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Effects of High-Temperature Creep on the Mechanical Properties of Duralumin

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ABSTRACT

This study aims to evaluate the creep behavior of Duralumin, signifying the effect of high temperature on the mechanical properties of Al-4Cu-1Mg to determine its potential in engineering applications. This research presents the creep behavior of Al-4%Cu-1%Mg at different temperatures i.e., 200°C, 250°C, 300°C, and 350°C, and also at varying loads of 4500N, 5500N, 6500N, and 7500N. The results obtained show that as the temperature increased from 200°C to 350°C, the creep rate increased from 2.35 x 10^-5/s to 3.34 x 10^-5/s, respectively. The results also show a sinusoidal high-temperature creep rate behavior of the alloy as the load increased from 4500N to 7500N. It was observed that the alloy has an ultimate tensile strength, hardness value, and toughness strength of 588.33 N/mm², 80.9 HRC, and 3.00 joules, respectively. The study concludes that variation in temperature between 250°C and 300°C at a constant load of 4500N leads to a relative increase in the creep rate of duralumin. Additionally, the variation in temperature between 200°C and 350°C affects the creep rate of duralumin. Moreover, the variation in load between 4500N and 7500N also impacts the creep rate, with a sinusoidal creep behavior observed in relation to changes in stress (load).

Keywords: Duralumin, Creep, High Temperature, Mechanical Properties, Alloy Composition.

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1. INTRODUCTION

In recent decades, the high-temperature mechanical behaviour of engineering materials has attracted significant attention. One key area of focus has been aluminium alloys, which offer a promising potential for high-temperature applications due to their lightweight properties and strength. Previous research by[1] mentioned that Aluminum-magnesium alloys offer the advantage of being lighter compared to other aluminum alloys and are less prone to flammability issues associated with high-magnesium alloys; however, this did not give in detail the compositions of these elements and their mechanical orientations for diverse applications, which this research is essential to bring to light. The addition of copper to aluminum alloys contributes to significant strength improvements and enables precipitation hardening [2], however, the inclusion of copper in aluminum can reduce ductility and corrosion resistance. The study of high-temperature creep behaviour of aluminium alloys has emerged as an important area of research, particularly as engineers explore the use of these materials in a variety of structural and aerospace applications [3].

Creep, defined as the time-dependent plastic deformation of materials under sustained stress, becomes especially critical in high-temperature environments [4]. Creep behavior can be split into three main stages. In primary, or transient, creep, the strain rate is a function of time. In Class M materials, which include most pure materials, strain rate decreases over time. This can be due to increasing dislocation density, or it can be due to evolving grain size. In class A materials, which have large amounts of solid solution hardening, strain rate increases over time due to a thinning of solute drag atoms as dislocations move[5].

While aluminium alloys offer excellent strength-to-weight ratios, their relatively low melting point compared to other metals like steel makes them susceptible to creep at lower temperatures[6]. This has prompted investigations into the behaviour of aluminium alloys at elevated temperatures to ensure their reliability and safety in critical applications, such as in aerospace, automotive, and construction industries. The alloy under consideration in this study is a specific Aluminium-Copper-Magnesium alloy (Al-4Cu-1Mg), also known as duralumin, a material known for its strength and light weight, but susceptible to creep under high temperatures and loads. Aluminium alloys have increasingly gained acceptance in modern engineering due to their beneficial attributes, such as being one-third the weight of steel while offering comparable strength. For example, 2xxx series aluminium alloys, commonly used in aerospace, exhibit proof strengths at ambient temperature that are equivalent to certain steel grades (S235, S275, S355). However, one significant limitation of aluminium alloys in construction is their high susceptibility to creep, especially at elevated temperatures. Due to their lower melting point (typically between 550°C and 600°C), aluminium alloys begin to experience creep at much lower temperatures than steel[7],[8],[9]. Research has shown that the onset of creep in aluminium alloys can begin as early as 200°C,[10], compared to steel which typically shows creep at much higher temperatures.

This behavior poses a challenge for aluminum structures, especially in fire conditions or other high-temperature environments, where the rapid reduction in strength and the development of creep strain can lead to early failure.[11]. The high thermal conductivity of aluminum exacerbates this issue, causing it to heat more quickly than steel, thus reaching the creep threshold faster. The 2xxx aluminum alloys, such as the Al-4%Cu-1%Mg alloy being studied, are known for their favorable mechanical properties at room temperature. However, their high-temperature behavior, particularly under prolonged exposure to stress, has been less extensively explored. This study aims to address this knowledge gap by examining the creep behavior of Al-4%Cu-1%Mg at various temperatures and stress levels, with the goal of determining its suitability for high-temperature applications.

Significant research has been conducted on the high-temperature deformation behavior of aluminum alloys,[12], but gaps remain regarding their creep and creep-rupture properties, particularly under varying stress and temperature conditions. Early work by [13] explored secondary creep deformation using the power-law creep model and investigated the [14] relationship to link creep deformation and damage. [15]Introduced the Ө projection method, which examines the shape of the creep curve to predict long-term creep failure. While these models have proven useful for some commercial aluminum alloys, their application to the specific alloy in this study (Al-4Cu-1Mg) remains underexplored.

Moreover, [16],[17] investigated the primary creep behavior and precipitation during creep exposure in Al alloys using the Ө method. Their findings demonstrated the importance of understanding both primary and secondary creep behavior, particularly for applications where long-term reliability is critical. Despite these advances, the high-temperature creep behavior of Al-Cu-Mg alloys, especially those used in aerospace applications, requires further investigation. These alloys are often used in conditions where long-term exposure to high temperatures can lead to significant creep strain, potentially leading to mechanical failure if not properly understood.[18],[19].

In a recent study by [20], it was noted that aluminum alloys, while offering superior strength-to-weight ratios, are more prone to creep-related deformation due to their lower melting points compared to steel. The study highlighted that aluminum structures in high-temperature environments, such as in fires, are particularly vulnerable to creep-induced failure. This underscores the need for a more comprehensive understanding of the behavior of aluminum alloys like Al-4%Cu-1%Mg under such conditions.

The aim of this study is to evaluate the effect of high-temperature creep on the mechanical properties of Al-4%Cu-1%Mg alloy (duralumin) and to establish its viability for engineering applications under sustained high-temperature stress. The study will focus on analyzing the creep rate of duralumin at varying temperatures and loads, as well as evaluating its mechanical properties, including tensile strength, hardness, and toughness.

To achieve this aim, the following objectives have been established: to fabricate the Al-4%Cu-1%Mg alloy for testing, to evaluate the effect of high-temperature creep on the alloy at a constant temperature (200°C, 250°C, 300°C, 350°C) under varying stresses (4500N, 5500N, 6500N, and 7500N), and to assess the impact of high-temperature creep on the alloy at a constant stress (4500N) under varying temperatures. Additionally, the study aims to determine the mechanical properties of the alloy, including tensile strength, hardness, and toughness, following exposure to high-temperature creep and to establish the temperature-creep rate relationship for the alloy.

2. MATERIALS AND METHODS

2.1. Materials and Equipment

The materials used in this study include aluminum billets with 98.9% purity, copper powder with 98.5% purity, and magnesium powder with 99.8% purity, purchased from scientific store. The fabrication process was conducted using a crucible furnace, and a permanent mold was specifically designed to manufacture standardized samples. A weighing balance was used to ensure accurate measurements of each component. Testing of the alloy involved several pieces of equipment, including a universal tensile strength testing machine to assess mechanical strength, a Charpy impact testing machine for impact resistance, a digital Rockwell hardness tester to evaluate hardness, and an optical microscope to observe the microstructure of the alloy.

2.2. Preparation of alloy

Aluminum alloy of 95 weight percent aluminum,4 weight percent copper, and 1 weight percent magnesium was designed and produced in the Department of Metallurgical and Materials Engineering, Enugu State University of Science and Technology, Enugu foundry shop. The crucible furnace used for melting the alloy was preheated to 200°C to eliminate any moisture content. The melting temperature was carefully controlled and varied between 450°C to 1100°C, considering the preheating, heat required for melting all constituents, and the homogenization process of the alloy mixture.

To achieve proper homogenization, the constituents were charged into the crucible in a specific order based on their melting point temperature and quantity. 95%wt Aluminum was added first and heated to a temperature of 900^0C for superheating to take place, then 4%wt copper, followed by the addition of Mg. It is important to note that precautions were taken during the addition of Mg to prevent contact with atmospheric oxygen, as Mg readily reacts and is flammable. A pipe was used as a guide to ensure the safe introduction of Mg into the alloy without exposure to oxygen.

In the experiment, a mold designed to accommodate 1200g of the alloy per charge was utilized, allowing for the production of three samples in a single pour. The final test samples were cast in a steel pipe with an internal diameter of 15mm and a gauge length of 200mm.

The molten alloy was poured into the mold and allowed to solidify. Samples were produced from the alloy for the following tests: creep, impact, hardness, and tensile tests.

Table 1. Experimental design for creep test at constant stress and different temperatures.

S/N	SAMPLES	LOAD (N)	STRESS (N/MM^2)	TEMPERATURE (^{0}C)
1	AI	4500	159.07	200
2	A2	4500	159.07	250
3	A3	4500	159.07	300
4	A4	4500	159.07	350

Table 2. Experimental design for creep test at constant temperature and different stresses.

S/N	SAMPLES	LOAD (N)	STRESS (N/MM^2)	TEMPERATURE (^{0}C)
1	BI	4500	159.07	300
2	B2	5500	194.41	300
3	B3	6500	229.76	300
4	B4	7500	265.11	300

2.3. Method of testing

Creep Test:

Each of the four samples A1, A2, A3 and A4 was subjected to creep test at different temperatures of 200^{0}C, 250^{0}C, 300^{0}C and 350^{0}C at constant stress of 159.07 N/mm^2 while their extensions at time interval of 120 seconds were deduced using extensiometer. The strains with respect to different extensions were calculated. Plots of strain-time were developed whereas the stain rates were deduced. Also each of the samples B1, B2, B3 and B4 was subjected to creep test at a constant temperature of 300^{0}C under varying stress. Their extensions at time interval of 120 seconds were deduced using extensiometer. The strains with respect to different extensions were calculated. Plots of strain-time were developed whereas the stain rates were deduced

Impact Test:

The impact tests were performed on the sample to determine their impact strength using the Charpy Impact testing machine, Model MT 3050. Prior to mounting on the machine, the test samples were notched (V-notched) to a depth of 2 mm with v-shaped hand file. The notched samples were mounted on the impact-testing machine, which was operated to apply a (constant) impact force (energy of 50 Joules) on the test sample. The impact strength (the amount of impact energy the specimen absorbed) was read off the calibrated scale on the impact testing machine.

Hardness Test (Rockwell Hardness):

Hardness tests were carried out on the sample using Digital Rockwell hardness tester, Model HRS-150. Three indentations were made on the sample of which the average value was calculated for the sample.

Tensile Test:

Tensile test was carried out on the sample, the specimen was strained at room temperature under standard conditions. The stresses and the corresponding strain values of the strained sample were deduced and were used to plot stress-strain curves for sample. Tensile specimen was of circular cross-section with threaded ends for griping. Diameter of gauge section was 6mm, its gauge length was 76mm and grip diameter of 13mm. The tensile strength ductility of the alloy was deduced and calculated, respectively.

Percentage elongation (ductility) = $\frac{increase\ in\ length}{original\ length} \times \frac{100}{1}$. The test was carried out consistent using a Universal Materials Tester, 20KN MODEL MT 2021, EDLABQUIP.

Microstructural Analysis:

Micro-structural study was also carried out, the sample specimen of dimension 10mm diameter and 10mm length of each material was cut off of the casts and processed accordingly.

Processing Steps:

The sample preparation involved several sequential steps. Initially, the samples were cut to size, followed by grinding with coarse emery paper. The samples were then polished using fine emery paper for a smoother finish. Etching was performed using Kroll's solution, which consists of 25 ml hydrochloric acid (HCl), 25 ml nitric acid, and 2 ml hydrofluoric acid (HF). The samples were immersed in this etchant for a few seconds, after which they were rinsed thoroughly with clean water. An electric blower was used to dry the samples completely. Next, the samples were examined using a laboratory electro-optical microscope, and micrographs of the prepared samples were subsequently developed.

3. RESULTS

3.1. Creep behavior at different temperatures and constant load.

In this section, results of the creep test performed on the alloy at different temperatures and a constant load of 4500N at a testing period of 1800 seconds were presented and discussed.

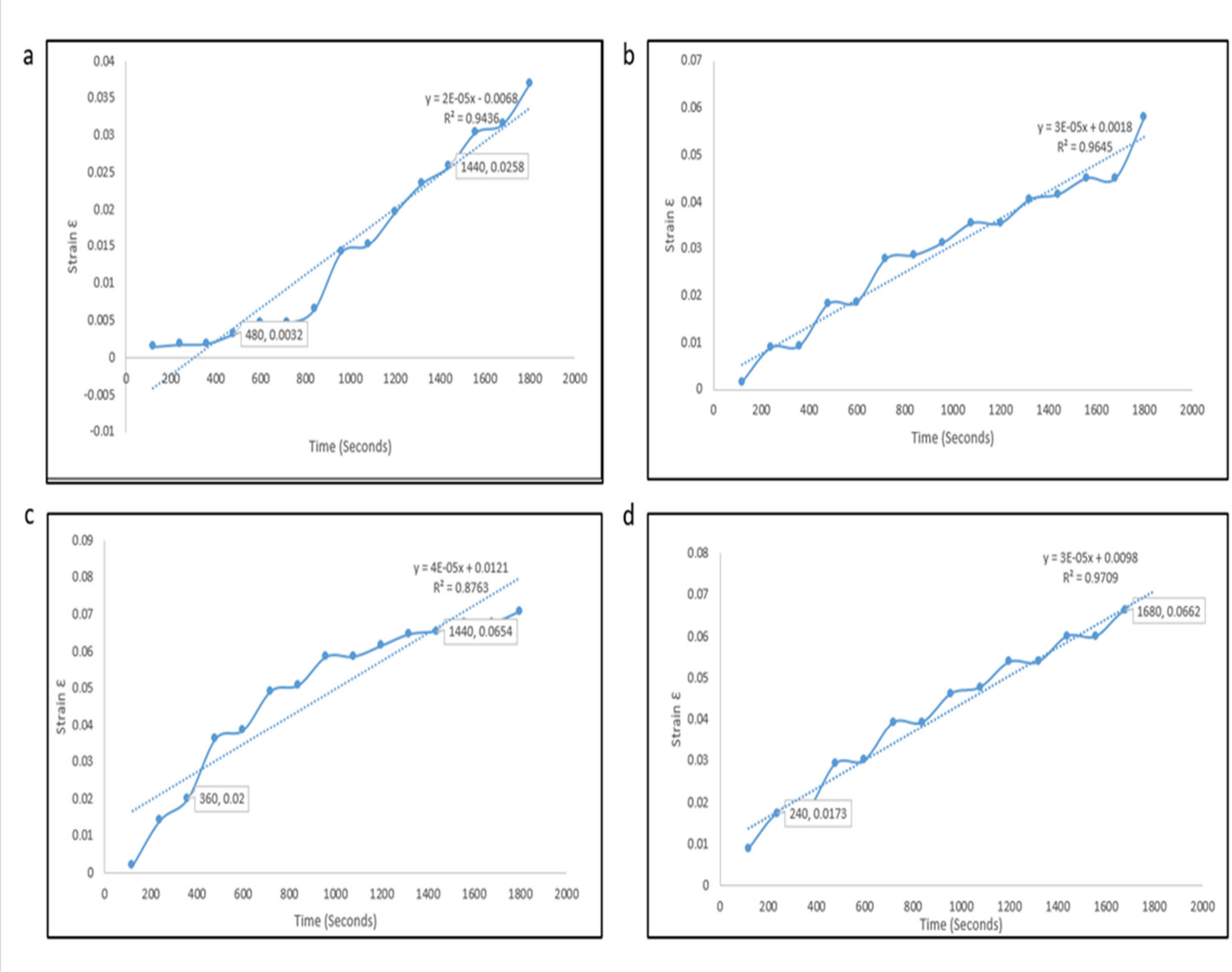

Figure 1. (a) Illustration of creep behavior of duralumin with time at 200^{0}C/4500N, calculated creep rate $\frac{\Delta y}{\Delta x}\ equals\ 2.35 \times\ 10^{-5}$ (b) Illustration of creep behavior of duralumin with time at 250^{0}C/4500N, calculated creep rate $\frac{\Delta y}{\Delta x}\ equals\ 2.93 \times\ 10^{-5}$ (c) Illustration of creep behavior of duralumin with time at 300^{0}C/4500N, calculated creep rate $\frac{\Delta y}{\Delta x}\ equals\ 4.2 \times\ 10^{-5}$ (d) Illustration of creep behavior of duralumin with time at 350^{0}C/4500N, calculated creep rate $\frac{\Delta y}{\Delta x}\ equals\ 3.4 \times\ 10^{-5}$.

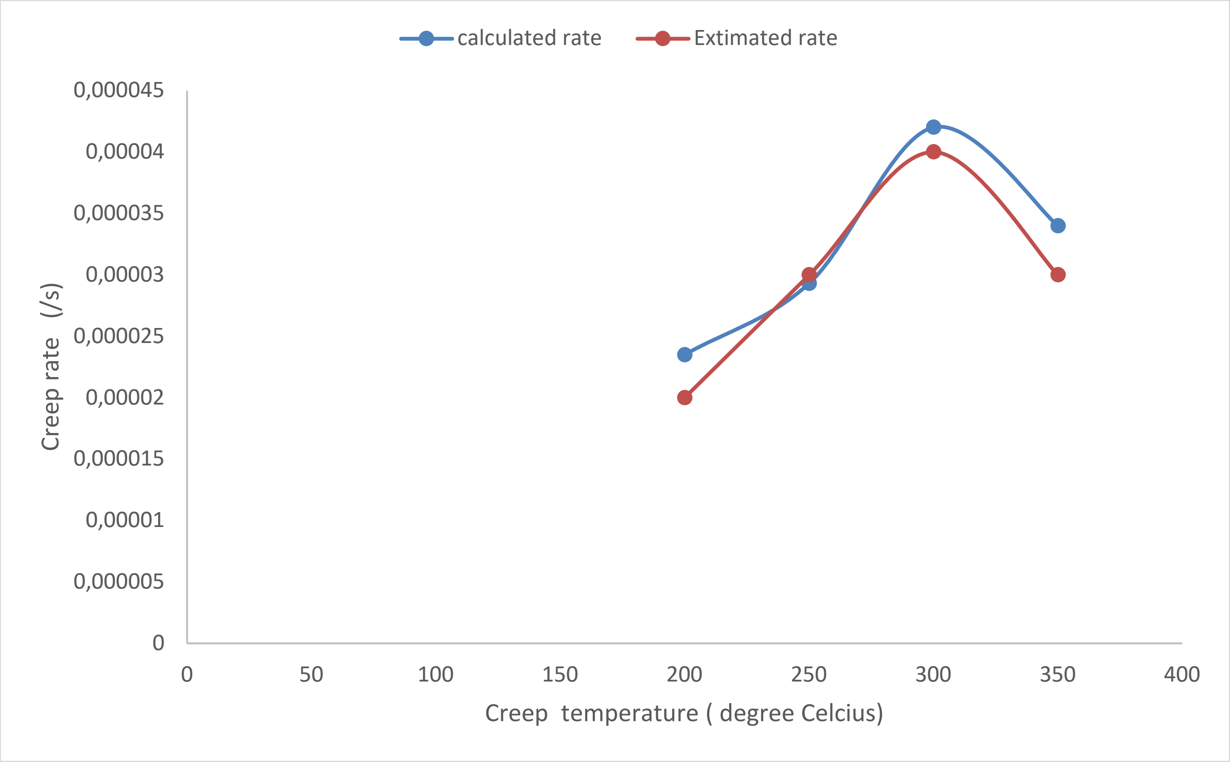

Figure 2. Illustration of creep rate with temperature at 4500N

Figures 1 (a – d) shows the straining trend of the alloy under varying temperatures of 200^0C, 250^0C, 300^0C and 350^0C at constant load of 4500N. It was observed that a relative straining behavior took place at all conditions. As the test time progressed the staining rate also increased. Figure 2 show the creep rates of the alloy at different temperatures. It was observed that as the test temperature increases from 200^0C to 300^0C, the creep rated relatively increased from 2.35×10^{-5} to 4.20×10^{-5} respectively. On further increase in the test temperature from 300^0C to 350^0C, the creep rate was observed to decrease to $3.4X\ 10^{-5}$. The decrease behavior observed can be attributed to stain hardening process which could have taken place in the alloy.

3.2. Creep behavior at varying loads and constant temperature.

In this section, results of the creep test performed on the alloy at constant temperature of 300^0C and varying loads at testing period of 1800 seconds were presented and discussed.

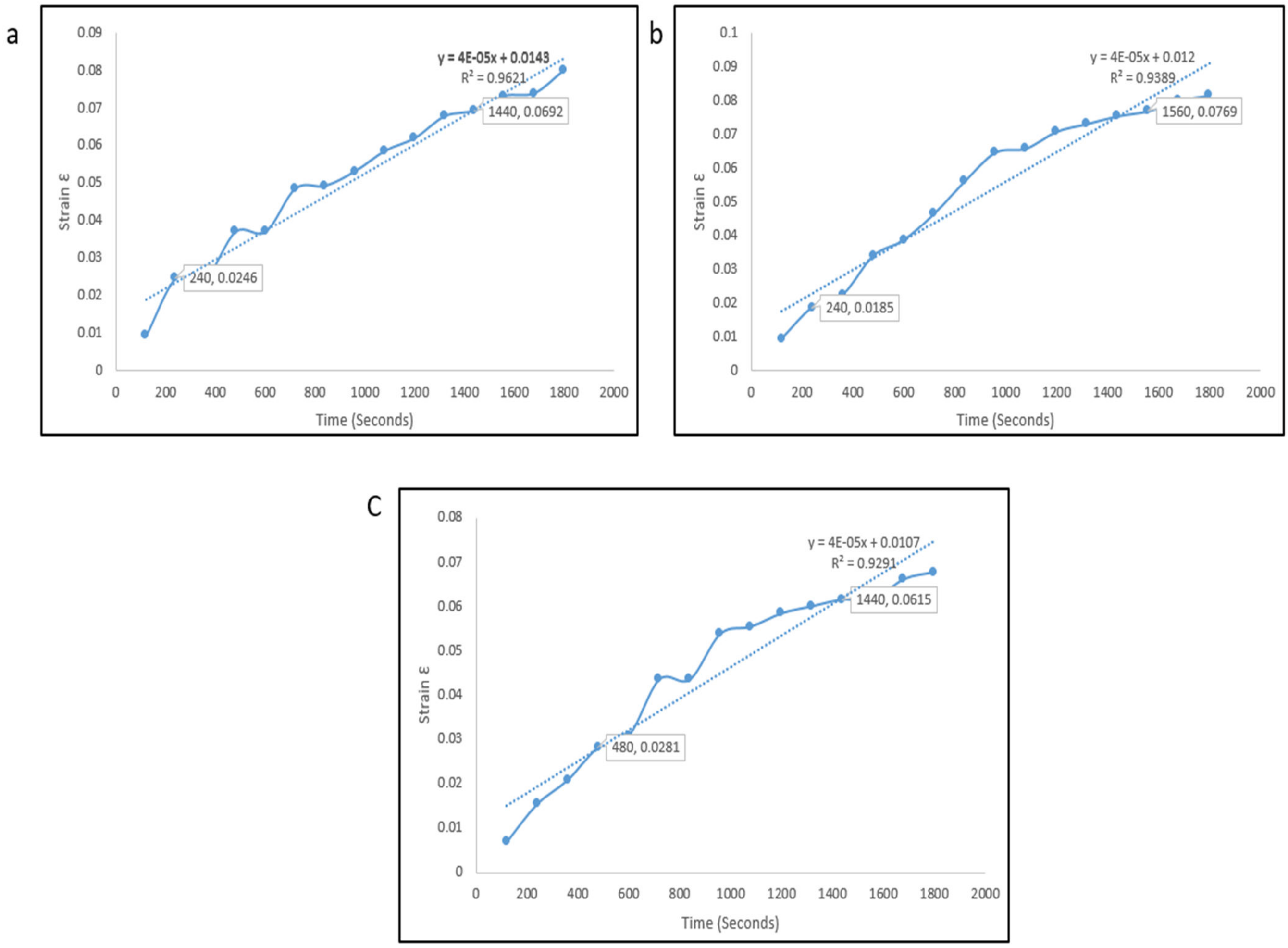

Figure 3. (a) Illustration of creep behavior of duralumin with time at 300^0C/5500N, calculated creep rate = $\frac{\Delta y}{\Delta X}$ $equals\ 3.7 \times\ 10^{-5}$ (b) Illustration of creep behavior of duralumin with time at 300^0C/5500N, calculated creep rate $\frac{\Delta y}{\Delta X}$ $equals\ 4.42 \times\ 10^{-5}$ (c) Illustration of creep behavior of duralumin with time at 300^0C/6500N, calculated creep rate = $\frac{\Delta y}{\Delta X}$ $equals\ 3.5 \times\ 10^{-5}$.

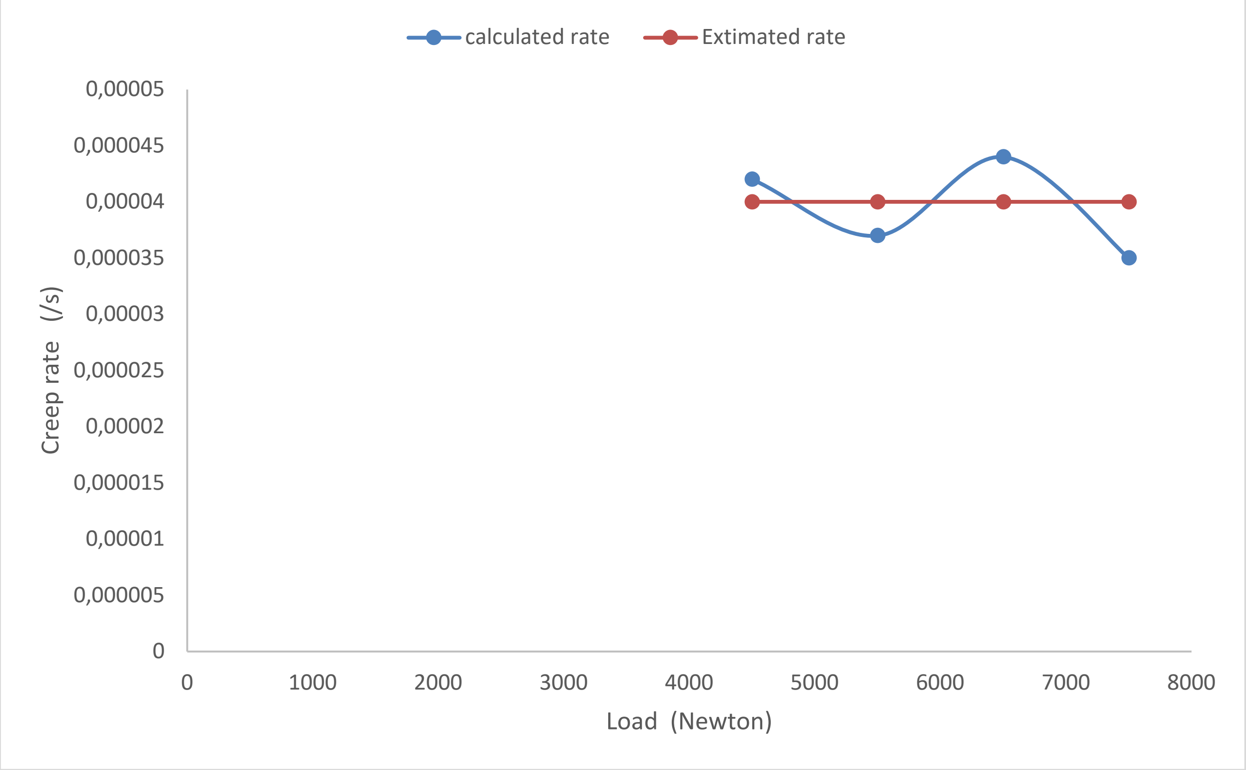

Figure 4. Illustration of creep rate with load at 300^0C

Figures 3a – 3c shows the straining trend of the alloy under varying loads of 5500N, 6500N and 7500N at constant temperature of 300^0C. It was observed that a relative straining behavior took place at all conditions. As the test time progressed the staining rate also increased. Figure 4 show the creep rates of the alloy at different loads. It was observed that as the test load increases from 4500N to 5500N, the creep rated relatively decreased from 4.2×10^{-5} to 3.7×10^{-5} respectively. On further increase in the test load from 5500N to 6500N, the creep rate was observed to increase to 4.42×10^{-5} as the load increased further to 7500N, the creep rate decreased again to 3.5×10^{-5}. Generally, a sinusoidal creep rate behavior was observed for the alloy as straining load increased.

3.3. Tensile test

The tensile test result of the allow is performed, the sample was strained by the application of a uni-axial load, the forces and the corresponding extensions were record which were used to plot the stress- strain graph as shown it figure 5 below.

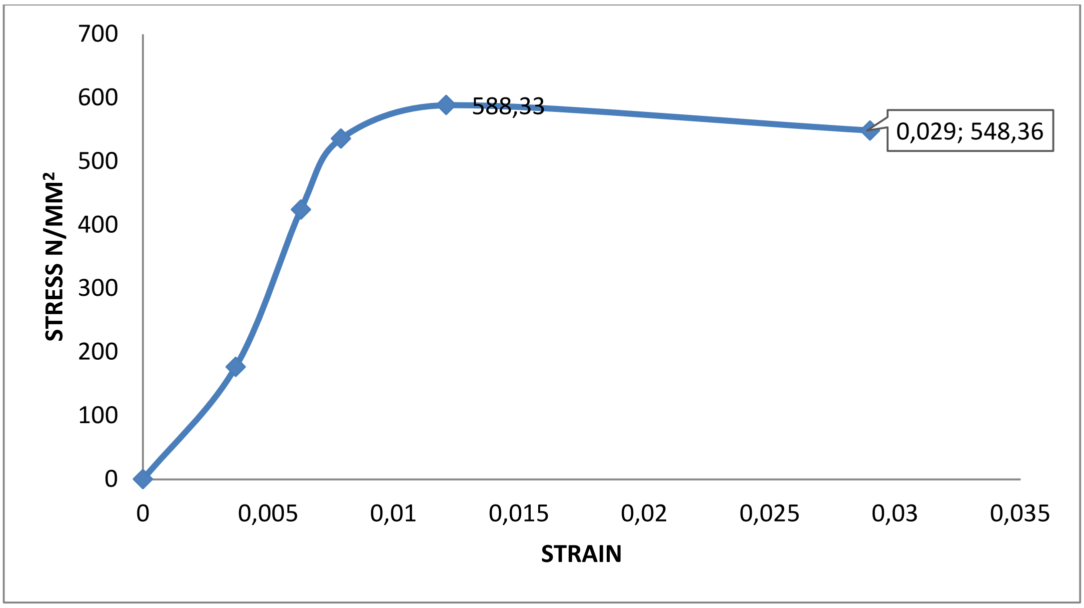

Figure 5. Illustration of stress-strain behavior of the alloy

Figure 5 above show the stress- strain behavior of duralumin, the alloy exhibited ductile characteristics, it has ultimate tensile strength of 588.33N/mm^2, low ductility of 2.9% and fracture strength of 548.36N/mm^2

3.4. Hardness value (Rockwell)

The alloy has an average hardness value of 80.9 HRC, the material is relatively considered to be hard.

3.5. Impact Test

It was observed that the alloy absorbed 3.00Joules of energy, this poor toughness strength was supported by its high hardness value and low ductility as indicated above.

3.6. Microstructure of the alloy

Microstructural examination was done using optical microscope using Kroll's etchant.

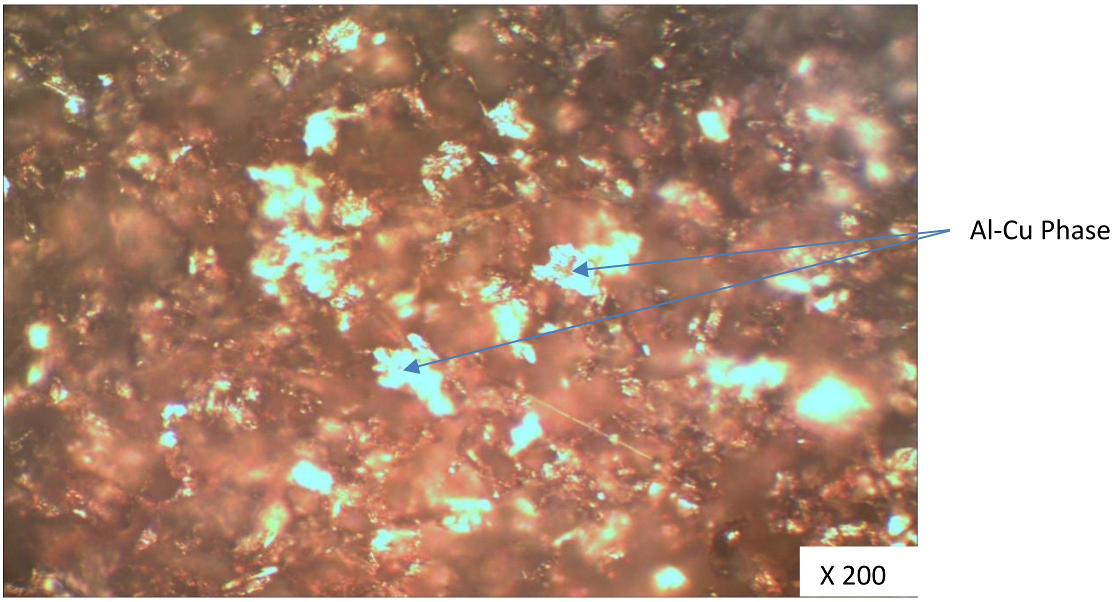

Figure 6. Micrograph of duralumin

The morphology of the micrograph shows relatively distributed Al-Cu phase which are seen to be the white patches on the micrograph. This Al-Cu phase can be said to be responsible for the relatively high ultimate tensile strength and hardness value.

4. CONCLUSIONS

The study reveals that a variation in temperature between 250°C and 300°C at a constant load of 4500N leads to a relative increase in the creep rate of duralumin. Additionally, temperature changes from 200°C to 350°C significantly impact the creep rate. It was also observed that variations in load from 4500N to 7500N influence the creep behavior of duralumin. Notably, the alloy exhibits a sinusoidal creep pattern in response to changes in stress (load). It is recommended that further study on the variation of load between 4500N and 5500N at varying load of 10N should be carried out.

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