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Microstructure, impact energy, density, and electrical properties of Cu-3Si alloy system doped with molybdenum

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Abstract: **The microstructure, impact energy, density, and electrical properties of Cu-3Si alloy system doped with molybdenum is investigated in this study. The influence of molybdenum contents on the surface morphology, physical, and electrical properties of Cu-3Si-xMo (x: 0.1-5 wt%) alloys was explored. The alloy compositions were designed using response surface optimal design (RSOD), melt, and cast using stir-casting technique. The fabricated Cu-3Si and Cu-3Si-xMo alloys were machined to required dimensions for impact energy, density, electrical resistivity, and conductivity. The microstructures of the developed alloys were analyzed using optical metallurgical microscope (OM). Results of the study showed that the Cu-3Si-Mo ternary alloy demonstrated excellent impact energy and density compared with the parent alloy. The Mo-doped Cu-Si alloy recorded lower electrical conductivity, indicating increased solid solution of molybdenum in the copper matrix as revealed by the microstructural images.The impact energy, density, and electrical properties of Cu-3Si-Mo alloy system decreased with increasing concentrations of molybdenum.**

Keywords: **Impact energy, electrical conductivity; resistivity; Cu-Si-Al alloy; density.**

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1. INTRODUCTION

Copper-based alloys are versatile materials that continue to play a vital role in various industries due to their unique combination of properties. Copper is renowned for its outstanding electrical conductivity, which is why it's widely used in wiring, cables, and electrical components. Efficient transmission of electrical power and signals is crucial in various industries, including electronics and telecommunications.Copper also possesses excellent thermal conductivity. This property is valuable in heat transfer equipment, making it suitable for applications like heat exchangers, radiators, and condenser tubes. Copper and its alloys are resistant to corrosion, making them suitable for applications in environments where corrosion is a concern. This includes water pipes and various components in the automotive and railway sectors (Xie et al., 2003; Qing et al., 2011; Yu et al., 2011; Jeong et al., 2009). Copper is highly ductile, so, can be easily formed into various shapes. This property is essential for fabricating components in industries like automotive, construction, and plumbing. Copper's ease of fabrication is a significant advantage, as it allows for efficient manufacturing processes in various industries(Yu et al., 2011; Jeong et al., 2009).

Cu-Be alloys are known for their high strength and electrical conductivity, but their limitations, such as toxicity and cost, have led to the exploration of alternative alloys like Cu-Ni-Si, Cu-Si, and Cu-Ti-Si. These alloys aim to maintain similar mechanical properties while mitigating the drawbacks of Cu-Be alloys. Research and development efforts in this area are ongoing, which may lead to further innovations in copper-based materials (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 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 β1-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 energy resistance is crucial. To address this limitation, the study aims to improve the impact energy and electrical conductivity of Cu-Si based alloys by introducing molybdenum. The primary objective of this research is to investigate the impact energy of Cu-Si-Mo ternary alloys, which is a novel approach in the context of these alloy systems. By introducing molybdenum into the Cu-Si alloy, we hope to achieve a balance between impact energy, density, and electrical conductivity, making these alloys more suitable for applications where impact resistance is essential.

2. EXPERIMENTAL PROCEDURE

For this experimental study, copper rods, molybdenum, and silicon powdersof percentage purity of 98.9%, 95.9%, 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 ^oC. 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. The Cu-3Si-xMo 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 (Δ45^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 Cu-3Si and Cu-3Si-xMo 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

The impact energy; density, electrical resistivity, and electrical conductivity of Mo-doped Cu-3Si alloys are presented in Figs. 1-4. The impact energy of the parent alloy (Cu-3Si) is shown to be13.2 J. Addition of molybdenum significantly increased the impact energy by 95.5%. The density of Cu-3Si was reduced from 8.21 g/cm^3 to 7.01 g/cm^3 by addition of 0.1 wt% molybdenum (Fig. 2). Fig. 4 showed that the Cu-3Si alloy recorded better electrical conductivity compared with the Mo-doped Cu-3Si alloy. This can be attributed to increased solid solution of molybdenum in the copper matrix. The impact energy and electrical conductivity of the Mo-doped Cu-3Si alloys decreased with increasing concentrations of molybdenum. The density of the Mo-doped Cu-3Si alloys increased with increasing concentrations of molybdenum.

Fig. 5 shows the microstructure analysis of the developed Cu-3Si and Cu-3Si-xMo alloys. Fig. 4a reveals evenely dispersed dendritiic grains in the copper matrix which are identified to be primary silicon and Cu_3Si intermetallic compounds. Figs. 5b, 5c, and 5d represent OM images of Cu-3Si-0.2Mo, Cu-3Si-1.5Mo, and Cu-3Si-5Moternary alloys. The imaged revealed adequate modification and refinement of the dendritic grains found in the parent alloy.This led to increased number of grain boundaries and dislocation density, leading to increase in the impact energy of the alloy. The OM image of Cu-3Si-5Al alloy reveals coarse grains in the copper matrix which can be attributed to the decrease in the impact energy of the alloy as shown in Fig. 1.

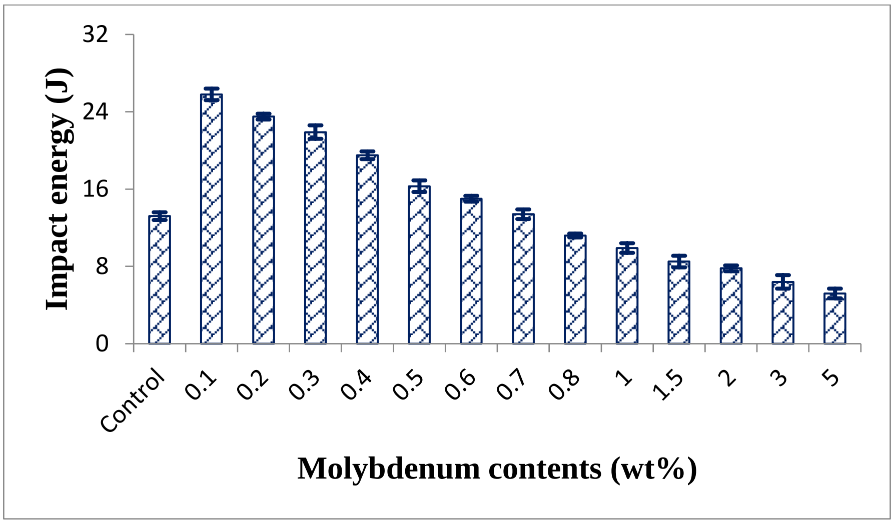

Fig. 1: Impact energy of Cu-3Si-xMo ternary alloys

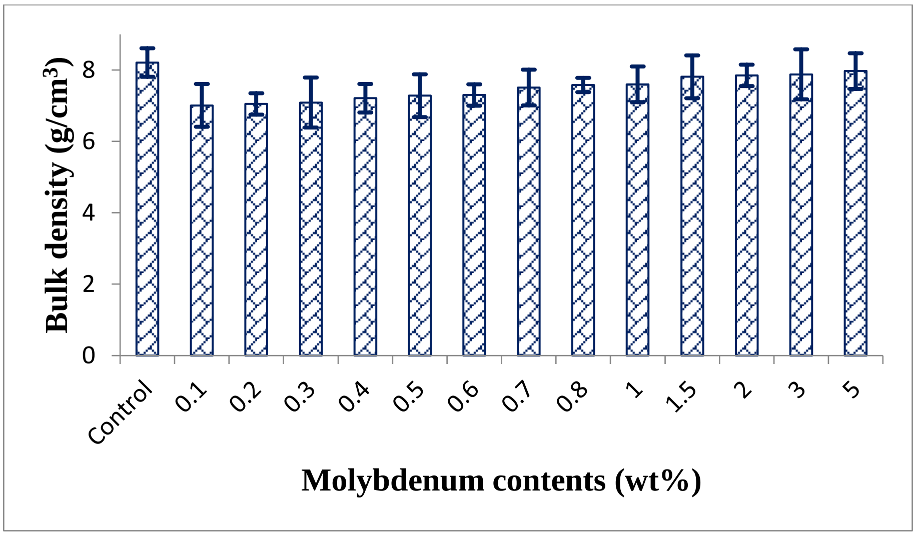

Fig. 2: Bulk density of Cu-3Si-xMo ternary alloys

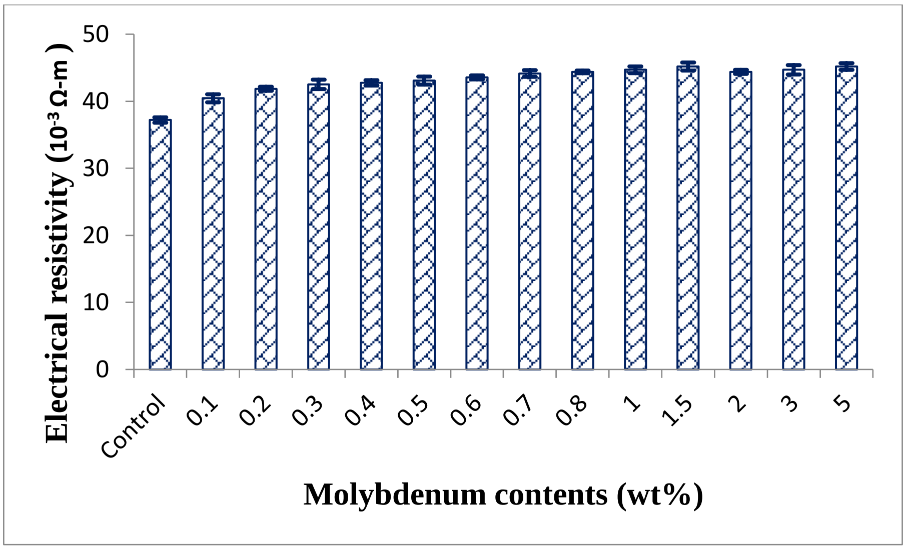

Fig. 3: Electrical resistivity of Cu-3Si-xMo ternary alloys

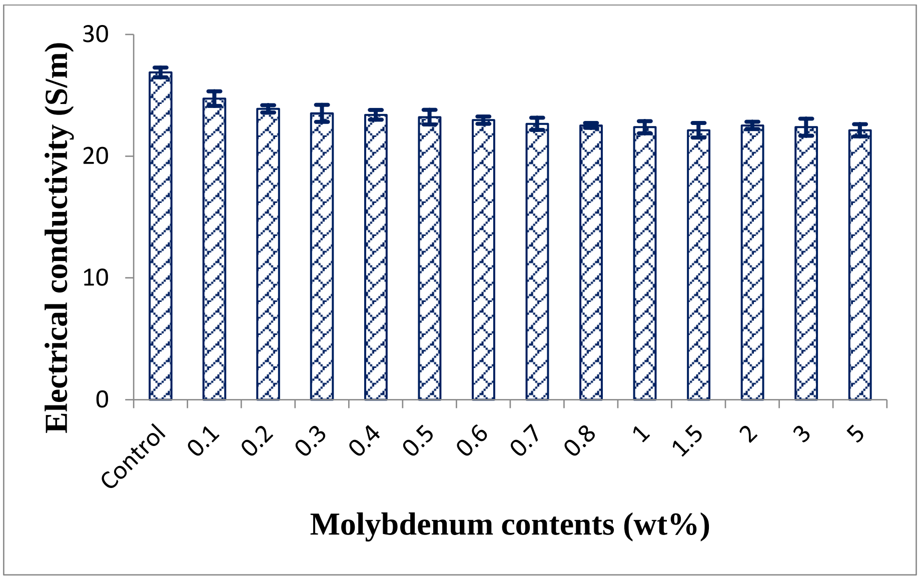

Fig. 4: Electrical conductivity of Cu-3Si-xMo ternary alloys

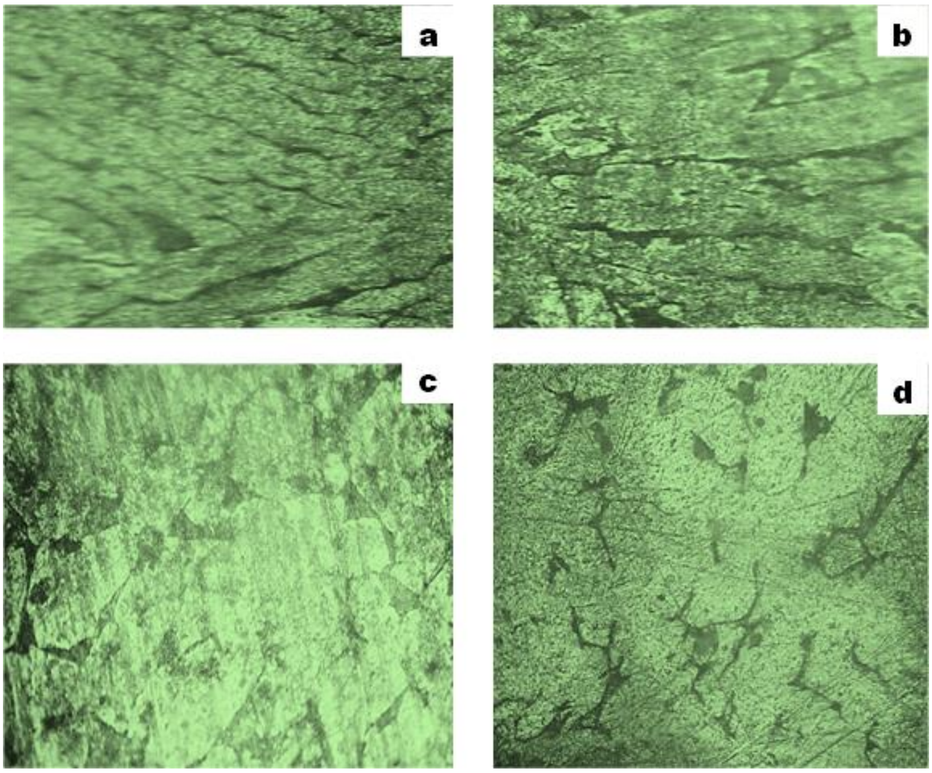

Fig. 5: OM microstructures of (a) Cu-3Si (b) Cu-3Si-0.2Mo (c) Cu-3Si-1.5Mo (d) Cu-3Si-5Mo alloys

4. CONCLUSIONS

The microstructure, impact energy, density, and electrical properties of Cu-3Si alloy system doped with molybdenum is investigated in this study. The influence of molybdenum contents on the surface morphology, physical, and electrical properties of Cu-3Si-xMo (x: 0.1-5 wt%) alloys was explored. The following conclusion can be drawn from the results of the study:

1. Addition of molybdenum to Cu-3Si alloy significantly increased the impact strength of the alloy by 95.5%.

2. The density of Cu-3Si was reduced from 8.21 g/cm^3 to 7.01 g/cm^3 by addition of 0.1 wt% molybdenum.

3. The Cu-3Si alloy recorded better electrical conductivity compared with the Mo-doped Cu-3Si alloy. This was attributed to increased solid solution of molybdenum in the copper matrix.

4. The impact energy and electrical conductivity of the Mo-doped Cu-3Si alloys decreased with increasing concentrations of molybdenum.

5. The density of the Mo-doped Cu-3Si alloys increased with increasing concentrations of molybdenum.

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