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Special Issue

A Themed Issue in Honour of Professor Ekedimogu Eugene Nnuka on His retirement.

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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Effect of Dopants Particulates on the Structure and Mechanical Properties of Copper- 12wt% Aluminium Alloy

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Abstract
This research focuses on the development of copper-12wt% aluminum alloys reinforced with 0.5wt% to 5.0wt% weight percentages of titanium, chromium, and nickel particulates. The mechanical (tensile strength, hardness, and percentage elongation) and structural properties of the copper-12wt% aluminum alloy was studied. The samples were tested according to ASTM standards. Metallographic analysis was conducted by scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) to complement observations from the implemented characterization techniques. The results showed that the addition of reinforcing particulates to copper-12wt% aluminum alloy modified the structure of the alloy, resulting in improvements in the ultimate tensile strength and hardness of the experimental alloy by 34.2%, and 31.5% respectively, at 2.5wt%. Furthermore, samples reinforced with nickel exhibit higher tensile strength (297MPa) and hardness (412BHN) than those reinforced with titanium and chromium. The percentage elongation of the alloy decreased as the quantity of reinforcing components increased. The metallographic analysis revealed an equitable distribution of reinforcing particles, precipitations of smaller kappa-phases, and the presence of large globular intermetallic compounds in the microstructure, all of which contributed to the alloy's improved mechanical properties

Keywords: Copper, Aluminium, Microstructure, Mechanical properties, Nickel, Titanium, Chromium.

1. Introduction

Copper matrix composites are among the essential materials in engineering industries because of their outstanding mechanical properties; they have a wide range of applications in aerospace, marine, and automobile industries (Nwaeju et al, 2017; Uyime et al, 2012; Sekunowo et al, 2013; Cenoz, 2010). Also, the desired mechanical properties (lightweight, damage/fracture-resistance, improved strength, and corrosion resistance) for engineering applications are highly dependent on the material composition and structure, which relate to the processing conditions and techniques applied (Ketut et al, 2011; Lei et al, 2013; Mattern et al, 2007; Nwambu & Nnuka, 2018; Hashim et al, 1999; Sevik & Can-Kurnaz, 2006; Ramesh et al, 2009; Ngozi et al, 2024; Onyia et al, 2024; Anyafulu et al, 2024). Despite some of the desirable characteristics of aluminium-bronze composites, its abysmally inadequate responses in specific applications necessitate mechanical property enhancement (Chee & Mohamed, 2000; Sevik et al, 2006).

Therefore, researchers have been developing novel approaches to address these issues. Kuppahalli et al. (2019) investigated the microstructure and mechanical properties of nickel-aluminium-bronze using permanent and shell moulded castings. The results revealed an outstanding improvement in mechanical properties and extensive grain refinement. Nwaeju et al. (2017) investigated the effect of vanadium and chromium macro-additions on the properties of aluminium-bronze using a sand-casting technique. The additives were added in different compositions (1.0 – 10wt%). Tensile strength, yield strength, and percentage elongation were the properties analyzed. Their findings showed that the properties were generally improved and vanadium gave the best result compared to chromium. Sekunowo et al. (2013) performed an investigation on the microstructure and mechanical properties of cast aluminium-bronze reinforced with iron granules composite. The metal mould containing mill scale in a varied amount from 2-10% was used to fabricate the composite samples.

Kalaiselvan et al (2011) studied the fabrication of aluminum (6o61-T6) matrix composites reinforced with various weight percentages of B_4C particulates by a modified stir-casting route. The result revealed the homogeneous dispersion of B_4C particles in the matrix and an improvement in mechanical properties with the increase in the additive content in the aluminum matrix. Mechanical property analyses such as tensile, Charpy impact and micro-hardness testing were utilised, while optical microscopy was employed to characterise the structures. The result revealed that the reinforcement provided an optimum enhancement of the mechanical properties. Lei et al. (2013) performed experiments on the mechanical properties and microstructure of Cu-1.8Si- 8.0Ni-0.6Sn-0.15Mg alloy. They found that the properties were significantly improved.

The effect of titanium content on the structure and mechanical properties of Cu-Ni-Si alloy were investigated by Eungyeong et al. (2011). Different ageing times were implemented to characterise the effect on material properties. They discovered that tensile strength and electrical conductivity of the alloy were significantly enhanced. Likewise, the effect of silicon content on the mechanical properties of silicon bronze was also evaluated by Ketut et al. (2011). The observations depict that the mechanical properties of Cu-Si were higher than Cu-20wt%Sn bronze. Furthermore, Lei et al. (2013) reported that the addition of aluminium to Cu-Ni-Si alloy has a significant effect on the physical and mechanical properties of the alloy. Mattern et al. (2007) also investigated the microstructure of silicon-bronze and observed suppression of the kappa phase (k-phase) through rapid quenching and the presence of different phases such as gamma, beta and kappa phases within the microstructure of the alloy. There have been very few research that compare the performance of copper-12wt% aluminum alloy supplemented with various additives (Sevik & Can-Kurnaz, 2006; Ramesh et al, 2009; Ngozi et al, 2024; Onyia et al, 2024; Anyafulu et al, 2024; Okoye et al, 2024). This study looked at the microstructure and mechanical properties of copper-12wt% aluminium alloy reinforced with nickel, titanium, and chromium granules. The mechanical properties and metallographic examinations of these alloys were compared to get useful insights into their industrial uses.

2.0 Material and Methods

2.1 Materials and Fabrication

The base alloy for this study was produced from commercial pure copper (99.99%) and commercial pure aluminum, titanium, nickel, and chromium (99.98%). Copper and aluminum were sourced from Cutix cable Plc, Nnewi, Nigeria, and the additives (Ti, Ni & Cr) particulates were sourced from Kermel Chemical Reagent Co. Ltd. Hebei, Tianjin, China. They were melted in a bailout crucible furnace and the additives added in concentrations of 0.5wt% to 5.0wt% before the permanent die casting technique was used for casting, 10 samples were cast for each dopant. Three (3) samples were used for each experiment and the value taken after each experiment was the average. The molten mixtures were stirred for proper homogeneity with the help of a mechanical stirrer (Ramesh et al, 2009; Ngozi et al, 2024).

2.2 Mechanical and Structural Characterisation

After solidification, these samples were prepared for mechanical testing (by machining to ASTM testing standards), and structural analysis by etching with alcoholic ferric chloride for 60 seconds. The tensile strength test was conducted according to the ASTM E8 standard, and the hardness, according to the ASTM B929-17 standard. The analyses were performed with a digital hydraulic universal tensile testing machine (Satec series, Instron 600DX) for tensile strength and a portable dynamic hardness testing machine (DHT-6) for hardness, respectively. 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 a 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, 30 cm^3 of hydrochloric acid, and 120 cm^3 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).

3.0 Results and Discussions

3.1 Evaluation of mechanical properties

According to the mechanical analyses presented in Figures 1 to 3, it is evident that the tensile strength of copper-12wt% aluminium alloy generally increased significantly with the inclusion of the additives as shown in Figure 1. The improvement on the tensile strength was caused by the modification of the microstructure, which led to an increase in the grain boundary area and the impediment of dislocation motion. Tensile strength gradually increased as the composition of doping elements increased. For instance, nickel content recorded a maximum value at 2.5wt %, (297MPa), titanium at 3.0wt% (285 MPa) and Chromium at 3.5wt% (284MPa). Their tensile strength values decreased afterwards as a result of the excess number of reinforcing elements, which made the alloys brittle.

Figure 2, depicts the improvement of the hardness of copper-12wt% aluminium alloy as the composition of reinforcing elements increased in the alloys. It is observed that the hardness of copper-12wt% aluminium alloys are linearly increasing when the reinforcement particulate content increases, but decreased at certain weight percentages. The presence of such hard surface area of particles offers more resistance to plastic deformation, which leads to an increase in the hardness of the composites. The samples with nickel had their maximum value at 2.5wt% (412BHN), followed by titanium content at 3.0wt% (295BHN) and chromium at 3.5wt% (396BHN). Ramesh et al (2009) also reported that the presence of a carbide forming element, such as nickel, in the soft, ductile matrix reduces the ductility of the alloy and causes a significant increase in the hardness. The decrease in the strength and hardness of the alloys at high nickel 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. It was observed that the percentage elongation decreased all through (Figure 3), as the doping elements increased in the alloy. The results of ultimate tensile strength (297MPa) and hardness (412HRB) exhibited substantial improvement when compared to the findings of Onyia et al. (2023), who reported ultimate tensile strength (288MPa) and hardness (87HRB).

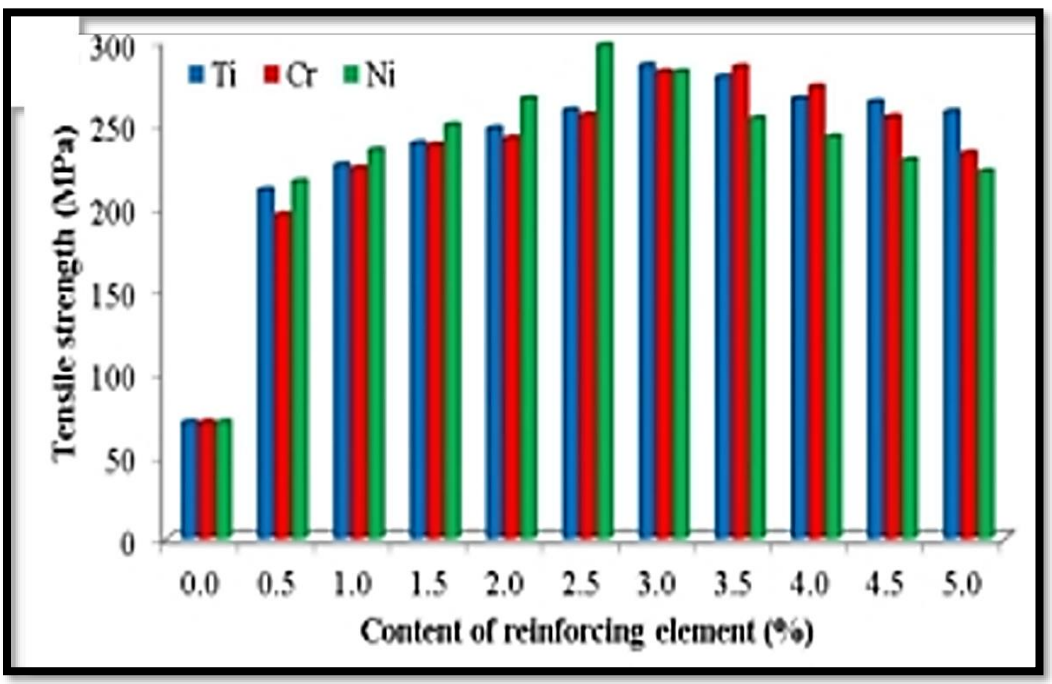

Figure 1: Effect of doping elements concentration on alloy tensile behavior of the cast alloys.

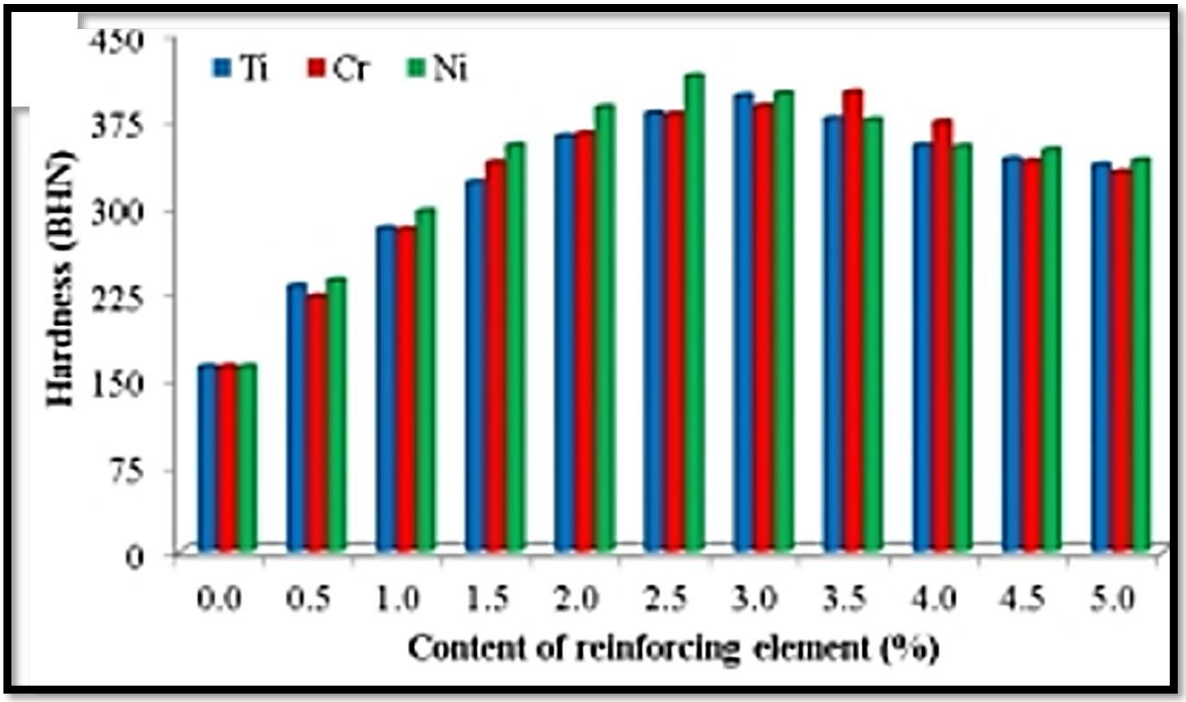

Figure 2: Effect of doping elements concentration on alloy hardness of the cast alloys.

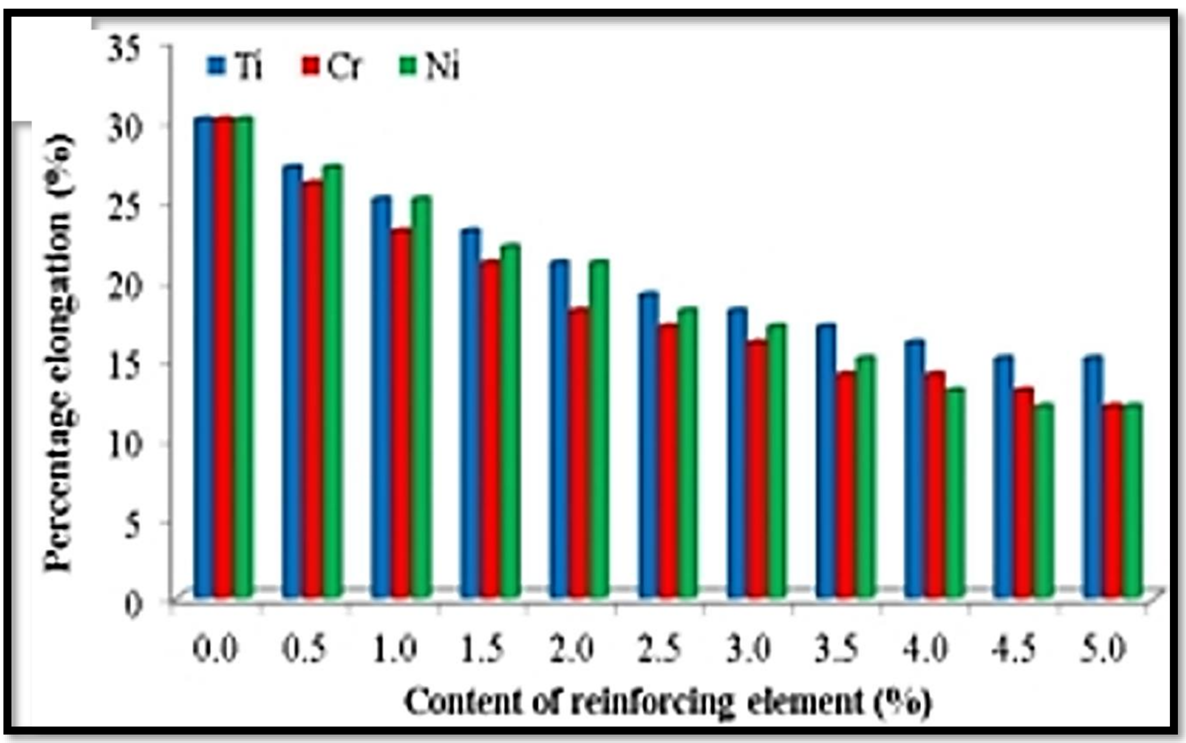

Figure 3: Effect of doping elements concentration on alloy percentage elongation of the cast alloys.

3.1 Evaluation of microstructure

Metallographic examination with a scanning electron microscope (SEM) revealed the precipitation of different phases (Figures 4a, 5a 6a & 7a), which are beta phase, small k-phases and α + k eutectoid (coarsened intermetallic compound) in the alloy structure. These precipitations of a small k-phase increase the tensile strength, while the presence of large globular precipitates improves the hardness of the alloy. These phases were precipitated from the α-phase and $CuAl_2$ intermetallic phase (dark dendrite). Therefore, the addition of carbide forming elements modified the microstructure of the alloy, which allowed the precipitation of k-phases, and the α+k-eutectoid phase, thereby impeding the dislocation motion. As shown in Figure 6a, samples that contain nickel have better grains refinement with more of refined grains and kappa phases present in the microstructure, compared to the samples with titanium (Figure 5a) and chromium (Figure 7a). This corresponds with the findings of Lei et al. (2013) on the microstructures of alloys. Scanning electron microscopy (Figures. 4a, 5a, 6a & 7a) revealed all the phases present in the alloy, such as the α -phase, β- phase, and α +k-phase with white and dark spots, while energy dispersive spectroscopy analyses (Figures. 4b, 5b, 6b, & 7b) indicated several peaks corresponding to the presence of significant elements in the alloys.

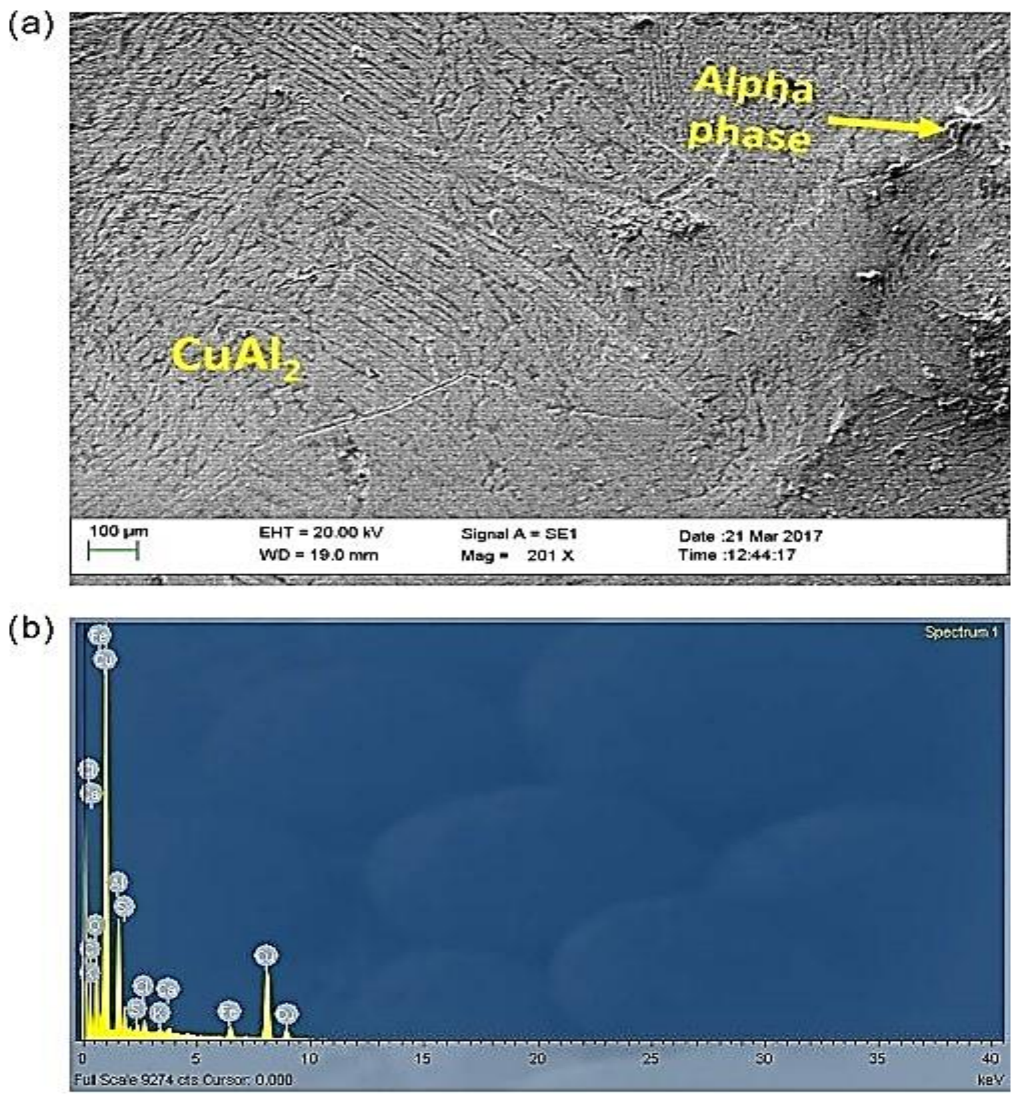

Figure 4: Scanning electron micrograph (a) and energy dispersive spectrum and (b) of copper-12wt% Aluminium alloys.

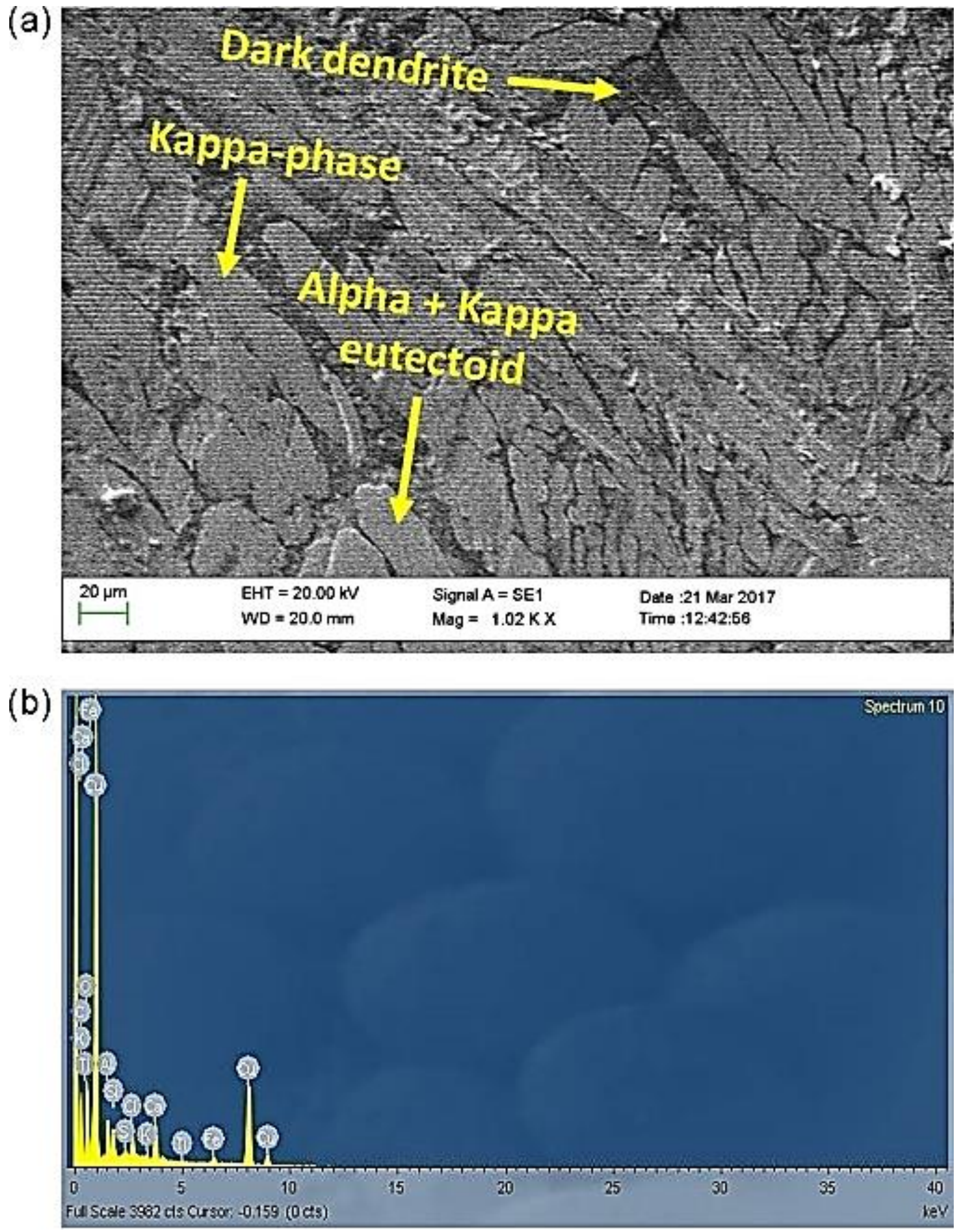

Figure 5: Scanning electron micrograph (a) and energy dispersive spectrum and (b) of copper-12wt% Aluminium + 3wt% titanium alloys

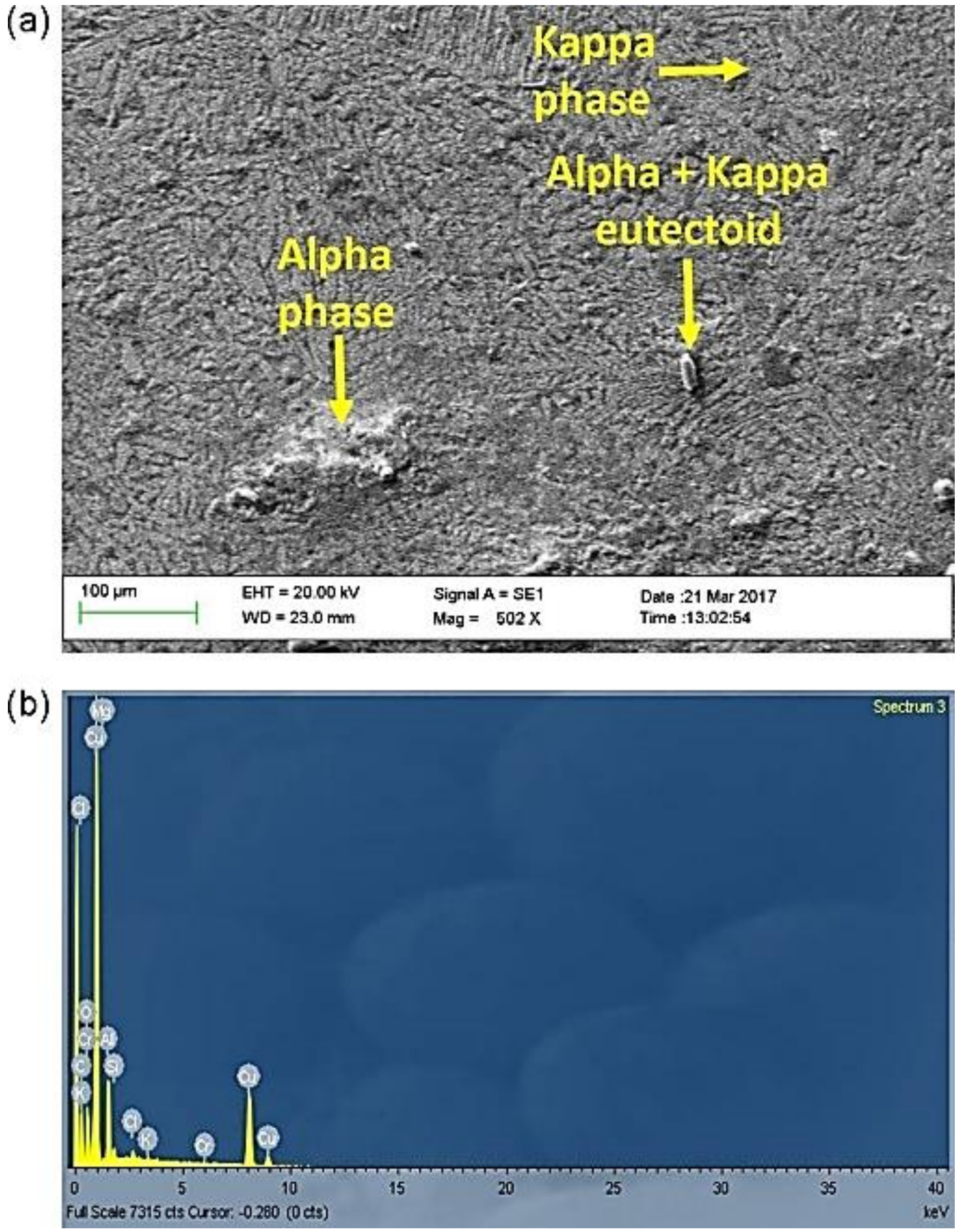

Figure 6: Scanning electron micrograph (a) and energy dispersive spectrum and (b) of copper-12wt% Aluminium + 3wt% nickel alloys

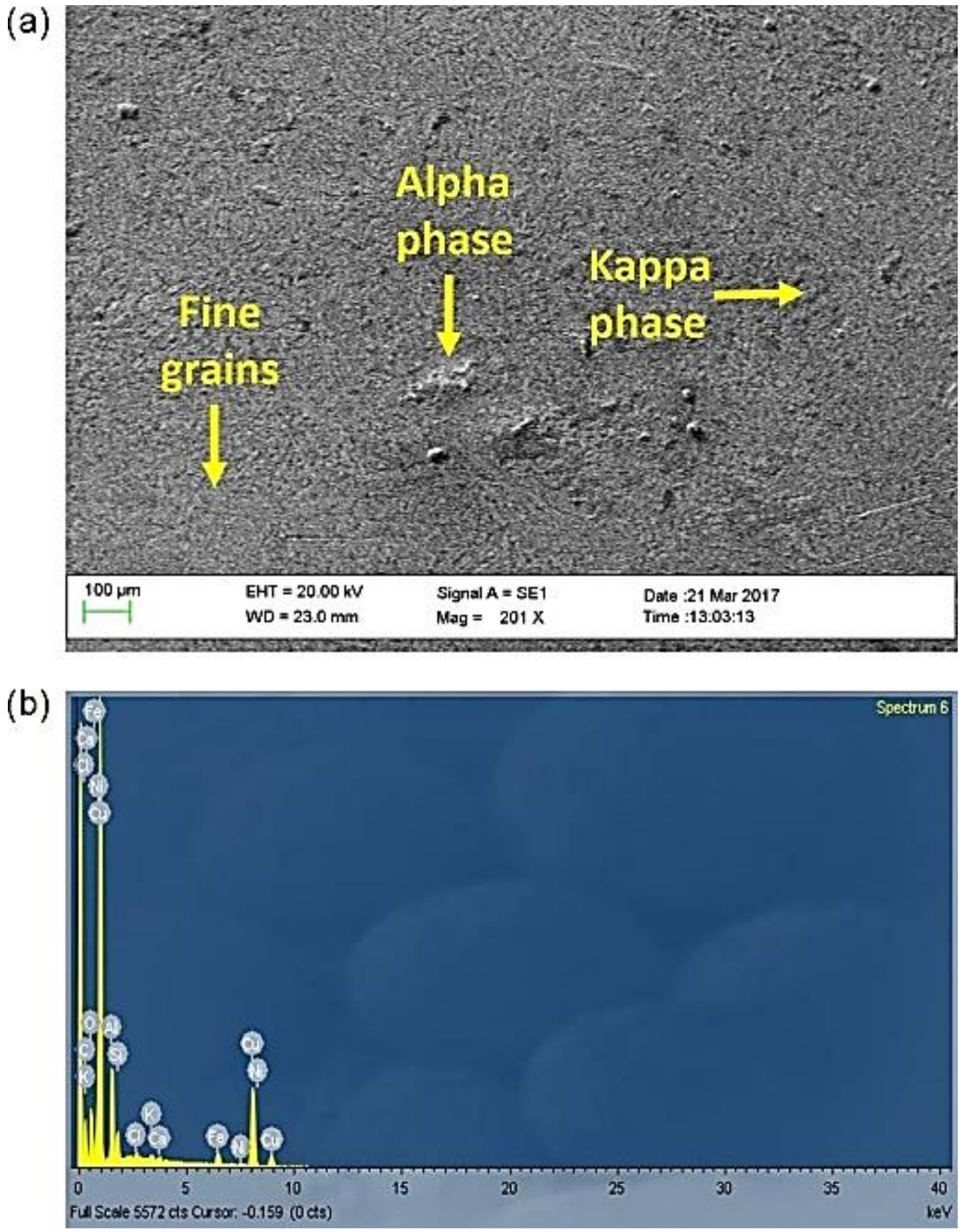

Figure 7: Scanning electron micrograph (a) and energy dispersive spectrum and (b) of copper-12wt% Aluminium + 3wt% chromium alloys.

4.0. Conclusion

The enhancement of the microstructure of copper-12wt% aluminum alloy using nickel, titanium, and chromium granules was undertaken and the findings led to the following conclusions.

- The mechanical properties such as tensile strength and hardness of the alloy increased with an increase in the weight percentage of nickel, titanium, and chromium, with peak values of 297 MPa and 412 BHN at 2.5 wt.%, 285 MPa and 395 BHN at 3.0 wt.%, 284MPa and 398 BHN at 3.5 wt.% observed.
- Further additions of the particulates yielded a decrease in both properties. The overall observation shows that the alloys that contain nickel particulates have the highest values of tensile strength and hardness (297

MPa and 412 BHN), while samples that were doped with titanium and chromium particles have insignificant differences among them.

- The dopants improved the mechanical properties of the alloy, resulting in the precipitation of the kappa phase and a massive globular phase within the microstructure. However, an increase in coarse intermetallic compounds due to excess dopant particles negatively affects the alloy's mechanical properties. These findings are consistent with those of Lei et al. (2013) and Eungyeong et al. (2011) regarding the mechanical reactions of alloys.
- Aluminum bronze with exceptional characteristics has been created to improve the service life of alloy components in sub-sea constructions, including propeller shafts and wind turbine blades.

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