International Journal of Research in Engineering and Innovation
(IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Effect of nickel addition on the structure and mechanical properties of aluminium bronze (cu-10%al) alloy

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Abstract

This research was undertaken to investigate the effect of nickel macro-addition on the structure and mechanical properties of aluminium bronze. Sand casting method was used in the production of a dual-phase aluminium bronze alloy with pre-selected composition of 10% Al-content. The properties studied were tensile strength, yield strength, percentage elongation using universal tensile testing machine (SRNO0723), impact strength using charpy machine (U1820) and hardness using Brinell hardness tester model B 3000(H). The tests were conducted according to BS 131-240 standards. The specimens were prepared by doping 1.0 -10wt% of nickel into Cu-10%Al alloy at 1.0 percent interval. Microstructural analysis was conducted using L2003A reflected light metallurgical bench microscope and PHENOM ProX scanning electron microscope. Results obtained showed that optimally improved mechanical properties were achieved at 4wt% nickel addition with respect to ultimate tensile strength and %elongation. Hardness on the other hand, decreased with increase in nickel content while impact strength increased with increase in composition of nickel from 1-10wt%. Microstructural analysis revealed the presence of primary α-phase, β-phase (intermetallic phases) and fine stable reinforcing kappa phase and these phases gave rise to the enhanced mechanical properties. This research have established that aluminium bronze doped with nickel increased the tensile strength, ductility, and impact strength and reduces hardness and is therefore recommended for applications in automobiles and allied engineering industry.

Keywords: microstructure, nickel additives, aluminium bronze, mechanical properties.

1. Introduction

Aluminium bronze is very useful in a great number of engineering structures with a variety of the alloy finding its applications in different industries [1]. Aluminium–bronze alloys are copper based alloys containing aluminium as the major alloying element usually in the range 5%-14% in the base alloy [2]. Other alloying elements such as nickel, iron, manganese, silicon, etc. are sometimes intentionally introduced into aluminium bronze depending on the intended property modification and applications. Presence of aluminium increases the mechanical properties of the alloy by the establishment of FCC phase which could improve the casting and high temperature properties of the alloy [3]. Other alloying elements improve the mechanical properties such as strength, toughness, resistance to corrosion and magnetic behaviour, and modify the microstructure. For instance nickel improves the corrosion resistance while iron is a grain refiner [4]. The relatively high strength of aluminium bronze compared with other copper alloys makes it suitable for the production of forgings, plates, sheets, extruder rods, and sections [5]. Its excellent corrosion resistance property makes it recommendable as an important engineering material for highly stressed components in corrosive environment [6].
Aluminium bronze is available both in wrought and cast forms and is readily weldable and fabricated into components such as pipes and pressure vessel.
The binary phase diagram of copper-aluminium is complex, but for the commercially important binary alloys the most important reaction is the eutectoid (phase transformation of one solid into two solids) which occurs at 565ºC [7]. It can be categorized into three distinct series

as can be seen from the equilibrium diagram of copper-aluminium system Figure 1. They constitute the α-series, the α +β series and $\alpha + \gamma_2$ series; possessing properties that can be obtained by suitable alloying and heat treatment which has opened immense possibilities for its application in various engineering field [8]. From the equilibrium diagram in Figure 1, it could be seen that the β- structure is stable only at high temperature and undergoes $\alpha + \gamma_2$ transformation at about 565ºC. β -phase gives high hardness combined with relatively high mechanical properties under normal condition, but severity of cooling results in the formation of β-phase martensitic structure which has lower elongation. The α/β alloys have favourable combination of strength and corrosion resistance. The eutectoid structure of $\alpha + \gamma_2$ which has a lower electrochemical potential corrodes at high rate and it has to be avoided. The decomposition of β to $\alpha + \gamma_2$ which occurs during slow cooling or reheating in the temperature range between 550ºC and 350ºC, has to be avoided [9].

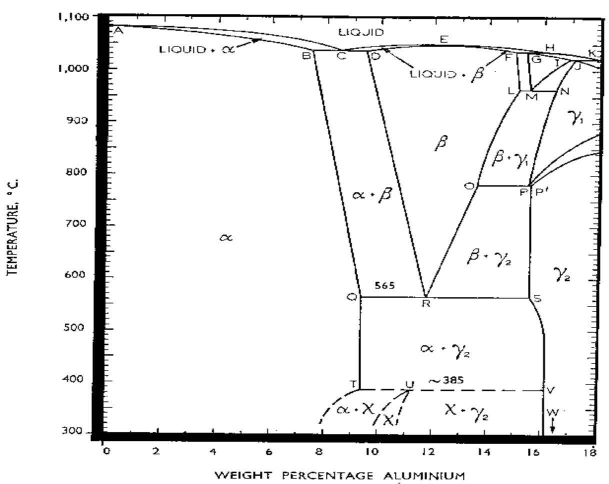

Figure 1: Cu-Al phase diagram. (Source: Copper Development Association. (1992). Equilibrium Diagrams.CDA Publication No.94, p. 17.)

The role of alloying elements is to stabilize β-phase and effectively permit slower cooling. When these alloying elements are present at certain composition level, they modified the structure of aluminium bronze and instead of normal α +β structure and α+ κ structure with small but tolerable amounts of β-structure formed. The complex aluminium bronze alloy which is notable for their high strength, corrosion and erosion resistance can be cast easily without the influence of the eutectoid structure [9]. Hence, this research work focuses on macro-addition of nickel to molten Cu-10%Al in order to improve and modify the structure and mechanical properties of aluminium bronze.

Nickel, positively affects the mechanical and corrosion properties of alloy. For instance, addition of nickel to copper alloy, improves its strength and durability and also resistance to corrosion and erosion cavitation [10]. Nickel is the most frequent alloying element in aluminium bronze. Its addition has a strong influence in the stabilization of β-structure [11].

2. Materials and Method

2.1 Materials and equipment

The under listed materials and equipment were used for the research work; pure copper scrap (99.9%), pure aluminium scrap, nickel granules, weighing balance, crucible furnace, vernier caliper, bench vice, lathe machine, electric grinding machine, hack-saw, stainless steel crucible pot, mixer, scooping spoon, electric blower, rammer, moulding box, impact testing machine (U1820), hardness testing machine (A 3000 H), universal tensile testing machine (model SRNO0723), emery papers of different grits, air drying machine, metallurgical bench microscope (L 2003A) with digital camera and PHENOM ProX scanning electron microscope.

2.2 Method

The methodology adopted to carry out these research essentially involved alloy preparation by melting and casting techniques. The alloying element (nickel) was added separately in concentration of 1-10% by weight to molten Cu-10%Al alloy, stirred and sand cast. Subsequently, specimens obtained from the casting were subjected to machining and mechanical test such as ultimate tensile strength, impact strength, yield strength, hardness and ductility. The microstructures of the samples were also studied using, metallurgical microscope and scanning electron microscope.

2.2.1 Experimental procedure

(a) Alloy preparation

The sequence of operations followed to obtain the studied specimens and mechanical test samples include; the use of calculated quantities of pure copper scrap, aluminium scrap, nickel granules. The materials were weighed out in their appropriate proportions respectively using a weighing balance.

Sand mould was prepared and used for the casting of the specimens. Meanwhile, impurities such as metals, hard lumps, stones etc. were removed from the moulding sand using 500μm and 400μm sieves to obtained fine and uniformly distributed grain size. The sand was mixed well in a sand mixing machine with the addition of a little quantity of water to ensure uniform distribution of the ingredients. The foundry floor was cleared of dirty and floor board was put in place. Some moulding sands were sprinkled on the floorboard surface and then patterns were introduced. Sand was introduced and rammed; the ingate runner and risers, plumbago (painting materials), rammers etc. were used to prepare the mould. The patterns were removed and the cavities created were repaired. The

pattern removal was done slowly to prevent mould damage. After the pattern was removed and mould repaired, ash was then sprinkled on the cavities to enhance easy flow of the molten metal inside.
The furnace used for the melting operation is a crucible furnace with a crucible steel pot of maximum controlled temperature of about 1750ºC. Prior to charging of metal into the furnace, the crucible pot was removed and properly cleaned to avoid contamination by other material inclusion.

(b) Melting and Casting of alloys

This operation was carried out to produce eleven separate specimens for the research work. The bailout crucible furnace with steel crucible pot was pre-heat for about 10minuties. For the control sample, 163.44g of Cu and 17.18g of Al were measured out. Copper was charged into the furnace pre-set at 1100ºC and heated till it melted. Aluminium was then allowed to dissolve in the molten copper for 6minutes and stirred properly to ensure homogeneity. The alloying element (nickel) were then introduced separately into the melt (Cu-10%Al) based on the compositions, after the control sample had been cast. The melt was manually stirred intermittently in order to ensure homogeneity and facilitate uniform distribution of the alloying element. Then molten metal was poured into the mould cavities and allowed to solidify for about 3minutes before shakeout from the mould.

(c) Machining

The machining operation was carried out using a three jaw chuck lathe machine. The samples to be machined were firmly clamped on the machine and facing, turning and shaping operations were done on the clamped samples with the aid of a cutting tool mounted on the post of lathe machine. Eventually the required dimensions for impact, tensile and hardness test samples as well as microstructural analysis were obtained.

(d) Tensile test

The tensile test was conducted using horizontal bench top Mansanto Tensometer machine (SRNO0723) and the test carried out at room temperature. Specimens for this test were machined to a dumbbell shape which is the standard specifications so as to fit the grips as shown in Figure 2. The testing process started with the specimen labelled 1 and continued on to 21. The specimens were placed each between the two grips, these held the specimen in place, gradually force was applied on the work piece till it fractured. Different values of force and extension were obtained and reported. Hence, the specimen were tested to determined their ultimate tensile strength, ductility (%elongation) and yield strength. These properties determined were tabulated in Table 1.

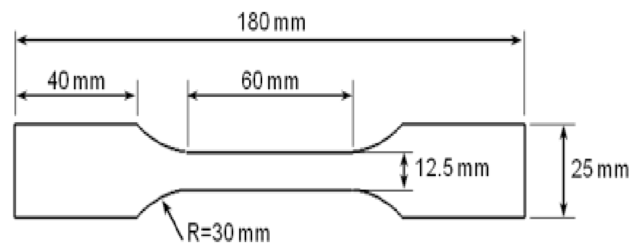

Figure 2: Tensile test specimens

(e) Hardness Test

This test was conducted using a Brinell testing machine model B3000 (H). The specimen each 20mm in diameter were polished, placed on an adjusting table below the control panel separately, the table was raised to the focus of the microscope which helped to determine the exact spot for indentation. On pushing the start button on, the microscope returned automatically to its resting position and the spherical indenter was carefully placed on the specimen surface. A specified force was applied and maintained for about 15seconds after which the indenter bounced back to its former position. The indentation was clearly seen on the monitor of the Brinell testing machine, the diameter of the indentation was obtained by placing four metric lines on the edges of the indentation using hand control knob. The diameter obtained and the force applied was used by the machine to calculate the Brinell hardness of the work piece. Brinell hardness result was displayed on the bottom left hand corner of the monitor. Three (3) indentations were taken on each specimen and the mean was obtained.

(f) Impact test

Impact test was carried out with charpy impact test machine model (U1820). The specimens were machined to a dimension of (10 x 10 x 55) mm with a V-notch of depth 2.5mm at its mid-point. The samples to be tested were placed at the machine's sample post with the notch facing the hammer. The hammer was raised to an angle of 45ºC and released to swing through the positioned sample in order to break it. As the sample was broken by the swing hammer, the impact energy absorbed was read from the charpy impact energy scale calibrated in joules. Hence, the impact energy of all the samples as well as the control sample was captured.

(g) Microstructural examination

The microstructure of the experimental specimen was studied using optical metallurgical bench microscope and Scanning electron microscope. In the process, a cubic sample was cut from each of the 11 cast samples. The samples were ground by the use of series of emery papers of different grits with decreasing coarseness from 220, 340, 400, 600, 800, 1000 and 1200 grades and polished using fine α-alumina powder. The specimens were washed thoroughly and dried using the oven dryer. After drying, the specimen were inserted into dilute hydrofluoric acid which was the etching reagent for about 10-15 seconds and layers of the specimens were attacked chemically until the polished surface were slightly discoloured or dull in appearance. The etched specimens were washed in water to stop the etching action. The specimens were dried and viewed under a high power electron microscope with a magnification of x400 and micrographs showing the different morphologies of the cast alloy were taken. For SEM observation, the test sample was placed on the setup. The setup was put in an ultrasonic cleaning process. Both the sample and the setup were placed in front of an air heater in order to make it dry before test. After the drying process, both the sample and stup were placed in a special tube for pre-vacuum process. The sample on the stup was put under scanning electron microscope machine for testing.

3. Results and Discussion

The results obtained from the investigation are presented in Table 1 and Figure 3-6 while the microstructures developed by the specimen are shown in plates 1-13.

Table1. Mechanical properties of Cu-10%Al doped with nickel

Sample Type	UTS (MPa)	Yield Strength (MPa)	% Elongation	Hardness (BHN)	Impact (joules)
A (Cu-10%Al)	144	98	9.30	103	15.1
A + 1%Ni	768	414	14.64	132	30.0
A + 2%Ni	788	440	15.10	127	32.0
A + 3%Ni	795	452	15.68	123	33.5
A + 4%Ni	835	464	15.68	122	33.6
A + 5%Ni	723	385	14.01	118	34.0
A + 6%Ni	714	366	13.90	116	35.0
A + 7%Ni	677	316	13.40	114	37.0
A + 8%Ni	541	296	12.90	112	38.0
A + 9%Ni	509	289	12.60	109	39.0
A + 10%Ni	489	223	12.00	106	39.2

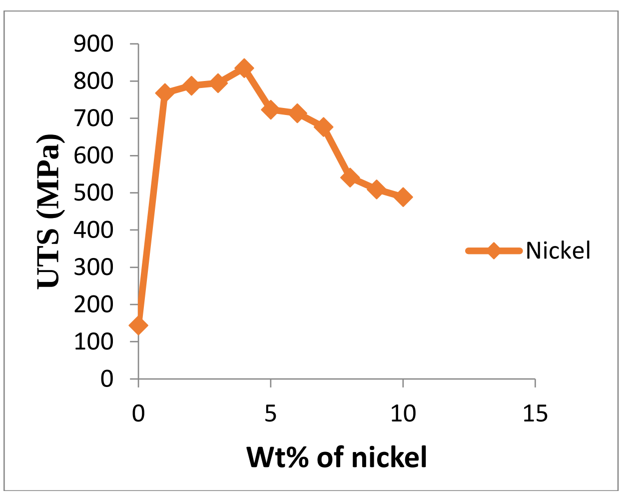

Figure. 3. Effect of nickel content on the UTS of Cu-10%Al alloy.

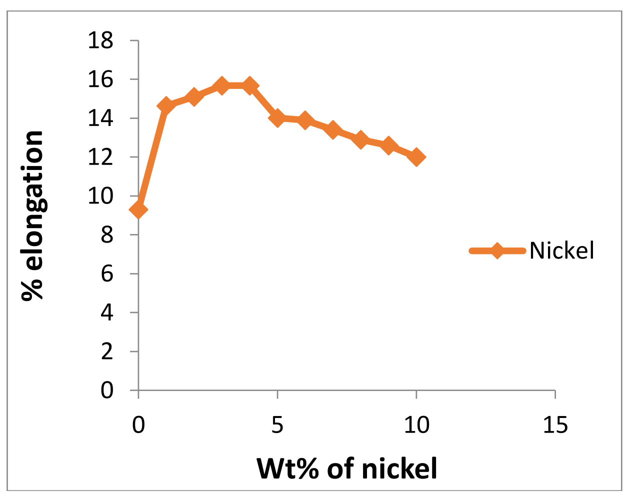

Figure. 4. Effect of nickel content on the % elongation of Cu-10%Al alloy

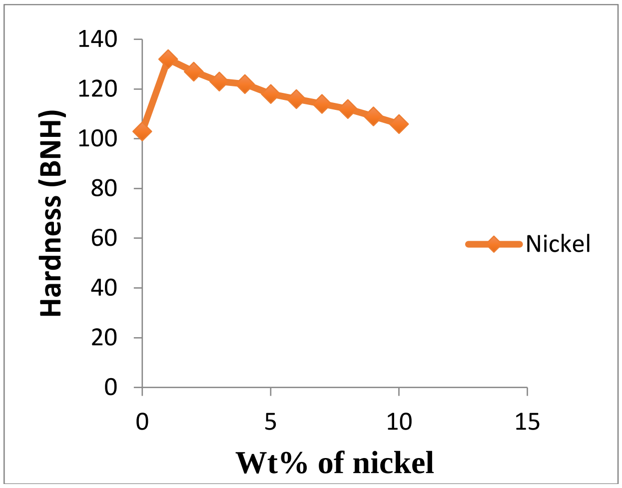

Figure. 5. Effect of nickel content on the hardness of Cu-10%Al alloy

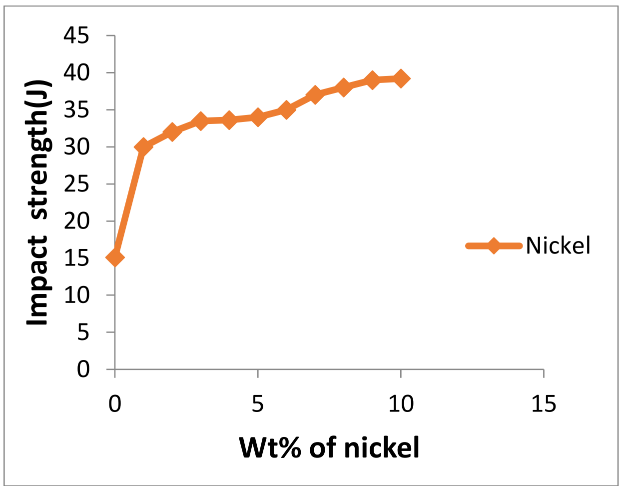

Figure. 6. Effect of nickel content on the impact strength of Cu-10%Al alloy

From the obtained result, addition of nickel within the studied range of composition improved mechanical properties of aluminium bronze as compared to the control sample (Cu-10%Al). Figures 3 and 4 revealed that ultimate tensile strength and percentage elongation of Cu-10%Al alloy increased up to 4% and decrease from 5-10 wt%.The figures indicated that the highest values were obtained at 4wt% before sharp fall on the properties occurred. The presences of nickel in the alloy matrix increased the nucleation sites for the transformation of kappa precipitates from α-phase. The kappa precipitates are soft, stable and coherent secondary phase in the copper matrix and this provided substantial level of impediments to dislocation motion, hence the improvement on the mechanical properties. Figure 5 and 6 show that hardness decreased with increase in composition of nickel while impact strength increased with increase in composition of nickel from 1-10wt%. The highest impact energy of 39.2J which is above control sample was obtained. It was shown in Figure 7 that the presence of nickel in cast Cu-10%Al alloys prevented the large proportion of β-phase to form in the microstructure Plates 2-5. β-phase is hard and brittle than α-phase and it gives high hardness [12]. Thus, steady decrease in hardness properties from 1-10wt% was observed.

The different microstructures developed by the alloys corresponding to the amount of nickel addition are shown in Plates 1-13. The microstructure of the control sample is shown in Plate 1 while microstructures with varied amount of nickel are presented in Plates 2-11. Apart from different intermetallic phases, two major phases are revealed under optical metallurgical microscope; α-dendrites and β-phase. The β-phase decompose into a lamellar eutectoid $\alpha + \gamma_2$ phase while the needle like α-phase leads to the formation of fine lamellar form of kappa-phase. Eutectoid $\alpha + \gamma_2$ structure is hard and brittle, undesirable for commercial applications.

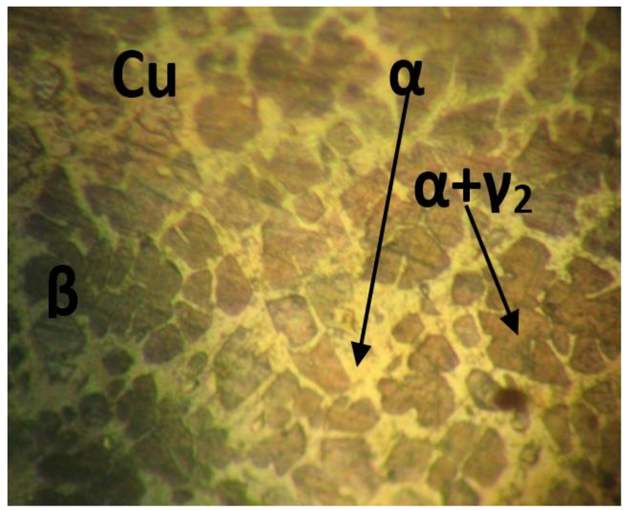

Plate 1

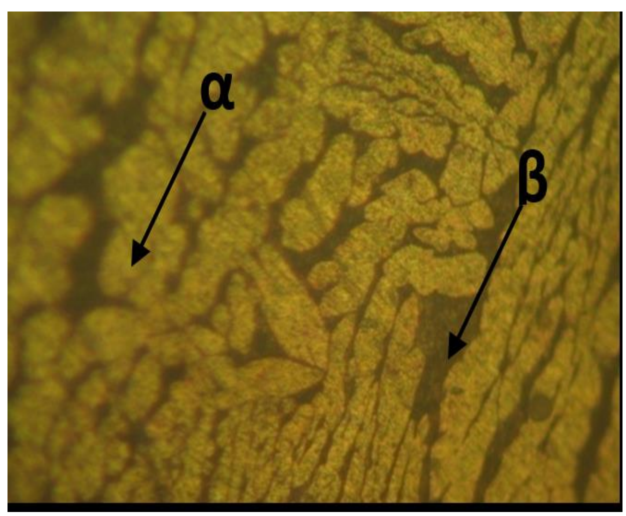

Plate 2

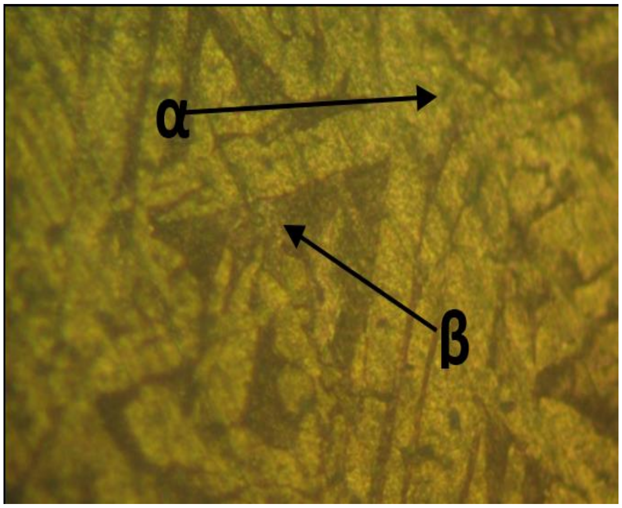

Plate 3

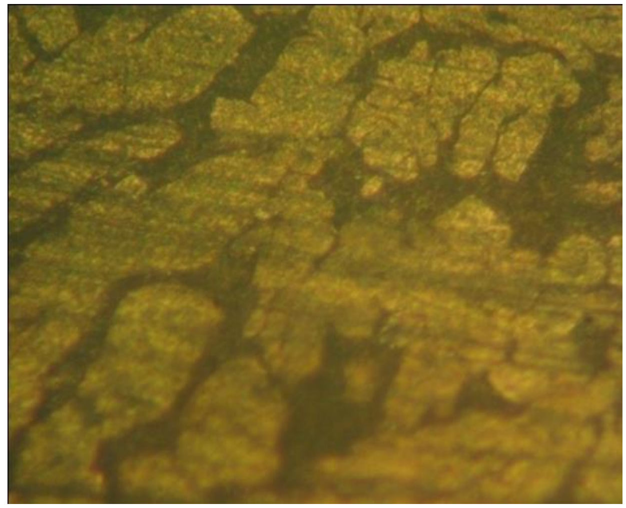

Plate 6

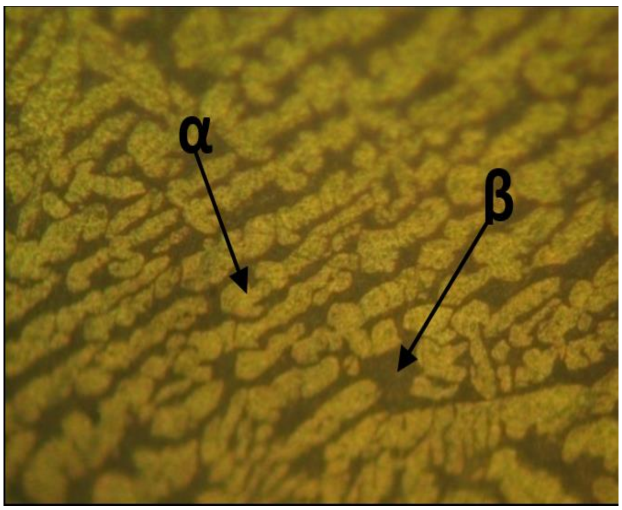

Plate 4

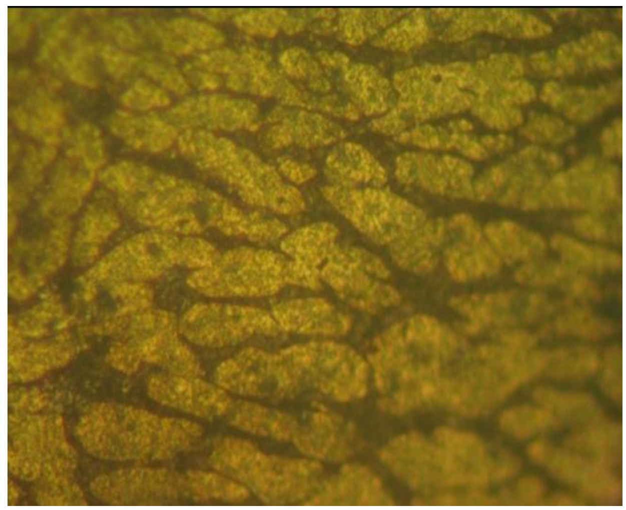

Plate 7

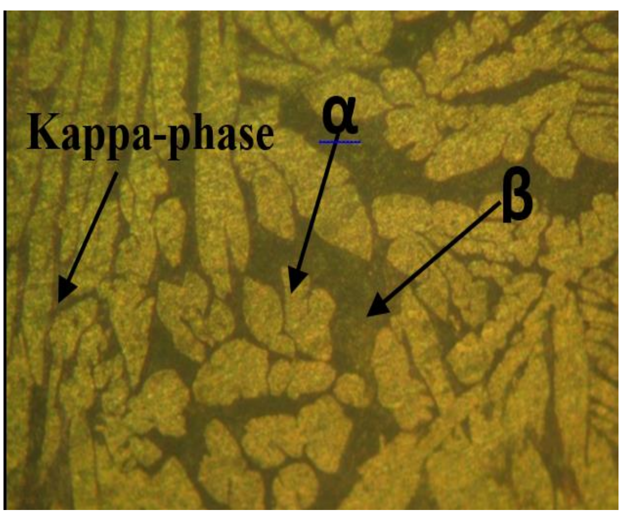

Plate 5

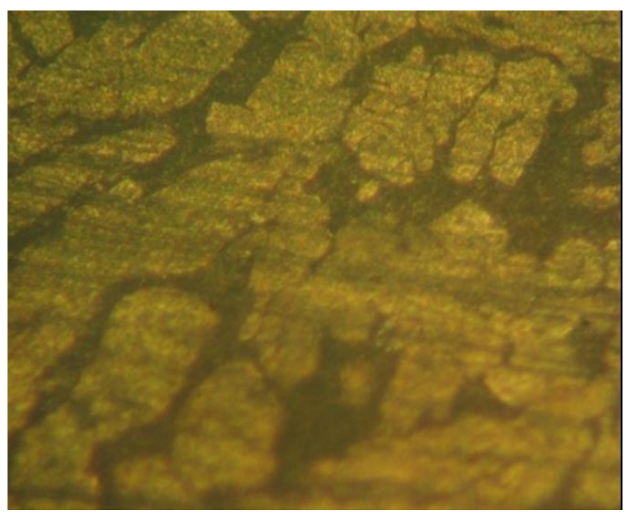

Plate 8

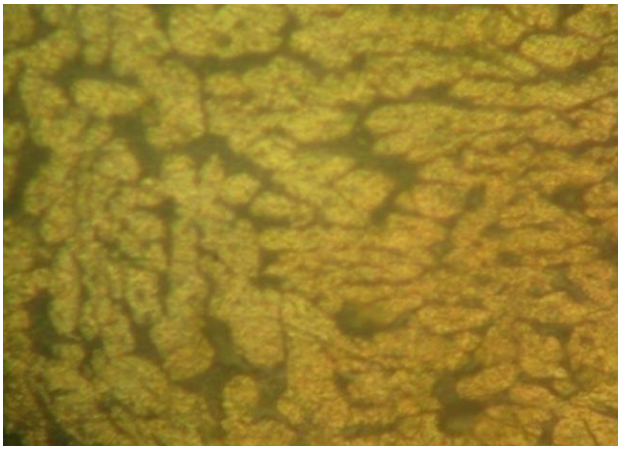

Plate 9

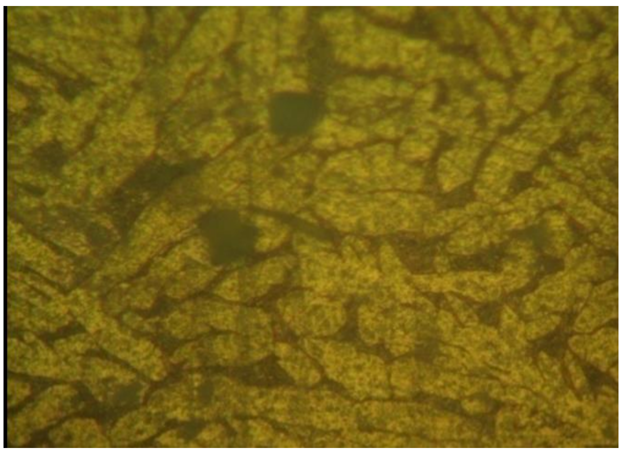

Plate 10

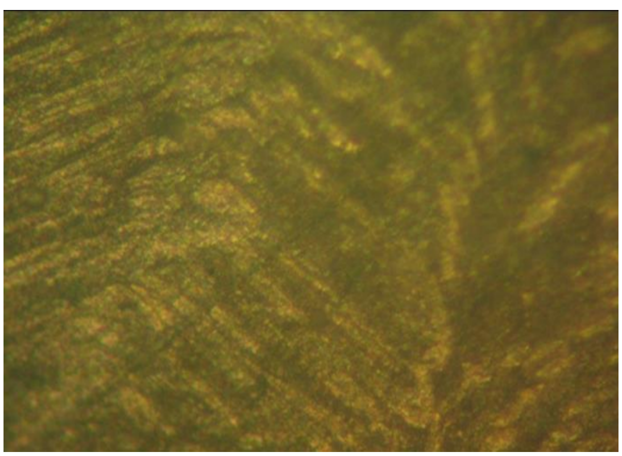

Plate 11

Figure 7: Aluminium- bronze morphologies with/without nickel at (1) 0% (2) 1% (3) 2% (4) 3% (5) 4% (6) 5% (7) 6% (8) 7% (9) 8% (10) 9% (11) 10%

It was observed that the microstructure in Plate 1 contains α-phase of the aluminium bronze in which the β-grains appear to have absorbed the α-dendrites thereby preventing the precipitation of other phases out of the solution. This must have been due to the absence of alloying elements. Hence, the presence of alloying elements apart from aluminium tends to stabilize β-phase and effectively permit slower cooling rate [9]. From Plate 2-11, precipitation of fine lamellar form of kappa (κ) evolve due to the presence of nickel as an alloying element in the Cu-10%Al alloys. The presence of nickel aided the nucleation of a few fine lamellar kappa precipitates. Plate 5, shows the effect of 4wt% nickel addition on the aluminium bronze microstructure. The amount of fine lamellar kappa-phase transformed within the matrix increased compared to 2 and 3wt% nickel addition. These further explain that presence of more nickel in the alloy matrix within the base metal provided an increase in nucleation sites for the precipitation of kappa-precipitates from α-phase to occur. The sharp fall in values of UTS and %elongation as seen in Table 1, could be as a result of casting defects noticed on the microstructure of the casted samples. The preponderance of nickel presence in the cast Cu-10%Al alloy effectively suppressed the formation $\alpha + \gamma_2$ within the alloy matrix. This stands in agreement with the work of Cook et al (1980). The addition of nickel to an alloy has a strong influence in stabilization of β-phase. When nickel is added to an alloy, it suppresses the formation of γ_2 –phase and α-solid solution range is extended towards higher aluminium contents. The combined effect produces a kappa-phase which has the same structure as the β-aluminium bronze [11]. The scanning electron micrographs of the control specimen (Cu-10%Al) shown on plate 12 revealed that the micrograph consists of α-phase (which is the grey region), β-phase, and eutectoid $\alpha + \gamma_2$ phase (the twin dark light region). The intermetallic phase Cu_9Al_4 existed in the form of coarse plate-like precipitating from the β-phase through the grain boundaries. Plate 13 showed micrograph of Cu-10%Al +10%Ni. It was observed that α-phase was surrounded by little dark etching β-phase. The combined effect of Cu-10%Al and nickel produces a kappa precipitate. The size and disposition of kappa phase present in the structure caused reduction in hardness value. However, there was good enhancement in their impact energy due to higher proportion of tough, ductile and soft kappa precipitate present.

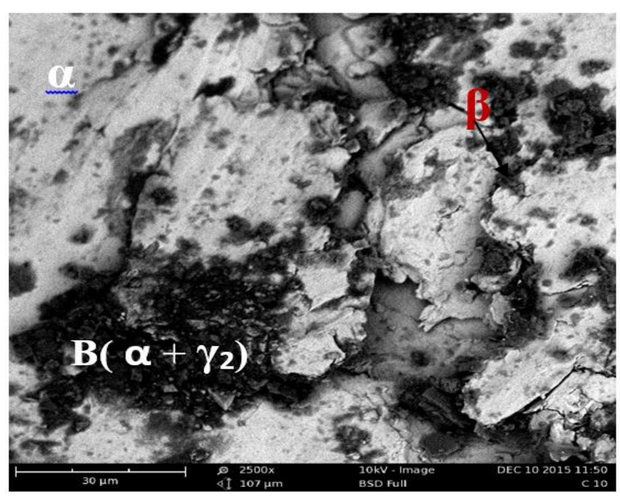

Figure 8: Plate 12: SEM micrograph of Cu-10%Al

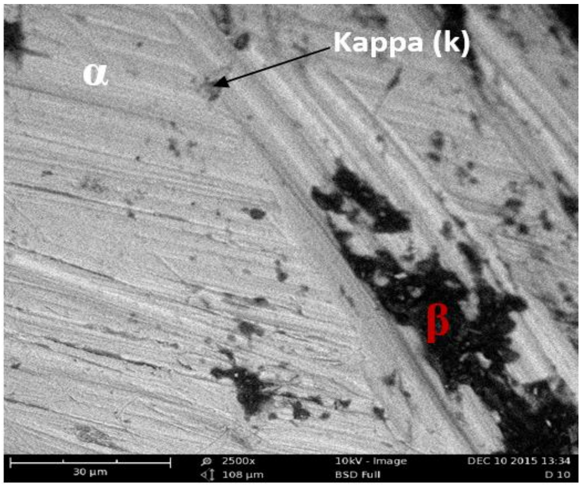

Figure 9: Plate 13: SEM micrograph of Cu-10%Al +10%Ni

4. Conclusions and Recommendation

The effect of nickel addition in percentage composition of 1-10wt% on the structure and mechanical properties of aluminium bronze has been investigated. The presence of nickel in the base alloy (Cu-10%Al) significantly influenced the microstructure which affected the mechanical properties. In summary, the overall results of this study show that;

- Fine lamellar band coherent kappa phase can be evolved in aluminium bronze using nickel.
- Increasing Ni content of the alloy up to 10% increased impact strength and decreased hardness property.
- The microstructure displayed were primary α-phase, eutectoid $\alpha+\gamma_2$-phase as well as retained β-phase. Alloying aluminium bronze with nickel led to microstructural alterations which significantly depends on the type and parameter employed. For instance, nickel presence in aluminium bronze system induced a stable reinforcing kappa phase by nucleation mechanism which resulted in the enhancement of mechanical properties.
- Optimum UTS and ductility are attainable with 4wt% nickel addition to aluminium alloy.
- Aluminium bronze alloyed with nickel at selected composition is therefore recommendable for applications in automobiles and allied engineering industry.

Acknowledgement

The authors are grateful to the management and the research staff of the Standard Organization of Nigeria (SON), Enugu and the Federal University of Technology, Owerri (FUTO) for their technical assistance.

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