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Research article

EFFECTS OF THERMOMECHANICAL TREATMENTS ON THE CHEMICAL AND MECHANICAL PROPERTIES OF Al-Cu Alloy

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ABSTRACT

The development of Al-9.37Cu alloy was characterized through metallographic examinations. The alloy having been cast using Die –Casting method was subjected to series of treatment such as solution treatment, water quenching and air-quenching as well as over –ageing. The result showed that the strength of Al9.37Cu was greatly enhanced when the alloy was rolled, and aged. This was as a result of the growth of large precipitates along and near the Aluminum grain boundaries which interfere with the movement of dislocations when the metal yields. However, when the alloy was heated beyond 200^{o}C (500^{o}C), the tensile values were observed to decline as a result of equilibrium tetragonal phase which is fully in –coherent and was characterized with low strengthening effect due to fibrous structures.

Keywords: Al-9.37Cu, metallography, precipitates, thermomechanical, deformation, INSTRON, over-ageing ductility and Hardnesss

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INTRODUCTION

Copper is used as an alloying element in aluminium alloys to increase the strength of the material. By mixing copper and aluminium the good corrosion resistance of the pure aluminium decreases giving the alloy a lower corrosion resistance. Aluminium does not have high mechanical strength in its pure metal form, therefore copper are added to the alloy to increase the mechanical strength of the material, this also decreases the corrosion resistance of the aluminium alloy drastically (Kacer et al 2003).

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When alloying light weight metal such as aluminium it is important to get an even distribution of the alloying elements so that the material properties become homogenous throughout the entire specimen. Aluminium has a lower density and a lower melting point compared to copper, and if the copper are not added in the right way to the melt, the aluminium alloy can suffer an uneven copper distribution.

As man continues to explore the earth, his desires to make life more comfortable for himself begin to increase. Aluminium was first produced by Christian Oersted in 1825. However it was not until 20 years later that significant quantities were produced. Wohler fused anhydrous aluminium chloride with potassium to set free aluminium. Later Ste Claire Deville in 1854 put together a production process using sodium instead of potassium (Ashby and Jones, 2006).

Huda 2009, discussed the solubility of copper in aluminium is 5.7 atm % at the eutectic temperature (548.2oC), and at 250oC this solubility sinks to between 0.1 and 0.2 atm % (Huda 2009). Between 0.2 and 5.7 atm % Cu, two equilibrium solid states can appear. Above the solidus curve, the copper is 100% soluble, and when the temperature is held above this temperature for a longer period of time, this permits the needed diffusion for the copper to go into solid solution. At temperatures below this solidus line, the equilibrium state consists of solid solution, α, and an intermetallic compound phase, θ (Al2Cu). From this short review of metallurgical developments it can be seen that as the early metallurgists became more sophisticated their ability to discover and separate all the metals grew. However in all of their work it was necessary for all the basic steps to be carried out e.g. the ore had to be identified, separated from gangue, sized, concentrated and reduced in a manner which accomplished a phase separation.

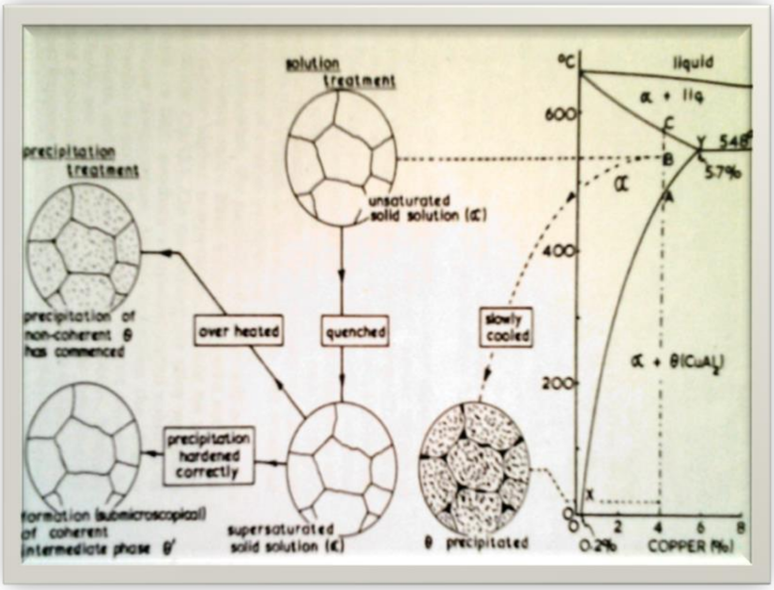

Fig.1: The Al-9.37%Cu alloy equilibrium phase diagram

Therefore, no fewer than 14 pure metals have densities less than 4.5mg/m^3. Of these Ti, Al and Mg are in common use as structural materials. Beryllium is difficult to work and is toxic, but it is used in moderate quantities for heat shields and structural members in rockets. Lithium is used as an alloying element in aluminium to lower its density and save weight on airframes. Yttrium has an excellent set of properties and, although scarce, may eventually find applications in the nuclear-powered aircraft project. But the majority is unsuitable for structural use because they are chemically reactive or have low melting points. (Watermann,1979). Aluminium is a low density material which gives it its lightweight property. When mixed with other elements in alloys it is also very strong. This unique combination of strength and weight is essential for the transport industry. As Force = Mass x Acceleration, the bigger the mass the more force will be needed to achieve a certain acceleration. This means that using aluminium in transport vessels saves money on fuel, allows more cargo to be carried, and is better for the environment. Aluminium's corrosion resistance perfect this profile making it absolutely ideal for its uses in aeroplanes, trains, cars, and ships.

In this work, the quest is to study the influence of thermo mechanical ageing on Aluminium alloy in which Aluminium is the principal element (parent metal) with traces of other elements such as Copper, Magnesium, Iron, and Zinc. Aluminium is subject to internal stresses and strains when it is overheated.

1.1 Aims and Objectives

The aims of this research are to

(i) Cast an Aluminium-Copper alloy material using die-cast method;
(ii) Subjecting the cast alloy produced in (i) to heat treatment;
(iii) Warm-work some of the cast alloy samples in (ii);
(iv) Determining the mechanical properties of the cast alloy samples in (i) & (iii) and finally examine the microstructure of the cast alloy samples in (i) & (ii).

This is targeted at providing an alternative non- ferrous alloy product that is of good corrosion, high strength-weight ratio capable of withstanding large percentage of deformation.

Research Problems

One of aluminium's weaknesses is its lack of strength is its pure form (Adegbola et al , 2013). To get around this and preserve aluminium's low density and lightweight other elements are added to the metal to "pin" dislocations reducing ductility but increasing strength. By this method some aluminium alloys can be as strong as steel. Adding different elements achieves slightly different effect but almost all alloys are stronger than the original aluminium metal.

What makes these alloys really special is the ability to retain the lightweight property of aluminium while gaining the extra properties that aluminium itself lacks. By considering the properties of these two materials it becomes possible to produce a non- ferrous alloy that possesses most, if not all, of the properties of two metals put together.

METHODOLOGY

Casting

Casting is defined as the production of a desire configuration by the introduction of materials into an already preferred cavity and allowing it to solidify. When molten metal is poured into the mould, chill crystals nucleate on the cold wall of the mould and grow inwards. The chill crystals are soon overtaken by the much layer column or grains. Finally, nuclei are swept into the remaining liquid and these grow to produce equated grain at the centre of the ingot. As the crystals grow they reject dissolved impurities into the remaining liquid, thereby causing segregation. This lead to band of solid impurities or to gas bubbles and because most metals construct when they solidify, there is substantial contraction cavity at the top of the ingot as well. This work was conducted with the following four-principal approaches:

Production of cast Al-Cu alloy materials were sourced from pure 98% Aluminium ingot and Copper wires from electric cables scraps.

(i) Cast the Al-Cu alloy in an ingot–rod form
(ii) Warm worked at a maximum limit of $300^{O}C$
(iii) Solution treatment and aging with the following steps :-
(iv) The Al-Cu alloy phase is dissolved in the matrix, at $550^{o}C$

(v) The alloy was quenched to room temperature to retain the solid solution formed at high temperature and soaked at 150^{o}C for 24 hours.
(vi) Following the quenching, the cast alloy was aged naturally (Held at room temperature) or aged artificially by heating at a relatively low temperature of precisely 165^{o}C.
(vii) Cut two samples each for tensile strength, impact test specimen samples
(viii) Carry out the metallographic tests , by picking 2 tested samples each
(ix) Performance evaluation

Production of Aluminium Copper AlloyAluminium ingot (base element) and Copper wires were used in the production of the cast Aluminium – Copper alloy sample in rod form. Aluminium has lower melting point of about 660^{o}C while copper possesses 1083^{O}C. Casting is termed as the fastest method of producing complex shapes from raw materials that can be melt. Die-casting process was used in the production. Copper was melted in the furnace for about 45 minutes and Aluminium was also melted for about 20minutes in two different pots. Melted copper was then poured into melted aluminium pot and were mixed at their molten form without loss in temperature. A solid solution was formed at 660^{o}C before pouring into the die-cast mould with two cavities of round and square shape capable of producing 25mm x 120mm rod. One rod each was used for impact test, tensile strength test and rolled. The cast samples were solution treated and rolled at different percentages to ascertain the ability of the cast alloy after heat treat to withstand load. The processes were as presented in Plates 1-10. The cast alloy formed and solidified into an ingot structure of cylindrical and square shape.

Plate 1: Aluminium Ingot-98% Al Of 22kg Weight, from Aluminium Rolling Mill (ARM) factory, Ota,, Nigeria

Plate II: Copper Wire, From Standards Org. Of Nig (SON), Laboratory, Lekki, Lagos

Plate III: Mixing of the two molten metals evenly a pot in the earth furnace

Plate IV: Pouring of the molten aluminium-copper in alloy into the second hole of die cast mold

Plate V: Solidified Al-9.37Cu rods

PlateVI: Aluminum alloy samples loaded inturn inside the Heat treatment oven at Obafemi Awolowo University, Ile-Ife, Nigeria

Plate VII: Digital Hardness Testing (Brinell Machine under the

Plate VIII: Mounting of Aluminium Alloy Sample

INSTRON Tensile Testing Machine at Center for Energy, Obafemi Awolowo, Ile-Ife, Nigeria

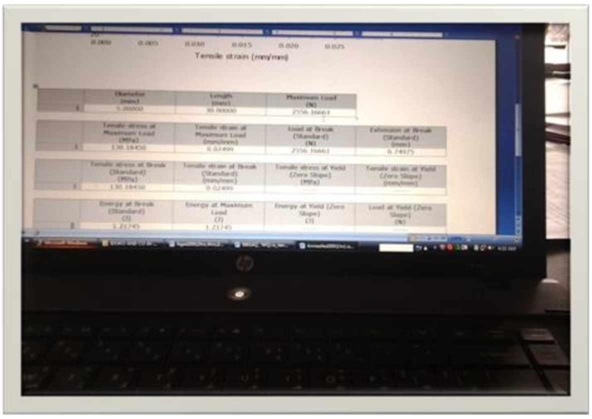

Plate IX: The interface of tensile tests for aged,

Air-Quenched, and Water Quenched samples

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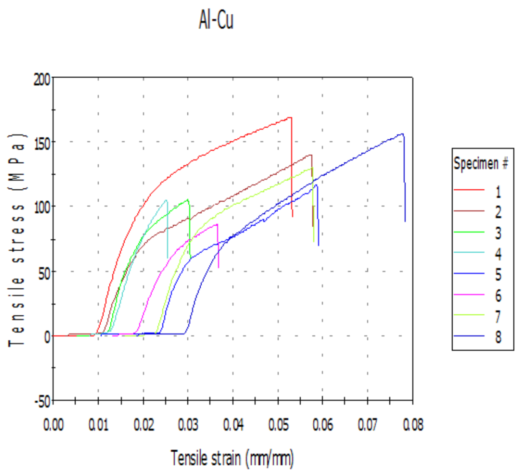
Table I: Chemical Analysis for Cast Aluminium-Copper alloy

Run	Mg	Si	Mn	Cu	Zn	Ti	Fe	Cr	V	Ca	Ni	Al%
1	0.003	0.1729	0.004	9.416	0.0496	0.000	0.5654	0.005	0.0140	0.0028	0.000	89.56
2	0.001	0.1573	0.004	9.198	0.0476	0.000	0.5746	0.005	0.0144	0.0014	0.000	89.80
Av	0.002	0.1651	0.004	9.307	0.0486	0.000	0.5700	0.005	0.0142	0.0021	0.000	89.68

RESULT ANALYSIS



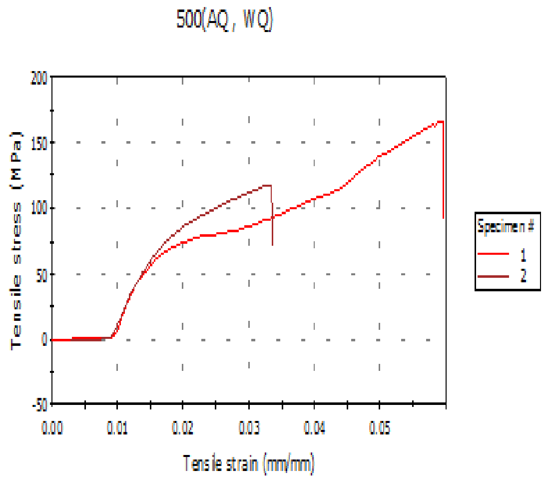
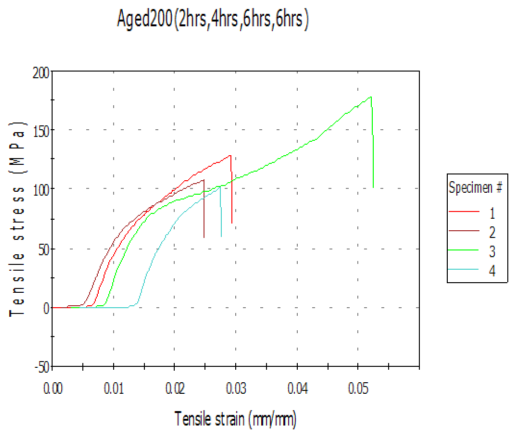


Fig.2: Stress (MPa) - Strain (mm/ mm) variation of cast Al-Cu alloy before heat treated.

Fig.3: Stress (MPa) - Strain (mm/ mm) variation of cast Al-Cu alloy after heat treated and cooled at different medium (Air- Water Quench).



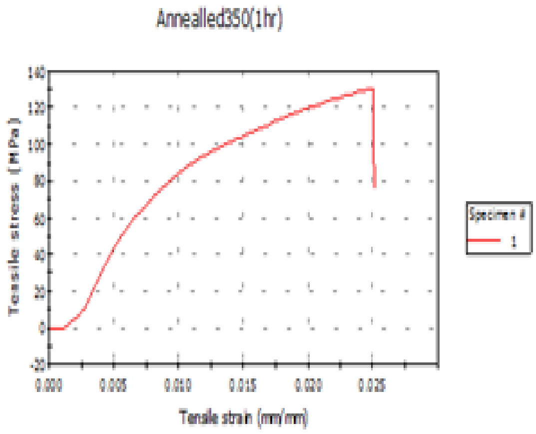


Fig.4: Stress (MPa) - Strain (mm/ mm)
variation of cast
variation of cast Al-Cu alloy
after ageing at different time

Fig. 5: Stress (MPa) - Strain (mm/ mm)
Al-Cu alloy after annealled at 350^{0}C for 1hr

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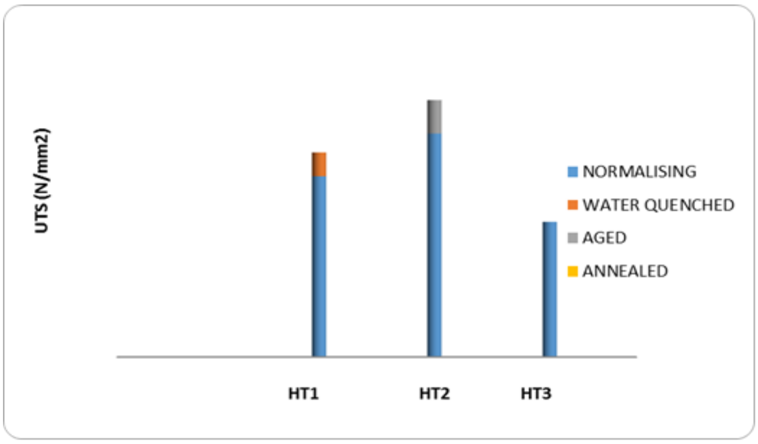

Fig.6: Variation of UTS(MPa) with Heat Treatment

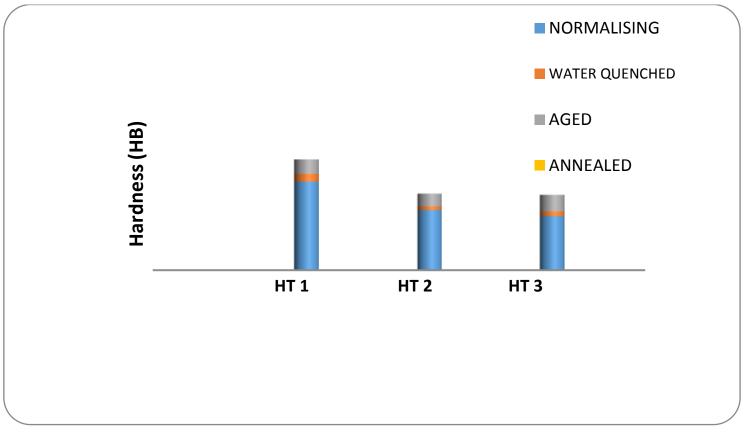

Fig.7: Variation of Hardness(HRB) with Treatment Processes

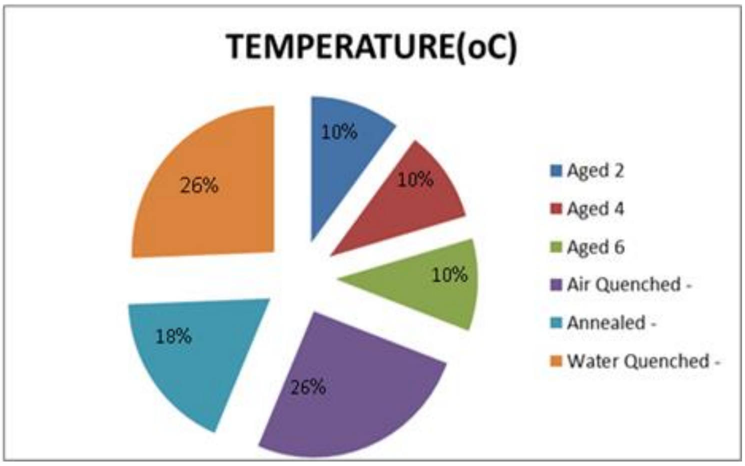

Fig.8:Pie Chart showing impact values variation Heat Treatment Processes

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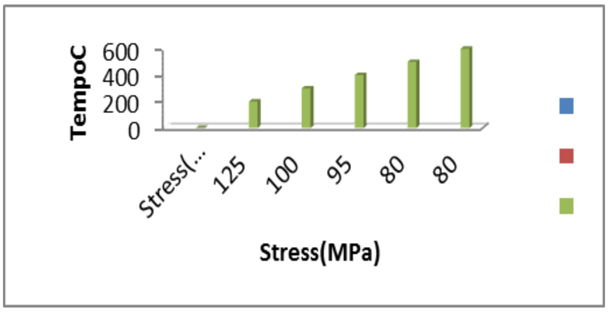

Fig. 9: The effect of Over-ageing on the Tensile Values (MPa) for different Hours of heat treatment processes

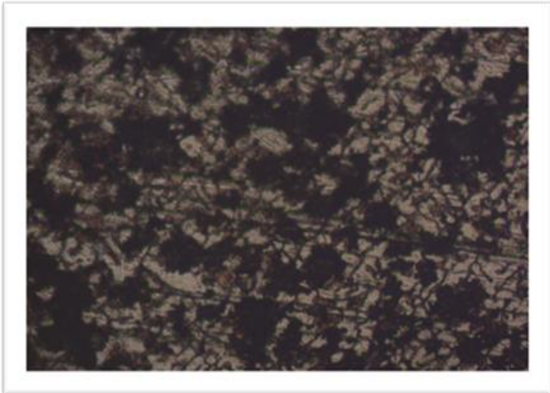

Plate X: Aluminum 9.37 Copper alloy as Cast

Plate XI: Aluminium 9.37Copper Alloy annealed at 350°C for o 1 hr. Polarized light , recrystallized grains and bands of unrecrystallized grains (caustic etch)

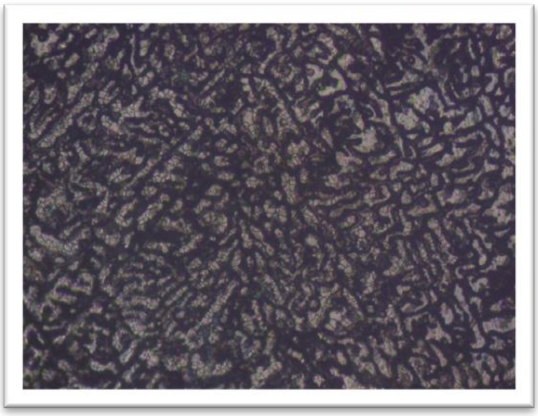

Plate XII:Aluminium 9.37 Cu water –quenched(WQ) at treated 500°C forming an overwhelming precipitates with an intermediate β^{I} and α matrix led to a distortion in the α-lattice (Caustic etch) X200°C

Plate XIII: Aluminium 9.37 Copper alloy Soution heat at 500°C but Air-Quenched. The slow cooling resulted in intragranular and grain boundary precipitation of AlCu alloy with .002Mg(Caustic etch) x200°C

Plate XIV: Aluminum 9.37Cu Artificially Aged at 200°C for 5hours (Caustic etch)x 200°C

Plate XV: Aluminium9.37 Copper alloy over aged at 500° (Caustic etch) x200°C

DISCUSSION OF RESULTS

The microstructure of As-Cast Al-9.37Cu alloy is shown in Plate X, dendrite structures were observed in fast cooling rate. This structure was observed from the ingot which has been cooled quickly to obtain equi-axed network structure. This network is made up of particles of several intermetallic compounds formed by combinations of the alloying elements as presented in Table I Some of these compounds are soluble while others have slight or practically insolubility. The mechanical properties of as-cast sample of Al-9.37Cu alloy are presented in Fig.2 in terms of Strength recording 119.38MPa which falls within the range of AalCo specification, 2012, but this could be enhanced to 690MPa (Adegbola et al, 2013) for some heat treatable non-ferrous alloys. The hardness value is high on Brinell Scale at over 60 HB, and low ductility of 10% and percent Area Reduction is 15.98%. This could be as a result of sparse distribution of suspected precipitates of α (Askland et al, 2006).

It is however, important to mention that, the application is only limited to where loads of 1/3 of its Ultimate Strength can only be useful. The application can only be enhanced when heat treated, whether, natural ageing or artificial ageing. During air-water quenching, the precipitates, though small, are closely spaced; get in the way of moving dislocations and make the alloy harder. This accounted for a declining value in Tensile stress (118.44MPa). This prevented the formation of any precipitate except for α –solid solution at this level which later became supersaturated with ϐ-phase. This occurred at a non-equlibrium condition. Hence, the alloy is said to be in a meta- stable state. Thermomechanically (loading at 350°C), it could be observed that Plate V showed the elongated rains as a result of 10% deformation . This contributed to high strength but low ductility than in sample 19. The tensile stress of 130.19MPa and energy of 1.217J with and extension of 10884.36 MPa were recorded during the annealing. This enhanced the ductility when the sample was heated to 350°C for 1 hour. This translated into the inability of the alloy to produce α structure with continuity. In other words there was a non –coherent structure which rendered the alloy soft. (Fig.2, Plates XI and XIII).

As a result of the fore-going, ageing was conducted to obtaining a larger number of precipitates in the Aluminium grains. These interfere with the movement of dislocations when the metal yields. This has a profound effect on increasing the strength of the alloy. Hence, in thermo-mechanical ageing, hardening is due to the increased work required to move dislocations through the strained lattice. This is called coherency –stress.

From Fig.4 and Plate XV, it was discovered that at the beginning of ageing, Al-9.37Cu is strengthened by the copper that is trapped in the supersaturated α, producing a supersaturated solid solution (SSSS). But at an ambient condition Cu atoms segregated by diffusion to form Copper rich zones called Gunner-Preston(GP Zone 1). This increased with further growth at 200°C to produce a GP zone 2 where a θ'' precipitate phase was formed. This produced a stronger effect as the precipitate generates stresses that helped in preventing dislocation movement.

This accounted for the variation between when the Al-9.37 Cu (as-cast) was tested on the 3369 INSTRON Tensile Testing Machine and when heated to 200^oC as a result of rapid diffusion at a higher temperature. As cast recorded 119 MPa with no precipitate formation, while at 200^oC in 6 hours ageing the Alloy recorded 177.67 MPa and 2.82 J as energy on impact. The only difference between Fig. 2 and Fig. 4 was due to larger number of precipitates and 10% percent deformation. This inferred that ageing and percent deformation (mechanical) have the tendency of increasing the strength of Al-4.23Cu alloy. With further ageing when heated to 400^oC, (Plate XV) it was discovered that higher grain coarsening was experienced and subsequently , hardness value decreased. This resulted into a declining value to 150 MPa as dislocation bowing between precipitates became easy and the strengthening contribution from coherency strain and precipitate cutting disappeared. This was probable due to the formation of equilibrium tetragonal phase ($CuAl_2$) which is characterized with incoherency and does not have a strengthening effect.

However, this effect can be eliminated if the averaged Al-9.37 Cu is solution treated to 550^0C quenched and aged again to 200^0C ageing temperature.With this treatment, it is possible for the alloy to possess peak strength, but with longer ageing time.

The effects of over aging was discovered when the Al-9.37Cu was heated above 200^oC, that is 500^oC. The alloy developed equilibrium tetragonal phase (Al_2Cu), which is fully in-coherent and seemed not to have a strong strengthening effect (Plate VII). This appeared as fibres with no strength (Adegbola et al, 2013). Fig.9 described the effect of Over-ageing on the tensile values (MPa). The increase in temperature resulted in the declining values of Stress. This is as a result of grain –Coarsening with increasing temperature.

CONCLUSION AND RECOMMENDATION

The mechanical properties of any material are as important as the service life of the material in which the microstructure analysis plays a tremendous role. It could be discovered that the properties of the cast AlCu alloy are determined by the treatments vis-a-vis the deformation, heating and cooling either rapidly or slowly.

(i) The microstructure of Al-9.37%Cu alloy resulting from solution treatment at 500^oC followed by slow cooling to room temperature reveals low strength and will be unsuitable for applications where high strength –weight ratio is required..

(ii) Hardening and strengthening by solution treatment at 500^oC, and water- quenching followed by ageing at room temperature (32^oC) for a maximum of 6hours imparts adequate strength to the alloy; and renders the material suitable for high strength-weight ratio like, piston in automobiles and equipment.

(v) The increase in temperature from 200^oC to 600^oC resulted in the undesirable decrease in Stress (MPa) values.

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