Investigation of The Effects of Varying Copper Concentrations on The Mechanical Properties of Aluminium

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Abstract

The effects of varying Cu concentrations on the mechanical properties of pure Al has been investigated. Seven samples of Al-Cu alloy systems with copper concentrations 0.0%,2.5%,5.0%,7.5%,10.0%,12.5% and 15.0% by wt% labelled A,B,C,D,E,F and G respectively were fabricated and subjected to hardness, tensile strength, yield strength, and ductility tests, optical microstructural examinations were carried out on each of the samples. Results showed that the tensile strength and hardness of the Al alloy samples increased with increase in copper concentration for all the samples, while the yield strength increased progressively from samples A to E and remained constant for samples E to G. However, the ductility of the samples decreased with increase in copper concentrations. The microstructural examinations of the alloy samples revealed decrease in the grain boundaries of Al-Cu alloy samples with increase in copper concentrations. This resulted to the increase in the hardness, tensile strength, yield strength and decrease in ductility as copper concentration increased. It can be concluded, that the mechanical properties of Al can be altered with systematic increase in copper concentration within the experimented samples.

Key words: Aluminium, Copper, Mechanical Properties, Grain Boundaries, Aluminium-copper alloy.

1.0 Introduction

Aluminum-copper alloy systems have found wide applications in mechanical structures such as construction of air crafts and airspace due to their desirable mechanical properties, machinability, lightness, formability and suitable surface appearance [6-8]. The wide applications and favourable properties have steered very large quantum of researches in the fabrications and utilizations of the Al-Cu alloys. The researches have centered on copper concentrations of range 3% and 10% weight percentage [3][5][10]. These researchers observed that addition of some percentage of copper in aluminium affects the mechanical properties such as impact energy, strength, hardness, fatigue and creep resistances as well as grain size and the electrochemical properties of the alloy. [5], attributed the increase in the mechanical properties and decrease in electrochemical potentials to the formation of AlCu intermetallic particles which are dispersed in the aluminium matrix. These particles are harder and more stable than the aluminium matrix. This may have accounted for the increase in the strength of the alloy.

The addition of copper affects the grain size, impact energy, flow stress and strain and mechanical characteristics of pure Al. According to [3], It can be seen that the addition of only 3 wt. % Cu resulted in grain refinement of aluminium as the average grain size is decreased by 50%, whereas, addition of Cu of 6 wt. % and 9 wt. % resulted in grain refinement of aluminium 69.2 % and 72.5 %, respectively. However, there is a direct relationship between the copper content and the reduction in the grain size diameter which is related to the enhancement of the mechanical characteristics of commercially pure Al. Also, addition of copper influences the impact energy in pure Al [10].

The impact energy may be defined as a measure of the work done to fracture a test specimen. Addition of Cu to pure aluminium increases the impact energy by 22.4%, 33 % and 43% for 3 wt. % Cu, 6 wt. % Cu and 9 wt. % Cu, respectively [3]. Further, copper addition to pure aluminium results in enhancement of the flow stress of pure aluminium by 85.7 %, 73.2 %, and 101.8 % for 3 wt. % Cu, 6 wt. % Cu and 9 wt. % Cu, respectively [3]. There is a direct relation between the copper addition and the mechanical characteristics and the value is higher for 3 wt. % Cu and 9 wt. % Cu additions, when compare to the value for 6% weight percent which may be considered optimal [3]. This can be attributed to the fact that the maximum solubility of copper in aluminium is about 5.65 %. Several studies on aluminium copper alloys systems were concentrated on copper compositions of 3% to 9% wt. [3] and 4% to 12% [1], 1% to 6% [9].

The effects of copper addition are not limited to the mechanical properties discussed so far but copper addition increases the density of the aluminium matrix, decreases the coefficient of thermal expansivity, heat and electrical conductivities, [4]. This research work investigates the effect of copper concentrations on the tensile strength, hardness, ductility and microstructure of Al-Cu alloys with copper percentage weights of 2.5%, 5.0%, 7.5%, 10.0%, 12.5% and 15% Cu wt. This is to obtain information on the mechanical properties of Al-Cu alloys for copper concentrations above 12%.

2.0 Materials and Methods

The fabrication of the aluminium- copper alloy systems were carried out using commercial pure aluminium pellet (99.9%) and pure copper (99.9%) in an electric resistance furnace. The Aluminum pellet was obtained from Inyishi Aluminium Extrusion Industry,Ltd, Nigeria, while copper was obtained from Shinko Fab Tech ltd. 14-1 ChoufuMinatomachi, Japan. From the copper material, six different copper concentrations of weight percentage of 2.5% to 15.0% added to the aluminium according to the weight percentage shown in table 2.1 and are designated B to G respectively while the pure aluminium is designated as A.

TABLE 2.1: Varying copper concentrations added to pure aluminium to make up the required 100 percentage.

SAMPLES	A	B	C	D	E	F	G
Al. wt.%	100	97.5	95.0	92.5	90.0	87.5	85.0
Cu. wt.%	0	2.5	5.0	7.5	10.0	12.5	15.0

Each of the metal samples of B to G were prepared by cutting both the aluminium and copper materials into small pieces and weighed proportionately and then each set of the samples was heated to a temperature slightly higher than 560^{0}C and stirred to ensure that the samples were properly melted and mixed. This is then cast into rods in a sand mould and allowed to cool in air for about 12 hours. Each of the fabricated samples was then prepared for tensile and hardness tests and microstructural observations. The results of the tensile tests recorded in table 3.1 were taken using a tensometer and the hardness tests were carried out using Brinell Hardness tester and the results are shown in table 3.2. The microstructural observations of each of the fabricated samples are shown in figure 3.10 using Metallurgical Microscope L201A. These samples were prepared after the surfaces were ground with Amery paper of grade #600 and #1200, polished using alumina/diamond paste, treated in a Keller reagent and allowed to dry in air before the microstructural observations.

3.0 RESULTS AND DISCUSSION

The results of the tensile stress, hardness, yield strength, and ductility tests with the microstructural examinations of the samples A to G of the aluminium alloys formed with different concentrations of copper are presented and discussed in this section.

3.1 Tensile Stress of the Aluminium-Copper Alloyed Systems

The results of the tensile stress tests obtained for the aluminium alloy samples of various concentrations of copper are presented in the figure 3.1.

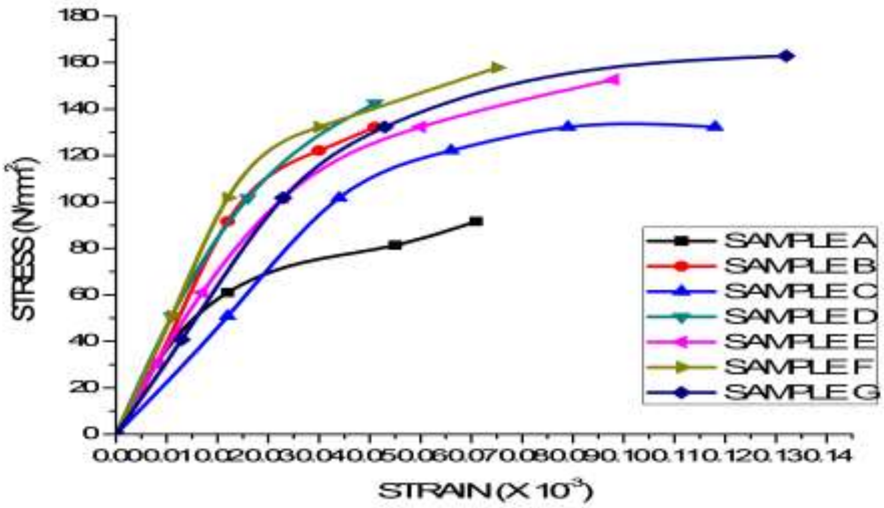

Fig. 3.1: **Variation of stress with strain of aluminium copper alloys with different concentrations of copper for samples A to G.**

The figure 3.1 shows the graphs of stress – strain for aluminium and aluminium- copper alloys systems. Definitely, these graphs exhibit typical stress – strain characteristics for metals and their alloys. The graphs show two distinctive features: regions of proportionality or elastic region and the plastic deformation region. The elastic regions for the alloy samples have been shown to increase with increase in copper concentrations. The elastic limits increase in the order for the alloy samples: A<B<C<D<E<F<G. This shows that the elastic regions of the samples increase with increase in the concentration of the copper materials.

The gradient of tensile stress- tensile strain graphs determines the Young modulus for particular metals and their alloys. For the aluminium and aluminium-copper alloys under study, it is observed that for all the alloys the gradients are higher than that of sample A with no copper addition. This is attributed to the fact that as the aluminium is alloyed with copper, its Young modulus is increased. It is therefore evident that tensile stress and Young modulus are increased as a result of addition of copper to the aluminium. It also shows that additional energy is required to break the bonds of the favoured pairs of reacting atoms in the alloy formation [2]. This shows that the aluminium and copper atoms must have strong affinity of each other which necessitated to forming strong bonds that eventually results to higher tensile strength and hence higher modulus of elasticity.

From fig. 3.1, we observed for SAMPLE A, that from the origin to point 30.5N/mm^{2}on the stress axis, Hooke's law is obeyed. The yield strength, YS, of sample A is 61.0N/mm^2. The yield strength of a material is a measure of its resistance to plastic deformation. From fig 3.1 above, the proportionality limit is at 30.5N/mm^2. The yield strength of sample A above is read off using strain offset method, usually 0.02%. Its tensile strength is read off and obtained to be 91.60 N/mm^2. The tensile strength of a material is the stress at the maximum on the engineering stress-strain curve. The ductility is recorded as 13.2%, with L_o = 30.0mm and L_f = 33.96mm.

In SAMPLE B, it can be seen that Hooke's law was obeyed from origin to point 91.6 N/mm^2 stress. The yield strength is 91.60 N/mm^{2}and its tensile strength is 132.3 N/mm^2 at strain 0.051 above which fracture occurred. This shows that the strength has improved with the addition of 2.5% copper. The ductility of the alloy reduced to 11.8% at L_0 = 30.0mm and L_f = 33.54mm.

The result of SAMPLE C showed that Hooke's law is obeyed from origin to point 101.8 N/mm^2. Yield strength of 122.1 N/mm^2 and a tensile strength of 132.3 N/mm^2 at a strain of 0.089. Fracture occurred after a little extension. The ductility is recorded as 9.8% at L_0 = 30.0mm and L_f = 32.94mm. The result above shows that tensile strength was improved as 5.0% Cu was added and the ductility was reduced.

From the graph above (fig. 3.1), SAMPLE D obeyed Hooke's law from origin to point 101.8 N/mm^2. A yield strength of 128.20 N/mm^2 is observed and a tensile strength of 142.50 N/mm^2 at strain of 0.051. The ductility was reduced to 7.5% at L_0 = 30.0mm and L_f = 32.25mm. The result above shows that the strength is increased at the addition of 7.5% Cu and the ductility reduces further.

The result above (fig. 3.1) shows that, SAMPLE E obeyed Hooke's law from origin to point 101.8 N/mm^2. A yield strength of 132.30 N/mm^2 is observed and a tensile strength of 152.7 N/mm^2 at strain of 0.098. The ductility was reduced to 7.1% at L_0 = 30.0mm and L_f = 32.13mm. The result above shows that the strength is increased at the addition of 10.0% Cu and the ductility reduces further.

From the above result (fig. 3.1), it is observed that SAMPLE F has yield strength of 132.30 N/mm^2 and a tensile strength of 157.8 N/mm^2 at strain of 0.075. The ductility was reduced to 7.1% at L_0 = 30.0mm and L_f = 31.53mm. Hookes's law is obeyed from the origin to 101.8 N/mm^2. We can observe from above that the strength is increased at the addition of 12.5% Cu and the ductility reduces further.

From the graph above (fig. 3.1), SAMPLE G obeyed Hooke's law from origin to point 101.8 N/mm^2. A yield strength of 132.30 N/mm^2 is observed and a tensile strength of 162.9 N/mm^2 at strain of 0.0132. A ductility 5.0% is recorded at L_0 = 30.0mm and L_f = 31.50mm. The result above shows that the tensile strength is increased at the addition of 15.0% Cu and the ductility reduces further.

3.2 Yield strength for Aluminium–Copper alloyed systems

The yield strength is obtained from the stress-strain graphs of the samples. It is normally obtained at a point just after the elastic limits, and this is plotted against the copper concentrations and is shown in figure 3.2.

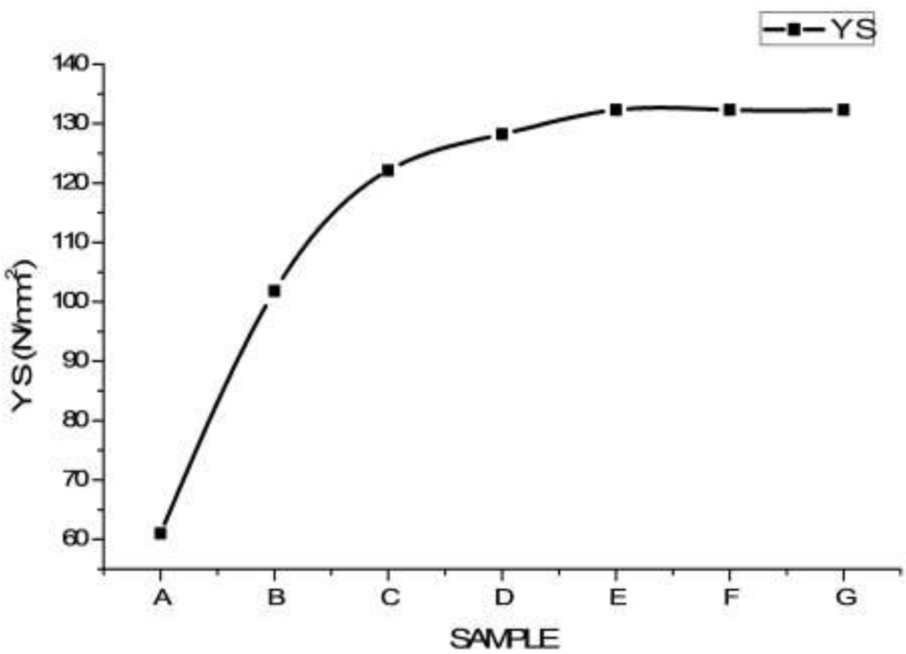

Fig. 3.2 A graph of Yield strength against copper concentrations of alumimun and aluminum copper designated samples A to G.

Fig. 3.2 depicts the variation of yield strength with the fractional copper addition in aluminum matrix to form aluminum copper alloys. It can be observed that the yield strength increases linearly with increase in copper fraction concentration from 2.5% to 10.0%, at 132.3 Nmm^{-2} and then remains at this value for 12.5% and 15.0%. This suggests that 10.0% copper addition in aluminum–copper alloy system would form an optimum fractional composition for this alloy system. The implication of the observation of the graph in fig. 3.2 is that the resistance offered by the aluminum –copper alloys to a plastic deformation increases with the copper fractional addition up to 10%, further addition may not result to increase in yield strength. The yield strength of the samples increased linearly from sample A to sample E (from 61N/mm^2 to 132.3 N/mm^2) as shown on fig. 3.2, where it then became constant at 132.3 N/mm^2 for samples E, F and G. It is observed that yield strength is optimal at sample E i.e. 90%wt Al 10%wt Cu.

Comparison of the ultimate tensile strengths and yield strengths of the fabricated Al-Cu alloy system, it is observed that optimum yield strength is obtained at 10% copper concentration while higher ultimate tensile strength is obtained even above 10% copper addition. This implies that in terms of applications if yield strength of the material is the emphasis or the requirement then excess of 10% copper addition would amount to wastage. But if the ultimate tensile strength is to be explored then 10% fractional copper addition or more up to 15% may be permissible.

3.3: Ductility of Aluminum and fabricated aluminum–copper alloy samples

A variation in ductility of the samples is shown in fig. 3.3.

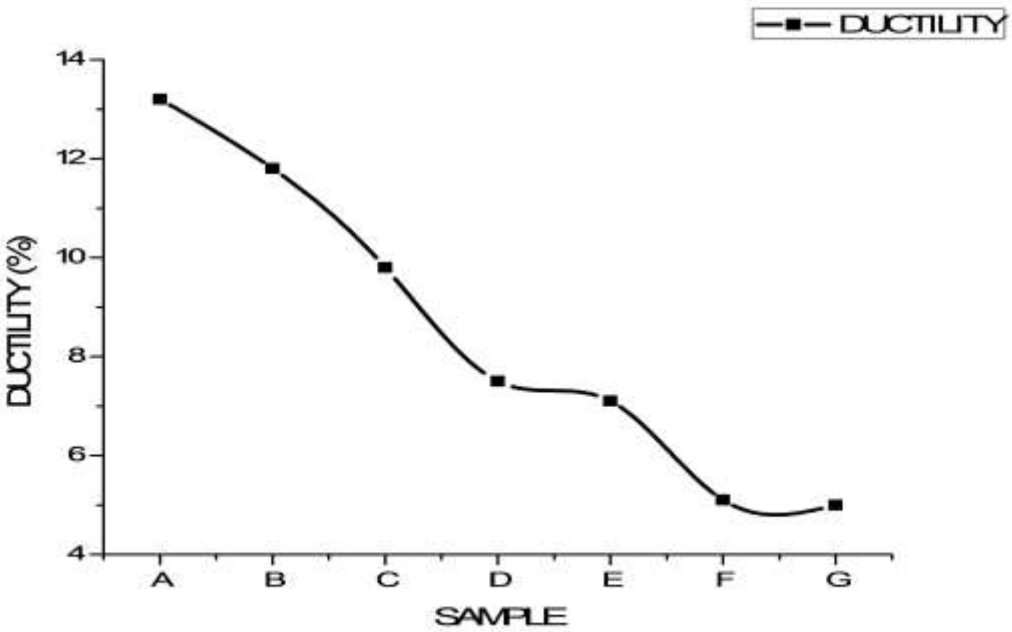

Fig. 3.3: Ductility of SAMPLES A to G

Figure 3.3 shows a fairly rapid decrease in the percentage ductility of the composite up to 5.1% Cu beyond which the decrease slows down. The decrease in percentage ductility follows from the increase in tensile and yield strength. This can also be from the point of view that the dislocation movement results in improved ductility.

The variations of ultimate tensile strength, yield strength and the ductility of the samples A to G with concentrations of copper are shown in the table 3.1. From this table it can be observed that the addition of copper to aluminium to form an Al-Cu alloy has tremendous effects on the ultimate tensile strength, yield strength and ductility. The addition of 2.5% wt. copper to aluminium caused a jump from 91.6 Nmm^{-2} to 132.3 Nmm^{-2} in the UTS, but remained there for 5%, thereafter it continues to increase with increase in copper concentration. The value for yield strength jumped from 61.0 to 101.8 Nmm^{-2} and continued to increase until it reached a maximum of 132.3 at 10% addition of copper and remain there for values of 12.5 % and 15%. There is a progressive decrease in ductility from 13.2% to 5.0% for samples of 0% to 15% copper concentrations.

Table 3.1: Variation of ultimate tensile strength, yield strength and ductility of the aluminium alloys with different concentrations of copper.

SAMPLE	Wt% of Cu	Ultimate Tensile Strength (N/mm^2)	% ductility	Yield Strength (N/mm^2)
A	0.0	91.6	13.2	61.0
B	2.5	132.3	11.8	101.8
C	5.0	132.3	9.8	122.1
D	7.5	142.5	7.5	128.2
E	10.0	152.7	7.1	132.3
F	12.5	157.8	5.1	132.3
G	15.0	160.9	5.0	132.3

3.4 Hardness test result

Hardened Al-Cu alloy is tested on Brinell scale with the diamond indenter and a 150kg major load and the following results where gotten:

Table 3.2: Indenter diameter (D_1), indentation (D_2) and hardness of the samples.

Prop. /samples	A	B	C	D	E	F	G
D_1(mm)	1.31	1.42	1.30	1.28	1.24	1.41	1.36
D_2(mm)	1.34	1.44	1.31	1.26	1.20	1.40	1.31
Daverage(mm)	1.325	1.430	1.305	1.270	1.220	1.405	1.335
HBW	35.40	41.20	41.90	43.30	44.80	44.90	50.10

F=612.90N

From the Table 3.2 above, it can be seen that the hardness was lowest in SAMPLE A (100%Al, 0%Cu) which has HWB value of 35.40. The addition of copper showed an increase in the hardness in SAMPLE B (97.5%Al, 2.5%)

with HBW 41.20. SAMPLE C (95.0%Al, 5.0%Cu) showed further increase in the HBW of 41.90. An increase in HBW was observed in SAMPLE D with value of 43.30. SAMPLE E and F showed further increase in the HBW. SAMPLE G (85.0%Al,12.5%) which has the highest value of copper addition showed the largest value in the hardness test with a HBW value of 50.10, see fig 3.4.

The result shows that there is a continuous increase in the HBW values as the copper content is increased. Therefore, hardness increases with increase in copper concentration.

The result is in line with [9], where it was observed that increasing the copper content of 1 to 6%, the hardness increases from 45 to 118 HB.

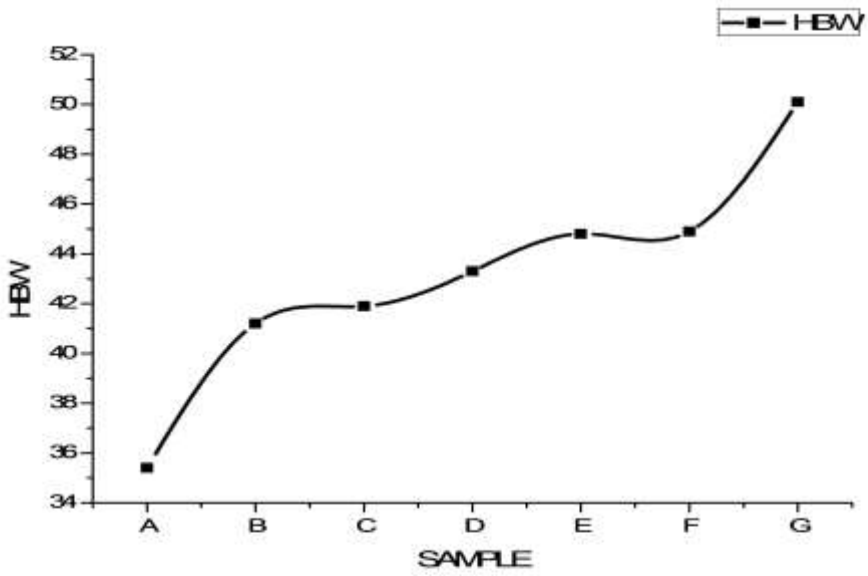

Fig 3.4 A chart of HBW (Hardness Brinell test) for the samples.

From fig 3.4, it is observed that the hardness increased from 35.40HB to 50.10HB as the copper content was increased from 0% to 15% weight.

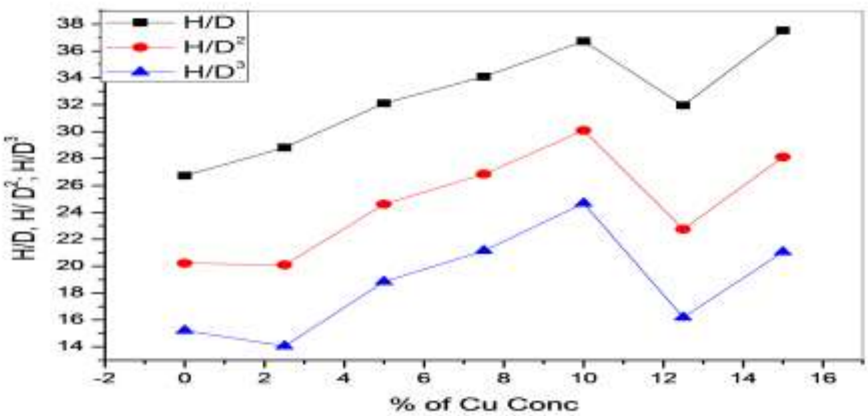

Fig. 3.5: Combined graph of H/D, H/D^2 and H/D^3 against % concentration of Cu for the designated samples

Table 3.3: Tensile properties of reinforced Al with different wt.% of Cu

SAMPLE	Wt% of Cu	Ultimate Tensile Strength(N/mm^2)	% ductility	Yield Strength (N/mm^2)
A	0	91.6	13.2	61.0
B	2.5	132.3	11.8	101.8
C	5.0	132.3	9.8	122.1
D	7.5	142.5	7.5	128.2
E	10.0	152.7	7.1	132.3
F	12.5	157.8	5.1	132.3
G	15.0	160.9	5.0	132.3

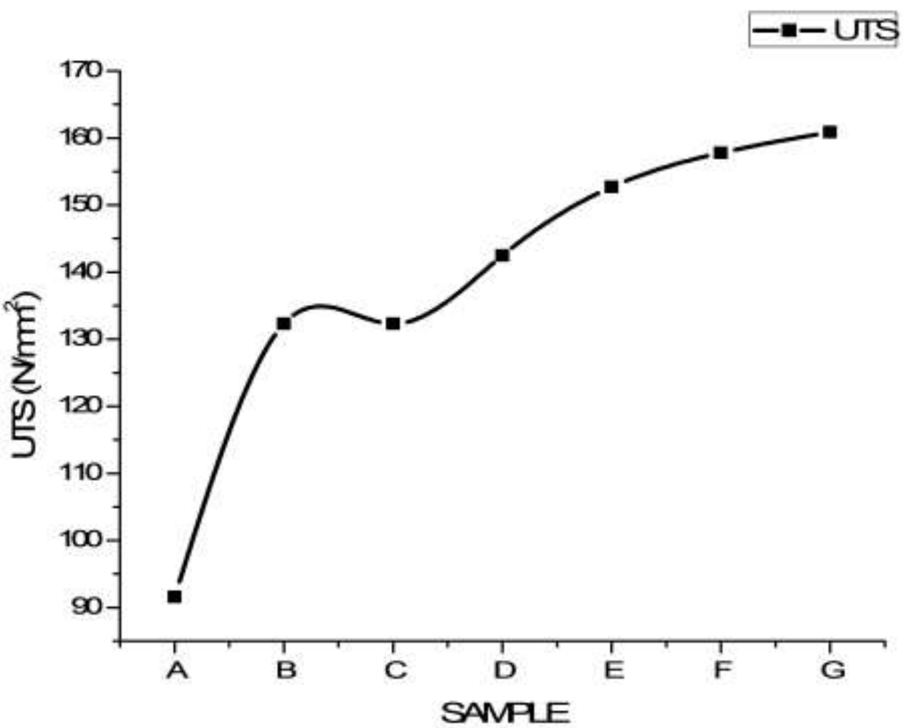

Fig 3.6: Ultimate tensile Strength

Figure 3.6 above shows that the % UTS increases with increase in the weight percent copper throughout the entire range of weight percent copper. At samples B and C, the UTS was constant and a linear increase continued from sample C to G.

3.5 Micro-Structure Examination Results

The micro-structure of pure aluminium and alloys of varying concentrates of copper was obtained using the optical microscope as shown below

Sample A The result of the micro examination showed that the grain boundaries were wider.

SAMPLE B The grain boundaries were reduced with the addition of Cu. (2.5%)

SAMPLE C it is observed that the grain boundaries were further reduced at 5.0% Cu.

SAMPLE D The grain boundaries were reduced the more at copper addition of 7.5%

SAMPLE E The grain boundaries were reduced further at 10.0% Cu

SAMPLE F The grain boundaries were reduced further at 12.5% Cu

SAMPLE G The grain boundaries were the most reduced at 15.0% Cu

Fig 3.7 Micrograph picture of samples A-G (Magnification of sample A –G × 400)

The micrographs show the effects of addition of different wt. % Cu to aluminium on the microstructure of the resulting aluminium matrix composite. Fig 3.7(A) shows the photomicrograph of the aluminium without any copper reinforcement. The homogeneity of the morphology is crystal clear. However, on addition of Cu, the change in morphology is again very clear from figures 3.7(B) to (G) where the Cu particles are visible along the aluminium matrix. The Cu particles gradually form a network in the aluminium matrix as its wt. % increases from 2.5% to 15.0%. This actually explains the reason for the improvement in strength of the system as wt. % Cu is increased as was seen in the tensile properties earlier discussed. These networks look like the branched chains found in high molecular weight polymer materials that account for their high mechanical strength.

The result of the microstructure examination therefore, implied that increase in the addition of Cu concentrations to the pure aluminium resulted to the reduction of the grain boundaries which in turn resulted an increase in the strength of the alloys and a decrease in its ductility.

4.0 Conclusions

The effects of varying copper concentration on the mechanical properties of aluminium have been investigated. The addition Cu particulate reinforcement to aluminium matrix significantly affects the physical properties of aluminium. The results obtained show that increasing the weight percent of copper in the aluminium matrix result in significant increase in the ultimate tensile strength, yield strength and the hardness values of the resulting Al-Cu alloy material. On the other hand, the ductility of the alloy is found to decrease with increasing copper content. Looking critically at the trend in %ductility, %yield strength and microstructure, the mechanical properties of pure aluminium using copper concentration ranging from 2.5%wt to 15.0%wt showed a linear increase in hardness and improved optimally the mechanical properties of aluminium.

Competing Interests

Authors have declared no competing interests regarding the publication of this paper.

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