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Influence of chromium on the structure and physic-mechanical properties of Cu-3wt%Si alloys

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Abstract
The structure and physico-mechanical properties of Cu-3wt%Si alloys produced by permanent mould technique were investigated in order to determine the effect of trace quantity of chromium on the microstructure and physico-mechanical properties. These research objectives were accomplished using tensile, hardness and electrical conductivity/resistivity tests. Optical microscopy was used to analyze the microstructure of the cast samples. The results showed that addition of chromium to Cu-3wt%Si alloy refined and modified the structure of the alloy and consequently improved the physico-mechanical properties. The observed maximum ultimate tensile strength, yield strength and hardness values were 316 MPa, 238 MPa and 85 HRB at 1.5wt%Cr content respectively while maximum percentage elongation value of 28.2% at 0.1wt%Cr content was observed. Maximum electrical conductivity (28.62 S/m) and minimum electrical resistivity (34.94x10^{-3}Ωm) were obtained at 0.1wt%Cr content.

Keywords: Chromium, Copper, Silicon, Structure, physic-mechanical properties.

1. Introduction

Alloying is very important in engineering due to its huge influence on the mechanical properties of materials. An alloy of a metal is made by combining it with one or more other metals or non-metals that often enhances its properties (Mehdi et al., 2015; Nwambu et al., 2017)). Additions of other metals are frequently made to improve properties such as strength, hardness, machinability, corrosion resistance or for other special reasons (Nwambu et al., 2017). Most of these elements are soluble to some extent in copper, retaining the alpha face-centred cubic structure up to the limit of solubility but with progressive effects on strength, hardness and rate of work hardening. Hence, the strong need to alloy copper with other metals or non metals such as silicon, tin, manganese, tungsten, zinc, nickel, magnesium, etc (Nnakwo et al., 2017a, 2017b; Lei et al., 2013a, 2013b, 2017; Cribb et al., 2013; Ilona et al., 2016; Wang et al., 2016; Li et al., 2017; Garbacz-Klempka et al., 2018; Qian et al., 2017; Gholami et al., 2017).

Commonly, alloys have different properties from those of the component elements. Copper and copper-based alloys are among the most commercially important metals because of their relatively good properties, ease of manufacture and numerous applications. They are normally exploited because of their good electrical and thermal conductivity, outstanding resistance to corrosion and ease of fabrication. A number of researchers have worked on improving the mechanical properties of copper alloys, silicon bronze (Cu-3wt%Si alloy) inclusive. Addition of tin to Cu-Ni alloys has been shown to increase the peak hardness of the alloy in solutionized and aged conditions (Shankar and Sellamuthu, 2017). Puathawee et al. (2013) worked on lead-free silicon brass (Cu-Zn-Si) with tin addition to investigate the comparative influence of the addition and non-addition of tin on the microstructures and microhardness of the alloys. According to their findings, tin addition enhanced the hardness of lead-free Cu-Zn-Si brass. Kozana et al., 2018 studied the influence of various nickel additions to Cu-10wt%Sn casting bronze and to Cu-8wt%Sn bronze of a decreased tin content. They reported that the addition of nickel to Cu-Sn alloys improved the mechanical properties: ultimate tensile strength (UTS), hardness (HB) and % elongation.

Nnakwo et al. (2017a) investigated the effect of zinc content on the structure and mechanical properties of silicon bronze (Cu-3wt%Si). They studied the percentage elongation, ultimate tensile strength and hardness of the alloys. Their results indicated increase in percentage elongation, ultimate tensile strength and hardness of the alloys as the zinc content increased. Addition of tin to Cu-3wt%Si alloy has been confirmed by Nnakwo et al. (2017b) to improve the hardness and ultimate tensile strength of the alloy. Wang et al. (2016, 2018) investigated the effects of Cr and Zr additions on microstructure and properties of Cu-Ni-Si alloys. They reported that the addition of Cr and Zr resulted to the formation of Cr_3Si and Ni_2SiZr intermetallic compounds, respectively, which led to an increase in the electrical conductivity of the alloy and refinement of the microstructure with attendant improvement in tensile properties. Silicon bronze has low mechanical properties and electrical conductivity (Nnakwo, 2019). The applications of silicon bronzes require that they have good combination of tensile strength, hardness, ductility and electrical conductivity which they do not have. There is then need for further research work on improving the mechanical properties of silicon bronze. Modification of solid-solution alloys by adding elements that react to form dispersed second phase compounds is one of the techniques used to improve the structure, mechanical and physical properties of alloys. This research focused on examining the influence of trace additions of chromium on structure, density, electrical conductivity/resistivity, and mechanical properties (ultimate tensile strength (UTS), yield strength, hardness and percentage elongation) of copper-silicon-chromium alloys. Choice of chromium as the additive was made after review of related literature (Wang et al., 2016, 2018). The effects of alloying element on the microstructure of the alloys were analysed and the impact of alloying element, second phases and changes in morphology on the properties of the cast alloys were determined. This research seeks to improve the structure and physico-mechanical properties of Cu-3wt%Si alloy through trace additions of chromium. Success in this area will go a long way towards widening the applications of silicon bronze in electronics, electrical, automobile and building industries

2.0 Material and methods

In this study, the materials used consisted of high purity copper wires and silicon powder. Elemental chromium in powder form was used to dope the silicon bronze (Cu-3wt%Si) with various concentrations of chromium. The required amounts of the materials for developing these alloys were calculated using weight percent calculation. Analytical balance with capacity-120g & readability-0.0001g was used to measure the weight in grams of each of the materials. To produce the control (Cu-3wt%Si) alloy samples, pre-determined amount of copper was first melted in a crucible furnace and appropriate amount of silicon powder wrapped in aluminium foil dipped into the melt and stirred to ensure even distribution of the silicon in the melt. The mixture was held for about 10 min to ensure complete dissolution of silicon in the copper melt and stirred again to achieve homogeneity before being cast into the metal mould which has been preheated to a temperature of 200°C and then allowed to cool to ambient temperature. Subsequently, doped Cu-3wt%Si alloy samples were produced by repeating the above described procedure and introducing the alloying additives in concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5, 2 and 3% by weight respectively.

Tensile test was performed on the experimental alloy samples according to ASTM E8/E8M-22 standards using a Universal Testing Machine (model WDW-10). The ultimate tensile strength, yield strength, % elongation and Young's modulus of the tested samples were determined from the test. Hardness test was carried out on the samples using a digital Rockwell hardness tester (model HRS-150) according to ASTM E18-22 standard. The following precautions were taken during the test: the surfaces to be tested were clean, dry, smooth, and free from oxide; the surfaces were placed flat and perpendicular to the indenter; the indenter and anvil were clean and well seated. Electrical resistivity and conductivity of the experimental alloys were determined using standard Ohm's experiment with a battery (source of electricity), ammeter and voltmeter. Microstructural analysis was carried out on the specimens using an optical metallurgical microscope (Model: L2003A) to examine the effect of the alloying additives on the structure of the Cu-3wt%Si alloys. The samples for microstructural analysis were subjected to filing, grinding, polishing and etching. The etchant used was a solution of 10g of iron (III) chloride, $30cm^3$ of hydrochloric acid and $120cm^3$ of water. Personal protection equipment such as gloves safety shoes and goggles were used as safety precautions during the tests. Sand buckets and first aid kit were also made available. Dry clean metals were used to prevent contamination of the melt with oxides and other impurities.

3.0 Results and Discussions

3.1 Microstructural analysis

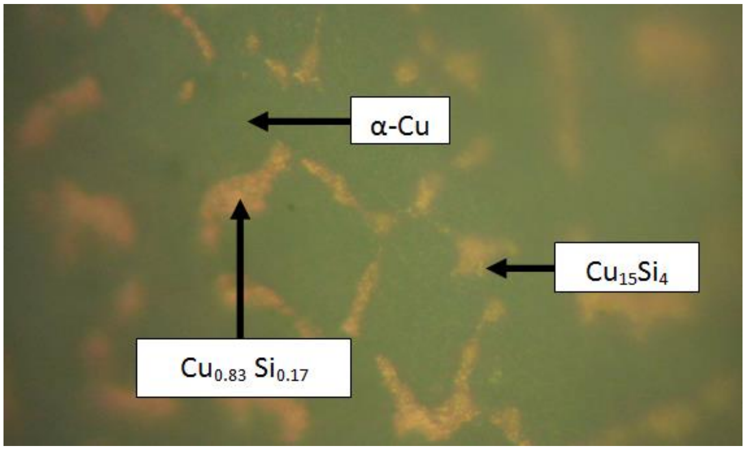

Figure 1: Micrograph of Cu-3wt%Si alloy

The optical micrograph of undoped Cu-3wt%Si alloy presented in Figure 1 shows the microstructure in which the α-copper primary phase (solid solution of silicon in copper), γ-$Cu_{0.83}Si_{0.17}$ (Cu_5Si) and ε-$Cu_{15}Si_4$ intermetallic phases are present. Coarse $Cu_{0.83}Si_{0.17}$ intermetallic phase can be observed at the grain boundaries in the microstructure of the alloy and owing to this, the mechanical properties of the alloy are not high enough which corresponds to the report of Nnakwo et al 2017.

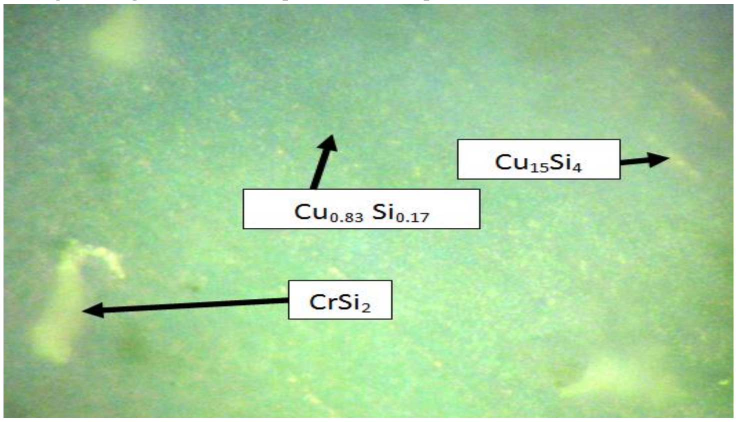

Figure 2: Micrograph of Cu-3wt%Si-0.1wt%Cr alloy

From Figure 2, it can be observed that the structure of the alloy has become refined and modified compared to the structure shown in Figure 1 for the undoped Cu-3wt%Si. Chromium formed $CrSi_2$ intermetallic compound with silicon which is indicated in the Figure.

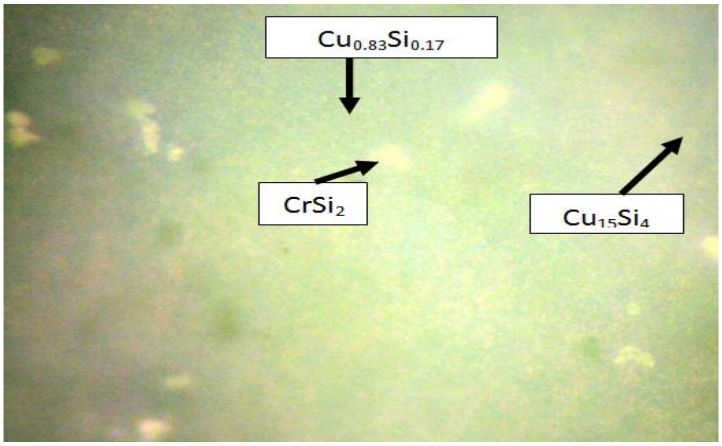

Figure 3: Micrograph of Cu-3wt%Si-0.8wt%Cr alloy

As chromium content is increased up to 0.8wt%Cr, further refinement and modification of the intermetallic phases can be observed as shown in Figure 3. Increase in chromium content resulted to increase in the amount of formed $CrSi_2$ intermetallic compound which has become less coarse with attendant improvement in the ultimate tensile strength, yield strength and hardness of the alloy (Qian et al., 2019, Grabacz-klempka et al., 2018).

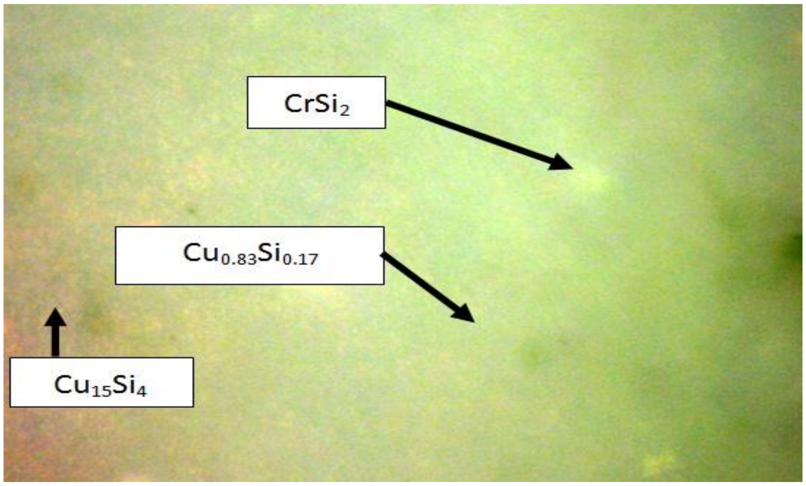

Figure 4: Micrograph of Cu-3wt%Si-1.5wt%Cr alloy

Addition of 1.5wt%Cr further refined and modified the structure of the intermetallic phases. The grain size further decreased with increase in concentration of chromium up to 1.5wt%. The improved grain size resulted to increase in number of grain boundaries which served as increased impediment to dislocation movement and consequently increased the ultimate tensile strength, yield strength and hardness of the alloy with corresponding decrease in percentage elongation. The improvement of the mechanical properties of the alloy supports the findings of Nnakwo et al., 2019 and Wang et al., 2018.

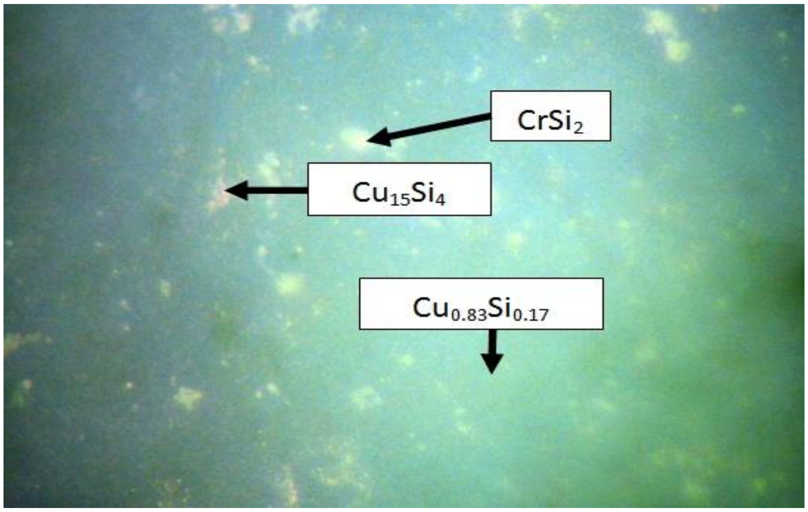

Figure 5: Micrograph of Cu-3wt%Si-2wt%Cr alloy

It is indicated in Figure 5 that increase in concentration of chromium beyond 1.5wt% coarsened the structure of the intermetallic compounds with larger amount of the intermetallic compounds formed.

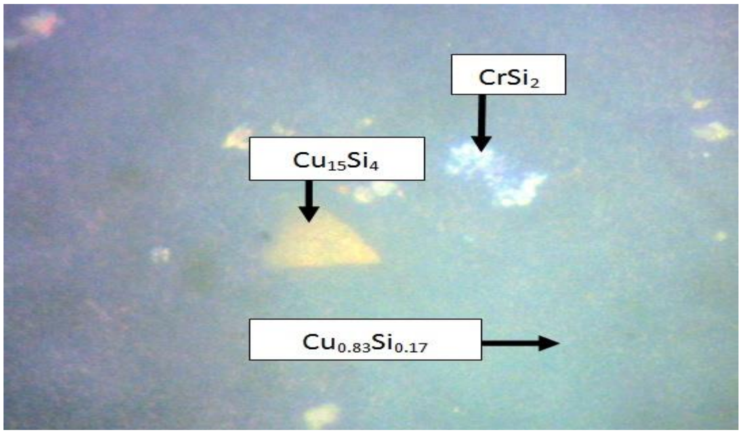

Figure 6: Micrograph of Cu-3wt%Si-3wt%Cr alloy

Further increase in concentration of chromium beyond 1.5wt% continued to coarsen the structure of the intermetallic compounds which resulted to decrease in the ultimate tensile strength, yield strength and hardness of the alloy.

3.2 Effect of chromium addition on the mechanical properties of Cu-3wt%Si alloy

Figures 7-9 show the effect of chromium on the mechanical properties – ultimate tensile strength (UTS), yield strength, hardness and percentage elongation of the alloy. It can be observed from the Figures that the ultimate tensile strength, yield strength and hardness increased with increasing chromium content up to 1.5wt%Cr before decreasing with further increase in concentration of chromium. Up to 1.5wt%Cr in Cu-3wt%Si alloy resulted to improvement in the ultimate tensile strength, yield strength and hardness of the experimental alloy by 507.69%, 495% and 66.67% respectively. The obtained maximum ultimate tensile strength, yield strength and hardness values were 316 MPa, 238 MPa and 85 HRB at 1.5wt%Cr content respectively. Presence of 0.1wt%Cr resulted to improvement in the percentage elongation by 158.72%. Maximum percentage elongation value obtained was 28.2% at 0.1wt%Cr content. The improvement in the strength and hardness of the alloys is attributed to the presence of refined and modified intermetallic phases in the structure of the alloys. The decrease in the strength and hardness of the alloys at high chromium concentrations is attributed to coarsening of the grains (Nnakwo et al., 2019).

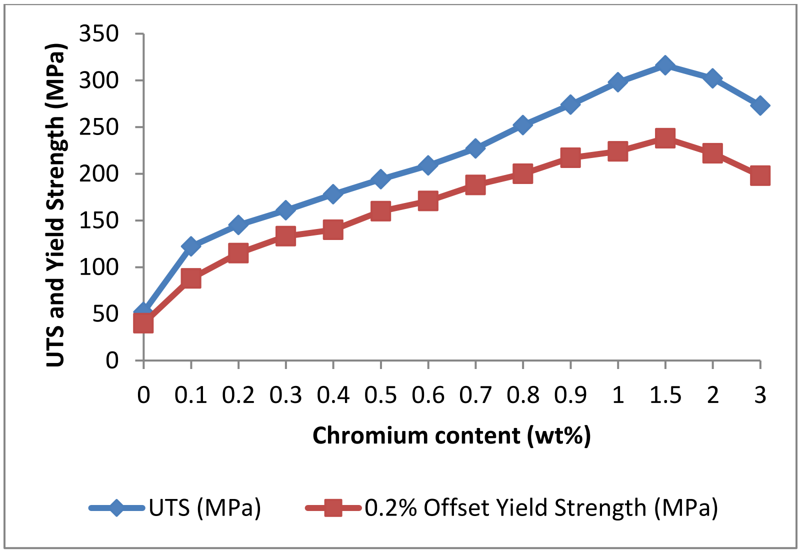

Figure 7: Effect of chromium content on the ultimate tensile strength and yield strength of Cu-3wt%Si alloy.

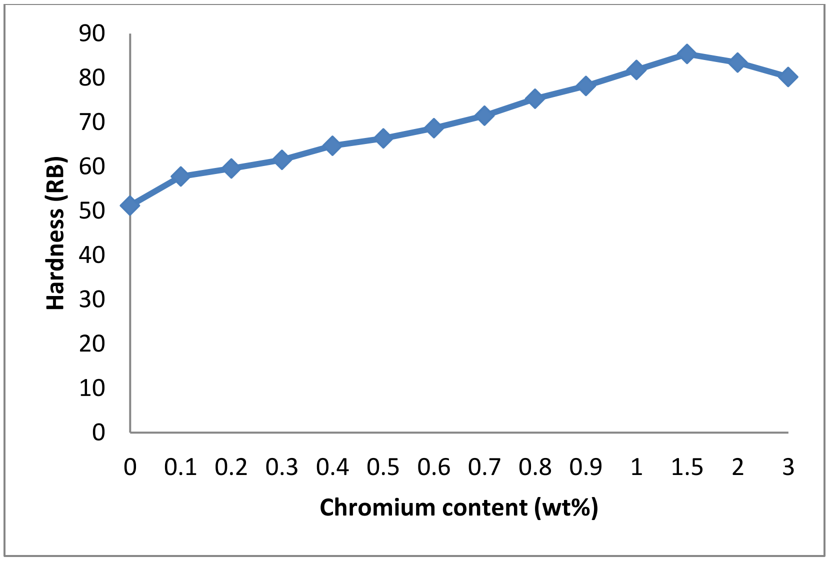

Figure 8: Effect of chromium content on the hardness of Cu-3wt%Si alloy.

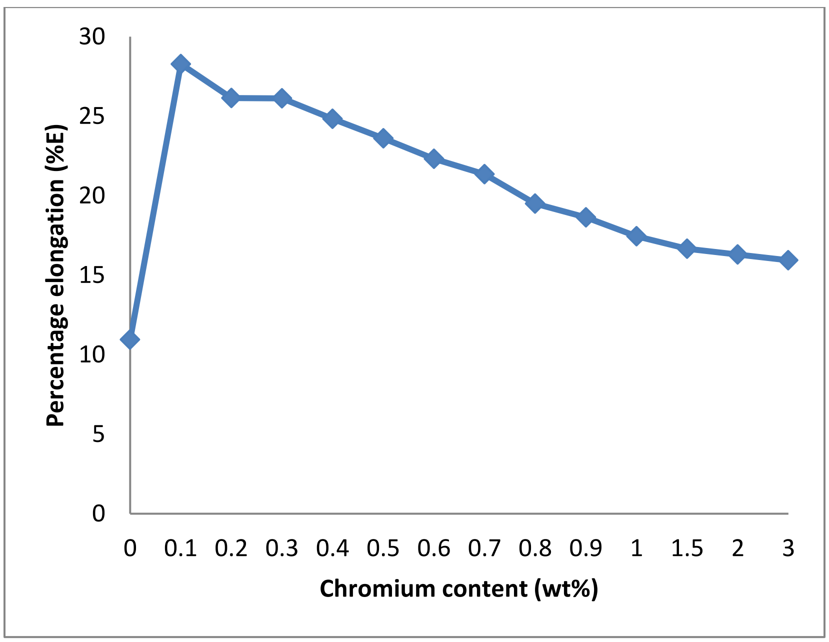

Figure 9: Effect of chromium content on the percentage elongation of Cu-3wt%Si alloy.

3.3 **Effect of chromium addition on the physical properties of Cu-3wt%Si alloy**

Figures 10-13 show the effect of chromium addition on the density, electrical conductivity and electrical resistivity of the experimental alloys. Addition of chromium to Cu-3wt%Si alloy results in increase in density and electrical conductivity of the experimental alloy by 12.81% and 22.9% respectively, and decrease in electrical resistivity by 18.69%. Maximum density (9.42 g/cm^3) and electrical conductivity (28.62 S/m) are obtained at 3wt%Cr and 0.1wt%Cr content respectively while minimum electrical resistivity (34.94x10^{-3}Ωm) is obtained at 0.1wt%Cr content. The density of the alloy is observed to increase with increase in chromium content while addition of chromium results in initial sharp increase in the electrical conductivity of the alloy and gradual decrease as chromium content increases. The initial increase in electrical conductivity is attributed to the formation of $CrSi_2$ intermetallic compound which reduces the silicon concentration of the copper matrix while the subsequent decrease is attributed to the continued formation of $Cu_{0.83}Si_{0.17}$ and $Cu_{15}Si_4$ which reduces the copper content of the copper matrix (Wang et al., 2016;

Nnakwo et al., 2017). Electrical resistivity being the reciprocal of electrical conductivity is observed to follow an opposite trend to that of electrical conductivity.

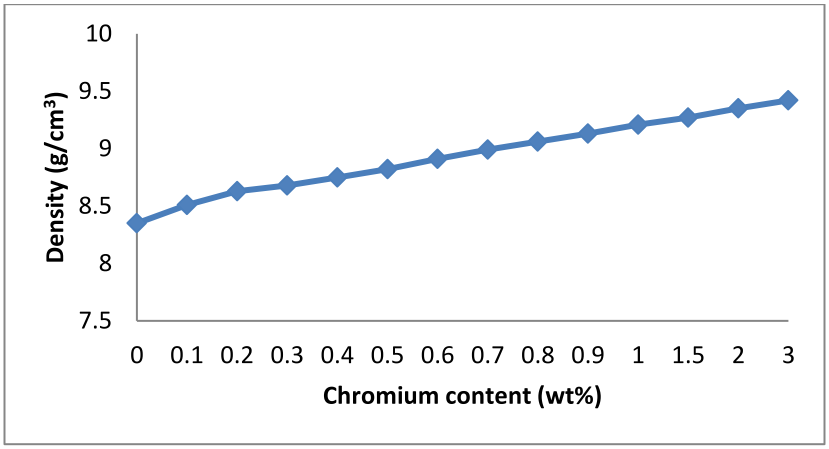

Figure 10: Effect of chromium content on the density of Cu-3wt%Si alloy.

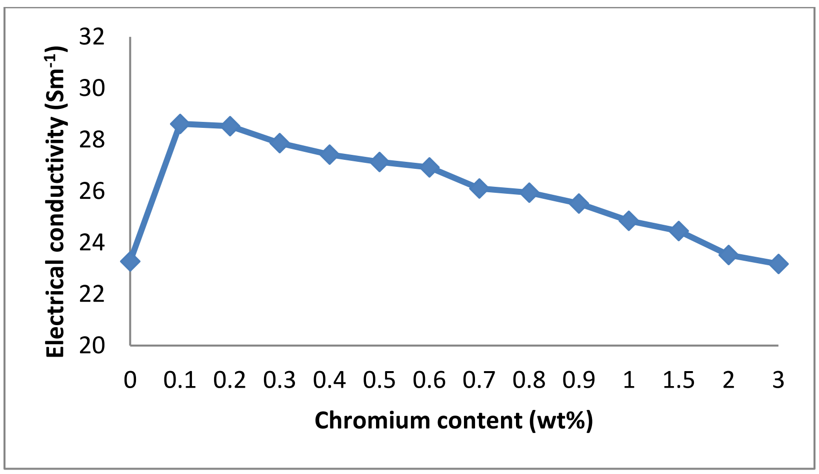

Figure 11: Effect of chromium content on the electrical conductivity of Cu-3wt%Si alloy.

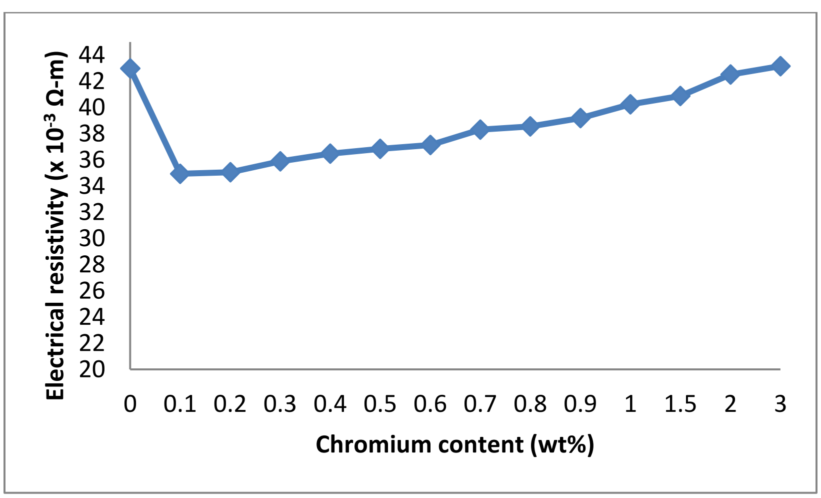

Figure 12: Effect of chromium content on the electrical resistivity of Cu-3wt%Si alloy.

Figure 13 shows that electrical conductivity and percentage elongation correlates very well. It was observed that both electrical conductivity and percentage elongation (ductility) decreased as concentration of chromium increased. This can be explained from the fact that obstruction of dislocation movement as a result of increase in amount of second phase particles will decrease ductility of the alloy and these second phase particles will on the other hand serve as electron scattering points and thus, decrease the electrical conductivity (Lei et al., 2013).

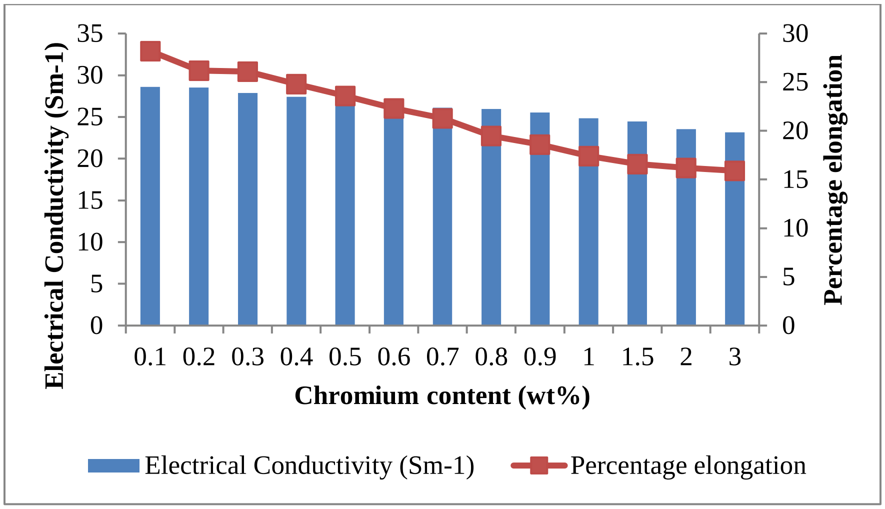

Figure 13: Correlation between the electrical conductivity and percentage elongation of chromium doped Cu-3wt%Si alloy.

4.0. Conclusion

The influence of trace quantity of chromium on the microstructure and physico-mechanical properties of Cu-3wt%Si alloys has been studied. The following conclusions can be made from the foregoing experimental results and theoretical analysis. Undoped Cu-3wt%Si alloy has low mechanical properties due to the presence of coarse γ-$Cu_{0.83}Si_{0.17}$ intermetallic phase at the grain boundaries of the alloy. Addition of chromium to Cu-3wt%Si alloy can successfully improve the mechanical properties by refining and modifying the structure of the alloy resulting to improvement in the ultimate tensile strength, yield strength, hardness, percentage elongation and electrical conductivity of the alloy by 507.69%, 495%, 66.67%, 158.72% and 22.9% respectively. Presence of chromium also resulted to the formation of $CrSi_2$ intermetallic compound which further contributed to the increase in strength and hardness of the alloy. The formed $CrSi_2$ intermetallic compound also contributed to the initial increase in electrical conductivity of the alloy at 0.1wt%Cr content while the subsequent decrease in electrical conductivity as chromium content was further increased is attributed to the continued formation of $Cu_{0.83}Si_{0.17}$ and $Cu_{15}Si_4$.

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