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DEVELOPMENT AND CHARACTERIZATION OF MODELING DEFORMATION OF AL-CU ALLOY

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ABSTRACT

The development and morphology of Al-9.37Cu alloy was characterized through metallographic examination and failure rate. The alloy was obtained by employing Die –Casting Technique before being subjected to series of mechanical and materials tests. The result showed that the strength of Al9.37Cu was greatly enhanced when the alloy was under different percent of deformations between 5-15%. Constitutive model was adopted to determine the isotropic material property in which the plane stress and plain strain conditions were considered as boundary conditions. Consequently, the effect of temperature was able to influence the strain rate in which the fracture strain determined the failure rate of the Al-Cu alloy.

INTRODUCTION

One of aluminium's weaknesses is its lack of strength in its pure form **[1]**. To obtain aluminium of 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. In order to obtain aluminium alloy of such, the research will examine various casting methods used in the production process, as well as heat treatment techniques. This is targeted at providing an alternative non- ferrous alloy product that is of good corrosion resistant and high strength- weight ratio capable of withstanding large percentage of deformation.

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. Copper is used as an alloying element in aluminium alloys to increase the strength of the material Aluminium has a lower density and 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. 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.

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 **[2].**

[3] determined the mechanical properties experimentally and it was recommended numerical approach could be introduced to his experimental approach. In a computational simulation of ageing process, material modeling is one of the key problems. Over the past 20 years, research has been conducted enabling the use of advanced analytical procedures to more accurately simulate the ageing process. Due to the complexity of the physical processes involved in ageing, however, simple mathematical solutions cannot address the practical manufacturing processes. Furthermore, it is also impossible for any experimental technique to obtain a complete mapping of the residual stress and distortion distribution in a general structure.

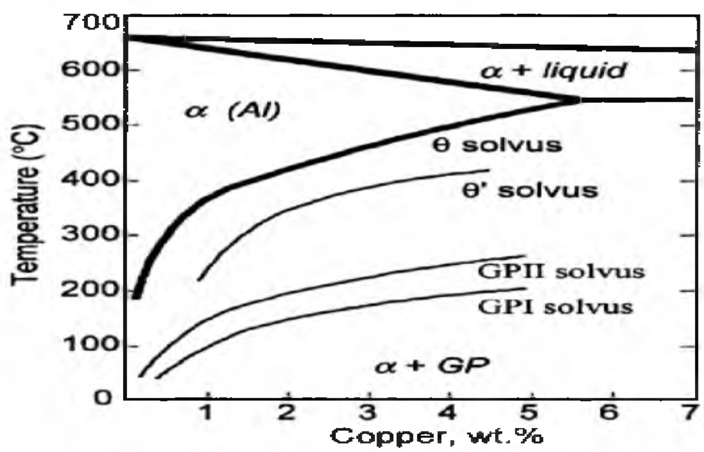


Fig 1: Aluminium-copper phase diagram along with metastable phase boundaries at Al end **[4]**

Computational simulation thus plays an in- dispensable role in the integrity analysis of such engineering structures. **[5]** marked the first step in applying a two-dimensional (2D) finite element analysis (FEA) to predict residual stresses in a weldment.

In a computational simulation of ageing process, material modeling is one of the key problems. Recently, **[6]** gave a detailed review on this topic, which includes the development of material constitutive relationships, material microstructures and material properties as functions of temperature. Most publications in material simulation adapted material properties that are dependent on temperature. However, in practice complete temperature-dependent material property data required for the analysis are difficult to obtain, especially at high temperatures. Since high temperature material properties are either difficult to obtain or do not exist for many materials, an engineering approach is proposed based on the results in this study.

This research is aimed at determining the effect of thermo-mechanical ageing experimentally and numerically on the Mechanical Properties of Al-Cu Alloy by formulating a model (constitutive) to determine the nodal value of certain parameters and to simulate the obtain results using Matlab (fematiso).

MATERIALS AND METHODS

- **Materials**

Cast Al-9.37Cu samples were used in this work. Rockwell Hardness and Tensile Testing Machines, Grinding and Polishing machines, Metallurgical microscope as well as MATLAB software were used.

- **Methods**

Production of cast Al-Cu alloy materials were sourced from pure 98% Aluminium ingot and copper wires from electric cables scraps. Aluminium 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 melts at $1083^{O}C$.
This work was conducted by casting (Die) Al-Cu in an ingot –rod form; in precipitation heat treatment, the alloy is first solutionized by heating into a single phase at about 490-500°C, and soaking for sufficient time to permit required diffusion. Copper goes into solid solution completely.(At temperatures below solvus line, the equilibrium state consists of solid solution plus an intermetallic compound phase($CuAl_2$).) After solution treatment, the alloy is quenched in water to get supersaturated solid solution (SSS).The rapid cooling prevents formation of equilibrium precipitates **[4]**. The cast alloy was aged naturally and artificially by heating it at relatively low temperature of precisely 165°C.Two samples each were cut for tensile and impact tests finally, metallographic test was carried out on the samples. Constitutive model and Matlab were then used to predict the mechanical performance of the Al 9.73-Cu alloyed formed.

Plate 1: Solidified Al-9.37Cu rods

Plate 2: Digital Hardness Testing (Brinell Machine)

- **Constitutive Model**

The reduction of a three-dimensional problem to a two dimensional problem can occur in two ways. The choices are plane stress and plane strain. Plane stress and plane strain models are both two-dimensional idealizations of three dimensional problems. The relationship between the two is called constitutive equation. The constitutive relationship for a linear, elastic material is given:

$$\boldsymbol{\sigma} = \boldsymbol{D}(\epsilon - \epsilon_0) + \sigma_0 \quad \text{OR} \quad \sigma = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \boldsymbol{D}\left(\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} - \varepsilon_0 \right)$$

The material property matrix D depends on whether the material is isotropic or anisotropic. Only the isotropic case is considered here **[7] [8] [9].** For an isotropic material, solving the above for plane stresses, the matrix D becomes

$$D = \frac{E}{1 - \nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu)/2 \end{bmatrix}$$

And the initial strain as

$$\varepsilon_0 = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

While solving the plane strains, the isotropic material matrix D becomes

$$D = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & (1-2\nu)/2 \end{bmatrix}$$

And the initial strains

$$\varepsilon_0 = \begin{Bmatrix} \varepsilon_{x0} + \nu\varepsilon_{z0} \\ \varepsilon_{y0} + \nu\varepsilon_{z0} \\ \gamma_{xy0} \end{Bmatrix}$$

Therefore, the element stiffness matrix for all problems in stress analysis is given by:

$$K^{\varepsilon} = B^T D B t A$$

Where: t is the thickness of the plate for plane stress or the length of the long prismatic member in plane strain. The thickness t is frequently taken to be unity for the plane strain case. Both B and D are composed only of constant matrices independent of x and y. A is the area of the element.

$$B = \frac{1}{2A}\begin{bmatrix} (y_2-y_3) & 0 & (y_3-y_1) & 0 & (y_1-y_2) & 0 \\ 0 & (x_3-x_2) & 0 & (x_1-x_3) & 0 & (x_2-x_1) \\ (x_3-x_2) & (y_2-y_3) & (x_1-x_3) & (y_3-y_1) & (x_2-x_1) & (y_1-y_2) \end{bmatrix}$$

It should be noted that K" is a 6 x 6 matrix because BT is 6 x 3, D is 3 x 3, and B is 3 x 6. This is consistent with the fact that there are six nodal displacements (two at each of the three nodes of the triangle).

- **Procedure for using Constitutive model in Matlab**

Create a directory called hw5 and copy the following 7 MATLAB files to your directory:

  - **hw5.m:** main file
  - **feaplyc2.m:** Apply constraints to matrix equation [kk]{u} = {ff}
  - **deriv.m:** Compute the derivatives of shape functions
  - **feasmbl1.m:** Assembly of element matrices into system matrix

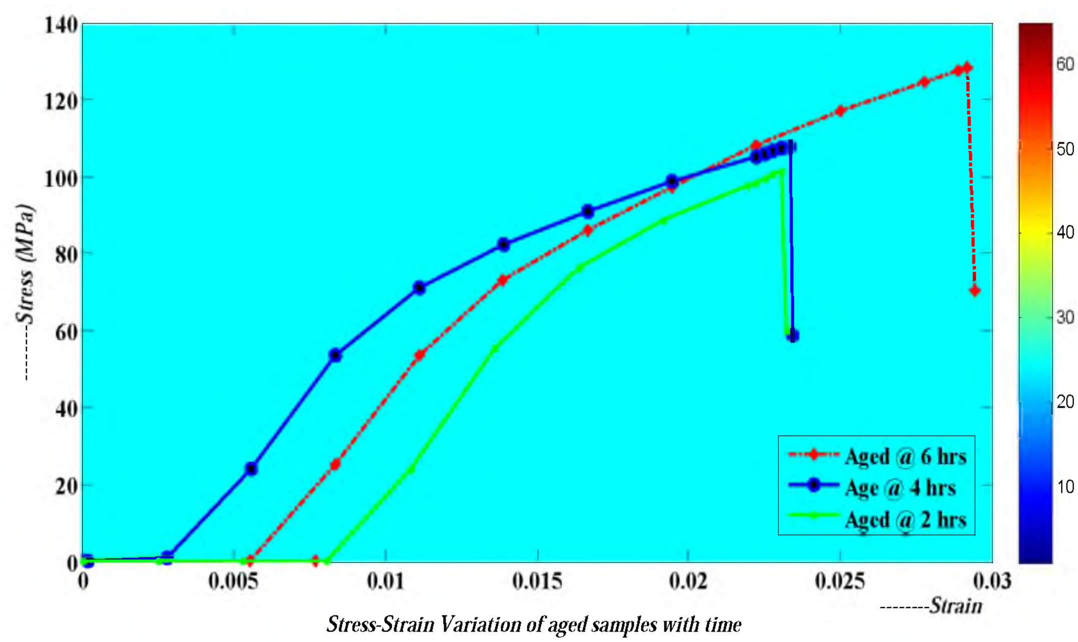
- **feeldof.m:** Compute system DOFs, associated with each element
- **fekine2d.m:** Determine the [B] matrix for 2D solids
- **fematiso.m:** Determine the constitutive equation for isotropic material

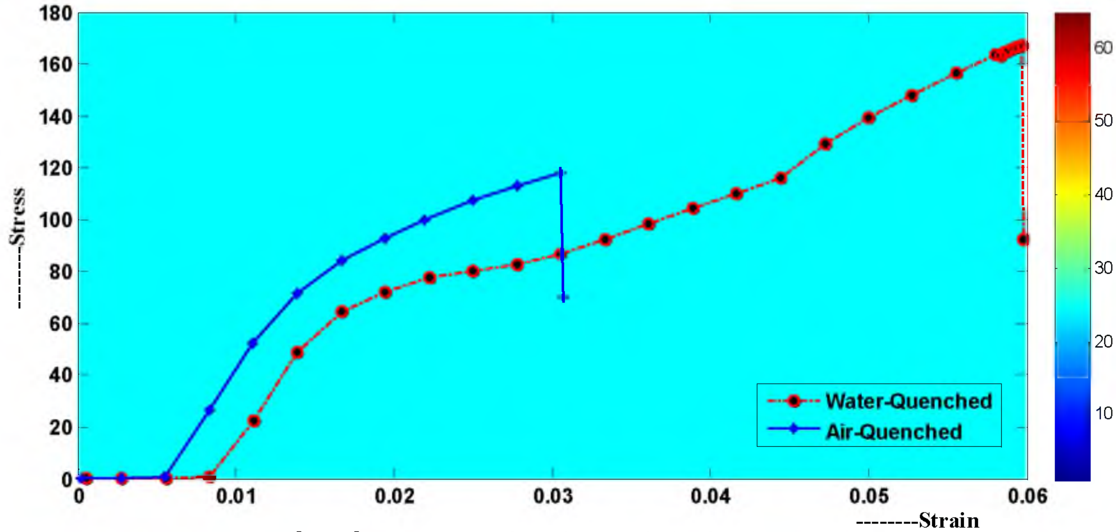
RESULTS AND DISCUSSION

The cast sample (Al-9.37Cu) was obtained from foundry unit, Mechanical Engineering Department, The Polytechnic, Ibadan- Nigeria. The finite element method (FEM) was applied to constitutive model and Matlab was used to simulate the obtained results **[10].** The obtained results are presented below.

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





Stress-Strain variation of samples quenched in 2 media

Metallographic Test Results

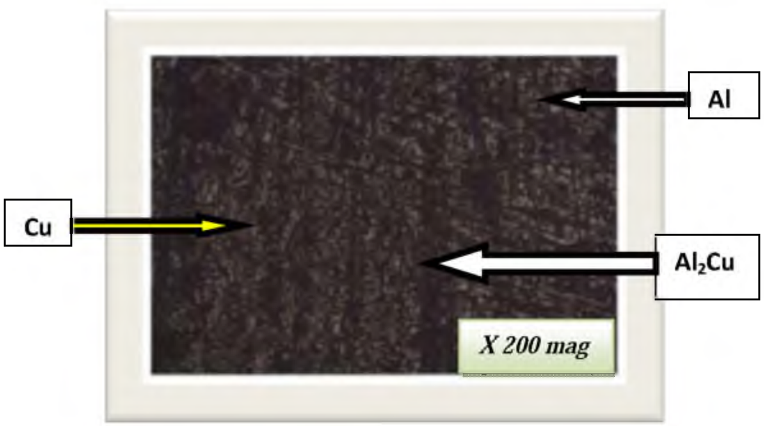


Plate 4:Aluminium 9.73 Copper Alloy as Cast

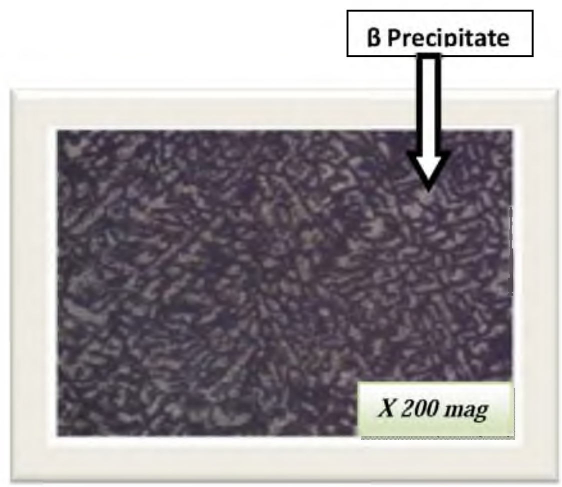


Plate 5: Al 9.37-Cu water-quenched at 500 degree Celcius

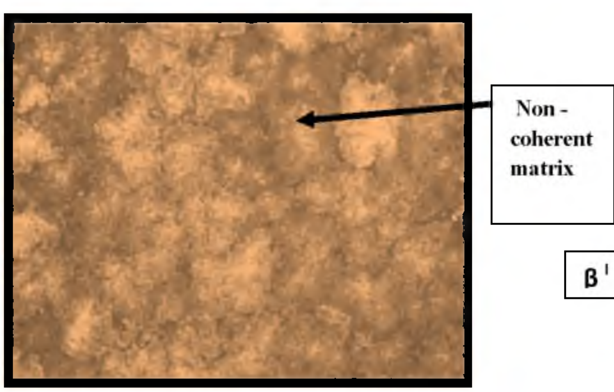


Plate 6: Al 9.37-Cu over aged at 500 degree celcius

Plate 7: Al 9.37-Cu artificially aged at 500 degree celcius

Plate 5 shows that quenching by water gives rise to the formation of supersaturated solid solution. This is because fast cooling will eliminate formation of thermal stresses and allow for proper diffusion of copper atom into the matrix of the aluminium. Air cooling ,on the other hand, has reverse effect on the rate of dissolution and holding time, i.e. it decreases the rate of dissolution of alloying element(copper)as shown in fig.3.

Quenching is immediately followed by aging to impart the needed strength in the alloy. From fig.2 the sample aged at 6 hours recorded highest tensile strength 128.105MPa than those aged at 4 and 2 hours with 107.657 MPa and 101.295 MPa respectively. This is because there is sufficient time for the dissolution of solute atoms in the atom of the matrix, resulting in the formation of fine scale transition structure within the matrix which lead to local distortions and strain fields restricting dislocation movement and consequently increase the strength of the alloy. This is evident from microstructure (Plate 7). The strength of the Al-Cu is a function of aging time, such that the longer the aging time the stronger the alloy. However, over aging should be avoided as this will result to coarsening of the grains with the fully loss of coherency and subsequent loss of hardness (Plate 6). The several stages associated with aging are: supersaturated solid solution, formation of Guinier-Preston zone 1(GP-I zone), GP-II zone and formation of $CuAl_2$ equilibrium phase **[4]**.

CONCLUSION AND RECOMMENDATION

The characterization of deformation of al-cu alloy has been developed using constitutive model and the obtained results have been simulated using Matlab (fematiso) in order to determine the effect of thermo-mechanical ageing numerically on the Mechanical Properties of Al-Cu Alloy and to predict stress-strain variations of the aged samples at time interval, as well as their failure rates.

The sparse distribution of the precipitate in the matrix of the aluminium ensured that the alloy form is isotropic in nature, especially when aged at 4 and 6 hrs. This makes constitutive model an appropriate tool for rational prediction on real life behaviour of the material.

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