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Tailoring the surface morphology of Al, Mo-doped Copper-silicon alloys for enhanced impact resistance

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Abstract: **This study explored the impact resistance of Al, Mo-doped copper-silicon alloy. 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 properties. Results showed that the Cu-3Si-3Al and Cu-3Si-3Mo alloys demonstrated excellent impact resistance. The Cu-3Si binary alloy initially recorded impact energy of 13.2 J. After adding Al, the impact energy increased to 14.2 J. The impact energy of Cu-3Si-Al ternary alloys was increased by 74.6% after undergoing solid solution treatment. The as-cast Cu-3Si-Mo alloy had lower impact resistance than the parent alloy but showed improved impact energy after solid solution strengthening; reaching 18.9 J. This change in impact resistance is attributed to increased solid solution of Al and Mo in the copper matrix. The density of the parent alloy (Cu-3Si) decreased when molybdenum (Mo) was incorporated, going from 8.21 g/cm^3 to 7.81 g/cm^3. After undergoing solid solution treatment, the density of Cu-3Si-Mo alloy decreased further to 7.6 g/cm3.The parent alloy (Cu-3Si) had better electrical conductivity compared to the ternary alloys. This difference in electrical conductivity was attributed to increased solid solution of Al and Mo in the copper matrix, which decreases the mobility of copper atoms.**

Keywords: **Impact resistance; surface morphology; strength; conductivity; properties.**

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1. INTRODUCTION

Copper-based alloys are essential materials with a wide range of properties that make them indispensable in various industries. Copper is well-known for its electrical and thermal conductivity, corrosion resistance, and ductility, however, ongoing research and development efforts are exploring alternative alloys to address specific limitations and drive further advancements in copper-based materials (Xie et al., 2003; Qing et al., 2011; Yu et al., 2011; Jeong et al., 2009). Copper is renowned for its excellent electrical conductivity, making it an ideal choice for electrical and electronic applications. It's used extensively in wiring, cables, and electrical components because it allows for efficient transmission of electrical power and signals. Copper also possesses outstanding thermal conductivity. This property makes it suitable for applications where efficient heat transfer is essential, such as heat exchangers, radiators, and condenser tubes. Copper's ability to conduct heat efficiently ensures effective heat dissipation in various industrial processes and systems. Copper and its alloys are highly resistant to corrosion, which is a critical factor in applications where exposure to moisture or corrosive environments is a concern(Yu et al., 2011; Jeong et al., 2009). This corrosion resistance makes copper alloys suitable for use in water pipes, automotive components, and railway infrastructure, where durability is essential. Copper is highly ductile, meaning it can be easily shaped and formed into various configurations. This property is invaluable for industries like automotive, construction, and plumbing, where copper components need to be fabricated into specific shapes and sizes to meet design requirements.

Copper-Beryllium (Cu-Be) alloys are known for their exceptional combination of high strength and electrical conductivity. However, they do have limitations, such as toxicity and cost. These drawbacks have led to the exploration of alternative alloys like Cu-Ni-Si, Cu-Si, and Cu-Ti-Si, which aim to maintain similar mechanical properties while addressing the issues associated with Cu-Be alloys(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).The field of copper-based alloys is continually evolving, with ongoing research and development efforts focused on improving existing materials and developing new alloys. This research aims to enhance the properties of copper-based materials, reduce toxicity concerns, and optimize cost-effectiveness. Such innovations can lead to the development of alloys better suited to specific applications and industries.

The high strength and electrical conductivity of Cu-Ni-Si alloyshave been reported to be achieved through various processing techniques such as alloying, thermo-mechanical treatments, and precipitation hardening (Gholami et al., 2017a; Jia et a., 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). These alloys exhibit excellent mechanical and electrical properties due to the presence of specific phases, including $\beta 1$-Ni_3Si, α-Cu (Ni,Si), γ'-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si, as reported in several studies (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).However, it is noted that the ductility of these alloys is low, which could limit their application in situations where impact resistance is crucial. To address this limitation, the study aims to improve the tensile strength, ductility, and hardness of Cu-Si based alloys by introducing molybdenum. The effectiveness of molybdenum as an alloying element and its impact on the properties of Cu-Si-based alloys would depend on the alloy's composition, processing techniques, and the specific phases that form within the material. The study aims to investigate these aspects to tailor the alloy's properties for applications that require a combination of high strength, ductility, and hardness

2. EXPERIMENTAL PROCEDURE

For this experimental study, copper rods, aluminium wire, molybdenum, and silicon powders of percentage purity of 98.9%, 98.7%, 98.5%, and 99.7% respectively were used. The predetermined quantities of these materials were determined using weight percent calculation and measured using an electronic compact scale (Model: BL20001).For the control alloy sample (Cu-3wt%Si), 1 Kg of copper was charged into the preheated bailout crucible furnace and heated until melting was achieved at 1084 ^{o}C. The melt was superheated to ensure adequate fluidity. Thereafter, 31g of pure silicon powder wrapped in an aluminium foil was introduced into the melt and stirred vigorously to achieve homogeneity. The mixture was left for 10 minutes to achieve a complete dissolution of the silicon metal and stirred again. The prepared permanent mold was preheated at temperature of 200^{o}C. The melt was poured into the preheated permanent mold and allowed to cool inside the mold. TheCu-3Si-xAl and Cu-3Si-Mo alloys were produced following the same procedure, cast and stored for machining. 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 variations of impact energy; density, and electrical conductivity of Cu-3Si-xAl and Cu-3Si-Mo alloys. The Cu-3Si binary alloy recorded impact energy of 13.2 J, which increased after solid solution treatment. The impact energy increased from 13.2 J to 14.2 J after adding Al. The impact energy of Cu-3Si-Al ternary alloys was increased by 74.6%after been subjected to solid solution treatment. The impact resistance of the as-cast Cu-3Si-Mo alloy is lower than the parent alloy, but exhibited better impact energy after undergoing solid solution strengthening; recording impact energy of 18.9 J. Analysis of Fig. 2 shows that the density of the parent alloy (Cu-3Si) decreased after incorporation of molybdenum. The density decreased from 8.21 g/cm^3 to 7.81 g/cm^3. The density of Cu-3Si-Mo alloy decreased further to 7.6 g/cm^3 after undergoing solid solution treatment. Figs. 3 showed that the parent alloy recorded a better electrical conductivity compared with the ternary alloys. This can be attributed to increased solid solution of Al and Mo in the copper matrix, thereby decreasing the mobility of copper atoms.

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 increased impact strength observd in the Cu-3Si-xAl alloy.

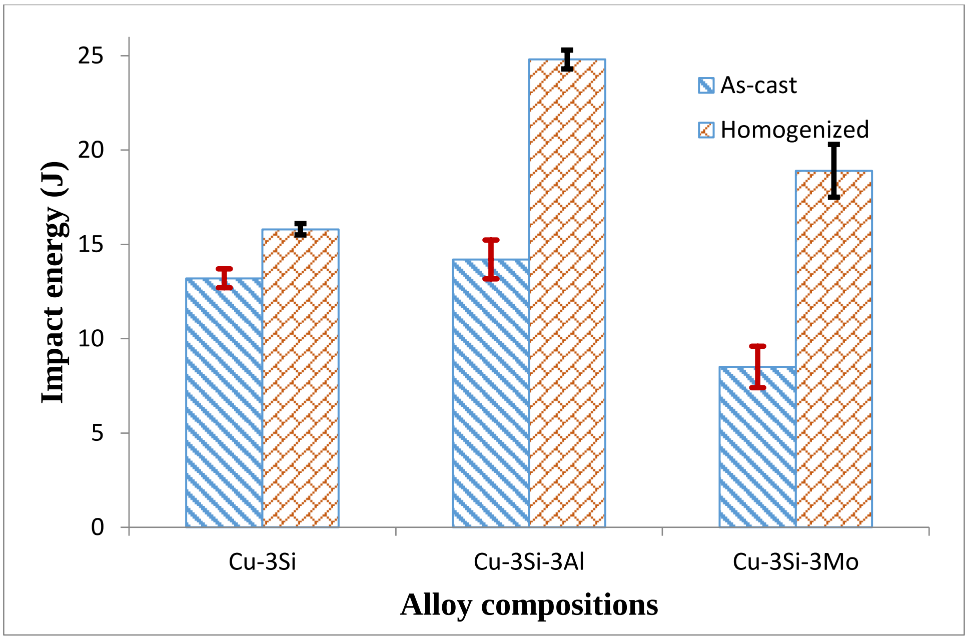

Fig. 1: Impact energy of Cu-3Si-3Al and Cu-3Si-3Mo alloys

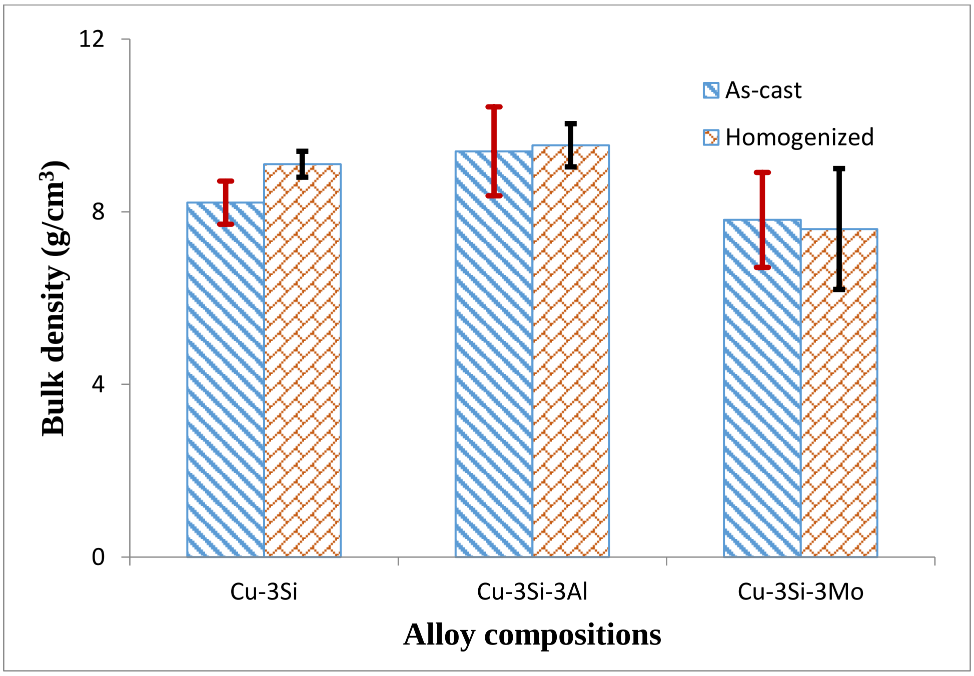

Fig. 2: Bulk density of Cu-3Si-3Al and Cu-3Si-3Mo alloys

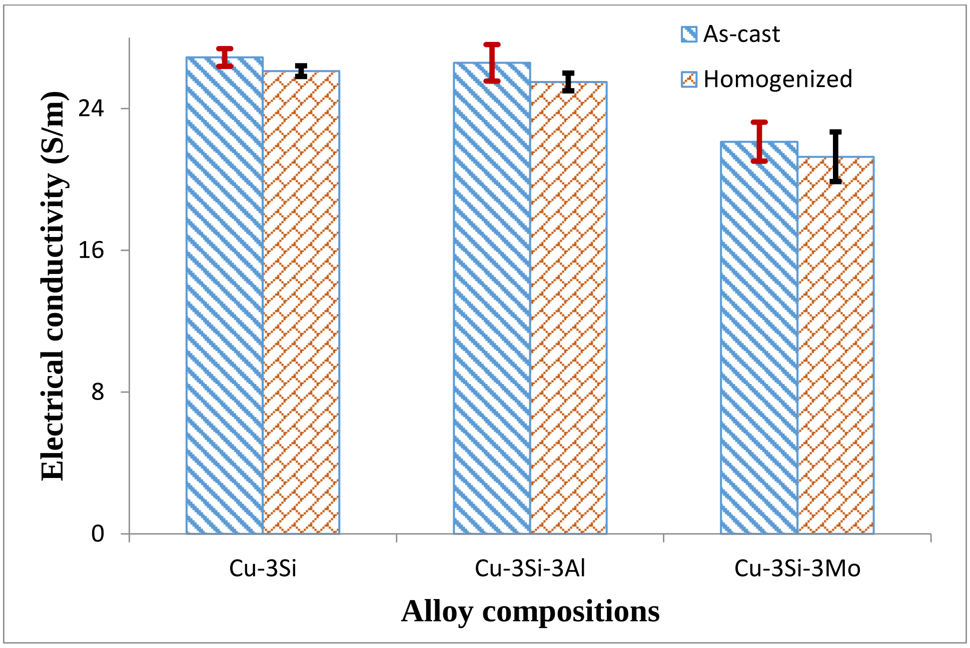

Fig. 3: Electrical conductivity ofCu-3Si-3Al and Cu-3Si-3Mo alloys

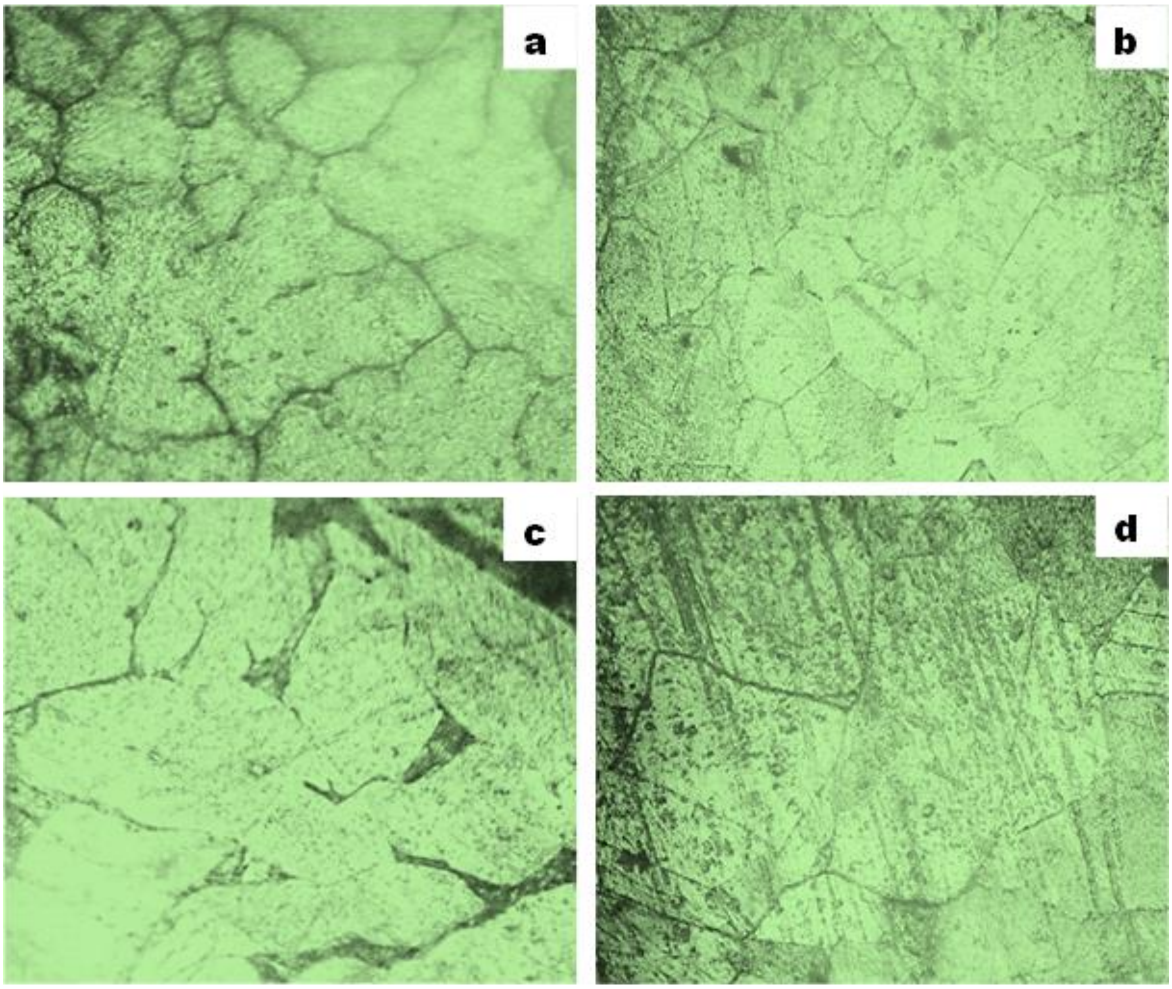

Fig. 4: OM microstructures of (a) Cu-3Si-3Al (as-cast) (b) Cu-3Si-3Al (homogenized) (c) Cu-3Si-3Mo (as-cast)(D) Cu-3Si-3Mo (homogenized).

4. CONCLUSIONS

A detailed study on the impact resistance, density, and electrical conductivity of Al, Mo-doped copper-silicon alloy has been carried out experimentally. The effects of Al and Mo additions on the impact resistance, density, and electrical conductivity of Cu-3Si-3Al and Cu-3Si-3Mo were investigated. The Cu-3Si-3Al and Cu-3Si-3Mo alloys demonstrated excellent impact resistance. The Cu-3Si binary alloy initially recorded impact energy of 13.2 J. After adding Al, the impact energy increased to 14.2 J. The impact energy of Cu-3Si-Al ternary alloys was increased by 74.6% after undergoing solid solution treatment. The as-cast Cu-3Si-Mo alloy had lower impact resistance than the parent alloy but showed improved impact energy after solid solution strengthening; reaching 18.9 J.This change in impact resistance is attributed to increased solid solution of Al and Mo in the copper matrix. The density of the parent alloy (Cu-3Si) decreased when molybdenum (Mo) was incorporated, going from 8.21 g/cm^3 to 7.81 g/cm^3.After undergoing solid solution treatment, the density of Cu-3Si-Mo alloy decreased further to 7.6 g/cm3.The parent alloy (Cu-3Si) had better electrical conductivity compared to the ternary alloys.This difference in electrical conductivity was attributed to increased solid solution of Al and Mo in the copper matrix, which decreases the mobility of copper atoms.

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