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Research Article

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Special Issue

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Influence of heat treatment parameters on mechanical properties and microstructure of Cu-10wt%Si-2wt%Ni alloy

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Abstract
The impact of heat treatment parameters on the tensile properties and microstructural characteristics of Cu-10wt%Si-2wt%Ni alloy produced by sand casting technique were investigated. The samples were subjected to solid solution heat treatment, brine quenched and subsequently analyzed for ultimate tensile strength, elastic modulus, yield strength, and microstructural characteristics. The results showed that solid solution heat treatment refined and modified the structure of Cu-10wt%Si-2wt%Ni alloy and significantly improve the tensile properties. Maximum yield strength (160.8 MPa) and ultimate tensile strength (193.83 MPa) were observed at 800°C for 2.5 hours after heat treatment while maximum elastic modulus of 1979.17 MPa were observed at 900°C for 3.5 hours. Maximum percentage elongation value of 32.79% was observed after solid solution treatment at 700°C for 0.5 hours. Microstructural analysis results revealed a transition from coarse grains dispersed within the copper matrix in the control sample to finer grains of intermetallic compounds in the heat-treated specimens.

Keywords: Brine, Copper-Silicon, Nickel, Solid solution heat treatment, Tensile Properties

1. Introduction

Copper-based alloys, characterized by a unique blend of properties including strength, ductility, malleability, non-magnetism, machinability, and resistance to wear and corrosion, have witnessed a surge in demand across various engineering sectors such as chemical, petroleum, automotive, and power generation (Gangwar et al., 2015; Wang et al., 2014). Unlike pure copper, which possesses low tensile strength owing to its soft and ductile nature, copper alloys offer a broader spectrum of applications owing to their enhanced mechanical properties (Lei et al., 2017; Qian et al., 2017; Romankiewicz & Romankiewicz 2016). Among these alloys, silicon bronze (Cu-Si) stands out for its remarkable strength, corrosion resistance, formability, and aesthetic appeal (Ketut et al., 2014). Silicon bronze finds utility across diverse industries including automotive, construction, automation, electrical, and electronics, serving in the fabrication of fasteners, electrical connectors, lead frames, screws, conduits, valve stems, bolts, electronic signals, nails, and nuts (Garbacz-Klempka et al., 2018; Nnakwo & Nnuka, 2018). The strength of silicon bronze can be further augmented by altering its microstructural characteristics, rendering it suitable for an array of applications through alloying (Nnakwo & Nnuka, 2018), heat treatment (Cheng et al., 2014; Nazeran et al., 2014), and metalworking (Wang et al., 2014). While alloying and metalworking have received considerable attention, research on the heat treatment of silicon bronze, particularly solid solution heat treatment, remains relatively underexplored (Kakani and Kakani, 2014). Solid solution heat treatment processes play a pivotal role in homogenizing the alloy's composition, mitigating segregation of secondary phases, and enhancing desirable properties such as strength, ductility, and other mechanical attributes (Ijomah et al., 2023a; Kakani and Kakani 2014).

This study aims to investigate the influence of solid solution heat treatment on the structure and tensile properties of Cu-10wt%Si-2wt%Ni alloy. Previous investigations shed light on the influence of various heat treatment methods on similar alloys. For instance, (Nwankwo et al., 2023) studied the effects of homogenization heat treatment on grain characteristics and mechanical properties of copper-silicon-zinc and copper-silicon-tin ternary alloys, revealing a notable increase in ultimate tensile strength and hardness following treatment. Similarly Ijomah et al., (2023a) investigate the effects of carbide-forming elements (manganese and tungsten) and solid solution heat treatment on the microstructure and mechanical properties of copper-silicon binary alloys, showcasing finer grains and heightened strength post-treatment. Moreover, studies such as Tao et al., (2022); Atapek et al., (2022) and Xu et al., (2024) have explored the effects of heat treatment and repercussion of aging treatment on microstructure and properties of Cu-Si-Ni alloys, unveiling valuable insights into the alloy's behavior under varied treatment conditions. However, specific attention to solid solution heat treatment and its effects on the Cu-10wt%Si-2wt%Ni alloy remains unexplored.

2.0 Material and methods

2.1 Equipment and Materials

Equipment: Electronic weighing balanace (SF-400A), steel crucible pot, rammer, moulding box, scoping spoon, pins, electric blower, stirrer, bench vice, hack saw, venier caliper, lathe machine, tubular electric heat treatment furnace (model:180-18), metal tongs, ceramic crucible pot, electric weighing scale (NKS-6), electronic universal testing machine (WDW-100KN), the rockwell hardness tester (model: 38506), impact strength testing machine (model: 33716), BG20 electric belt grinder (model: 800-500), Handimet 11 Patents manual grinder (model:39-1472), Lion D72605 Bisigen air gun drying machine, digital camera, Genius – IF Xenemetrix XRF Equipment (S.N: AI4901), olympic optical metallurgical microscope (model:GX51F) and scanning electron microscopy (SEM) (Model: Joel-JSM 7600F) equipped with energy dispersive spectroscopy (EDS).

Materials: Pure copper wire (99.87%), pure silicon powder, and 99.7% pure nickel wire. Other materials used for this research were water, quenching media (brine), 10% concentration of NaCl for quenching, bowl, distilled water, gamma micropolish alumina paste (for polishing), silicon carbide grinding paper of grits sizes, solution of 2g of $K_2Cr_2O_7$, 8ml of H_2SO_4, 4 drop of HCL and 100 ml of water (for etching) and rotary ultrafine polishing cloth.

Procedure: The Cu-10wt%Si-2wt%Ni alloy was synthesized using copper wire (99.87% purity), pure silicon powder, and nickel wire (99.7% purity) via the sand-casting technique. After precisely weighing each material in grams using an electric weighing scale (NKS-6), they were loaded into the bail-out crucible furnace. The resulting melt was poured into a prepared sand mold cavity with dimensions of 14 mm diameter and 240 mm length, then left to cool. Subsequently, the fabricated alloy underwent machining and was subjected to solution heat treatment at temperatures of 700°C, 800°C, and 900°C for durations of 0.5, 1.5, 2.5, and 3.5 hours, respectively, utilizing a tubular electric heat treatment furnace (model: 180-18), followed by quenching in brine. Tensile test specimens were prepared in accordance with ASTM E8M standards utilizing an electronic universal testing machine (WDW-100KN) to determine ultimate tensile strength, percentage elongation, yield strength, and elastic modulus. For microstructural analysis, samples were subjected to metallographic procedures including filing, grinding, polishing, and etching. Subsequently, surface morphology was examined utilizing an Olympus optical metallurgical microscope (model: GX51F) and scanning electron microscopy (SEM) (Model: Joel-JSM 7600F) equipped with energy dispersive spectroscopy (EDS).

3.0 Results and Discussions

Tensile Properties (ultimate tensile strength, % elongation, yield strength and elastic modulus) of the studied alloy. Figures 1 to 4 present a comprehensive analysis of the impact of solutionizing temperature, soaking time, and cooling rate (brine) on the mechanical properties (percentage elongation, ultimate tensile strength, yield strength, and elastic modulus) of silicon bronze in both as-cast and solid solution heat-treated states. These figures collectively underscore the substantial influence of solid solution heat treatment on the tensile properties of silicon bronze. From Figure 1, it is evident that the as-cast sample exhibited a percentage elongation ranging from 15.3% to 32.79% following solid solution heat treatment at 700°C for 0.5 hours with brine quenching. This notable increase in percentage elongation can be attributed to grain modification and the expansion of the α-solid solution region within the copper matrix, as corroborated by the microstructural analysis (Plates 1-3). However, a decrease in percentage elongation was observed with higher solid solution temperatures and longer soaking times. At 700°C, the percentage elongation decreased by 8.36% as the soaking time increased from 0.5 hours to 1.5 hours with brine quenching. This is because as increasing solid solution temperature and time, the diffusion rate increased leading to precipitation of more grains at the grain boundaries which leads to the grains coarsening. The presence of coarse grains is associated with a decrease in the percentage elongation of the alloy which correspond with the study by (Nwankwo et al., 2023). Figures 2 and 3, illustrates that the as-cast Cu-10wt%Si-2wt%Ni alloy displayed yield strength and ultimate tensile strength values of 70 MPa and 117.82 MPa, respectively. Following solid solution heat treatment at 700°C for 2.5 hours with brine quenching, both yield strength and ultimate tensile strength were significantly enhanced to 104 MPa and 182 MPa, respectively. Notably, an optimal yield strength of 160.8 MPa and ultimate tensile strength of 193.83 MPa were achieved at a solid solution temperature of 800°C for 2.5 hours, likely attributable to the formation of fine, evenly dispersed grains within the copper matrix. The fine grains observed is as a result of increased number of grain boundaries and dislocation density within the alloy and this is in line with the study by Ijomah et al., (2023a); Ijomah et al., (2023b) and Nwankwo et al., (2023). Additionally, it was also observed that at higher temperatures, the alloy exhibited lower yield strength and ultimate tensile strength due to grain coarsening under varying solid solution times and quenching media. Lastly, Figure 4 indicates that the as-cast alloy possessed an elastic modulus value of 2274.46 MPa. However, the elastic modulus of the as-cast sample decreased under alternative heat treatment parameters. This is attributed to grain coarsening.

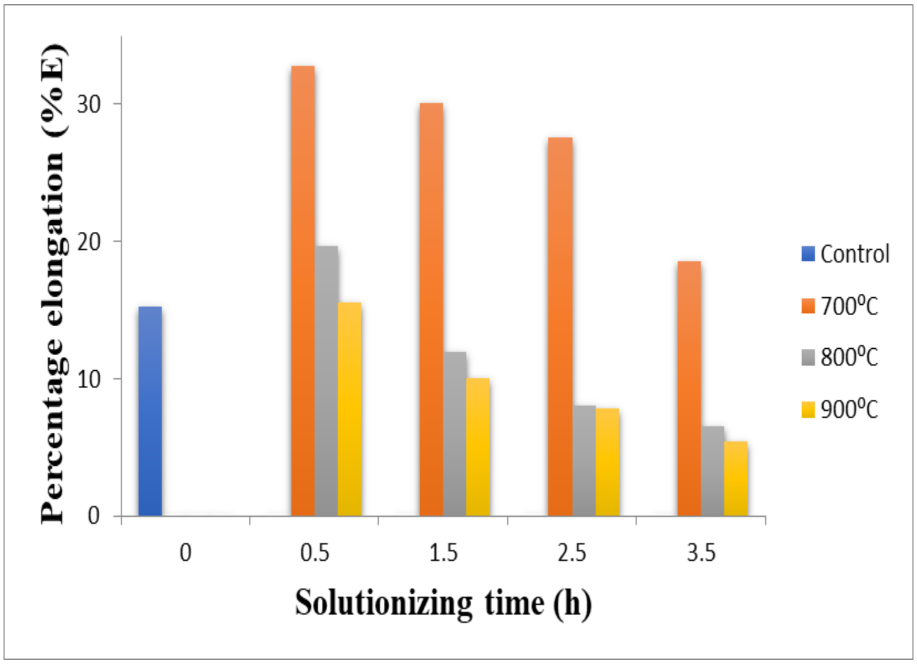

Figure 1: Effect of solutionizing temperatures and times on the percentage elongation of Cu-10wt%Si-2wt%Ni cooled in brine

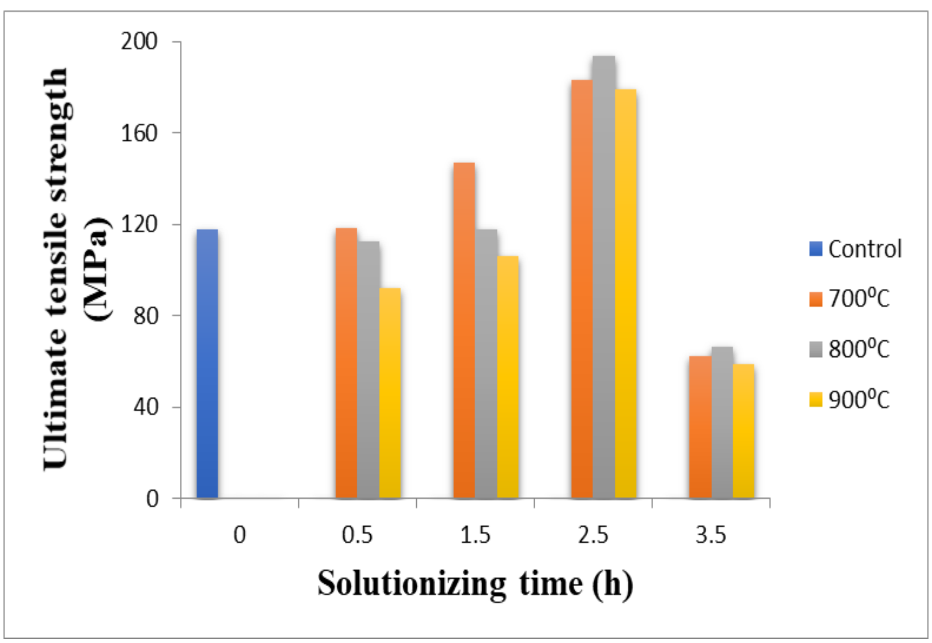

Figure 2: Effect of solutionizing temperatures and times on the ultimate tensile strength of Cu-10wt%Si-2wt%Ni cooled in brine.

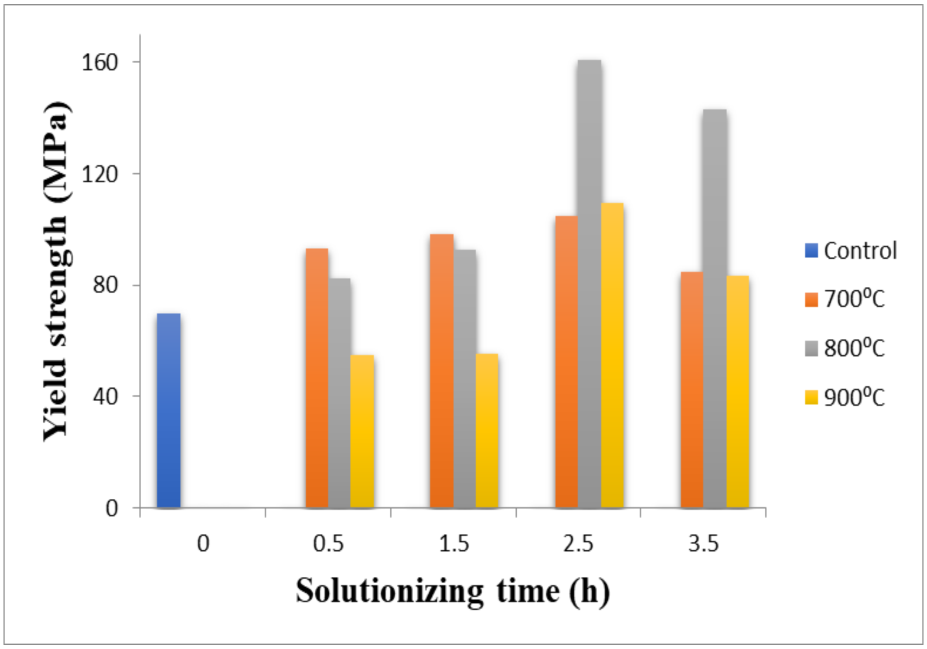

Figure 3: Effect of solutionizing temperatures and times on the yield strength of Cu-10wt%Si-2wt%Ni cooled in brine

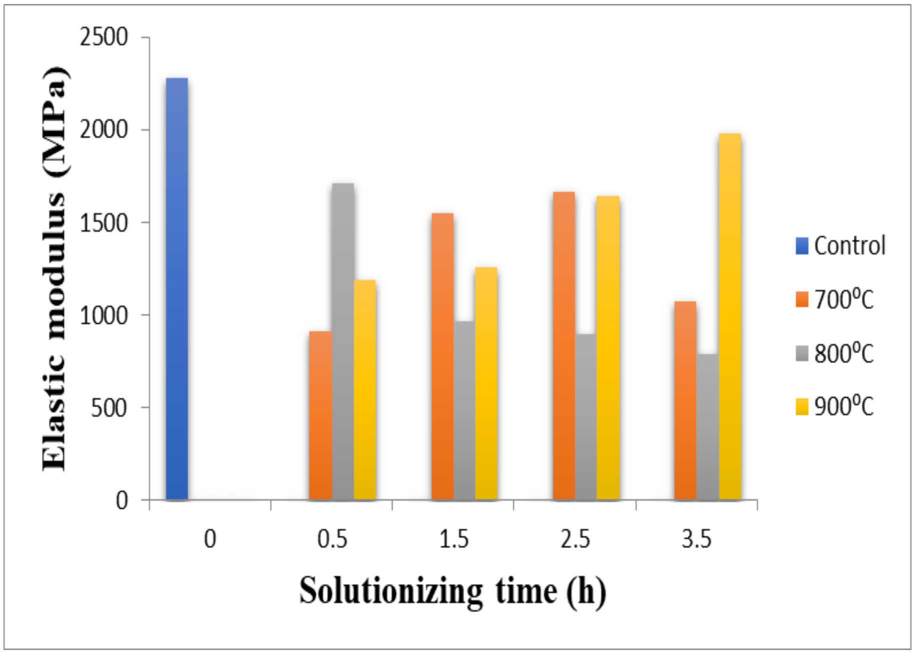

Figure 4: Effect of solutionizing temperatures and times on the elastic modulus of Cu-10wt%Si-2wt%Ni cooled in brine

In summary, the results clearly show the profound influence of solid solution heat treatment on the mechanical properties of silicon bronze, underscoring the importance of optimizing treatment parameters to achieve desired material characteristics for specific engineering applications.

3.1 Microstructural Analysis

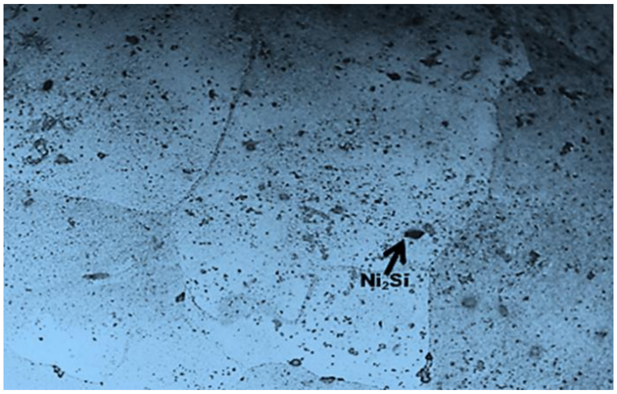

Plate 1: OM Cu-10wt%Si-2wt%N alloy (as-cast)

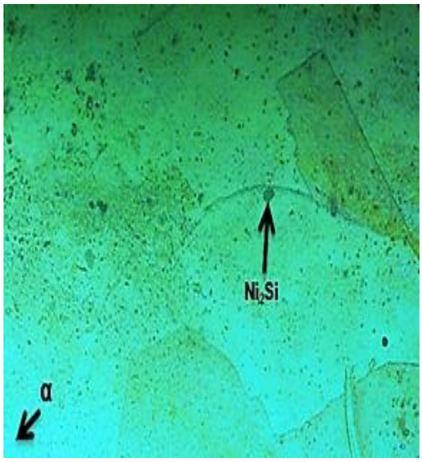

Plate 2: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 700ºC for 0.5 h and cooled in brine

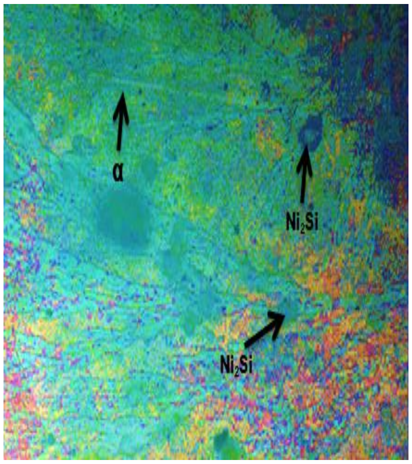

Plate 3: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 700ºC for 1.5 h and cooled in brine

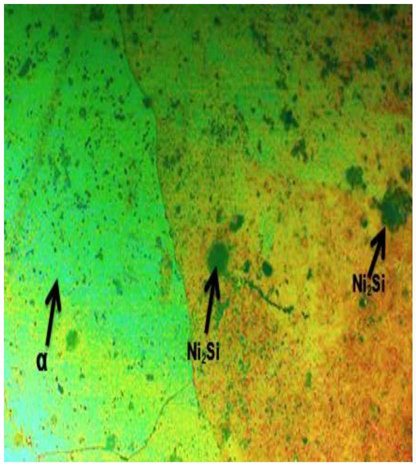

Plate 4: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 700ºC for 2.5 h and cooled in brine

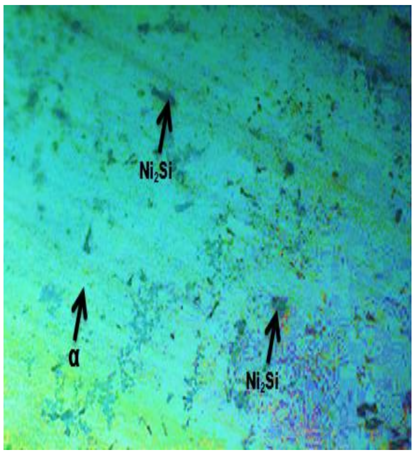

Plate 5: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 700ºC for 3.5 h and cooled in brine

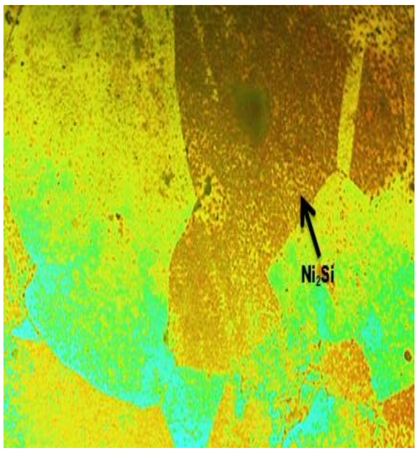

Plate 6: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 800ºC for 0.5 h and cooled in brine

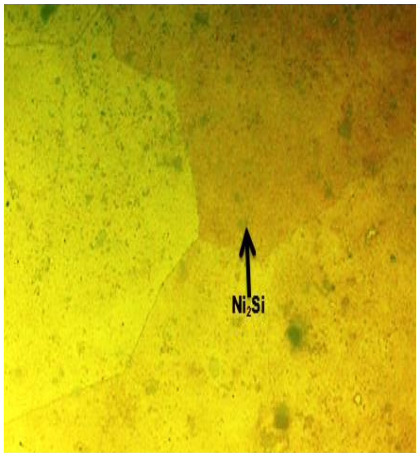

Plate 7: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 800ºC for 1.5 h and cooled in brine

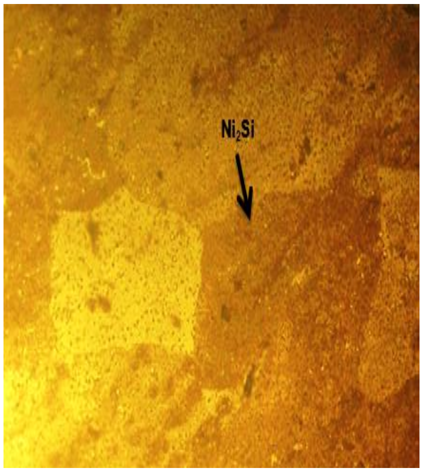

Plate 8: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 800°C for 2.5 h and cooled in brine

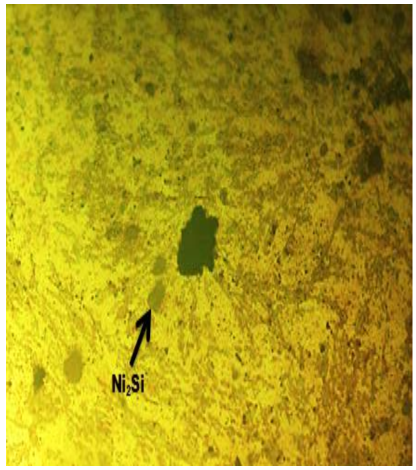

Plate 9: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 800°C for 3.5 h and cooled in brine

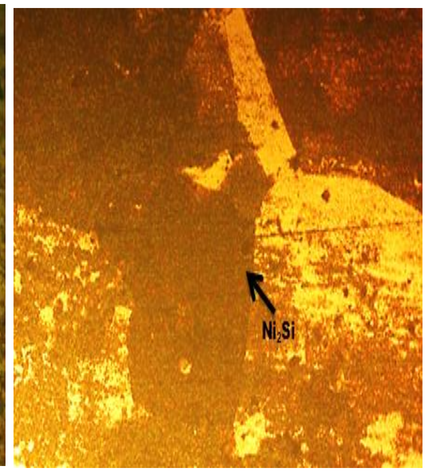

Plate 10: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 900°C for 0.5 h and cooled in brine.

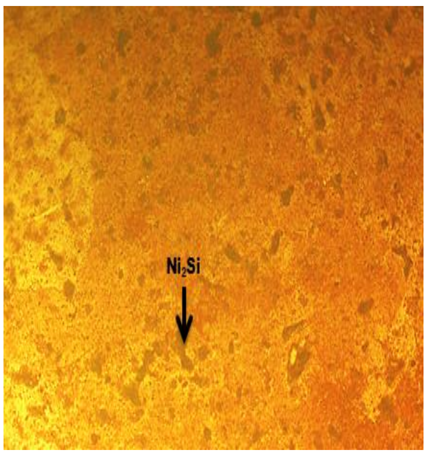

Plate 11: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 900°C for 1.5 h cooled in brine

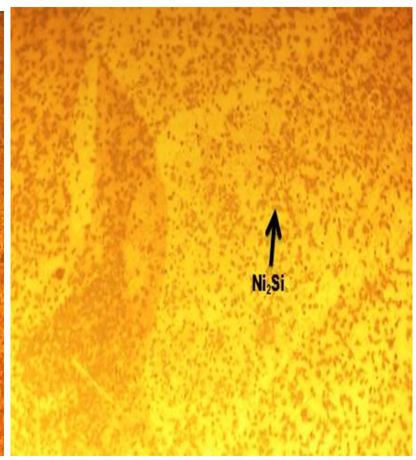

Plate 12: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 900°C for 2.5 h and cooled in brine

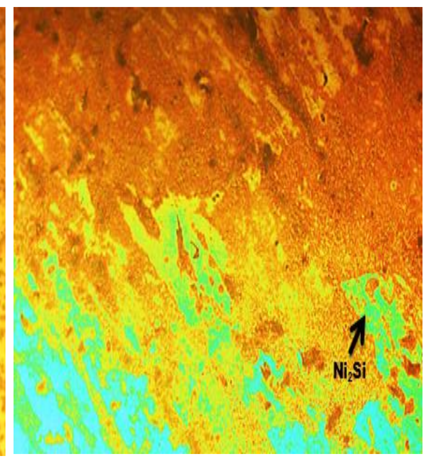

Plate 13: OM Cu-10wt%Si-2wt%Ni alloy solutionized at 900°C for 3.5 h and cooled in brine

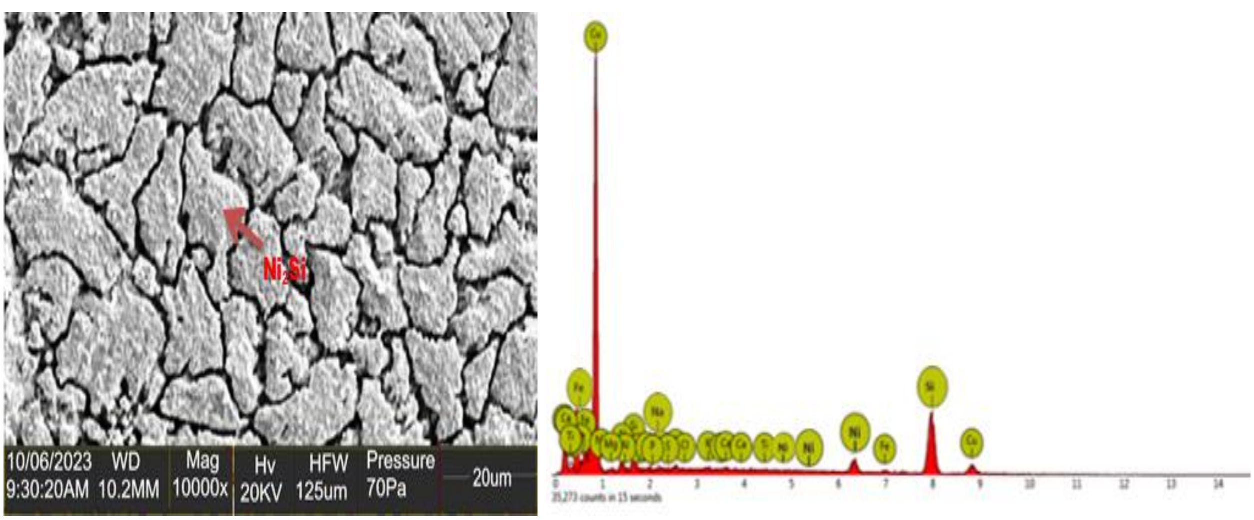

Plate 14: SEM/EDS spectrum of Cu-10wt%Si-2wt%Ni alloy (as-cast)

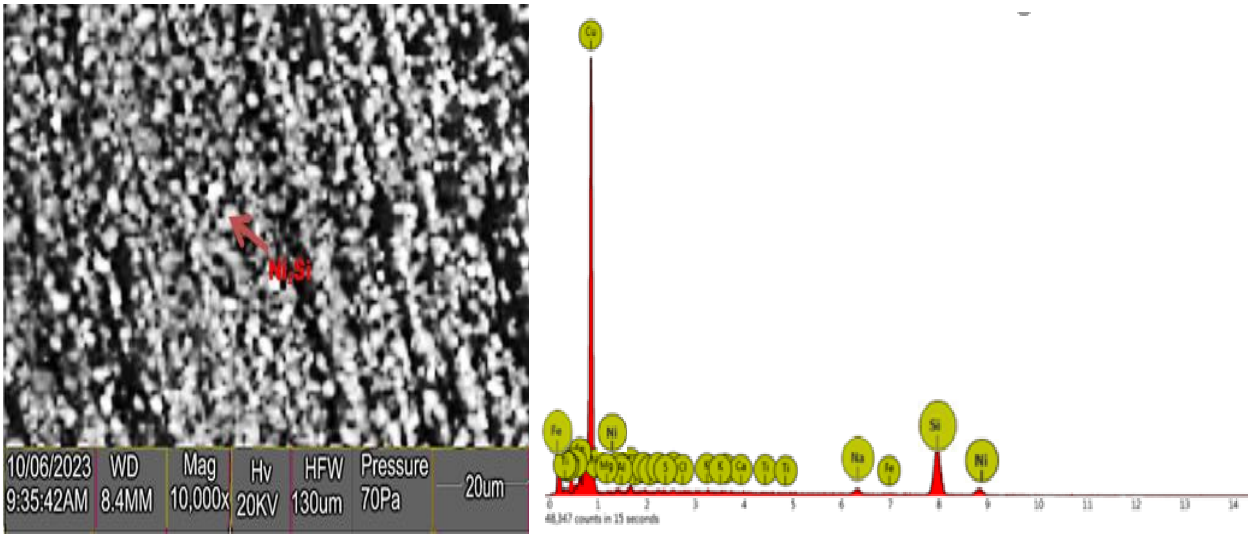

Plate 15: SEM/EDS spectrum of Cu-10wt%Si-2wt%Ni alloy solutionized at 700^{o}C for 1.5 h and cooled in brine

The microstructural examination of the Cu-10wt%Si-2wt%Ni alloy in both as-cast and solid solution heat-treated states was conducted using optical microscopy (OM) and scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS), as detailed in Plates 1-15. Figure 1 and 14 depict the surface morphology of the control sample, revealing dendritic primary grains embedded within the copper matrix. At a solutionizing temperature of 700°C, the microstructure of samples cooled in brine after a 0.5-hour soaking time exhibited finer grains, indicative of enhanced structural refinement which correspond to the report by (Ijomah et al., 2023b). However, as the solutionizing temperature and time increased, the grain size also increased as seen from Plate 6.

Nonetheless, compared to the control samples, the microstructures of samples subjected to solid solution heat treatment and cooled in brine showcased finer grains and more uniform grain distributions within the copper matrix. This phenomenon likely contributes to the observed improvements in tensile properties in the brine-cooled samples, aligning with previous findings by (Ijomah et al., 2023; Nwankwo et bal., 2023a)s, who reported enhanced tensile properties in silicon bronze alloys characterized by finer grain structures and improved grain distribution. The superior grain refinement observed in the heat-treated samples, as depicted in Figures 2-4, correlates with enhanced tensile and microstructural properties compared to the as-cast sample. Additionally, SEM images of both the as-cast and heat-treated samples, as presented in Plates 14 and 15, further evidenced grain refinement in the heat-treated samples, attributable to the presence of Ni2Si precipitates acting as intermetallic phases in the alloy. This observation aligns with the microstructural findings obtained via optical microscopy. Moreover, EDS spectra confirmed the presence of major elements such as Cu, Si, Ni, Fe, Na, Al, and Mg within the examined samples.

In summation, the structural analysis underscores the pivotal role of solid solution heat treatment in refining the grain structure of the Cu-10wt%Si-2wt%Ni alloy, thereby contributing to improved tensile properties and microstructural characteristics essential for enhancing the alloy's performance in diverse engineering applications.

4.0. Conclusion

this study, the impact of heat treatment parameters on both the tensile properties and microstructure of Cu-10wt%Si-2wt%Ni alloy was thoroughly investigated. The as-cast alloy's percentage elongation, ultimate tensile strength, elastic modulus, and yield strength were meticulously analyzed and correlated with its microstructural features. The findings can be summarized as follows:

1. By subjecting the alloy to solid solution heat treatment at various temperatures and durations, a refined grain structure was achieved.
2. The solid solution heat treatment exerted a significant influence on the percentage elongation, ultimate tensile strength, elastic modulus, and yield strength of the as-cast Cu-10wt%Si-2wt%Ni alloy.

3. The percentage elongation of the as-cast Cu-10wt%Si-2wt%Ni alloy exhibited a notable increase, from 15.30% to 32.79%, following solid solution heat treatments at 700°C for 0.5 h and subsequent quenching in brine. However, an 8.36% reduction in percentage elongation was observed at the same temperature with an increase in solid solution time from 0.5 h to 1.5 h, also followed by brine quenching.
4. Samples quenched in brine demonstrated peak yield strength and ultimate tensile strength, reaching 160.8 MPa and 193.83 MPa, respectively, when subjected to solid solution treatment at 800°C for 2.5 h.
5. The elastic modulus of the as-cast sample was measured at 2274.46 MPa, which exhibited a decrease following solid solution heat treatment at each solutionizing temperature and duration.

5.0 Recommendation

It is recommended that further study on the effects of nickel/silicon ratio on the structure and mechanical properties of the alloy studied is recommended. An advanced study of the microstructure evolution and mechanical properties of the alloy, considering additional parameters such as equal channel angle (EQCA) and thermomechanical treatment is recommended for further study also.

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Nomenclature

Cu: Copper; Si: Silico; Ni: Nickel; HRB: Rockwell Hardness Test; Mn: Manganese; W: Tungsten; Zn: Zinc; Sn: Tin; BHN: Brinell Hardness Test; MPa: Megapascal; SEM: Scanning Electron Microscope; EDS: Energy Dispersive Spectroscopy; OM: Optical Microscope

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