.96 GPa. This decline suggests that heat treatment enhances hardness, likely due to precipitation hardening and microstructural refinement, but also reduces the capacity for elastic deformation relative to plastic deformation. These results align with [49], indicating that adding hard particles like SiC increases hardness more significantly than the elastic modulus, leading to a lower E/H ratio. The decrease in E/H after heat treatment across all samples highlights a trade-off between hardness and elasticity, crucial for optimizing mechanical performance in composite materials for applications that demand both high strength and toughness.

Yield pressure, represented by H^3/E^2 , is a parameter used to describe the resistance of materials to plastic deformation under an applied load during nanoindentation testing. This metric is crucial for evaluating composite materials' structural integrity and performance. In Fig. 10b, the yield pressure profiles of the AlCu composites reveal distinct trends influenced by the addition of SiC, SS particles, and heat treatment. The incorporation of SiC particles significantly enhances the resistance to plastic deformation, resulting in the AlCuSiC composites exhibiting the highest yield pressure. This enhancement is due to the high hardness and stiffness of SiC, which effectively impedes dislocation movement and grain growth within the AlCu matrix. The addition of stainless-steel particles also improves yield pressure, albeit to a lesser extent than SiC, by providing additional reinforcement within the matrix. Heat

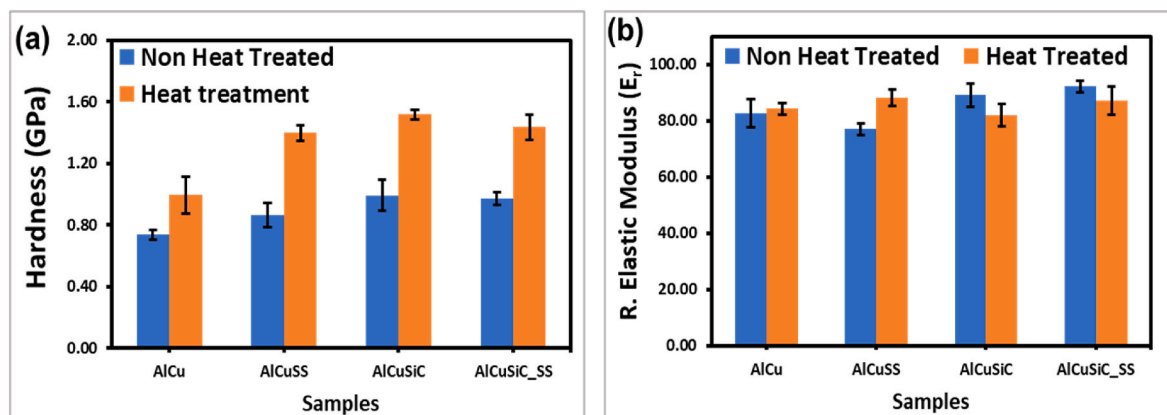


Fig. 9. Variation in (a) hardness property and (b) reduced elastic modulus variation in AlCu composite induced by SiC and SS addition and heat treatment.

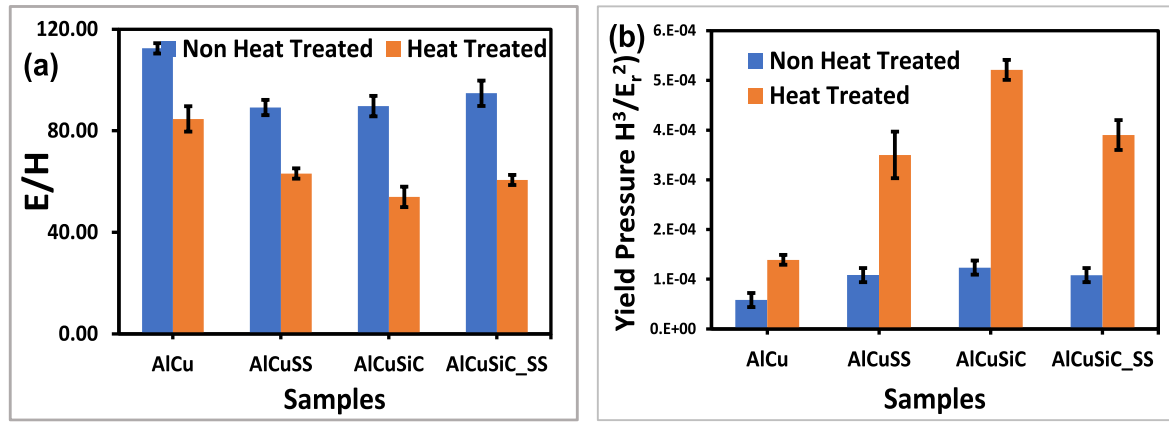


Fig. 10. Variation in (a) elastic-to-plastic deformation characteristics (b) Yield pressure (resistance to plastic deformation) variation in AlCu composite induced by SiC and SS addition and heat treatment.

treatment further increases the yield pressure across all reinforcement types by refining the microstructure and promoting the formation of strengthening precipitates, which hinder dislocation movement and grain boundary sliding [50,51]. It is important to note that H^3/E_r^2 in nanoindentation testing should not be taken as a direct measure of the material's yield stress. This parameter reflects the material's resistance to deformation under indentation and is influenced by factors like indenter tip geometry and strain-hardening behavior. Therefore, while yield pressure offers insights into the composite's resistance to plastic deformation, it does not directly correlate with yield stress obtained from uniaxial tensile tests. This distinction is crucial for accurately interpreting the mechanical properties of composites.

The plasticity index, derived from nanoindentation tests, provides crucial insights into the plastic deformation behavior of materials [52]. Fig. 11a provides insight by illustrating the plasticity index as the ratio of elastic and plastic work done during nanoindentation. This representation quantitatively measures the material's ability to withstand plastic deformation relative to its elastic behavior. Fig. 11b depicts the plasticity index, showcasing the influence of SiC, SS addition, and heat treatment on the plastic deformation tendencies of AlCu composites. AlCuSiC exhibited the lowest plasticity index among all materials in the as-cast condition. This inference arises from hard, dispersed SiC particles impeding plastic deformation within the AlCu matrix. The stiff SiC particles act as formidable obstacles for dislocations, hindering their movement and restraining the material's propensity for plastic flow. Upon heat treatment, all samples exhibit a decrease in plasticity index.

This phenomenon suggests that the heat treatment process induces structural changes within the composites, reducing their plastic deformation tendencies. The reduction in plasticity index post-heat treatment can be attributed to various factors, including grain refinement, precipitation hardening, and alterations in microstructural morphology [53,54]. These structural modifications enhance the material's plastic deformation resistance, lowering the plasticity index across all samples.

The correlation between the E/H ratio and the plasticity index shows that the E/H ratio also tends to rise as the plasticity index increases. This indicates that composites with a higher plasticity index (AlCu), exhibit greater elastic recovery relative to hardness, while those with a lower plasticity index (reinforced with SS and SiC), show a lower E/H ratio, reflecting increased resistance to plastic deformation.

3.5. Correlation between mechanical properties and microstructure

The observed mechanical properties of the AlCu composites, including enhanced hardness, wear resistance, and reduced plasticity index, can be directly correlated with the microstructural features revealed in the SEM images. The uniform dispersion of SiC and SS particles within the AlCu matrix, as shown in the SEM micrographs, contributes to effective load transfer and impedes dislocation motion, leading to improved hardness and anti-wear properties. Additionally, the formation of fine precipitates and improved particle-matrix bonding after heat treatment, evident from the refined microstructure, enhances the material's resistance to plastic deformation. These strengthening

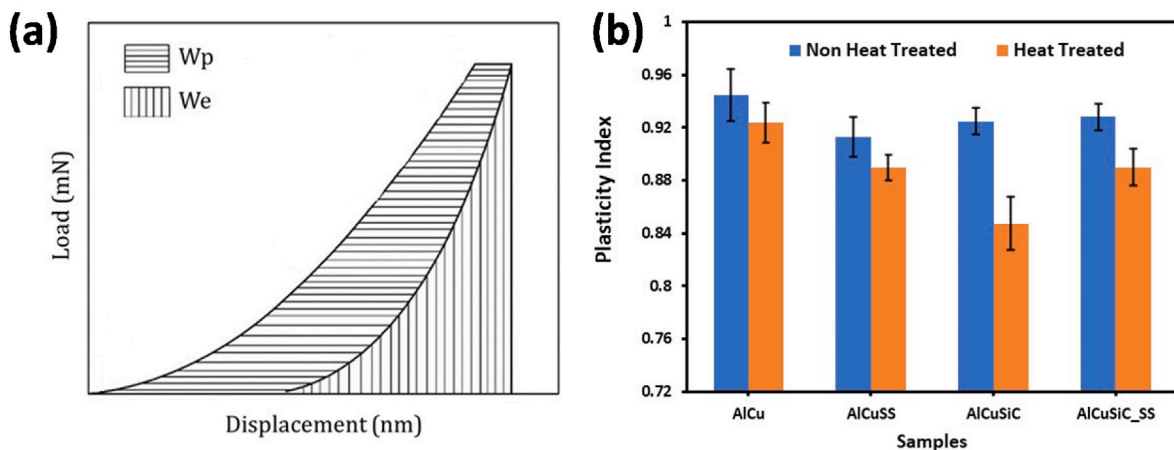


Fig. 11. (a) Plasticity index illustrates the elastic and plastic work ratio during nanoindentation. (b) Variation in plasticity index of the AlCu composites induced by SiC and SS addition and heat treatment.

effects align with Orowan strengthening and grain boundary pinning mechanisms, where dispersed particles act as obstacles to dislocation glide, reducing plasticity and increasing yield pressure. Furthermore, residual stresses and microstructural changes due to particle interactions and heat treatment variations influence the elastic modulus, as stiffer reinforcement phases limit matrix deformation. These correlations underscore the critical role of microstructural refinement and particle-matrix interactions in dictating the mechanical behavior of the composites.

4. Conclusion

The study demonstrates the significant impact of SiC and SS particle reinforcement, combined with heat treatment, on the microstructural and nanomechanical properties of AlCu composites. Heat treatment refined the microstructure, forming fine precipitates and improving particle-matrix bonding, which enhanced hardness, reduced indentation depths, and improved load-carrying capacity and wear resistance. SiC reinforcement increased the elastic modulus in the as-cast state, though heat treatment caused variations due to residual stresses and microstructural changes. SiC-reinforced composites exhibited the highest anti-wear resistance, further enhanced by heat treatment due to the hard and stiff nature of SiC particles. Heat-treated composites with SiC and SS reinforcements demonstrated higher yield pressure and a reduced plasticity index, reflecting improved resistance to plastic deformation. Challenges of uniform dispersion and clustering of reinforcement particles during stir casting were addressed through preheating and controlled stirring, and undesirable phase transformations during heat treatment were avoided through precise temperature control. Future studies should employ advanced in situ characterization techniques to understand the structure and deformation mechanisms better.

CRediT authorship contribution statement

Samuel Ranti Oke: Writing – original draft, Formal analysis, Conceptualization. **Gabriel Elojo Ugwu:** Writing – review & editing, Methodology. **Nthabiseng Maledi:** Funding acquisition. **Oluwasegun Eso Falodun:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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