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EFFECT OF COPPER/ALUMINA HYBRID REINFORCEMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF STIR CAST ALUMINUM ALLOY AA6063

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Abstract: The present study investigated the microstructural characteristics and mechanical behavior of hybrid composites with an aluminum matrix reinforced with copper and alumina. To prepare these composites, copper and alumina were mixed in varied weight ratios and added to a 10 wt% hybrid reinforced Al–Mg–Si alloy using a two–step stir casting process. The resulting composites were characterized using hardness, tensile properties, and scanning electron microscopy. The findings reveal that composites with Al–90%/Cu–7.5%/Al_2O_3–2.5% and Al–90%/Cu–7.5%/Al_2O_3–2.5% exhibited the optimum mechanical properties, including hardness and tensile properties. The microstructure of all composites showed the presence of copper particles and Al_2O_3 reinforcement, which were distributed nearly uniformly throughout the metal matrix despite the presence of pores. The EDS profile of a representative composite showed peaks of aluminum (Al), copper (Cu), carbon (C), magnesium (Mg), silicon (Si), oxygen (O), manganese (Mn), and traces of calcium (Ca), sulfur (S), and potassium (K). Based on these results, further investigation could be conducted on the wear and corrosion properties of the aluminum alloy when reinforced with copper and alumina.
Keywords: aluminum; alumina; copper; composites; mechanical properties; hybrid

1. INTRODUCTION

In contemporary times, the metal of choice in industries such as defense, aerospace, and automobile is aluminum, as opposed to iron. This preference can be attributed to aluminum's low density, exceptional wear and corrosion resistance, superior malleability, high strength to weight ratio, good thermal conductivity, and excellent formability. The evolution of technology necessitated the development of economical, harder, stronger, and lighter materials in these aforementioned industries (1). In recent years, there has been a noticeable shift in research advancement towards the field of composite materials, which have played a pivotal role in the development of numerous industries and engineering applications (1, 2). Currently, the primary objective of material selection research is focused on producing lightweight materials with improved properties, while simultaneously maintaining the required strength for optimal application in areas of interest. These desired property enhancements are accomplished through the use of composite materials, which are essentially materials that are engineered by combining two or more materials with contrasting physical and chemical properties to augment the properties of the selected base material. Composite materials are categorized based on the matrix materials into metal matrix composites (MMCs), polymer matrix composites (PMCs), and ceramic matrix composites (CMCs) (3). Metal matrix composites fall under the category of composite materials that are currently being developed for use in structural and lightweight applications. These composites possess a noteworthy combination of physical and mechanical properties, including high specific strength, hardness, ductility, impact strength, high thermal resistance, good damping capacity, wear resistance, high specific stiffness, and corrosion resistance, which are all essential for various engineering applications. Due to the combinations of matrices and hard particles called reinforcements, metal matrix composites are one of the most engineered materials, offering a wide range of properties, and therefore gaining significant industrial significance amongst conventional metallic alloys (4) among these composites aluminum metal matrix composites have found widespread application in meeting the ever–growing demands of industry. The utilization of these composites in the manufacturing sector has experienced a substantial surge. This can be attributed to the various enhanced properties of aluminum composites, including superior wear resistance, heightened hardness, reduced density, increased strength, enhanced stiffness, and a relatively low cost when compared to alternative materials (2–5). The production of aluminum matrix composites (AMCs) has resulted in the creation of materials that exhibit enhanced weight, specific strength, stiffness, wear resistance, and corrosion resistance. These attributes are attained via various manufacturing techniques including stir casting, powder metallurgy, and infiltration method.

Nonetheless, stir casting is the favored approach amongst numerous scholars due to its economical nature, ease of use, and capacity to produce intricate geometries (3, 6–7). The improvements observed in the properties of AMCs have been documented as a result of the incorporation of a second phase into the fabrication process, commonly referred to as reinforcements. Synthetic materials have been utilized by numerous researchers for this purpose, with reinforcements such as SiC, Al_2O_3, and B_4C being frequently

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employed (6, 8–9). These reinforcements have been shown to significantly enhance mechanical, corrosion, and wear properties. Research conducted on AMCs has undergone a shift from the production of binary materials to ternary materials. This transition has been necessitated by the need to offset the high costs associated with binary materials, while simultaneously enhancing their properties and machinability. Ternary AMCs incorporate hybrid reinforcements, which entail the use of two or more particulates to strengthen the base metal. The most commonly employed hybrid reinforcement for AMC production involves the combination of synthetic and sustainable materials. A typical example is the addition of copper and ceramic reinforcement in the aluminum matrix for improved properties. Aluminum–copper composites have been subject to extensive investigation, with numerous research studies documenting the enhancement of hardness, tensile properties, strength, and erosion resistance resulting from the incorporation of particles, including alumina, SiC, SiO_2, zirconia, magnesium oxide, and CNTs, which has garnered particular attention in the context of Al–Cu–based composites (10).

In a research conducted on Development and Characterization of Al_2O_3 and SiC Reinforced Al–Cu Metal Matrix Hybrid Composites by Behera et al (11). In this particular study, the objective was to conduct an investigation into the synthesis and characterization of a hybrid metal matrix composite consisting of Al–Cu–SiC–Al_2O_3 with varying percentages of Al_2O_3. The hybrid composite samples were synthesized and subjected to conventional sintering at two distinct temperatures, namely 500°C and 600°C for a duration of 1 hour each. Based on SEM analysis, it can be predicted that the reinforcing particles were uniformly distributed throughout the samples. Furthermore, the SEM and XRD results of the sintered composites revealed the presence of a newly formed intermetallic alloy $CuAl_2$ phase in addition to the Al and SiC phases. Our observations demonstrated that the density and hardness of the Al–Cu–SiC–Al_2O_3 hybrid composite increased with a rise in the weight percentage of Al_2O_3 and the sintering temperature. Furthermore Mechanical properties of Al–Cu alloy metal matrix composite reinforced with B_4C, Graphite and Wear Rate Modeling by Taguchi Method was investigated by Sekar & Vasanthakumar(12). The study investigated the fabrication of AA2017+ B4C+Gr Composites with varying weight percentages of B_4C, while keeping graphite constant, through stir casting and thixoforming processes. The SEM analysis demonstrated the consistent dispersion of B4C particulate reinforcement and Gr particles within the AA2017 metal matrix. The hardness of the AA2017 alloy and its composites witnessed a 31% increase from 87.3 VHN (base metal) to 114.5 VHN (Cast 5). The Ultimate Tensile Strength (UTS) value of the composite, with constant 1% wt. Graphite and 0.5, 1 and 1.5% wt. of B4C relative to the base alloy, increased by approximately 12.5% from 224MPa to 252MPa. Moreover, the compression value escalated from 445 MPa to 689 MPa for the composite, with constant 1% wt. Graphite and 0.5, 1, 1.5, and 2% wt. of B4C as compared to the base alloy. The Taguchi analysis indicated that the signal–to–noise ratio depicts the inverse relationship between the weight percent of reinforcement particles and the wear rate with the applied load and sliding velocity.

Through the literature survey, investigations into the use of both copper and sustainable reinforcements for the creation of ternary aluminum matrix composites (AMCs) have been conducted. The studies reviewed have successfully identified enhancements to the aluminum matrix that have been characterized. However, the amalgamation of two materials as reinforcements in AMCs has been given minimal attention. This research aims to address this notable research gap by exploring the feasibility of the effect of alumina–copper hybrid reinforcement on the mechanical characteristics and microstructural properties of stir cast Al6063 aluminum alloy.

2. MATERIALS AND METHODS

The raw material utilized in the current investigation for the fabrication of the Al–Cu–Al_2O_3 composite material consisted of ingot pieces of aluminum alloy (Al6063) procured from NIGALEX (Nigerian Aluminum Extrusions), an Aluminum industry located at 31–37 Apapa Oshodi Expressway, Oshodi Industrial Scheme, Oshodi–Isolo, Lagos. The chemical composition of the aluminum alloy which is the metal matrix is shown in Table 1. Pure copper particles, exhibiting an average particle size of 25µm, were sourced from a local vendor in Obafemi Awolowo University, a Federal Government–owned University located in the ancient city of Ile–Ife, Osun State, Nigeria. Alumina (Al_2O_3) powder, also obtained from a local vendor, was procured from the Federal University of Technology Akure, located in Ondo State, Nigeria. Both the copper particles and Alumina were chosen as hybrid reinforcements for the aluminum–based composites manufactured.

Table1. Chemical Composition of Aluminum alloy (Al-Mg-Si alloy)

Element	Weight (%)
Ca	0.01
Si	0.04
Fe	0.22
Cu	0.01
Mn	0.01
Mg	0.40
Cr	0.30
Zn	0.02
Ti	0.01
Ni	0.01
Al	98.88

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3. COMPOSITE PRODUCTION

The production of composites utilized a liquid metallurgy route through a two–step stir casting process. The process initially involved determining the necessary quantities of copper and alumina to produce 10wt% particle reinforced composites with specific weight ratios, as outlined in Table 2. Preheating of the copper and alumina particles was conducted separately at a temperature of 250°C to eliminate any dampness and enhance wettability with the molten Al–Mg–Si alloy. The Al–Mg–Si alloy was then introduced into a gas–fired crucible furnace, equipped with a temperature probe, and heated to 720 C ± 30 C, above the liquidus temperature of the alloy, to ensure complete melting. The resultant liquid alloy was allowed to cool in the furnace to a semi–solid state at approximately 600°C before the preheated copper and alumina particles were manually charged into the mixture and stirred for 10 minutes. Subsequently, the semi–solid composite mixture was superheated to 780 C ± 30 C and stirred using an automated mechanical stirrer, with stirring performed at 400 rpm for an additional 10 minutes prior to casting into sand moulds inserted with metallic chills. The produced as–cast composites from the two–step stir casting process were of representative sizes, as presented in Figure 1. This process was done in accordance with Alaneme & Sanusi (9).

Table 2. Percentage composition of (Al–Cu–Al_2O_3) prepared samples

Samples	Aluminum Alloy	Copper (Cu)	Alumina (Al_2O_3)
Control	100%	0%	0%
A	90%	10%	0%
B	90%	7.5%	2.5%
C	90%	5.0%	5.0%
D	90%	2.5%	7.5%
E	90%	0%	10%

Figure 1. As–cast aluminum based composites.

4. MECHANICAL INVESTIGATION

Mechanical tests help to evaluate various mechanical properties of a material, and helps to determine its application. For this research, two mechanical tests were carried out. These tests include: hardness test and tensile test.

Tensile Test

Tensile Testing is a type of tension test that belongs to the field of materials science and falls under the category of destructive engineering tests. This approach involves the application of controlled tension to a sample until it fails, making it one of the most commonly utilized mechanical testing methods. Its purpose is to determine a material's strength and the extent to which it can be stretched prior to fracture. The experimental procedure consisted of conducting uniaxial tension tests on cylindrical tensile samples with dimensions of 5 mm in diameter and 38 mm in gauge length, which were obtained from monolithic alloys and composites at room temperature. The Instron universal testing machine was used to perform the test, operating at a constant cross head speed of 1 mm/s, while adhering to the ASTM E8M—91 standards(13). To ensure the data generated was reliable, at least two repeat tests were conducted for each test condition. The stress–strain curves developed from the tension test provided the tensile properties, which included ultimate tensile strength, 0.2% offset yield strength, energy at yield, strain to fracture, and elastic modulus.

Hardness Test

Hardness testing is a method used to determine a material's ability to resist permanent deformation when subjected to penetration by a harder material. In order to derive definitive outcomes from a hardness test, a quantitative value is typically assessed in conjunction with the load on the indenter, a specific loading time profile or load duration, and a particular indenter geometry. The testing process involves pressing an object (indenter) with specific dimensions and loading into the material surface being tested, with the

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hardness being determined by measuring the depth of indenter penetration or the size of the impression made by the indenter. The Brinell hardness tester, in compliance with the ASTM E10–15a standard test method (14), was utilized to evaluate the hardness of composites. Prior to testing, samples were taken from each composite composition and polished to achieve a flat and smooth surface finish. Brinell hardness is obtained by driving a hard steel or carbide sphere of a specific diameter under a specified load into the material surface for a designated time period and measuring the diameter of the indentation left after the test. The Brinell hardness number is calculated by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. Multiple hardness tests were performed on each sample, and the average value was taken as a measure of the specimen's hardness (15).

Microstructural Examination

For the purpose of examining the microstructural and compositional properties of composite samples, a comprehensive analysis was conducted utilizing a JSM 7600F Jeol ultra–high resolution field emission gun scanning electron microscope (FEG–SEM) equipped with an EDS. This instrument was utilized to determine the elemental compositions of the composites. The samples were precisely sectioned using a secotom–10 precision cutting machine with a diamond coated blade. Subsequently, a silicon carbide abrasive wheel with varying grit sizes (600, 800, 1200, 2400 and 4000) was utilized for grinding purposes. The surface underwent polishing until a mirror finish was achieved with alumina suspension. Afterwards, conventional Keller's reagent was applied to the samples by swabbing for etching purposes. Finally, the samples were thoroughly cleaned with water and ethanol and then dried using compressed air in preparation for their microstructural examination. Furthermore, EDS was employed to investigate the elemental composition of the composite samples.

5. RESULTS AND DISCUSSION

Microstructure Examination

The micrographs of hybrid metal matrix composites (HMMCs) of Al–Cu–Al_2O_3 with varying compositions were obtained using a scanning electron microscope at magnifications of 300µm, 100µm, and 200µm. The resulting micrographs are displayed in Figure 2, which includes images of Al–100%/Cu 0%/Al2O3–0%, Al–90%/Cu–0%/Al_2O_3–10%, Al–90%/Cu–2.5%/Al_2O_3–7.5%, Al–90%/Cu–5%/Al_2O_3–5%, Al–90%/Cu–7.5%/Al_2O_3–2.5%, and Al–90%/Cu–10%/Al_2O_3–0% composites.

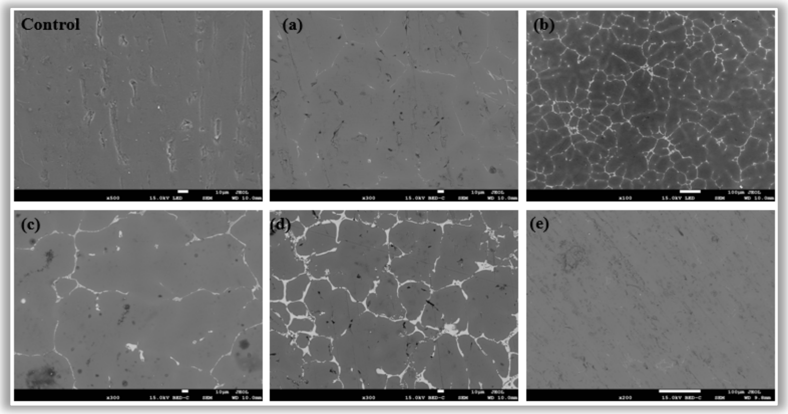

Figure 2. Representative SEM photomicrograph of sample composites

Microstructural analysis revealed the presence of copper particles and Al2O3 reinforcement that were distributed uniformly throughout the metal matrix. Figure 3 shows a fairly even dispersion of Cu particles and Al_2O_3 reinforcement in the Al alloy matrix, with the exception of the presence of pores in samples A and D. This indicates that there is no significant issue of segregation or sedimentation that commonly arises during the solidification of MMCs containing components with distinct densities and wettability characteristics (9, 16).

Hence, this serves as a manifestation of the reinforcement of boundaries within the material, implying that the material shall possess elevated strength. It is evident from the microstructures depicted in Figure 3 that the two–stage stir casting methodology employed for the synthesis of composites can be deemed dependable. Similar results was recorded by Alaneme et al. (16) in research on Influence of Rice Husk Ash – Silicon Carbide

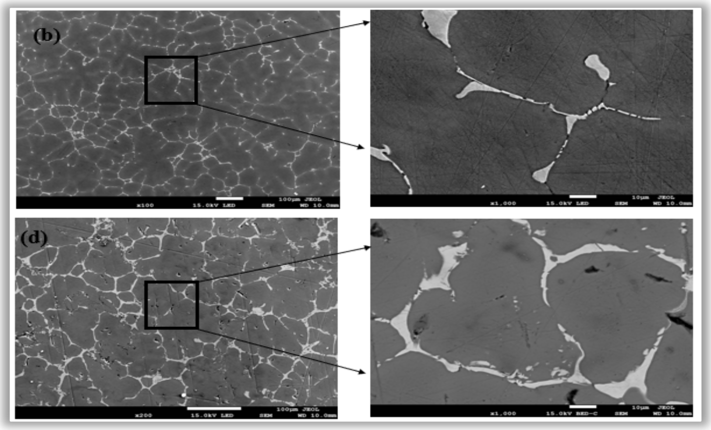

Figure 3. SEM photomicrograph of (b) Al–90%/Cu–7.5%/Al_2O_3–2.5% and (d) Al–90%/Cu–2.5%/Al_2O_3–7.5% sample composites

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Weight Ratios on the Mechanical behaviour of Al-Mg-Si Alloy Matrix Hybrid Composites. The microstructural result showed that, the RHA and SiC particles are shown to be evenly distributed throughout the Al alloy matrix, and there are no obvious large particle clusters. Hence, the segregation or sedimentation that happens constantly during the solidification of MMCs with components having varying densities and wettability properties is not a significant issue. Also Alaneme & Sanusi (9) presented similar results on Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite. This demonstrates the dependability of the two–step stir casting method used to produce the composites based on the microstructures. Furthermore, the EDS profiles of Al–90%/Cu–2.5%/Al_2O_3–7.5% presented in Figure 4–6 showed peaks of aluminium (Al), copper (Cu), carbon (C), magnesium (Mg), silicon (Si), oxygen (O), manganese (Mn), and traces of calcium (Ca), sulphur (S) and potassium (K). The presence of oxygen confirms the presence of Al_2O_3, which is the reinforcement used in the matrix. Also, the presence of carbon, sulphur and potassium may be due to the presence of Al_2O_3 or during the process of scaling and polishing the sample.

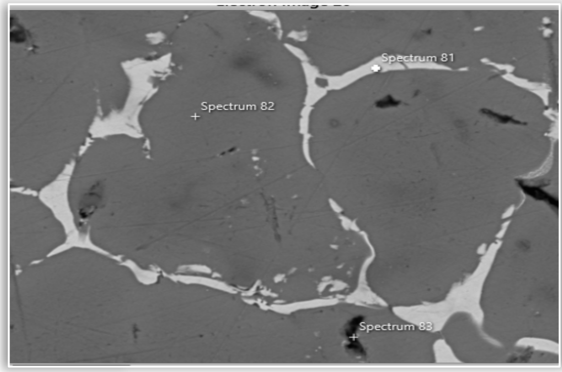

Figure 4. Secondary electron image of Al–90wt% matrix with Cu particles of 2.5wt. % and Al_2O_3 reinforcement of7.5wt% showing different spectra

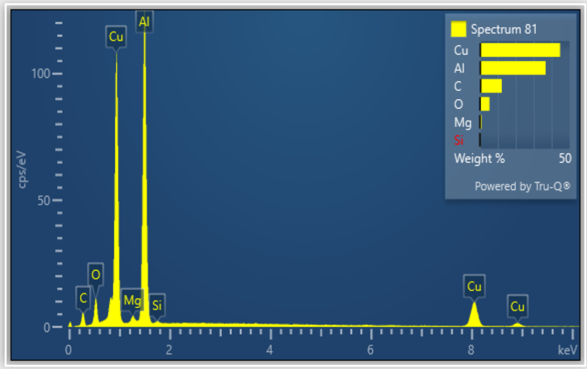

Figure 5. EDS profile for the sample at spectrum81

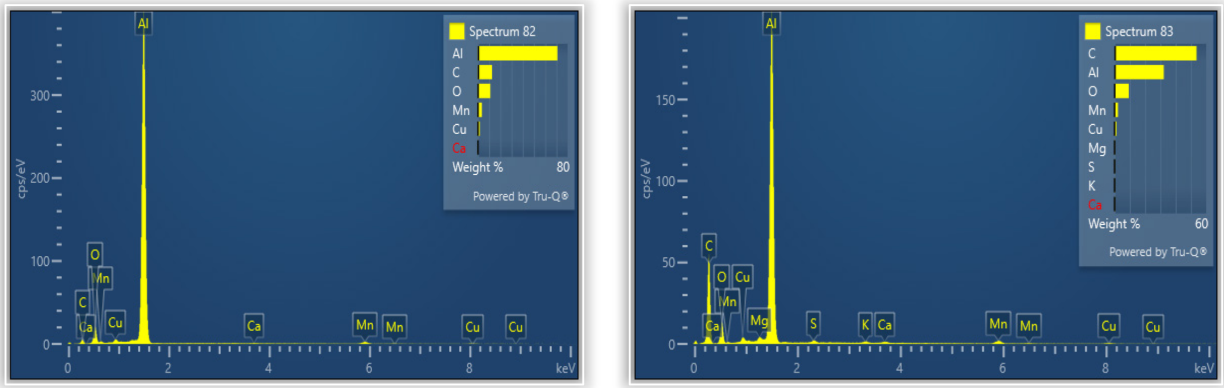

Figure 6. EDS profile for the sample at spectrum 82 and spectrum 83.

Mechanical Behaviour

The mechanical properties of the composites produced are presented in Figure 7–12.

— Hardness

The results of the hardness measurements of the single and hybrid reinforced composites are presented in Figure 7. It is noteworthy that samples A (90 wt.% Al, 0 wt.% Al_2O_3, 10 wt.% Cu) and sample D (90 wt.% Al, 7.5 wt.% Al_2O_3, and 2.5 wt.% Cu) demonstrated a lower hardness value compared to the control sample, except for samples B, C, and E. The reduction in hardness can be attributed to the dispersion of reinforced particles throughout the sample. Furthermore, the presence of pores has a detrimental effect on hardness, as depicted in Figure 2. As the porosity of the samples increases, the hardness decreases due to the increase in alumina content. However, among the samples that exhibited higher harness compared to the unreinforced composite, sample C (90 wt. % Al, 5 wt. % Al_2O_3/Cu) demonstrated the highest hardness value. This can be explained by a more uniform dispersion of reinforced particles throughout the sample and the strengthening effect of the hard Al2O3 oxide ceramic, as the hardness test was conducted at three different locations on each sample. Sample E (90 wt. % Al, 10 wt. % Al_2O_3, and 0wt. % Cu) and sample B (90 wt. % Al, 2.5 wt. % Al_2O_3, and 7.5wt. % Cu) demonstrated a higher hardness value than its unreinforced

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counterpart (control). The increase in hardness is attributed to the higher weight fraction of Al_2O_3 and Cu added to complement the hardness of Al. The percentage composition of each composite sample is shown in Table 2. Similar findings were reported by Mohammed et al. (17) for alumina particles reinforcement.

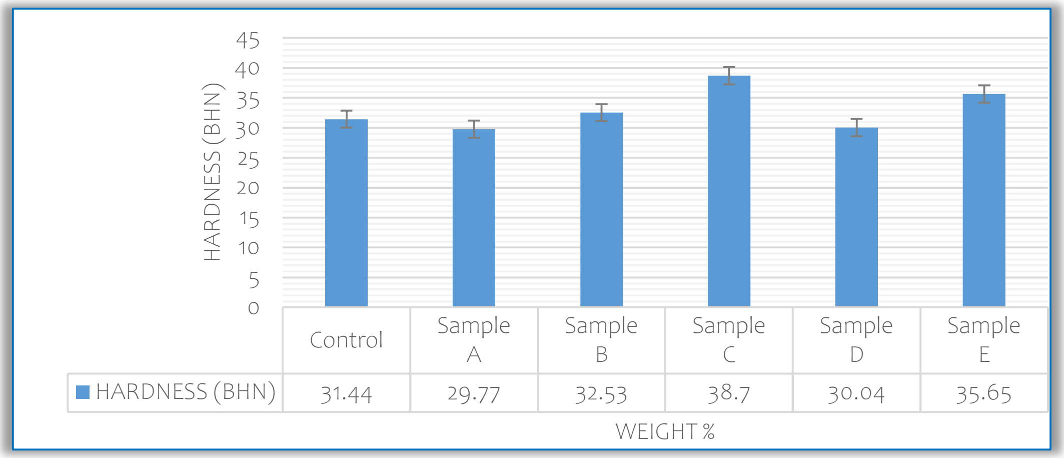

Figure 7. Variation of hardness with weight% of samples.

— Tensile Properties

The result of the variation of tensile stress on tensile strain is presented in Figure 8. It is observed that sample B (90 wt. % Al, 2.5 wt. % Al_2O_3, and 7.5 wt. % Cu) has the highest degree of tensile strain with a stress of about 82Mpa. Sample D and E (90 wt. % Al, 2.5 wt. % Al_2O_3, 7.5wt. % Cu; 90 wt. % Al, 10 wt. % Al_2O_3, 0wt. % Cu respectively) have the least elongation. Sample C (90 wt. % Al, 5 wt. % Al_2O_3/Cu) was able to withstand the highest load of about 103Mpa. It can be deduced that the decrease in elongation for sample A, C, D, and E was as a result of increase in addition of reinforcement particle to composite samples. Similar result was reported by Alaneme & Sanusi (9) where alumina, RHA and graphite were used as reinforcement material.

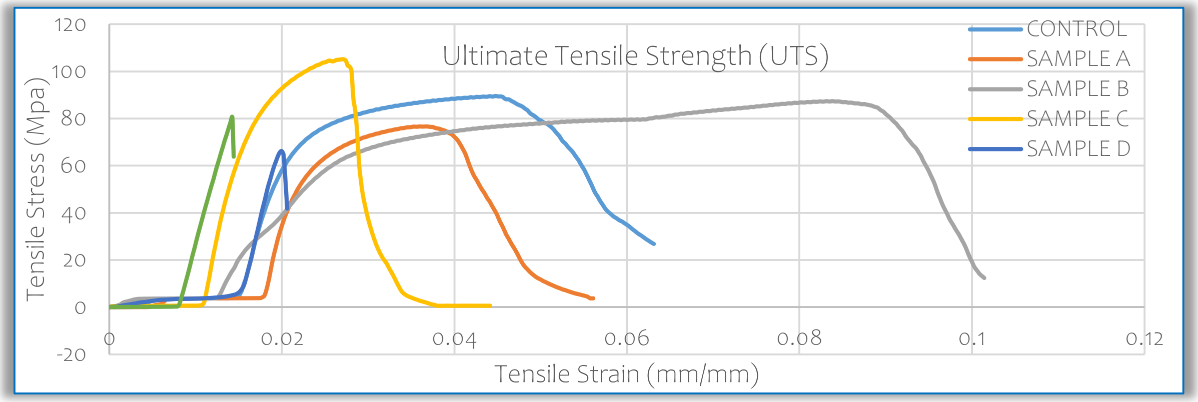

Figure 8. Variation of tensile stress with tensile strain of composite samples

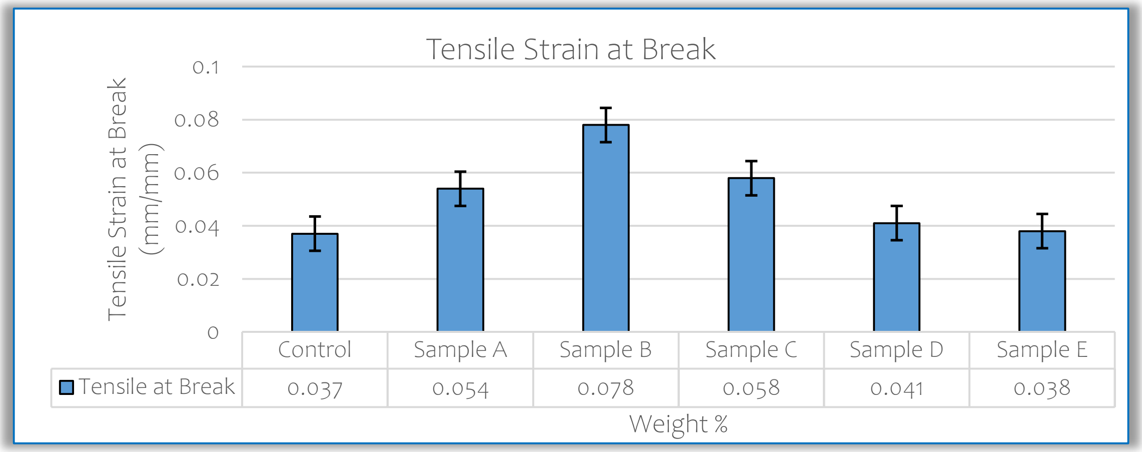

Figure 9. Variation of tensile strain at break with percentage weight of each sample

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As delineated in Figure 9, which illustrates the variation of tensile strain at break of composite samples, it is evident that the strain at break of the reinforced samples was superior when compared to that of the unreinforced sample and sample B (90 wt. % Al, 7.5 wt. % Cu, 2.5 wt. % Al_2O_3), which exhibited the highest strain at break. This finding indicates that sample B enhances the composite's ability to sustain greater plastic strain prior to fracturing when compared to other composite compositions produced. Moreover, the increase in hardness among the reinforced composites can be attributed to the utilization of the two stir casting method, which facilitated proper particle dispersion in the matrix.

The results for maximum tensile stress are presented in Figure 10, which reveals that the maximum tensile stress of the reinforced samples was greater than that of the unreinforced samples. Sample B (90 wt. % Al, 7.5 wt. % Cu, 2.5 wt. % Al_2O_3) exhibited the highest maximum tensile stress, which could be attributed to the proper dispersion of Al_2O_3 and copper in the matrix during casting. This finding indicates that the reinforced samples can withstand a greater load when compared to the unreinforced sample. Nonetheless, among the reinforced composites, sample E (90 wt. % Al, 0 wt. % Cu, 10 wt. % Al_2O_3) had the lowest maximum tensile stress, which could be attributed to the elevated addition of alumina and absence of copper. This finding suggests that this sample may not have the ability to withstand higher loads.

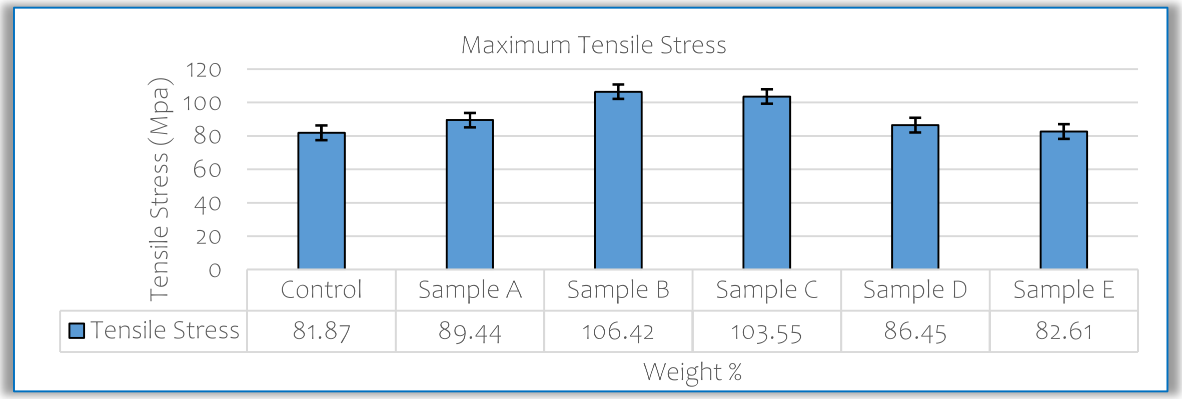

Figure 10. Variation of maximum tensile stress with percentage weight of each sample

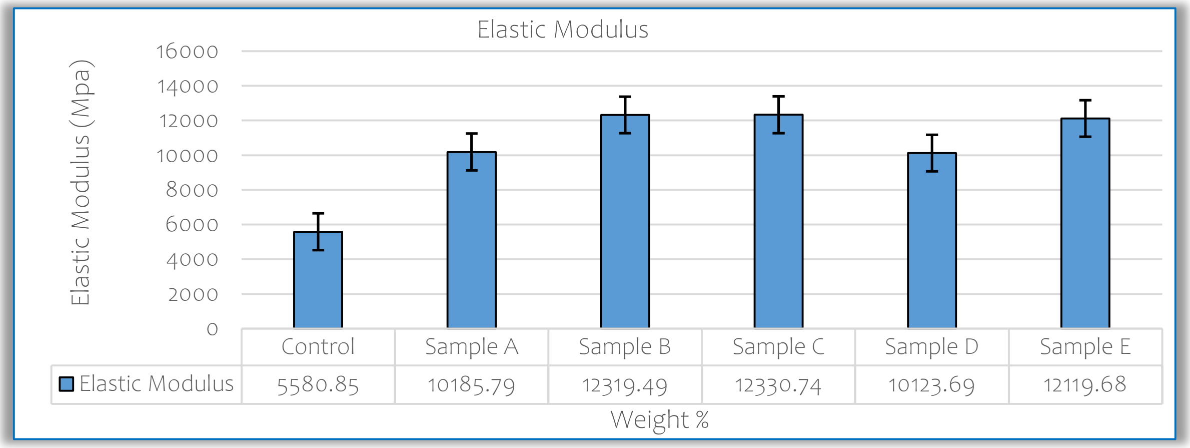

Figure 11. Variation of elastic modulus with percentage weight of each sample.

As depicted in Figure 11, which illustrates the elastic modulus of the produced composites, it can be observed that the reinforced sample C (90 wt. % Al, 5 wt. % Cu, 5 wt. % Al_2O_3) exhibited the highest elastic modulus. Elastic modulus is an indicator of a material's ability to resist elastic deformation under applied stress. Therefore, it can be inferred that sample C possesses the highest ability to resist elastic deformation compared to the other samples. This phenomenon could be attributed to the equal weight of alumina and copper added and the proper dispersion of the reinforcement in the matrix, as evidenced by the absence of agglomerates in Figure 2. However, samples A, B, D, and E had higher elastic modulus compared to the unreinforced composite, indicating that the reinforced samples exhibit higher stiffness than the unreinforced composite, but not to the extent of sample C. This variation in elastic modulus could be attributed to the difference in weight percentages of the added reinforcements. Furthermore, it can be observed that sample B (90 wt. % Al, 7.5wt. % Cu, 2.5wt. % Al_2O_3) exhibited a lower elastic modulus compared to the reinforced samples, indicating that it possesses lower stiffness than the other samples,

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thus making it more ductile. This can be attributed to the increased percentage of copper particles (7.5wt %) added to the matrix and the lower quantity of alumina (2.5wt %) added, as illustrated in Figure 8. The stress–strain curve for each sample, as shown in Figure 8, supports the results obtained for the elastic modulus.

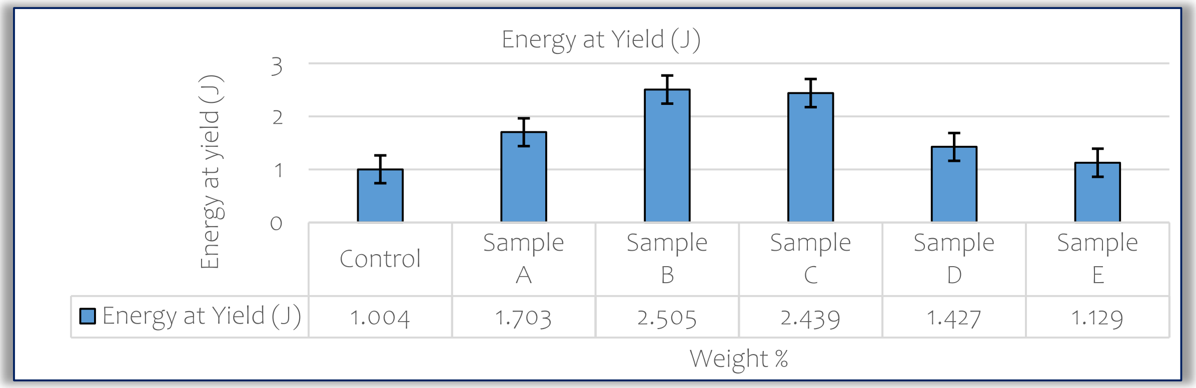

Figure 12. Variation of energy at yield with percentage weight of each sample.

Furthermore, the energy at yield, as shown in Figure 12, was analyzed. It can be observed that the energy at yield of the reinforced samples was higher than that of the unreinforced composite (control), with sample B (90 wt. % Al, 7.5wt. % Cu, 2.5wt. % Al_2O_3) exhibiting the highest yield energy. This indicates that the composite can absorb more energy before it begins to deform plastically, as yield energy is the ability of a material to absorb more energy before it begins to deform plastically. Therefore, it can be inferred that the material is more ductile. This result is consistent with the stress–strain curve shown in Figure 8. Additionally, it can be observed that sample E (90 wt. % Al, 0wt. % Cu, 10wt. % Al_2O_3) exhibited the lowest yield energy compared to the other reinforced composites. This could be attributed to the addition of only alumina and no copper, which exhibited high yield than the unreinforced sample, making it slightly ductile and possessing higher strength (toughness) than the unreinforced composite.

6. CONCLUSIONS

The microstructural characteristics and mechanical behaviour of Aluminium matrix hybrid composites reinforced with copper and alumina, was investigated in this research. The results show that:

- Samples A and D exhibited lower hardness values compared to the control sample, with the exception of samples B, C, and E, which displayed higher values relative to the control sample. Notably, sample C demonstrated the highest hardness value, which may be attributed to the more uniform dispersion of reinforced particles throughout the sample and the strengthening effect of the hard Al_2O_3 oxide ceramic.
- Regarding tensile properties, sample B displayed the highest elongation among all the produced composites, while samples A, C, D, and E had lower elongation compared to the unreinforced sample. The decrease in elongation may be attributed to an increase in the addition of reinforcement particles to the composite samples.
- The strain at break for the reinforced composites exceeded that of the unreinforced composite, with sample B demonstrating the highest strain and break. This indicates that sample B enhances the composite's capacity to sustain more plastic strain before fracture. The maximum tensile stress for reinforced composites was higher than that of the unreinforced composite, with sample B having the highest maximum tensile stress. This is an indication that the reinforced samples can withstand more load compared to the unreinforced sample.
- With the exception of sample B, which had a low elastic modulus, and sample E, which had no recorded value, the elastic modulus of reinforced samples A, C, and D was higher than that of the unreinforced sample. This implies that the reinforced samples A, C, and D will exhibit higher stiffness than the unreinforced sample. Sample C had the highest elastic modulus, indicating that the composite will resist deformation under elastic stress and is less ductile compared to the unreinforced sample. Meanwhile, sample B had the highest energy at yield, signifying that the sample can absorb more energy before it deforms plastically. Both results were in relation to the stress–strain curve.
- Microstructural analysis revealed that copper particles and Al_2O_3 reinforcements were present and distributed nearly uniformly throughout the metal matrix. This suggests that there is no significant

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problem of segregation, which often occurs during the solidification of MMCs having components with different densities and wettability characteristics, although pores were present in the microstructure. The EDS profile of sample D, having a composition of Al–90%/Cu–7.5%/Al_2O_3–2.5%, showed peaks of aluminum (Al), copper (Cu), carbon (C), magnesium (Mg), silicon (Si), oxygen (O), manganese (Mn), and traces of calcium (Ca), sulfur (S), and potassium (K).

Therefore, based on the outcomes of the mechanical property examinations, specifically the hardness and tensile tests, it can be concluded that sample B (consisting of Al–90%, Cu–7.5%, and Al_2O_3–2.5%) and sample C (comprising of Al–90%, Cu–5%, and Al_2O_3–5%) are the more appropriate choices for engineering applications that require optimal hardness and tensile properties. Nonetheless, further investigation and comparison of the microstructural and mechanical features of Al matrix–based composites with diverse additions of agro–waste reinforcement is warranted. Furthermore, an examination of the impact of copper and alumina on the wear and corrosion properties of aluminum alloys would also be valuable.

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