Novelty Journals

ISSN 2394-7349

International Journal of Novel Research in Engineering and Science
Vol. 10, Issue 2, pp: (7-11), Month: September 2023 - February 2024, Available at: www.noveltyjournals.com

Enhancing the structure and mechanical properties of Cu-3Si-Al ternary alloy by addition of aluminium

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DOI: https://doi.org/10.5281/zenodo.8344418

Published Date: 14-September-2023

Abstract: **The enhancement of the structure and mechanical properties of a Cu-3Si-Al ternary alloy by the addition of aluminum was achieved through careful alloy design and processing techniques. In this study, aluminium was introduced into the Cu-3Si binary alloy in concentrations of 0.1-5wt% and fabricated using stir-casting technique. The microstructural changes in the alloy were investigated using an optical metallurgical microscope (OM). The OM results show increased solid solution regions and finer grains in the Cu-3Si alloy doped with aluminium compared to the parent alloy (Cu-Si), leading to improvements of ultimate tensile strength, percentage elongation, and hardness, with maximum values of 314 MPa, 28%, and 278 BHN, respectively.**

Keywords: **Alloy design; aluminium; Cu-Si-Al alloy; microstructure; properties.**

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).

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2. EXPERIMENTAL PROCEDURE

The alloy compositions were designed and cast using an analytical grade copper wiresilicon 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.

Tensile strength tests were conducted according to British standards: BS EN ISO 6892-1:2016. Hardness tests were carried out following BS EN ISO 6505-1:2014.Testing Equipment: Tensile strength tests were performed using a 100kN capacity automated JPL tensile strength tester (Model: 130812). Hardness tests were conducted using a Brinell hardness tester (Model: DHT-6). Prior to microstructural analysis, alloy sample surfaces were prepared by grinding with emery paper of different grit sizes, polishing with pure aluminum powder, and etching in an iron III chloride, HCl, and water mixture.

3. RESULTS AND DISCUSSION

The ultimate tensile strength, percentage elongation, and hardness of Cu-3Si binary alloys doped with different concentrations of aluminium are presented in Figs. 1-3.It is noted in Figs. 1-3 that addition of aluminium led to significant increase in the ultimate tensile strength, percentage elongation, and hardness of Cu-3Si binary alloys. The percentage elongation decreased as the concentrations of aluminium increases. Both hardness and ultimate tensile strength values increased correspondingly with increasing concentration of aluminium up to 3wt%, before witnessing a decline at further increase in aluminium content. Maximum ultimate tensile strength and hardness were obtained at 3wt%Al, with maximum values of 314 MPa and 278 BHN, respectively.These improvements in mechanical properties can be attributed to increased solid solution region and fine grains accompanying increasing addition of aluminium. The sudden decline in both ultimate tensile strength and hardness can be linked to coarsening of grains at increased aluminium content (5wt%).

The surface morphologies of the developed Cu-3Si ad Cu-3Si-Al alloys are presented in Fig. 4. The OM image of the parent alloy (Cu-3Si) reveals the presence of well-dispersed large dendrites of grains. These grains are primary silicon and Cu_3Si intermetallic compounds (Fig. 4a). The formation of these phases occurs when the alloy is slowly cooled to room temperature due to the limited solid solubility of silicon in the copper matrix. Fig. 4b, 4c, and 4d display the microstructures of Cu-3Si-0.2Al, Cu-3Si-3Al, and Cu-3Si-5Al alloys. Fig. 4b, 4c show well-dispersed fine grains in the alloy structure. The fine grains led to an increased number of grain boundaries, which, in turn, impede the dislocation motion. This systematic change contributes to an increase in the ultimate tensile strength (UTS) and hardness of the alloy. Enlarged grains in Cu-3Si-5Al alloy as shown in Fig. 4d, led to a sudden decrease in ultimate tensile strength and hardness of th alloy.

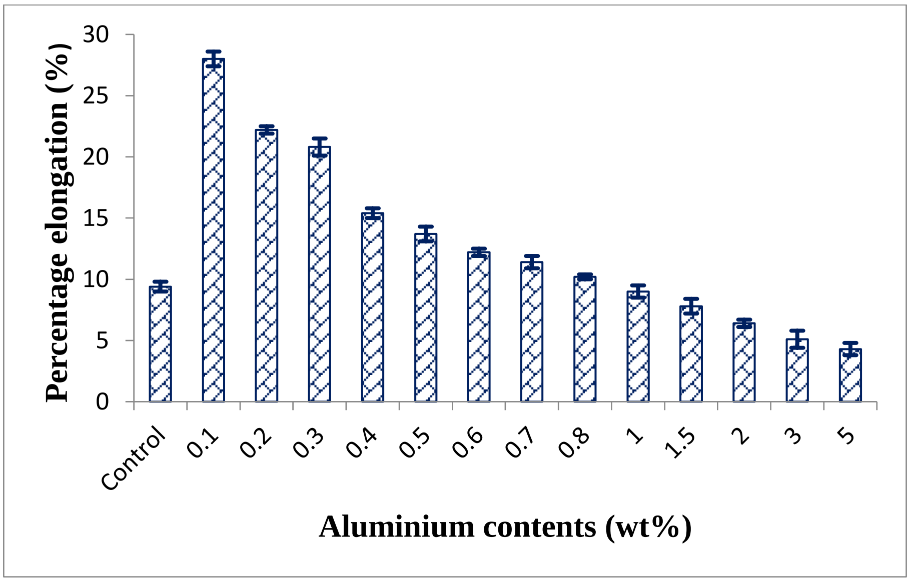

Fig. 1: Percentage elongation of Cu-3Si-Al ternary alloys

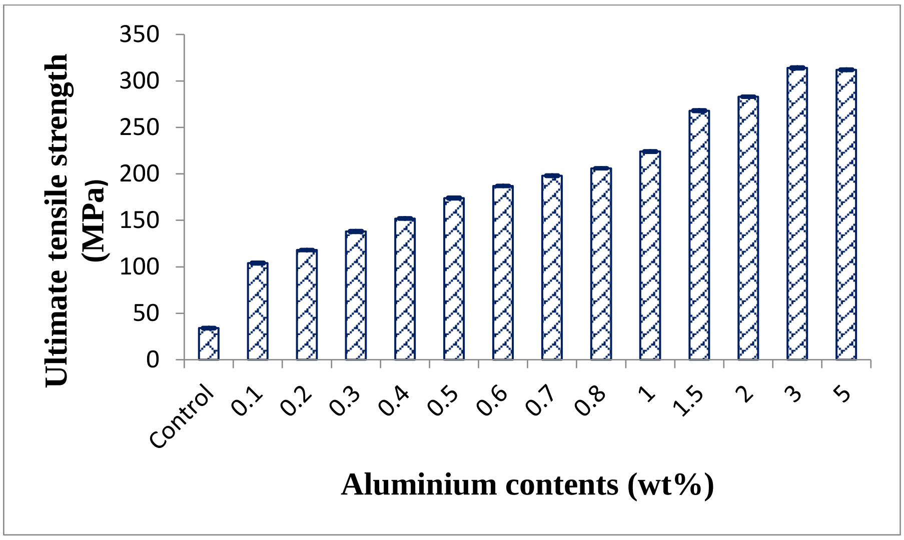

Fig. 2: Ultimate tensile strength of Cu-3Si-Al ternary alloys

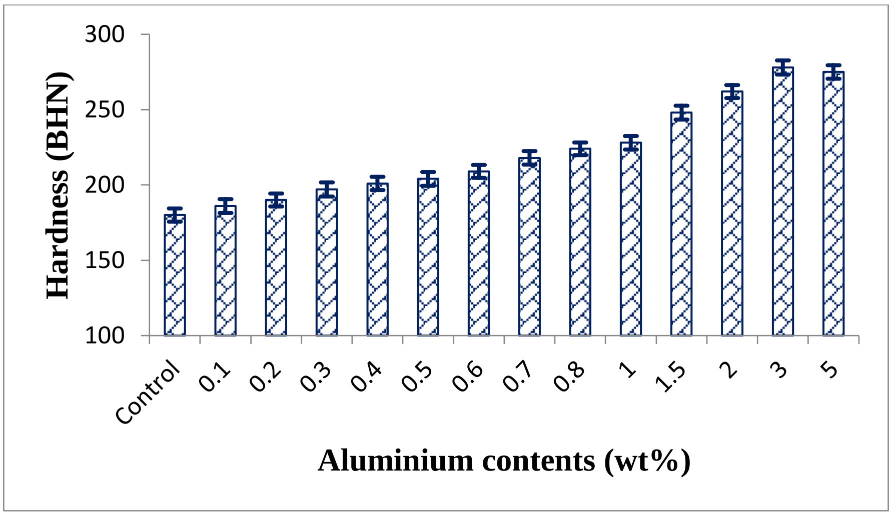

Fig. 3: Hardness of Cu-3Si-Al ternary alloys

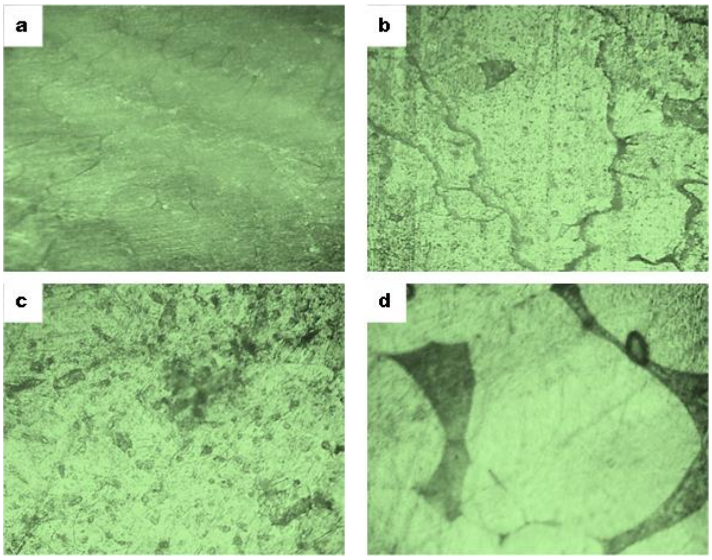

Fig. 4: OM microstructures of (a) Cu-3Si (b) Cu-3Si-0.2Al (c) Cu-3Si-3Al (d) Cu-3Si-5Al alloys

4. CONCLUSIONS

The structure and mechanical properties of Cu-3Si-xAl ternary alloy has been investigated experimentally. The Cu-3Si-xAl ternary alloy demonstrated excellent combination ofpercentage elongation, ultimate tensile strength, and hardness. The improvements of mechanical properties are linked to the increased solid solution region and fine grains associated with the addition of aluminium. The percentage elongation decreased as the concentrations of aluminium increases. Both hardness and ultimate tensile strength values increased correspondingly with increasing concentration of aluminium up to 3wt%, before decreasing with further increase in aluminium content. Maximum ultimate tensile strength and hardness were obtained at 3wt%Al, with maximum values of 314 MPa and 278 BHN, respectively. The sudden decline in both ultimate tensile strength and hardness are linked to the coarsening of grains at increased aluminium content (5wt %). These findings can have practical implications for designing and optimizing materials for various applications in industries such as automotive, aerospace, and electronics, where a combination of these properties is crucial.

ACKNOWLEDGEMENT

The authors appreciate the management of Cutix Cable Plc, Nnewi Nigeria for their unalloyed support for this experimental study.

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