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Effect of manganese and niobium macro-additions on the structure and mechanical properties of aluminum bronze (Cu-10%Al) alloy

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Abstract

This research work investigated the effect of manganese and niobium macro-additions on the structure and mechanical properties of aluminium bronze (Cu-10%Al alloy). 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 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 to 10wt% of each of the element into Cu-10%Al alloy at interval of 1.0 percent. Microstructural analysis was conducted using L2003A reflected light metallurgical microscope and PHENOM ProX scanning electron microscope. Result obtained shows that impact strength, %elongation and UTS of aluminium bronze increased with increase in concentration of niobium while only hardness and impact strength increased with increase in concentration of manganese. Microstructural analysis revealed the primary α-phase, β-phase (Cu_3Al), α +γ_2 intermetallic phase and fine stable reinforcing kappa phase and these phases resulted in the enhanced mechanical properties. Aluminium bronzes doped with manganese and niobium proved to increase mechanical properties and therefore is recommended for applications in engineering industry for the production of offshore and shipboard plant, marine propeller, iron and steel making.

Keywords: Microstructure, aluminum bronze, manganese, niobium, mechanical properties.

1. Introduction

Aluminum bronze has been established as a material that has excellent corrosion resistance properties. They are range of copper based alloy in which aluminum content ranging from 2-14% is the major alloying element [1]. The aluminium confers on copper such attributes as good solid-solution strengthening, work hardening and corrosion resistance. Aluminium increases the mechanical properties of copper by establishing a face-centred cubic (FCC) phase which also improves the casting and hot working properties of the base metal [3]. Other optional alloying elements which are sometimes intentionally introduced into aluminium bronze are iron, nickel, manganese, silicon, tin etc. depending on the intended applications. Aluminium bronzes are available both in wrought and cast forms and they offer good combinations of mechanical and corrosion resistance properties. They can have strength greater than carbon steels and corrosion resistance better than most stainless steels [4].

Applications of aluminium bronzes include high pressure flange for sub-sea weapons ejection system, clutch components for shipboard winch, propellers, landing gear components on aircraft, wear rings for hydro-turbines, impellers shafts , pumps and valves, exchange parts, non-sparking tools, tube sheets and lots more [5, 6]. The relative higher strength of aluminium bronze compared with other copper alloys makes it more suitable for the production of forgings, plates, sheets, extruded rods and sects [7, 8]. They give a combination of chemo-mechanical properties which supersedes many other alloy series, making them preferred, particularly for critical applications [9, 10]. In spite of all these features exhibited by aluminium bronze, it is worthy to note that not much work has been done on this alloy especially in the developed country. Structural

applications mostly based on ferrous metals especially steels. Findings have shown that aluminium bronze are fast replacing contemporary steel materials for specific applications especially in components for marine and sub-sea applications. Mechanical properties of bronze alloy are dependent on their chemical compositions, microstructure and production condition, and this can be significantly improved by heat treatment, alloying process and deformation. This research work aims at modifying the structure of Cu-10%Al alloy by using manganese and niobium and by impacting on the types, forms and distribution of phases within the matrix, and their effects on the mechanical properties. Also to establish which of the alloying elements gave the best improved structure and mechanical properties.
Niobium and its alloy exhibit properties that provided unique technological capabilities among refractory metals. It can be used as hardening element in cast version and also it improves weldability [12, 10]. Niobium is a strong ferrite and carbide former. It enhances mechanical properties at high temperature and improves the resistance to intergranular corrosion [13]. Manganese is an austenite former. Their foundry properties are better than aluminium bronze and it has excellent welding properties, good resistance to impingement and cavitation as well as being heat-treatable [5]. Manganese is added to the complex alloy because of its deoxidizing effect on metal. It improves the corrosion resistance of aluminium bronze as it stabilizes the β-phase and reduces the risk of decomposition of the eutectoid [14]. The stabilization of β-phase can be achieved with addition of low level of manganese while high level of Manganese is sufficient to retain α/β at usual cooling rates in actual practice [14].

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 scraps, manganese powder, niobium powder, weighing balance, crucible furnace, venier calliper, bench vice, lath machine, electric grinding machine, hack-saw, stainless steel crucible pot, mixer, scoping 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 a 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 elements (manganese and niobium) were added separately in concentration of 1-10% by weight to the 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 microstructure of the samples were also studied using, metallurgical bench microscope.

2.2.1. Experimental procedure

2.2.1.1. 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 scraps, aluminium scraps, manganese and niobium powders. 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. Impurities such as metals, hard lumps, stones etc. were removed using sieves 500μm and 400μm to obtained fine grain size. The sand was mixed in a sand mixing machine with little quantity of water added to it. The sand was mixed well 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 pattern was removed and the cavities created were repaired. Ash was then sprinkled on the cavities to enhance easy flow of the molten metal.
The furnace used for the sample preparation is a crucible furnace with a steel crucible pot of maximum controlled temperature of about 1750ºC.

2.2.1.2. Melting and Casting of alloys

This operation was carried out to produce twenty one separate specimens for the research work. The bailout crucible furnace with steel crucible pot was pre-heated for about 10minutes. 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 is molten. Aluminium was then allowed to dissolve in the molten copper for 6minutes and stirred properly to ensure homogeneity. The alloying elements (manganese and niobium) 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 alloying elements. Then molten metal was poured into the mould cavities and allowed to solidify for about 3 minutes before removal from the mould.

2.2.1.3. 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 microstructure analysis were obtained.

2.2.1.4. 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 required standard specifications so as to fit the grips as showed in Figure 1. 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 recorded. Hence, the specimen were tested to determined their ultimate tensile strength, ductility (%elongation) and yield strength. These properties determined were tabulated in Table 2.1.

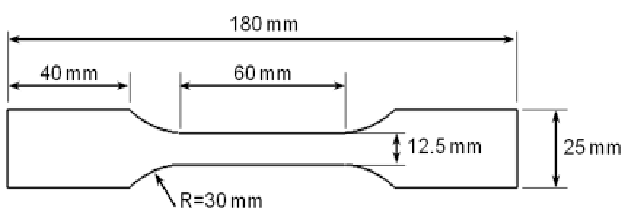

Figure 1: Tensile test specimens

2.2.1.5. 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 formal 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.

2.2.1.6. 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 45^{o}C 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.

2.2.1.7. Microstructure examination

The microstructure of the experimental specimen was studied using optical metallurgical microscope and scanning electron microscope. In the process, a cubic sample was cut from each of the 21 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 dis-colored 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 for microstructural analysis and micrographs showing the different morphologies of the cast alloy were taken. For SEM observation, the test sample was placed on the stup. The stup was put in an ultrasonic cleaning process. Both the sample and the stup were placed in front of an air heater in order to make them 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 result and discussion of effect of manganese and niobium macro-additions on the structure and mechanical properties of aluminium bronze are summarised below.
Plate 2-21 shows microstructure of Cu-10%Al and Cu-10%Al doped with manganese and niobium at percentage weight composition of 1-10%. Apart from different intermetallics, three major phases were revealed under optical metallurgical microscope such as: α-phase, retained β-phase and $\alpha+\gamma_2$ eutectoid phase in proportions determine by manganese and niobium contents and mould materials during casting. The alloy contents influenced the grain sizes and the nature of α-phase (Cu-Al solid solution), extent of coring as well as the amount of $\alpha+\gamma_2$ intermetallic phase.

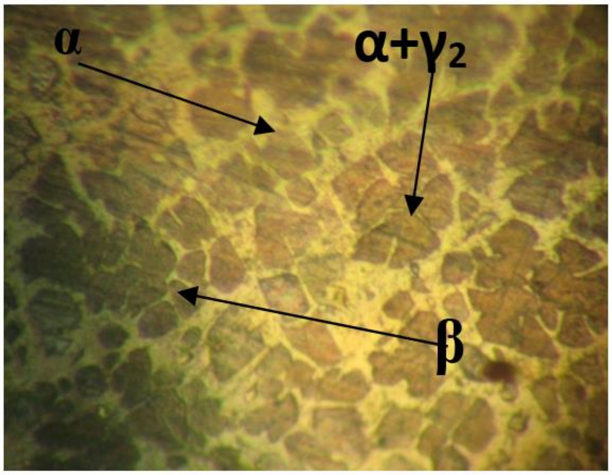

Plate 1 (Cu-10%AL)

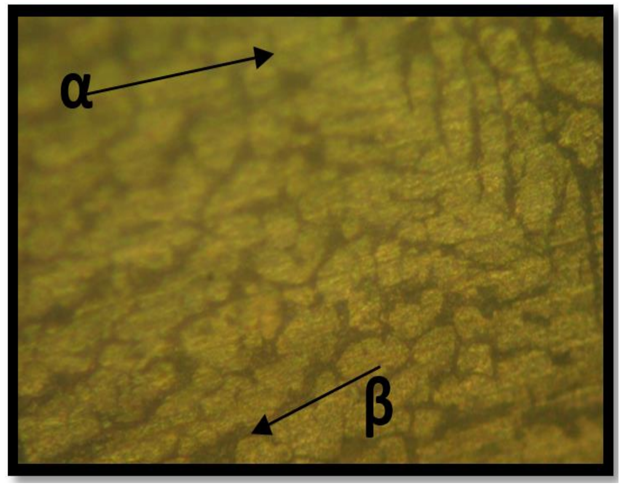

Plate 4

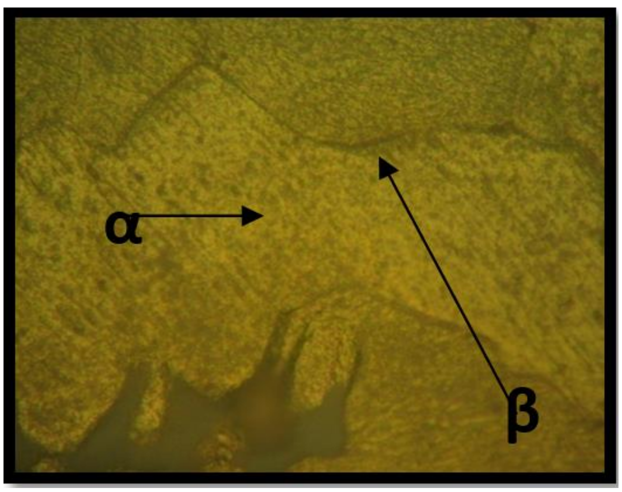

Plate 2

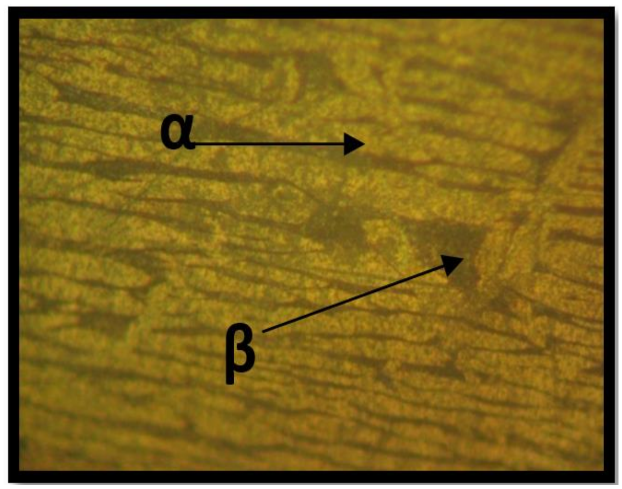

Plate 5

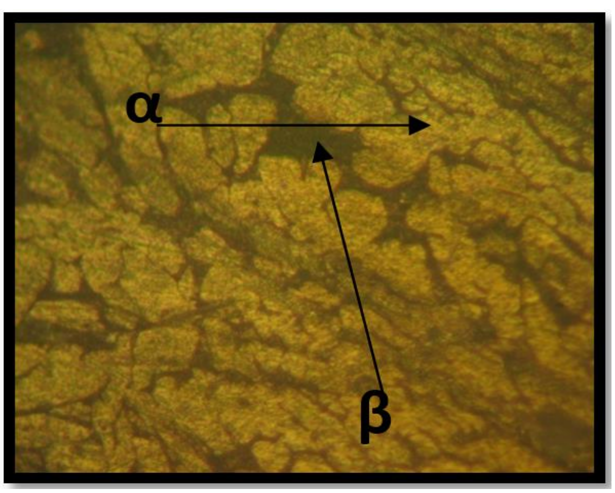

Plate 3

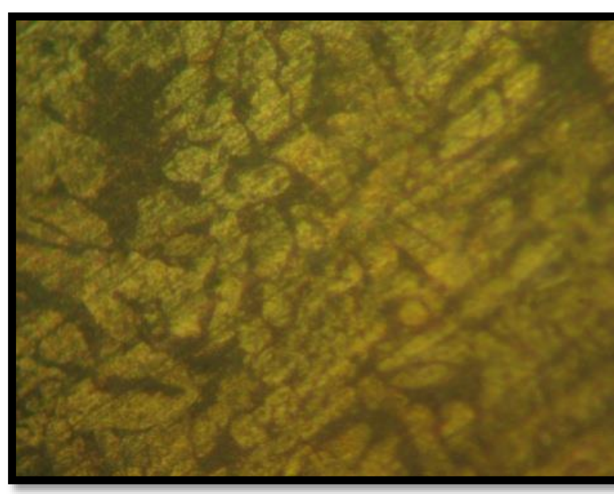

Plate 6

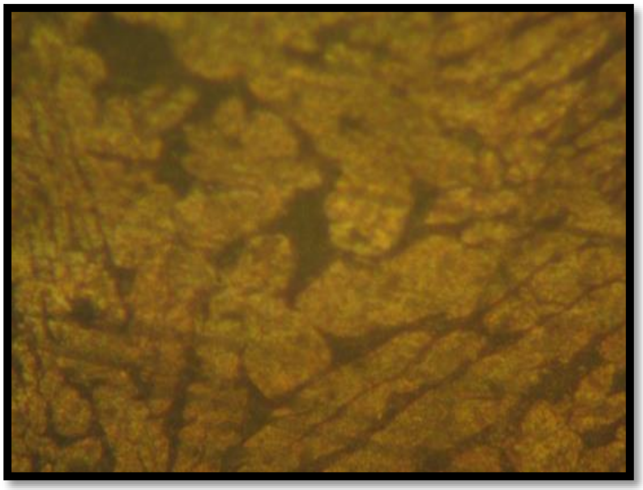

Plate 7

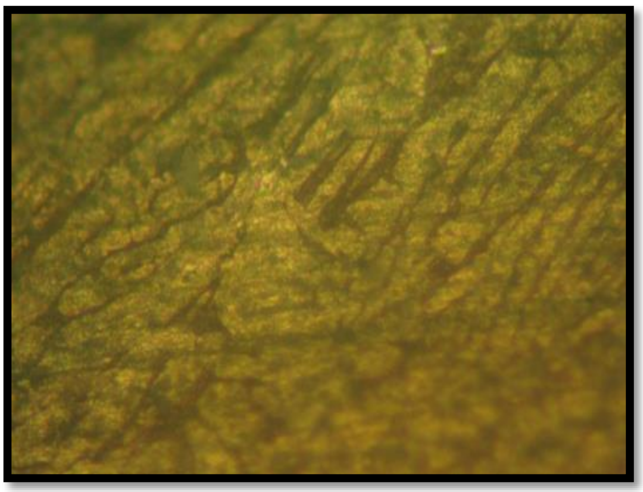

Plate 8

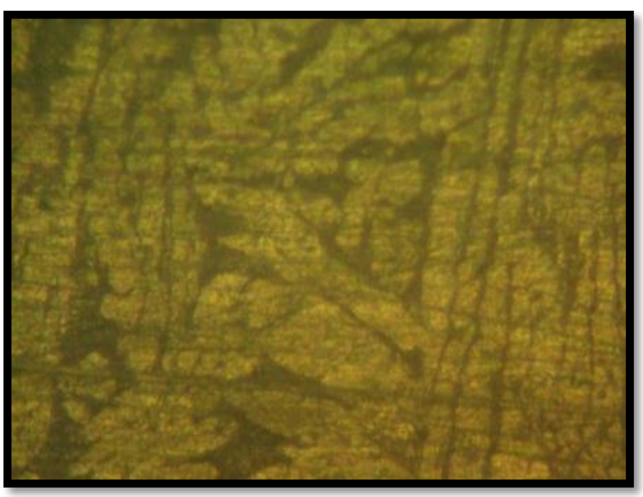

Plate 9

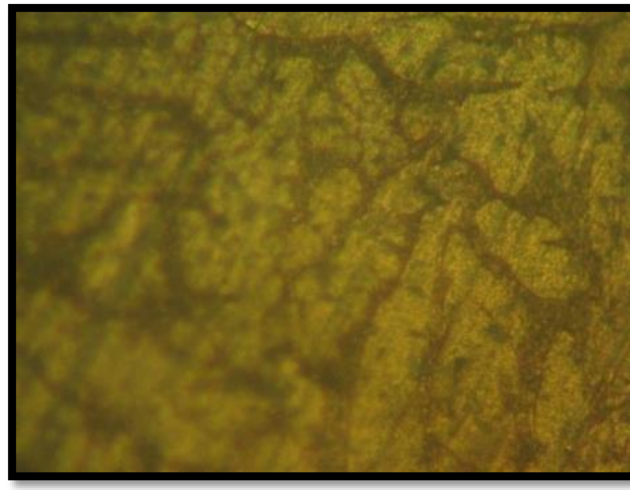

Plate 10

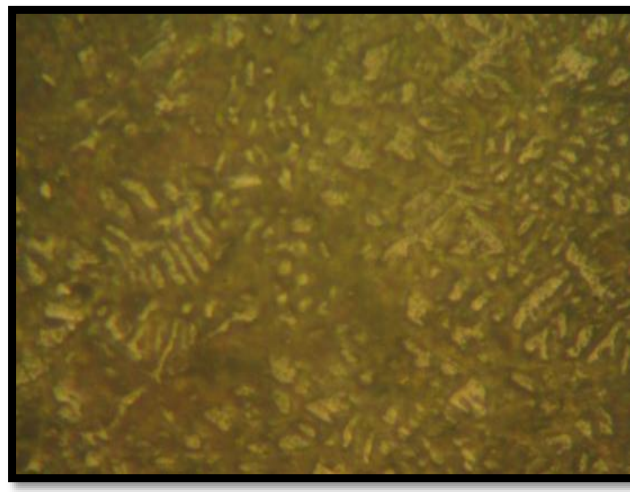

Plate 11

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

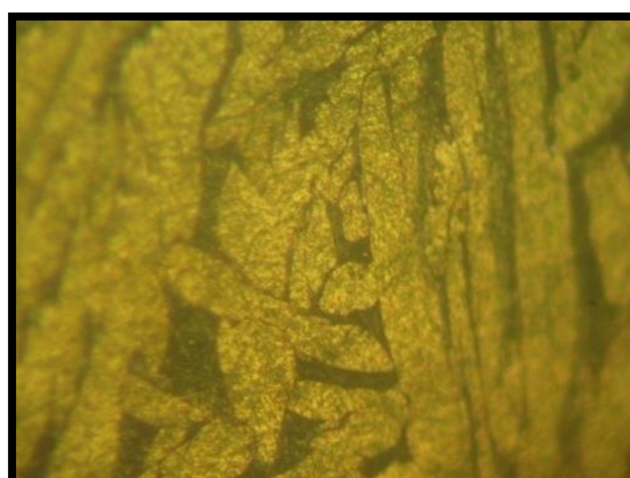

Plate 12

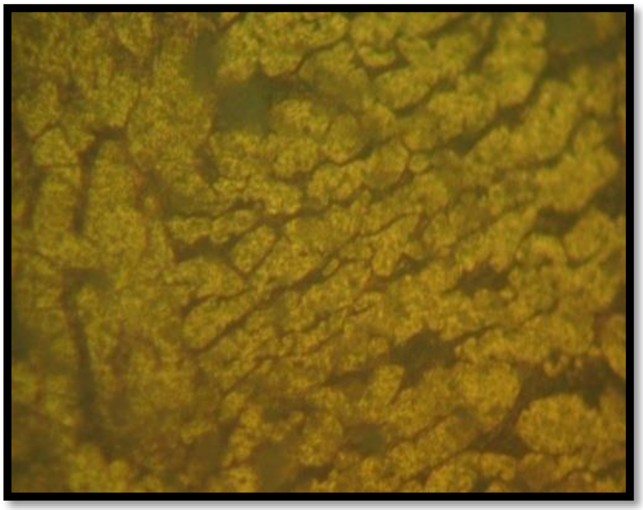

Plate 13

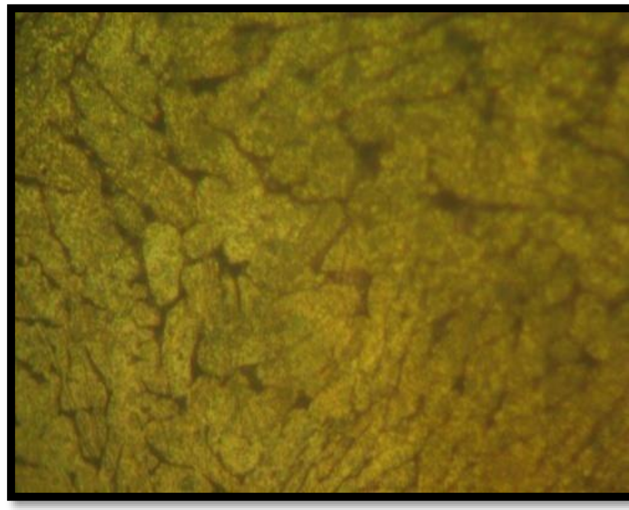

Plate 16

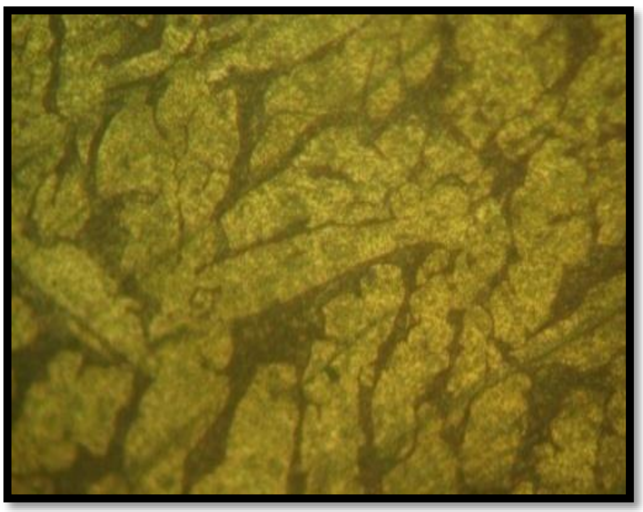

Plate 14

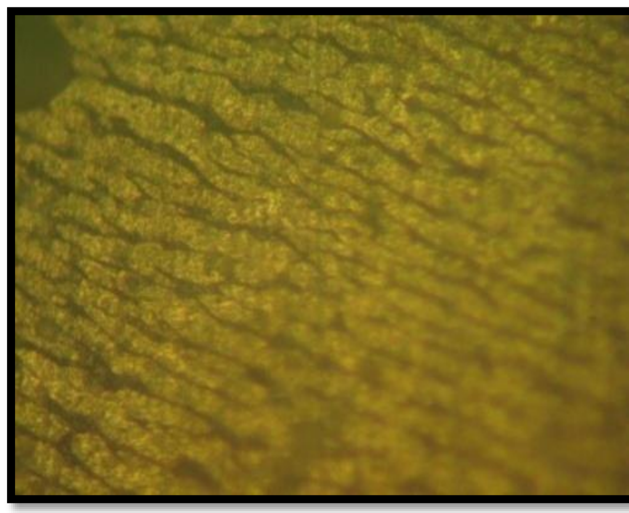

Plate 17

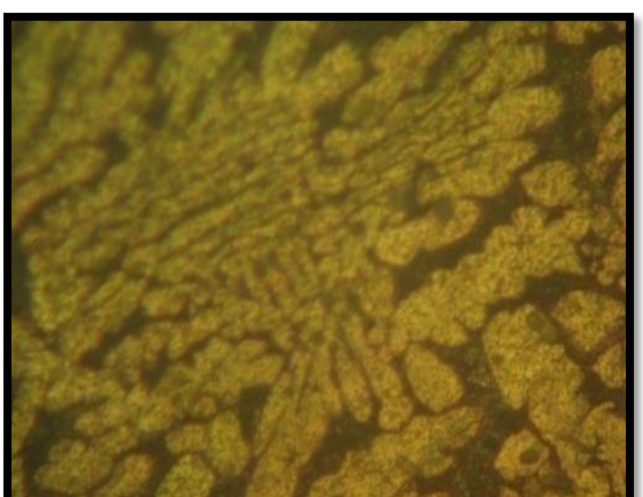

Plate 15

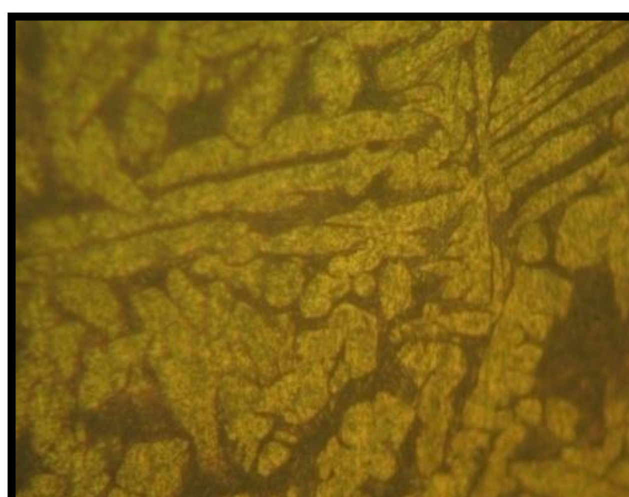

Plate 18

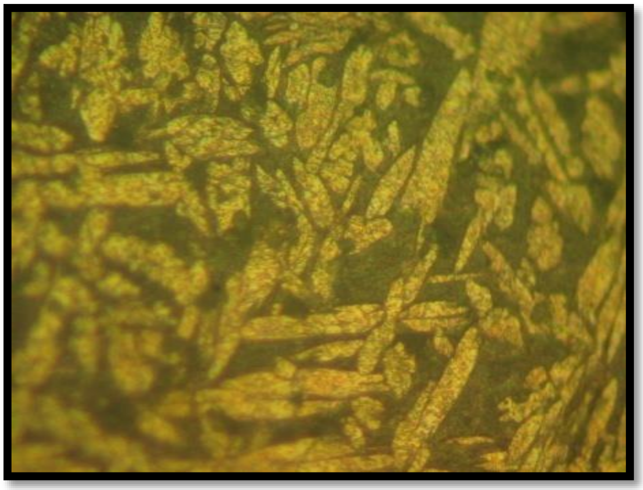

Plate 19

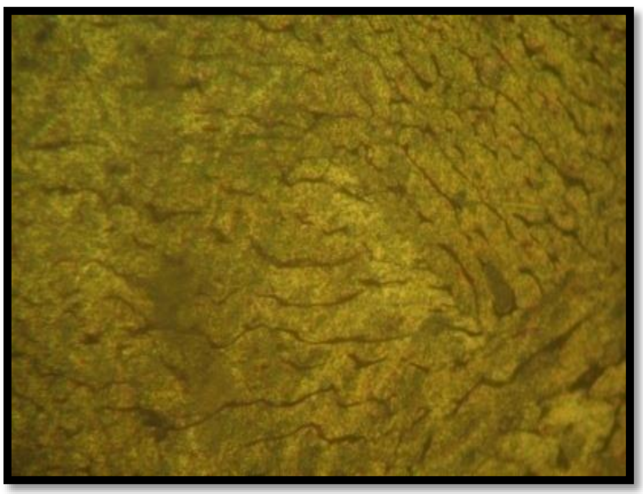

Plate 20

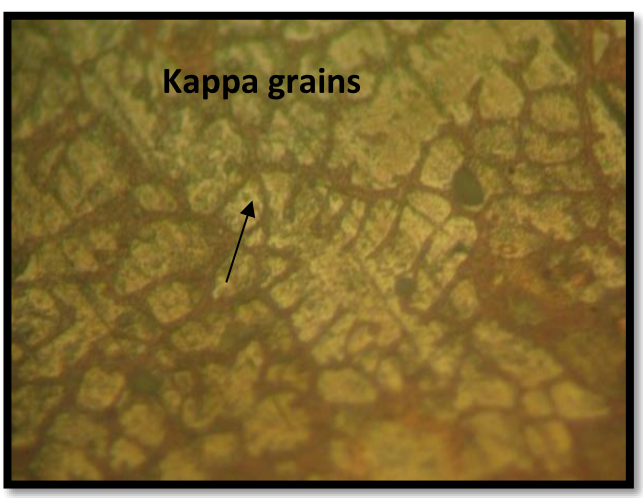

Plate 21

Figure 3: Aluminium- bronze morphologies with niobium at (12) 1% (13) 2% (14) 3% (15) 4% (16)5% (17) 6% (18) 7% (19) 8% (20) 9% (21) 10%

Plate 1 which is the micrograph of the control sample. It was observed that the microstructure consists of α-phase which is the region where aluminium formed solid solution with copper matrix, large coarse interconnected intermetallic (Cu_9Al_4) compound and β-phase. This alloy exhibits the lowest mechanical properties in terms of tensile strength, impact strength, ductility and hardness because of the presence of coarse microstructure. In Plate 2-11, the analysed microstructure revealed that there was increase in the quantity of β-phase as compared to α-phase. Reduction of these phase (α) present in the microstructure caused the hardness value of the alloy to increase as the concentration of manganese increased. This significantly corroborates the work of Vaidyanath (1980). The stabilization of β-phase can be achieved with low level manganese addition. From Plate 12-21, it was observed that the α-phase increased both in size and quantity as the composition of niobium increase. This led to the formation of fine lamellar form of kappa precipitates. Presence of sparse distribution of kappa phase in predominant $\alpha+\gamma_2$ matrix caused smaller grains to emerge creating smaller lattice distance which resulted to the improvement in mechanical properties. From the SEM micrographs, it could be observed that there was gradual increase in the intermetallic compound through the grain boundaries as the concentration of manganese and niobium increased. In Plate 22 which is the SEM micrograph of the control sample, it could be seen that the intermetallic compound (Cu_9Al_4) exist in the form of plate-like, precipitating from the α-phase region through the grain boundaries. This phase ($\alpha+\gamma_2$) is hard and brittle with complicated cubic lattice. Plate 23 shows that the spread of intermetallic compound ($\alpha+\gamma_2$) become limited which further explain how an increase in percentage composition of niobium improved UTS, impact strength and ductility. The combined effect of Cu-10%Al and niobium suppressed the formation of $\alpha+\gamma_2$ –phase and produced kappa-phase. The fine lamellar form of kappa phase precipitating from α-region has a pronounced effect on the properties of aluminium bronze and considerably increased mechanical properties. In Plate 24 which is the SEM micrographs of Cu-10%Al alloy doped with Manganese at 10wt%. It was revealed that $\alpha+\gamma_2$ increased both in size and quantity thereby suppressing the size of α-phase present in the microstructure. The coarse $\alpha+\gamma_2$ intermetallic compound present in the cast sample transformed into retained β-phase. Formation of this phase made the sample hard and brittle and therefore, undesirable for engineering applications. But because there were regions of α +β phase present in the micrograph, the sample gave high hardness combined with relative high mechanical properties under normal condition. Hence, manganese addition improves corrosion resistance, impact strength, and hardness and lowers ductility of aluminium bronze.

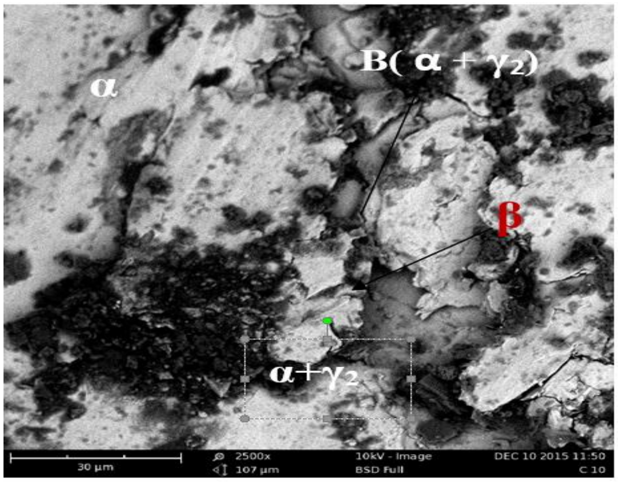

Figure 4: Plate 22: SEM micrograph of Cu-10%Al

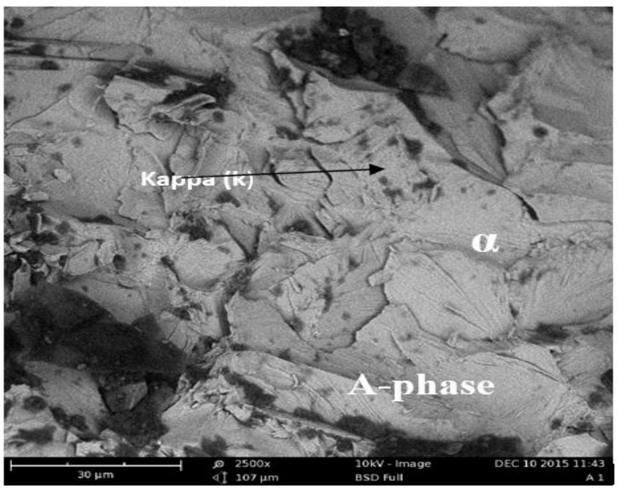

Figure 5: Plate 23: SEM micrograph of Cu-10%Al +10%Nb (X2500)

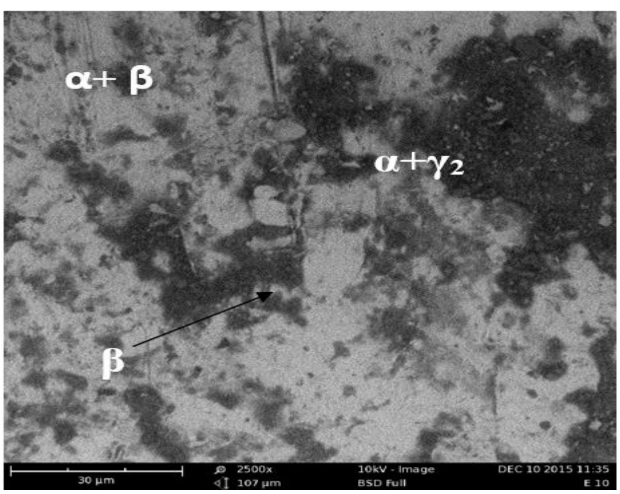

Figure 6: Plate 24: SEM micrograph of Cu-10%Al +10%Mn

Table1. Mechanical properties of Cu-10%Al doped with manganese and niobium

Sample Type	UTS (MPa)	Yield Strength (MPa)	% Elongation	Hardness (BHN)	Impact (joules)
A (Cu-10%Al)	144	98	9.3	103	15.1
A + 1% Mn	898	496	17.64	115	32
A + 2% Mn	873	457	17.43	119	31
A + 3% Mn	744	398	16	121	32.5
A + 4% Mn	724	341	15.6	124	33.6
A + 5% Mn	674	296	14.5	127	34
A + 6% Mn	663	284	14.11	133	35.5
A + 7% Mn	603	245	13.9	131	36
A + 8% Mn	573	230	13.5	135	36.1
A + 9% Mn	544	226	12.91	137	37
A + 10% Mn	501	221	12.8	139	37.9
A + 1% Nb	478	281	10.7	118	23
A + 2% Nb	535	306	12.2	115	24
A + 3% Nb	647	328	13.17	112	24.2
A + 4% Nb	680	337	13.92	108	25.1
A + 5% Nb	713	362	14.02	107	26
A + 6% Nb	745	397	14.35	107	26
A + 7% Nb	801	438	14.9	105	30
A + 8% Nb	867	457	15.25	104	31.2
A + 9% Nb	915	498	15.6	102	32

The result of ultimate tensile strength, hardness, %elongation and impact strength of the test alloys as a function of manganese and niobium content are shown in Table 1 and Figures 7-10. It was generally observed in Table 1 and Figure 7 that macro-additions of niobium and manganese within the studied range of composition improved ultimate tensile strength as compared to the control sample (Cu-10%Al). Ultimate tensile strength of Cu-10%Al alloy increase as the composition of niobium increased. The highest UTS value of 973MPa was recorded when 10wt% niobium was added to Cu-10%Al, while least UTS value of 144MPa was obtained for the control. Niobium at 10wt% gave the highest value of ultimate tensile strength among the dopants. Steady decrease in UTS was observed when manganese was doped with Cu-10%Al alloy. Manganese recorded highest UTS value of 898MPa at 1wt%. This can be attributed as a result of formation of interstitial solid solution between the copper lattice and manganese. Its structure forms β- phase with smaller quantity of α-phase grains as seen in Plate 8, 9, 10, and 11. Manganese increased hardenability which causes formation of manganese sulphide during casting (CDA, 1986).

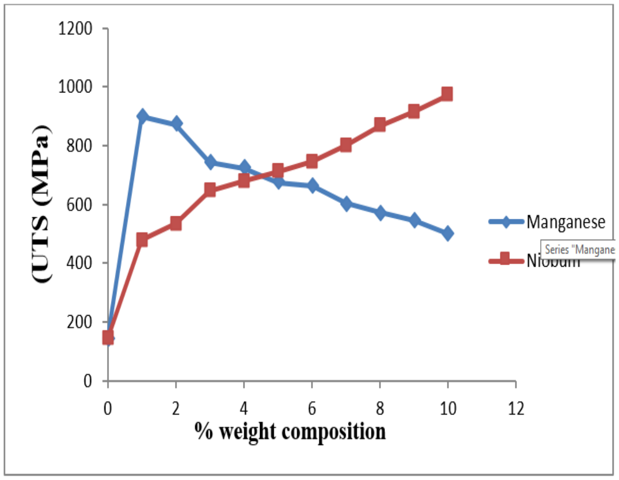

Figure 7: Effect of alloy compositions on the UTS of aluminium bronze (Cu-10%Al)

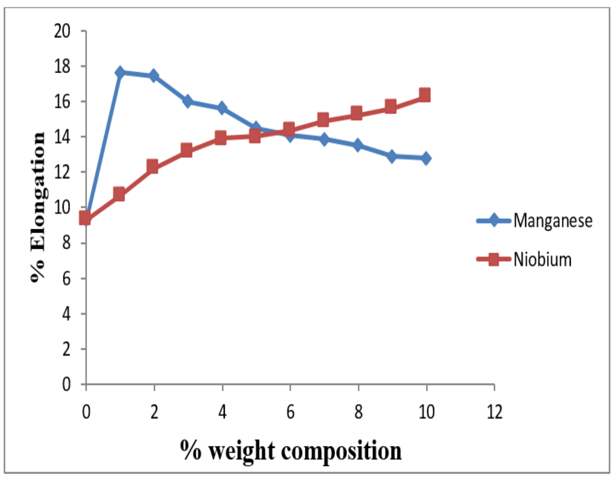

Figure 8: Effect of alloy compositions on the % elongation of aluminium bronze (Cu-10%Al)

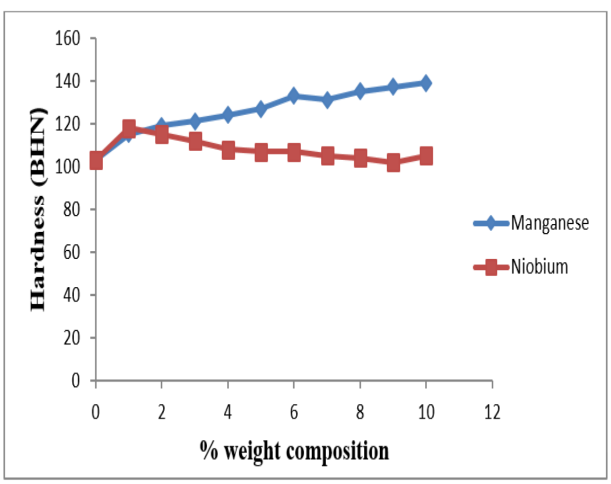

Figure 9: Effect of alloy compositions on the hardness of aluminium bronze (Cu-10%Al)

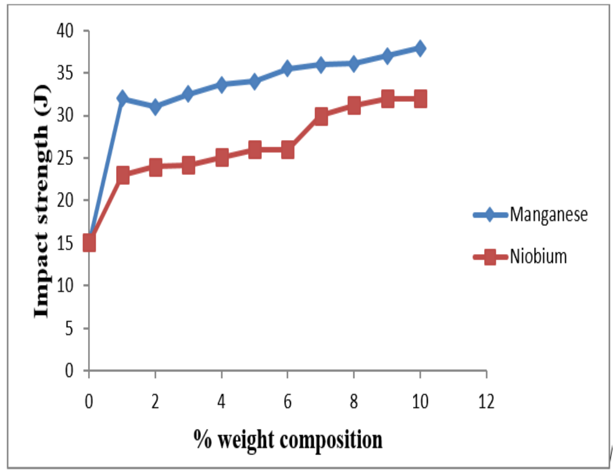

Figure 10: .Effect of alloy compositions on the impact strength of aluminum bronze (Cu-10%Al)

As observed in Figure 9, hardness increased with increase in percentage composition of manganese. Maximum hardness value of 139BHN was obtained when Cu-10%Al alloy was doped with manganese at 10wt%. Steady decrease in hardness properties of aluminium bronze was equally observed as the concentration of niobium increased. The linear changes in respect to the composition of the alloying element in the base alloy were based on type of microstructure developed by the alloying elements. The α-phase is a soft Cu-based substitutional solid solution of FCC structure while the β-phase is Cu_3Al base solid solution with BCC structure. Hence, the face-centred cubic structure always yields least hardending properties among elements (CDA, 1992).

4. Conclusions and Recommendation

This study has revealed that ultimate tensile strength, hardness, %elongation and impact strength of aluminium bronze can greatly improve with addition of 1-10wt% niobium and manganese. The effects of macro-additions of alloying elements on mechanical properties of aluminium bronze depend on the percentage composition. The following conclusions are therefore deduced from the research:

- Niobium greatly improved UTS, ductility and impact strength while hardness showed reversed trend.
- Increasing manganese and niobium content of the alloy up to 10%, increased impact strength of the aluminium bronze.
- Manganese showed improvement on hardness and impact strength.
- Aluminium bronze alloyed with manganese and niobium can be used as substitute for steel in the pipe line industry, marine, offshore and shipboard applications because of excellent properties shown in this study.

- For a good tensile strength and ductility, manganese should be added to Cu-10%Al alloy in micro-quantity.
- Aluminium bronze alloyed with niobium in macro-quantity is recommended for use in making propellers, marine components, landing gear components, aircrafts etc. as against aluminium bronze alloyed with manganese.

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