The Effect of Copper Addition on the Amenability to Precipitation Hardening of Al-Si-Fe-Alloy

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ABSTRACT

The effect of copper addition on the amenability to precipitation hardening of the as-cast Al-Si-Fe alloy was investigated. The percentage copper in the alloy was varied from 2 to 8%. It was observed that all three mechanical properties (Hardness Tensile Strengths and Impact Energy) of the as-cast alloys increased after precipitation hardening for all levels of copper addition considered. However, beyond 4% Cu addition, the hardness and the tensile strength of the precipitation hardened alloys began to fall, while the impact energy of both the as-cast and precipitation hardened alloys generally decreased with increase in copper addition.

Keywords: AL-Si-Fe alloy, Copper addition, Effect and Precipitation hardening

INTRODUCTION

Aluminium alloys are the largest proportions of non-ferrous alloys used in the production of automotive components, buildings and constructions, containers and packaging, marine, aviation, aerospace and electrical industries /1/. They are characterised by light weights, corrosion resistance and excellent resistance against corrosive elements in the atmosphere, water (including salt water), oils and many other chemicals /2/. They are highly reflective to radiant energy, visible light, heat and electromagnetic waves apart from possessing high strength, excellent machinability and good resistance to scratching (hardness). As a result of the possession of these mechanical properties, aluminium alloys can be forged, stamped, extruded and sand cast /3/. Aluminium based alloys also have high thermal conductivity and low coefficient of linear expansion values and based on these two properties, they can be forged to the desired shapes at elevated temperatures and then solution treated and aged hardened to obtain desired microstructures and excellent mechanical properties /4/. The Al-Si-Fe-Cu alloy system represents the largest volume of aluminium alloys produced by

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sand casting method /3/. The alloy provides good combination of cost, strength, corrosion resistance, together with high fluidity and freedom from hot shortness /5/. The compositional specification of these alloys rests mainly on the iron, silicon and copper contents, while addition of copper alone imparts to the alloy the ability to be sand cast. Copper also increases strength, fatigue properties and make the alloys responsive to heat treatment /6/. While Iron also increases strength and hardness, reduces tendency to hot cracking while Silicon improves the fluidity of the molten metal as well as its castability and mechanical properties /7/. Based on these properties these alloys have found wide applications as manifolds, valve bodies, automotive cylinders heads and pistons /8/. Precipitation hardening is the most common heat treatment process used in improving the mechanical properties of aluminium alloys. Works carried out on Al-Cu and Al-Si alloys /9/ showed that age hardening through precipitation hardening strengthens them. Interactions of the various phases in the alloy systems during precipitation and how the interactions affect their mechanical properties have not been studied. Hence, the objective of this work is to investigate the effects of copper addition on the response of the alloy system to precipitation hardening heat treatment.

MATERIALS AND METHODS

Materials

Aluminium alloys of varying composition of Cu and constant percentage of Si and Fe (Table I) were produced at the foundry shop of the National Metallurgical Development Centre, Jos. The alloys were produced using high purity copper and aluminium electrical wires obtained from the Northern Cable Company NOCACO (Kaduna) while the iron and silicon were introduced as high purity ferrosilicon.

Table I

Composition of the As- Cast Alloy Systems

Specification	%Si	%Fe	%Cu	%Al
1	1.2	0.384	----	Bal
2	1.2	0.384	2	Bal
3	1.2	0.384	4	Bal
4	1.2	0.384	6	Bal
5	1.2	0.384	8	Bal

METHODS

The alloys were cast into bars of diameter 20mm and 300mm length. The bars were then cut and machined into tensile, impact and hardness test samples. Some of the machined test samples were then solution heat-treated at temperatures of 490°C in an electric heat-treatment furnace at a heating rate of 7°C / minute and then soaked for six (6) hours at this temperature before quenching in water. After quenching, they were aged at 200°C for six (6) hours before cooling in air /2, 14/. After ageing, the tensile strengths, hardness values, impact energy and microstructure of all the specimens were determined.

Determination of the Tensile Strengths

The tensile strengths of the machined specimens were determined using a Denison universal tensile testing machine. The test pieces were machined to the standard shape and dimensions as specified by the American Society for testing and Materials (ASTM standard of 1990) /10/. The test began by first of all marking the specimen gauge length with prick punch marks, then measuring the cross-sectional area of the reduced section. The specimens were then locked securely in the grips of the upper and lower crossbeams of the testing machine. A small load was initially applied to seat the specimen in the grips and then the load was increased until failure occurred.

Ultimate Tensile Strength (UTS)

The ultimate tensile strength (UTS) was determined from the relationship /7/.

$$\text{UTS} = \frac{P_{max}}{A_o} \qquad (1)$$

where

Pmax is the maximum load from the graph (Pmax),

(A_o) is the original cross sectional area of the test specimen

Yield strength (δ_y)

The convention denoting 0.2% offset was used in determining the yield strength. Selecting 0.002mm by 1mm scale and drawing a line parallel to the elastic or linear portion of the load-extension curve did this. The intersection of this line with the load-extension curve gave the yield load (Py) and the ratio of the yield load to the original cross sectional; area (A_o) gave the yield strength /7/.

$$\delta_y = \frac{P_Y}{A_o} \tag{2}$$

Percentage elongation (%∑)

This was determined by fitting together the broken halves of the specimen and measuring the distance between the original gauge marks and then it was estimated from the relationship /7/.

$$\%\sum = \left(\frac{L_f - Lo}{Lo}\right) \times 100 \tag{3}$$

where

L_f= Final gauge length

L_o= Original gauge length

Percentage reduction in cross-sectional area (%RCSA)

This was determined using the measured values of the areas of the necked–down portion of the failed specimen and that of the initial/original specimen. The percentage reduction in cross sectional area was then estimated from the relationship /7/.

$$\%RCSA = \left(\frac{A_O - A_F}{A_O}\right) \times 100 \tag{4}$$

where

A_o = Original cross-sectional area

A_f= Final cross-sectional area

Hardness values determination

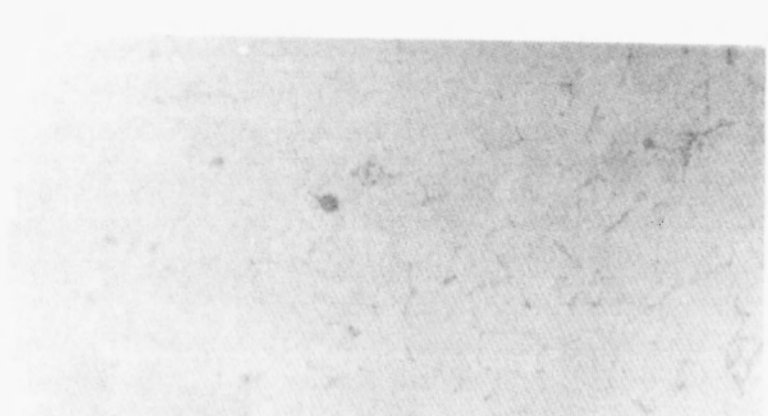
The hardness values of the specimens were determined using the Rockwell hardness tester on "B" scale with 5mm steel ball indenter, minor load of 10kg, major load of 100kg and hardness value of 101.2HRB as the standard block. Before the test, the mating surface of the indenter, plunger rod and test samples were thoroughly cleaned by removing dirt, scratches and oil and calibration of the testing machine using the standard block. The samples were placed on anvils, which act as a support for the test samples. A minor load of 10kg was applied to the sample in a controlled manner without inducing impact or vibration and zero datum position was established, and then the major load of 100kg was then applied; the reading was taken when the large pointer came to rest or had slowed appreciably and dwelled for up to 2 seconds. The load was then removed by returning the crank handle to the latched position and the hardness value read directly from the semi automatic digital scale /10/. Three readings were taken for each sample with the average value taken as the hardness value for a sample.

Impact Strength Determination

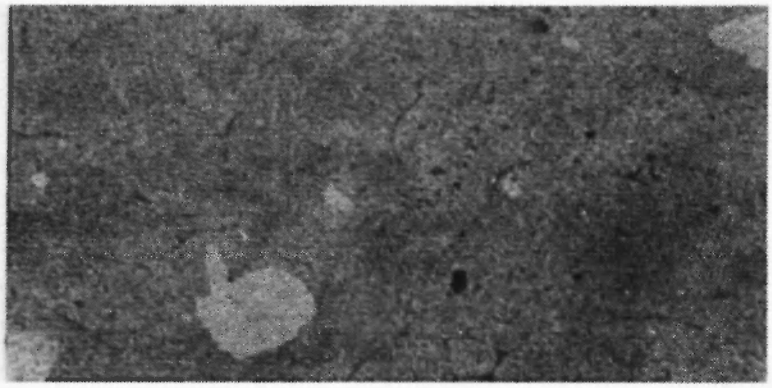
The impact test was carried out according to the recommended standard Charpy V-notched method and each test specimen was prepared to that specification. Before the test specimen was mounted on the machine, the pendulum was released to zero the scale. The test specimens were then gripped horizontally in a vice and the force required to break the bar was released from the freely swinging pendulum. The value of the angle through which the pendulum has swung before the test specimen was broken corresponded with the value of the energy absorbed in breaking the sample and this was read from the calibrated scale on the machine /10/.

Microstructural Examination

Metallographic specimens were cut from the as-cast alloy and age-hardened alloy. The cut specimens were then mounted in Bakelite, and mechanically ground progressively on grades of SiC impregnated emery paper (80-600 grits) sizes using water as the coolant. The ground specimens were then polished using one-micron size alumina polishing powder suspended in distilled water. Final polish was done using 0.5 micron alumina polishing powder suspended in distilled water. Following the polishing operation, etching of the polished specimen was done using Keller's reagent /5/. The structures obtained were photographically recorded using an optical microscope with built in camera. The photomicrographs are given in micrographs1 to 10.

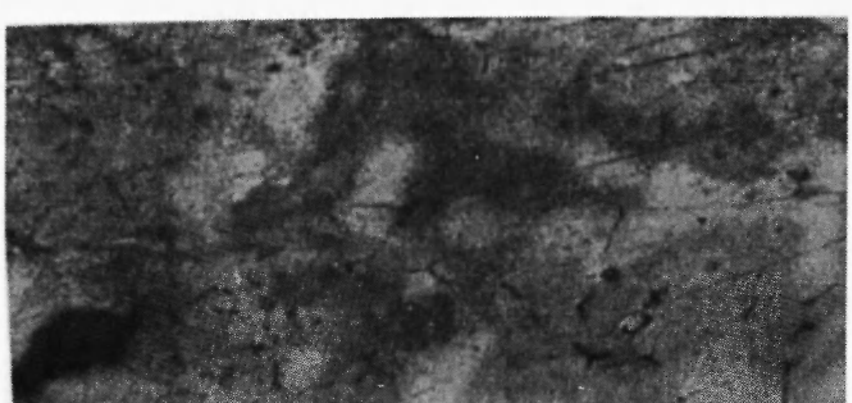


Micrograph 1: Al-Si-Fe Alloy (0% Cu) Network of Fe_2SiAl_8 Eutectic and Particles of $FeAl_2$ (black)



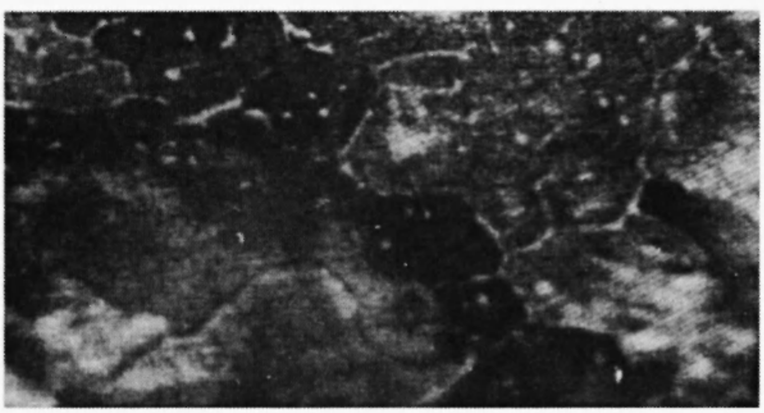
Micrograph 2: Al-Si-Fe Alloy (0% Cu) Aged. Precipitation of Network Fe_2SiAl_8 Eutectic and Particles of $FeAl_2$ (black)

Micrograph 3: Al-Si-Fe Alloy (2% Cu) Network of Fe_2SiAl_8 Eutectic and Particles of $CuAl_2$ (black)

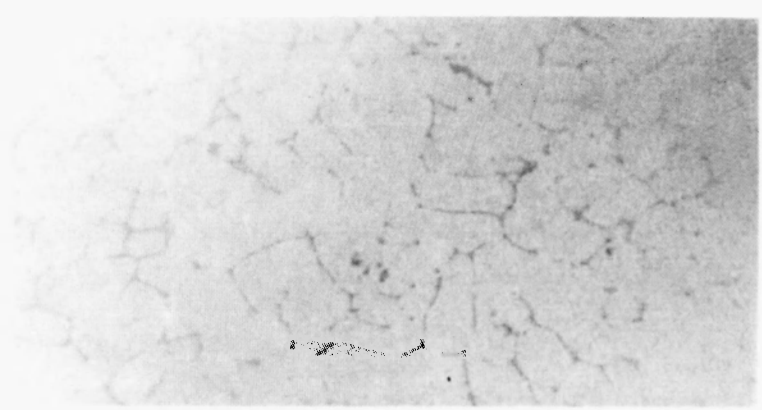


Micrograph 4: Al-Si-Fe Alloy (2% Cu) Aged. Precipitation of Network Of Fe_2SiAl_8 Eutectic and Particles of $CuAl_2$ (black)

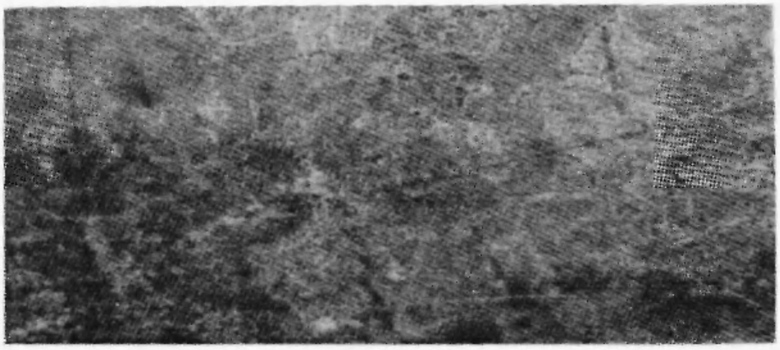
Micrograph 5: Al-Si-Fe Alloy (4% Cu) structures of interdendritic $CuAl_2$ (Gray)



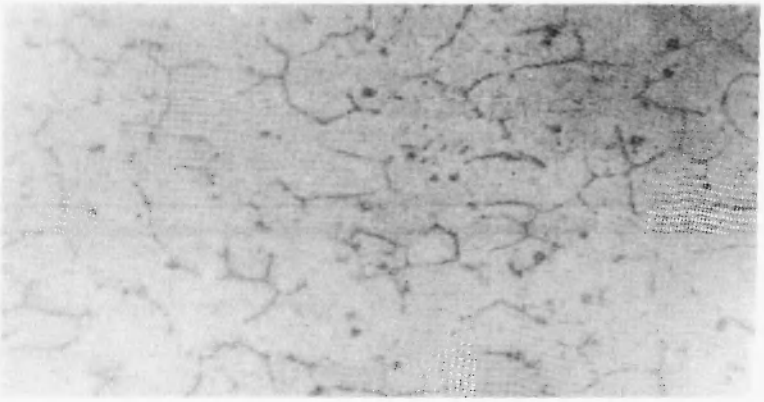
Micrograph 6: Al-Si-Fe Alloy (4% Cu) Aged. Precipitation of coarse eutectic $CuAl_2$ (Gray) to form a lacy network of $CuAl_2$



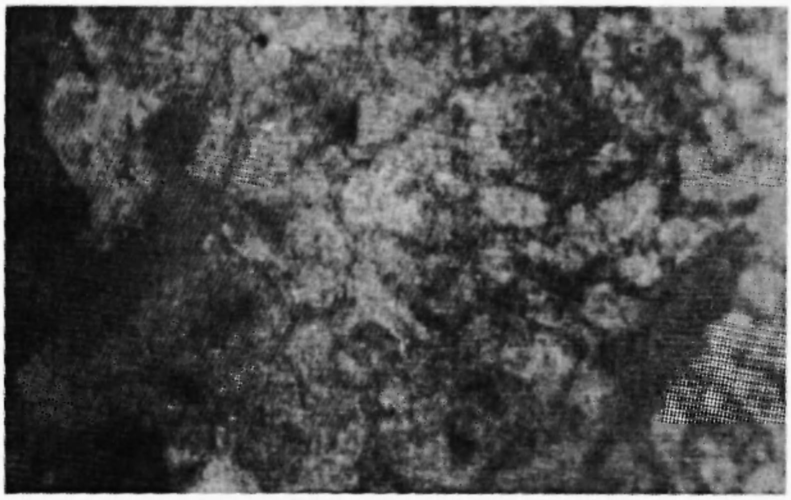
Micrograph 7: Al-Si-Fe Alloy (6% Cu) structures of interdendritic $CuAl_2$ (Gray)



Micrograph 8: Al-Si-Fe Alloy (6% Cu) aged. Precipitated, coarse interdendritic structures of $CuAl_2$ (Gray)



Micrograph 9: Al-Si-Fe Alloy (8% Cu) coarse interdendritic $CuAl_2$ (Gray) containing some Fe_2SiAl_8 scripts



Micrograph 10: Al-Si-Fe Alloy (8% Cu) Aged. Precipitation of coarse interdendritic structures and eutectic of Fe_2SiAl_8 (gray scripts)

RESULTS AND DISCUSSIONS

Results

The mechanical properties of the as-cast and precipitation hardened alloys are given in Tables II - VI and Figures 1-4 while their microstructures are given in micrographs 1 to 10.

Table II

The hardness values of the as-cast alloys

% of Cu Addition	Hardness Values (HRB)			
	1st	2nd	3rd	Mean (HRB)
0	18.0	20.0	21.0	19.7
2	23.0	22.5	21.5	22.3
4	49.0	49.0	49.7	49.7
6	44.0	47.5	45.0	45.5
8	39.0	36.0	32.0	35.7

Table III

The hardness values of the precipitation hardened alloys

% Copper Addition	Hardness Values (HRB)			
	1st	2nd	3rd	Mean (HRB)
0	19.7	20.7	21.0	20.5
2	28.0	32.0	30.0	30.0
4	58.0	57.0	55.0	56.7
6	55.0	57.0	57.0	56.3
8	41.0	38.0	44.0	41.0

Table IV

The tensile properties of the as-cast alloys

% Copper Addition	Yield Load (N)	Yield Strength (N/mm^2)	Max Load (N/mm^2)	Tensile Strength (N/mm^2)	% RCSA	% E
0	4724.00	38.50	5121,60	41.70	25.20	9.6
2	5131.80	41.80	7547.30	61.50	16.80	7.0
4	9021.5	73.50	11717	95.49	3.20	4.0
6	7181.7	58.50	7767.7	63.3	4.70	2.4
8	6503	53.00	9021.5	73.5	3.12	1.6

Table V

The tensile properties of the precipitation hardened alloys

% Copper Addition	Yield Load (N)	Yield Strength (N/mm^2)	Max Load (N/mm^2)	Tensile Strength (N/mm^2)	% RCSA	% E
0	4974	40.50	5451.2	44.4	12.38	5.0
2	6391	52.00	7910.4	64.5	7.4	1.6
4	9710	79.14	13670	109.4	4.7	1.55
6	9508	77.47	13412	109.3	4.0	1.22
8	7767.7	63.3	9508	77.47	2.5	0.8

Key

Gauge Length = 50mm

Original Diameter = 12.5mm

% RCSA = Percentage reduction in cross sectional area

% E = Percentage elongation

TABLE VI

The impact energies of the as-cast and precipitation hardened alloys

%Cu addition	Impact energy (J) of the as-cast alloys	Impact energy (J) of the precipitation hardened alloys
0	12.4	42.0
2	11.9	40.0
4	10.5	30.5
6	9.6	21.0
8	8.0	19.0

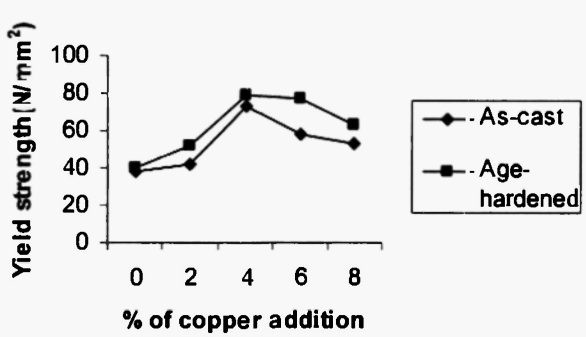


Fig. 1: Variation of yield strength with percentage of copper addition

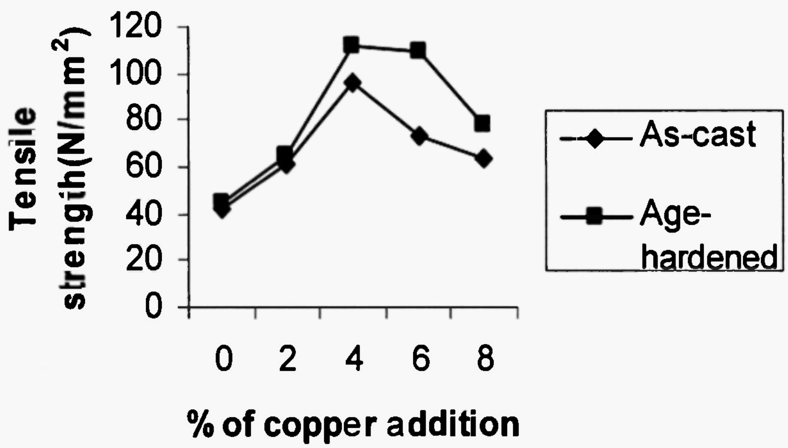


Fig. 2: Variation of tensile strength with percentage of copper addition

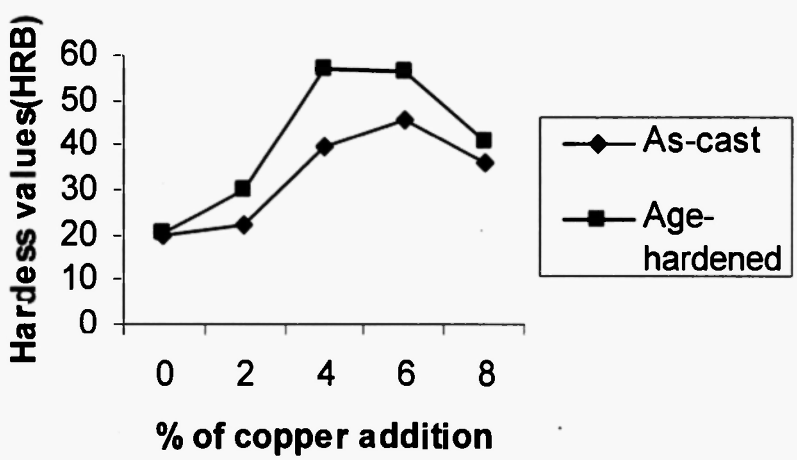


Fig. 3: Variation of hardness values with percentage of copper addition

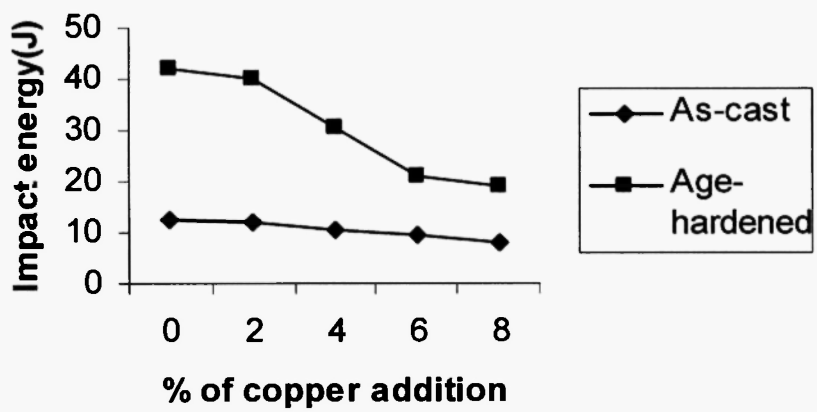


Fig. 4: Variation of impact energy with percentage of copper addition

DISCUSSION

From results in Tables II and III, it can be seen that the hardness values of the alloys after precipitation hardening are higher for all percentages of copper addition (2-8%). However, the hardness values of the precipitation hardened alloys only increase on copper addition up to a maximum of 4% before beginning to decrease as from 6% copper addition. For example, a maximum hardness value 56.7HRB was obtained at 4% Cu addition, which decreased slightly to 56.3HRB at 6%Cu and then dropped sharply to 41.0 HRB at 8% Cu addition (Tables II, III and Figure 3)

The same trend could be observed for the variation of the tensile properties (strengths) with percentage copper addition in which the yield and ultimate tensile strengths of the precipitation hardened alloys are all higher than those of the as-cast alloys for all percentages of Cu addition (Tables IV and V). Also the variation of tensile strengths with copper addition exhibits a similar trend with the hardness values within the precipitation hardened alloys in which a maximum value for the yield (79.14 N/mm^2) and ultimate tensile strength (111.4 N/mm^2) is obtained at 4% Cu addition before these values fell to a minimum value of 63.3 N/mm^2 and 77.47 N/mm^2 for the yield and tensile strengths respectively at 8% copper addition(Table V and Figures 1 and 2). This is in line with the observation of Markandeya *et al* /11/ on the Cu-Ti-Zr alloys.

For the impact energy, a large increase was observed after precipitation hardening for all percentages of copper addition. For example at 2% Cu addition the impact energy increased from 11.9 to 40.0J. However, the impact energy generally decreases with increase in copper addition for both as-cast and precipitation hardened alloys (Table VI and Figure 4).

The observed increase in tensile strengths and hardness values of the precipitation hardened alloys compared with the as-cast on copper addition is as a result of the precipitation of $CuAl_2$ phase(black) from α-solid solution (martensite phase analogue) formed during quenching to metastable, ordered and coherent β^1-$CuAl_2$ phase having (bct) crystal structure(micrographs 4 and 6). These precipitates act as keys and build up resistance to slip thereby increasing both the strength and hardness after the precipitation hardening treatment/12 /.

For the precipitation hardened alloys, the attainment of highest values for both hardness and strengths at 4% Cu addition is due to the very high density of the dislocations characteristics of the precipitated phases at 4% copper (micrograph 6). Beyond 4% Cu addition, the mechanical properties(hardness and strength) of the as-cast and precipitation hardened alloys began to decrease with increase in copper addition as a result of the formation and precipitation of non-uniform, coarse and soft complex plate-like precipitates of $((FeCu)_3SiAl_{12}$(micrographs7-10)

While the general decrease in impact energy with increase in Cu addition for the as-cast and precipitation hardened alloys is also as a result of the formation and precipitation of the hard and brittle phase of $CuAl_2$ as the formation and subsequent precipitation of this phase increases with increase in percentage of copper in the alloys/13 and 14/.

CONCLUSION

The three mechanical properties (Hardness, Tensile Strength and Impact Energy) of the as-cast alloys generally increased after precipitation hardening for all levels of copper addition considered. However, beyond 4% Cu addition, the hardness and the tensile strength of the precipitation hardened alloys began to fall, while the impact energy generally decreased with increase in copper addition. This means that copper addition beyond 4% decreases the amenability of the alloy (Al-Si-Fe) to precipitation hardening. Therefore for attainment of optimum mechanical properties the copper addition to this alloy should not be beyond 4% for both as-cast and precipitation hardened alloys

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