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Grain refinement, impact energy, and physio-mechanical properties of Cu-3Si-3W and Cu-3Si-3Mn alloys via alloying and solid solution treatment

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Abstract

The grain refinement, impact energy, and physio-mechanical properties of Cu-3Si-3W and Cu-3Si-3Mn alloys can be tailored through alloying and solid solution treatment. Careful selection of alloying elements and precise control of processing parameters can lead to alloys with specific combinations of properties suitable for various applications, such as in aerospace, automotive, and electrical industries. This study explored the refining effects of tungsten, manganese, and subsequent solution heat treatment on the impact energy, density, and electrical conductivity of Cu-3Si-3W and Cu-3Si-3Mn alloys.The prepared alloys compositions were fabricated using the stir-casting technique and then machined to the required dimensions for property tests. The cast samples were subjected to solid solution heat treatment at a temperature of 900°C for 5 h. The microstructures of the cast samples were examined using an optical metallurgical microscope (OM). After heat treatment, there was an increased precipitation of secondary phases in the copper matrix. The results showed that impact energy of the parent alloys bot in as-cast and heat treated conditions are higher compared with the Cu-3Si-3Mn alloys. The Cu-3Si-3W exhibited better impact energy and electrical conductivity with maximum values of 16.6 J and 29.34 S/m, respectively. The Cu-3Si-3Mn alloy recorded lower bulk density after solution treatment, compared with both the parent alloy and the Cu-3Si-3W alloy. The bulk density of the parent alloy decreased from 8.21 g/cm^3 to 7.96 g/cm^3.

Keywords: Tungsten; manganese; carbide formers; microstructure; solid solution strengthening

1. Introduction

The combination of electrical conductivity, cost-effectiveness, and formability of copper-based alloy makes it a preferred material in a wide range of applications across industries, particularly in electronics and manufacturing. The use of alloying elements, like silicon, allows for tailoring its properties to suit specific needs, although this may involve trade-offs between different characteristics (Nnakwo, 2019; Nnakwo et al., 2017a,b; 2019a,b; 2020, 2021, 2022;Nnakwo and Nnuka, 2018; Garbacz-Klempka et al., 2018). Copper is renowned for its high electrical conductivity. This property allows it to efficiently transmit electrical signals, making it an ideal choice for electrical connectors, lead frames, and micro-electronic devices.Copper possesses excellent ductility and malleability, hence can be easily shaped, bent, or formed into various components such as bolts, nuts, valves, and fittings. 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. Silicon improvethe fluidity and hardness of copper. However, this enhancement comes at the expense of reduced ductility and electrical conductivity. The addition of silicon can induce 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 due to their ability to enhance battery performance in terms of capacity and cycling stability (Ketut et al., 2011). It also serves 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). Copper-silicon alloys are employed in the fabrication of musical equipment owing to their excellent damping properties (Cai et al., 2011). Copper-silicon alloys are versatile materials with a range of applications, and their properties can be tailored by incorporating different alloying elements to meet specific requirements in various industries. Nickel is 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). Elements like aluminium, chromium, iron, magnesium, and tin have also been used to modify Cu-Si alloys. For example, iron enhances both hardness and electrical conductivity, while chromium and zirconium induce microstructural refinement and the precipitation of specific intermetallic phases, leading to improved strength.Combining chromium and zirconium in nickel-doped Cu-Si alloys has been shown to result in alloys with excellent hardness and electrical conductivity. Precipitation of various phases (β1-Ni_3Si, α-Cu(Ni, Si), γ'-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si) occurs as a result of the alloying elements and subsequent aging processes, contributing to the strengthening of copper alloys. 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).

This present study seeks to modify Cu-Si base alloys with zinc and tin additions and optimize their properties through solid solution heat treatment. This is to enhance the impact energy and electrical conductivity, hence making the alloys more attractive for a wide range of engineering applications, thus contributing to the advancement of materials science and technology.

2. Experimental procedure

The Cu-3Si-3W and Cu-3Si-3Mn ternary alloys were prepared using analytical grades copper rods (99.8% pure), silicon powder (99.7% pure), tungsten powder (98.5% pure), and manganese powder (98.7% pure). The weight in gram of each material was determined, measured using an electronic compact scale (Model: BL20001), and charged into the platinum crucible pot in an inert gas atmosphere. The melt was cast into a steel mold of dimensions 250 x 16 mm^2 and cooled inside the steel mold to ambient temperature. The developed alloys were subjected to solid solution heat treatment at 900^oC for 5 h using a tube furnace (TSH12/25024166CG) equipped with an external thermocouple ($\pm 1^oC$ accuracy). The Impact energy testing is used to measure the toughness of materials. In this case, samples with dimensions 55 cm x 10 cm x 10 cm and notched at the center (2 mm deep at 45°) were tested according to the BS EN ISO 148-1:2016 standard. The bulk density of the materials was measured using Archimedes' principle. This method involves measuring the weight of the sample in air and then in a liquid (water) to determine its density.The electrical conductivity was determined using Standard Ohm's experiment. The surface morphologies of Cu-3Si-3W and Cu-3Si-3Mn ternary alloys were examined using an optical metallurgical microscope (OM). Prior to analysis, the sample surfaces underwent several preparation steps: grinding with emery paper of different grit sizes to smoothen the surface, polishing with pure aluminium powder, to achieve a fine and reflective surface, and etching in a solution of iron III chloride (FeCl3), HCl (hydrochloric acid), and water.

3. Results and Discussion

Figs. 1-3 show the effects of manganese and tungsten additions, and solid solution heat treatment on the impact energy, density, and electrical properties of Cu-3Si-3W and Cu-3Si-3Mn ternary alloys. It is shown in Fig. 1 that impact energy of Cu-3Si alloys was improved after solid solution heat treatment. The impact energy decreased on addition of manganese. The Cu-3Si-3W alloy recorded better impact energy and electrical conductivity compared with the parent alloy and Cu-3Si-3Mn alloy. The maximum impact energy of 16.6 J was recorded by the as-cast Cu-3Si-3W alloy. After solution heat treatment, the impact energy of Cu-3Si-3W alloy decreased from 16.6 J to 12.8 J. The electrical conductivity of the parent alloy was increased from 26.88 S/m to 29.34 S/m after tungsten addition in as-cast condition. The electrical conductivity was decreased by 22.81% after solution heat treatment. This can be attributed to the breakdown of grains morphology after solid solution treatment. These fine grains cause electron scattering effect in the alloy structure, leading to a decline in electrical conductivity. The Cu-3Si-3Mn alloy recorded lower bulk density after solution treatment, compared with both the parent alloy and the Cu-3Si-3W alloy. The bulk density of the parent alloy decreased from 8.21 g/cm^3 to 7.96 g/cm^3.

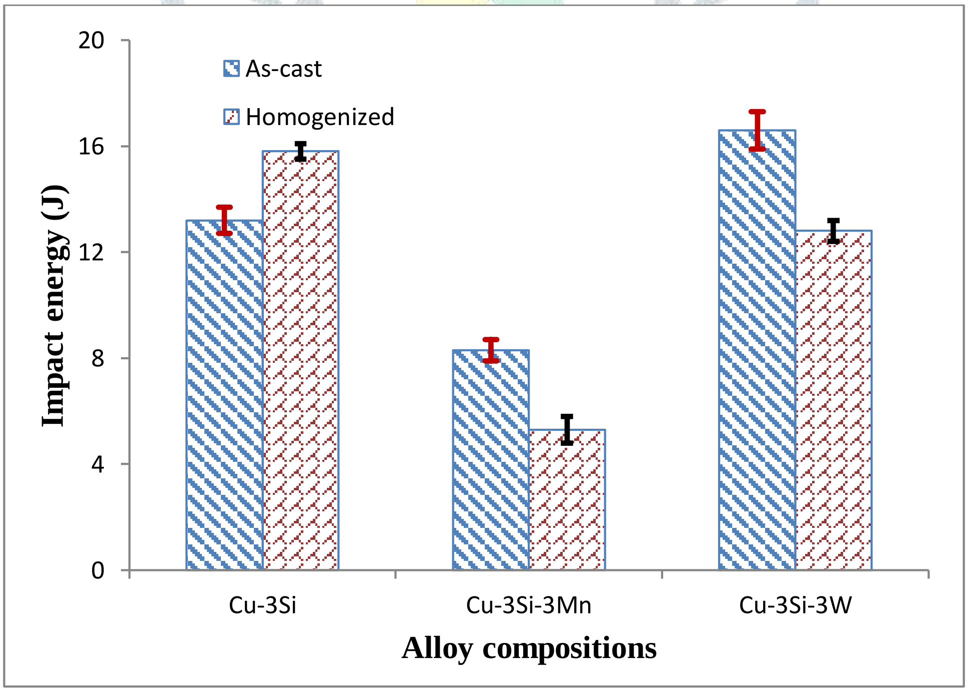

Fig. 1: Impact energy of Cu-3Si-3W and Cu-3Si-3Mnalloys

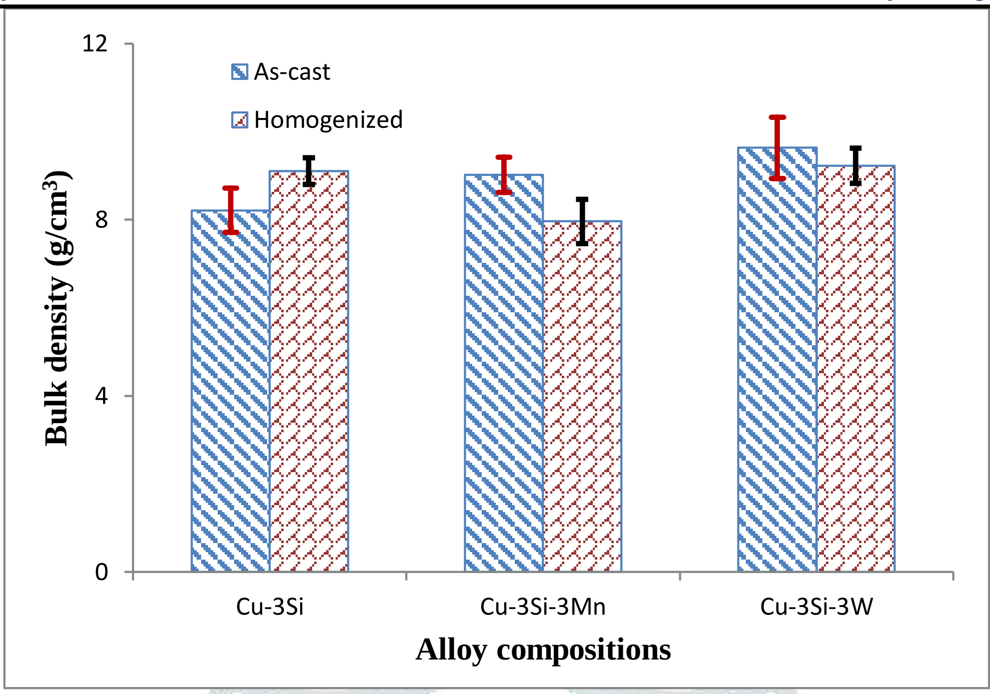

Fig. 2: Bulk density of Cu-3Si-3W and Cu-3Si-3Mn ternary alloys

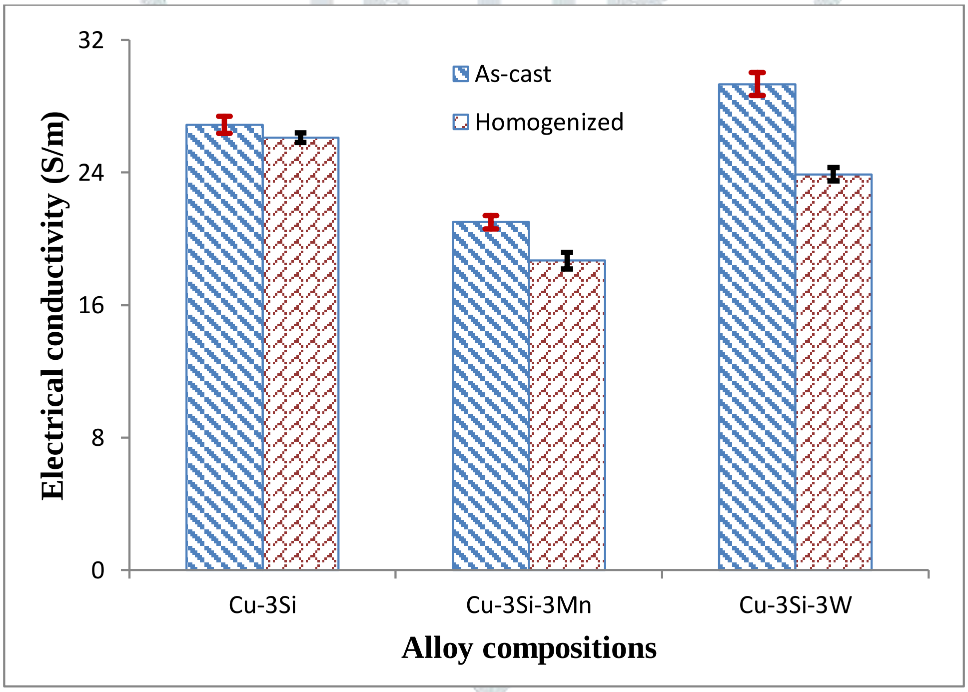

Fig. 3: Electrical conductivity of Cu-3Si-3W and Cu-3Si-3Mn ternary alloys

Fig. 4 shows the optical microstructures of Cu-3Si-3Mn and Cu-3Si-3Walloys in as-cast and homogenized conditions. Analysis of Fig. 4a shows networks of spherical grains separated by grain boundaries. The surface morphology of both alloys revealed fine grains after solid solution heat treatment. The Cu-3Si-3W alloy showed finer grains, evenly distributed in the copper matrix.A plate-like structure was observed in microstructure of as-cast Cu-3Si-3W alloy. The grains were modified and refined into cored fine grains after undergoing solid solution heat treatment. Thesemicrostructural changes can be linked with increased impact energy and electrical conductivity recorded by Cu-3Si-3W alloy.

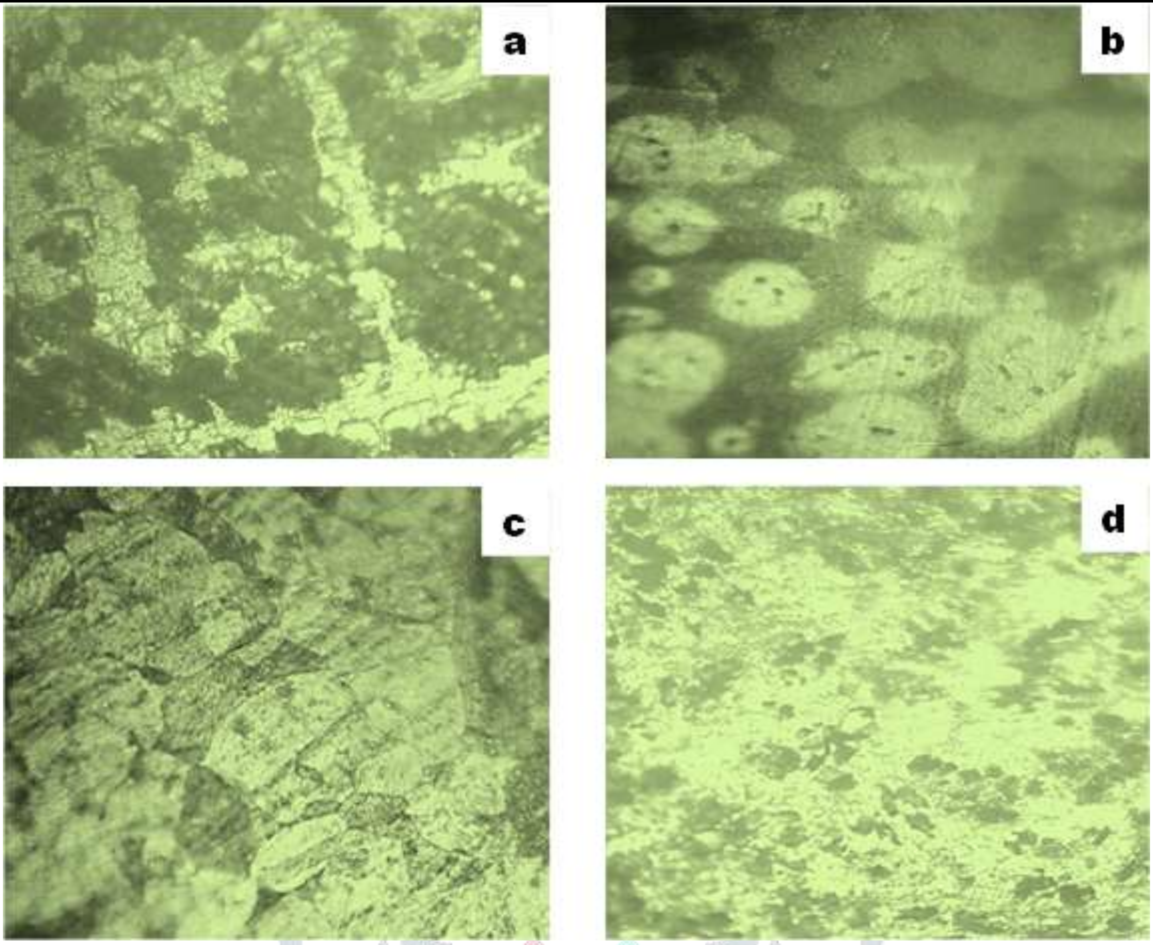

Fig. 4: Optical microstructure of (a) Cu-3Si-3Mn (as-cast)(b) Cu-3Si-3Mn (homogenized)(c) Cu-3Si-3W (as-cast)(D) Cu-3Si-3W (homogenized).

4. Conclusions

The grain refinement, impact energy, and physio-mechanical properties of Cu-3Si-3W and Cu-3Si-3Mn alloys via alloying and solid solution treatment have been investigated experimentally. The response of Mn and W-doped Cu-3Si alloy to solid solution heat treatment was determined. Analysis of the results indicated that the addition of manganese had a negative impact on impact energy, while the addition of tungsten improved impact energy and electrical conductivity in the as-cast condition. However, solution heat treatment had varying effects on these properties, with a decrease in impact energy and electrical conductivity for the Cu-3Si-3W alloy and a decrease in bulk density for the Cu-3Si-3Mn alloy. These changes are attributed to microstructural alterations in the alloys due to the heat treatment process.

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