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Heat treatment effects on electrical conductivity and structure of newly fabricated Cu-10%Ni alloy

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Abstract

The present work focus on the production and heat treatment of Cu-10%Ni alloys, as well as their impact on electrical conductivity. A bailout crucible furnace was used for the casting of the pure copper-nickel alloy. The as-cast alloy was modified by subjecting to various precipitation hardening processes such as homogenizing, solutionizing, quenching, and age hardening. The age hardening conditions were performed at different temperatures of 400°C, 450°C and 500°C at constant time of 2hr, after which the electrical conductivity measurement was carried on the heat-treated and non-heat treated alloy. An optical metallurgical microscope and scanning electron microscopy were used to analyze the structural properties (SEM). The most essential attribute linked with the age hardening of Cu-Ni alloys is electrical conductivity, which reflects the internal state of the alloy's electrons. The study reveals that electrical conductivity improves in the heat-treated Cu-Ni alloy in comparison to non-heat-treated Cu-Ni alloy. The maximum value of electrical conductivity of 59.01%IACS is obtained after ageing at 500°C for 2hr. The microstructural features are directly responsible for the considerable improvement in electrical conductivity demonstrated by heat-treated Cu-10%Ni alloy.

Keywords: Cu-10% alloy, casting, ageing temperature, conductivity, Microstructure

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1. Introduction

Copper-nickel based alloys are of interest to metallurgists and material scientists for industrial applications requiring high strength and conductivity. As a group of copper alloy, it exhibits an excellent age hardenability besides high corrosion resistance and remains, therefore, best used for spring materials for substituting highly hazardous high strength copper alloys (Miki and Ogino 1984; Sahu, et al., 2004). Copper largely influences the fundamental properties of its alloy. The alloys of copper have long been recognized as satisfactory materials for several applications in the marine environment (William, 2010). For applications in the microelectronics industry, copper alloys are widely used for integrated circuits of lead frame materials that plays an important role in supporting the electrical signal transmission and heat dissipation. Because of its high strength and hardness, outstanding processing qualities, and low electrical conductivity, copper-nickel has become a study priority among copper alloys. (Wang et al. 2014; Zhang et al. 2015; Jia et al. 2013).

Copper-nickel alloy also called cupronickel is an alloy of copper with nickel as the principal alloying element. The addition of nickel to copper in this regard improves strength, corrosion and oxidation resistance. The major compositions of Cu-Ni alloys vary as follows: 90:10, 80:20, 70:30. The most important Cu-Ni alloys currently used universally are 90/10 Cu-Ni (UNS-C70600) and 70/30 Cu-Ni (UNS-C71500) (Callcut, 2000). However, 90-10 Cu-Ni alloy is most commonly used and is made up of 90% copper and 10% nickel. It has sufficient corrosion resistance and is also the best resistance alloy to organic biofouling. Copper with 30wt% nickel has the best impact corrosion resistance as compared to copper with 10wt% Ni, although the most expensive. Both alloys, (90/10 Cu-Ni and 70/30 Cu-Ni) possess good thermal conductivity and ductility at cryogenic temperatures and are mainly used in steam and marine applications (Shifler 2005; Powell and

Michels 2000 ; Taher et al., 2011; Shen et al. 2014; Jirapure et al., 2017). Copper and nickel, have the same crystal lattice structure (face-centred cubic) and form a single-phase solid solution (Callcut, 2000; Taher, et al., 2011). The binary system of Cu-Ni alloy is a simple isomorphous system. It depicts an unlimited solid solubility of Cu dissolved in Ni or Ni dissolved in Cu. The two elements (Cu and Ni) are completely soluble in each other both in liquid and solid-state. Due to similar atomic radii and lattice parameters that exist between the two elements, the phase diagram of Cu-Ni alloy is simple (Schleich, 2005).

Engineering components are subjected to heat treatment techniques to change their surface and structure-sensitive properties (Rhu et al. 1999). The alloy system's precipitation sequence is known to be particularly sensitive to ageing temperature and ageing time (Shen et al. 2014). The Cu-Ni alloys are commercially manufactured through a conventional precipitation hardening procedure. Copper containing nickel are solution-treated at temperature below recrystallization region then quenched in water, followed by ageing temperature and time. The treatment procedure relates to the development of the ageing-effect of Ni precipitates in the Cu matrix (Semboshi et al. 2016). Good electrical conductivity of Cu-Ni alloys are attributed to the precipitation hardening effect during the ageing process (Shen et al. 2015; Shen et al. 2014). In order to achieve equal electrical conductivity to the copper matrix, mechanical resistance in metallic alloys is determined by the precipitation distribution. Increasing the electrical conductivity of Cu-Ni alloys can improve signal transmission efficiency and lower temperature rise, hence can extend the component's service life (Zhao et al. 2003). The number of charge carriers in a material, as well as their mobility and ease of movement, can be exploited to change the electrical conductivity of the material. Atomic bonding, lattice flaws, and microstructure all influence the rate of diffusion in ionic compounds (Ranganatha et al. 2011). Cu-Ni alloys with high strength and electrical conductivity are widely employed in the automobile, electrical, and electronics industries, which has sparked a lot of interest, with most of the research focusing on the alloys' strengthening mechanisms. In order to improve the electrical conductivity and keep the high strength of the alloy, the Cu-Ni alloy has been heat-treated in this study. The aim of this work was to determine the effect of heat treatments on the electrical conductivity Cu-10% alloy using precipitation hardening process.

2.0 Material and methods

2.1 Experimental

The materials used for the research work are pure copper wire (99.9%) provided by Cutis Cable Plc Nnewi, which served as the matrix to be developed, and pure nickel granules (99.5%) sourced from Cifa laboratories (CIBIS) New Heaven Enugu, which served as the major alloying element. The alloy was produced by direct stir casting in a bailout crucible furnace. The two metals (copper and nickel) were weighed out, and copper wire was first put into the furnace, heated to a temperature of about 1000^{o}C, followed by introducing the nickel granules into the melt and continuously stirring until homogeneity is attained. The molten mixture was left for about 10mins to achieve complete dissolution of nickel metal. The melt under the argon atmosphere was cast in a pre-heated steel mould with a size of 45x55x155mm^3. The ingots produced from the casting process were homogenized at 600^{o}C for 5 hours, followed by air ooling at room temperature.

2.2 Heat Treatment

The ingots were then solutionized at 900^{o}C for 2hours and afterwards quenched in cold water. The quenched samples were aged at different temperatures of 400^{o}C, 450^{o}C and 500^{o}C and soaked for 2hr respectively in the furnace as shown in Figure 1. The samples were removed from the furnace and allowed to cool in the air.

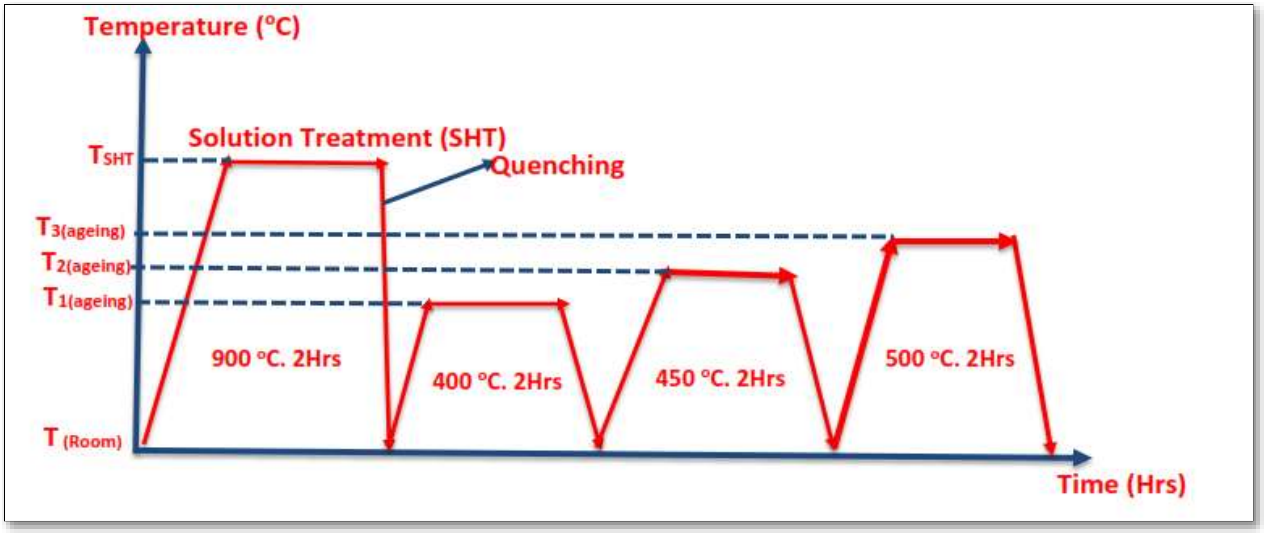


Figure 1. Schematic diagram for the heat treatment process applied.

2.3 Conductivity Measurement

The electrical resistivity and conductivity of the developed alloys were measured using a four-point probe method as shown in Figure 2 according to the study by (Pankade, et al; 2018; Abdoet al. 2021) based on ASTM B193-87 standard. The resistance of the specimen to the electric flow (R) can be estimated in ohms (Ω) using Ohm's equation:

$$V = IR \quad (1)$$

Where V is the voltage applied to the specimen, R is the resistance of the specimen and I is the current in Amp.

The electrical conductivity (σ), which is given as:

$$\sigma = \frac{1}{\rho} \quad \mathbf{(2)}$$

Is the inverse of resistivity where σ is electrical conductivity and ρ is the electrical resistivity.s

The equation:

$$\rho = \frac{RA}{L} \quad \mathbf{(3)}$$

Can be used to calculate the resistivity measured in Ωm where R is the sample's resistance to electric flow, A is the sample cross-sectional area in m^2, and L is the sample length in meters.

A 4-point probe instrument (Model 6221, Keithley Instruments, Inc., Solon, OH, USA), which is a digital voltmeter and constant current source in one instrument, was used to evaluate conductivity. A four-point probe system can offer a continuous current source to detect volume resistivity or sheet resistance, as well as the resulting voltage. The alloys' resistivity was measured, and conductivity values were derived.

Figure 2 Circuit set up for Ohm's experiment

2.4 Structural Analysis

Structural examination for each of the experimental alloys was carried out using both an optical metallurgical microscope (Model: L2003A) and scanning electron microscope equipped with energy-dispersive X-ray EDS (Model-JEOL JSM 7600F). Grinding, polishing, and etching were used to prepare the samples such that the structure could be examined using the metallurgical microscope. The samples were polished with fine alumina powder after being ground with a series of emery papers with grits of 220, 500, 800, and 1200. Before mounting the samples on the microscope for microstructure examination and micrographs, an iron (iii) chloride acid was utilized as an etching agent.

3.0 Results and Discussions

3.1 Electrical conductivity measurement

The electrical resistivity of all Cu-Ni alloy in different heat-treated conditions was directly measured and the electrical conductivity was calculated. The conductivity values in %IACS after the various heat treatment conditions were compared and is shown in Figure 3. As shown in Fig.3, the electrical conductivity of non-heat treated Cu-10%Ni alloy was determined to be 46.76%IACS, and following the precipitation hardening processes, the alloy was seen to be enhanced. The value of electrical conductivity increases drastically at various ageing temperatures and constant time.

The removal of foreign atoms from the lattice of the parent alloy during precipitation hardening eliminates much distortion of electron disturbance in the lattice. Hence, these actions favour the movement of electrons through the metal and therefore results in higher conductivity (Diehl et al. 2020). The multiple precipitation stages created following artificial ageing treatment for different temperature periods are attributable to the change in electrical conductivity for distinct heat treatment conditions for the copper-nickel alloy (Pankade et al., 2018)

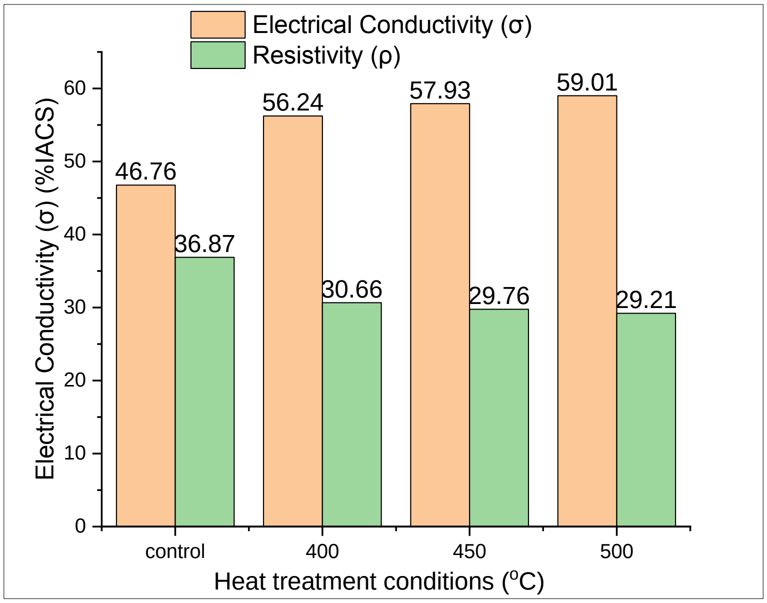


Figure 3 Electrical conductivity measurement

3.2 Structural examination of the fabricated Cu-10%Al alloys

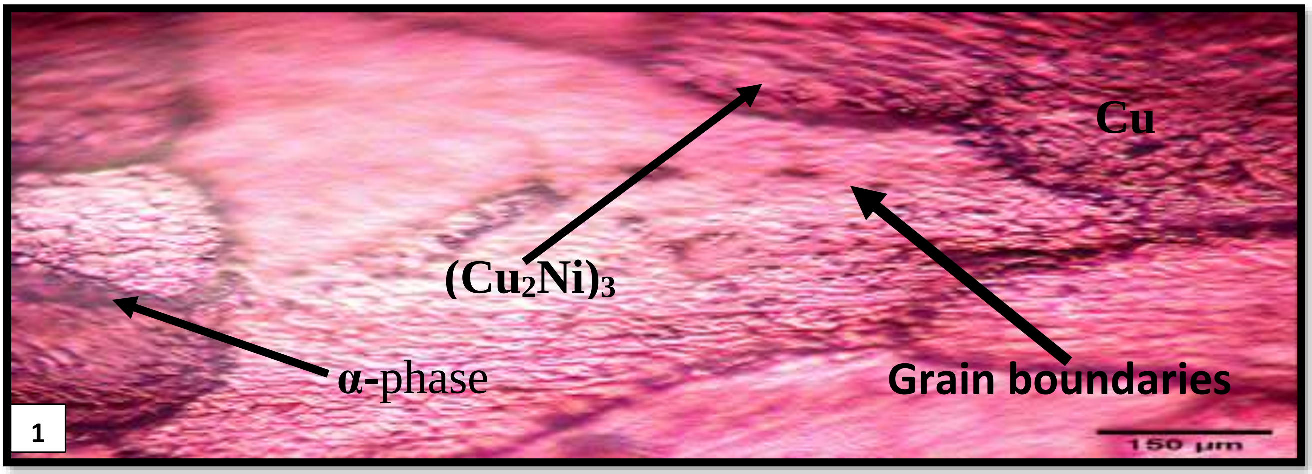


Plate 1. Microstructure of Cu-10%Al (As-cast)

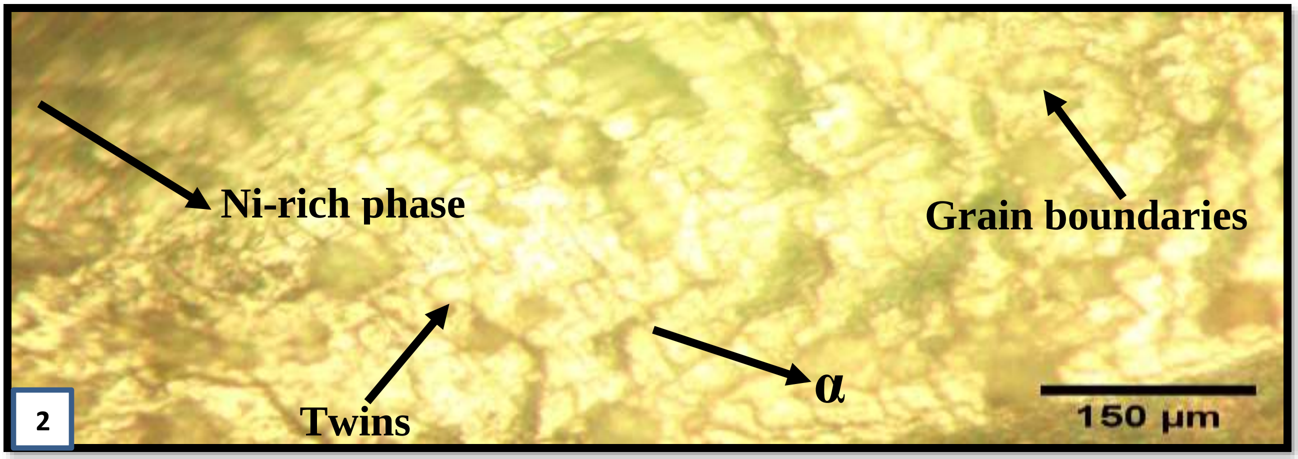


Plate 2. Microstructure of Cu-10%Al (Aged at 400ºC)

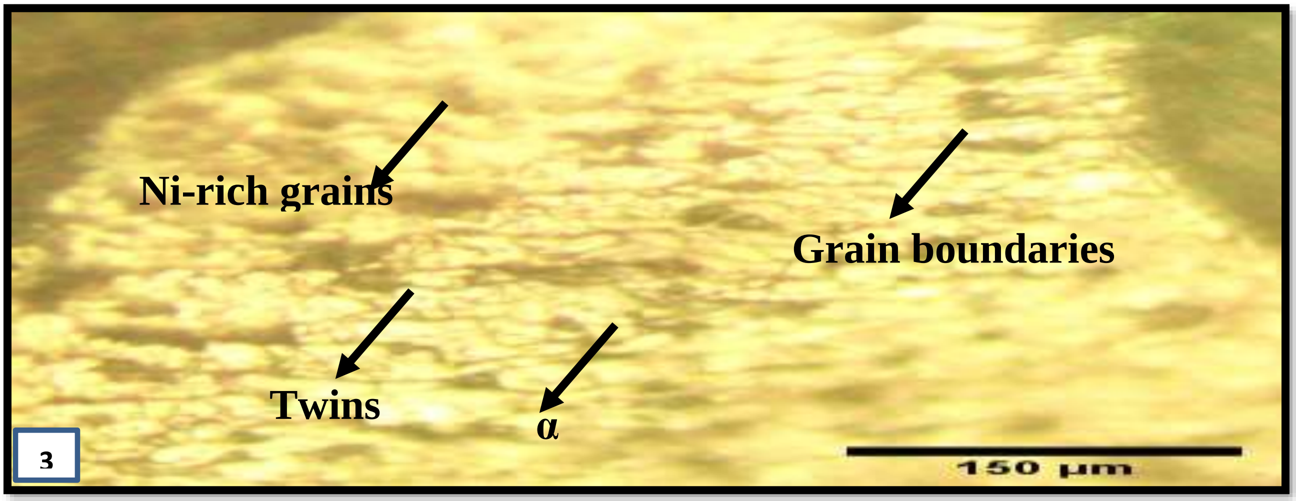


Plate 3. Microstructure of Cu-10%Al (Aged at 450ºC)

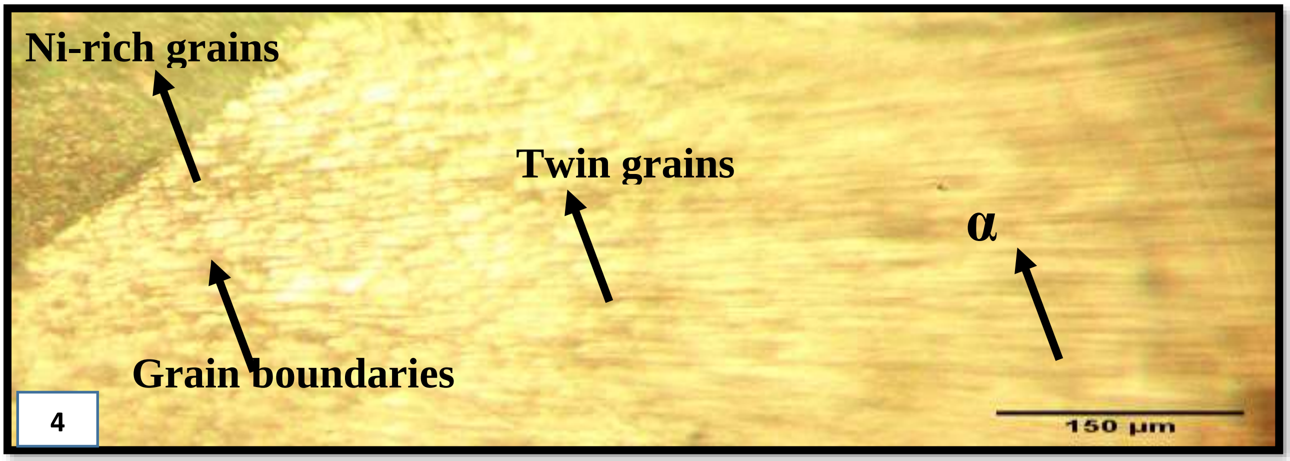
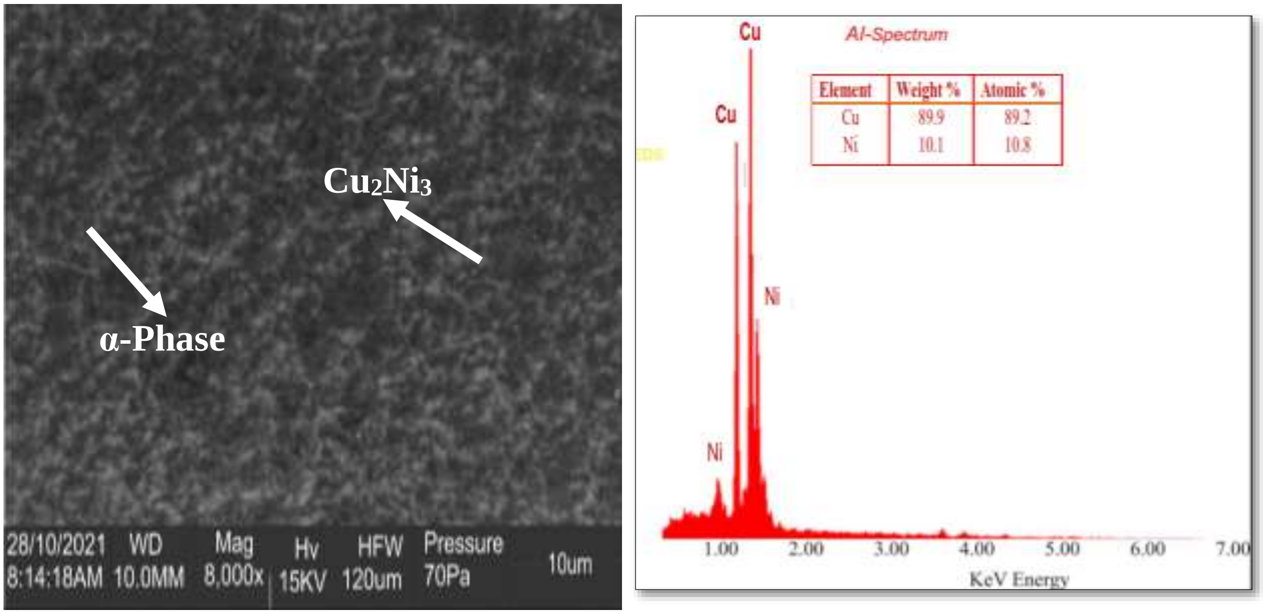


Plate 4. Microstructure of Cu-10%Al (Aged at 500ºC)

Plates 1-4 show the microstructures of heat-treated and non-heat treated Cu-10%Ni alloy. The heat-treated microstructures (plates 2-4) were presented as a function of the ageing temperature (400^0C, 450^0C and 500^0C). The electrical conductivity of the developed alloys is observed to be greatly influenced by the microstructural changes that take place during the synthetic and ageing treatments. From Plate 1, the microstructure of non-heat treated Cu-10%Ni alloy, revealed the presence of large coarse interconnected intermetallic $(Cu_2Ni)_3$ compound and α-phase. The α-phase is the region where nickel formed solid solution with the copper matrix. Large grain boundaries are observed to be distributed within the grain. The effect attributed to the minimum performance of electrical conductivity exhibited with the as-cast Cu-10%Ni alloy. Ageing at different temperatures influences the electrical conductivity of the fabricated Cu-10%Ni alloy, and this was posited in Plate 2-4. The micrographs at different ageing temperatures revealed homogenous recrystallized fine grains that contained numerous twins. The twins have a Ni-rich γ-phase with an orthorhombic structure which presented a modified structure from the non-heat treated Cu-10%Ni alloy. The fine α-phases and Cu_4Ni_2 intermetallic particles were formed as a result of the ageing process. The variation in grain size after the heat treatment process represents the main reason for the improved electrical conductivity (Abdo et al. 2021). The change in the electrical conductivity for different ageing conditions is attributed to precipitation stages formed during artificial ageing treatment for different temperatures and constant time. Electron scattering can be slowed by dislocations, vacancies, and grain boundaries, which can reduce electrical conductivity (Gao et al. 2018).

Plates 5-6 verified the formation of the intermetallic compound. SEM technique is utilized to provide confidence of phase classification of the metallographic study. Plate 5 shows the SEM micrographs and EDS of non-heat treated Cu-10%Ni alloy. Distinct distribution of undissolved $(Cu_2Ni)_3$ that transformed to α-phase was observed. The EDS revealed phases with the composition of Cu and Ni detected. The presence of fine intermetallic particulates, homogeneously distributed, results in the improvement of electrical conductivity as shown in Plate 6. The micrograph consists of precipitated grains of fine particles of Cu_2Ni_3 uniformly distributed. The combined effect of heat treatment through precipitation hardening induce the improvement of electrical conductivity. In the EDS analysis, Cu, Ni, and C were indicated after the heat treatment process.



Element	Weight %	Atomic %
Cu	89.9	89.2
Ni	10.1	10.8

Plate: 5 SEM Micrograph of Cu-10%Ni and their corresponding EDX spectrum (As-cast)

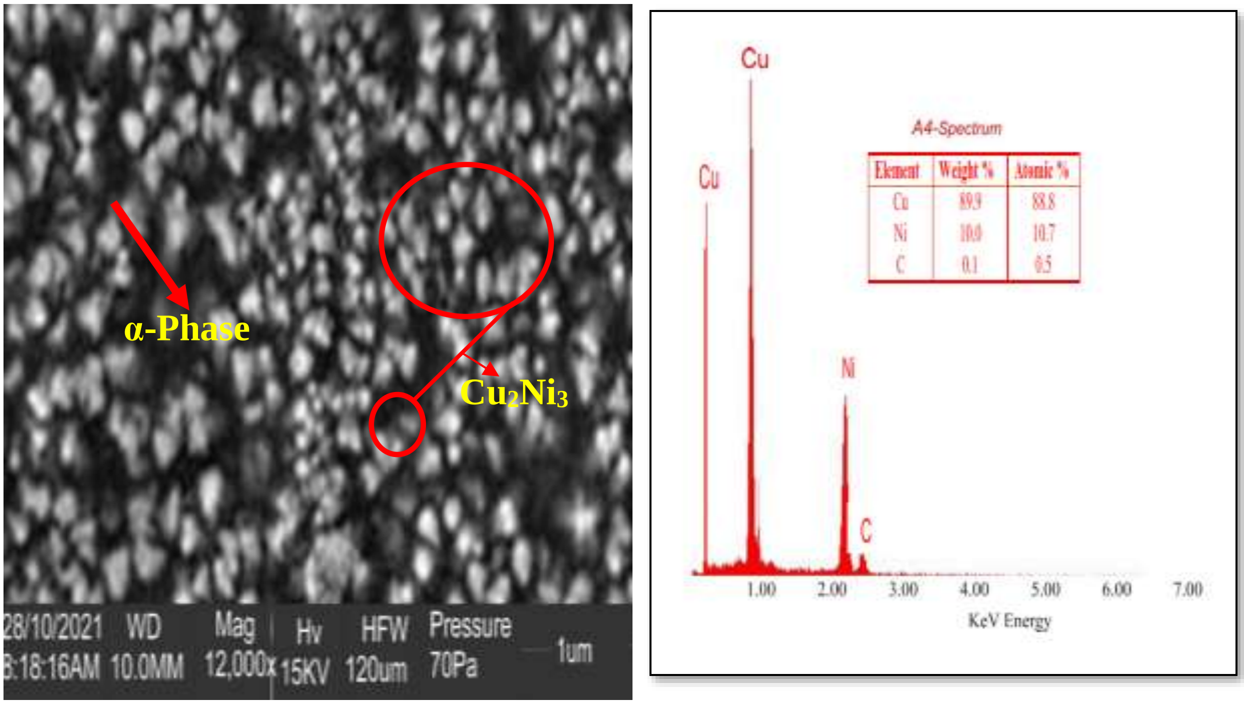


Plate: SEM Micrograph of Cu-10%Ni and their corresponding EDX spectrum (Aged at 500°C)

4.0. Conclusion

In this research, the electrical conductivity of Cu-10%Ni alloy heat-treated at different ageing temperatures and constant time had been examined. Electrical conductivity improves in the heat-treated Cu-Ni alloy in comparison to non-heat-treated Cu-Ni alloy. The conductivity is maximum at the ageing of 500°C-2hr with an electrical conductivity value of 59.01%IACS, while the non-heat-treated Cu-10%Ni alloy recorded the minimum electrical conductivity (46.76%IACS) value. The improvement in the electrical conductivity of the age-hardened alloy as it exhibited greater conductivity may be attributed to the grain disassociation and temperature changes. The microstructure characteristics are directly responsible for the considerable improvement in electrical conductivity demonstrated by heat-treated Cu-10%Ni alloy. The ageing process of Cu-10%Ni alloy transformed the coarse interconnected dendrite grains to equi-axial small grains. The presence of larger grain boundaries after the synthetic process of the developed alloys are the reason for the low electrical conductivity of the non-heat treated Cu-10%Ni alloy. The aged samples exhibit greater conductivity.

5.0 Recommendation

The developed heat-treated Cu-10%Ni alloy should be used to make bulk conductors such as cables, transformer windings, and motor stators and rotors for sea-going vessels. As a result, the alloy is suitable for application in the nautical, aerospace, and other engineering fields.

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