DEVELOPMENT OF SPARK PLASMA SINTERED ALUMINIUM-NICKEL-COPPER (I) OXIDE METAL MATRIX COMPOSITE

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Received 30 May 2026
Accepted 20 July 2026
DOI: 10.59957/jctm.v61.i5.2026.12

ABSTRACT

Effects of varied contents of copper (I) oxide (Cu_2O) and heat treatment on the phases and properties of spark plasma sintered Al-Ni-Cu_2O metal matrix composite was studied. The raw materials used were aluminium (Al) powder, nickel (Ni) powder and copper (I) oxide Cu_2O powder. Samples were made by blending pre-calculated amounts of raw materials in tubular mixer at a speed of 72 revolutions min^{-1}. The homogenous mixture was sintered at 550°C at a sintering pressure of 40 MPa, heating rate of 50°C min^{-1} and holding time of 10 min in a graphite die of 20 mm. The phases in the sintered samples were characterized using X-ray diffractometry analysis (XRD). Addition of Cu_2O to the samples progressively improved on densification of the samples with increased Cu_2O contents. Hardness of the sintered samples was also investigated using Brinell hardness tester. It was observed that the phases which evolved in the sample were influenced by Cu_2O content. The presence of 12 % Cu_2O in sample C aided development of intermetallic phases within the sample. Presence of 16 % Cu_2O in the binary alloy led to development of more intermetallic phases in the sample. Additionally, the hardness and tensile strength notably improved, reaching approximately 107 HB for hardness and 369 MPa for tensile strength particularly with a 12 % copper addition after heat treatment at 260°C. It was concluded that the formation of intermetallic phases within the composite matrix is responsible for the improved hardness and tensile property of the samples.

Keywords: metal-matrix composite, microstructure, hardness, intermetallic phases, spark plasma.

INTRODUCTION

Metal-matrix composites are gaining prominence as promising structural materials, primarily owing to their lightweight characteristics, impressive strength, and exceptional resistance to elevated temperatures. These attributes have captured substantial interest and adoption across a range of industries, including aerospace, electronics, biotechnology, nanotechnology, high-temperature industrial applications [1 - 3].

The application of Metal-Matrix Composites derived from micro and nano powders holds a key motive: the exploitation of their enriched mechanical and physical characteristics. The reduction in precursor material size to the nano-scale has yielded substantial enhancements in the mechanical and physical traits of nano-materials. As particle size diminishes to the nano scale, properties like diffusivity, strength, specific heat, electrical conductivity, and resistivity can be notably improved. The collaborative weight-bearing ability of the matrix and reinforcement phases enables Metal Matrix Composites to endure greater loads and tensile stresses [4 - 6].

These composites serve various applications, covering fields such as electrical and magnetic applications, high-sensitivity sensors, hydrogen storage, biotechnology, semiconducting properties, kinematic energy penetrators, high-energy density batteries, satellite manufacturing, and robust medical implants, addition to their role in aerospace, defence, and automotive industries. For the fabrication of MMCs, two primary methods exist: solid-state processing route (powder metallurgy) and liquid-state processing (casting methods) route, each carrying its own set of merits and drawbacks. Powder metallurgy routes, more frequently employed, serve as the preferred route for synthesizing MMCs [7].

Processing and fabricating nano-materials on the nano-scale give rise to various challenges. These include an amplified specific surface area, leading to pronounced particle interactions that can result in aggregation and agglomeration problems. Elevated temperatures during processing can expedite grain growth, potentially causing modifications in material attributes. Consequently, the precise management of microstructure during processing and consolidation holds paramount importance in nanomaterial production, as their distinctive properties emanate from their fine composition and diminutive grain dimensions [8 - 12].

Another obstacle related to nano-materials pertains to porosity, which can exert an influence on their mechanical characteristics. Electrode position techniques can be utilized to fabricate materials devoid of pores yet concerns about contamination might negatively impact mechanical properties. The abundance of grain boundaries found in nano-materials, in contrast to other microstructures, emerges as a pivotal factor in governing mechanical properties due to the significant role played by these interfaces. Recent strides in aluminium-based (Al-based) and copper-based (Cu-based) Metal Matrix Composites (MMCs) revealed substantial potential, driven by advancements in manufacturing methods and tailored applications [13].

Their extraordinary physical and mechanical attributes, characterized by an impressive strength-to-mass ratio, position them as highly appropriate for addressing the lightweight requisites in the realms of automotive and aerospace industries. An array of techniques has been harnessed to craft components tailored to meet the demands of the commercial market. Within the automotive sector, a surging need for materials that are not only lightweight but also fuel-efficient and endowed with high strength has spurred the advancement of sophisticated composites. Within the realm of Metal Matrix Composites (MMCs), those constructed from aluminium matrices (AMCs) have garnered considerable attention across both academic exploration and industrial investigation. AMCs offer a blend of lightweight qualities and superior performance, which manifests as augmented strength, stiffness, compressive strength, enhanced wear resistance, reduced thermal conductivity, and heightened dimensional stability [14 - 17].

While aluminium and copper matrices can be made perfect with micro or nanoparticles of assorted dimensions and shapes to amplify their properties and microstructural attributes, the fabrication of such composites presents challenges, particularly in ensuring an even dispersion and as well as the interface connection for varying volume proportions of reinforcement material. Inter-particle spacing between the reinforcement materials significantly influences the strength of these composites. The correlation involving particle size, fractional volume of reinforcing particles and the inter-particle spacing gap has been meticulously examined by Kellie and Wood [18]. Thus, furnishing insights into the manipulation of inter-particle spacing through diverse volume fractions and size distributions.

Among the assortment of metallic matrices, aluminium shines by virtue of its lightweight essence, ecological compatibility, lower processing melting point, and the ameliorated mechanical traits it possesses. Aluminium matrix composites augmented with rigid ceramic particles present a personalized spectrum of properties apt for specific applications.

These materials showcase impressive formability and resistance to wear, making them a fitting choice for high-temperature scenarios, as exemplified by copper matrices reinforced with alumina particles [19 - 23].

EXPERIMENTAL

First stage

Homogenization and solution treatment - The composite specimens underwent gradual heating in an electric furnace up to 500°C at a rate of 3°C min^{-1}. They were maintained at this temperature for one hour before being gradually cooled within the furnace. Subsequently, a solution treatment was administered at 450°C for duration of 15 min, followed by rapid quenching in water to ambient temperature.

Second stage

The specimens underwent heat treatment within an electric furnace at distinct temperatures of 200°C, 220°C, 240°C, and 260°C. The samples were gradually raised from room temperature to the designated heat treatment temperature at a rate of 3°C min^{-1}. Once the target heat treatment temperature was reached, the specimens were held at that temperature for one hour. Subsequently, the samples were allowed to naturally cool in the ambient air. Following the heat treatment process, each treated sample was subjected to experimental testing.

The raw materials used were aluminium (Al) Powder, nickel (Ni) powder and copper (I) oxide (Cu_2O) powder. Specimens were readied by mixing predetermined quantities of raw materials in a Tubular mixer, operating at a velocity of 72 revolutions per min. The particle size of the Al-Ni powder was approximately 100 μm, and it was sourced from South Africa. Cu_2O sourced from Krish Met in Chennai, South Africa, with a particle size of 10 μm and a density of 4.52 g cm^{-3} was utilized to strengthen the matrix.

Preparation of the composites

The aluminium and nickel powders were mixed thoroughly for 8 h to ensure homogeneity. Different proportions of Cu_2O (0, 4, 8, 12, 16, and 20 wt. %) were introduced into the blend. The sintering procedure was conducted using a Spark Plasma Sintering (SPS) system, specifically the DR. Sinter 21050 SPS furnace. Sintering took place in an argon atmosphere at a temperature of 550°C, with a heating rate of 50°C per min. Throughout the entire heating and sintering process, the powder compact underwent uniaxial pressure of 40 MPa.

Table 1. The composition of produced samples used for the experimental investigation.

Samples	Aluminium	Nickel	Cu_2O
A	94.30	5.70	0
B	90.53	5.47	4
C	86.76	5.24	8
D	82.98	5.02	12
E	79.21	4.79	16
F	75.44	4.56	20

The composition of the developed composite is presented in Table 1.

RESULTS AND DISCUSSIONS

Phases and mechanical properties of developed SPS Al-Ni-Cu_2o MMCs

Fig. 1 shows the SEM micrographs of the developed SPS Al-Ni-Cu_2O MMCs. These micrographs provide visual information about the microstructure of the composite. Additionally, the EDS element analysis provides information about the elemental composition of the composite in these micrographs. For sample of eutectic alloy (0 % Cu_2O), it consists of a eutectic structure comprising short, round nickel constituents that appear at the grain boundaries of the α-phase aluminium matrix [24, 25]. The major peaks observed were aluminium (Al), aluminium nickel (Al_3Ni_2). Additionally, other phase detected include nickel aluminate (Ni_2Al_3) which were revealed by the XRD pattern in Fig. 1a. The eutectic alloy hardness is observed to be 43 HB, while the tensile strength of 155 MPa. This agrees with the findings by Maiti and Chakraborty [26]. They reported on the development of in-situ Al-Si/$CuAl_2$ metal matrix composites as well as the in-situ synthesizing of Al_3Ni for fabrication of intermetallic-reinforced aluminium alloy composites by friction stir processing using powdered aluminium and nickel.

Effect of Cu_2o on the phases developed

4 % Cu_2O

The presence of Cu_2O as reinforcement in the matrix of eutectic binary alloy form a new fine inter-dendritic structure distributed at the grain boundaries of the

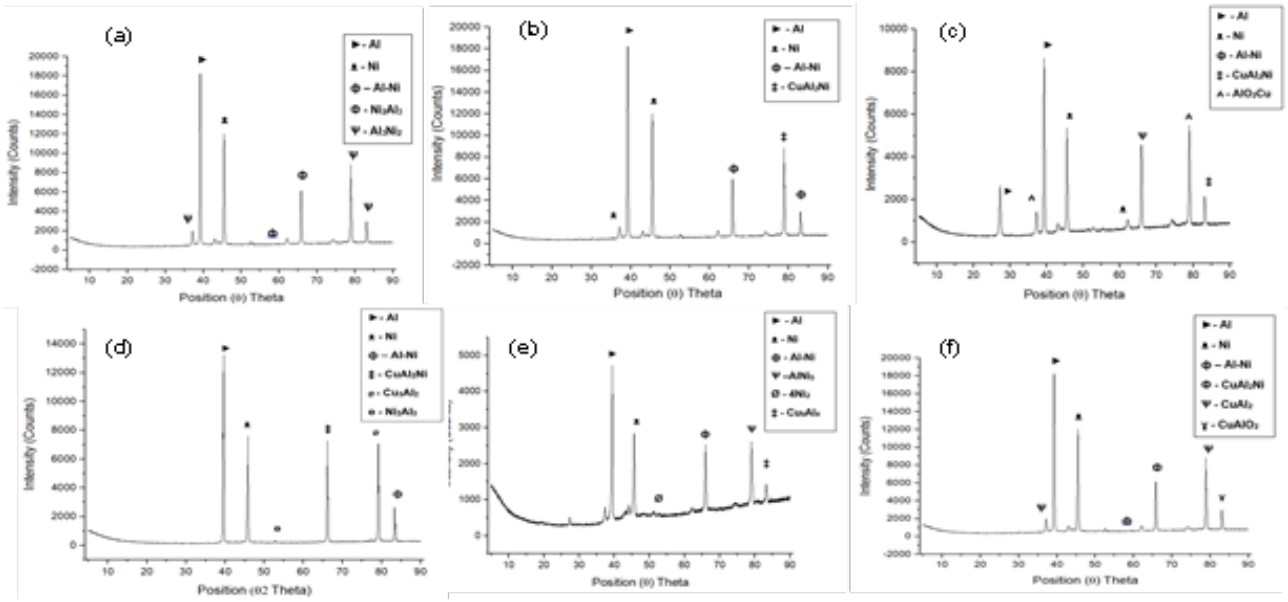

Fig. 1. XRD patterns obtained for the composite at 0, 4, 8, 16, 20 Cu_2O wt. % composition.

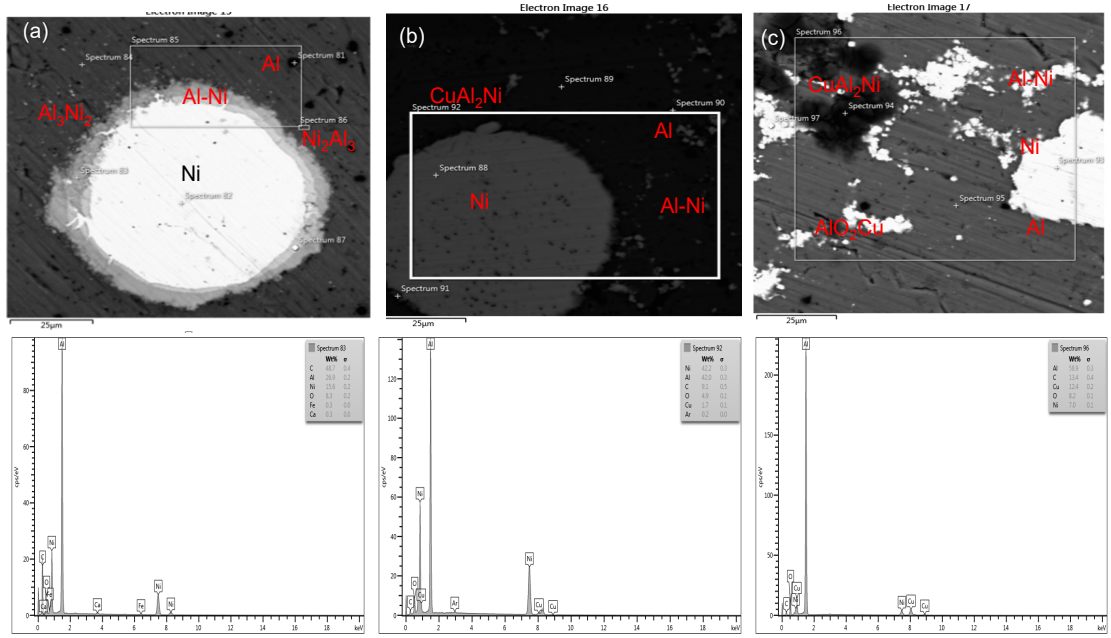

Fig. 2. SEM micrographs of the formed composite obtained at (a) 0 % (b) 4 % (c) 8 % Cu_2O with EDS analysis.

α-phase, in addition to the regular short, round nickel dendrites as the Al-Ni matrix structure as presented by the SEM/EDS image in Fig. 2b. The nickel constituents have transformed from short needles to a more fine and rounded morphology. Furthermore, the added copper (I) oxide (Cu_2O) is also present at the grain boundaries of the aluminium α-grains. The intermetallic compounds that formed indicate that the Cu_2O particles have reacted with the aluminium-nickel matrix, forming $CuAl_2Ni$ intermetallic confirmed by XRD analysis in Fig. 1b. To clarify the appearance of these new fine inter-dendrites, an SEM image and EDS element mapping are provided in Fig. 2. The mapping of the SEM micrograph reveals that the nickel constituents have transformed from short needles to a more fine and rounded morphology. Furthermore, the added copper is also present at the grain boundaries of the aluminium α-grains. The atomic concentrations of copper and aluminium-nickel

estimated from the EDS spectra in this phase are approximately 31 % and 65 %, respectively. The data suggests that the presence of impurities in the aluminium matrix influences the phases that form during the heat treatment process agreed with Aramide et al [11].

8 % Cu_2O

As presented in Fig. 2c, at the grain boundaries of aluminium, intermetallics can be observed. The particles dispersed within the matrix are predominantly round and fine, consisting of copper particles. Numerous dendrites of nickel (Ni) and copper (Cu) are visible as presented in Fig. 2c. The structure consists of mixtures of Al, Al-Ni eutectic, $CuAl_2$, AlO_2Cu intermetallics confirmed by XRD analysis in Fig. 2c. The high intensities of the Al and Al-Ni eutectic peaks mainly arise from the matrix. The presence of Cu peaks in the EDS pattern indicates the presence of unreacted Cu_2O in the matrix. When increasing the Cu_2O powder to 8 %, the particles tend to cluster in relatively large patches within the Al grains. Many bulk Cu_2O areas or cavities were detected within the matrix. These findings align with the research by Buraq [12]. He reported on the development of in-situ Al-Si/$CuAl_2$ metal matrix composites in which Cu_2O particles reacted with the Al matrix, forming typical eutectic $CuAl_2$ intermetallics. This suggests that the fine particles primarily consist of copper, while the eutectic phase corresponds to the $CuAl_2Ni$ intermetallic compound. Observations from the heat-treated samples indicate that as the heat treatment temperature increases, the mechanical properties are enhanced, resulting in an increase in hardness and a modest increase in tensile strength. These findings demonstrate that the composite remains suitable for high-temperature applications [28, 29].

12 % Cu_2O

In comparison with the binary eutectic alloy, the structure exhibits a new fine inter-dendritic structure distributed at the grain boundaries of the α-phase, in addition to the regular short, round nickel dendrites. To clarify the appearance of these new fine inter-dendrites, an SEM image and EDS element mapping are provided in Fig. 3a. The mapping of the SEM micrograph reveals that the nickel constituents have transformed from short needles to a finer and rounded morphology. Furthermore, the added Copper (I) oxide is also present at the grain boundaries of the aluminum α-grains. The atomic concentrations of copper and aluminum-nickel estimated from the EDS spectra in this phase are approximately 31 % and 65 %, respectively. Cu_2O particles have reacted with the aluminum-nickel matrix, forming $CuAl_2Ni$ intermetallics as shown in XRD analysis in Fig. 1c. Observations from the heat-treated samples indicate that heat treatment has enhanced the mechanical properties, with an increase in hardness and an increase in tensile strength properties. These results indicate

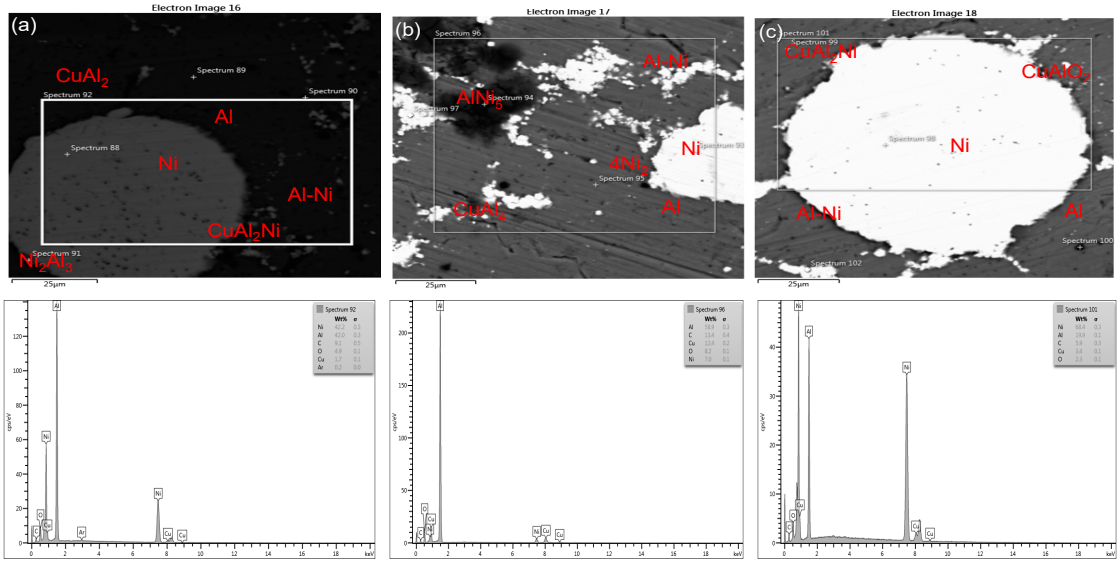

Fig. 3. SEM micrographs of the formed composite obtained at (a) 12 % (b) 16 % (c) 20 % Cu_2O with EDS analysis.

that the composite is suitable for high-temperature applications. These findings align with that of Aramide [13]. He reported on the synthesis and Properties of Advanced Aluminium and Copper Based Metal Matrix Composites.

16 % Cu_2O

The inclusion of Cu_2O as reinforcement promoted the reaction of the Cu_2O particles with the Al matrix forming the $CuAl_2$ intermetallic illustrated by XRD analysis in Fig. 1d. The reinforcement caused shape perturbations and spheroidization of the eutectic constituents, including Al-Ni. The eutectic phases coarsened and precipitated at the grain boundaries of the larger Al grains. Numerous dendrites of nickel (Ni) and copper (Cu) are visible. EDS analysis shown in Fig. 3b reveals that the atomic concentration of Cu in the round particles and the eutectic phase is approximately 93 % and 68 %, respectively. The high intensities of the Al and Al-Ni eutectic peaks mainly arise from the matrix. The presence of Cu peaks in the EDS pattern indicates the presence of unreacted Cu in the matrix. Generally, it is observed that the presence of Cu_2O particles as reinforcement improves the properties of all the samples; this is because the mechanical property, tensile strength and the hardness values obtains is remarkably higher than the value of non-heat-treated binary alloy. Meaning that Cu_2O as reinforcement in the matrix of Al-Ni binary alloy with heat treatment as a strengthening mechanism has a positive impact on the properties of the composite.

This behaviour aligns with the findings of Buraq [12]. He concluded that the reaction between Cu_2O particles and the Al matrix is enhanced with increasing heat treatment temperature.

20 % Cu_2O

The SEM-EDS image presented in Fig. 3c indicates that the atomic concentrations of copper (I) oxide (Cu_2O) and aluminium (Al) in these patches were approximately 20 % and 75 %, respectively, suggesting the formation of $CuAl_2$ intermetallics. Additionally, new eutectic patches were formed, as shown in the magnified SEM image. The dendritic morphologies almost disappeared within the matrix, and large particles with curved edges were observed at the grain boundaries of the enlarged Al grains, as observed in SEM-EDS Micrograph. Some eutectic $CuAl_2$ intermetallics are distributed inside the grains and at the grain boundaries shown by XRD analysis in Fig. 3f. The eutectic phases coarsened and precipitated at the grain boundaries of the larger Al grains. The presence of Cu_2O particles in the cavities within the matrix was observed in Fig. 3c EDS. Most of these Cu_2O particles underwent a reaction with the Al matrix, resulting in the formation of characteristic eutectic $CuAlO_2$ intermetallics depicted by XRD analysis. This suggests that the fine particles primarily consisted of Cu_2O, while the eutectic phase corresponded to the $CuAl_2Ni$ intermetallic compound. This behaviour aligns with the findings of Buraq, who concluded that the reaction between Cu_2O particles and the Al matrix is enhanced with increasing heat treatment temperature [12]. Generally, it is observed that heat treating the composite sample improves the properties of all the heat-treated samples; this is because the mechanical property, tensile strength and the hardness values obtain is remarkably higher than the value of Al-Ni binary alloy. The presence of Cu peaks in the EDS pattern indicated the existence of unreacted copper (I) oxide within the matrix. Upon increasing the Cu_2O powder content to 20 %, the particles tended to aggregate in relatively large patches within the Al grains [30].

Effect of Cu_2o content and heat treatment on the hardness properties

Fig. 4 illustrates the impact of incorporating Cu_2O into an Al-Ni alloy of eutectic composition. As the proportion of Cu_2O reinforcement within the composite's matrix rises, there is a concurrent elevation in composite hardness. This correlation between Cu_2O content and hardness underscores the strengthening influence of Cu_2O on the composite developed.

Fig. 4 presents the impact of Cu_2O content on the hardness of the composite developed. The trend in the figure reveals a consistent augmentation in hardness as the Cu_2O content is elevated. Notably, the initial hardness of the sample devoid of Cu_2O (0 % content) measured 45 HB before any heat treatment. Strikingly, after heat treatment, this hardness escalated significantly to 75 HB at 200°C, further increasing to 85 HB at 220°C, 87 HB at 240°C, and finally reaching 89 HB at 260°C. Similarly, for samples containing 4 % Cu_2O content, the initial hardness was recorded at 43 HB before any heat treatment. Impressively, after heat treatment, this hardness experienced a remarkable surge, registering at

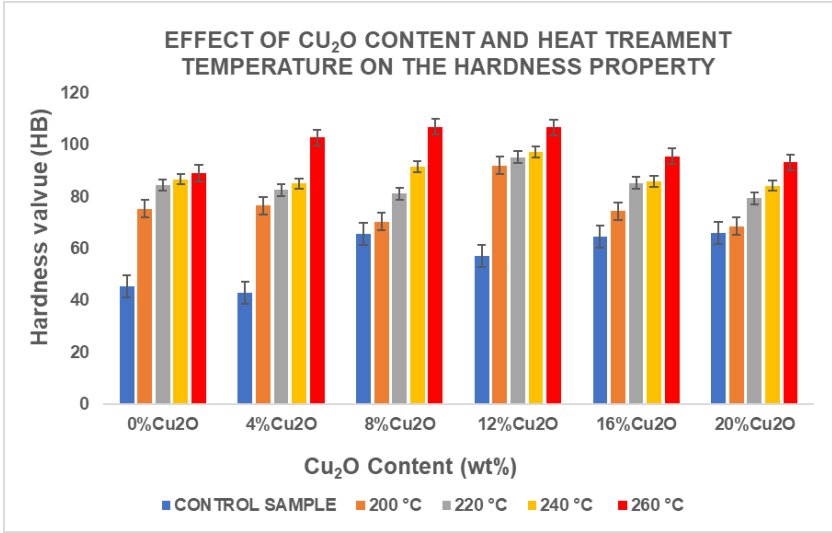

Fig. 4. Hardness property of the SPS Composite reinforced with Cu_2O.

77 HB at 200°C, and then climbing to 83 HB at 220°C, and 85 HB at 240°C. The most striking enhancement was observed at 260°C, where the hardness peaked at an impressive 103 HB. Upon increasing the Cu_2O content to 8 %, a corresponding elevation in its hardness was observed, measuring 66 HB before any heat treatment. Notably, following the application of heat treatment, a remarkable progression in hardness was noted. Specifically, the hardness experienced increments to 70 HB at 200°C, further rising to 81 HB at 220°C, and significantly surging to 97 HB at 240°C. The most substantial enhancement occurred at 260°C, where the hardness achieved an impressive peak of 107 HB.

Additionally, with a subsequent increase in Cu_2O content to 12 %, the initial hardness was determined to be 57 HB prior to undergoing any heat treatment. Impressively, after subjecting the sample to heat treatment, there was a discernible elevation in hardness. Specifically, the hardness values displayed an ascent to 92 HB at 200°C, followed by a further rise to 95 HB at 220°C. Moreover, at 240°C, the hardness notably increased to 97 HB, and the peak enhancement was observed at 260°C, where the hardness reached an impressive 107 HB. With the Cu_2O content elevated to 16 %, the hardness of the sample was established at 65 HB prior to any heat treatment. Subsequently, a notable augmentation in hardness was witnessed following the application of heat treatment. Specifically, the hardness values exhibited increments to 75 HB at 200°C, followed by a further rise to 85 HB at 220°C. Furthermore, at 240°C, the hardness experienced a discernible upsurge to 86 HB, culminating in the highest enhancement observed at 260°C, where the hardness reached a substantial 97 HB. Finally, upon a further increase in Cu_2O content to 20 %, the initial hardness value was recorded at 66 HB prior to any heat treatment. Moreover, after undergoing heat treatment, there was a progression in hardness. Specifically, the hardness values demonstrated an increase to 69 HB at 200°C, followed by a subsequent rise to 79 HB at 220°C. Additionally, at 240°C, the hardness displayed an elevation to 84 HB, and the highest point of enhancement was attained at 260°C, where the hardness achieved 91 HB. The behaviour in the hardness trend could be associated with the presence of dendrite intermetallic phases within the composite. The refining effect of precipitated particles and the matrix decreased the inter-particle distance, hindering dislocation movement. Additionally, the increase in the number of fine copper aluminide intermetallic particles dispersed in the fine matrix contributed to material strengthening. The development of the phases in the sample could account for the increase in the hardness. This behaviour aligns with the findings of Aramide and Popoola, who concluded that the development of these intermetallic phases within the composite matrix is responsible for the increased hardness of the sample [10].

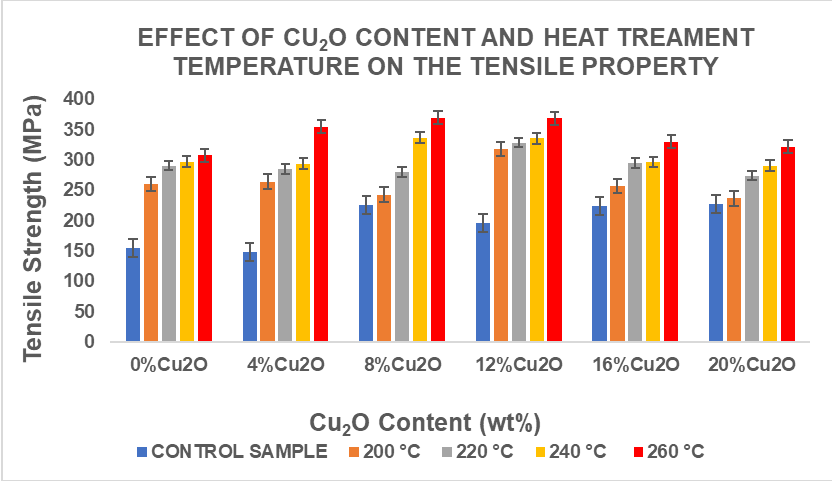

Fig. 5. Tensile property of the SPS composite reinforced with Cu_2O.

Effect of Cu_2O content and heat treatment on the tensile strength

Fig. 5 illustrates the impact of incorporating Cu_2O into an Al-Ni alloy with a eutectic composition. As the proportion of Cu_2O reinforcement within the composite's matrix rises, there is a concurrent elevation in composite tensile strength. This correlation between Cu_2O content and tensile strength underscores the strengthening influence of Cu_2O on the composite developed.

Fig. 5 presents the influence of Cu_2O content on the tensile strength of the specimens, both before and after heat treatment. The figure reveals a discernible trend wherein the tensile strength of the samples demonstrates a rise in response to increasing Cu_2O content following the application of heat treatment. The initial observation from the figure is that the tensile strength of the samples, after heat treatment, exhibited an augmentation proportional to the elevated Cu_2O content. Prior to any heat treatment, the tensile strength of the sample with (0 % Cu_2O) content was measured at 151 MPa. Remarkably, after undergoing heat treatment, this strength exhibited a substantial increase to 261 MPa at 200°C, followed by further elevations to 291 MPa at 220°C, 297 MPa at 240°C, and reaching the highest value of 307 MPa at 260°C. Upon raising the Cu_2O content to 4 %, the initial strength measured 148 MPa prior to undergoing any heat treatment. Subsequently, following heat treatment within the temperature range of 200 to 260°C, the tensile strength demonstrated significant improvement, reaching values of 265 MPa, 285 MPa, 294 MPa, and 355 MPa respectively for varying conditions. Upon increasing the Cu_2O content to 8 %, the initial strength registered at 226 MPa prior to subjecting it to any heat treatment. Following heat treatment in the temperature range of 200 to 260°C, the resulting tensile strengths were measured at 243 MPa, 280 MPa, 337 MPa, and 369 MPa correspondingly. Similarly, when augmenting the Cu_2O content to 12 %, the initial tensile strength of the specimen reached 197 MPa in the absence of any heat treatment. Subsequent heat treatment in the temperature range of 200 to 260°C led to significant enhancements in strength, resulting in values of 318 MPa, 329 MPa, 336 MPa, and 369 MPa respectively. With the Cu_2O content elevated to 16 %, the tensile strength of the sample was established at 223 MPa prior to any heat treatment. Subsequently, a notable augmentation in strength was witnessed following the application of heat treatment. Specifically, the tensile strength values exhibited increments to 257 MPa at 200°C, followed by a further rise to 295 MPa at 220°C. Furthermore, at 240°C, the tensile strength experienced a discernible upsurge to 297 MPa, culminating in the highest enhancement observed at 260°C, where the strength reached a substantial 330 MPa. Finally, for samples containing 20 % Cu_2O content, the initial tensile strength was recorded at 228 MPa before any heat treatment. Impressively, after heat treatment, this tensile strength experienced a remarkable surge, registering at 237 MPa at 200°C, then climbing to 274 MPa at 220°C, and 291 MPa at 240°C. The most striking enhancement

was observed at 260°C, where the tensile strength peaked at an impressive 322 MPa.

Analysis of Fig. 2 and Fig. 3 reveals that in the sample devoid of Cu_2O (0 % Cu_2O), the discernible phases are the eutectic AlNi and Al_3Ni phases. This composition consequently exhibits the lowest recorded tensile strength. For sample containing (4 % Cu_2O), the phases identified in it are $CuAl_2$, $CuAl_2Ni$ intermetallics. The increase in the number of fine copper aluminide intermetallic particles dispersed in the fine matrix contributed to material strengthening. The development of the phases in the sample could account for the increase in the Tensile strength. Furthermore, for sample containing (8 % Cu_2O) the identified phases are AlCuO, $CuAl_2Ni$, $AlNiO_2$. The evolvement of these phases and alumina could be said to influence the further increase in the tensile strength of the sample. Moreover, for sample containing (12 % Cu_2O) the phases identified in it are $CuAl_4$, Al_2Ni_3. The existence of aluminium nitrate within the composite matrix could be said to further improve the tensile strength of the sample. For sample containing (16 % Cu_2O), the identified phases are Al-Ni, $CuAl_2$ intermetallics. The existence of aluminium nitrate within the composite matrix could be said to further improve the tensile strength of the sample. Lastly, for the sample containing (20 % Cu_2O), the identified phases are $CuAl_2Ni$, $CuAl_2$, and alumina. The refining effect of precipitated particles and the matrix decreased the inter-particle distance, hindering dislocation movement. This behaviour aligns with the findings of Aramide and Popoola, who concluded that the development of these intermetallic phases within the composite matrix is responsible for the increased tensile strength of the sample [10]. Also, these findings agree with the research of Buraq, who reported on the synthesis and properties of advanced aluminium and copper-Based Metal Matrix Composites [12].

CONCLUSIONS

Based on the findings of this study, it could be concluded that:

- The added copper particles reacted with the Al matrix, resulting in the formation of fine copper aluminide intermetallics. Most of the resulting intermetallics were $CuAl_2$.
- It is observed that heat treating the composite sample improves the properties of all the heat-treated samples; this is because the mechanical property, tensile strength, and the hardness values obtain is remarkably higher than the value of the non-heat-treated sample. Meaning that heat treatment has a positive impact on the properties of the composite.
- The hardness of the resulting composite materials was improved. The hardness of the 12 % Cu_2O sample with heat treatment was almost twice that of 107 HB, compared to that of the composite without heat treatment, 93 HB. Al-Ni eutectic binary alloy, while the hardness increased up to about 89 HB after heat treating at 260°C.
- The tensile strength of the resulting composite materials was remarkably improved, especially at 12 % additions of Cu_2O and at the heat treatment temperature 260°C.
- Heat treatment temperature affects the prevailing solid-state reactions in the sample which also determine the intermetallic developed within the sample.
- Intermetallic phases improved the tensile strength TS of all the samples containing Cu_2O with increase in the heat treatment temperature.
- Samples containing 8 - 12 %Cu_2O, when heat treated at 260°C has the optimum hardness and tensile strength.
- Based on these observations, it can be inferred that there is an upper limit to the amount of copper (I) oxide powder that can be added to the alloy under investigation.

Acknowledgement

The authors wish to acknowledge the technical support and contributions of Workshop technologists at the Department of Materials and Metallurgical Engineering, Federal University of Technology, Akure. Ondo State. Nigeria.

Authors' contributions

T.A.: Experimental work, Writing; A.A.: Design of the research, Conceptualization, Review, Editing; A.F.: Editing, Project management; B.O.: Review, Editing, Analysis; E.A.: Project management, Data Analysis; A.S.: Review, Editing.

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