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Solid solution-induced ultrafine Cu-3Si-Al and Cu-3Si-Mo ternary alloy

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Abstract: **Adequate control of composition, cooling rates, and heat treatment parameters is crucial to achieving the desired ultrafine microstructure and properties in copper-based alloys. In this experimental study, an ultrafine Cu-3Si-Al and Cu-3Si-Mo ternary alloy with improved tensile strength and hardness is developed. The alloys system were developed via stir-casting technique and subjected to solid solution heat treatment at 900°C for 5 h. The microstructures of the ternary alloys were analyzed and correlated with the investigated mechanical properties. Results showed that Cu-3Si-3Al alloy recorded ultimate tensile strength and hardness of 314 MPa and 278 BHN in as-cast condition. Incorporation of molybdenum to the parent alloy significantly increased the ultimate tensile strength, percentage elongation, and hardness. As-cast Cu-3Si-3Mo alloy recorded ultimate tensile strength and hardness of 130 MPa and 192 BHN, respectively. After solution heat treatment, ultimate tensile strength and hardness of Cu-3Si-3Al alloy increased from 314 MPa to 322 MPa, and from 192 BHN to 201 BHN. On the same condition, Cu-3Si-3Mo alloy recorded about 29.2% and 4.7% increase in ultimate tensile strength and hardness compared to the as-cast Cu-3Si-3Mo alloy. This mechanical behavior can be attributed to increased solid solution region and fine grains accompanying increasing addition of aluminium and molybdenum.**

Keywords: **Solid solution; microstructure; properties; tensile strength; hardness.**

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).

2. EXPERIMENTAL PROCEDURE

Analytical grade copper rod, aluminium wire, silicon, and molybdenum powders with different percentage purities (98.9%, 95.9%, 98.8%, and 99.7%) were used as starting materials for this experimental study.The alloys were produced by melting the materials together using a bailout crucible furnace. The molten alloys were cast into iron molds with specific dimensions of 16 mm diameter and 250 mm length. The alloys were allowed to cool inside the molds until they reached 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 25 mm length and 15 mm diameter. The cast samples were heat treated at 900^{o}C for 5 h and cooled in air. The surfaces of the samples were ground and polished thoroughly to ensure a consistent surface finish.

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. 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, the surfaces of the alloy samples were prepared through several steps: grinding with emery paper of different grit sizes, polishing with pure aluminum powder, and etching in a mixture of iron III chloride, HCl, and water.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

The ultimate tensile strength, percentage elongation, and hardness of Cu-3Si, Cu-3Si-3Al, and Cu-3Si-3Mo alloys 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 and hardness of Cu-3Si binary alloys with corresponding decrease in percentage elongation. Cu-3Si-3Al alloy recorded ultimate tensile strength and hardness of 314 MPa and 278 BHN in as-cast condition. Incorporation of molybdenum to the parent alloy significantly increased the ultimate tensile strength, percentage elongation, and hardness. The percentage elongation of the parent alloy increased from 9.4% to 12.1% on addition of molybdenum. As-cast Cu-3Si-3Mo alloy recorded ultimate tensile strength and hardness of 130 MPa and 192 BHN, respectively. After solution heat treatment, ultimate tensile strength and hardness of Cu-3Si-3Al alloy increased from 314 MPa to 322 MPa, and from 192 BHN to 201 BHN. On the same condition, Cu-3Si-3Mo alloy recorded about 29.2% and 4.7% increase in ultimate tensile strength and hardness compared to the as-cast Cu-3Si-3Mo alloy. This mechanical behavior can be attributed to increased solid solution region and fine grains accompanying increasing addition of aluminium and molybdenum.

3.2. Surface morphology of the developed alloys

Fig. 4 shows the microstructure analysis of the developed Cu-3Si-3Al, and Cu-3Si-3Mo alloys. In Fig. 4a and 4c, the microstructure analysis revealed even dispersion of spherical grains. This refinement resulted in an increased number of grain boundaries and dislocation density within the alloys.The changes observed in the microstructure, such as grain refinement and increased dislocation density, are correlated with an increase in the tensile strength and hardness of the alloy.This suggests that the modified microstructure due to the addition of Mo contributed to improved mechanical properties.

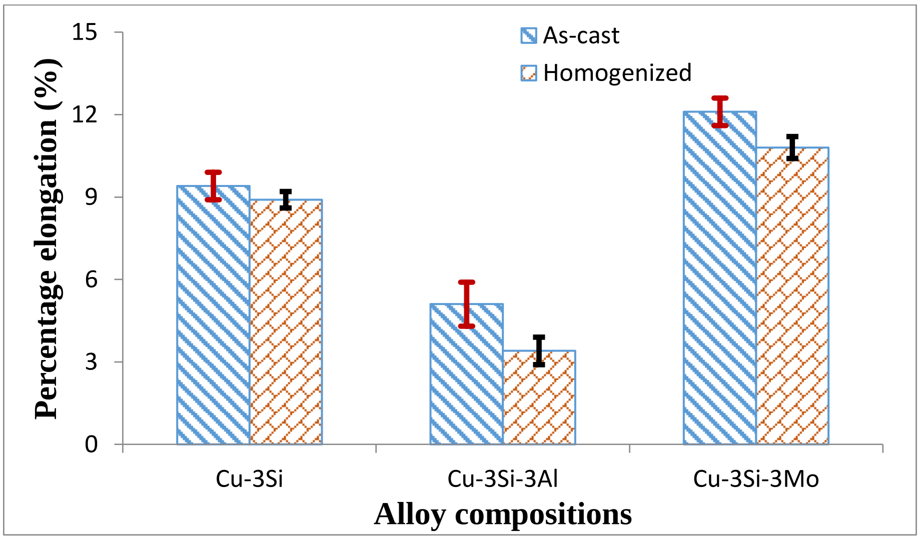

Fig. 1: Percentage elongation of Cu-3Si-3Al, and Cu-3Si-3Mo alloys

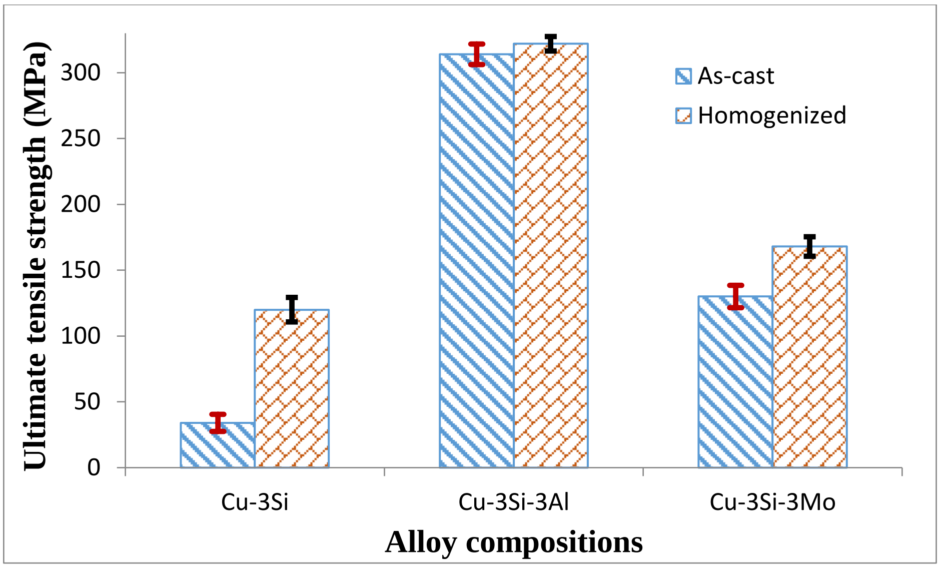

Fig. 2: Ultimate tensile strength of Cu-3Si-3Al, and Cu-3Si-3Mo alloys

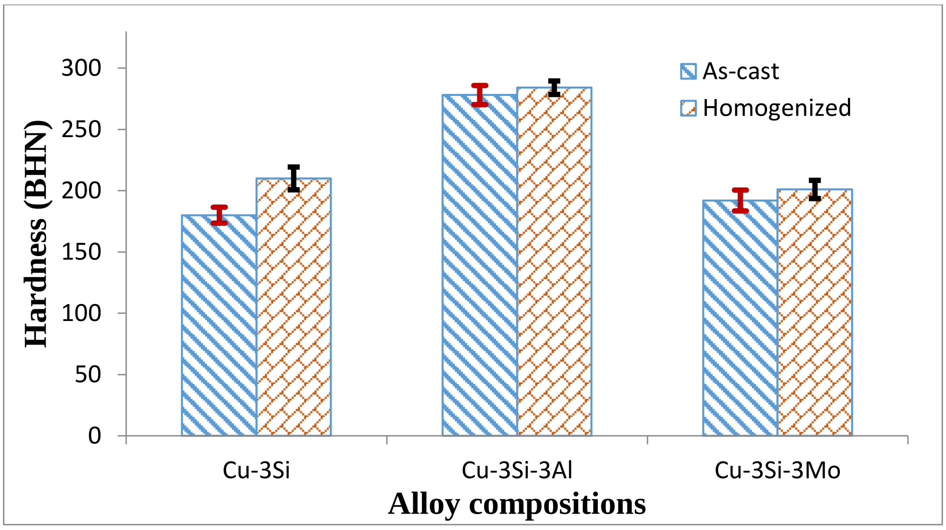

Fig. 3: Hardness of Cu-3Si-3Al, and Cu-3Si-3Mo alloys

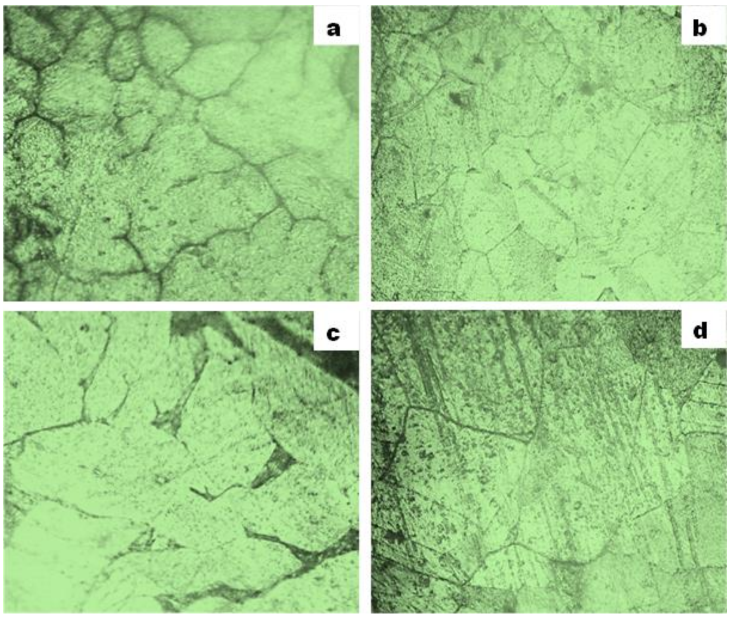

Fig. 4: OM microstructures of (a) Cu-3Si-3Al (as-cast) (b) Cu-3Si-3Al (homogenized) (c) Cu-3Si-3Mo (as-cast)(D) Cu-3Si-3Mo (homogenized).

4. CONCLUSIONS

A detailed experimental study on the solid solution-induced ultrafine Cu-3Si-Al and Cu-3Si-Mo ternary alloy was carried out successfully. The effects of aluminium and molybdenum on the response of Cu-3Si alloy on the solid solution strengthening were investigated appropriately. Results of the study showed addition of aluminium led to significant increase in the ultimate tensile strength and hardness of Cu-3Si binary alloys with corresponding decrease in percentage elongation. Cu-3Si-3Al alloy recorded ultimate tensile strength and hardness of 314 MPa and 278 BHN in as-cast condition. Incorporation of molybdenum to the parent alloy significantly increased the ultimate tensile strength, percentage elongation, and hardness. The percentage elongation of the parent alloy increased from 9.4% to 12.1% on addition of molybdenum. As-cast Cu-3Si-3Mo alloy recorded ultimate tensile strength and hardness of 130 MPa and 192 BHN, respectively. After solution heat treatment, ultimate tensile strength and hardness of Cu-3Si-3Al alloy increased from 314 MPa to 322 MPa, and from 192 BHN to 201 BHN. On the same condition, Cu-3Si-3Mo alloy recorded about 29.2% and 4.7% increase in ultimate tensile strength and hardness compared to the as-cast Cu-3Si-3Mo alloy. This mechanical behavior can be attributed to increased solid solution region and fine grains accompanying increasing addition of aluminium and molybdenum.

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