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N.M. Okelekwe, C.N. Nwambu, E.E. Nnuka

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Influence of chromium addition on the microstructural and mechanical properties of copper-magnesium alloys

N.M. Okelekwe[1,2], C.N. Nwambu[2*], E.E. Nnuka[2]

[1]National Board of Technical Education (NBTE), Kaduna, Nigeria

[2]Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria

[*]Corresponding Author's E-mail: cn.nwambu@unizik.edu.ng

Abstract
The study investigated the influence of trace additions of chromium on grain characteristics, electrical conductivity, and mechanical properties of Cu-4wt%Mg alloys. The experimental alloys were produced with various chromium concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0% by weight using the permanent mold casting technique. Tensile, hardness, impact, and conductivity tests were carried out on the cast samples. Microstructures of the specimens were also analyzed using optical microscopy. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses were used to characterize the cast specimens. The results showed that adding chromium to Cu-4wt%Mg alloy refined and modified the structure of the alloy, resulting in improvements in the ultimate tensile strength, hardness, and conductivity of the experimental alloy by 31.0%, 33.2%, and 24.7%, respectively, at 0.9wt% Cr content, and percentage elongation, impact strength, and electrical conductivity by 13.48%, 131J, and 32.3Sm-1, respectively, at 0.1wt%Cr content. The addition of chromium also led to the formation of the intermetallic phase which further contributed to the increase in strength and hardness of the alloy.

Keywords: Copper, magnesium, mechanical properties, scanning electron microscope, phase.

1. Introduction

Non-ferrous metals have become so important in recent years that no technological development would be possible without them. Non-ferrous metals such as copper and its alloys are among the most commercially important metals because of their relatively good properties, ease of manufacture and numerous applications. They are normally exploited because of their good electrical and thermal conductivity, outstanding resistance to corrosion and ease of fabrication. Copper alloys are generally non-magnetic with medium values of strength and fatigue resistance (Anene et al., 2015; Onyia et al., 2024).

Structural applications are mostly based on ferrous materials, steels in particular (Nnuka, 1991) but findings have shown that copper alloys (bronzes) are fast replacing contemporary steel materials for some specific applications especially in components for marine/subsea applications (Nwambu et al. 2017). Magnesium bronze is a copper-based alloy containing magnesium as the major alloying element usually in the range of 3-5wt% (Mattern et al., 2007). Copper-magnesium is a solid solution alloy providing high strength with nominal reduction in conductivity relative to copper. It also improves fluidity and gives excellent welding qualities to Cu-Mg alloys (Ketut et al., 2011). Copper is a dense, orange-tinged metal which conducts electricity, while magnesium is a light, silvery metal that is far more reactive than copper. They are commonly formed to create wires and cables for a wide range of industries. The corrosion resistance, strength, and formability of magnesium bronze allow for their use in a wide range of applications, including electrical conduit, valve stems, tie rods, fasteners, nuts, bolts, screws, rivets, and wires (Kulczyk et al., 2012). The excellent mechanical and functional properties of copper and its alloys have made it attractive to industries for use in various fields of engineering applications (Nwambu et al. 2017; Nwaeju et al. 2023; Okelekwe et al. 2024).

Recent studies reported that modification of copper-based alloys with additives with subsequent aging heat treatment has been found to yield good mechanical properties and electrical conductivity (Shankar & Sellamuthu, 2017; Kim et al., 1999; Plewes, 1975; Cribb et al., 2013; Cribb & Grensing, 2011; Rhu et al., 1999). Therefore, some previous researchers, (Xiangyang et al., 2009 and Pandey, 2006) reported that copper-magnesium alloy alone is not sufficient for high-rate of physical and mechanical performance mostly in an aggressive corrosive environment, especially in salt seawater. It was reported that failure occurs with the components of binary Cu-Mg alloy within a longer period such as 2000-3000 hours of service. In order to guarantee the anticipated service life, the addition of other alloying elements at certain percentage compositions has been recommended and will be investigated in this research. This work will report the effect of chromium addition on the physic-mechanical properties of Cu-4wt%Mg alloys.

2.0 Material and methods

2.1 Materials

The base alloy for this study was produced from commercial pure copper (99.99%) and commercial pure chromium (99.98%). The doped magnesium bronze was produced by the addition of chromium in concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0% by weight using the permanent mould casting technique. A bailout crucible furnace was used for the melting process. For the production of the control alloy cast samples, the required amounts of pure copper in the form of copper wire were first charged into the preheated furnace and melted. A pre-determined amount of magnesium in powder form wrapped in aluminum foil was added to the molten copper and stirred. The melt was held for about 10 minutes to ensure complete dissolution of magnesium in the copper melt and stirred again to achieve homogeneity before pouring into preheated permanent mould and being allowed to cool to ambient temperature (Onyia et al. 2023). Subsequently, the Cu-4wt%Mg alloys with the additives were produced by repeating the above-described procedure and introducing the different concentrations of chromium.

A tensile test was carried out on the cast specimens using a Universal Testing Machine (model WDW-10) as per ASTM E8/E8M-22 standard to determine the ultimate tensile strength and % elongation. Hardness test was carried out on 10mm x 10mm long cylindrical test bars machined from the cast samples, using a digital Rockwell hardness tester (model HRS-150) according to ASTM E18-22 standard. A Charpy impact test was performed on the cast samples following the ASTM E23 standard using an impact tester (model JB-300B). Three (3) samples were used for each experiment and the value taken after each experiment was the average. The resistivity and conductivity of the experimental alloys were determined based on standard Ohm's experiment. Structural analysis was carried out on the cast alloy specimens. Before the structural analysis, the surfaces of the specimens were ground with different grades of emery papers from rough to fine grades (400, 600, 800, and 1200μm). After grinding, the specimens were polished to mirror finish using an aluminum oxide powder, rinsed with water, and dried using a hand drier. The dried samples were etched with a solution of 10g of iron (III) chloride, 30cm3 of hydrochloric acid, and 120cm3 of water for 60 seconds. Finally, the surface morphology of the etched samples was examined using an optical metallurgical microscope (Model: L2003A). Scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) of the experimental alloys was carried out on the samples using a TESCAN scanning electron microscope, model number (VEGA III LMH) and a PANalytical X'Pert PRO X-ray diffractometer (XRD) respectively.

3.0 Results and Discussions

3.1 Mechanical properties of Cu-4wt%Mg alloy

Figures 1-5 show the effect of chromium addition on the mechanical properties – ultimate tensile strength (UTS), percentage elongation, hardness, impact strength, and electrical conductivity of the alloy. It was observed from the Figures that the ultimate tensile strength and hardness increased with increasing concentration of chromium up to 0.9% before decreasing with further increase in concentration of the additive. The addition of 0.9wt%Cr to Cu-4wt%Mg alloy resulted in improvement in the ultimate tensile strength and hardness of the experimental alloy by 31.0%, 33.2%, and 24.7% respectively. Maximum ultimate tensile strength and hardness values obtained were 443MPa, and 182 HRB at 0.9wt%Cr content respectively. The addition of 0.1wt%Cr to Cu-4wt%Mg resulted in improvement in the percentage elongation, impact strength, and electrical conductivity of the alloy by 15.31%, 17.16%, and 12.05% respectively. Maximum percentage elongation, impact strength, and electrical conductivity values obtained were 13.48%, 131 J and 32.3 Sm^{-1} at 0.1wt%Cr content respectively. The decrease in the strength and hardness of the alloys at high chromium concentrations was attributed to coarsening of the grains. The improvement in the strength and hardness of the alloys was attributed to the presence of refined and modified intermetallic phases in the structure of the alloys. The results of ultimate tensile strength (443MPa) and hardness (182HRB) exhibited substantial improvement when compared to the findings of Onyia et al. 2023, who reported ultimate tensile strength (288MPa) and hardness (87HRB).

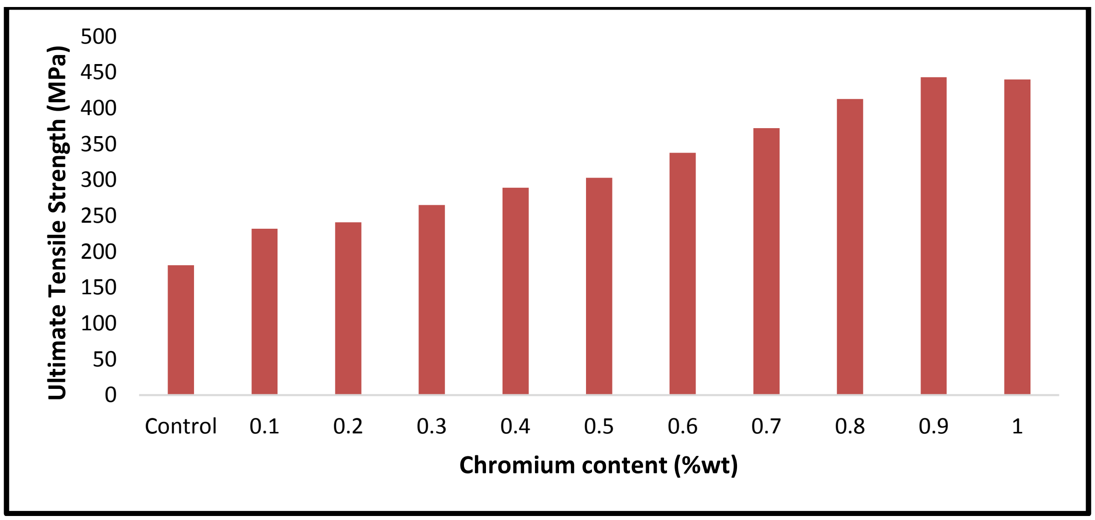


Figure 1: Effect of chromium content on the ultimate tensile strength of Cu-4wt%Mg alloy.

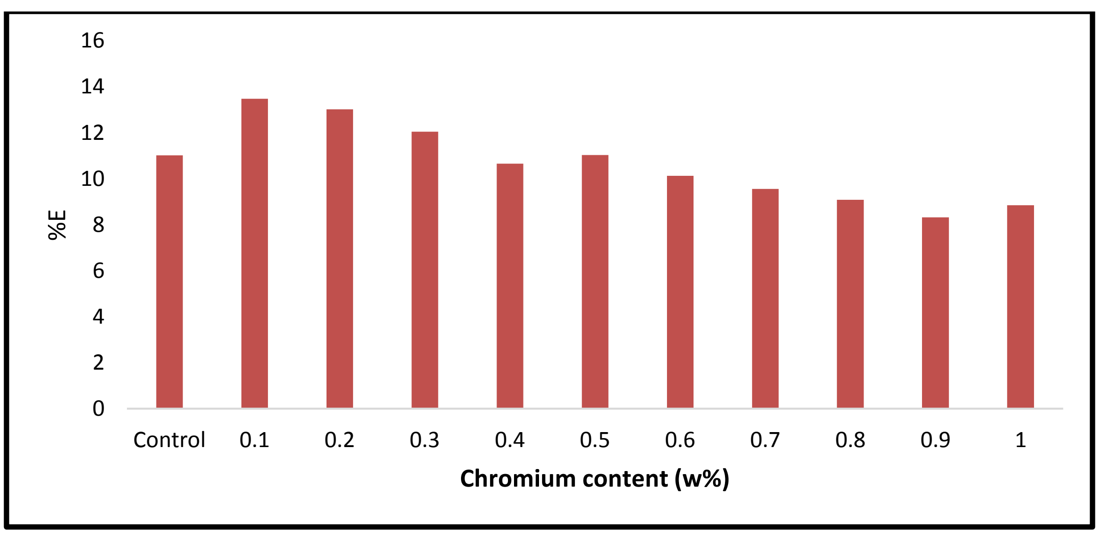


Figure 2: Effect of chromium content on the percentage elongation of Cu-4wt%Mg alloy.

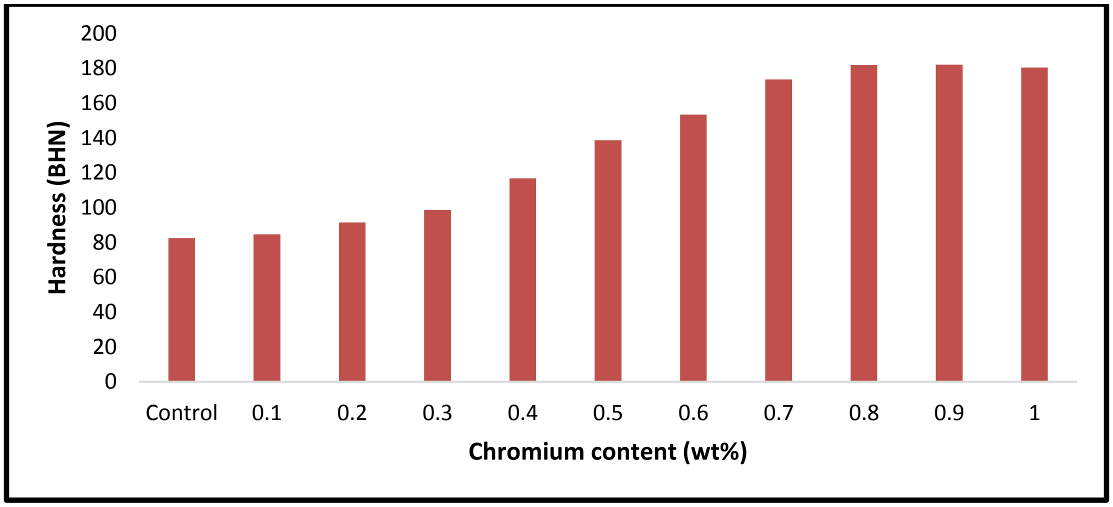


Figure 3: Effect of chromium content on the hardness of Cu-4wt%Mg alloy.

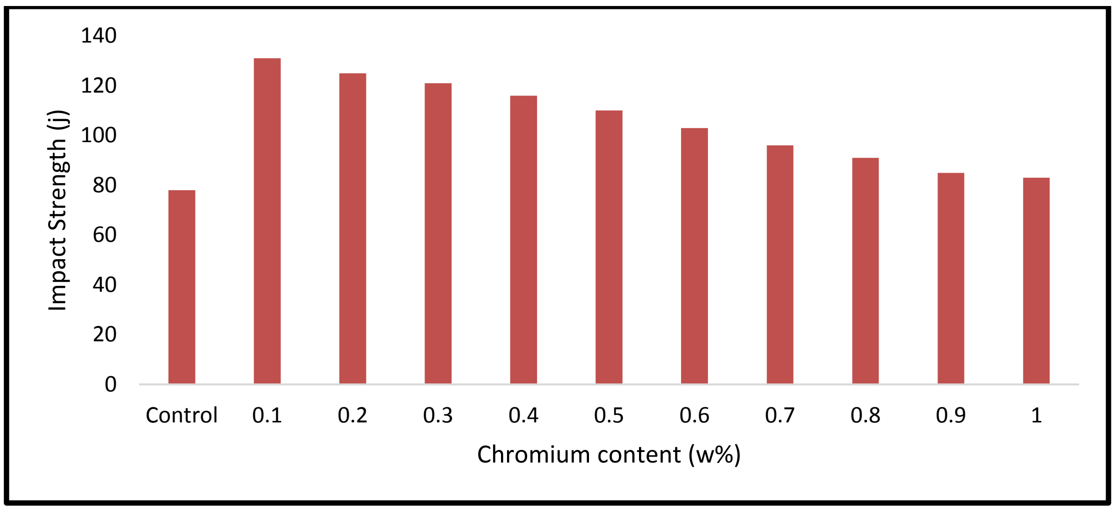


Figure 4: Effect of chromium content on the impact strength of Cu-4wt%Mg alloy.

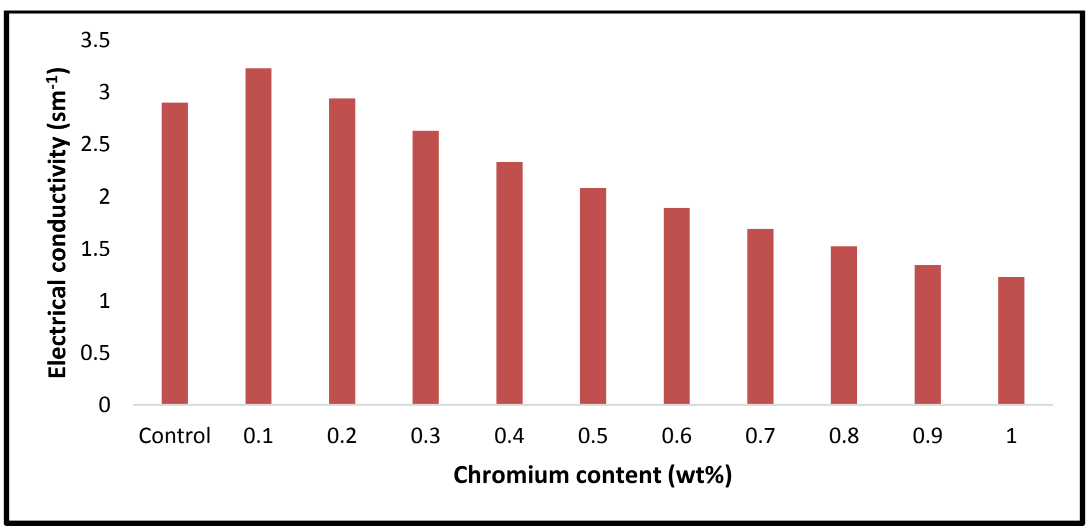


Figure 5: Effect of chromium content on the electrical conductivity of Cu-4wt%Mg alloy.

3.2 Optical, scanning electron microscopy (SEM) and electron dispersive spectroscopy (EDS) analyses of the alloys

The optical, scanning electron microscopy and electron dispersive spectroscopy analyses of the alloys are presented in Figures 6-12. Figure 8 presents the micrograph of undoped Cu-4wt%Mg alloy casting showing microstructures in which the primary α-copper phase (solid solution of magnesium in copper), γ-$CuMg_2$ and ε-Cu_2Mg_4 intermetallic phases are present. Coarse γ-Cu_2Mg_4 intermetallic phase can be observed at the grain boundaries in the microstructure of the alloy and owing to this, the mechanical properties of the undoped alloy are poor. Figures 7-10 reveal the presence of the intermetallic phases in the structure of the alloys doped with chromium. It can be observed that addition of chromium refines and modifies the morphology of the intermetallic compounds with attendant increase in ultimate tensile strength, percentage elongation, hardness, and impact strength. The grain size decreases with increase in concentration of chromium up to 0.9wt%Cr. The small grain sizes result to increased number of grain boundaries which served as increased impediment to motion of dislocations and consequently increased the ultimate tensile strength, and hardness with corresponding decrease in percentage elongation and impact strength of the alloys. Increase in concentration of chromium beyond 0.9wt% coarsened the morphology of the intermetallic compounds which resulted to decrease in the ultimate tensile strength, and hardness of the alloy. The presence of $CuCr_2$ compounds in the structure of the alloy further improved the strength and hardness of the alloy.

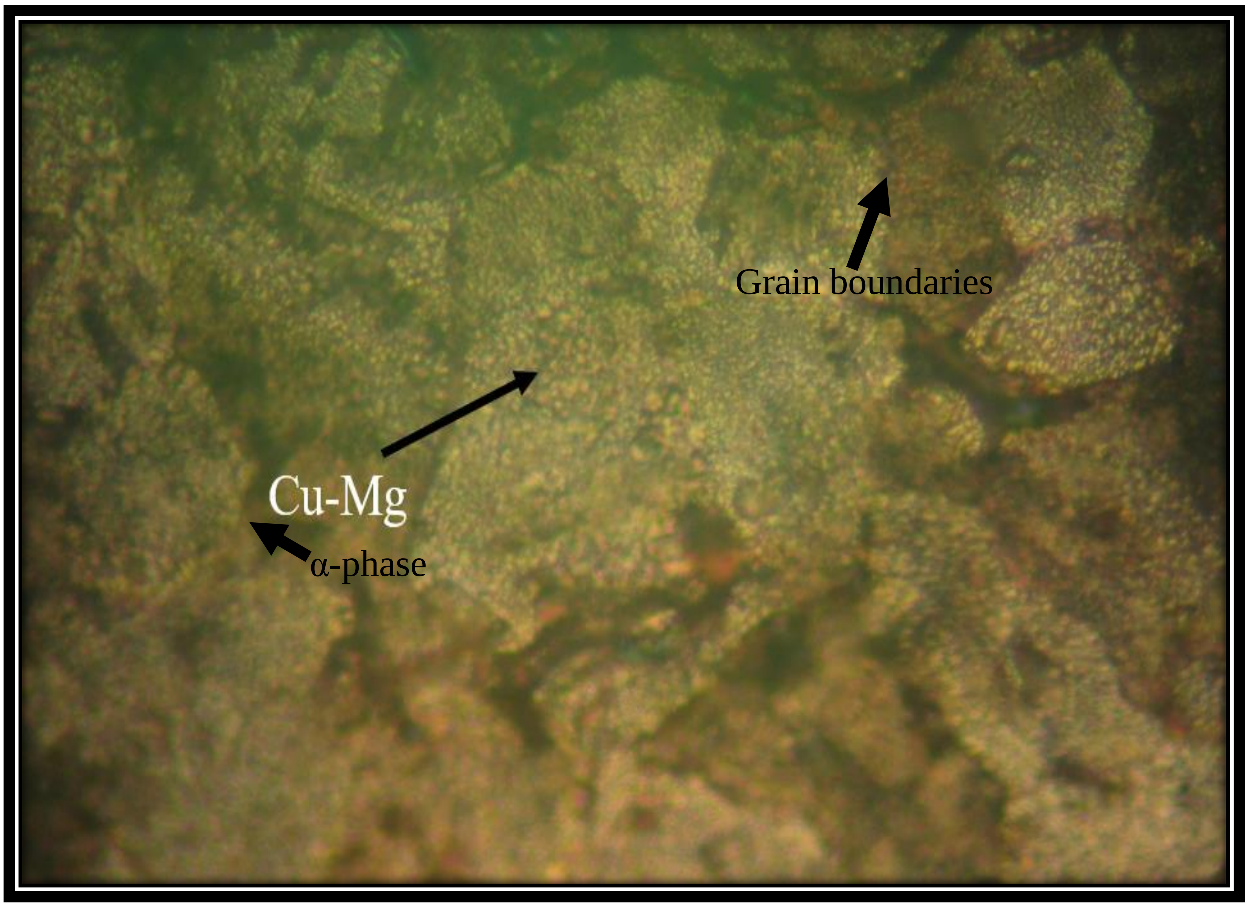
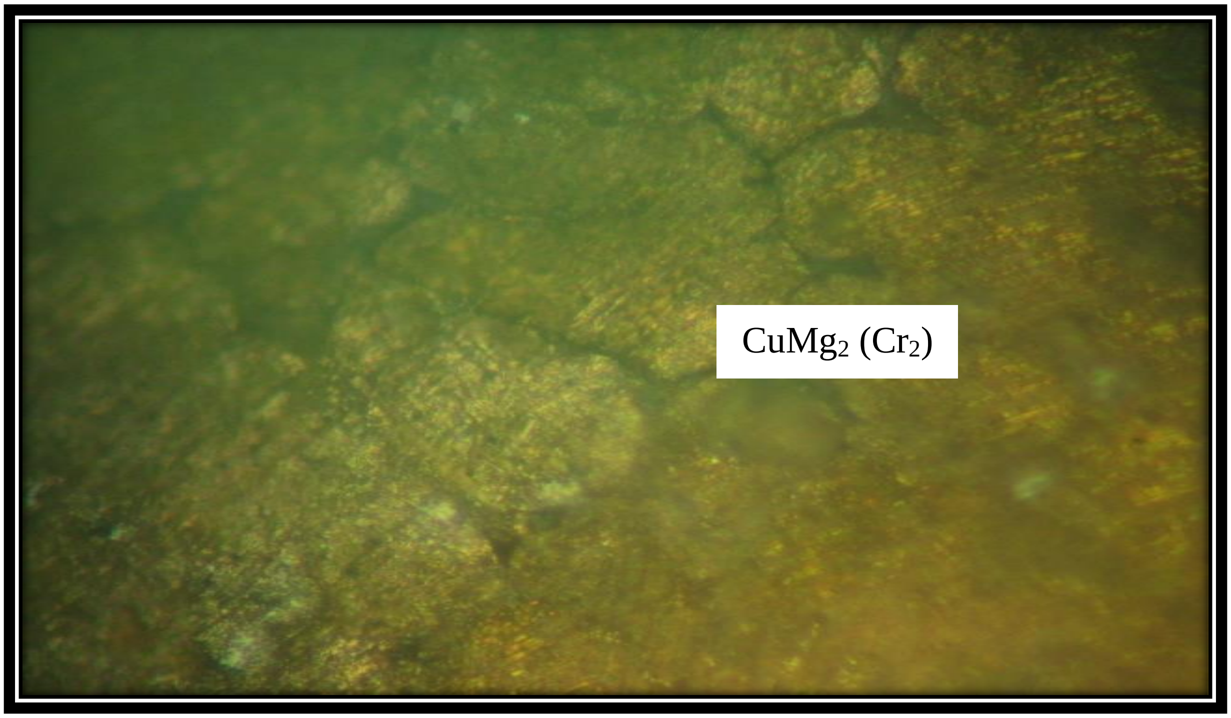
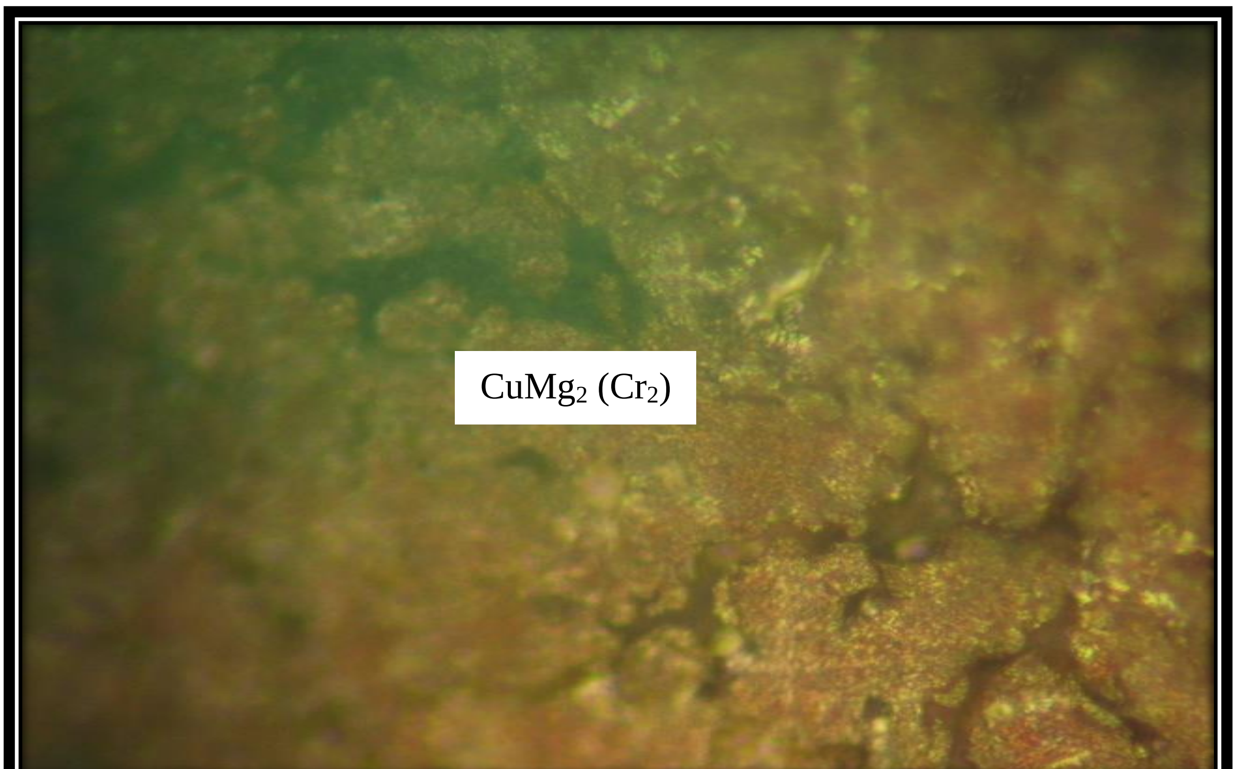


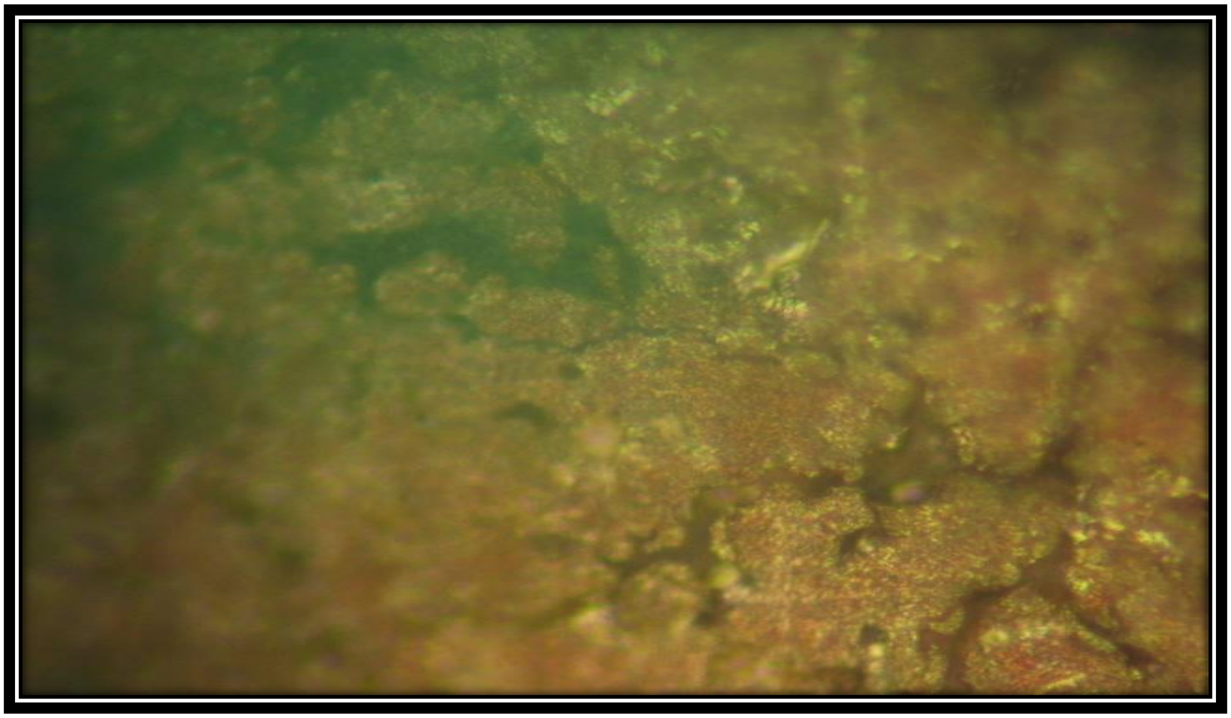
Figure 6: Micrograph of Cu- 4w% Mg (As-cast)



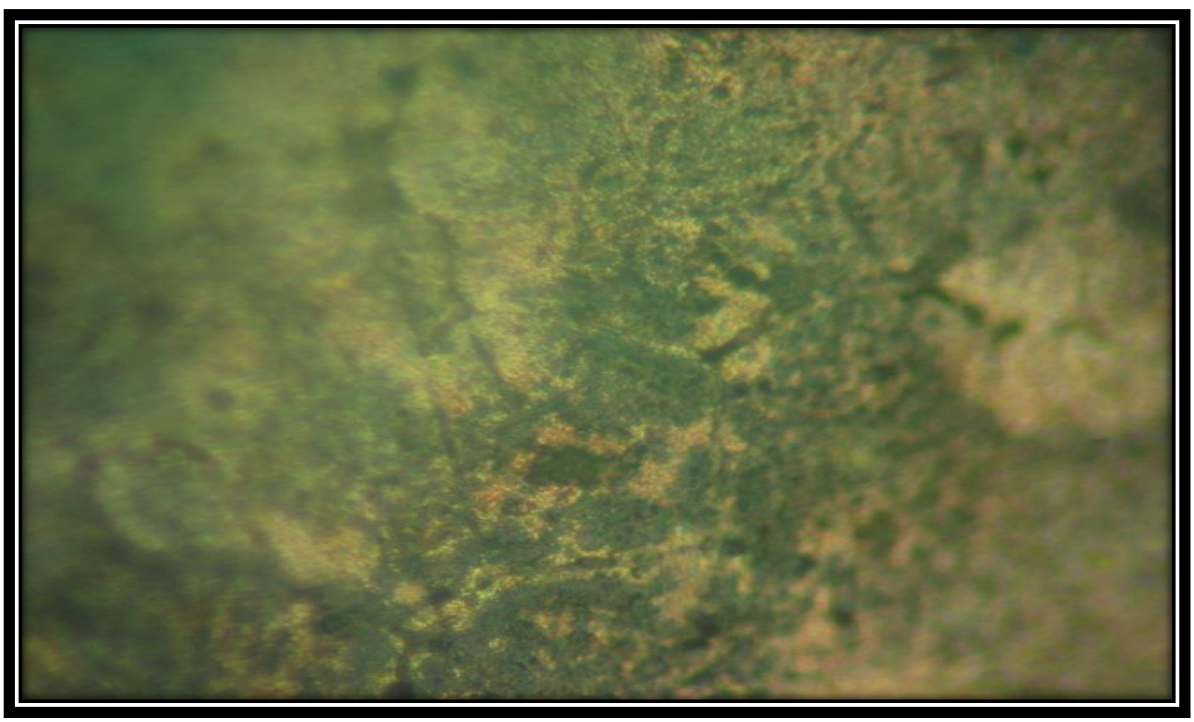
Figures 7: Micrograph of as-cast Cu-4w%Mg + 0.7% Cr



Figures 8: Micrograph of as-cast Cu-4w%Mg + 0.8%.



Figures 9: Micrograph of as-cast Cu-4w%Mg + 0.9w% Cr.



Figures 10: Micrograph of as-cast Cu-4w%Mg + 1.0w% Cr.

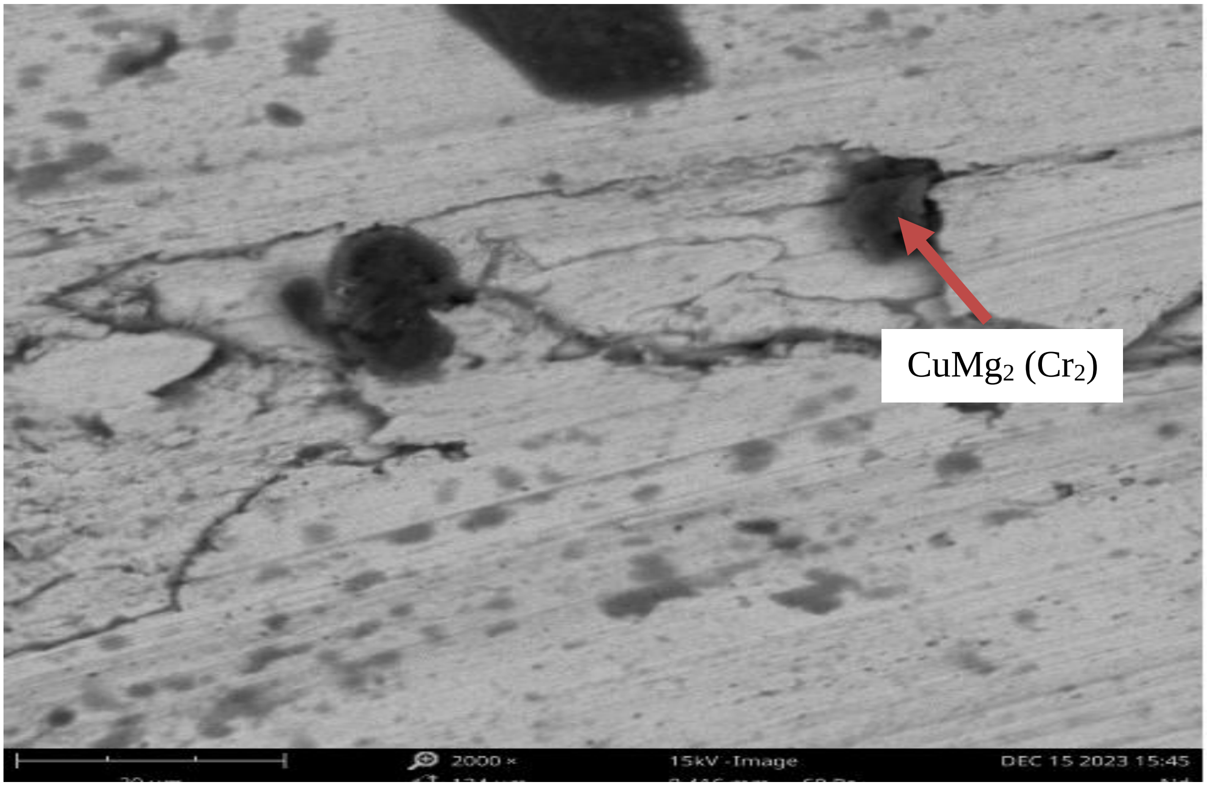


Figure 11: Micrograph (SEM) of Cu-4w%Mg-0.9w%Cr.

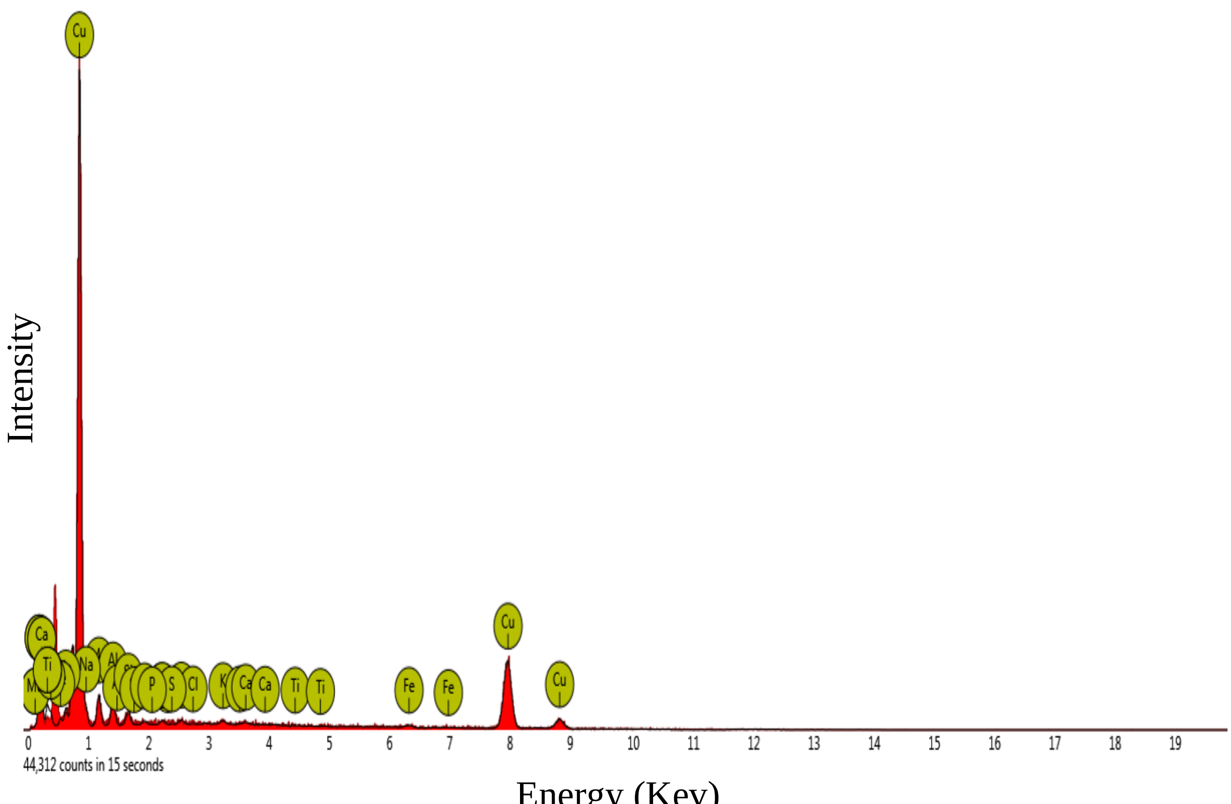


Figure 12: EDS spectrum of Cu-4w%Mg-0.9w%Cr.

5.0 Conclusions

The effect of chromium content on the structure, electrical conductivity and mechanical properties of Cu-4wt%Mg alloy has been investigated. The following conclusions can be made from the experimental results and theoretical analysis:

- Undoped Cu-4wt%Mg alloy has low mechanical properties due to the presence of coarse γ-$CuMg_2$ intermetallic phase at the grain boundaries of the alloy.

- Addition of chromium to Cu-4wt%Mg alloy successfully refined and modified the structure of the alloys which resulted to improvement in the ultimate tensile strength, hardness, percentage elongation, impact strength and electrical conductivity of the experimental alloy by 31.0%, 34.21%, 33.2%, and 24.75% respectively.

- Addition of chromium also resulted to the formation of $CuCr_2$ which further contributed to the increase in strength and hardness of the alloy.

- Maximum ultimate tensile strength, hardness, percentage elongation, impact strength and electrical conductivity values of 443MPa, 182 HRB, 13.48%, 131 J and 32.3 Sm^{-1} respectively were obtained.

- Magnesium bronze with exceptional characteristics has been created to improve the service life of alloy components in sub-sea constructions, including propeller shafts.

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