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Effects of Nickel on the Structure and Mechanical Properties of Aluminum Bronze (Cu-10wt%Al).

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ABSTRACT: *This research was carried out to investigate the effects of nickel addition in macro-quantities on the structure and mechanical properties of aluminum bronze (Cu-10wt%Al). The alloy samples were prepared by modifying 0.5-5.0wt% of nickel into the Cu-10wt%Al alloy at interval of 0.5wt%, cast by permanent die casting technique and then machined to the required dimensions for the mechanical tests and microstructural analysis. The specimens were prepared according toASTM E8M standard.The mechanical properties studied included percentage elongation, ultimate tensile strength, Brinel hardness, impact strength and they were conducted using JPL tensile strength tester (Model: 130812), Phase II 900-355 digital motorized Brinell hardness tester equipped with 20X optical microscope and digital impact strength tester (U1820) respectively. The micro structural analysis was conducted using optical metallurgical microscope (model: L2003A) and Carl Zeiss scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). Microstructural analysis of the control sample indicated a continuous region of single α-phase which is believed to be responsible for the high ductility of Cu-10wt%Al alloy as compared to the Cu-10wt%Al-xNi with region of dendrites of $CuAl_2$ intermetallic compound. In the alloy doped with nickel, structural analysis revealed large amounts of fine and evenly distributed dual phase and small single-phase regions. The mechanical properties test results revealed that nickel significantly improved the ultimate tensile strength and hardness but decreased the percentage elongation and impact strength of aluminum bronze.*

Keywords: *Bronze, mechanical properties, microstructure, intermetallic phases, dual phases.*

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I. INTRODUCTION

Aluminum bronzes are a family of copper-based alloys that has found wide industrial application more than any other alloy series (Vin C.2002). The alloy offers a combination of mechanical and chemical properties unmatched by any other alloy series (Vin C, 2002). Their high strength and excellent corrosion resistance have made them most preferred to other forms of bronzes for the fabrication of pipes and pressure vessels (Copper Development Association, 1986).

Generally, aluminum bronzes are used where other materials might fail prematurely or would be more expensive. For example, the alloys find widespread applications in chemical, petrochemical and desalination plants as well as in marine, offshore and shipboard hardware and equipment (CDA 1986).

Aluminum bronzes are copper based alloys containing aluminum as the major alloying element, usually in the range 2-15wt% (Haydar et al. 2014). They differ from other forms of bronzes such as tin bronzes which contain tin as the major alloying element. Aluminum bronzes are mostly available either as cast or wrought form (CDA, 1986). Other alloying elements such as iron, nickel, manganese, tin or silicon can be added to aluminum bronzes, mostly to increase the fluidity, refine and modify the grains, thereby improving the mechanical properties of the alloy.

Studies by Moradlon et al. (2011) show that slow cooling of Cu-10wt%Al base alloy induces a precipitation of very hard but brittle (γ_2-phase) in the alloy structure which drastically reduces the strength and ductility of the alloy. The quest for solution to this problem prompted this research with the sole aim of refining and modifying the deleterious phase through alloying thereby improving the mechanical properties of the alloys. Efforts have been on going by various researchers towards refining the segregatedγ2-phase in the structure of slowly cooled aluminum bronze through alloying thereby improving the mechanical properties.

Haydar et al. (2014) studied the effect of graphite on mechanical properties of aluminum bronzes. Graphite particles of 0.05, 0.1, 0.3, 0.6, 1.0 and 3.0 weight percentages were added as reinforcing elements to the alloy. The microstructural analysis was carried out using scanning electron microscope (SEM), X-ray fluorescence (XRF) and X-ray diffraction (XRD). The results of the tests revealed that addition of 0.3wt% of graphite particles to the alloy brought about a significant improvement on the hardness and compressive strength. The microstructural analysis also revealed the presence of the alpha and beta- phases.

Nwaeju et al. (2017a) investigated the effect of nickel on the structure and mechanical properties of aluminum bronze. Sand casting method was used in the production of a dual-phase aluminum bronze alloy with pre-selected composition of 10% Al-content. The study revealed that the best mechanical properties were obtained with the addition of 4wt% nickel with respect to ultimate tensile strength and % elongation and that hardness decreased with increasing nickel content while the impact strength increased with increasing nickel content from 1wt%-10wt%. Microstructural analysis revealed the presence of primary α-phase, β-phase (intermetallic phases) and fine stable kappa phase which guaranteed the improvement of mechanical properties.

Moradlon et al. (2011) studied the effect of different concentrations of Mg and Ni on the structure and mechanical properties of aluminum bronzes. The study revealed Mg and Ni as grain refiners and that with increasing Mg and Ni content, the wear resistance, tensile strength and hardness of the alloys increased progressively. Labanowski and Ollkowski (2014) studied the microstructure and mechanical properties of BA1055 bronze using optical microscope (OM) and scanning electron microscope (SEM). Results of the study revealed increased mechanical properties resulting from decrease in grain size and increased distribution of the iron-rich k-phase in the alloy microstructure. Nwambu et al. (2017b) examined the effect of zirconium and titanium on the structure and mechanical properties of aluminum bronze. The properties studied were tensile, hardness and impact strength. The specimens were prepared by doping 0.5-2.5wt% zirconium and titanium into the aluminum bronze (Cu-10%Al) at interval of 0.5 percent. The study revealed that tensile strength, impact strength and ductility increased respectively with increasing alloying elements and that the best property was obtained with the addition of 2.5wt% each of zirconium and titanium.Microstructural analysis revealed primary α-phase, β-phase (intermetallic phases) and fine stable reinforcing kappa phase which enhanced the alloy's mechanical properties.

Albuquerque et al. (2010) investigated the refining effect of NbNi on Cu-Al-Be alloy. The correlation of the grain size with the mechanical properties of the alloy was also examined. Results of the investigation revealed increase in toughness and impact strength of the alloy with decrease in grain size.

Nwaeju et al. (2017b) investigated the effect of vanadium and chromium on the structure and mechanical properties of aluminum bronze (Cu-10%Al). The properties studied were tensile strength, yield strength and percentage elongation and the tests were conducted according to BS 131-240 standards. Results obtained showed that hardness, impact strength, % elongation and tensile strength of aluminum bronze increased with increasing concentration of chromium and that the tensile strength, impact strength and hardness also showed increasing trends with increasing concentration of vanadium (from 1wt%-6wt%). Microstructural analysis revealed the primary α-phase, β-phase ($\alpha + \gamma 2$ intermetallic phase) and fine stable reinforcing kappa phase leading toimprovement of the mechanical properties.

Pravir et.al. (2015) studied the effects of zinc, chromium, magnesium and silicon on the structure and mechanical properties of Cu-Al-Mn alloy using differential scanning calorimetry and x-ray diffraction. The microstructural analysis revealed transformation peaks and martensitic structures leading to increase in hardness. Nair et al. (2018) investigated the effect of nickel content on microstructure, hardness and wear rate of surface modified cast aluminum bronzes. The heat source used was gas tungsten arc for modification of the surface. The cast aluminum bronze was coated with nickel using electroplating technique. The coating thickness was varied, the hardness and resistance of the surface modified aluminum bronze increased compared to the parent alloy. EDS results confirmed the presence of $AlNi_3$ and AlNi intermetallic compounds, leading to the increased hardness and wear resistance. Sekunowo et al. (2013) investigated the microstructure and mechanical properties of cast aluminum bronze reinforced with iron granules (millscale). Cast samples of the composite made from metal mould contained millscale in varied amount from 2wt%-10wt%. The samples were homogenized at 1100^{o}C for 10minutes in order to modify the as-cast structure. Standard specimens were prepared from these homogenized samples for tensile, charpy impact, and micro hardness tests while the composite microstructures were studied using an optical microscope. Results revealed that optimum mechanical properties were achieved at 4wt% millscale addition with ultimate tensile strength (UTS) of 643.8MPa, representing 10% increase compared to the conventional aluminum-bronze. The composite also demonstrated impact resilience of 83.9J and micro-hardness of 88.7HRB. The results also indicated that the presence of millscale in the aluminum bronze system induced a stable reinforcing kappa phase resulting to improvement of mechanical properties.Kocak et al. (2018) studied the effect of titanium on the microstructure, mechanical properties and wear behavior of nickel aluminum bronze. Samples with low and high titanium contents were prepared by casting and forging method. Hardness, tensile strength and ductility of samples were measured and wear tests were also performed. Microstructural analysis revealed that grain sizes of cast alloys were refined by titanium addition. With addition of 0.2wt% titanium, the hardness and yield strength slightly increased. However, when titanium addition increased to 0.9wt%, both strength and elongation of cast alloys decreased respectively. These improvements of properties were linked to the increasing K_{111} phase and volume fraction of alpha phase. The wear resistance showed no improvement. Through forging, the volume fraction of fine β phase increased to 37wt%-39wt%, leading to increased strength, hardness and wear resistance.

Nwambu and Nnuka (2018) studied the effect of addition of molybdenum on the microstructures, physical and mechanical properties of copper-10%aluminum alloy produced using sand casting techniques, as a potential replacement for conventional structural materials. Their first approach was casting a specimen with a crucible furnace. Molybdenum was introduced into the cast in different proportions from 1wt%-10 wt%. After the alloying process, the specimens were sectioned, ground, polished and etched before viewing under an optical metallographic microscope. Mechanical and physical tests were carried out on the specimens such as hardness, yield strength, tensile strength, electrical resistivity and electrical conductivity.The results showed that the addition of molybdenum upto 7wt% to copper-10wt%Al alloys increased the hardness, yield strength, tensile strength and electrical resistivity of the alloy with corresponding decrease in ductility and electrical conductivity.

Okayasu et al. (2013) examined the mechanical and wear properties of a new bronze (CADZ). The CADZ consists of the elements 10.5wt%Al, 4.2wtFe%, 3.7wt%Sn and 3.1wt%Ni. Its design was based on Cu-10.5%Al alloy. The Cu-10.5%Al is very hard and brittle. Results showed that a high ductile Cu-10.5%Al alloy was obtained by adding micro quantity of Sn. In the same way, high strength Cu alloy was made by adding the right quantity of Fe and Ni (Fe/Ni = 0.89) so as to create microstructure with small grains. The mechanical properties of the CADZ sample were examined and were compared with commercial bronzes. The tensile strength and wear resistance of CADZ were higher than for the commercial bronzes.

Lin et al. (2016) studied the effects of heat treatments on microstructure and properties of nickel–aluminum bronze fabricated by centrifugal casting (CC) and gravity casting (GC). The microstructural analysis showed that CC alloy, which was totally different from GC alloy, consists of α, k_I, k_{II}, k_{III}, k_{IV} and β phases and the microstructures of the alloy also showed non uniformities from external to internal layer mainly because of the distribution of iron and nickel which were influenced by centrifugal force. The result also revealed that mechanical properties of CC alloys were superior to those of GC alloys. The ultimate tensile strength and hardness increased and this was attributed to the presence of the finely reinforcing kappa phases.

II. MATERIALS AND METHOD

Pure copper wire (99.99%) and pure aluminum wire (99.99%) were used as the base materials for the experimental study while nickel of 98.7% purity was used as the alloying element. For fabrication of the Cu-10wt%Al base alloy, 727g of the pure copper was first charged into the preheated crucibleand heated to melt at about 1134^{o}C. The molten copperwas superheated for 5 minutes to increase its fluidity. After superheating, 82g of the pure aluminum wire was introduced into the molten copper. After 5 minutes, the melt was stirred vigorously to ensure homogeneity. The melt was poured into a preheated iron mould with dimension 20mm in diameter and 350mm in length and allowed to cool to room temperature. The same fabrication process was repeated and the melt was doped with pure nickel wrapped in an aluminum foil at concentrations of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0wt% respectively for the fabrication of Cu-10wt%Al-xNi alloy. The melt was stirred and cast. The cast specimens were machined to the required dimensions for the mechanicaltests. The mechanical tests were carried out using100KN capacity JPL tensile strength tester in acordance with ASTM E8M standard, Phase II 900-355 digital motorized Brinellhardness tester equipped with 20X optical microscope and digital impact strength tester (U1820) for the evaluation of the ultimate tensile strength, hardness and impact strength of the developed alloys respectively. The samples for structural analysis were subjected to filing, grinding, polishing and etching using a rectangular file, an electric grinding machine, emery paper of grit sizes (400, 600, 800, 1200μm), polished to mirror surface using an aluminum oxide powder, rinsed with water and dried using an air-gun drying machine and then etched with 8g $FeCl_3$ + 20ml HCl+120cm^3 H_2O solution. The etched surfaces were dried using Bosch GHG660LCD heat gun machine.Thereafter, the microstructure was observed by using L2003A type optical microscope (OM) and Carl Zeiss scanning electron microscope (model: EVO LS 10) at magnifications of X400 and X1500 respectively. Elemental composition was verified by using energy-dispersive x-ray spectroscopy (Edax EDS) at accelerating voltage 5kV.

III. RESULTS AND DISCUSSIONS

3.1 Microstructural Analysis and Mechanical Properties of the developed Alloys.

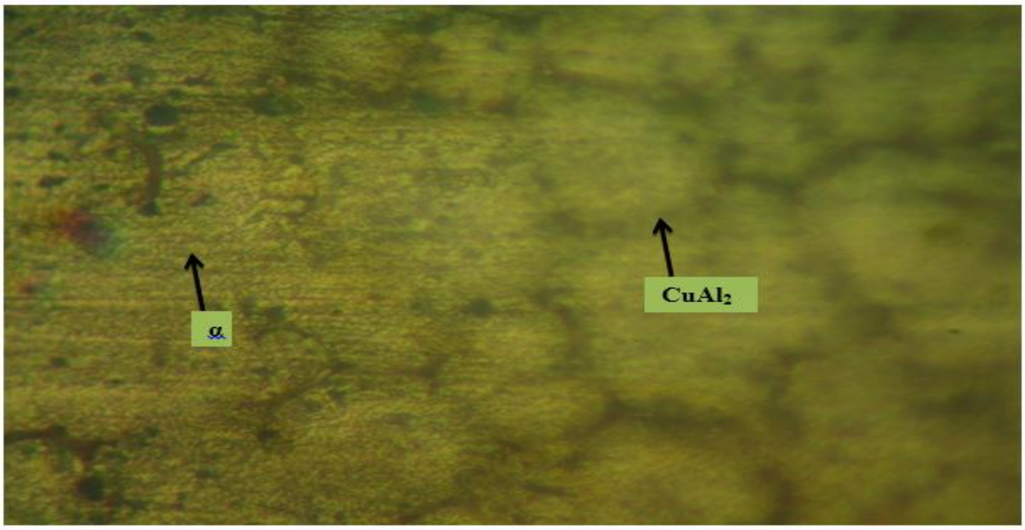

Plate 1: Micrograph of Cu-10wt%Al alloy

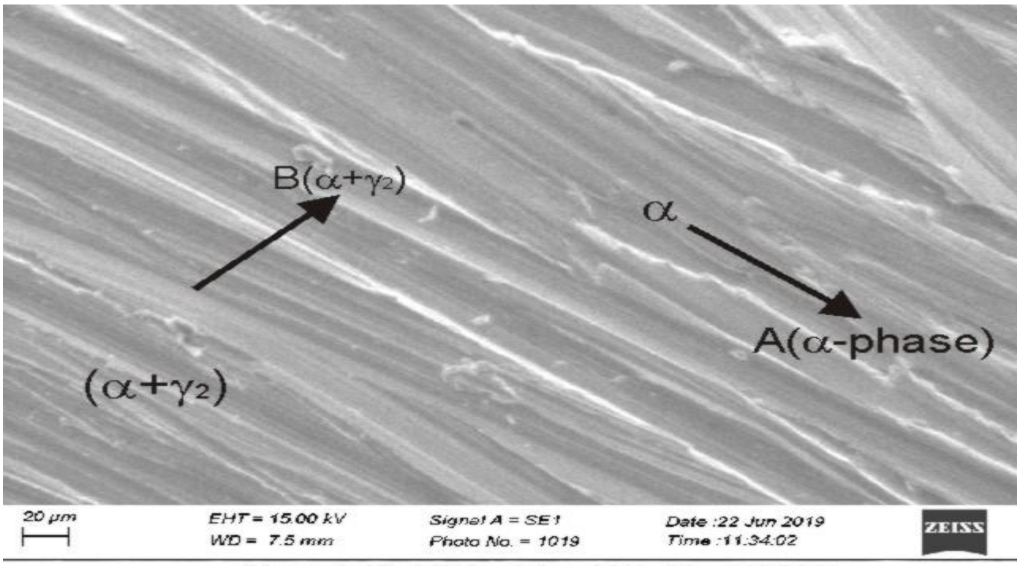

Plate 2: Scanning electron micrograph (SEM) of Cu-10wt%Al alloy (As-cast).

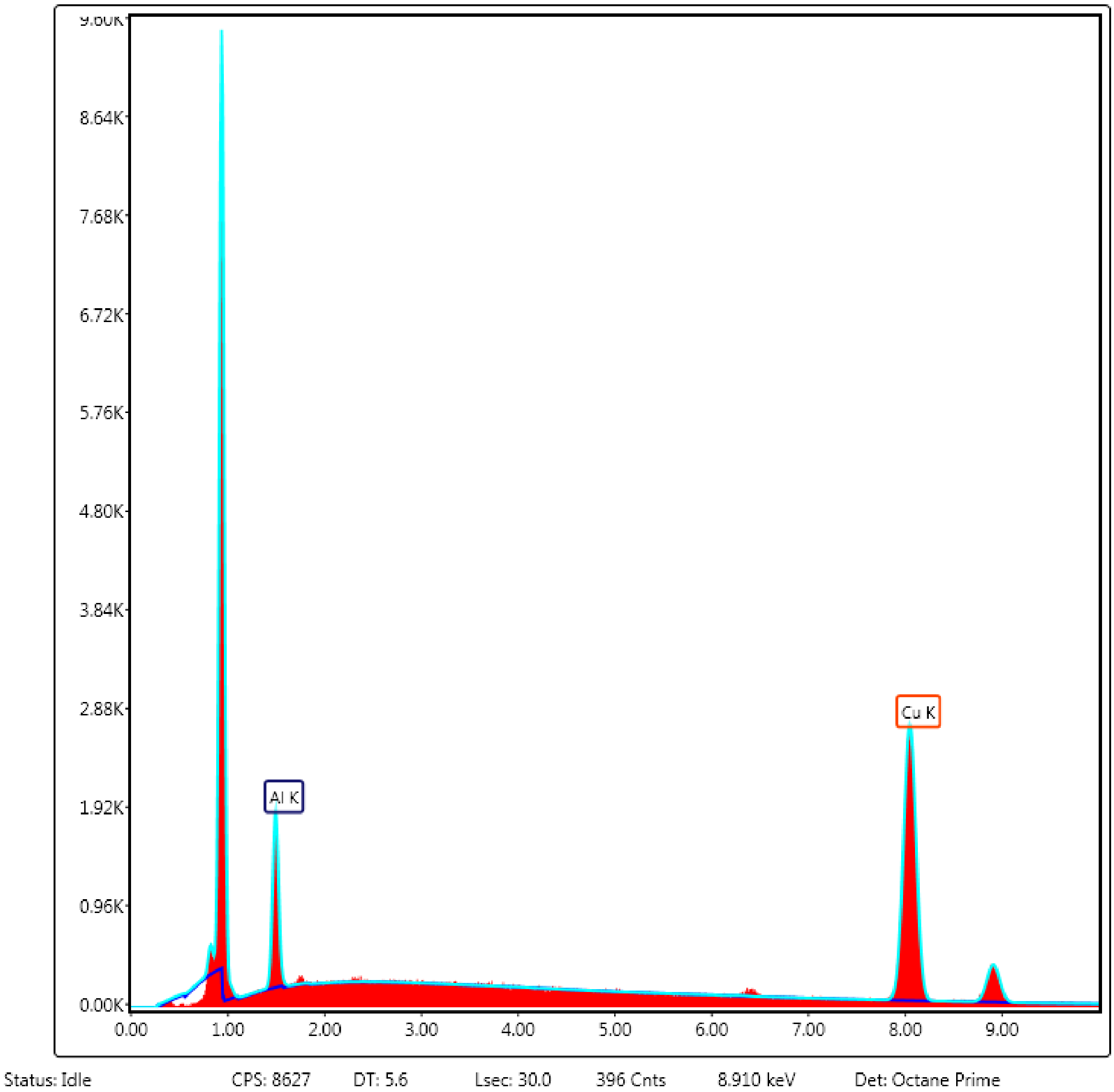

Plate 3: Energy dispersive spectrum (EDS) of Cu-10wt%Al alloy

Plates 1,2 and 3 show the optical, scanning electron microscope (SEM) and EDS spectrum analyses of the surface morphology of the as-cast aluminum bronze (Cu-10wt%Al) respectively. Analysis of the micrographs and SEM revealed the presence of two regions which included the eutectic α-solid solution of aluminum in the copper matrix and the unevenly distributed typical dendrite of intermetallic phase $CuAl_2$. The $CuAl_2$ intermetallic phase is present in form of dark dendrite in the copper-aluminum alloystructure. The microstructure indicates large region of α-single phase which is believed to be the cause of the high ductility of Cu-10wt%Al alloy compared to the rest of the alloys as shown in Figure 1.

Analysis of the spectrum indicated that the as-cast sample is composed of copper, nickel and aluminum as the major elements.

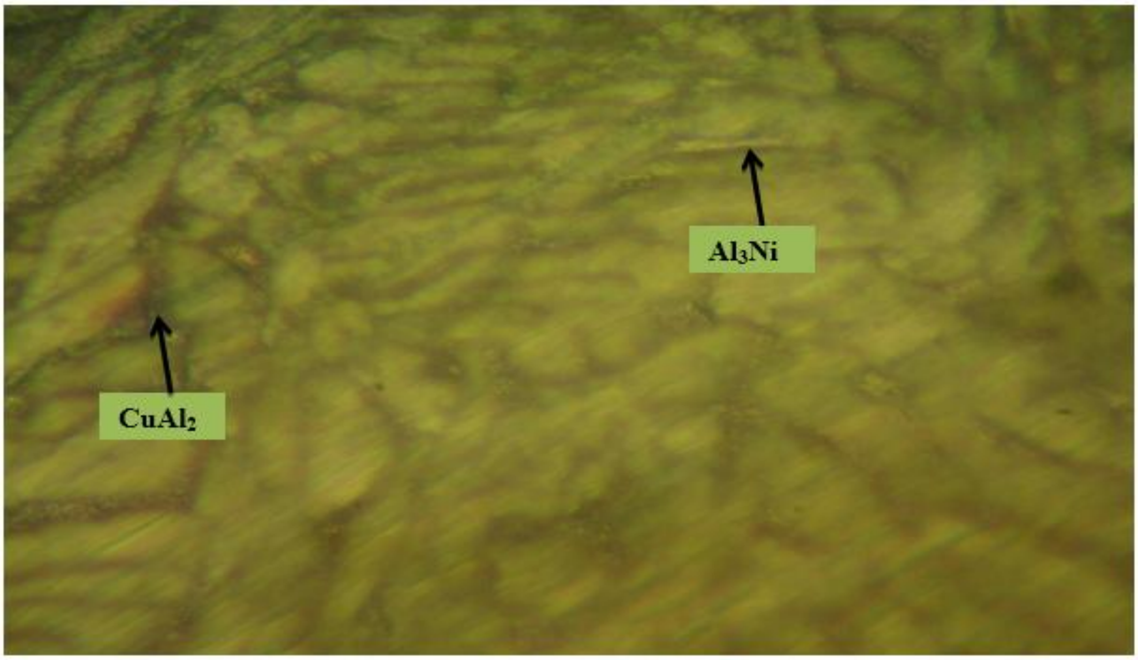

Plate 4: Micrograph of Cu-10wt%Al-0.5wt%Ni alloy

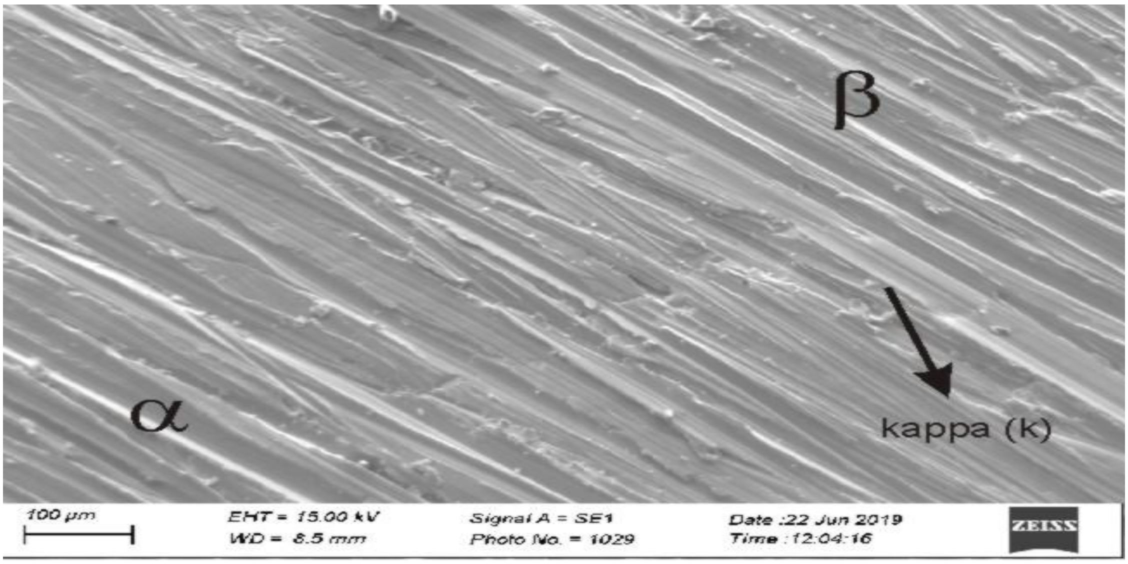

Plate 5:SEM of Cu-10wt%Al-0.5wt% Ni alloy

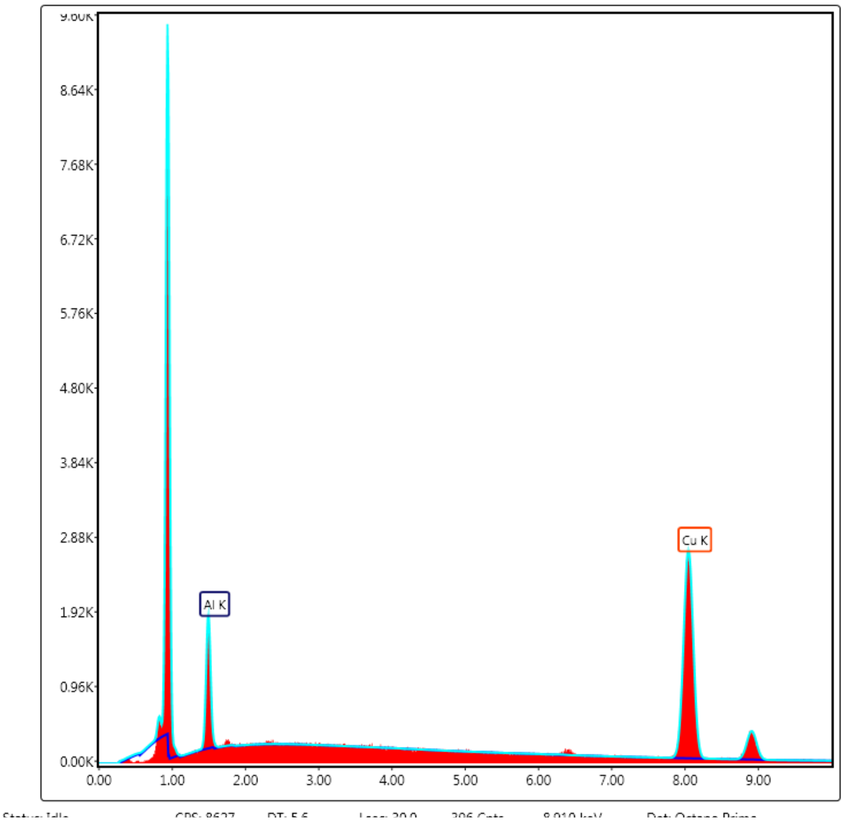

Plate 6:EDS of Cu-10wt%Al-0.5wt%Ni alloy

The analysis of the surface morphology of aluminum bronze doped with 0.5wt% of nickel is presented in Plates 4-6.

The micrographs of the alloy doped with nickel showed the presence of intermetallic compound (Al_3Ni) precipitated in the copper matrix. It was also observed that the microstructure of the alloy revealed α-phase surrounded by elongated dark β-phase. The combined effect of aluminum and nickel produces a kappa precipitate which has the same structure as that of β-phase present. The size and disposition of kappa (k) phase present in the structure caused the reduction in ductility with an increase in hardness of Cu-10wt%Al-xNi alloy as evidenced in figure 1 and 2.

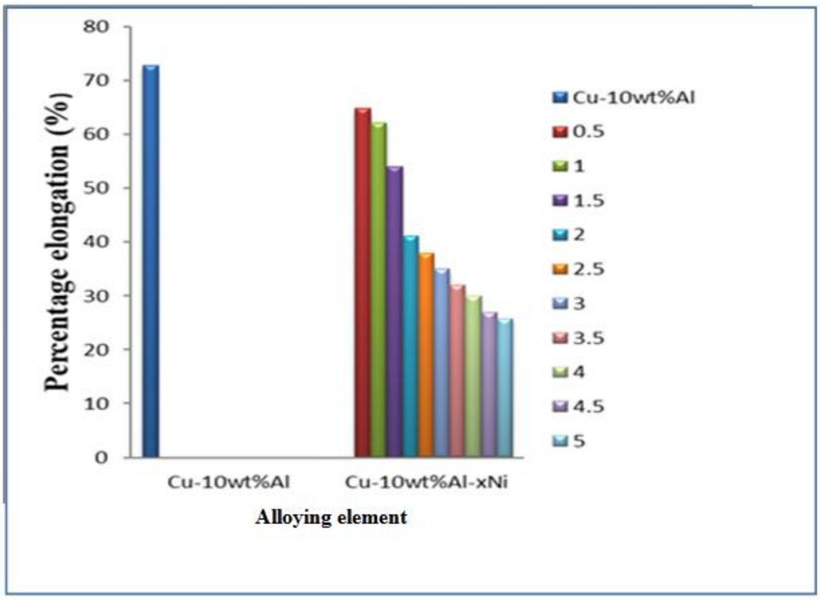

Figure 1: Effect of nickel on the percentage elongation of aluminum bronze (Cu-10wt%Al)

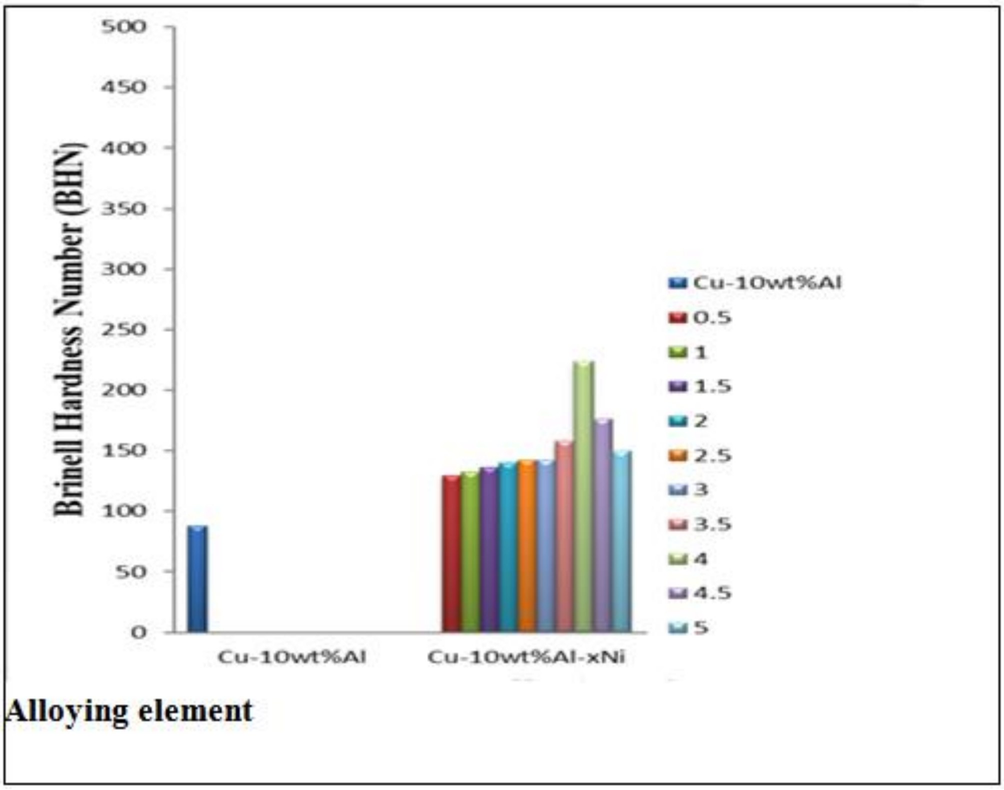

Figure 2: Effect of nickel on the hardness of aluminum bronze (Cu-10wt%Al).

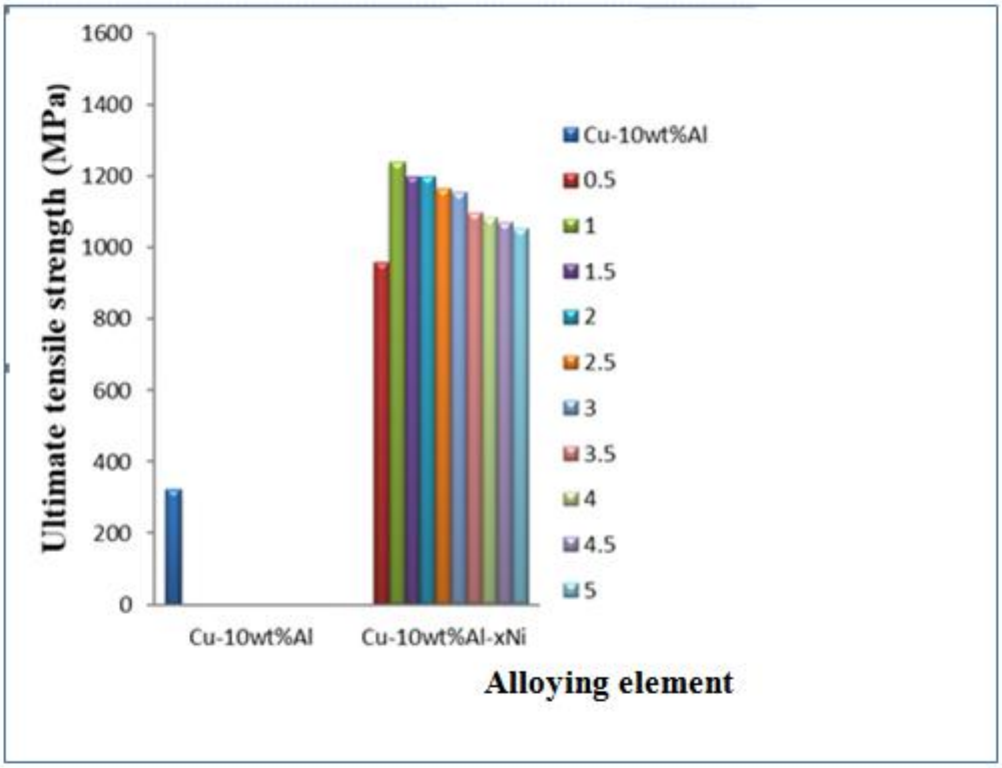

Figure 3: Effect of nickel on the ultimate tensile strength of aluminum bronze (Cu-10wt%Al)

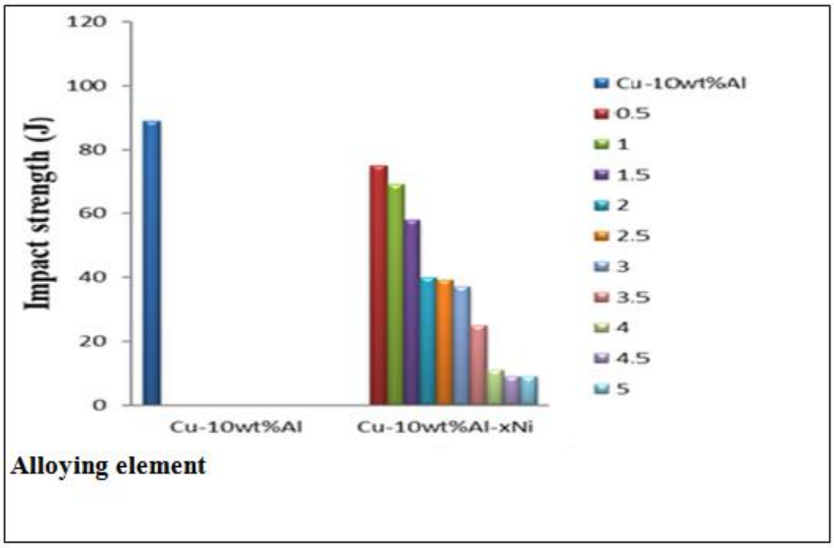

Figure 4: Effect of nickel on the impact strength of aluminum bronze (Cu-10wt%Al)

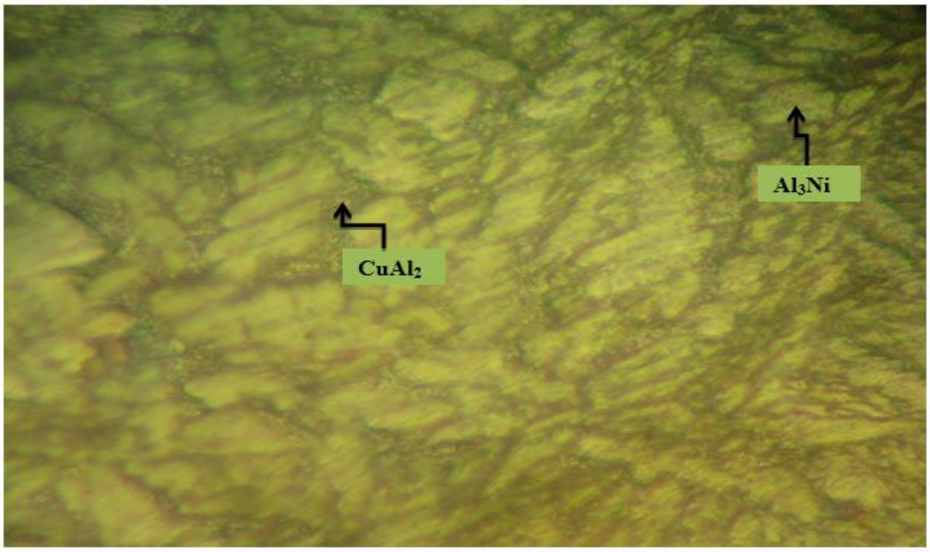

Plate 7: Micrograph of Cu-10wt%Al-1.5wt%Ni alloy

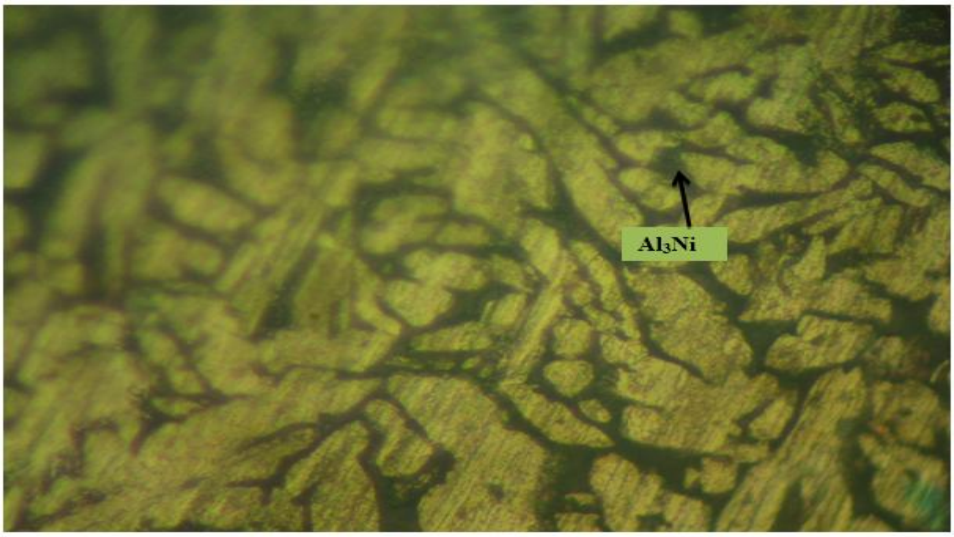

Plate 8: Microgragh of Cu-10wt%Al-2.5wt%Ni alloy

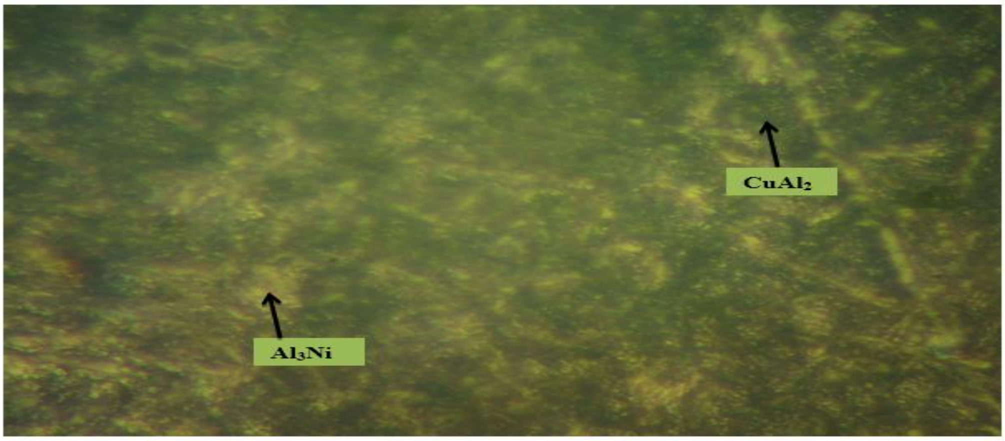

Plate 9: Microgragh of Cu-10wt%Al-3.5wt%Ni alloy

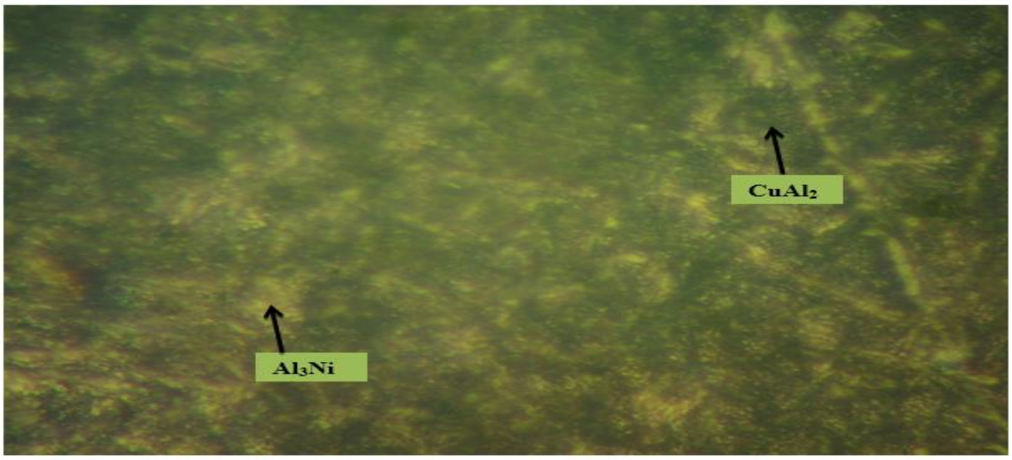

Plate 10: Microgragh of Cu-10wt%Al-4.5wt%Ni alloy

The resultant effect of addition of other concentrations (1.5wt%-4.5wt%) of nickel on the structure and tested mechanical properties of aluminum bronze, that is, percentage elongation, ultimate tensile strength, hardness and impact strength is presented in plates 7-10 and figures 1-4 respectively. Figure 3 clearly showed that the ultimate tensile strength of Cu-10wt%Al alloy was increased significantly by increasing concentrations of nickel within the range of 0.5-1wt%. The improvement on the tensile strength of the doped alloy was induced by the refinement and modification of the $CuAl_2$ intermetallic compound which led to increase in grain boundary area and increased barriers to dislocation movement and hence increase in the tensile strength of the alloys. Within the range 0.5-1wt% nickel, the ultimate tensile strength of Cu-10wt%Al-Ni alloy increased; reaching maximum at 1wt%. Cu-10wt%Al-1wt%Ni recorded maximum of 1240 MPa (286.3% increase). The tensile strength decreased rapidly with increasing concentrations of nickel above the range (0.5-1wt%). The decrease in tensile strength resulted from increase in evolution of the amount of Al_3Ni phase which is brittle.

The variation of percentage elongation of copper-10wt%aluminium with different concentrations of nickel is shown in Figure 1. The analysis of Cu-10wt%Al alloy showed that it recorded about 72.8% percentage elongation. By addition of 0.5wt% nickel, the percentage elongation decreased from 72.8% to 64.8%, indicating about 11.0% decrease. Figure 1 also showed a decreasing trend in percentage elongation of Cu-10wt%Al-Ni alloy with increasing concentration of nickel.

Figure 2 shows the variations of hardness of Cu-10wt%Al and Cu-10wt%Al-xNi alloys with x representing different concentrations of nickel. The Figure shows that the hardness of Cu-10wt%Al alloy was increased from 88 BHN to 129 BHN by addition of 0.5wt% nickel indicating about 46.6% increase in hardness of Cu-10wt%Al alloy. The improvement of hardness of the alloys was induced by the refinement and modification of the $CuAl_2$ intermetallic compound in the copper matrix. This increased the number of the grain boundary which served as dislocation motion impediment, and so increased the hardness of the alloy. Cu-10wt%Al-Ni alloy showed its peak hardness at 4wt% (224 BHN).

Figure 4 shows the variation of impact strength of copper-10wt%aluminum alloy with different concentrations of nickel. The Cu-10wt%Al alloy showed the highest impact energy, (89J). The impact strength of the alloy decreased on addition of higher concentrations of nickel decreasing from 89J to 75J which indicated about 15.7% decrease on addition of 0.5wt%Ni.

IV. CONCLUSION

A thorough investigation of the effect of nickel addition on the structure and mechanical properties of aluminum bronze (Cu-10wt%Al) was carried out using standard engineering techniques. The following conclusions were drawn from the results of the investigation. The Cu-10wt%Al alloy showed better ductility than Cu-10wt%Al-Ni alloy and the structure and mechanical properties of the studied alloy were sensitive to the concentration of the alloying element. The Cu-10wt%Al-Ni alloy showed decreasing trends in percentage elongation with increasing concentrations of nickel. The improvement of the ultimate tensile strength and hardness properties of the alloy doped with nickel was as a result offormation of fine grains and modification of the $CuAl_2$ intermetallic compound produced by nickel addition. Within the range, 0.5-1wt% nickel, the ultimate tensile strength of Cu-10wt%Al-Ni alloy increased reaching maximum at 1wt%. The tensile strength decreased rapidly with increasing concentrations of nickel above the range (0.5-1wt%). The decrease in tensile strength is attributed to the increase in evolution of the amount of Al_3Ni-phase which is brittle. The impact strength of Cu-10wt%Al-Ni alloy decreased in line with the increasing concentrations of the alloying element just as the case with percentage elongation.

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