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Microstructure, impact and electrical behavior of fine grained Cu-Si-(Mg, Ti) alloy after solid solution strengthening

Agatha Ifeoma Ijomah, Kingsley Chidi Nnakwo, Jerome Ugwu Odo*, and

Ifeanacho Uchenna Okeke

Corresponding author email address: ju.odo@unizik.edu.ng

Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria

Abstract

Solid solution strengthening generally improves the strength of the material, making it more resistant to deformation and fracture under applied loads. In this study, microstructure, impact, and electrical behavior of fine grained Cu-Si-(Mg, Ti) alloy after solid solution strengthening are studied. The impact energy, density, and electrical conductivity of the fabricated Cu-Si-(Mg, Ti) alloys were investigated. The microstructure analysis was done using optical metallurgical microscope (OM). Results indicated that magnesium and titanium induced increased precipitation of fine grains in the copper matrix, resulting to improvements of both the impact energy and electrical conductivity of the alloys, especially in the magnesium doped Cu-3Si alloy. Solution heat treatment enhanced the grain refinement and distribution in the alloy structure. This guaranteed the further increase in impact energy of the Cu-Si-(Mg, Ti) alloy, with maximum values of 34.2 J and 25.6 J, respectively. The as-cast Cu-3Si-3Mg recorded maximum electrical conductivity of 28.55 S/m. Both alloys recorded higher density at all conditions compared with the parent alloy.

Keywords: Microstructure; magnesium; titanium; impact energy; density.

1. Introduction

Cu-Si alloys are used in various industries, including automobile, automation, building, electrical, and electronics for the fabrication of screws, electrical connectors, lead frame, conduits, fasteners, bolts, electronic signals, valve stems, nails, and nuts (Xie et al., 2003; Qing et al., 2011; Yu et al., 2011; Jeong et al., 2009). These alloys are potential materials for casting intricate shapes due to their high fluidity accompanying silicon addition. Research has shown that properties of copper-based alloys can be enhanced through alloying (changing the chemical composition), heat treatment, and metalworking. While heat treatment and metalworking have received significant attention, limited research has focused on the impact of chemical composition, particularly the role of aluminium content (Nnakwo, 2019; Nnakwo et al., 2017a,b; 2019a,b; 2020, 2021, 2022;Nnakwo and Nnuka, 2018;Cheng et al., 2014; Qing et al., 2011; Qian et al., 2010; Gholami et al., 2017b; Cheng et al., 2014; Wang et al., 2014). This research aims to investigate how varying levels of aluminium content affect the structure and mechanical properties of Cu-3Si-Al ternary alloy.

Cu-Ni-Si alloys are recognized for their high strength, hardness, and electrical conductivity. However, they tend to exhibit high brittleness and low elongation (Yu et al., 2011; Jeong et al., 2009). Research efforts are also aimed at improving the ductility of Cu-Si alloys while maintaining their hardness through alloy refinement. The properties of copper-nickel-silicon-based alloys are linked to the precipitation of specific phases, such as β1-Ni3Si, α-Cu (Ni,Si), γ′-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si, either individually or in combined forms (Qian et al. 2017; Suzuki et al. 2006; Wang et al. 2016; Srivastava et al. 2004; Li et al. 2017; Pan et al., 2007; Li et al., 2009; Lei et al., 2013a; Lei et al., 2013b). These alloys can exhibit high electrical conductivity and varying levels of ductility and strength. Different studies have reported a range of properties for copper-nickel-silicon-based alloys, including strength (704-2700MPa), hardness (270-381HV), electrical conductivity (25.2-48.2%IACS), and ductility (2.75-14%) (Gholami et al., 2017a; Jia et al., 2012; Xie et al., 2009; Lei et al., 2017; Qing et al., 2011; Qian et al., 2010; Gholami et al., 2017b; Cheng et al., 2014; Wang et al., 2014).

This present study is aimed to explore the microstructure, impact, and electrical behavior of fine grained Cu-Si-(Mg, Ti) alloy after solid solution strengthening.

2. Experimental procedure

The alloy compositions were designed and cast using an analytical grade copper wire silicon powder, and aluminium wire of percentage purities of 98.9%, 98.7%, and 99.7% respectively. Alloys were produced by melting the materials using a bailout crucible furnace. The molten alloys were cast into iron molds with dimensions of 16mm diameter and 250mm length. The alloys were allowed to cool inside the molds to room temperature. Tensile strength samples were milled to specific dimensions: 120mm total length, 50mm gauge length, and 8mm gauge diameter. Hardness samples were milled to 25mm length and 15mm diameter. Sample surfaces were ground and polished thoroughly.The samples were solid solution heat treated at temperature of 900°C for duration of 5 h. The impact energy was carried out on samples of dimensions 55 x 10 x 10 $mm^3$with a 2mm deep notch ($\Delta 45^o$) inscribed at the center of the sample, following BS EN ISO 148-1:2016 standards. The bulk density was measured using Archimedes principle. The electrical resistivity and conductivity were determined using Standard Ohm's experiment.The surface morphology of the developed alloys was analyzed using an optical metallurgical microscope (OM). Prior to the analysis, the sample surfaces were ground with emery paper of different grit sizes, polished with pure aluminum powder, and etched in solution of iron III chloride, HCl, and water.

3. Results and Discussion

3.1. Mechanical properties

Figs. 1-3 show the impact energy, density, and electrical conductivity of Mg and Ti-doped copper-silicon alloy subjected to solid solution strengthening. The parent alloy recorded impact energy of 13.2 J. After solid solution heat treatment, the impact energy was increased to 15.8 J. The impact energy was significantly improved after addition of magnesium and titanium. Cu-3Si-3Mg and Cu-3Si-3Ti alloys recorded impact energy values of 28.6 J and 21.8 J respectively in as-cast conditions (Fig. 1). The impact energy was increased further from 28.6 J to 34.2 J and from 21.8 J to 25.6 J, respectively after undergoing solid solution strengthening. This can be associated with increased precipitations of fine grains in the copper matrix. Fig. 2 shows the variations of density of the parent alloy with additions of alloying elements and solid solution treatment. It is noted from the Fig. 1 that the density of the parent alloy is lower than the as-cast and heat treated Cu-3Si-3Mg and Cu-3Si-3Ti alloys. The Cu-3Si-3Mg alloy recorded a better electrical conductivity compared with the parent alloy and Cu-3Si-3Ti alloys in as-cast conditions, with maximum values of 28.55 S/m.

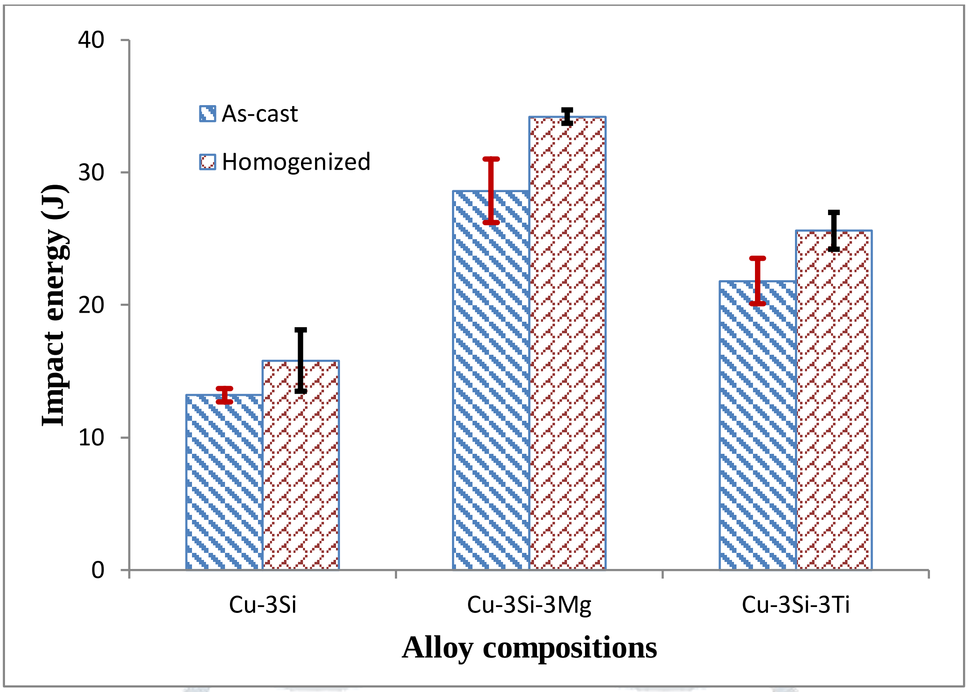

Fig. 1: Impact energy of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

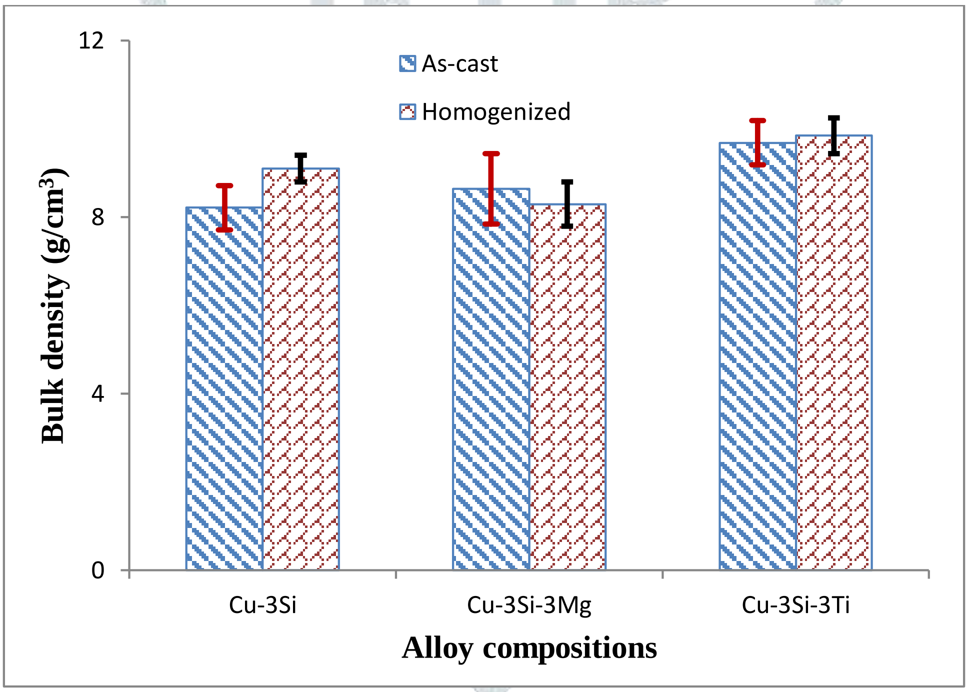

Fig. 2: Bulk density of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

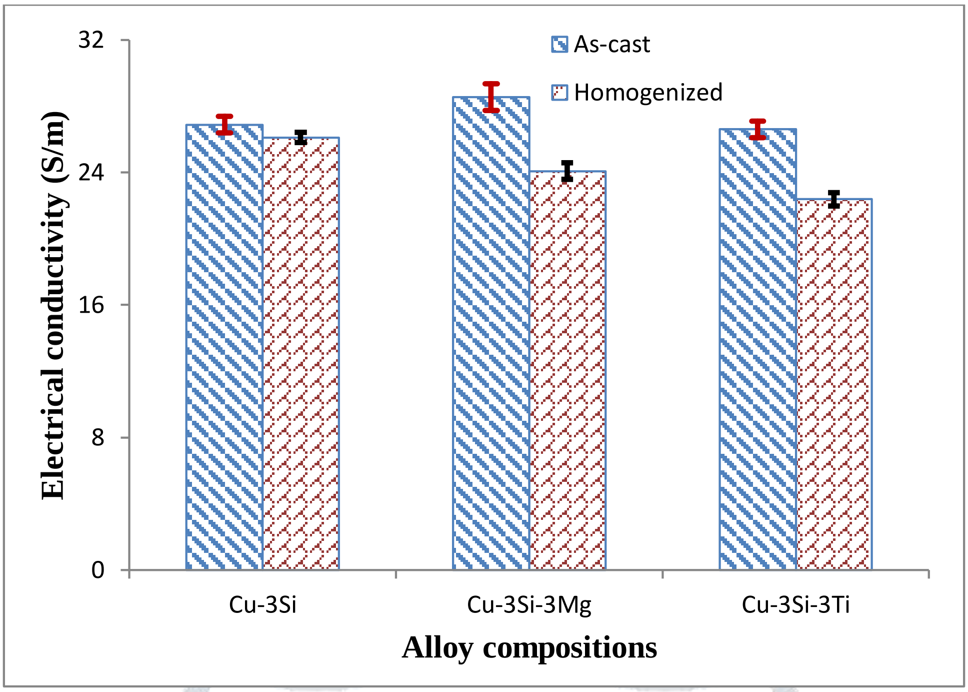

Fig. 3: Electrical conductivity of Cu-3Si-3Mg and Cu-3Si-3Ti alloys

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.

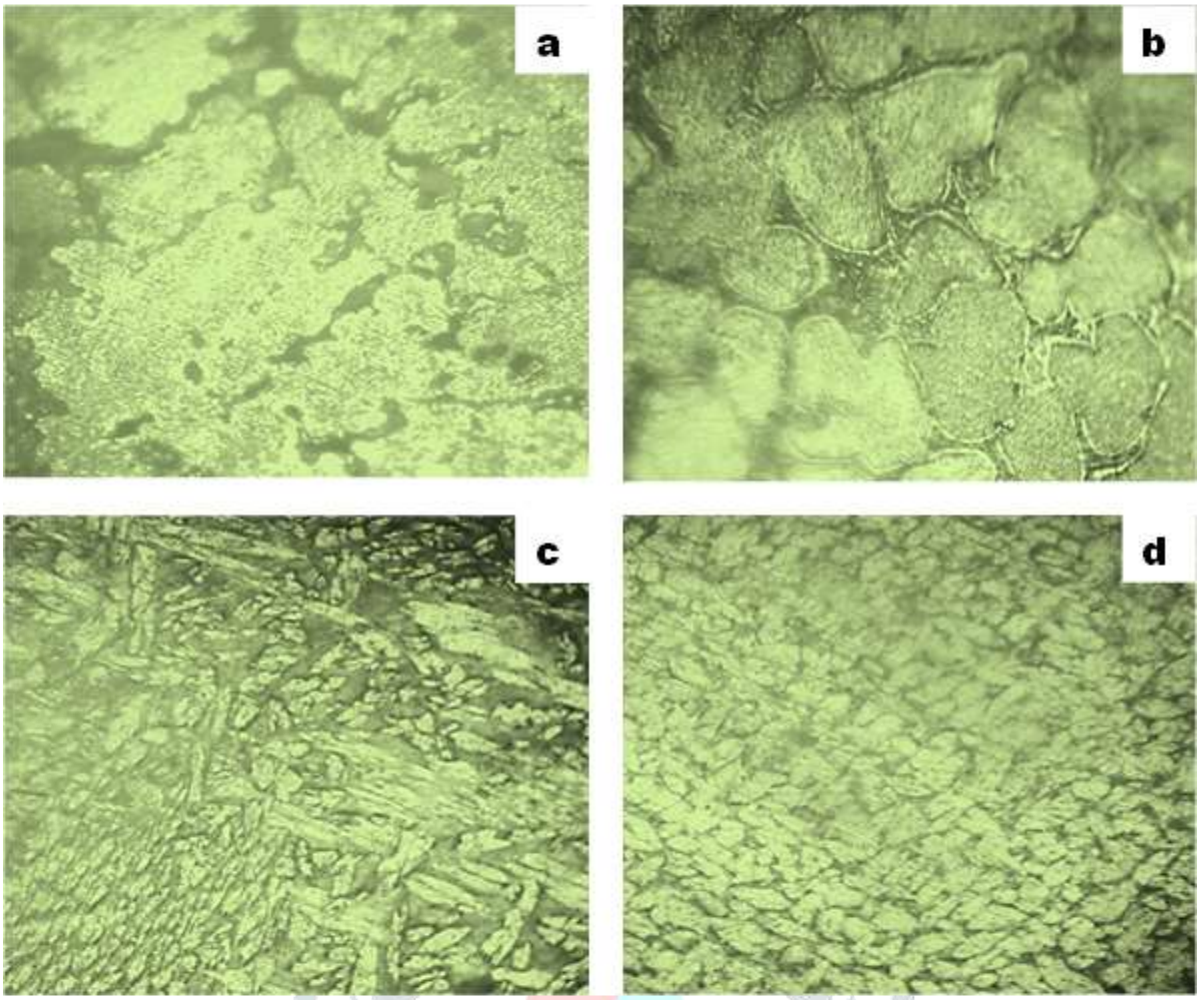

Fig. 4: Optical microstructure of (a) Cu-3Si-3Mg (as-cast)(b) Cu-3Si-3Mg (homogenized)(c) Cu-3Si-3Ti (as-cast)(D) Cu-3Si-3Ti (homogenized).

4. Conclusions

The microstructure, impact, and electrical behavior of fine grained Cu-Si-(Mg, Ti) alloy after solid solution strengthening has been investigated experimentally. The alloys demonstrated excellent impact energy and electrical conductivity at various conditions. The addition of magnesium and titanium to the copper-silicon alloy improved its impact energy and electrical conductivity, with magnesium showing particularly significant enhancements in impact energy. Additionally, solid solution strengthening was found to further enhance these properties by promoting the formation of fine grains in the alloy. The density of the parent alloy was lower than that of the as-cast and heat-treated Cu-3Si-3Mg and Cu-3Si-3Ti alloys. In as-cast conditions, Cu-3Si-3Mg alloy exhibited better electrical conductivity compared to both the parent alloy and Cu-3Si-3Ti alloy, with a maximum value of 28.55 S/m.

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