Open Access Library Journal
2023, Volume 10, e10902
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Effect of Titanium Content on the Structure, Electrical Conductivity and Mechanical Properties of Cu-3wt%Si Alloys

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How to cite this paper: Onyia, C.W., Nnuka, E.E., Nwambu, C.N. and Ekwedigwe, C.M. (2023) Effect of Titanium Content on the Structure, Electrical Conductivity and Mechanical Properties of Cu-3wt%Si Alloys. *Open Access Library Journal*, **10**: e10902.
https://doi.org/10.4236/oalib.1110902

Received: October 21, 2023
Accepted: December 24, 2023
Published: December 27, 2023

Abstract

In the present study, the effect of titanium content on the structure, electrical conductivity and mechanical properties of Cu-3wt%Si alloys were investigated. The experimental alloys were produced with various titanium 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 using permanent mould casting technique. Tensile, hardness, impact and conductivity tests were carried out on the cast samples. Microstructures of the specimens were also analyzed using optical microscopy. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were used to characterize the cast specimens. The results indicated that the addition of titanium to Cu-3wt%Si alloy refined and modified the structure of the alloy resulting in improvement in the ultimate tensile strength, yield strength, hardness and Young's modulus of the experimental alloy by 442.3%, 425%, 70.59%, 53.9%, respectively at 1.5wt%Ti content and percentage elongation, impact strength and electrical conductivity by 186.24%, 187.67% and 7.26% respectively at 0.1wt%Ti content. The addition of titanium also led to the formation of $CuTi_2$ phase which further contributed to the increase in strength and hardness of the alloy.

Subject Areas

Materials Engineering, Mechanical Engineering

Keywords

Cu-3wt%Si Alloys, Titanium, Electrical Conductivity, Mechanical Properties

1. Introduction

Copper and its 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. Copper alloys are generally non-magnetic with medium values of strength and fatigue resistance (Caron, 2001 [1]; Nwambu *et al*., 2017 [2]).

Structural applications are mostly based on ferrous materials, steels in particular (Nnuka, 1991) [3] but findings have shown that copper alloys (bronzes) are quickly replacing contemporary steel materials for some specific applications especially in components for marine/subsea applications (Nwambu *et al*., 2017) [4]. Silicon bronze is a copper-based alloy containing silicon as the major alloying element. The commercial silicon bronzes contain 1 to 3wt%Si (Russell & Lee, 2005) [5]. The addition of silicon decreases the density, electrical conductivity and melting point of the alloy. It also improves fluidity and gives excellent welding qualities to Cu-Si alloys.

Silicon bronzes find applications in electronics, electrical, automobile and building industries for the fabrication of connectors, bolts, electrical conduits, screws, tie rods, lead frames, etc (Kulczyk *et al*., 2012 [6]; Ilona *et al*., 2016 [7]). Silicon bronzes are also used for tanks, pressure vessels, marine construction, and hydraulic pressure lines (Avner, 1974) [8].

Addition of Sn to Cu-Ni alloys with subsequent aging heat treatment has been found to yield Cu-Ni-Sn alloys with good mechanical properties and electrical conductivity (Shankar & Sellamuthu, 2017 [9]; Kim *et al*., 1999 [10]; Plewes, 1975 [11]; Cribb *et al*., 2013 [12]; Cribb & Grensing, 2011 [13]; Rhu *et al*., 1999 [14]). However, some previous researchers (Cribb & Grensing, 2011) [13] reported that a serious segregation phenomenon of Sn element exists in the conventional casting process for Cu-Ni-Sn alloys, which has a negative influence on the subsequent processing and mechanical properties of the alloys. Titanium has been shown to significantly improve the tensile properties of Cu-15Ni-8Sn alloys. Tensile elongation increased from 2.7% for the alloy without Ti to 17.9% for the alloy with 0.3% Ti, while tensile strength increased from 935 MPa to 1024 MPa (Zhao *et al*., 2017) [15]. Watanabe *et al*. (2015) [16] found that the addition of 0.04wt%Ti enhanced the strength of Cu-2.0wt%Ni - 0.5wt%Si alloy without reducing its electrical conductivity. The addition of zinc (Nnakwo *et al*., 2017a) [17] and tin (Nnakwo *et al*., 2017b) [18] to Cu-3wt%Si alloys resulted in an increase in the hardness and ultimate tensile strength of the alloys. This work will report the effect of titanium additions on the physic-mechanical properties of Cu-3wt%Si alloys.

2. Materials and Method

The base alloy for this study was produced from commercial pure copper (99.99%) and commercial pure silicon (99.98%). The doped silicon bronze was produced by the addition of titanium 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 using permanent mould casting technique. A bailout crucible furnace was used for the melting process. For the production of the control alloy cast samples, the required amounts of pure copper in the form of copper wire were first charged into the preheated furnace and melted. A predetermined amount of silicon in powder form was added to the molten copper and stirred. The melt was held for about 10 min to ensure complete dissolution of silicon in the copper melt and stirred again to achieve homogeneity before pouring into preheated permanent mould and allowed to cool to ambient temperature. Subsequently, the Cu-3wt%Si alloys with the additives were produced by repeating the above-described procedure and introducing the different concentrations of titanium.

A tensile test was carried out on the cast specimens using a Universal Testing Machine (model WDW-10) as per ASTM E8/E8M-22 standard to determine the ultimate tensile strength, yield strength, % elongation and Young's modulus. Hardness test was carried out on 10 mm × 10 mm long cylindrical test bars machined from the cast samples, using a digital Rockwell hardness tester (model HRS-150) according to ASTM E18-22 standard. Charpy impact testing was performed on the cast samples following the ASTM E23 standard using an impact tester (model JB-300B). The resistivity and conductivity of the experimental alloys were determined based on standard Ohm's experiment. Structural analysis was carried out on the cast alloy specimens. Prior to the structural analysis, the surfaces of the specimens were ground with different grades of emery papers from rough to fine grades (400, 600, 800 and 1200 μm). After grinding, the specimens were polished to mirror finish using an aluminum oxide powder, rinsed with water and dried using a hand drier. The dried samples were etched with a solution of 10 g of iron (III) chloride, 30 cm^3 of hydrochloric acid and 120 cm^3 of water for 60 seconds. Finally, the surface morphology of the etched samples was examined using an optical metallurgical microscope (Model: L2003A). Scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD) analyses of the experimental alloys were carried out on the samples using a TESCAN scanning electron microscope, model number (VEGA III LMH) and a PANalytical X'Pert PRO X-ray diffractometer (XRD) respectively.

3. Results and Discussion

3.1. Mechanical Properties and Conductivity of Cu-3wt%Si Alloy

Figures 1-7 show the effect of titanium addition on the electrical conductivity and mechanical properties – ultimate tensile strength (UTS), yield strength, percentage elongation, hardness, Young's modulus and impact strength of the alloy. It is observed from the Figures that the ultimate tensile strength, yield strength, hardness and Young's modulus increased with increasing concentration of titanium up to 1.5% before decreasing with further increase in concentration of the additive. The addition of 1.5wt%Ti to Cu-3wt%Si alloy resulted in improvement in the ultimate tensile strength, yield strength, hardness and Young's modulus of

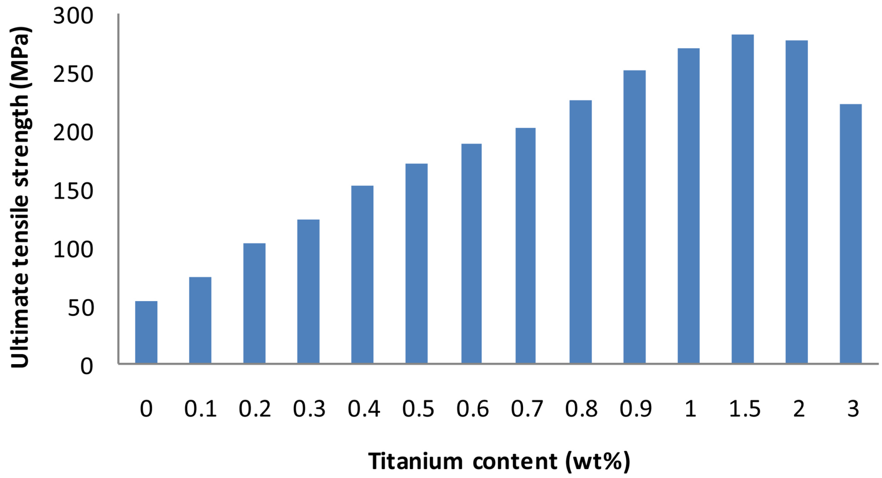

Figure 1. Effect of titanium content on the ultimate tensile strength of Cu-3wt%Si alloy.

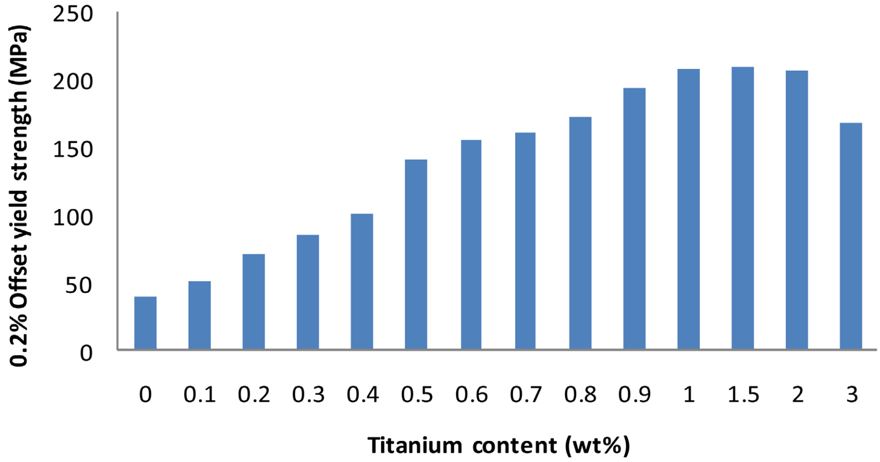

Figure 2. Effect of titanium content on the yield strength of Cu-3wt%Si alloy.

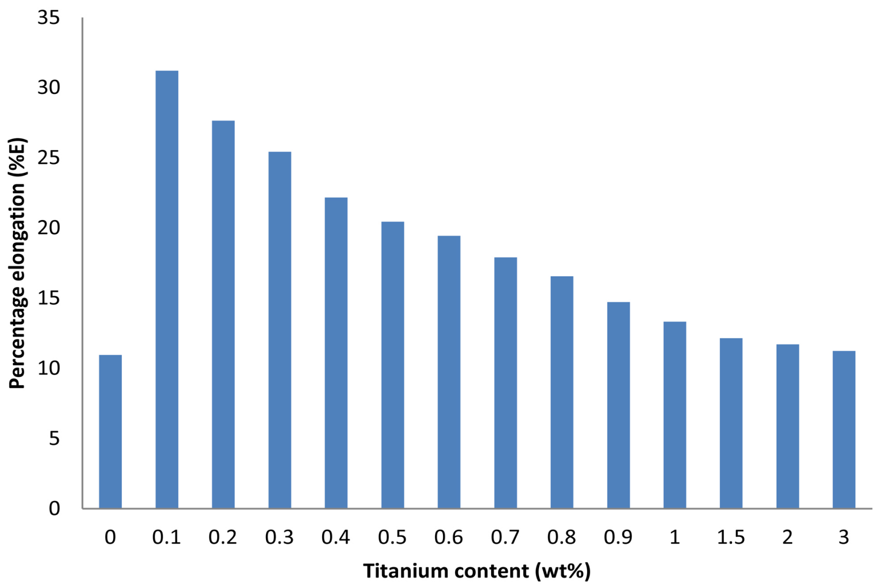

Figure 3. Effect of titanium content on the percentage elongation of Cu-3wt%Si alloy.

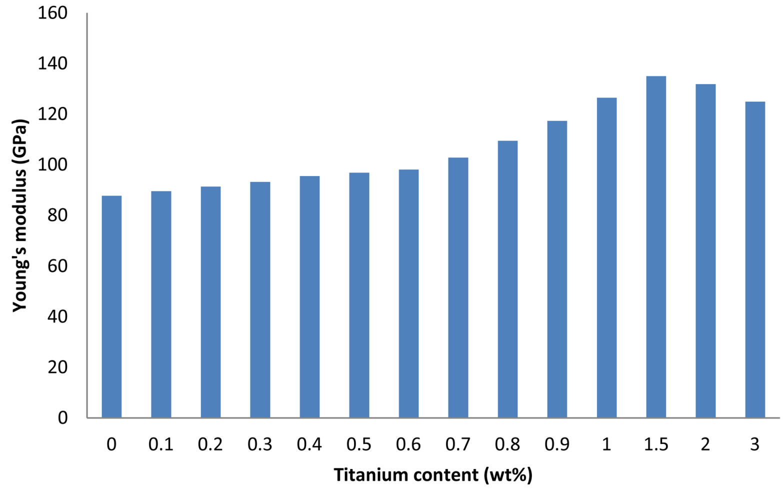

Figure 4. Effect of titanium content on the Young's modulus of Cu-3wt%Si alloy.

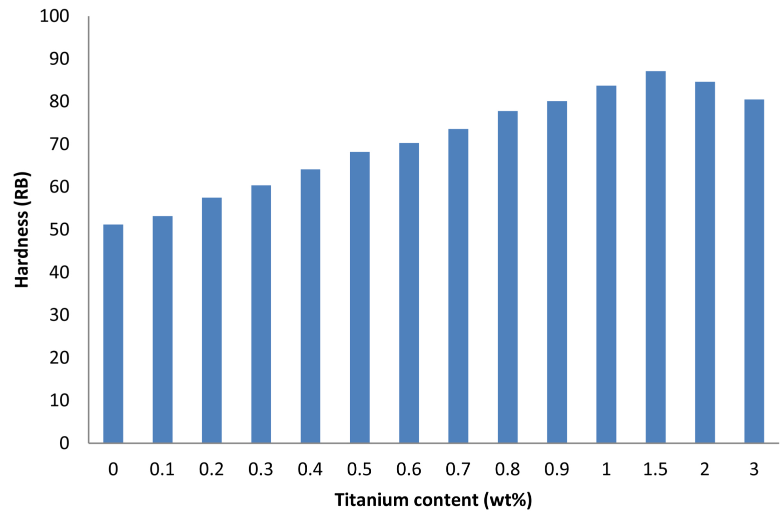

Figure 5. Effect of titanium content on the hardness of Cu-3wt%Si alloy.

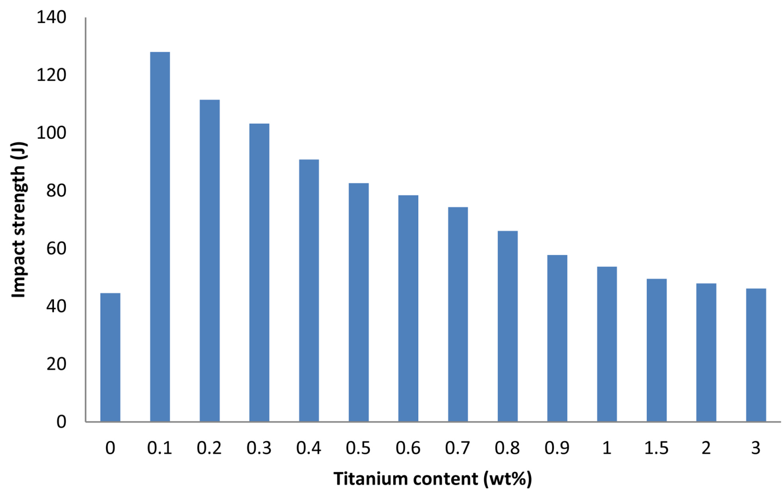

Figure 6. Effect of titanium content on the impact strength of Cu-3wt%Si alloy.

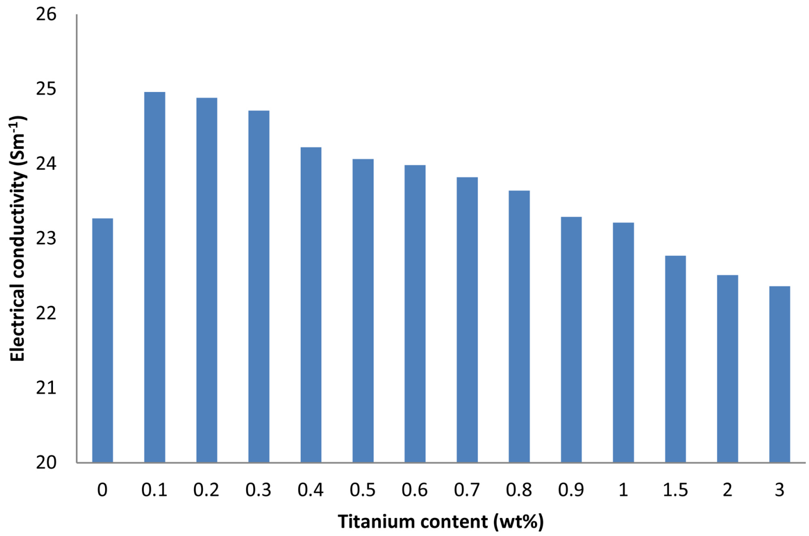

Figure 7. Effect of titanium content on the electrical conductivity of Cu-3wt%Si alloy.

the experimental alloy by 442.3%, 425%, 70.59% and 53.9% respectively. Maximum ultimate tensile strength, yield strength, hardness and Young's modulus values obtained were 282 MPa, 210 MPa, 87 HRB and 135 GPa at 1.5wt%Ti content respectively. The addition of 0.1wt%Ti resulted in an improvement in the percentage elongation, impact strength and electrical conductivity of the alloy by 186.24%, 187.67% and 7.26% respectively. Maximum percentage elongation, impact strength and electrical conductivity values obtained were 31.2%, 128.3 J and 24.96 Sm^{-1} at 0.1wt%Ti content respectively. The improvement in the strength and hardness of the alloys was 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 titanium concentrations was attributed to the coarsening of the grains.

3.2. Optical, Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) Analyses of the Alloys

The optical, scanning electron microscopy and X-ray diffraction analyses of the alloys are presented in **Figures 8-21**. **Figure 8** presents the micrograph of undoped Cu-3wt%Si alloy casting showing microstructures in which the primary α-copper 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 γ-$Cu_{0.83}Si_{0.17}$ intermetallic phase (**Figure 18**) can be observed at the grain boundaries in the microstructure of the alloy (**Figure 8**) and owing to this, the mechanical properties of the undoped alloy are poor.

Figures 9-17 reveal the presence of $Cu_{0.83}Si_{0.17}$, $Cu_{15}Si_4$, and $CuTi_2$ intermetallic phases in the structure of the alloys doped with titanium. X-ray diffraction (XRD) analyses of the alloy samples also indicate the presence of these intermetallics in the structure of the alloys (**Figure 19** and **Figure 21**). It can be observed that

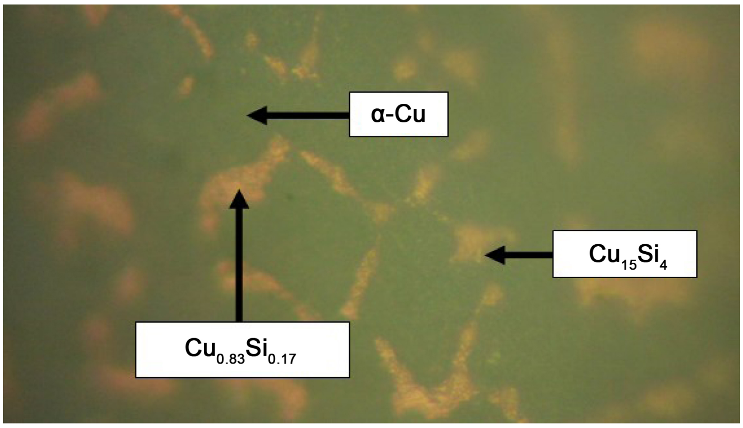

Figure 8. Micrograph of Cu-3wt%Si alloy.

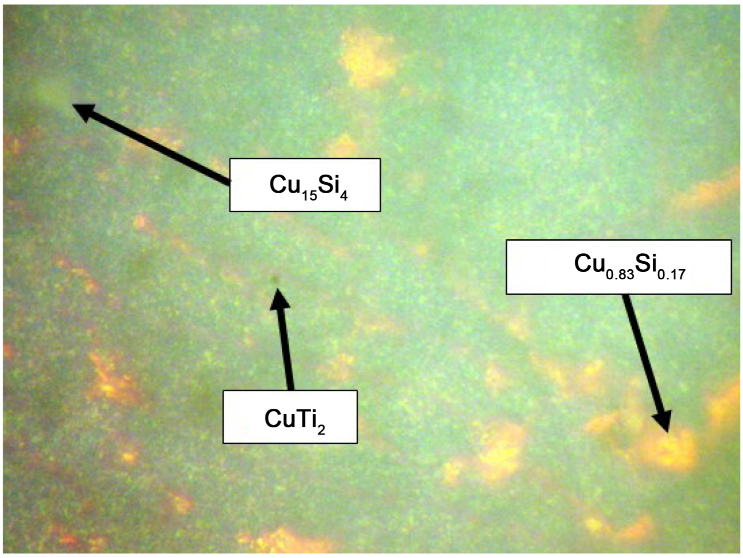

Figure 9. Micrograph of Cu-3wt%Si - 0.1wt%Ti alloy.

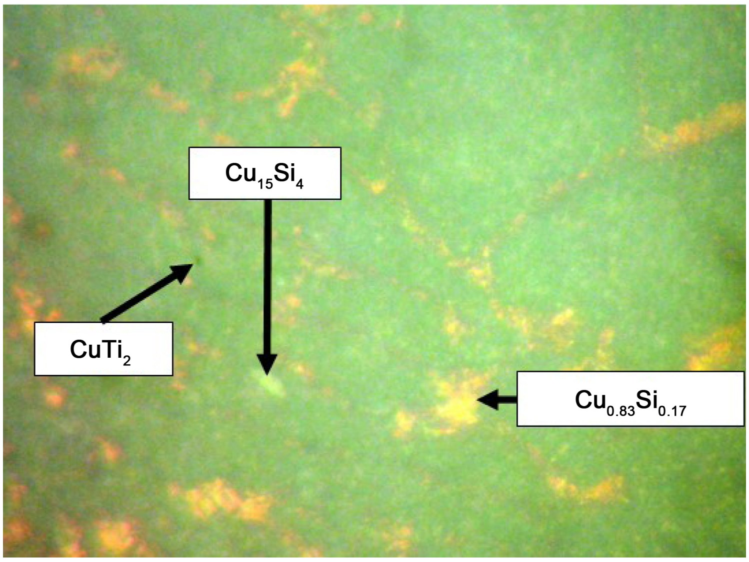

Figure 10. Micrograph of Cu-3wt%Si - 0.3wt%Ti alloy.

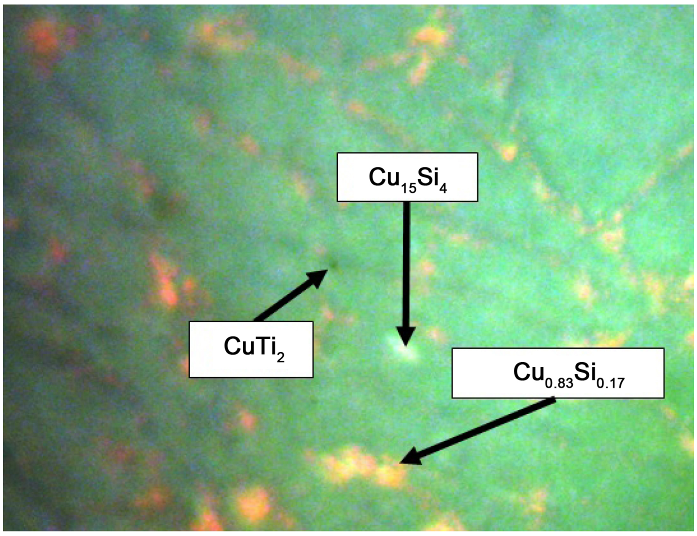

Figure 11. Micrograph of Cu-3wt%Si - 0.5wt%Ti alloy.

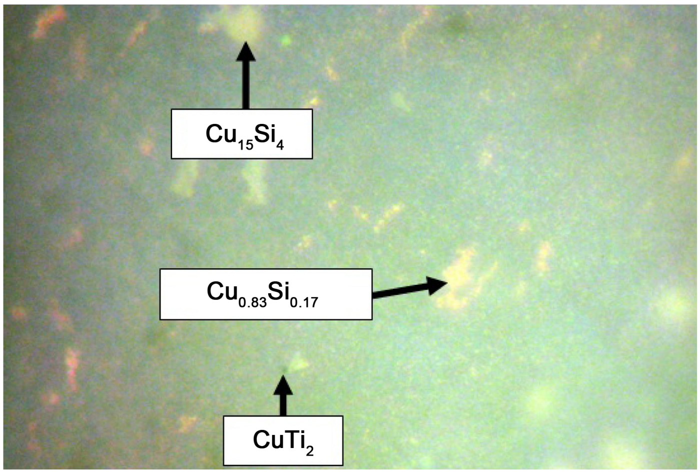

Figure 12. Micrograph of Cu-3wt%Si - 0.7wt%Ti alloy.

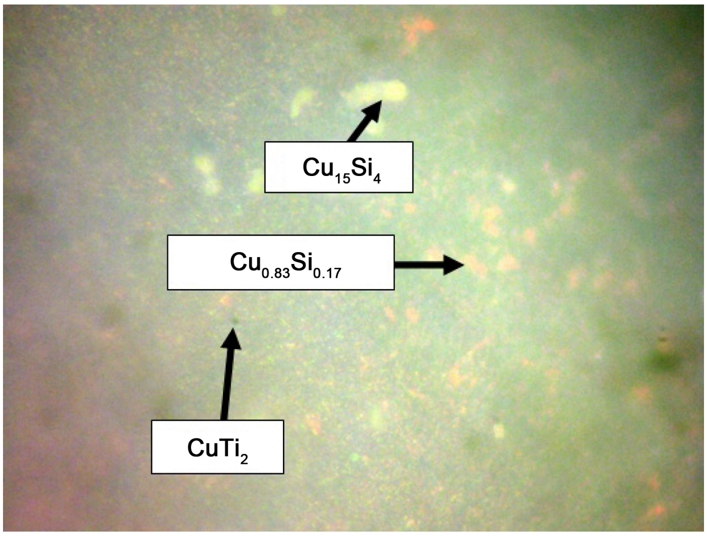

Figure 13. Micrograph of Cu-3wt%Si - 0.8wt%Ti alloy.

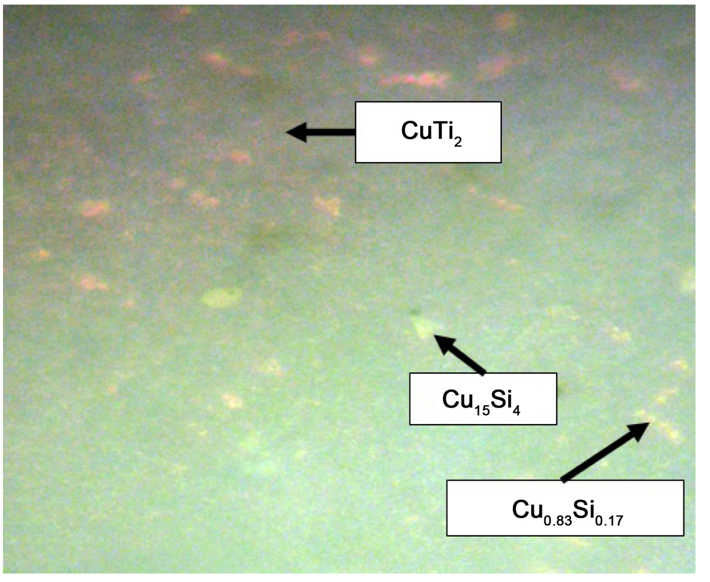

Figure 14. Micrograph of Cu-3wt%Si - 1wt%Ti alloy.

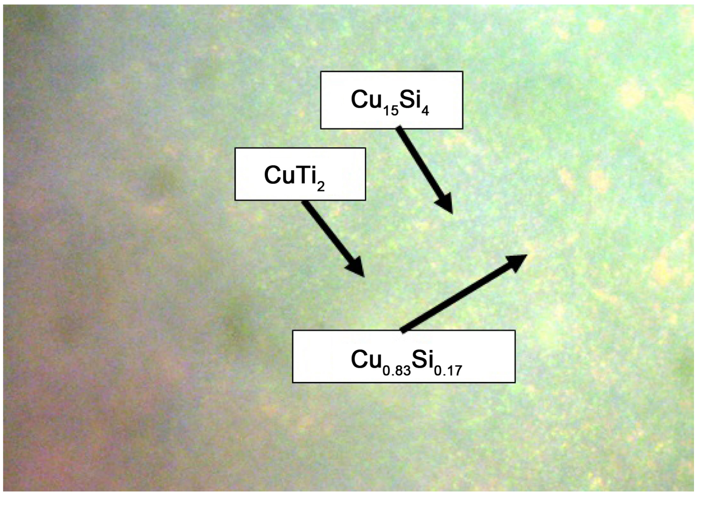

Figure 15. Micrograph of Cu-3wt%Si - 1.5wt%Ti alloy.

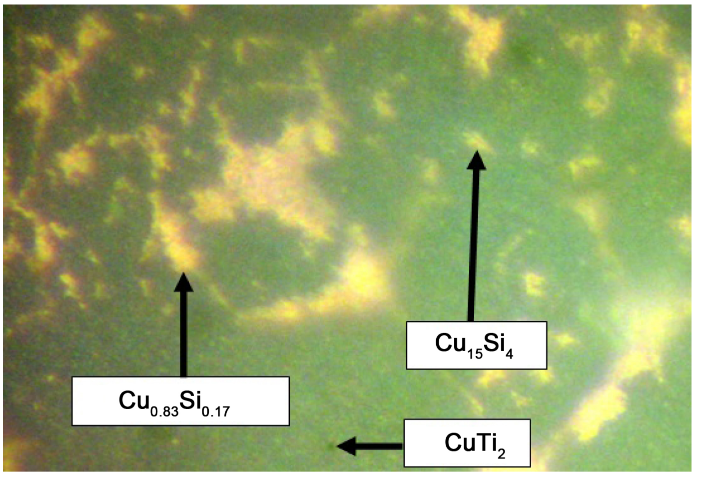

Figure 16. Micrograph of Cu-3wt%Si - 2wt%Ti alloy.

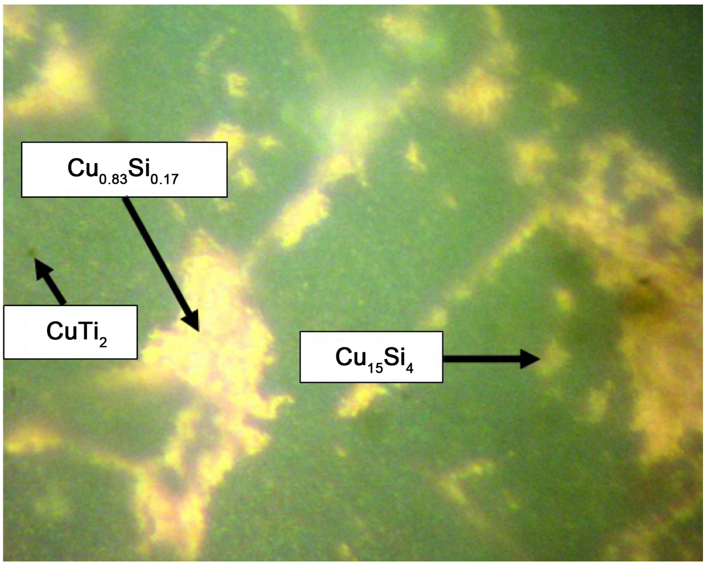

Figure 17. Micrograph of Cu-3wt%Si - 3wt%Ti alloy.

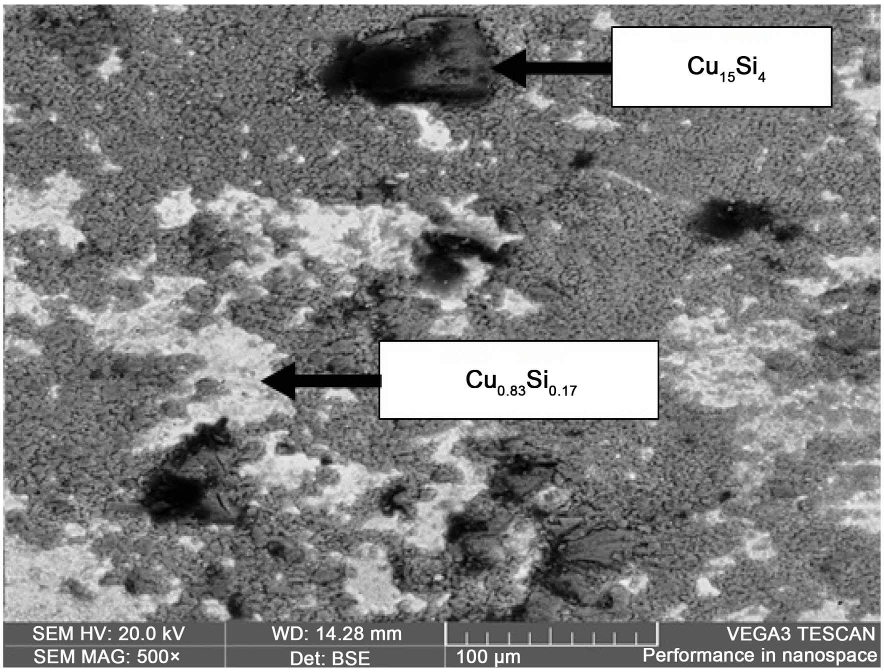

Figure 18. Scanning electron microscopy of Cu-3wt%Si alloy (backscattered electrons analysis).

addition of titanium refines and modifies the morphology of the intermetallic compounds with attendant increase in ultimate tensile strength, yield strength, percentage elongation, hardness, impact strength and Young's modulus. The grain size decreases with increase in concentration of titanium up to 1.5wt%Ti. The small grain sizes result to increased number of grain boundaries which served as increased impediment to motion of dislocations and consequently increased the ultimate tensile strength, yield strength, hardness and Young's modulus with corresponding decrease in percentage elongation and impact strength of the

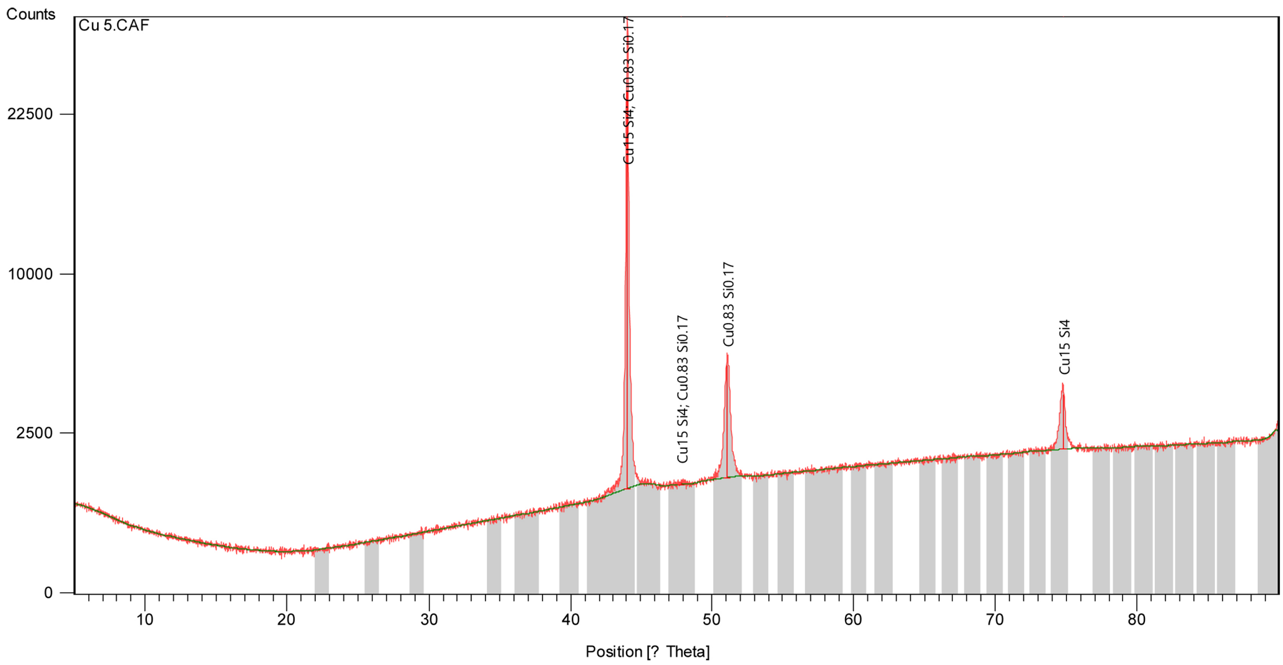

Figure 19. X-ray diffraction (XRD) patterns of Cu-3wt%Si alloy.

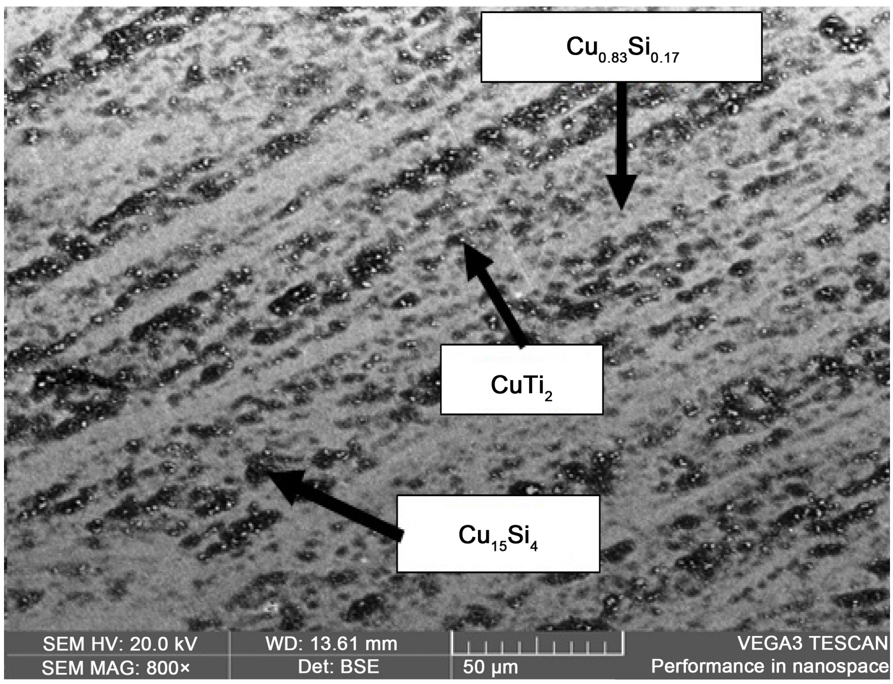

Figure 20. Scanning electron microscopy of Cu-3wt%Si - 1.5wt%Ti alloy (backscattered electrons analysis).

alloys. Increase in concentration of titanium beyond 1.5wt%coarsened the morphology of the intermetallic compounds which resulted to decrease in the ultimate tensile strength, yield strength and hardness of the alloy. The presence of $CuTi_2$ compounds in the structure of the alloy further improved the strength and hardness of the alloy.

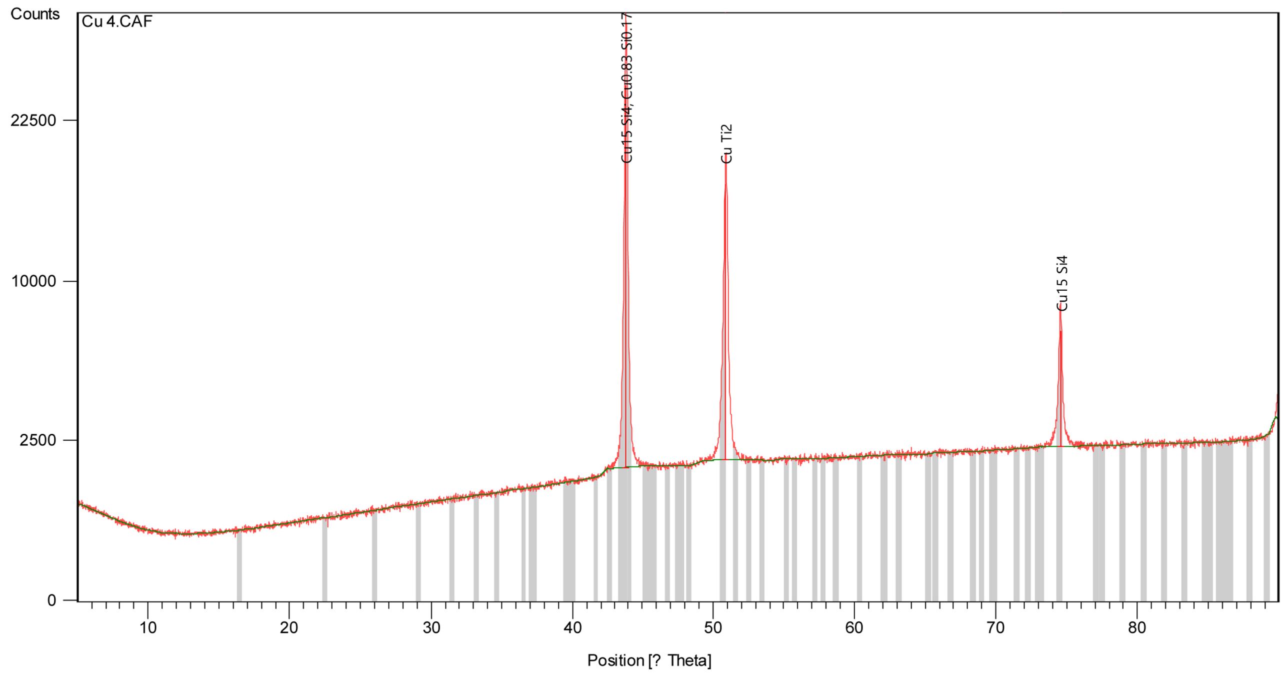

Figure 21. X-ray diffraction (XRD) patterns of Cu-3wt%Si - 1.5wt%Ti alloy.

4. Conclusions

The effect of titanium content on the structure, electrical conductivity and mechanical properties of Cu-3wt%Si alloy has been investigated. The following conclusions can be made from the 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.
- The addition of titanium to Cu-3wt%Si alloy successfully refined and modified the structure of the alloys which resulted in improvement in the ultimate tensile strength, yield strength, hardness, Young's modulus, percentage elongation, impact strength and electrical conductivity of the experimental alloy by 442.3%, 425%, 70.59%, 53.9%, 186.24%, 187.67% and 7.26% respectively.
- The addition of titanium also resulted in the formation of $CuTi_2$ which further contributed to the increase in strength and hardness of the alloy.
- Maximum ultimate tensile strength, yield strength, hardness, Young's modulus, percentage elongation, impact strength and electrical conductivity values of 282 MPa, 210 MPa, 87 HRB, 135 GPa, 31.2%, 128.3 J and 24.96 Sm^{-1} respectively were obtained.

Conflicts of Interest

The authors declare no conflicts of interest.

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