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Correlation of the Structure, Mechanical and Physical Properties of Cu-3wt%Si-xwt%Sn Silicon Bronze

K. C. Nnakwo[1*]and **E. E. Nnuka** [2]

[1]Department of Metallurgical and Materials Engineering, Enugu State University of Science and Technology, P.M. B. 01660, Enugu

[3]Department of Metallurgical and Materials Engineering, NnamdiAzikiwe University, Awka

[*]CorrespondingAuthor's E-mail: kingchidiebere@yahoo.com

Abstract

This research investigated the correlation of the structure, mechanical and physical properties of Cu-3wt%Si-xwt%Sn silicon bronze. The effect of tin content on the structure, mechanical and physical properties of Cu-3wt%Si-xwt%Sn silicon bronze was also investigated. Tin was added in concentrations of 0.1, 0.3, 0.5, 0.8, 1 and 1.5wt%. The samples were developed using permanent die casting technique and machined to the required dimensions for the structural analysis, physical and mechanical tests. Mechanical properties such as percentage elongation, ultimate tensile strength and hardness of the developed alloy were investigated using a 100KN JPL tensile strength tester (Model: 130812) and portable dynamic hardness testing machine (Model: DHT-6) respectively. The physical properties such as electrical resistivity and conductivity were also determined using standard Ohm's experiment. The structural analysis was conducted using an optical metallurgical microscope (Model: L2003A) and scanning electron microscopy (SEM). The microstructural analysis of the control sample (Cu-3wt%Si) revealed the presence of segregated primary silicon and coarse intermetallic phase (Cu_3Si). The surface morphology of the doped alloy consisted of refined and modified intermetallic phases evenly dispersed in the alloy structure. The mechanical tests results showed that the percentage elongation, ultimate tensile strength and hardness of the alloy increased significantly by addition of tin. The ultimate tensile strength and hardness of the alloy increased with increase in tin content with corresponding decrease in percentage elongation. It was also observed that the electrical resistivity of the alloy increased with corresponding decrease in electrical conductivity by addition of 0.1wt% of tin. Results obtained also showed that the ultimate tensile strength and hardness correlate with electrical resistivity while the percentage elongation correlates with electrical conductivity. This was concluded to be as a result of grain refinement of the alloy structure by tin addition which caused scattering of electrons, hence increased the electrical resistivity with corresponding decrease in electrical conductivity of the alloy.

Keywords: Electron scattering; mechanical properties;physical properties; silicon bronze; grains.

1. Introduction

Copper based alloys have gained an increasing demand in engineering applications mostly in chemical, petroleum, automotive and power generating industries (Garcia et al., 2010). This is because of its combination of excellent properties such as corrosion resistant, ductility, malleability, non-magnetism, wear resistance, machinability; good thermal and electrical conductivities (Shabestariand Moemeni, 2004). Commercially, pure copper is very soft, ductile and malleable with low tensile strength, containing up to about 0.7% total impurities (William, 2010). Various engineering applications demand high strength, therefore substantial increase in strength of pure copper is paramount in order to increase its applications (Zhang et al., 2003). Silicon bronze is among the most widely used copper based alloys because of its combination of corrosion resistance, strength, and formability (Ketut et al., 2011).

It is mostly used in production of electrical conduits, valve stems, tie rods, fasteners, marine and pole-line hardware, nuts, bolts, screws, rivets, nails, and wire (Kulczyk et al., 2012).

This research was propelled by the interest to modify the segregated primary silicon and coarse copper silicide (Cu_3Si) phases present in a slowly cooled silicon bronze which have detrimental effect on the mechanical properties of the alloy. Ohkubo et al. (2005) reported that three inter-metallic phases exist at room and high temperatures. The room temperature intermetallic phases included; ε-($Cu_{15}Si_4$), γ-(Cu_5Si) and η''- (Cu_3Si) while the high temperature intermetallic phases included α, β and κ. The η''- (Cu_3Si) phase has two high temperature modifications such as η' and η. Ketut et al. (2011) established in their study of the effect of silicon content on the mechanical and acoustical properties of silicon bronze alloys for musical instruments that the mechanical properties and damping capacity of Cu-xSi were higher than Cu-20wt.%Sn bronze alloys. Mattern et al. (2007) reported the presence of different meta-stable phases such as η, σ and κ on rapidly quenched silicon bronze. The study also established that room temperature phase, ε was suppressed by rapid quenching. Puathawee et al. (2013) revealed that addition of tin to Cu-Si-Zn alloy increased the amount of beta (β) and gamma (γ) phases in the alloy structure. An optimum hardness of 123.4 HV was noted by 60Cu-0.5Si-39.5Zn alloy. Study by Božića et al. (2008) has shown that the rapidly solidified Cu-1.2Ti-3$TiSi_2$ powder microstructure was characterized by the presence of fine, dispersed primary $TiSi_2$ particles and high super saturated solid solution. The study indicated that the microstructure of the studied alloys was not completely homogenous but rather exhibited the presence of homogenous fluctuations in the range of 5–10μm. Cu-1.2Ti-3$TiSi_2$ powder yielded much higher microhardness values compared with the Cu-1.2Ti powder, owing to primary $TiSi_2$dispersoides formed during atomization.

2.0 Material and methods

Copper and silicon pure metals were used as the base materials for this research while tin metal of 99.99 pure was used as the dopant. The dopant was added in concentrations of 0.1, 0.3, 0.5, 0.8, 1 and 1.5wt%. Permanent die casting technique was adopted for producing the alloys samples used for this research. For the control sample, the required amount of pure copper wire was melted in a bailout crucible furnace and the predetermined amount of silicon powder wrapped in an aluminium foil was added to the copper melt and stirred vigorously to ensure homogeneity. The mixture was superheated to increase fluidity and poured into a preheated mould. The procedure was repeated and the alloy melt was doped with the different concentrations of tin and cast. The cast samples were machined to the required dimension and stored for the mechanical and physical tests such as percentage elongation, ultimate tensile strength, hardness, electrical resistivity and conductivity. The tensile strength, hardness and impact strength of the developed alloy were determined using an automated 100KN JPL tensile strength tester (Model: 130812), portable dynamic hardness testing machine (Model: DHT-6) and impact testing machine (Model: U1820) respectively. Standard Ohm's experiment was adopted in determining the electrical resistivity and conductivity of the developed alloy (Joseph et al., 2014). The samples 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 of x400 and x1500 respectively.

3.0 Results and Discussions

3.1. Mechanical properties of the studied alloy

The effects of tin content on percentage elongation, ultimate tensile strength and hardness of silicon bronze are presented in Figure 1. Analysis of Figure 1 indicated that addition of tin to Cu-3wt%Si alloy significantly increased the percentage elongation, ultimate tensile strength and hardness of the alloy by 180.9%, 526.5% and 43.3% respectively. Figure 1 also showed that the ultimate tensile strength and hardness of the alloy increased with increase in tin content with maximum values of 213MPa and 258MPa respectively obtained at 1.5wt% tin content. The percentage elongation of the alloy showed different trend as it decreased with increase in tin content with maximum value of 26.4% obtained at 0.1wt% tin addition. At 0.1wt% tin addition, a significant increase in percentage elongation and ultimate tensile strength was observed unlike in hardness where a significant increase was observed at 0.8wt tin addition. This trend in mechanical properties was quantified by the microstructural changes as evidenced in Figures 5-10.

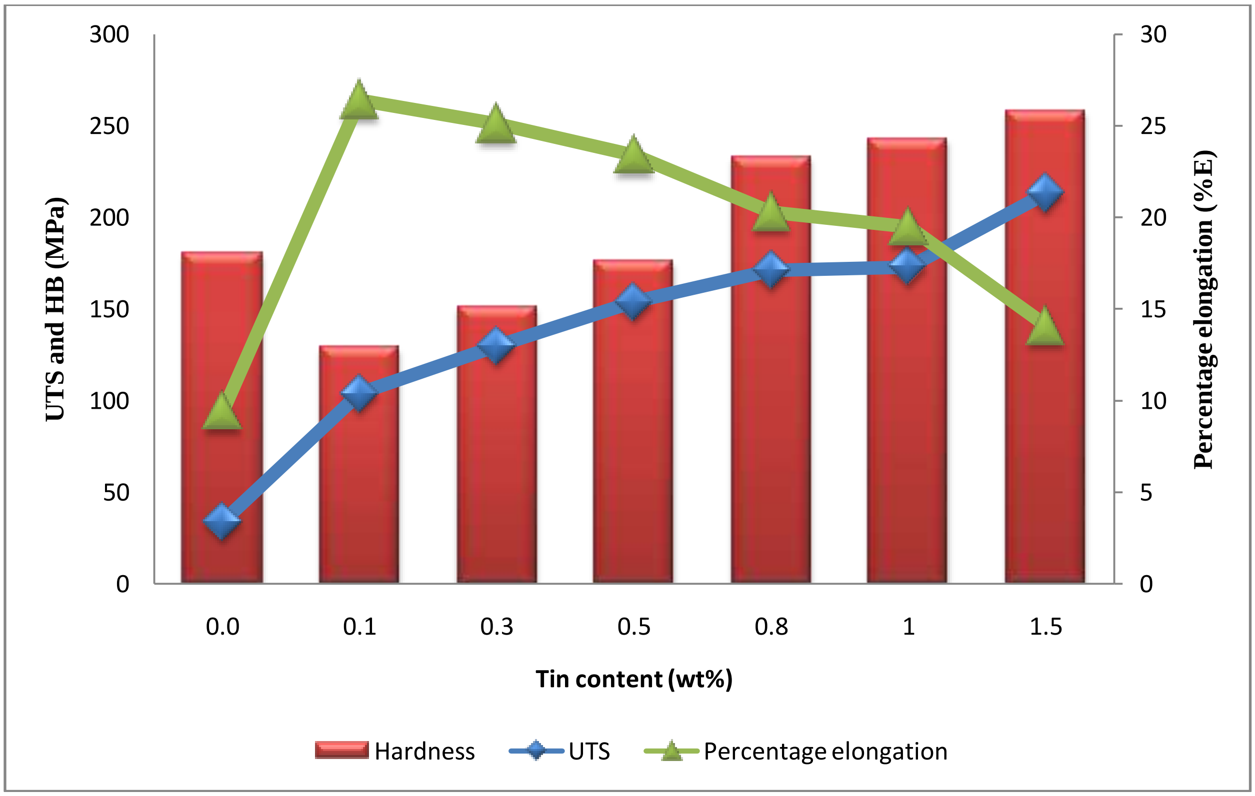

Figure 1: Effect of tin content on the percentage elongation, ultimate tensile strength (UTS) and hardness (HB) of silicon bronze

3.2. Physical properties of the studied alloy

Figure 2 shows the electrical resistivity and conductivity of silicon bronze doped with different concentration of tin. Analysis of Figure 2 showed clearly that addition of 0.1wt% of tin to silicon bronze increased the electrical resistivity (ρ), hence decreased the electrical conductivity (σ) of the alloy. It was noted in Figure 2 that the addition of tin to Cu-3wt%Si increased the electrical resistivity of the alloy by 18.8%, thereby decreased the electrical conductivity of the alloy by 15.8%. Figure 2 showed that the electrical resistivity of the alloy increased progressively with corresponding decrease in electrical conductivity as the tin content increased. This could be attributed to the refining effect of tin on the dendritic primary silicon formed in the alloy structure as evidenced in Figures 5-10.

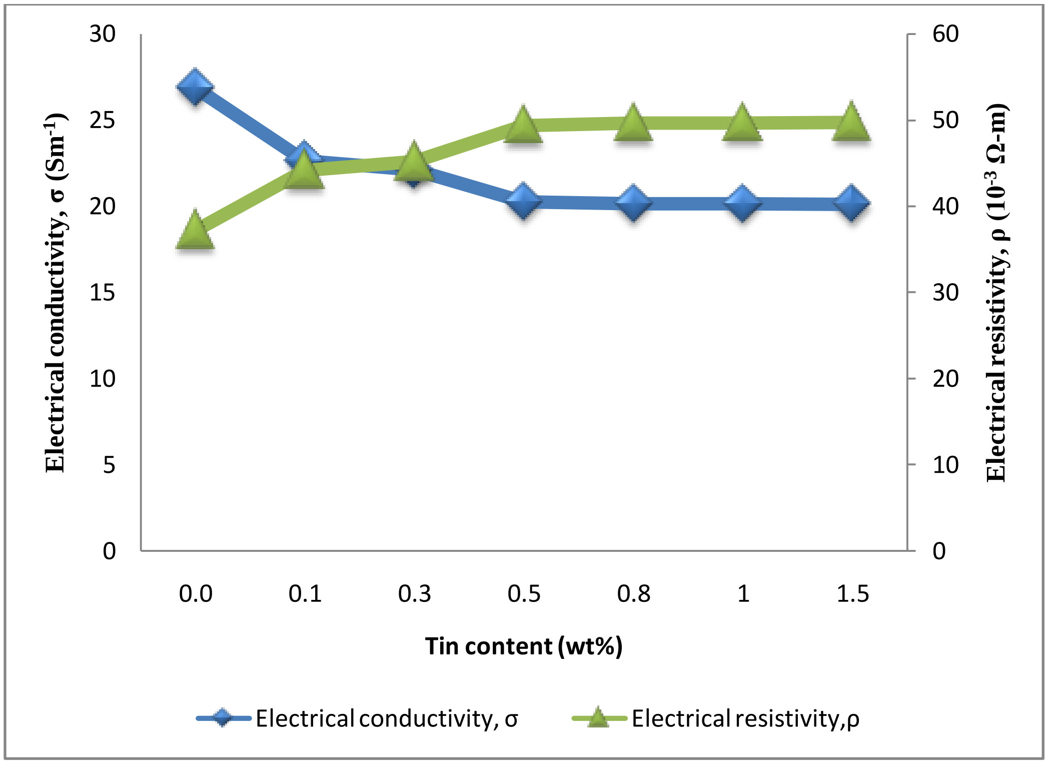

Figure 2: Effect of tin content on the percentage electrical resistivity and conductivity of silicon bronze

3.3 Correlation of mechanical and physical properties of the developed alloy

The correlations of the mechanical and physical properties of silicon bronze doped with different concentrations of tin are presented in Figures 3 and 4. Analysis of Figure 3 showed clearly that the ultimate tensile strength and hardness of the alloy studied increased correspondingly with increase in the electrical resistivity of the alloy as the tin content increased. It was also noted in Figure 4 that the percentage elongation decreased correspondingly with increase in electrical conductivity of the alloy as the tin content increased. These trends indicated that the ultimate tensile strength and hardness of the studied alloy correlate with electrical resistivity while the percentage elongation correlates with electrical conductivity. These correlations could be linked with the electron theory which states that the electrical resistivity, ρ for metal is a measure of the non-forwards electron scattering when the external electric field is accelerated. Addition of tin to Cu-Si alloy system modified and decreased the grain size of the alloy. The decrease in grain size resulted to increased grain boundary in the alloy structure which hindered the dislocation motion, hence increased the ultimate tensile strength and hardness of the alloy with corresponding decrease in percentage elongation. The decreased grain size also served as the point of electron scattering which increased the electrical resistivity and decreased the electrical conductivity of the alloy (Nnuka, 1994). As the grain size decreased, the rate of electron scattering increased, thereby caused a systematic decrease in electrical conductivity of the alloy (Joseph et al., 2014).

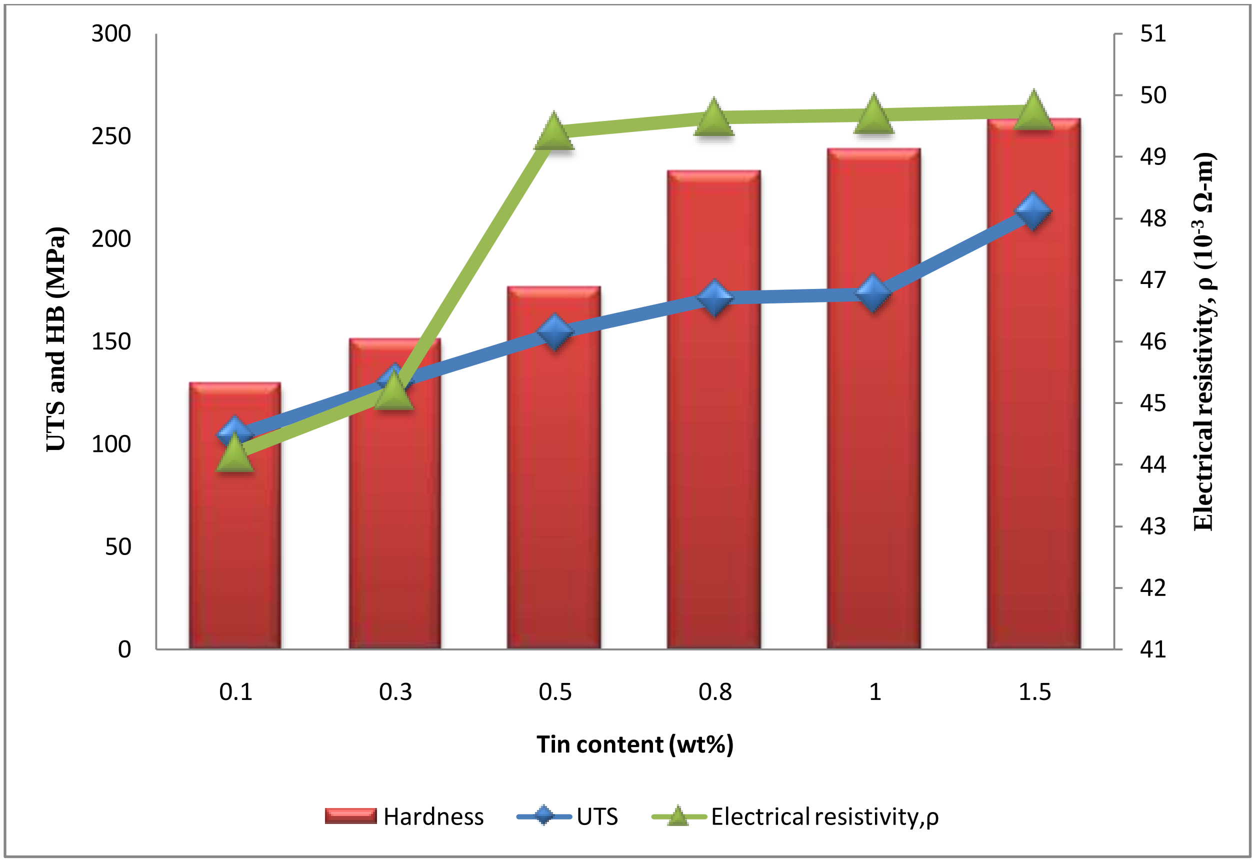

Figure 3: Correlation of the ultimate tensile strength (UTS), hardness (HB) and electrical resistivity (ρ) of silicon bronze.

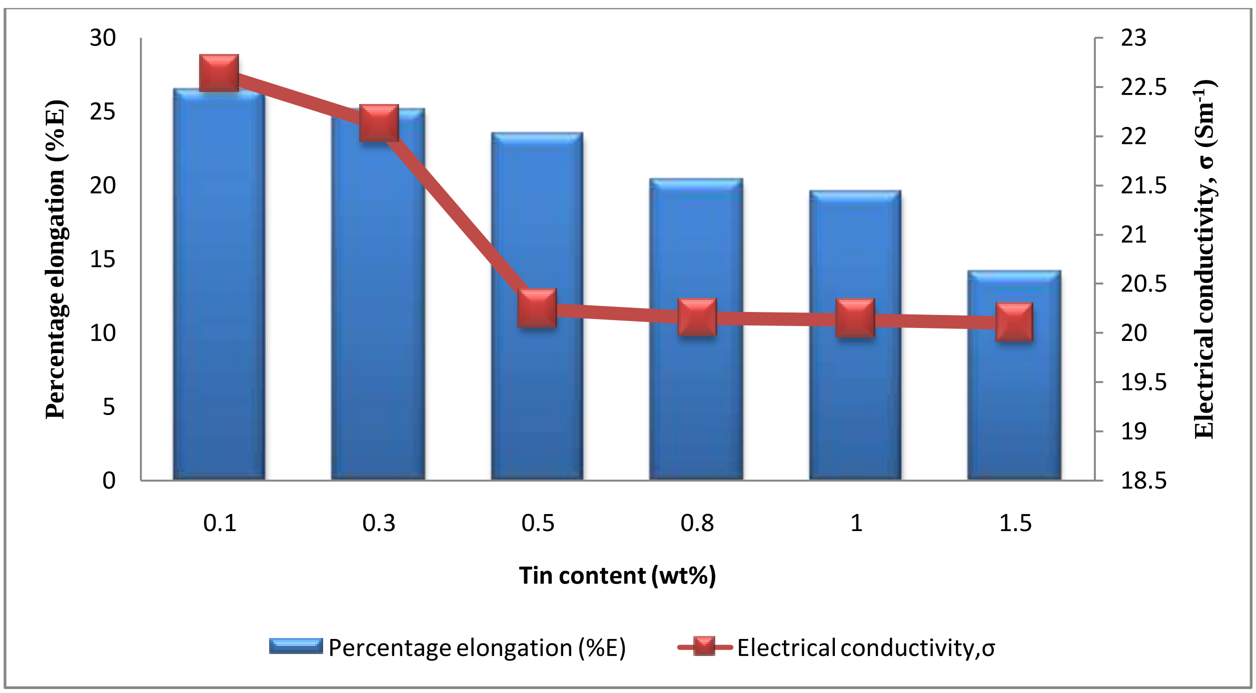

Figure 4: Correlation of the percentage elongation and electrical conductivity (σ) of silicon bronze

3.4 Optical and scanning electron microscopy analyses of the studied alloy

The optical and scanning electron microscopy analyses of Cu-3wt%Si-xwt%Sn of different concentrations of tin are presented in Figures 5-10. The surface morphology of the control sample presented in Figure 8 revealed the presence of dendritic primary silicon and coarse intermetallic phase (Cu_3Si). The micrographs of the alloy doped with different concentrations of tin presented in Figures 5-7, 9 and 10 revealed the presence of spherical intermetallic compound evenly dispersed in the alloy structure. This indicated that addition of tin to Cu-3wt%Si significantly modified and refined the dendritic primary silicon in the alloy structure into spherical pattern, thereby increased the grain boundary which impede the dislocation motion, hence caused an increase in ultimate tensile strength and hardness of the alloy with corresponding decrease in percentage elongation as evidenced in Figures 1-4.

Figure 5: Micrograph of Cu-3%wt.Si-0.1%wt.Sn alloy

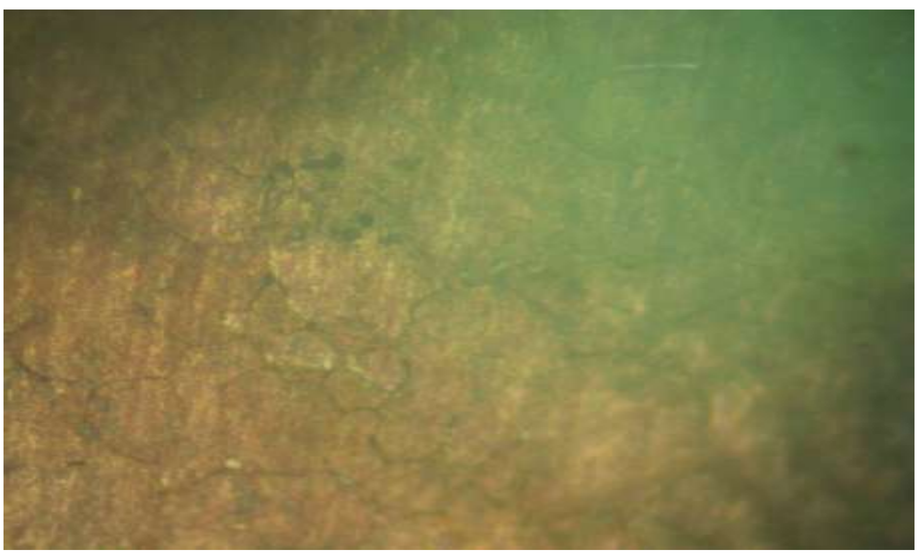

Figure 6: Micrograph of Cu-3%wt.Si-0.5%wt.Sn alloy

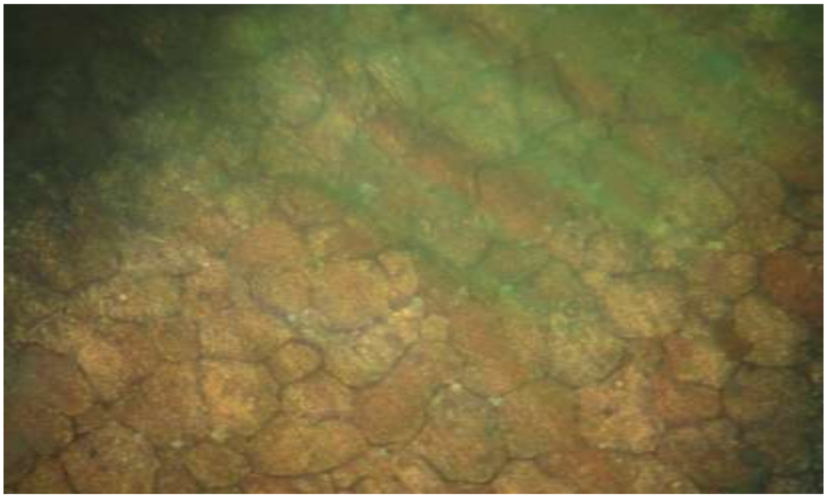

Figure 7: Micrograph of Cu-3%wt.Si-1%wt.Sn alloy

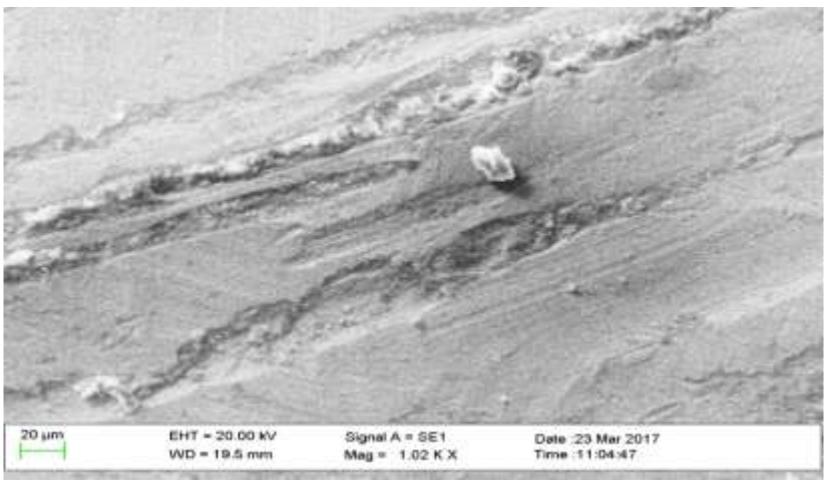

Figure 8: Micrograph (SEM) of Cu-3%wt.Si alloy (Control)

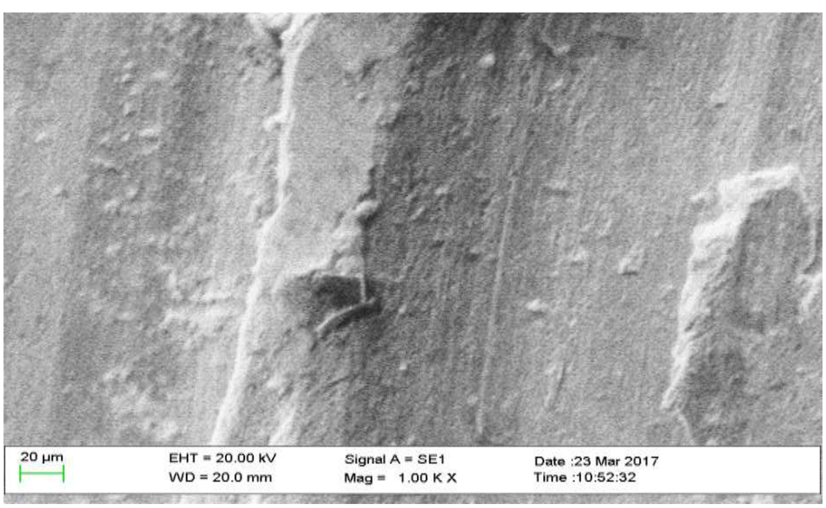

Figure 9: Micrograph (SEM) of Cu-3%wt.Si-1wt%Sn alloy

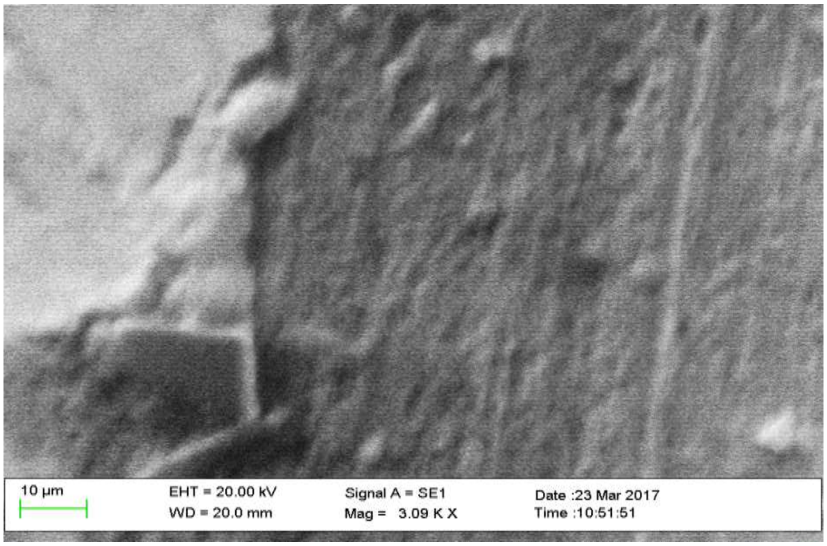

Figure 10: Micrograph (SEM) of Cu-3%wt.Si-1.5wt%Sn alloy

4.0. Conclusion

The correlation of the structure, mechanical and physical properties of Cu-3wt%Si-xwt%Sn alloy was studied in details using standard techniques. The following conclusions were drawn from the results of the study:

a. The low mechanical properties of Cu-Si alloy system were as a result of the presence of the segregated primary silicon and coarse intermetallic phase in the alloy structure.

b. The amount and size of the segregated primary silicon in Cu-3wt%Si alloy system were decreased significantly by addition of tin.

c. Addition of 0.1wt% tin to Cu-3wt%Si alloy system significantly improved the percentage elongation and ultimate tensile strength of the alloy. This was quantified by the formation of spherical intermetallic phase in the alloy structure.

d. The significant improvement in the percentage elongation, ultimate tensile strength and hardness of Cu-3wt%Si alloy system was attributed to the decrease in size, refinement and modification of the segregated primary silicon and coarse intermetallic compound in the alloy structure.

e. Addition of 0.1wt% tin to Cu-3wt%Si silicon bronze increased the electrical resistivity and decreased the electrical conductivity of the alloy.

f. The ultimate tensile strength and hardness correlate with electrical resistivity while the percentage elongation correlates with electrical conductivity of the alloy studied.

5.0 Recommendation

From the results achieved from the study of the correlation of the structure, mechanical and physical properties of Cu-3wt%Si-xwt%Sn silicon bronze, it is thus recommended that addition of other alloying elements that can improve the electrical conductivity of the alloy without the expense of improved mechanical properties should be investigated.

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