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Effect of Heat Treatment Parameters on the Structure and Mechanical Properties of Aluminium Bronze (Cu-10wt%Al)

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Abstract

An investigation was carried out to study the effect of heat treatment parameters on the structure and mechanical properties of aluminium bronze (Cu-10% wt. Al). The heat treatment parameters investigated were solutionizing temperature (800 and 900°C) and soaking time (0.5, 1, 2 and 3hrs). The alloy samples were produced using permanent die casting technique. Standard specimens were prepared from the as-cast and heat treated samples for tensile, hardness and impact strength tests as well as microstructural analysis according to standard. The samples were solutionized at temperature of 800°C and 900°C for 0.5, 1, 2 and 3hrs respectively and quenched in brine. The tensile, hardness and impact strength test were conducted using JPL tensile strength tester (Model: 130812), dynamic hardness tester and impact testing machine (U1820) respectively. The alloy microstructures were studied using an optical metallurgical microscope (Model: L2003A) and scanning electron microscopy (SEM). Microstructural analysis result indicated sparse distribution of coarse needle-like $\alpha + \gamma_2$ precipitates in the as-cast specimen and presence of fine pearlite ($\alpha + \gamma_2$) in a matrix of α dominance in the heat treated specimens. The presence of coarse intermetallic compounds (β`- phase) was revealed as the soaking time increased at high solutionizing temperature (900°C). The obtained results indicated that heat treatment significantly improved all the tested mechanical properties. Maximum percentage elongation was obtained in the specimens solutionized at 800°C for 3hrs and quenched in brine with %E of 73.1%. The specimen solutionized at 900°C for 0.5hr gave the maximum hardness of 513MPa. The ultimate tensile strength of aluminium bronze in as-cast condition increased from 240MPa to 609MPa when the alloy was solutionized at 900°C for 0.5hr. The heat treated alloy also demonstrated impact strength of 106J at solutionizing temperature of 800°C for 0.5hr.

Keywords

Solutionizing Temperature, Soaking Time, Quenching Media, Heat Treatment, Properties

1. Introduction

The consumption of aluminium bronzes has increased significantly in the world due to their mix of chemo-mechanical properties which supersede many other alloy series. These properties are toughness, corrosion resistance in a wide range of aggressive media and marine environment, wear resistance, low magnetic permeability, non-sparking characteristics, excellent castability, excellent machinability and weldability in either cast or wrought form [1]. These excellent properties, favourably comparing with low alloyed steels and cast irons, make aluminium bronzes one of the most versatile engineering materials [2].

Aluminium bronzes are copper based alloys with aluminium as the major alloying element usually in the range of 5% - 14% [3]. Aluminium bronzes are used for parts intended for the chemical industry, for power and electrical equipment, coins, sliding contacts, parts of bearings, shafts, bolts, sieves and high pressure flange for sub-sea weapons ejection system, clutch components for shipboard winch, propellers, landing gear components on aircraft, wear rings for hydro-turbine, impellers shafts, pumps and valves, exchanger parts, non-sparking tools and tube sheets etc [4]. Commercially, pure copper is very soft, ductile and malleable with low tensile strength, containing up to about 0.7% total impurities [3]. Various engineering applications demand high strength, therefore substantial increase in strength of pure copper is paramount in order to increase its applications. This can be obtained by alloying, heat treatment and cold working [5].

This research work was propelled by the study of Uyime et al., [6] which revealed the presence of coarse intermetallic compound ($\alpha + \gamma_2$) in the structure of slowly cooled aluminium bronze (Cu-10%Al) alloy. The structure has negative impact on the mechanical properties of the alloy. So, this research was carried out to examine the effect of heat treatment parameters on the structure and mechanical properties of aluminium bronze alloy.

Various researches have been conducted on the effect of heat treatment techniques on the structure and mechanical properties of aluminium bronze. Uyime et al [6] revealed that normalizing gave the optimum mix of tested mechanical properties with ultimate tensile strength value of 325MPa, elongation of around 60% and Rockwell hardness values of 46.5 - 63.7 HRc. Jinquan et al [7] established that heat treatment under 1GPa refined the microstructure; however, it showed little effect on composition of phases and hardness. Praveen and Prabhash, [8] indicated that heat treated alloy attained superior tensile strength and elongation as compared to that in the as-cast condition. The study of Praveen and Prabhash, [8] revealed that aged samples attained higher hardness and tensile strength than the solutionized specimens while their elongation tended to follow a reverse trend. The compressive strength of the heat treated alloy samples was less than that of the as-cast alloy while the aged samples attained higher strength compared to the solutionized ones. Mechanical characterization of aluminium bronze-iron granules composite was investigated by Sekunowo et al., [1]. Cast samples of the alloy contained varied amount of iron from 2-10 wt%. The samples were homogenized at 1100°C for 10minutes in order to relieve the as-cast structures. The results showed that optimum mechanical properties were achieved at 4 wt% Fe addition with ultimate tensile strength (UTS) of 643.8MPa which represented 10.1% improvement over conventional aluminium bronze. The alloy also demonstrated impact resilience of 83.9J and micro-hardness value of 88.7HRB. Prabhash and Praveen, [9] revealed that the hardness of heat treated alloy increased after solutionizing and ageing treatments compared to the as cast one. Also, the samples aged at 400°C for 3 hrs attained the highest hardness. Abdul and Praven, [10] indicated that as-cast Cu-Al-Fe alloy specimens showed granular structure consisting of primary α, eutectoid α+γ_2 and Fe rich phase. The study revealed that solutionizing heat treatment led to microstructural homogenization by way of the elimination of the dendrite structure and dissolution of the eutectoid phase and other micro-constituents to form the single phase structure consisting of β. This was followed by the formation of the β' martensite, retained β and α. Ageing brought about the transformation of the martensite and other microconstituents into the eutectoid phase [10]. The specimens that were solutionized at 850°C for 2 hrs obtained the highest hardness in the category of solutionized specimens while ageing at 300°C for 2 hrs offered maximum hardness amongst the aged specimens. The as-cast specimens obtained the highest compressive strength and strain followed by the heat treated ones while the trend reversed for tensile properties.

The effects of production methods on the microstructure and mechanical properties of aluminum bronze were studied by Kaplan and Yildiz, [11]. The solidification structure, the effects of solution treatment, tempering heat treatment and mould types on the microstructure of the aluminium bronze produced in two different moulds were examined. The results of the study showed that the metallographic structure of aluminium bronze was heterogeneous in the preheated die casting specimen before the treatments, but homogenous in the sand casting. It was observed that the structure of the sand mould casting contained fine rounded grains along outermost cross section and lengthwise inclined column grains towards inside and big grains at the innermost section. Considering such grain structure, it was suggested that die mould before casting should be preheated up to 450–500°C to annul the negative effects of the heterogeneous solidification structure of the material. Peter et al [12] indicated that the structure of the rapidly cooled aluminium bronze specimens was fine, consisted of α-phase grains and the α+ κ eutectoid while the structure of the annealed specimens consists of αgrains and coarse eutectoid regions with κ_{III}-type precipitates. Maximum hardness was obtained by quenching and ageing at 400°C and this was attributed to the dispersion of fine particles of κ in the martensitic (β') phase. Peter et al., [12] revealed that upon annealing, with subsequent air cooling, the fraction of γ_2 increased which resulted to the increased hardness of the alloy. Increasing the annealing temperature led to the increase in the size of α grains and the size of the eutectoid areas between them. Anene et al., [13] established in their study of the effect of ageing time and temperature on the mechanical properties of aluminum bronze alloy that the specimens aged at 350°C for 1hr and 2hrs gave optimum mix of tested mechanical properties with impact strength of 30J and yield strength of 480MPa respectively. Obi et al., [14] investigated the effect of soaking time and quenching media on the structure and mechanical properties of aluminium bronze (Cu-10%wt. Al). The study indicated that maximum ultimate tensile strength and hardness of 710MPa and 513MPa respectively were obtained by the samples solutionized at temperature of 900°C for 30 minutes and quenched in water and brine respectively. This was attributed to the presence of fine pearlite ($\alpha + \gamma_2$) in a matrix of α dominance in the heat treated samples. Hajek et al., [15] established that with decreasing cooling rate, the fraction of needle-like pattern of the proeutectoid α-phase diminishes and massive grains of this phase prevail. The study also indicated that with decreasing cooling rate, the fraction of κ_I and κ_{IV} precipitates increased.

2. Materials and Method

Copper and aluminium wires of 99.9% and 99.8% pure respectively were used as the base materials for this research. Heat treatment parameters investigated were solutionizing temperature (800 and 900°C), soaking time (0.5, 1, 2, and 3hrs) and quenching medium (brine). The base alloy (Cu-10wt%Al) was melted and cast into dimension of 250mm in length and 16mm in diameter using permanent die casting technique. The cast samples were machined to the standard dimension for the mechanical tests (tensile strength, hardness and impact strength) and structural analysis. The machined samples were subjected to solution heat treatment at temperature of 800 and 900°C for 0.5, 1, 2 and 3hrs respectively using a muffle heat treatment furnace. The specimens for structural analysis were subjected to filing, grinding, polishing and etching. The filing was performed using a rectangular file and an electric grinding machine. Subsequently, the specimens were ground using emery paper of grid sizes (400, 600, 800 and 1200µm), polished to mirror finish using an aluminium oxide powder (gamma alumina, Al_2O_3), rinsed with water and dried using an air-gun drying machine. The specimens were subjected to etching by swabbing them to a mixture of 10g of iron (III) chloride, 30cm^3 of hydrochloric acid and 120cm^3 of water) for 60seconds, after which the surface morphology was examined using an optical metallurgical microscope (model: L2003A) and scanning electron microscopy (SEM) at magnification x 400 and x 1500 respectively.

The chemical composition of the alloy produced was determined using energy dispersive X-ray fluorescence (EDXRF) and the result is presented in Table 1.

Table 1. *Chemical composition of aluminium bronze developed.*

Elements	Composition by weight (%wt)
Cu	89.950
Al	9.963
Si	0.040
Fe	0.020
Mg	0.010
Zn	0.001
Mn	0.002
Pb	0.004

3. Results and Discussion

3.1. Mechanical Properties of the Developed Alloys

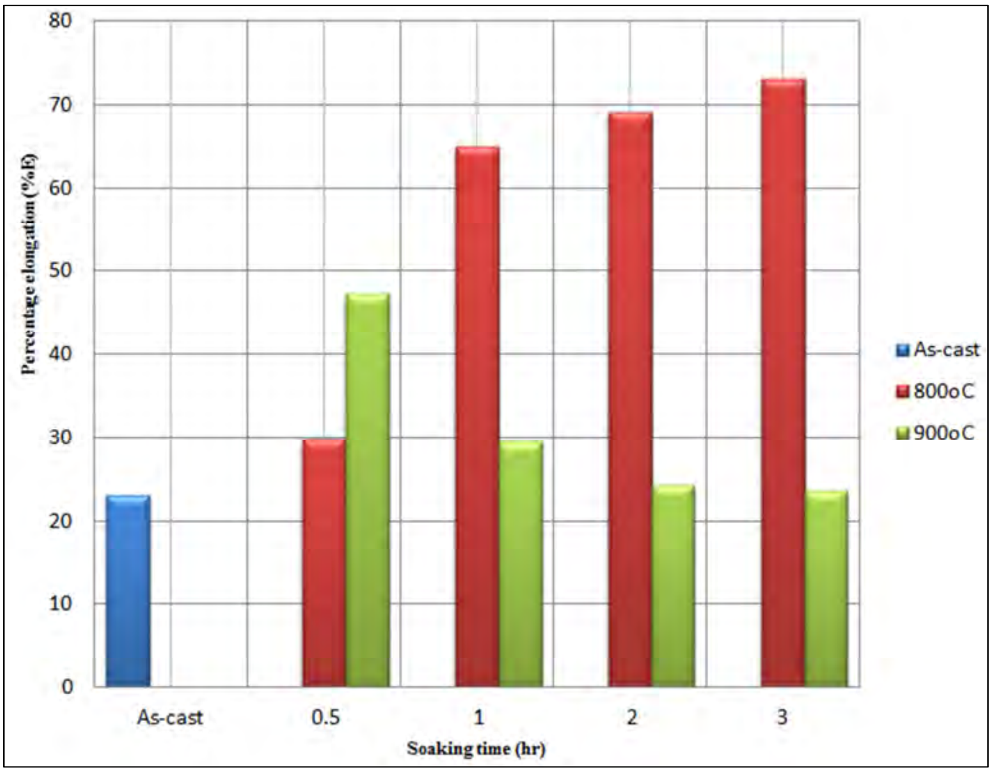

Figure 1. *Effect of solutionizing temperature and soaking time on the percentage elongation of aluminium bronze (Cu-10wt%Al).*

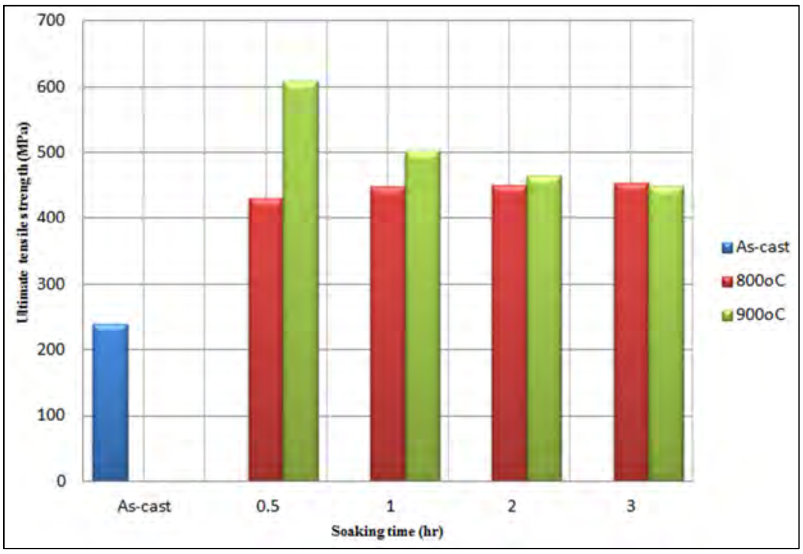

Figure 2. *Effect of solutionizing temperature and soaking time on the ultimate tensile strength of aluminium bronze (Cu-10wt%Al).*

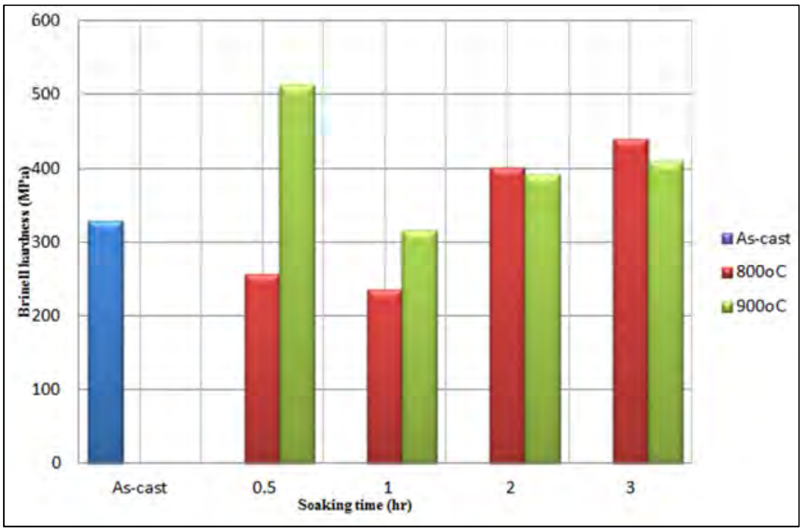

Figure 3. *Effect of solutionizing temperature and soaking time on the hardness of aluminium bronze (Cu-10wt%Al).*

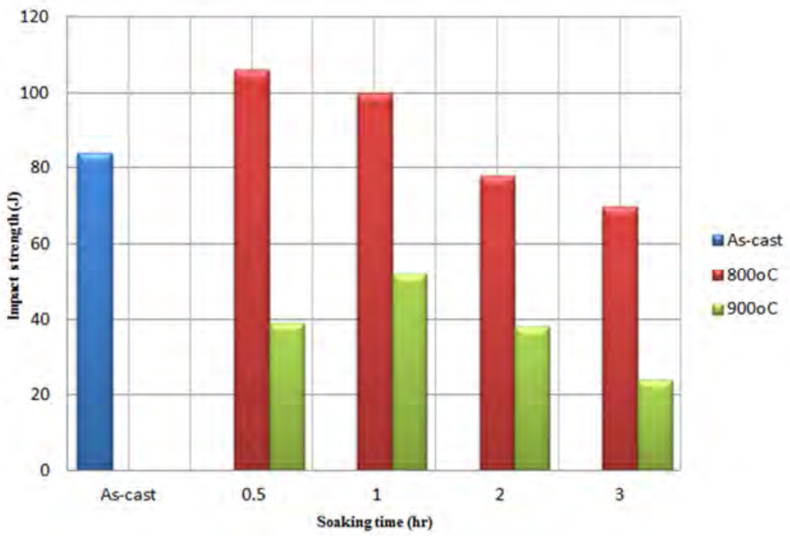

Figure 4. *Effect of solutionizing temperature and soaking time on the impact strength of aluminium bronze (Cu-10wt%Al).*

The effect of solutionizing temperature and soaking time on the percentage elongation, ultimate tensile strength, hardness and impact strength of aluminium bronze is presented in Figures 1-4. Analysis of Figures 1-4 shows clearly that heat treatment increased the percentage elongation, ultimate tensile strength, hardness and impact strength of aluminium bronze significantly with maximum values of 73.1%, 609MPa, 513MPa and 106J respectively. This could be attributed to reduction in grain size which resulted to increase in the number of grain boundaries that hinder the dislocation motion. Figure 1 and 2 showed that at 800°C solutionizing temperature, the percentage elongation and ultimate tensile strength increased with increase in soaking time while at solutionizing temperature of 900°C, different trends in percentage elongation and ultimate tensile strength were observed. It was evidenced in Figure 4 that the impact strength of the studied alloy decreased with increase in soaking time at solutionizing temperature of 800°C. Analysis of Figure 4 shows clearly that the as-cast aluminium bronze sample had better impact strength than the samples solutionized at temperature of 900°C. Figure 3 showed at both solutionizing temperatures, the hardness of the heat treated alloy decreased as soaking time increased to 1 hr and increased at further increase in soaking time. Maximum percentage elongation and impact strength of 73.1% and 106J respectively were obtained by the alloy solutionized at 800°C for 3hrs and 0.5hr respectively. Alloy samples solutionized at temperature of 900°C for 0.5hr showed maximum ultimate tensile strength and hardness values of 609MPa and 513MPa respectively. These trends in the tested mechanical properties are quantified by the microstructural changes as shown in Figures 5-14.

3.2. Microstructure Analysis of the Studied Alloy

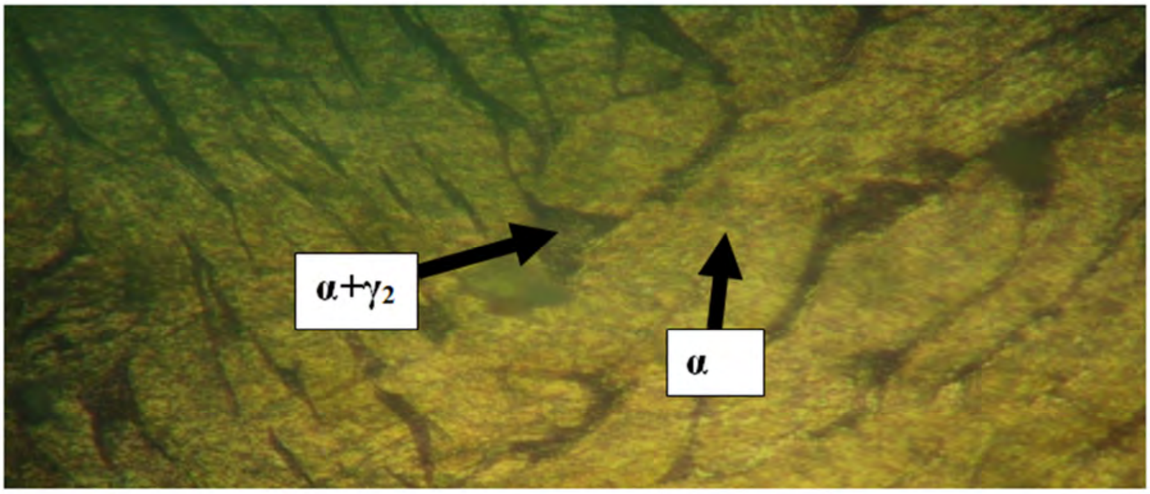

Figure 5. *Micrograph of as-cast aluminium bronze (Cu-10wt%Al).*

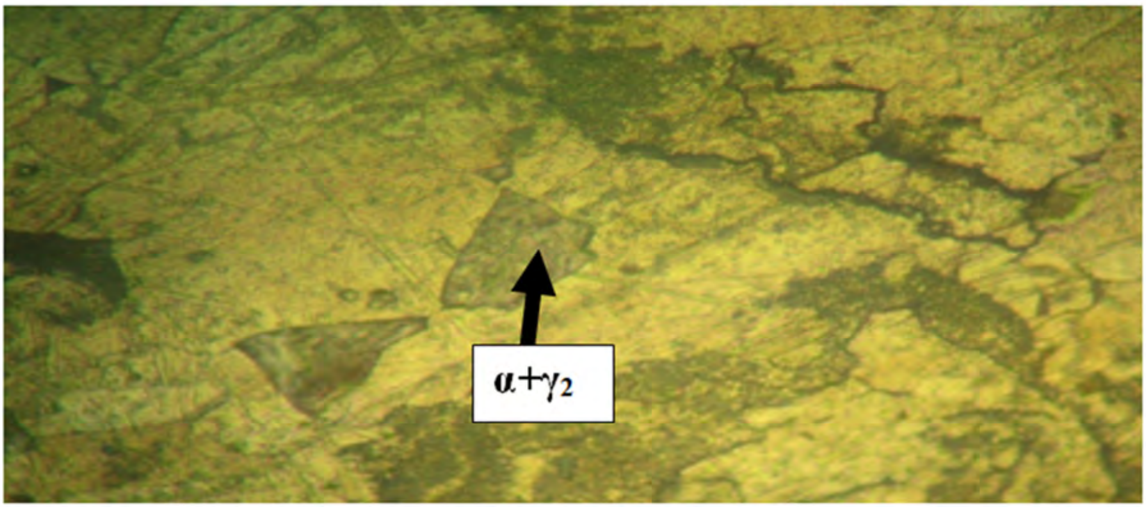

Figure 6. *Micrograph of aluminium bronze solution heat treated at 800°C for 0.5hr and quenched in brine.*

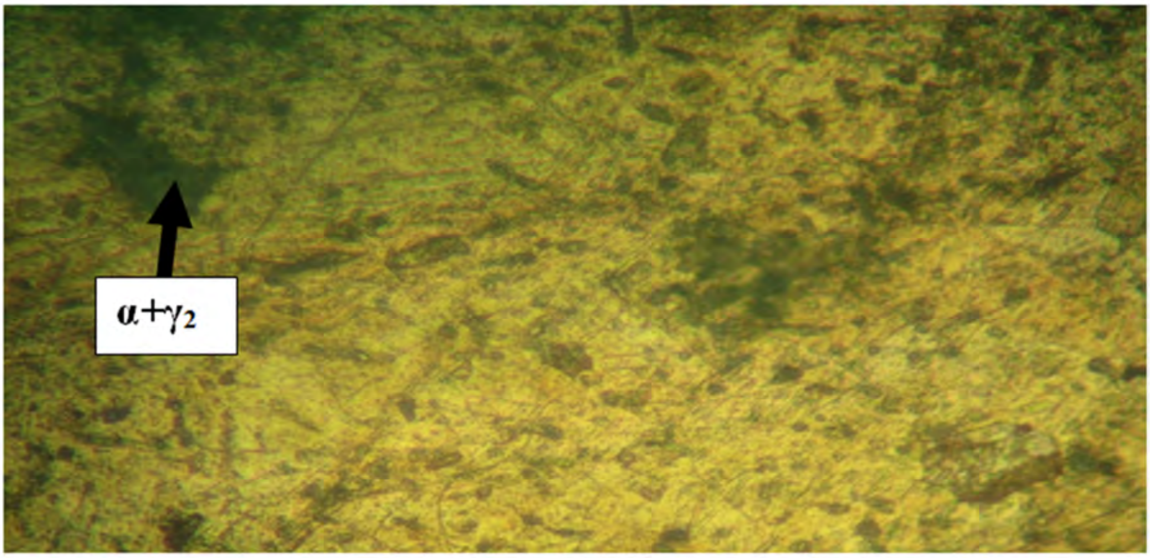

Figure 7. *Micrograph of aluminium bronze solution heat treated at 800°C for 1hr and quenched in brine.*

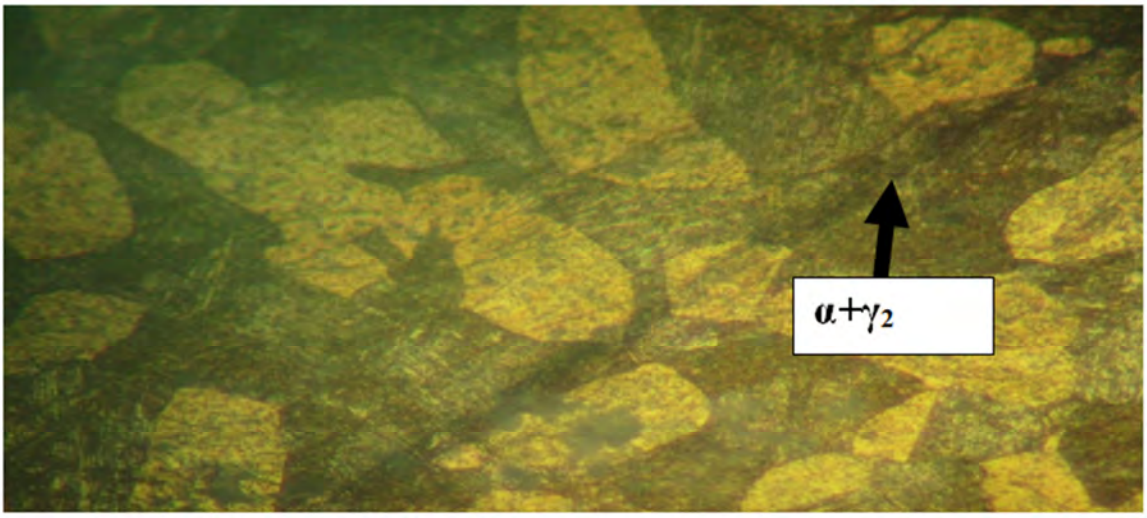

Figure 8. *Micrograph of aluminium bronze solution heat treated at 800°C for 3hrs and quenched in brine.*

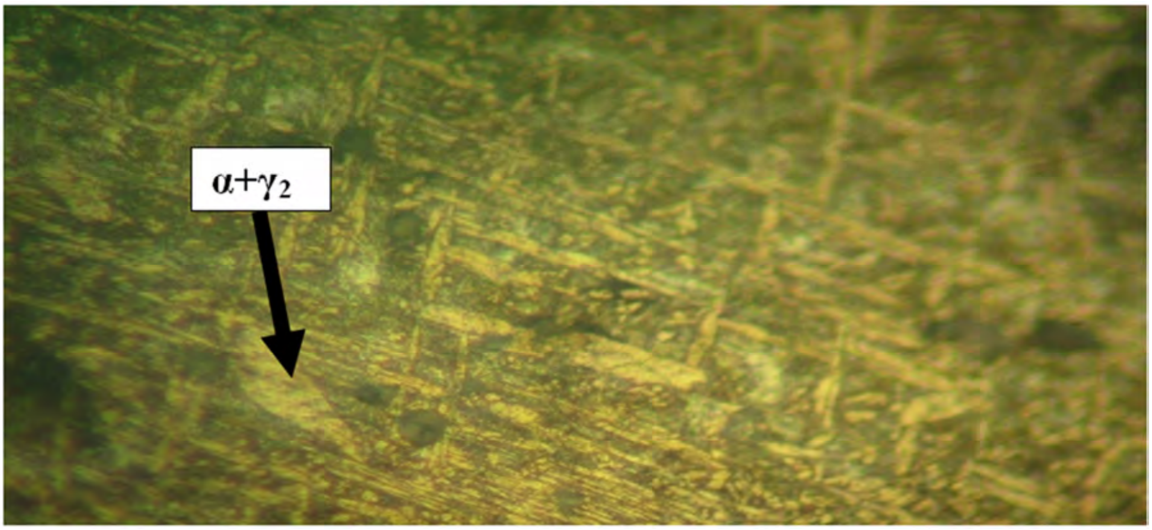

Figure 9. *Micrograph of aluminium bronze solution heat treated at 900°C for 0.5hr and quenched in brine.*

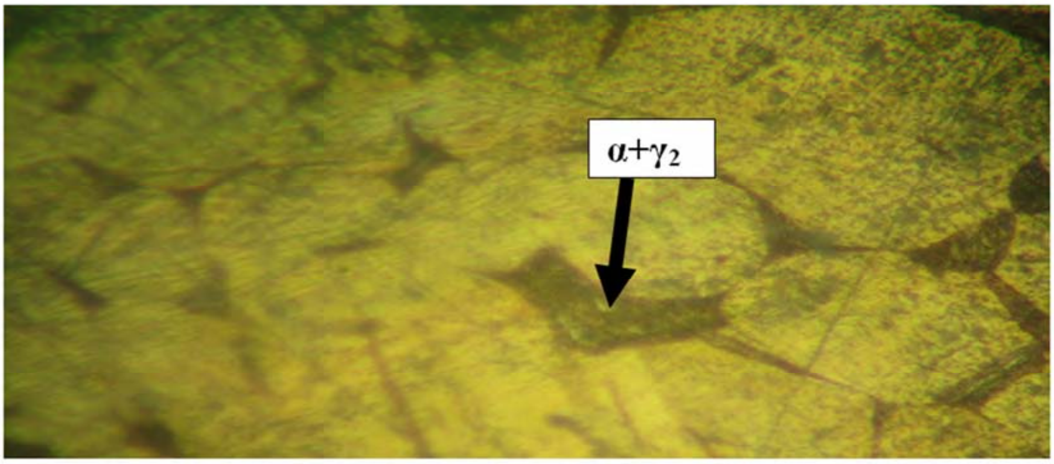

Figure 10. *Micrograph of aluminium bronze solution heat treated at 900°C for 1hr and quenched in brine.*

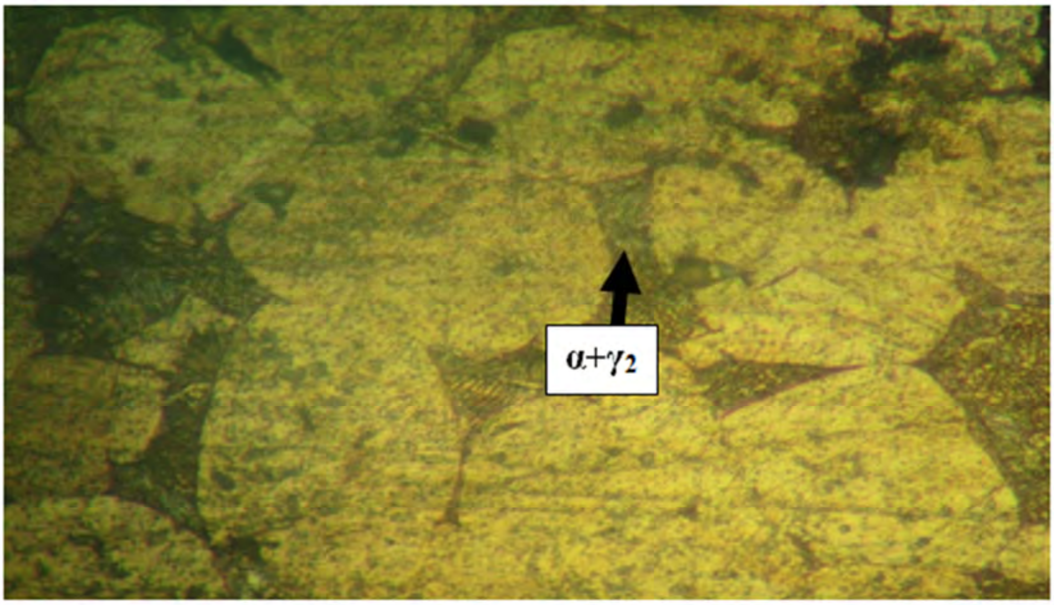

Figure 11. *Micrograph of aluminium bronze solution heat treated at 900°C for 3hrs and quenched in brine.*

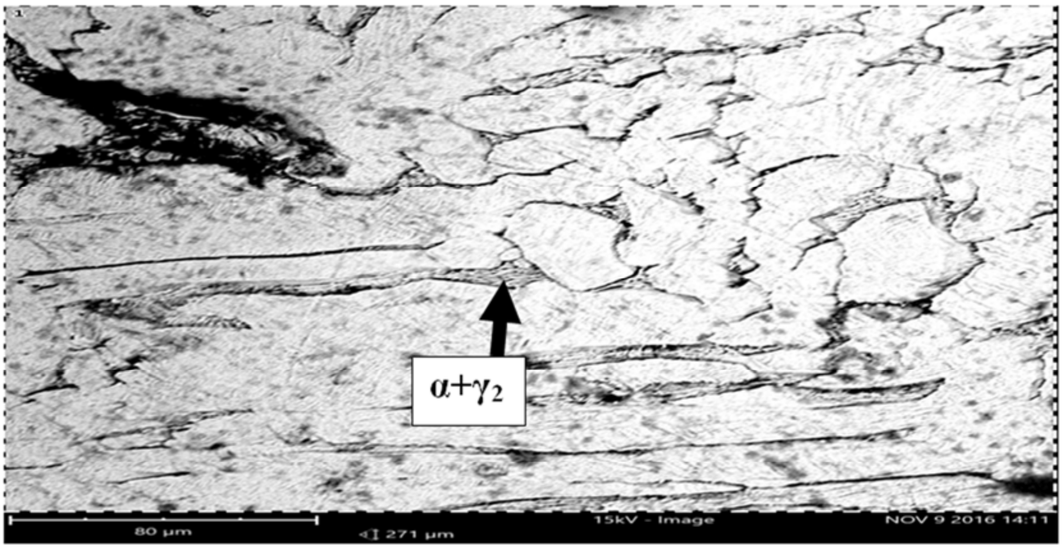

Figure 12. *Micrograph (SEM) of Cu-10%Al (As-cast).*

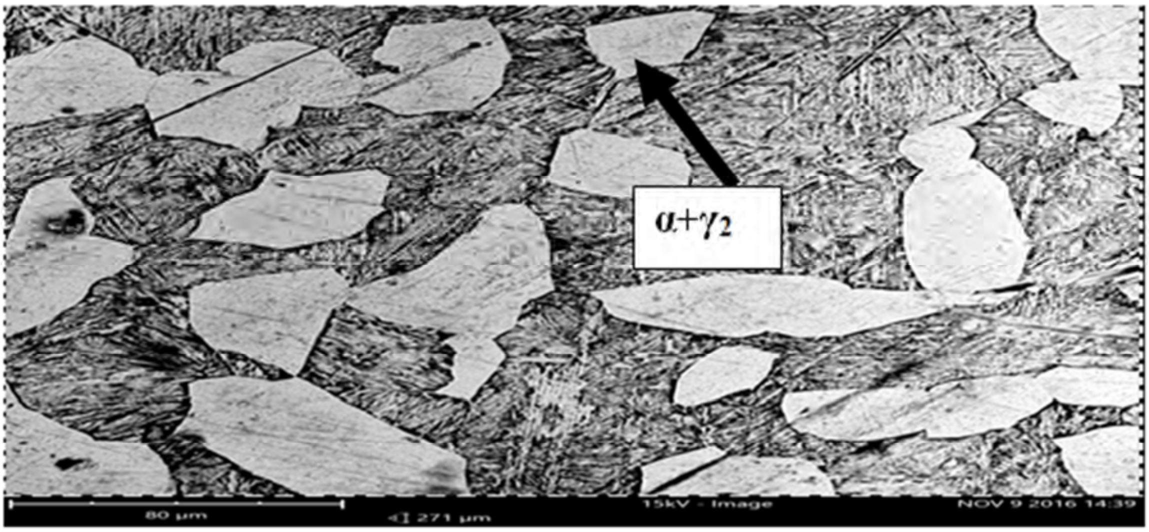

Figure 13. *Micrograph (SEM) of aluminium bronze solution heat treated at 800°C for 3hrs and quenched in brine.*

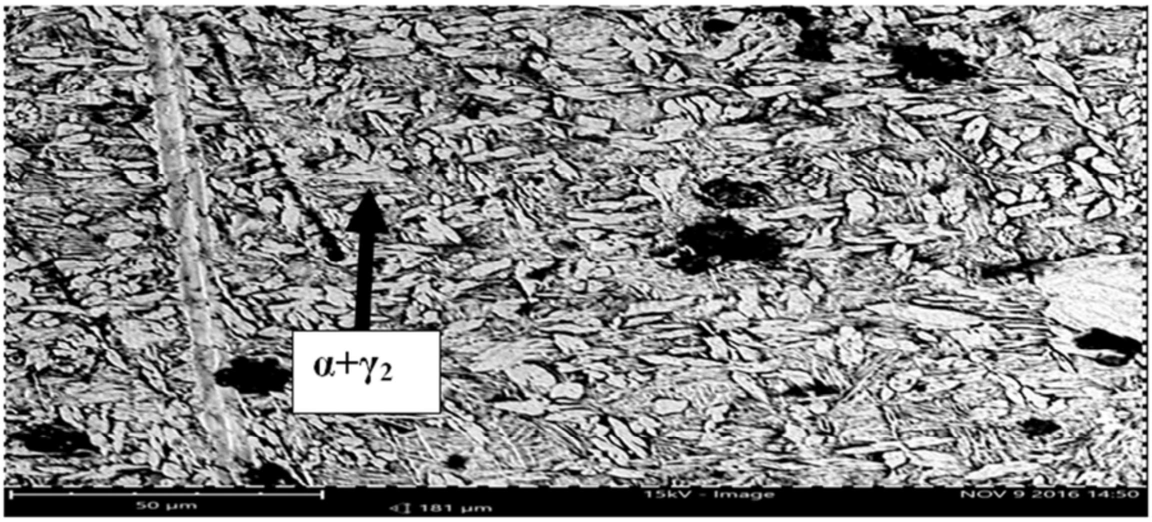

Figure 14. *Micrograph (SEM) of aluminium bronze solution heat treated at 900°C for 0.5hr and quenched in brine.*

A detailed analysis of the surface morphology of heat treated and as-cast aluminium bronze (Cu-10wt%Al) are presented in Figures 5-14. The surface morphology of the as-cast aluminium bronze shown in Figures 5 and 12 revealed the presence of primary α-phase and coarse needle-like intermetallic compound ($\alpha+\gamma_2$), evenly dispersed in the aluminium matrix. The micrographs of the heat treated aluminium bronze revealed the presence of evenly dispersed fine spherical intermetallic compound in the aluminium matrix. Figures 9-11 and 14 showed even distribution of small grains of intermetallic compound in the aluminium matrix. This increased the number of grain boundaries in the alloy structure which impede or hinder the dislocation motion, hence increased the ultimate tensile strength and hardness of the alloy. Greater extents of microstructural homogenization along with coarsening of the intermetallic compounds was evidenced in Figures 6-11 as the solutionizing time increased.

4. Conclusion

The effect of heat treatment parameters on the structure and mechanical properties of Cu-10wt%Al alloy was studied in detail using standard technique. The following conclusions were drawn from the results of the study.

The structure and mechanical properties of aluminium bronze were greatly controlled by the heat treatment parameters such as the solutionizing temperature and time of the treatments.

Formation of coarse sparse distribution of $\alpha+\gamma_2$ precipitates in the structure of as-cast aluminium bronze resulted to high hardness and low ductility of the alloy.

Maximum ultimate tensile strength and hardness of 609MPa and 513MPa were obtained by the alloy solutionized at 900°C for 0.5hr.

Maximum percentage elongation of 73.1% was obtained by the alloy solutionized at 900°C for 3hrs.

Maximum impact strength of 106J was obtained by the alloy solutionized at 900°C for 0.5hr.

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