UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES (UJEAS)

Research Article

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Special Issue
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This themed issue honors Professor Ekedimogu Eugene Nnuka, celebrating his distinguished career upon his retirement. His legacy of exemplary scholarship, mentorship, and commitment to advancing knowledge is commemorated in this collection of works.

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UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 3(2), June (2024), 691-698
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Effect of Bismuth and Lead on the Mechanical Properties of Aluminium-4%Copper Alloy

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Abstract

This study investigated the effect of Bismuth and Lead on the mechanical properties of aluminium-4wt% copper alloy. The doping elements were added in amounts of 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0%, 3.5%, and 4.0% by weight, mixed, and cast using gravity die casting method. The samples were then machined. Percentage elongation, ultimate tensile strength, hardness, and impact strength of the developed alloys were determined for each specimen. The microstructure of the samples was also studied using metallurgical microscope. Results obtained from the research showed that bismuth and lead improved percentage elongation of the alloy significantly. The highest value was achieved at 4.0wt% bismuth, followed by 4.0wt% lead. These values were 15.9% and 15.1% for bismuth and lead respectively; a very significant improvement beyond the 10.0% elongation observed from the control specimen (Al-4%Cu). Such specific data was not seen in available literatures as at the time of carrying out this study. The hardness values and Impact strength of the alloys doped with lead and bismuth significantly reduced as the percentage weight of the dopants increased, while a relatively slight decrease in tensile strength was observed. It was also observed that beyond 2.0wt% Bi, there was a significant drop in the strength and hardness of the alloy, which is not good for engineering applications. Results from this research also show that bismuth would be a better, and more environmentally friendly, substitute to lead when improved machinability, weldability, or workability of Al-4wt%Cu alloy is desired.

Keywords: phase, dopants, grain size, concentration, microstructure, elongation, tensile and impact strength.

1. Introduction

Aluminium alloys acquired increasing significance due to their high technological values and versed applications, especially in aerospace industries (Stojanovic et al. 2018). Its strength, low density, relative formability, and corrosion resistance makes the alloys highly suitable for a number of engineering uses (Ozen et al. 2017). Aluminum alloys are highly economical in various applications, as stated by D Feron (2017). These intermetallic materials, which are formed by combining two or more elements in a homogeneous composition, offer significant advantages over pure metals (French 2018; Nwambu et al. 2024). Aluminium alloys possess higher heterogeneous microstructures than many other alloys (Cavanaugh et al. 2014; Anyafulu et al. 2024).

It has been observed that the production of complex alloys that cannot be forged involves extensive machining. Lead and bismuth help reduce the dimension of the chips produced during machining, thereby increasing productivity (Pilote et al. 2018). However, reduction of lead levels, or totally replacing it with another dopant, is necessary in machining alloys, due to strong regulations on its use in materials. Studies in the area of machining alloys show that bismuth produces the desired reduced chip-length, and is more environmentally friendly than lead (Bale et al. 2016; Onyia et al. 2024).

Research shows that Al-4wt%Cu alloy exhibits moderate strength as a result of brittle nature of the intermetallic compound (Al_2Cu) formed as precipitates when the alloy cools slowly to room temperature (Udoh and Iffiok, 2017). Strengthening of the alloy in non-heat-treatable alloys is as a result of solid solution formation, second phase microstructure and dispersion of the precipitates.

A study by Nwaokafor et al. (2020) reveals an increase in the hardness, tensile strength, toughness, with a consequent decrease in ductility of aluminum-copper alloy as the concentration of copper in the alloy matrix increases. The copper in aluminum significantly reduced its percentage elongation and corrosion resistance. The increase in hardness and tensile strength was observed to be due to the interaction of the stress field around the particles with a moving dislocation, as well as physical obstruction by the hard particles to the moving dislocation. This also increases the susceptibility of the alloy to solidification cracking; thereby reducing the weldability of aluminium-copper alloy (Mehdi et al. 2015, Okelekwe et al 2024).

Review of related literatures has also shown that, while there are general statements on the effect of Bismuth and Lead on the ductility of Aluminum alloys, specific data on their effects on Al-4wt%Cu alloy were not available at the point of this study. Also, the effect of doping Al-4wt%Cu alloy with 0.5-4.0wt% Bismuth and Lead on other mechanical properties of the alloy was not available on public domains as at the time of carrying out this study. Hence, this paper focuses on the effect of doping Al-4wt%Cu alloy on the ductility, tensile strength, hardness, and toughness of the alloy, with the specific goal of improving the ductility of the alloy. This would abate the adverse effect of copper on the weldability, machinability and workability of the alloy. The scope of this study was narrowed to the effect of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0%wt of bismuth and lead in Al-4%Cu alloy, based on the fact that the solubility of both dopants in aluminium is small (Bale et al. 2016). The extent to which each concentration of the dopants influenced the ductility of Al-4wt%Cu alloy was studied and the concentration that gave optimal ductility (within the scope of the study) was established.

2.0 Material and methods

2.1 Materials

Pure aluminum ingots and pure copper wires were used as the base metals in this research. Varying percentage weights of bismuth and lead were used as the dopants. The weight of each material adopted for the study was calculated using weight percent calculation. Measurements were taken by the use of electronic compact scale (Model: BL 20001). Other materials used in this research include aluminium oxide powder (for polishing) and solution of 10g of $FeCl_3$, 30cm^3 of Hydrogen Chloride and 120cm^3 of water (for etching).

Equipment used in this study include a bailout crucible furnace, electronic scale (Model: BL 20001), lathe machine, silicon carbide papers, ZMAK-GA5030/2 electric grinder, as well as a heat gun machine (Bosch GHG660LCD). The tests were conducted using JPL130812 tensile strength tester, hardness tester equipped with 20X optical microscope (digital phase II 900-355), U1820 digital impact strength tester, L2003A optical microscope, Carl Zeiss scanning electron microscope, and EDAX energy dispersive x-ray spectroscopy.

2.2 Method

The pure aluminium was melted in a bailout crucible furnace, followed by the dissolution of the copper powder in the aluminium melt. Bismuth and lead, respectively, were added in percentage weights of 0.5 to 4.0 (0.5wt% intervals), mixed, and then cast via gravity die casting method. The specimens were then machined to standard dimensions for the various mechanical tests (BS EN ISO 6892- 1:2016, BS EN ISO 6505-1:2014, and BS EN ISO 148-1:2016 for tensile strength, hardness and impact strength, respectively). The specimens for microstructure examination were grinded using different grades of emery paper (230, 240, 400 and 600 grits respectively), polished using aluminium oxide, and etched in Keller's reagent. They were further rinsed in water and dried by the use of METASER specimen dryer.

3.0 Results and Discussions

3.1 Mechanical Properties of the Doped Al-4wt%Cu

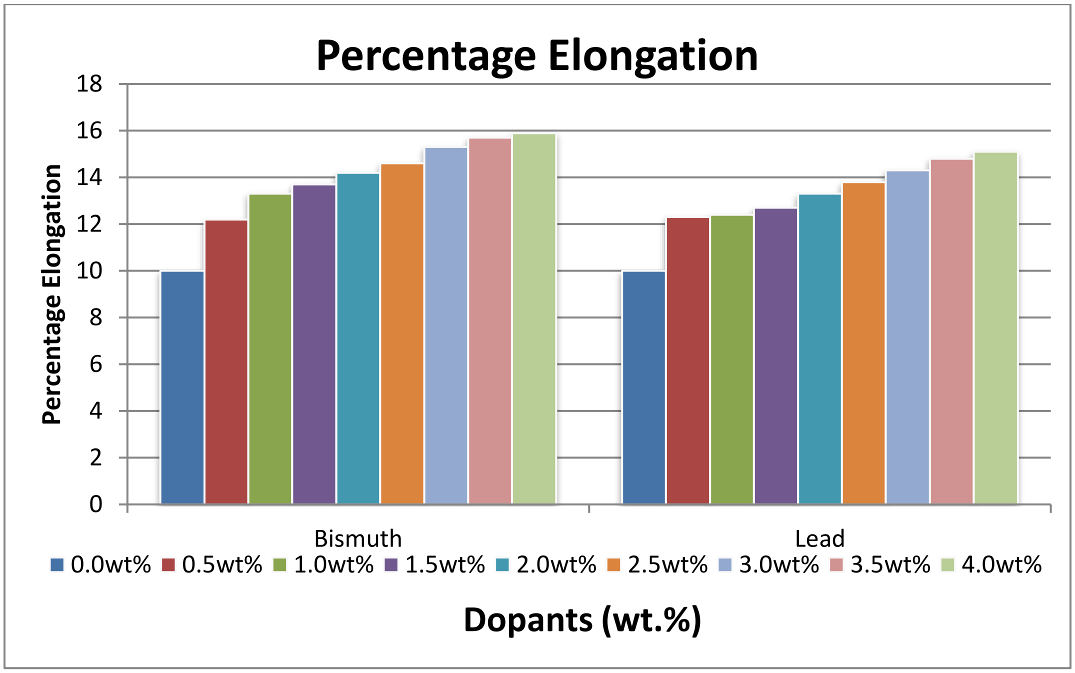

Figure I: Effect of bismuth and lead on percentage elongation of Al-4wt%Cu

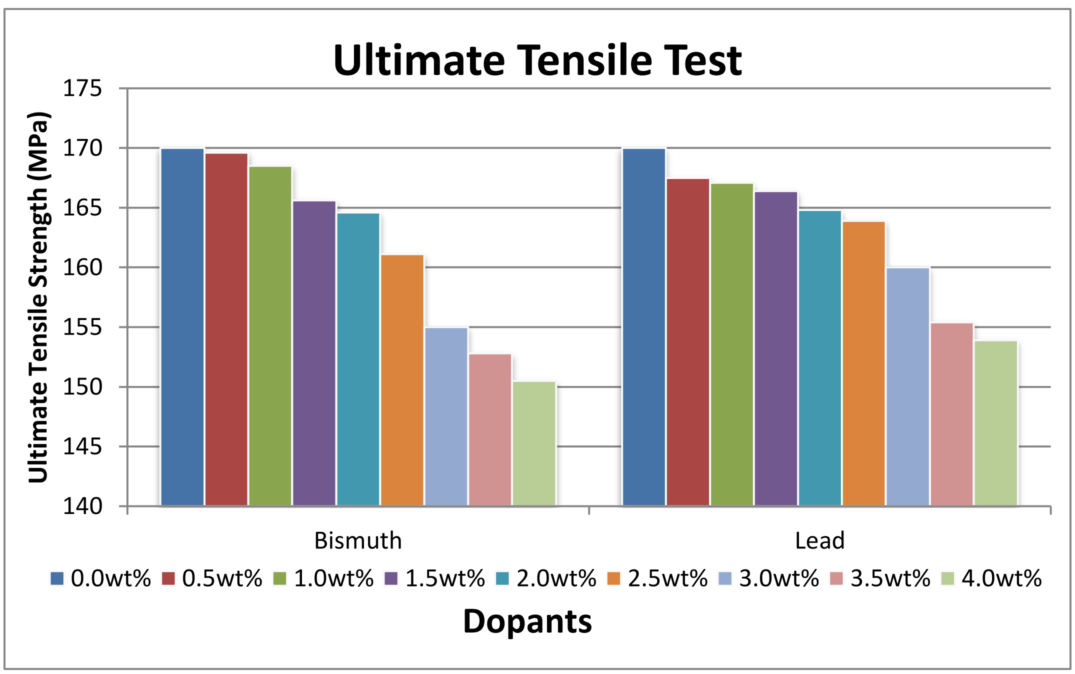

Figure 2: Effect of bismuth and lead on Ultimate Tensile Test of Al-4wt%Cu

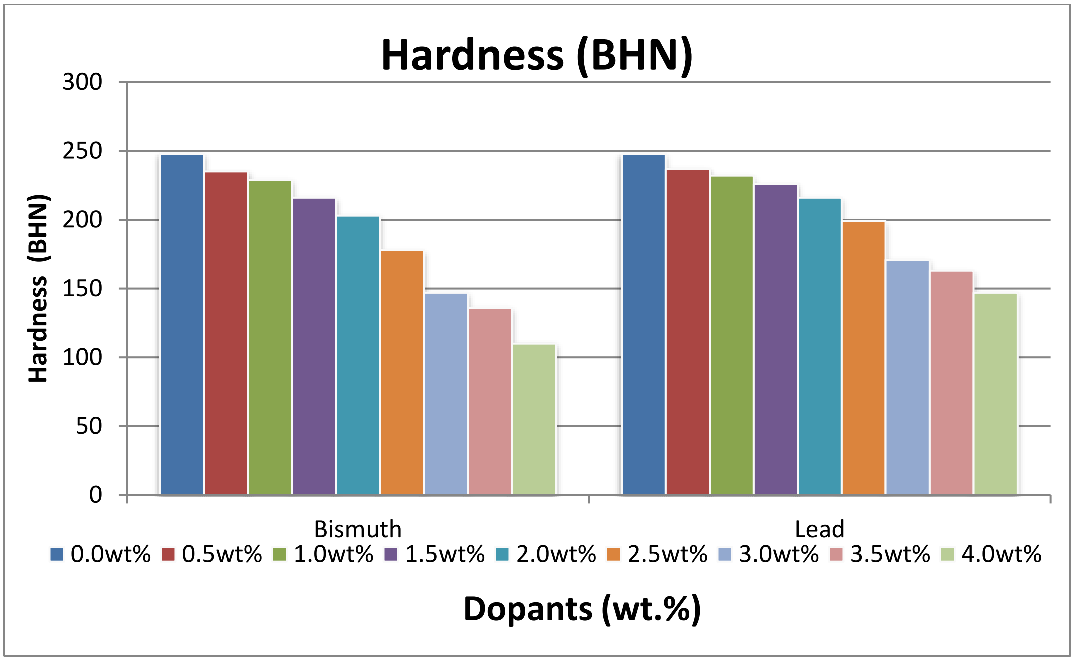

Figure 3: Effect of bismuth and lead on Hardness (BHN) of Al-4wt%Cu

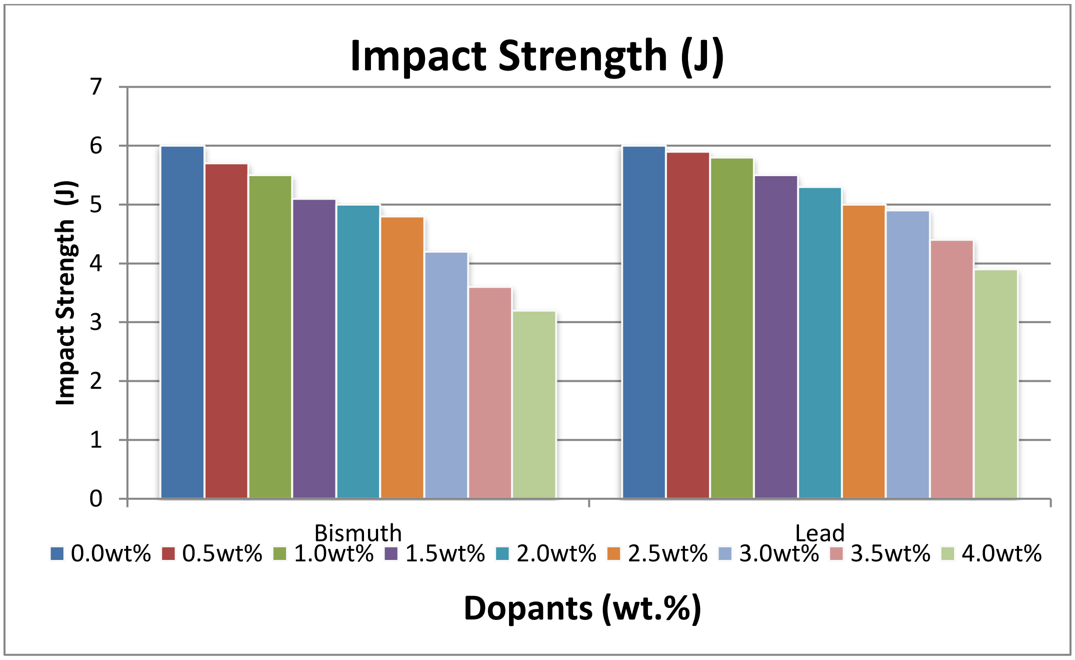

Figure 4: Effect of bismuth and lead on Impact Strength (J) of Al-4wt%Cu

The effect of addition of bismuth and lead on the ductility (%elongation), tensile strength, hardness, and impact strength of aluminium-4wt%copper alloy are presented on Figures 1 to 4. From the results, it was observed that values of the mechanical properties of aluminium-4%copper alloy were significantly affected by the dopants. Bismuth, being a low melting point metal with small solid solubility in aluminium, negatively affected the strength of the base alloy. Doping with lead slightly reduced the ultimate tensile strength (UTS). The solid solubility of lead in aluminium is small (about 0.2%), hence the slight reduction in the strength of the alloy.

Findings from the research show that bismuth and lead improved percentage elongation of the alloy significantly, thereby improving its machinability. The highest value was achieved at 4.0wt% bismuth, followed by 4.0wt% lead.

These values were 15.9% and 15.1% for bismuth and lead respectively, which are higher than the 10.0% elongation obtained from the control alloy (Al-4wt%Cu). The hardness values of the alloys doped with lead and bismuth significantly reduced as the percentage weight of the dopants increased. This is due to the formation of a soft and low melting s-phase. When found with lead in the base alloy, bismuth forms small inclusions ($AlCu_6BiPb$) that melt at low temperature. It was also observed that beyond 2.0wt% Bi, there was a significant drop in the strength and hardness of the alloy, which is not good for engineering applications.

It is a common fact that the optimal means to ease machining is to allow a certain amount of these breaking agents to separate out from aluminum, thereby promoting a liquid phase and also weakening the bond between grains when the machining processes increase the temperature locally (Pilote et al. 2018).

3.2 Micrographs of the Doped Al-4wt%Cu

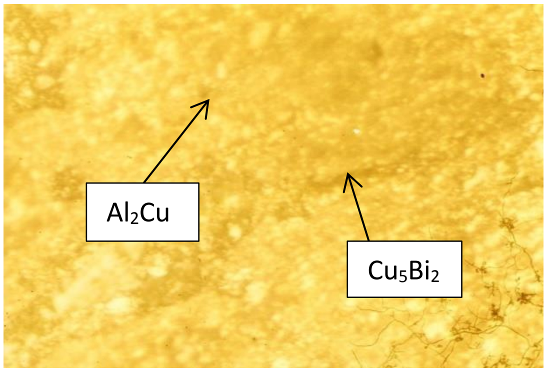

Figure 5 Al-4%Cu-0.5%Bi alloy

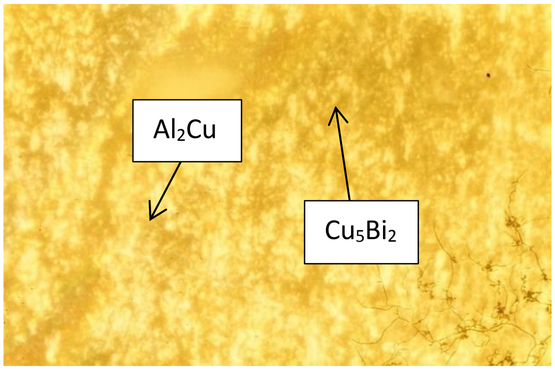

Figure 6 Al-4%Cu-1.0%Bi alloy

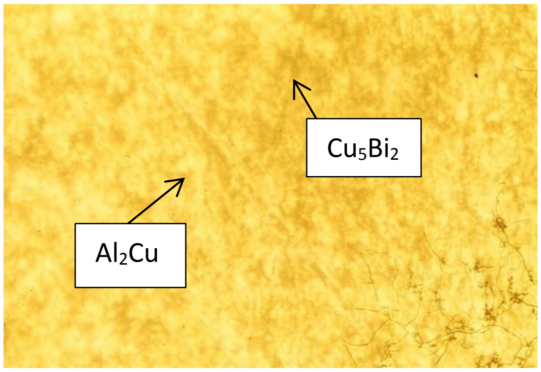

Figure 7 Al-4%Cu-1.5%Bi alloy

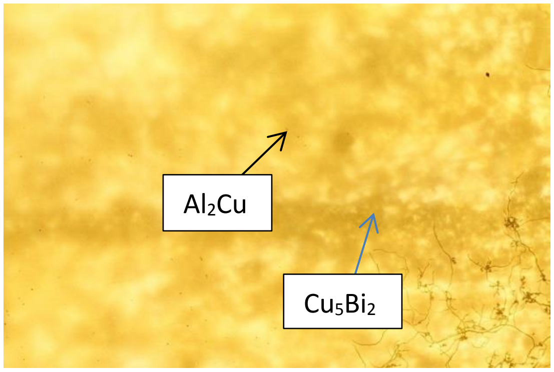

Figure 8 Al-4%Cu-2.0%Bi alloy

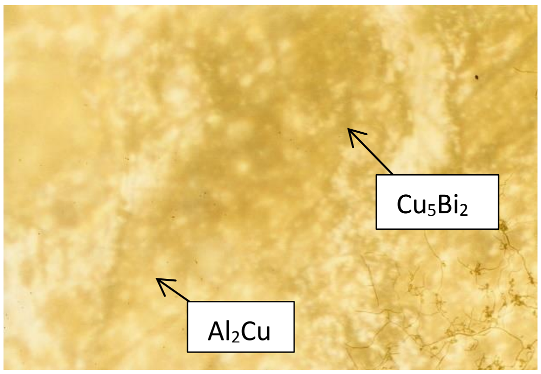

Figure 9 Al-4%Cu-2.5%Bi alloy

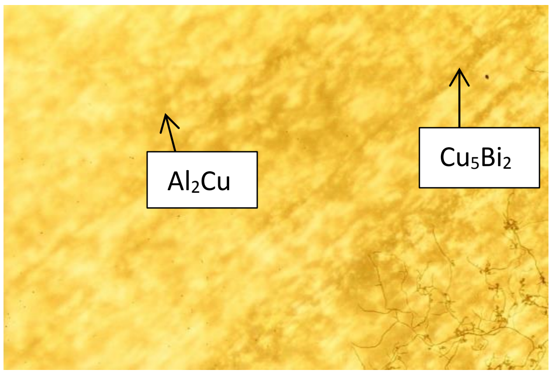

Figure 10 Al-4%Cu-3.0%Bi alloy

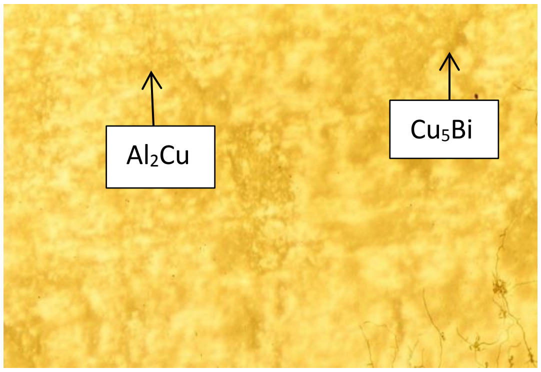

Figure 11 Al-4%Cu-3.5%Bi alloy

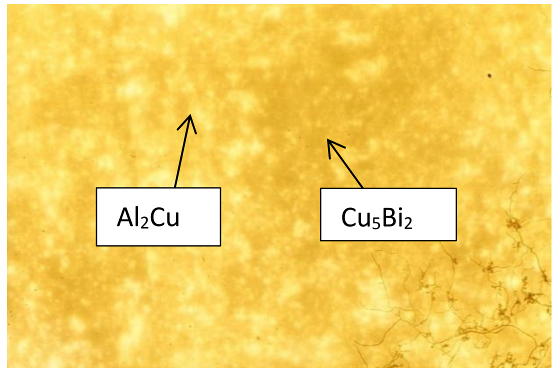

Figure 12 Al-4%Cu-4.0%Bi alloy

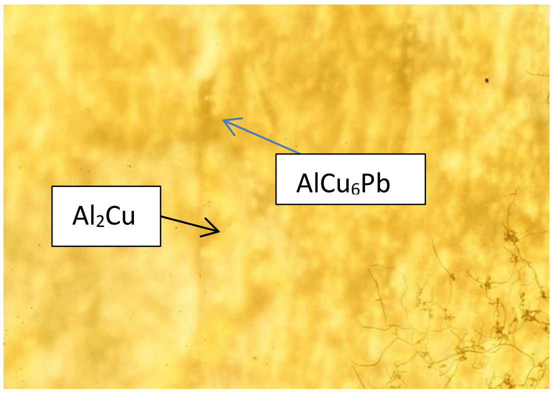

Figure 13 Al-4%Cu-0.5%Pb alloy

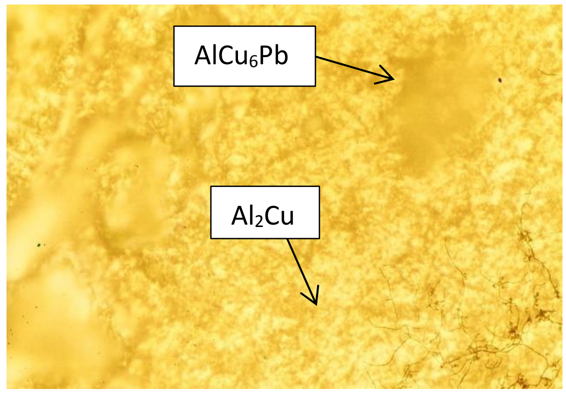

Figure 14 Al-4%Cu-1.0%Pb alloy

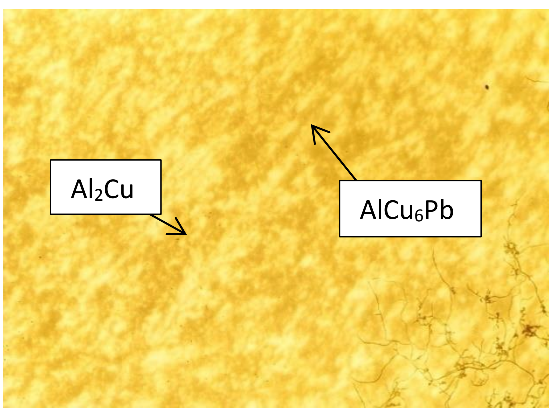

Figure 15 Al-4%Cu-1.5%Pb alloy

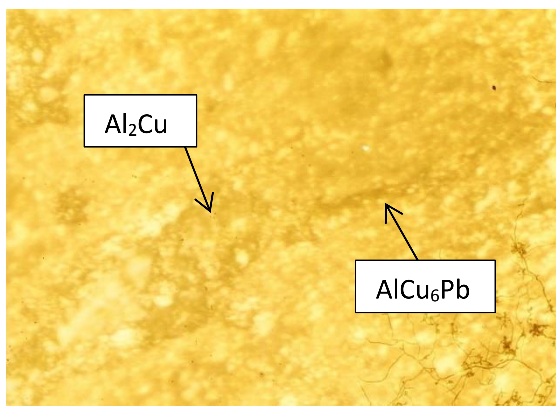

Figure 16 Al-4%Cu-2.0%Pb alloy

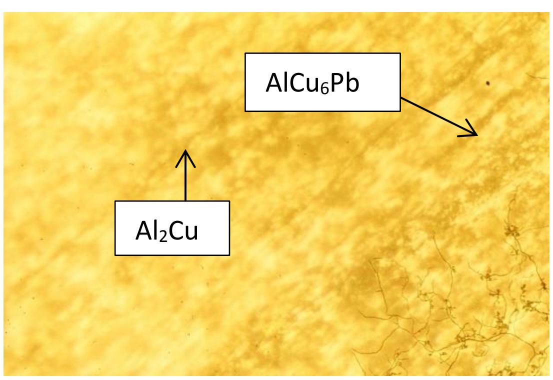

Figure 17 Al-4%Cu-2.5%Pb alloy

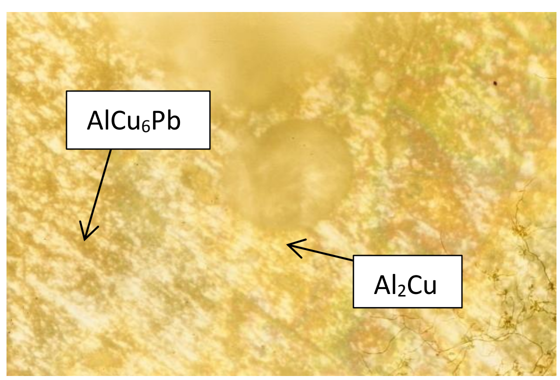

Figure 18 Al-4%Cu-3.0%Pb alloy

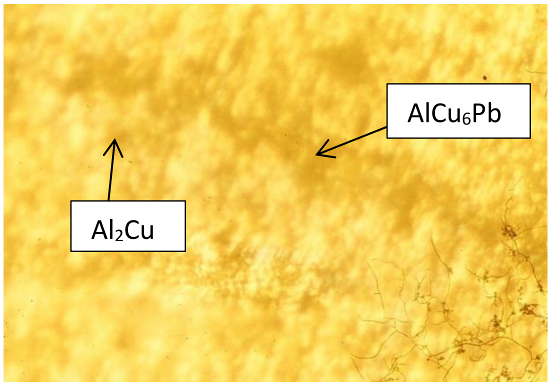

Figure 19 Al-4%Cu-3.5%Pb alloy

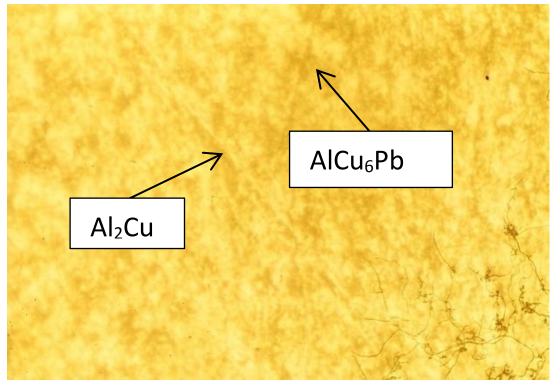

Figure 20 Al-4%Cu-4.0%Pb alloy

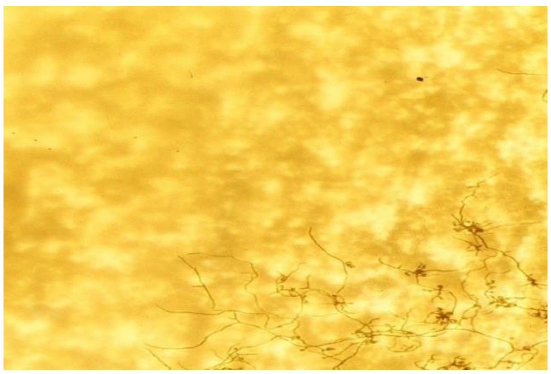
Figure 21 Al-4%Cu alloy (x400)

Microstructural examinations of the produced alloys show that Bismuth forms a soft and low melting s-phase (Cu_5Bi_2) and also expanded on solidification. The micrographs also show that Lead shrinks on solidification.

5.0 Conclusion

This study on the effect of bismuth and lead on the mechanical properties of Al-4%Cu alloy has established that when Al-4wt%Cu is doped with 0.5 to 4.0wt% bismuth and lead, percentage elongation of the alloy increased significantly. The highest value was achieved at 4.0wt% bismuth, followed by 4.0wt% lead. These values were 15.9% and 15.1% elongation for bismuth and lead respectively; a very significant improvement beyond the 10.0% elongation observed from the control specimen (Al-4%Cu). The hardness values and Impact strength of the alloys doped with lead and bismuth significantly reduced as the percentage weight of the dopants increased, while a relatively slight decrease in tensile strength was observed. It was also observed that beyond 2.0wt% Bi, there was a significant drop in the strength and hardness of the alloy, which is not good for engineering applications. This study shows bismuth is a better, and more environmentally friendly, substitute to lead in improving the machinability, weldability and workability of Al-4wt%Cu alloy.

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