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Grain characteristics, tensile strength and hardness of solid solution heat treated copper-silicon-titanium and copper-silicon-magnesium alloys

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***Abstract:* The Grain characteristics, tensile strength and hardness of solid solution heat treated copper-silicon-titanium and copper-silicon-magnesium alloys have been investigated. The alloy was melted in an inert gas-controlled vacuum melting furnace to ensure purity and prevent oxidation. The cast samples were solution heat treated at 900°C for 5 h. The microstructure of the developed alloys was examined using optical metallurgical microscope (OM). The OM images revealed even dispersion of fine grains in the copper matrix after additions of titanium and magnesium. This microstructural changes led to improvements of both ultimate tensile strength and hardness of the alloy. Application of solid solution treatment led to further refinement and modification of grains in the Cu-3Si-3(Mg, Ti) alloys, leading to further increase in the mechanical properties. The ultimate tensile strength values of Cu-3Si-3Mg and Cu-3Si-3Ti alloys were increased by 7.4% and 3.8% after solution heat treatment, while about 21% and 9.2% increase in hardness, respectively were recorded. Addition of magnesium increased the percentage elongation of the parent alloy from 9.4% to 19.1% in as-cast condition, but after heat treatment process, a decline in percentage elongation was recorded.**

***Keywords:* Cu-Si-Ti; Cu-Si-Mg; surface morphology; solid solution; strength.**

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1. INTRODUCTION

Due to excellent combination of ductility, strength, hardness, and electrical conductivity of copper, it is recommended as base materials for various applications, including electronics, electrical components, railways, building materials, and automotive components.Copper is a widely used metal, particularly in various industrial and electronic applications, due to its unique combination of properties. Copper is renowned for its high electrical conductivity, which makes it an ideal choice for electrical connectors, lead frames, and micro-electronic devices(Nnakwo, 2019; Nnakwo et al., 2017a,b; 2019a,b; 2020, 2021, 2022;Nnakwo and Nnuka, 2018; Garbacz-Klempka et al., 2018). This property allows for efficient transmission of electrical signals. Copper is relatively low in cost compared to many other metals with similar electrical conductivity characteristics, making it a cost-effective choice for various applications.Copper possesses excellent ductility and malleability, making it suitable for applications where it needs to be shaped, bent, or formed into various components such as bolts, nuts, valves, and fittings (Qing et al., 2011; Xie et al., 2003; Lei et al., 2017; Gholami et al., 2017; Qian et al., 2017; Suzuki et al., 2006).Copper is often alloyed with other elements like silicon, tungsten, zinc, tin, magnesium, manganese, and nickel to enhance its properties. These alloying elements can increase strength and hardness while minimizing the reduction in electrical conductivity.Silicon, when added to copper, can improve its fluidity and hardness. However, it comes at the expense of reduced ductility and electrical conductivity. The addition of silicon induces the precipitation of hard but brittle phases, such as Cu_3Si, $Cu_{15}Si_4$, and Cu_5Si, when the material cools slowly to ambient temperature (Wang et al., 2016; Li et al., 2017; Pan et al., 2007; Li et al., 2009; Lei et al., 2013a, 2013c; Eungyeong et al., 2011; Ho et al., 2000).

Copper-silicon alloys are used as electrodes in lithium-ion batteries(Ketut et al., 2011). The addition of silicon can enhance the performance of these electrodes in terms of capacity and cycling stability. Copper-silicon alloys can also serve as catalysts in various chemical processes, such as the production of nanosized and nanotube zinc oxide rods(Pak et al., 2016; Mattern et al., 2007). They are also employed in the fabrication of musical equipment due to their excellent damping properties. These alloys help reduce vibrations and unwanted noise, making them suitable for musical instruments (Cai et al., 2011).Effects of various alloying elements on the enhancement of properties have been explored by various researchers. Nickel is one of the key alloying elements known to enhance the hardness and electrical conductivity of Cu-Si alloys(Qian et al., 2017; Suzuki et al., 2006; Wang et al., 2016; Pan et al., 2007; Li et al., 2009; Lei et al., 2013b; Eungyeong et al., 2011; Ho et al., 2000). Other elements like aluminium, chromium, iron, magnesium, and tin have also been used to modify Cu-Si alloys. For example, iron has been found to enhance both hardness and electrical conductivity, while chromium and zirconium induce microstructural refinement and the precipitation of specific intermetallic phases, leading to improved strength.Combined Addition of Chromium and Zirconium: Combining chromium and zirconium in nickel-doped Cu-Si alloys has been shown to result in alloys with excellent hardness and electrical conductivity.The strengthening of copper alloys is achieved through the precipitation of various phases, including $\beta1$-Ni_3Si, α-Cu(Ni, Si), γ'-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si. These phases form as a result of the alloying elements and subsequent aging process (Suzuki et al., 2006; Wang et al., 2016, 2018; Li et al., 2017; Wang et al., 2018).

The main objective of this research is to develop Cu-Si base alloys with improved tensile strength and hardness through additions of grain refiners (titanium and magnesium) and appropriate solid solution treatment.

2. EXPERIMENTAL PROCEDURE

The Copper wire: 99.9% pure, silicon powder: 98.5% pure, magnesium powder: 99.5% pure and titanium powder: 98.8%used for this experimental study were sourced from Cutix Cable Plc, Nnewi, Nigeria andKermel Chemical Reagent Co. Ltd., Hebei, Tianjin, China.The weight in gram of each material was measured using an electronic compact scale (Model: BL20001), and charged into the platinum crucible pot in an inert gas atmosphere. The alloys were prepared by melting the materials using a crucible furnace. The molten alloy was cast into metal molds with dimensions of 16mm diameter and 250mm length.The prepared alloys were standardized according to standards for mechanical test.The solid solution heat treatment was carried out at 900°C for duration of 5 h. This temperature and time are critical for achieving the desired microstructure and properties in the alloys. The heat treatment was performed using a tube furnace, specifically a TSH12/25024166CG model. The tensile strength of the alloys was tested using a 100KN capacity automated tensometer (Model: 130812). The hardness testing was conducted using a Brinell hardness tester (Model: DHT-6).Samples were subjected to grinding and polishing using different grit sizes (400, 800, 1200µm) of emery paper and aluminum oxide powder, and swabbed for 30 seconds in iron III chloride powder dissolved in an aqueous solution of hydrochloric acid. The samples were rinsed with water and dried using a hot air gun machine (Bosch PHG500-2-1600W) for microstructural analysis using optical metallurgical microscope.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

The percentage elongation, ultimate tensile strength, and hardness of copper-silicon, copper-silicon-titanium, and copper-silicon-magnesium alloys in bot as-cast and solid solution heat treated are presented in Figs. 1-3. The parent alloy recorded percentage elongation of 9.4%. After solid solution heat treatment, the percentage elongation decreased to 8.9%. Addition of magnesium increased the percentage elongation of the parent alloy from 9.4% to 19.1% in as-cast state (Fig. 1). Figs. 2 and 3 showed that the ultimate tensile strength and hardness of the parent alloy increased after adding magnesium and titanium. The Cu-3Si-3Mg and Cu-3Si-3Ti alloys recorded ultimate tensile strength of 285 MPa and 265 MPa, respectively in as-cast conditions. After solution heat treatment, the Cu-3Si-3Mg and Cu-3Si-3Ti alloys recordedsignificant increase in ultimate tensile strength values from 285 MPa to 306 MPa; and from 265 MPa to 275 MPa. The hardness values of Cu-3Si-3Mg and Cu-3Si-3Ti alloys were also improved after incorporation of magnesium and titanium in the parent alloy. Solution heat treatment of Cu-3Si-3Mg and Cu-3Si-3Ti alloys further increased the hardness values, with maximum values of 387 MPa and 308 MPa, respectively.The improvements in hardness andultimate tensile strengthmay be associated with a microstructural changes. This change in grain structure led to an increased grain boundary area, which is a source of dislocation motion impediment, contributing to higher mechanical properties.

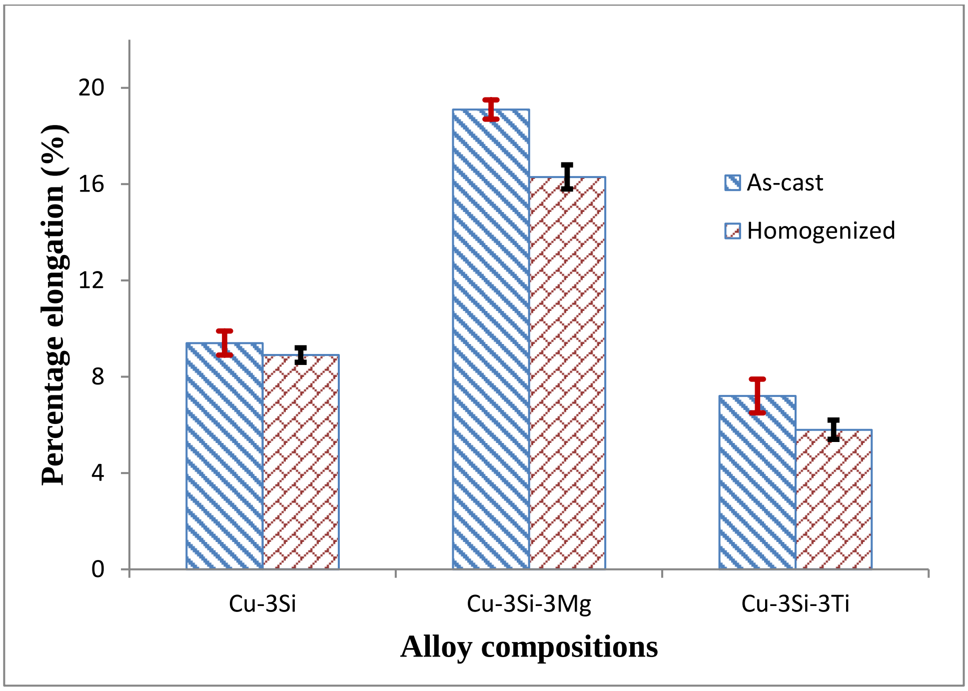

Fig. 1: Percentage elongation of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

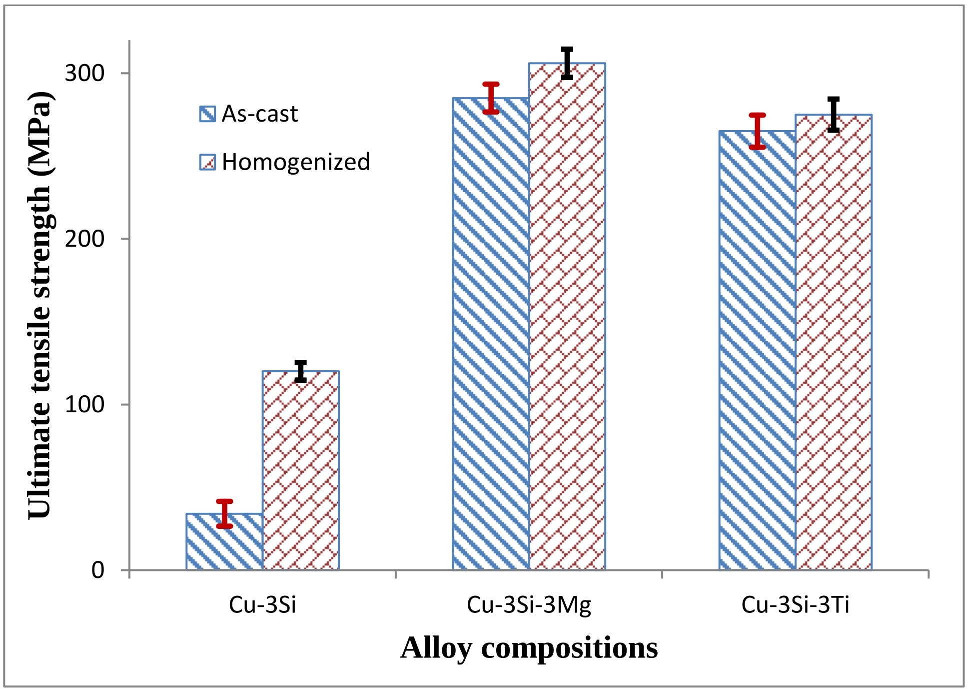

Fig. 2: Ultimate tensile strength of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

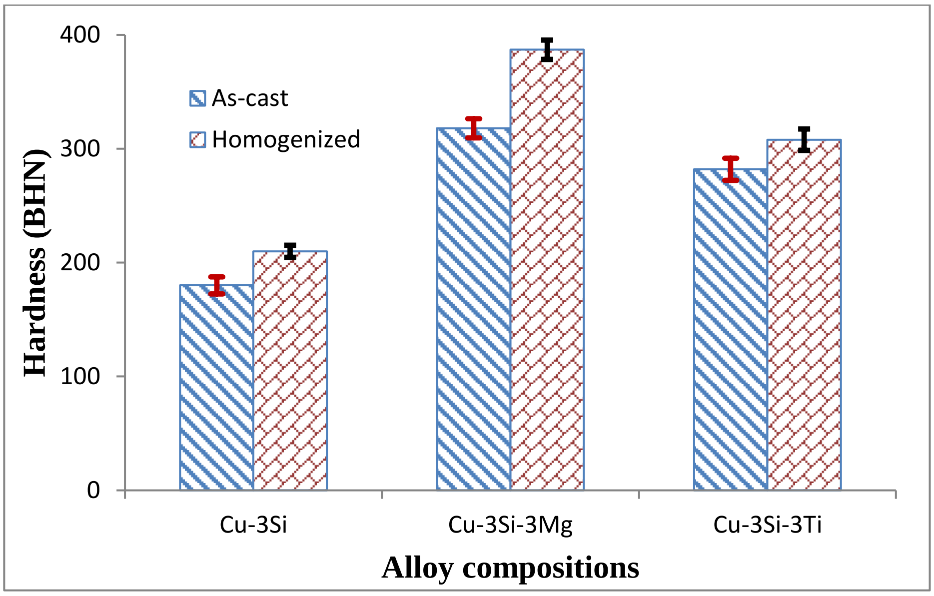

Fig. 3: Hardness of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

3.2. Microstructure of the Cu-3Si-3Mg and Cu-3Si-3Ti alloys

Fig. 4 shows the optical micrograph (OM) of the Cu-3Si-3Mg and Cu-3Si-3Ti alloys in as-cast and solid solution heat treated conditions.Fig. 4 shows the microstructural changes accompanying the incorporation of titanium and magnesium in the parent alloy and subsequent solid solution heat treatment. The surface morphologies of Cu-3Si-3Mg and Cu-3Si-3Ti alloys in as-cast conditions revealed spherical grains,evenly dispersed in the copper matrix withhigh number of grain boundaries. The application of solid solution heat treatment led to precipitation of finer grains with greater number of grain boundaries. This could be attributed to further increase in the ultimate tensile strength and hardness of Cu-3Si-3Mg and Cu-3Si-3Ti alloys.

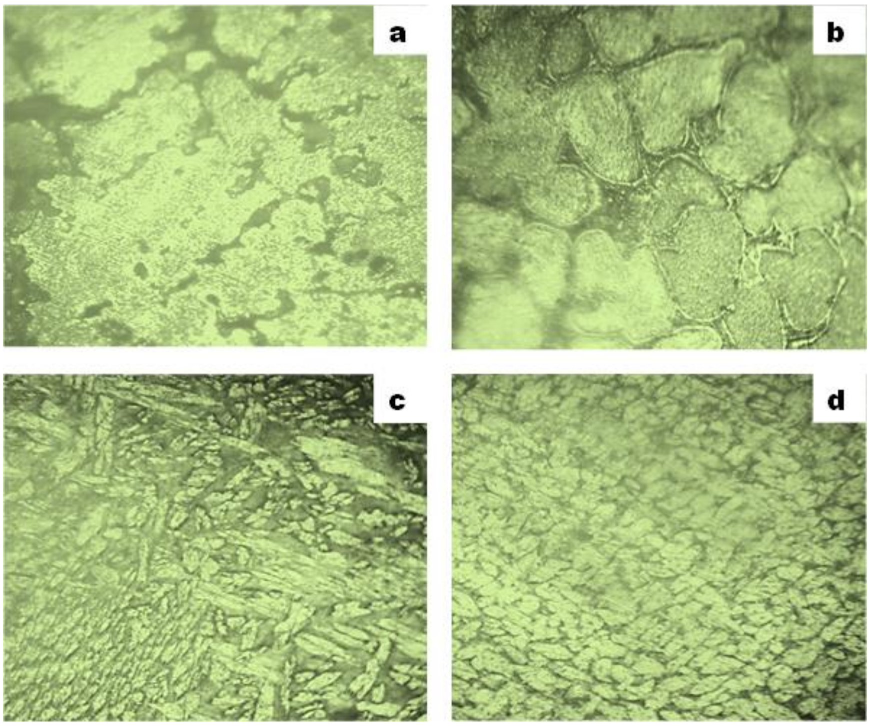

Fig. 4: Optical microstructure of (a) Cu-3Si-3Mg (as-cast)(b) Cu-3Si-3Mg (homogenized)(c) Cu-3Si-3Ti (as-cast)(D) Cu-3Si-3Ti (homogenized).

4. CONCLUSIONS

The study explored the grain characteristics, tensile strength and hardness of solid solution heat treated copper-silicon-titanium and copper-silicon-magnesium alloys. Analysis of the results indicated that the addition of magnesium and titanium had a positive impact on the mechanical properties of the copper-silicon alloy, both in the as-cast state and after solid solution heat treatment. The following conclusions can be drawn from the experimental results:

1. The parent alloy had a percentage elongation of 9.4%. After solid solution heat treatment, the percentage elongation decreased to 8.9%.

2. The addition of magnesium significantly increased the percentage elongation of the parent alloy from 9.4% to 19.1% in its as-cast state.

3. The ultimate tensile strength of the parent alloy increased after adding magnesium and titanium, with maximum values of 285 MPa and 265 MPa, respectively.

4. After solid solution heat treatment, the ultimate tensile strength increased to 306 MPa, and 275 MPa.

5. The hardness values of both the Cu-3Si-3Mg and Cu-3Si-3Ti alloys improved after incorporating magnesium and titanium into the parent alloy, recording maximum values of 387 BHN and 308 MPa, respectively after solution heat treatment.

6. The improvements in hardness and ultimate tensile strength are attributed to microstructural changes.

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