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Experimental study of microstructure, impact energy, physical, and electrical properties of Al-doped Cu-3Si-Al ternary alloy

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Abstract: **This research explored the microstructure, impact energy, density, and electrical properties of Al-doped Cu-3Si-Al ternary alloys. The Cu-3Si-xAl (x: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 1.5, 2, 3, 5 wt%) alloys were prepared via stir-casting method. The effects of aluminium contents on the impact energy, density, electrical conductivity and resistivity of Cu-3Si were investigated. The microstructures of the developed alloys were analyzed using optical metallurgical microscope (OM). Results of the study showed that the addition of aluminium increased both the impact energy and electrical conductivity of Cu-3Si alloy, recording maximum values of 39 J and 34.21 S/m. The density of the parent alloy (Cu-3Si) increased from 8.21 g/cm^3 to 8.4 g/cm^3, after adding 0.1 wt% aluminium.**

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

1. INTRODUCTION

Copper and its alloys are versatile materials with a wide range of industrial applications, owing to their exceptional combination of properties, including electrical conductivity, thermal conductivity, corrosion resistance, ductility, and ease of fabrication. Their excellent electrical conductivity makes them ideal for use in wiring, cables, and various electrical components (Xie et al., 2003; Qing et al., 2011; Yu et al., 2011; Jeong et al., 2009). They ensure efficient transmission of electrical power and signals. Copper-based alloys are employed in the automotive sector for various applications such as building components, electrical parts, valves, and fittings. The combination of properties, including corrosion resistance, ductility, and good thermal conductivity, makes them valuable in this industry. Copper and its alloys find application in railway systems, including locomotive fireboxes and electrical components(Yu et al., 2011; Jeong et al., 2009). Their non-magnetic nature is advantageous in certain railway applications. Their excellent corrosion resistance and ease of fabrication makes them potential materials for water pipes, heat transfer equipment, and condenser tubes. Additionally, its excellent thermal conductivity makes it suitable for heat transfer equipment.

Cu-Be alloys are renowned for their high strength and excellent electrical conductivity. However, their use is limited by the toxicity and high cost associated with beryllium. Cu-Ni-Si alloys have emerged as potential alternatives due to their high strength, lower cost, and ease of fabrication. These alloys can offer similar mechanical properties while avoiding the drawbacks of beryllium.Efforts to develop alternative alloys like Cu-Si and Cu-N-Si aim to maintain these properties while addressing issues such as toxicity and cost(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 ongoing research and development in this field will likely continue to drive innovation in the use of copper-based materials across various industries.

Earlier studies have reported the high strength and electrical conductivity of Cu-Ni-Si alloys via different processing techniques such as alloying, thermo-mechanical treatments, and precipitation hardening. According to the studies the excellent mechanical and electrical properties of the alloys are attributed to specific phases, such as β1-Ni_3Si, α-Cu (Ni,Si), γ′-Ni_3Al, β-Ni_3Si, and δ-Ni_2Si (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). Studies by 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), and Wang et al (2014) recorded maximum electrical conductivity, tensile strength, hardness, and ductility in the range 25.2-48.2%IACS, 704-2700MPa, 270-381 HV, 2.75-14%, respectively. From these studies, it is shown that the ductility of the alloy is very low, hence could limit their application where impact energy is most essential. For the first time the impact energy of Cu-Si-Al ternary alloys is investigated. So, this study is aimed at improving the impact energy and electrical conductivity of Cu-Si based alloy via addition of aluminium.

2. EXPERIMENTAL PROCEDURE

For this experimental study, copper rods, aluminium wire, and silicon powder of percentage purity of 98.9%, 98.7%, 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-xAl 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-xAl 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

Figs. 1-4 show the variations of impact energy; density, electrical resistivity, and electrical conductivity of Cu-3Si-Al ternary alloys with increasing concentrations of aluminium. The Cu-3Si binary alloy recorded impact energy of 13.2 J. The impact energy increased from 13.2 J to 39 J after adding 0.1wt% Al. The impact energy of Cu-3Si-Al ternary alloys shows a decreasing trend with increasing concentrations of aluminium. This behavior can be attributed to increased grains refinement and solid solution strengthening. Analysis of Fig. 2 shows that the parent alloy (Cu-3Si) is lighter than the Al-doped Cu-3Si alloy system, having recorded lower density value. The density of Cu-3Si alloy increased slightly after the addition of 0.1wtAl. After adding 0.1wt%, the density was increased by 2.31%. Further increase in aluminium contents in the Cu-3Si-Al alloy system, the density increased correspondingly with increasing aluminium contents. Figs. 3 and 4 showed that the parent alloy recorded electrical resistivity and conductivity values of 37.2 $x10^{-3}$ Ω-mand 26.88 S/m, respectively. The electrical conductivity increased from 26.88 S/m to 34.21 S/m, after adding 0.1 wt% Al. The electrical conductivity decreased with increasing concentrations of aluminium.

The microstructure analysis of the developed Cu-3Si and Cu-3Si-xAl alloys are presented in Fig. 5. Fig. 5a reveals dendritiic grains evenly dispersed in the copper matrix. These grains are likely to be primary silicon and Cu_3Si intermetallic compounds. Fig. 5b, 5c, and 5d show the microstructures of Cu-3Si-0.2Al, Cu-3Si-3Al, and Cu-3Si-5Al alloys. The dendritic grains are found to be modified and refined after aluminium addition. Fig. 5b, 5c show well-dispersed fine grains in the alloy structure. The fine grains led to an 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. This grain morphology could be associated wit the decrease in the impact energy of the alloy.

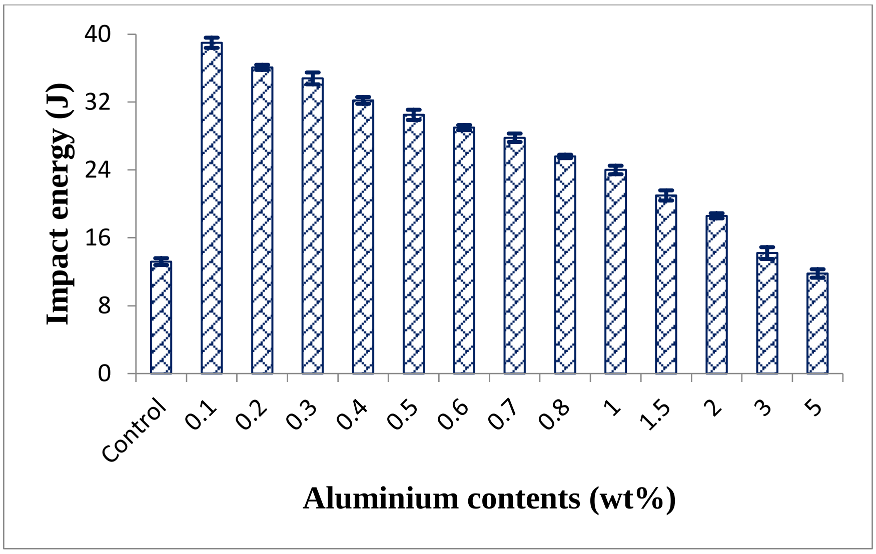

Fig. 1: Variations of impact energy of Cu-3Si-xAl ternary alloys with aluminium contents

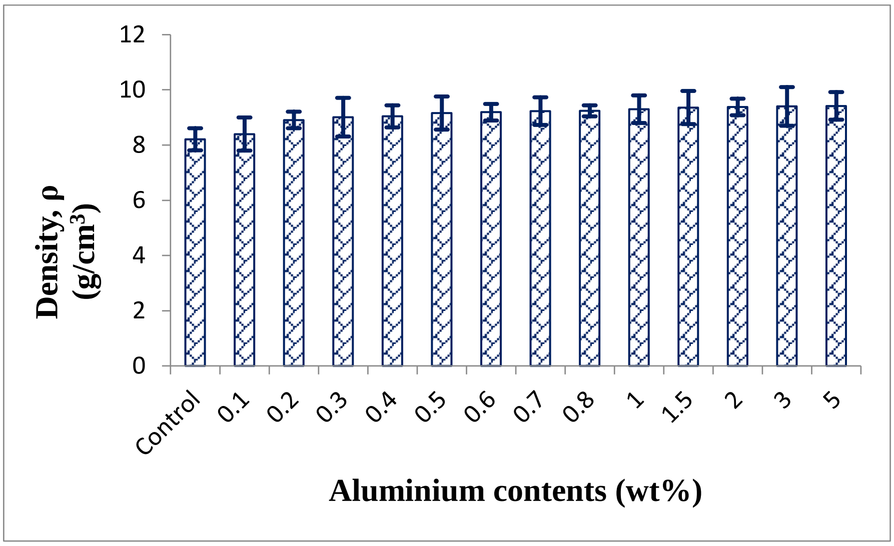

Fig. 2: Variations of density of Cu-3Si-xAl ternary alloys with aluminium contents

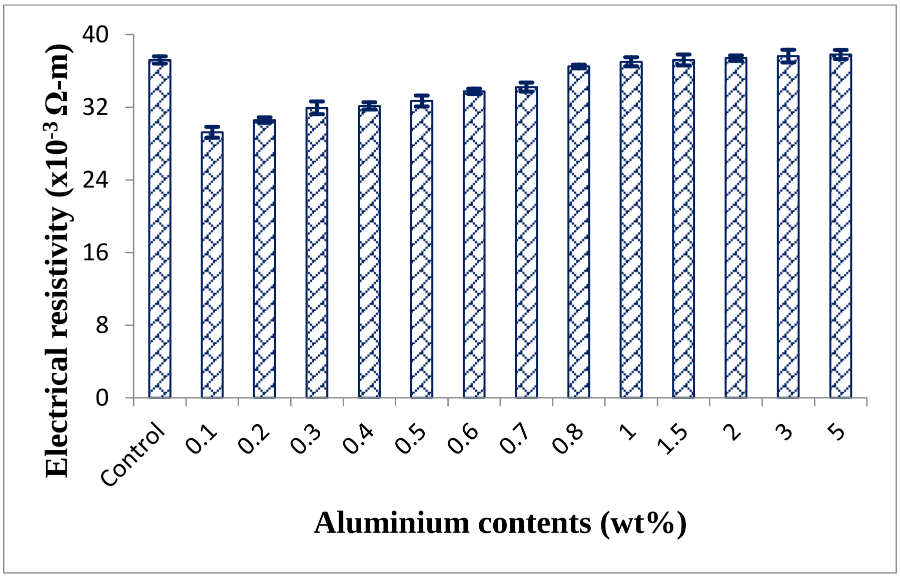

Fig. 3: Variations of electrical resistivity of Cu-3Si-xAl ternary alloys with aluminium contents

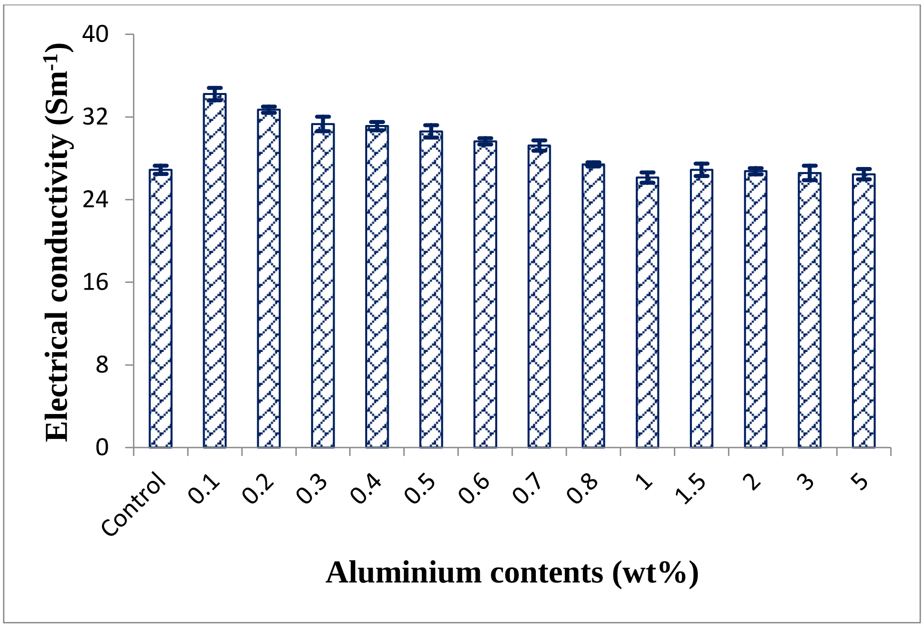

Fig. 4: Variations of electrical conductivity of Cu-3Si-xAl ternary alloys with aluminium contents

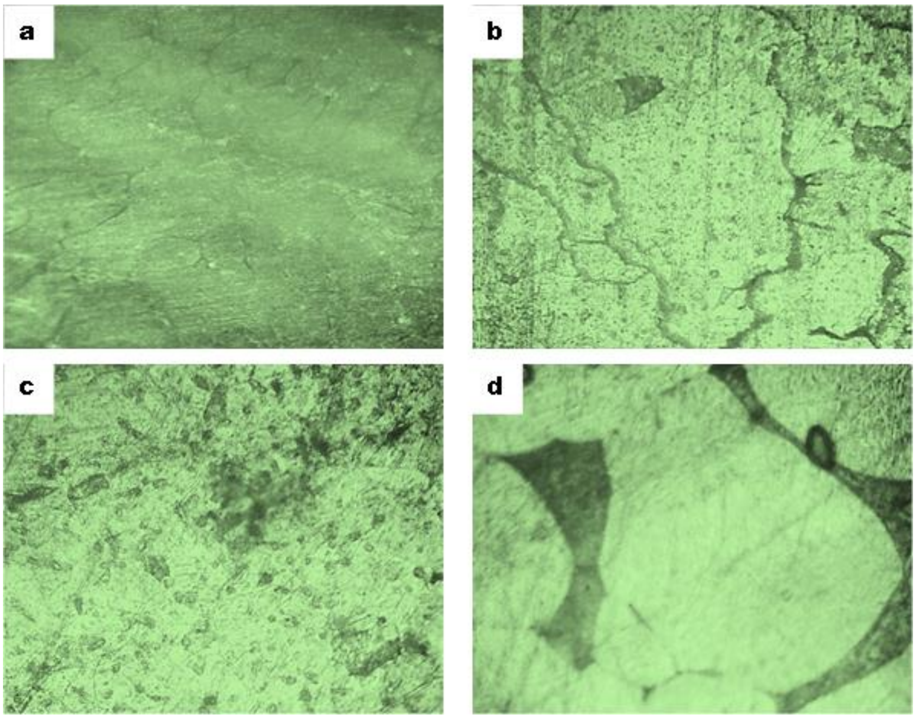

Fig. 5: OM microstructures of (a) Cu-3Si (b) Cu-3Si-0.2Al (c) Cu-3Si-3Al (d) Cu-3Si-5Al alloys

4. CONCLUSIONS

This present study explored the microstructure, impact energy, physical, and electrical properties of Al-doped Cu-3Si-Al ternary alloy.The effects of aluminium contents on the microstructure, impact energy, density, and electrical conductivity were investigated. Results of the study showed that addition of aluminium to Cu-3Si alloy significantly improved the impact energy and electrical conductivity of Cu-3Si alloy. The impact energy and electrical conductivity decreased with increasing concentrations of aluminium in the Cu-3Si-Al alloys. The density of the parent alloy increased slightly after adding aluminium. Maximum impact energy and electrical conductivity values of 39 J and 34.21 S/m respectively were obtained by Cu-3Si0.1Al alloy. The developed Cu-3Si alloy recorded low density of 8.21 g/cm^3. 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.

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