# TABLE OF CONTENTS

DECLARATION ................................................................................................................................. i

ACKNOWLEDGEMENT ....................................................................................................................... ii

ABSTRACT ......................................................................................................................................... iii

CHAPTER ONE .................................................................................................................................... 1
  1.1 INTRODUCTION .......................................................................................................................... 1
  1.2 THE SCOPE OF THE PROJECT .................................................................................................... 1
  1.3 OBJECTIVES ................................................................................................................................ 2

CHAPTER TWO .................................................................................................................................... 3
  2.1 DEFINITION .................................................................................................................................. 3
  2.2 CREEP MECHANICAL PROPERTIES ............................................................................................ 3
    2.2.1 Elastic properties in Metals ..................................................................................................... 4
    2.2.2 Crystal shear strength ................................................................................................................ 4
  2.3 CREEP PROPERTIES IN VARIOUS METALS ............................................................................... 4
    2.3.1 CREEP IN STEEL ...................................................................................................................... 4
    2.3.2 CREEP IN CAST IRON ................................................................................................................ 7
    2.3.3 CREEP IN ALUMINIUM ............................................................................................................ 7
    2.3.4 CREEP IN COPPER ................................................................................................................... 7
  2.4 CREEP TESTING AND MEASUREMENT ...................................................................................... 9
  2.5 THE CREEP TESTING MACHINE ................................................................................................. 10
    2.5.1 THE APPARATUS ...................................................................................................................... 10
    2.5.2 THE CREEP TEST SPECIMEN ............................................................................................... 14
  2.6 TEMPERATURE MAINTENANCE AND CONTROL ...................................................................... 14
    2.6.1 Precautions ............................................................................................................................... 15
    2.6.2 Extension measurements .......................................................................................................... 15
    2.6.3 Measurements to be taken ....................................................................................................... 15
  2.7 CREEP DATA/RESULTS ................................................................................................................. 17
    2.7.1 Primary creep stage .................................................................................................................. 17
2.7.2 The secondary (Steady state) creep stage................................................................. 18
2.7.3 Tertiary creep stage ............................................................................................... 18
2.8 CREEP DATA PRESENTATION ................................................................................ 18
  2.8.1 Temperature effects and strain rate .................................................................... 18
  2.8.2 Stress effects and strain rates .............................................................................. 18
  2.8.3 Effects of Alloying and Creep rate ..................................................................... 19
  2.8.4 Engineering Creep Data ..................................................................................... 20
2.9 CREEP DATA CORRELATIONS/ANALYSIS ............................................................. 22
  2.9.1 Larson Miller creep parameter ......................................................................... 22
  2.9.2 Dorn Parameter ($P_d$) ..................................................................................... 23
  2.9.3 Marson Haford Parameter ($P_{MH}$) ................................................................. 24
  2.9.4 Zenner Holloman Parameter ($Z$) ..................................................................... 25
CHAPTER THREE .............................................................................................................. 26
METHODOLOGY .............................................................................................................. 26
  3.1 TENSILE TEST ......................................................................................................... 26
    3.1.1 APPARATUS .................................................................................................. 26
    3.1.2 EXPERIMENTAL PROCEDURE ................................................................. 28
  3.2 CREEP TEST ........................................................................................................... 28
    3.2.1 CREEP TESTING APPARATUS ................................................................. 28
    3.2.2 EXPERIMENTAL PROCEDURE ................................................................. 31
  3.3 CHALLENGES AND CONSEQUENT MODIFICATIONS ON THE CREEP TESTING MACHINE .................................................................................................................. 32
    3.3.1 SPECIMENS ................................................................................................. 32
    3.3.2 LOADING SYSTEM ...................................................................................... 32
    3.3.3 TEMPERATURE CONTROL ......................................................................... 32
    3.3.4 THE STRAIN MEASUREMENT ..................................................................... 32
    3.3.5 HEAT LOSS CONTROL ................................................................................. 33
CHAPTER FOUR ............................................................................................................... 34
  4.0 EXPERIMENTAL RESULTS .................................................................................... 34
  4.1 THE TENSILE TEST RESULTS ............................................................................... 34
Table 4.1: Mechanical Properties of Metals ................................................................. 35
5.4 LARSON- MILLER CURVES ............................................................................................................. 62

5.4.1 Copper ...................................................................................................................................... 62

5.4.2 Aluminium ............................................................................................................................... 62

5.4.3 Brass ......................................................................................................................................... 63

5.4.4 Steel .......................................................................................................................................... 63

CHAPTER SIX ........................................................................................................................................ 64

6: CONCLUSION ................................................................................................................................. 64

RECOMMENDITIONS ......................................................................................................................... 65

REFERENCES ....................................................................................................................................... 66

Creep test data/tables

Tensile graphs

Creep and Tensile test Specimen drawings
CHAPTER ONE

1.1 INTRODUCTION
Various components of power plants, steam generators/turbines, rotors etc operate at high temperatures under significant stresses. For example, pipes in steam turbine power plants carry steam at temperatures up to 6500°C and pressures of about 25 MPa\(^1\). Temperatures can go to as high as 1500°C in jet engines and initiate creep deformation even in the turbine blades. The structures/components need to be designed against excessive creep distortion/failure within the expected operating life of the component and it is thus vital to understand creep behavior in metals in order to ensure functionality of these engineering components without threat to catastrophic failures that may lead to loss of lives and economic implications in investments.

Creep occurs in metals by dislocation and atomic diffusion mechanisms. As the temperatures increase, these creep mechanisms and effects become significant and thus leads to failure which may become catastrophic if not properly checked.

Creep tests are thus carried out to investigate the creep properties of the materials at high temperatures using the specified standards including the British and American standards. This information can thus be used to develop creep resistant alloys that inhibit creep failure.

1.2 THE SCOPE OF THE PROJECT
The project aims to study creep properties of various metallic materials including copper, mild steel, aluminium and brass through laboratory experimentations. Consequently, proper analysis follows using the creep parameters available such as the Larson Miller Creep Parameter.

This is a continuing project previously undertaken where the creep properties of the various metals was investigated and analyzed. In Korir and Charles’ 2007/2008 report, creep tests and analysis were carried out using Larson Miller Creep Parameter on copper, aluminium, mild steel and brass. From the report, it emerged that creep deformation is time dependent and exhibits three stages including the primary, secondary and tertiary stages. The 2008/2009 report also gave the same trend.

\(^1\) MPa-Mega Pascal=10\(^6\)Nm\(^2\)
1.3 OBJECTIVES
The main objectives of this project include;

- To investigate creep properties of the various materials including mild steel, copper, brass and aluminium.
- To establish the creep rate variation of the metals at different temperature and stress levels.
- To analyze and correlate data obtained using the most appropriate Creep parameters that can give useful information needed for design purposes against creep.
CHAPTER TWO

2.1 DEFINITION OF CREEP
Creep is progressive deformation of solid materials under the influence of stresses due to prolonged application. Creep deformation is experienced at certain stresses usually lower than their yield strengths. Creep is pronounced in materials subjected to heat for long periods and near the melting point of the material, that is, temperatures above 30% of the melting point of the material.

Creep rate deformation is a function of the material properties, exposure time, temperature and the applied stress (commonly referred to as external variables).

Creep strain accumulates due to long term stress thus it is a time-dependent deformation.

2.2 CREEP MECHANICAL PROPERTIES
Creep is time dependent deformation and the mechanical properties and performance of materials change with increasing temperature.

Ductility increases with increasing temperature while elastic modulus (E) and strength decrease with increasing temperature.

We describe atomic mobility which is related to diffusion described by Fricks law\(^2\)

\[
D = D_0 \exp^{-\frac{Q}{RT}}
\]

Where

- \(D\) - Diffusion rate
- \(Q\) - Activation energy for atomic motion (Joules)
- \(D_0\) - Diffusion constant
- \(R\) - Universal gas constant = 8.314 J/mol K
- \(T\) - Temperature (in kelvins)

\(^2\) Deformation and Fracture Mechanics-Hertzberg
Diffusion controlled mechanism will thus have significant effects on high temperature mechanical properties and performance; for example, dislocation climb, vacancies concentrations, new slip systems and grain boundary sliding are all diffusion controlled.

Furthermore, corrosion and oxidation mechanisms that are dependent on diffusion rate affect the life time of materials at high temperatures.

2.2.1 Elastic properties of Metals
Elastic range of a solid is determined when stress components are linearly related to strain component. As a result of temperature influence, there is change in crystallographic structure of metals for example, Face Centered cubic (FCC) transforms to Body Centered Cubic (BCC) in metals due to temperature increase.

2.2.2 Crystal shear strength
When large stresses are applied to metals then removed, some permanent deformation takes place. The stress is called critical resolved shear stress whose absolute value depends on the sensitivity of strain measurement. The moment critical resolved shear stress is reached, the crystals glide considerably before strain hardening becomes effective. The critical resolved shear stress increases with increasing temperature up to the re-crystallization range. For example, between 200-300°C for aluminium.

It should however be noted that crystal perfection is vital in this case thus this is the major assumption made while dealing with metals.

2.3 CREEP PROPERTIES IN VARIOUS METALS

2.3.1 CREEP IN STEEL
Steel is an alloy that consists mainly of iron, and has carbon content between 0.2% and 2.1% by weight depending on the grade. Carbon is the most common alloying material for Iron, but various
other alloying materials can be used such as manganese, vanadium, tungsten, molybdenum and chromium depending on the desired effect.

Mild steel melts at about 1450°C and creeps at a temperature of about 500°C.

Mild steel is categorized into low, medium and high carbon steels.

2.3.1.1 Carbon and alloy steels

These are widely used creep resistant alloys where resistance to deformation at elevated temperatures. Steel change structurally thus modifying their creep behavior during creep tests in the service range of temperatures

Creep properties in wrought steel are determined by considering:

I. The composition

II. Manufacturing methods

III. Heat treatment and microstructure

In steel therefore, creep properties are properly investigated by varying one of the factors while maintaining others at a constant

2.3.1.2 Composition

Different elements added to steel give different creep resistant properties with the best combination of chromium, molybdenum, vanadium, steel giving high creep resistance between 550°C-650°C³

Plain carbon steel

Creep resistance in long term tests increase with increase in % carbon up to 400°C but varies at higher temperatures

Low alloy steels

³ Refer to Reference 6; Metallic Creep and Creep resistant alloys by A.H Sully
Effects of carbon depend on the particular conditions of the test.

Lower carbon steels pass rapidly through the secondary creep stage

*Alloy additions effects*

Silicon reduces amount of primary creep at low temperatures

Higher silicon content shortens period of secondary creep rate

Manganese has high creep resistance at low temperatures that is about 450\(^\circ\)C and high stresses

*Metallurgical conditions*

Steels are normally used in quenched and tempered conditions thus high mechanical strength.

Steel have good creep resistance at temperatures lower than 450\(^\circ\)C. This resistance however reduces above 450\(^\circ\)C up to 700\(^\circ\)C associated with spherodization of carbides that is less creep resistant. As service temperatures increase up to near tempering temperatures, creep properties of quenched and tempered steels falls off rapidly.\(^4\)

Creep resistance can be improved by coarsening the structure through increasing normalization temperature to produce a large austenitic grain size prior to cooling

High alloyed steels- martensitic stainless chromium steels with 12\% chromium are less creep resistant.\(^5\)

Ferritic steels- creep properties decrease rapidly as temperatures increase above 600 \(^\circ\)C. These alloys cannot thus be used in high temperature applications due to heavy scaling on prolonged exposure.

Austenitic steels-these have high resistance to creep and oxidation at high temperatures.

\(^4\) Reference 6

\(^5\) Reference 6
2.3.2 CREEP IN CAST IRON
In cast iron, the material undergoes dimensional change at high temperatures even in the absence of stress due to progressive graphitization of the cementite of the pearlitic structure of iron. Creep property is improved when iron is heat treated between 600°C-650°C.

Cast iron is not used in high temperature applications.

2.3.3 CREEP IN ALUMINIUM
Aluminum is a strong, light, ductile material resistant to both corrosion and oxidation. Yield strength of Aluminium alloys ranges from 200-600MPa. It is malleable thus easily machined, cast, extruded or drawn. It has a face-centered cubic (FCC) atomic structure with stacking fault energy of about 200MJ/m². It melts at about 660°C.

Age hardening improves aluminium strength and thus improves creep properties at reasonable temperatures. At higher temperatures however, precipitation in age-hardened alloys is progressive and atomic interchange (due to nucleation and growth of precipitated particles) increase creep rate which is different for different alloys, the best being □-alloys.

For alloys used at temperatures higher than the minimum re-crystallization temperatures, a high resistance to creep is favored by large crystal size.

2.3.4 CREEP IN COPPER
Copper is a ductile metal with high thermal and electrical conductivity. It has Young’s modulus (E) of 110-128GPa, melting temperature of about 1084°C and density of about 9g/cm³.
Creep properties depend on alloy composition, for example, the combinations for copper-beryllium, copper-beryllium-cobalt have good creep resistance as they are precipitation hardened alloys. At elevated temperatures however, creep resistance reduces especially for longer hours with copper-beryllium-cobalt combination giving a superior creep behavior. At temperatures higher than the recrystallization temperatures, creep resistance is higher in coarse-grained samples for long durations. Creep resistance is also affected by heat treatment method as indicated in the graph below.
2.4 CREEP TESTING AND MEASUREMENT
Creep test is carried out on either constant load or stress conditions over time. Conventionally, constant stress test is applied where the load is progressively reduced with decreasing specimen cross-sectional area (i.e. as the test proceeds). This can be done manually or automatically by load shedding creep devices in the creep stand load strain.

![Graph showing strain against log time at constant load and stress](image)

Figure 2.4.1; Plots of strain against Log time at constant load and stress

Either creep or rupture test can be performed which can be distinguished as follows;

**Table 2.1.1; differences between creep and rupture test**

<table>
<thead>
<tr>
<th>Creep test</th>
<th>Rupture test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures time against strain at constant load/stress</td>
<td>Measures stress against time to rupture at constant temperature</td>
</tr>
<tr>
<td>Relatively low loads used</td>
<td>Higher loads applied</td>
</tr>
<tr>
<td>Exhibits relatively low creep rates</td>
<td>Exhibits high creep rates</td>
</tr>
<tr>
<td>Performed for long durations(usually 2,000-10,000 hours)</td>
<td>Performed for short durations usually less than 100 hours</td>
</tr>
<tr>
<td>Test not always done to fracture</td>
<td>Test always done to fracture</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Strain measured accurately using sensitive equipment i.e. inductance gauges to determine creep rate</td>
<td>Simpler and less sensitive strain gauge used to measure creep rate</td>
</tr>
<tr>
<td>Strain typically less than 0.5%</td>
<td>Strain up to 50%</td>
</tr>
</tbody>
</table>

Creep rapture tests usually give the rapture life ($t_R$) which decreases with increasing temperature and stress. Generally, empirical relationship between $\varepsilon$ and $t_R$ can be given by

$$\log t_R + m \log \varepsilon = B$$

(Vonkman and Grant equation)

Where

- $t_R$ - rapture life
- $\varepsilon$ - steady state creep rate
- $m$ and $B$ are constants

$0.77 < m < 0.93$ for aluminium, copper, iron and titanium alloys\(^6\)

$0.48 < B < 1.3$ for aluminium, copper, iron and titanium alloys\(^7\)

### 2.5 THE CREEP TESTING MACHINE

To accurately measure creep properties in metals, the following should be put into account;

- Design of testing machine and load application mode
- Constant temperature maintenance of the specimen while the experiment is in progress
- Precise measurement of extension with time

### 2.5.1 THE APPARATUS

A typical creep test set ups are as shown below;

\(^6\) Reference 2
Figure 2.5.1; typical creep testing machine
The load is mostly applied by means of a lever. The creep testing machine has a massive cast-iron base plate. Specimen is screwed at the top end into an adaptor placed in a holder that connects through the medium of double knife edges at right angles to each other to the end of the straining screw which accurately selects appropriate adaptors selected at the top and bottom aligns the specimen along stress direction.

The top adaptor has a hole to accommodate the specimen and the other end drilled and tapped for eye-bolt. It is attached to the top plate through a hook and eye arrangement. Top adaptor is fixed.
Bottom adaptor is similar to the top one, but made such that an aircraft cable may be slipped through. Bottom end of the specimen is connected through a ball seat joint to the knife edge of a reduction lever by use of the adapter and holder.

Reduction lever hangs from the specimen and has its fulcrum on the underside of base plate. A cable supporting the load emerges from the centre of the bottom adapter to ensure axial loading. The cable is knotted and a metal button soldered on in a way that it allows the cable to come out of the center of the end of the lower adapter. The cable is attached to a wooden disk (about 25 mm in diameter) producing a platform for weights.

The specimen is not to be tightly screwed in the adapters. The ends of the specimen are forced slightly into the ends of the threaded holes, thus introducing slight cracking. This loading is checked by use of two resistance wire strain gauges which are mounted longitudinally on the specimen 1800 apart on its circumference.

Strain gauges, opposing one another are connected to the indicator such that for no movement on the indicator, the specimen would be axial.

Stress is applied to the specimen via a steel yard with its fulcrum on a bracket mounted on the base plate and connected on the base plate to the end of the reduction lever by links and knife edges. A poise weight may be moved along the steel yard to load by means of a hand wheel and pulleys.

The straining gear at the top of the machine is used periodically to re-level the beam as creep proceeds. The loading should be done with minimal shock avoiding eccentricity. The weights are anchored to stable objects that reduce rotation of the cable. Load is applied by placing the loading pan on extended ram of hydraulic jack and loading the needed weights upon it. Load is applied by allowing the jack ram to return slowly into the jack until the specimen is supporting the load on the pan.


2.5.2 THE CREEP TEST SPECIMEN

For high accuracy in strain measurement, the specimen ought to be as long as possible which ensures that maximum elongation is obtained for a given strain. However, it should not be too long to ensure constant temperature control and elongation effects of the specimen. Therefore, compromise between high strain sensitivity and small temperature gradient ought to be arrived at.

The specimen also needs to be checked for alignment by measuring strain on diametrically opposite sides of the specimen.

2.6 TEMPERATURE MAINTENANCE AND CONTROL

The creep test specimen is usually kept in a furnace lined with refractory materials for high temperature tests. Temperature control is essential and ought to be nearly constant because any slight variations may present difficulties in differentiating between the specimen movement due to thermal expansion and that due to creep. A small temperature variation would thus result in the prediction of more or less life of a material from the actual life depending on the variation.

Heating is usually done by winding of electrical resistance furnace and the furnace tube with the specimen always kept vertical. The furnace may either have graded winding where windings are closely packed at the top and bottom, with center parts loosely packed or have many/several windings. The heating elements are placed in front of a fan both connected to proportioning controller through a relay. The proportioning controller then connected to a chromel-annumel thermocouple placed in the air at head height. A two point micro-max recorder with temperature range of 0-100°C is used to record air temperature. A fan is also recommended at the top to circulate air constantly. Metal sleeves may also be fitted inside the furnace tube which should be refractory with very high thermal conductivity, for example, silver metal.

For very long periods of creep, automatic temperature is necessary due to fluctuations of the normal voltage supply producing greater multitudes of temperature fluctuations. This can be achieved in the following ways;
Control exercised by electromotive force (e.m.f) of a thermocouple attached to specimen. The e.m.f is applied to a self balancing Wheatstone bridge circuit and this switching furnace current on and off between maximum and minimum values.

Control is exercised by expansion/contraction of the refractory furnace tube such that the differential expansion and the other members of constant length operate the contacts of a circuit controlling the current of the furnace heating the specimen.

2.6.1 Precautions
High sensitivity creep test apparatus should be kept in draught free environment and in rooms maintained at uniform temperature. Draughts (variations in ambient temperatures) can produce variations in the gradient within the heating furnace by variable heat abstraction from the furnace casing and from adapters and holders securing the specimen.

Temperature measurements are usually carried out by thermocouples in contact with the specimen. For reliable temperature measurements, thermocouples should be shielded from direct radiation from the furnace walls. Room temperature maintained should be in such a way that it is higher than or above the expected outside temperature.

The room temperature should be kept within the range of \( \pm 0.5^0C \)

2.6.2 Extension measurements
Extensometers of comparatively low sensitivity are used. However, time interval is increased between readings. They should have strain sensitivity at least equal to the variations in length produced by the temperature variations encountered during the test. In most cases, mechanical extensometers designed using lever arm are used made up of lower and upper parts attached to the specimen by means of Allen screws.

The extensometers should take into account the strains of opposite sides of the specimen.

2.6.3 Measurements to be taken
The measurements that need to be taken during creep test include;
- Extension
- Cross-sectional area of the specimen
- Temperature
- Gauge length of the specimen
- Time/duration of the creep test
2.7 CREEP DATA/RESULTS

After extension are measured at frequent time intervals till fracture or pre-determined time, strains are calculated by dividing the extension by the gauge length. The strain obtained is thus plotted against time that yields the standard creep curve with 3 distinct stages as shown;

![Image of creep curve]

Fig 2.7

2.7.1 Primary creep stage

This is a period of decelerating creep rate due to progressive work hardening that slows down creep strain rate.
2.7.2 The secondary (steady state) creep stage
This is a period of constant creep rate and associated with equilibrium between hardening and softening mechanisms in the material.

2.7.3 Tertiary creep stage
This is a period of accelerating creep rate that leads to fracture. It is associated with necking and consequent stress increase, cracking, metallurgical instability and over-aging. The material is thus less resistant to creep at this stage.
The tertiary and secondary creep stages are dominant at high temperatures greater than half the melting temperatures leading to fracture.
Primary creep is dominant at low temperature that is temperatures lower than melting point and decreases to a constant. Various creep data can be obtained and presented.

2.8 CREEP DATA PRESENTATION

2.8.1 Temperature effects and strain rate
Here, plots of strain are made against that time at constant temperature.

![Strain vs Time Graph](image)

Fig 2.8.1

2.8.2 Stress effects and strain rates
Plots of strains against time at constant stress are made.
The plots are as follows:

\[ \sigma_4 > \sigma_3 \]
\[ \sigma_3 > \sigma_2 \]
\[ \sigma_2 > \sigma_1 \]

\[ \sigma_1 \]

**Fig 2.8.2**

**2.8.3 Effects of Alloying and Creep rate**

This gives a plot of strain and time for different alloying components. This is necessarily taken at constant/same temperature and stress for the different alloys so as to establish their effects on creep rate.
It is evident that as the percentage alloy increases, the creep rate decreases e.g. as titanium amount increases, the creep rate decreases.

From the above curves, other curves that give more useful information during design can also be obtained known as Engineering creep data.

2.8.4 Engineering Creep Data

2.8.4.1 Iso-Strain (Isometric) Stress-Time curves
Here, the constant strain lines are plotted on creep curves at various stresses and constant temperature thus a particular time required to reach a particular strain can be read off for a specified temperature and stress.

2.8.4.2 Isochronous stress Temperature curves
These are obtained by plotting constant time lines on creep curves and reading off combination of stress and temperature needed for a given strain.

Maximum stress can thus be read off at specified temperature from the curves.
Fig 2.8.6; Isochronous Stress-temperature curves

2.8.4.3 Isochronous stress-strain rate curves

This relates contours of constant time plots on Log-Log plot of strain rate against stress. This determines the stress-strain behavior of materials.
2.9 CREEP DATA CORRELATIONS/ANALYSIS

Several creep parameters are utilized to correlate creep data to be presented in a format that gives more meaning in design. From the data, various curves can be plotted known as master curves. The parameters are as discussed below;

2.9.1 Larson Miller creep parameter

The Larson Miller creep parameter (LMCP) is expressed as;

$$\text{LMCP} = T(C + \log t)$$

where LMCP=Larson Miller Creep parameter; T=Temperature in kelvins; t=time to rupture in hrs and C= material constant

The parameter is then plotted against the log of stress to give the master curve as below;

![Graph showing Larson Miller Parameter vs Log Stress at various strains](image)

Fig 2.9.1: Log stress against Larson Miller Creep Parameter at various strains

The Larson Miller parameter gives better consistence with deformation process occurring at lower temperatures. It also offers better results with interpolation and extrapolation.
2.9.2 Dorn Parameter ($P_D$)

This correlation assumes creep to be thermally activated. The Dorn Parameter is normally expressed as:

$$P_D = t e^{-Q/RT}$$

Where
- $Q$ - activation Energy
- $T$ - temperature
- $t$ - time
- $P_D$ - Dorn Parameter

The graph of Log against Log of the parameter is as shown;
2.9.3 Marson Haford Parameter ($P_{MH}$)

This parameter is more reliable for data prediction at higher temperatures. It explains complex deformation pattern controlled by several mechanisms.

It is expressed as;

$$P_{MH} = \frac{T - T_a}{\log t - \log t_a}$$

Where

- $T_a$ - constant temperature
- $t_a$ - constant time

$P_{MH}$ = Mason Harford Parameter

The graph of the log of stress ($\sigma$) against the parameter is as shown below:
2.9.4 Zenner Holloman Parameter (Z)

The Zenner-Holloman parameter predicts that if strain rate is to produce a given stress at a given temperature is plotted on a logarithmic scale against 1/T, a straight line results with slope of (-Q/R)

It is mostly applicable for pure metals and accurate for secondary creep.

Expressed as;

\[ Z = e^{Q/RT} \]

Where;

\( \square \) - The creep rate

Q - activation energy

Z - Zenner-Holloman creep parameter

Can be represented as either the log of the parameter against log of strain rate or the plot of strain rate against reciprocal of time as shown below;

Fig 2.9.4

Fig 2.9.5
CHAPTER THREE

METHODOLOGY

3.1 TENSILE TEST
The tensile test was conducted to determine the mechanical properties of the materials used, including the yield strength, ultimate tensile strength, percentage elongation and percentage area reduction.

The tensile test was also done to determine the maximum loads to be applied so as to avoid yielding of the materials during the creep test.

3.1.1 APPARATUS

3.1.1.1 Tensile test specimens
The specimens were machined using lathe machines in the workshops and prepared according to the British Standards

3.1.1.2 Hounsfield Tensionmeter

Figure 3.1

The tensiometer was used to carry out tensile test for the various specimens to determine the yield strength, ultimate tensile strength and maximum load that can be applied before yielding.
3.1.1.3 Lock jaws

The lock jaws were used to mount the specimens on the Hounsfield tensiometer.

3.1.1.3 Reduction in area gauge

Figure 3.2

The gauge was used to measure the percentage Area reduction after the tensile test. It is a measure of the ratio of final to the original area.

3.1.1.4 Elongation gauge

Figure 3.3

The elongation gauge was used to measure the percentage elongation after the test. It is a measure of the ratio of final to the original length.

3.1.1.5 Vernier calipers

Vernier Calipers was used to take measurements of the specimens and confirm that the dimensions met the specified British standards.
3.1.1.6 Graph papers
The graph papers were mounted on the drum of the Hounsfield Tensiometer to obtain the plots of the Force against extension resulting from the tensile test. Marks were made on the graph paper using a pin that followed the mercury level as the drum rotated during the experiment.

3.1.2 EXPERIMENTAL PROCEDURE
The prepared test specimens were held firmly by the lock jaws and then mounted on the Hounsfield Tensiometer.

A suitable beam corresponding to the maximum loads expected for the specimens was selected to be used and mounted on the Hounsfield Tensiometer.

The graph paper was carefully rolled on the rotating wheel/drum of the Hounsfield Tensiometer with the first mark made on it after the mercury level was set to zero.

The motor was turned on and the mercury level followed with the punch and marks made on the graph paper as the drum rotated. This was done until failure. The marked points were then joined and appropriate curves obtained as indicated in the results (appendix I).

3.2 CREEP TEST

3.2.1 CREEP TESTING APPARATUS

3.2.1.1 Creep testing specimens
The specimens were machined using lathe machined according to the British Standards (BS) specifications

3.2.1.2 Electric heating furnace
The electric heating coil had a special assembly used to heat the specimens to the required temperatures. It consisted of the following sub-components;
3.2.1.2.1 The heating coil

The coil used was Kanthal wire with high ductility, high resistance to oxidation, high resistivity, high melting point and above all, economically friendly.

The coil was heated by means of electricity supplied by a step-down transformer and heat regulated by means of a simmer switch to achieve desired temperature through a control knob.

3.2.1.2.2 Insulating materials

Furnace body was made of fire clay with grooves to accommodate the heating coil. Fire clay was used due to its high refractory, stability at high temperatures and economical viability. It is also readily available.

3.2.1.2.3 The housing

The housing was made of mild steel and provisions made for the thermocouple and coil connections.

3.2.1.2.4 Inner refractory core

The core is the innermost sub-component made of porcelain and placed between the specimen and the heating coil which was used to prevent direct contact between the specimen and the coil. It is highly refractory and has high melting point.

3.2.1.3 Pyrometer

![Pyrometer Image](image)

Figure 3.4
The pyrometer was used to record temperature of the furnace as it was measured by the thermocouple at any particular time

3.2.1.4 Thermocouple
Thermocouple was used to measure temperature of the furnace by virtue of the temperature difference between the furnace and the environment.

3.2.1.5 Loads
The loads were applied to the specimen to obtain the desired stresses for the specific metals.

3.2.1.6 Stop watch
Stop watch was used to record time from the beginning to the end of the test (rupture).

3.2.1.7 Vernier calipers
The Calipers was used to confirm the dimensions of the specimens to verify their conformance with the British Standard dimension specifications.

3.2.1.8 Loading system
The loading system set-up was used to mount the specimen to the electric heating system.
Constitutes the threaded upper and lower parts into which the threaded specimens are fixed.

3.2.1.9 Dial gauge

Figure 3.5
The dial gauge was used to measure extensions with time and consequently obtain the strain for the various metals as time progressed.

3.2.2 EXPERIMENTAL PROCEDURE

The specimen dimensions were confirmed by use of the Vernier calliper and specimens that were improperly machined or were not as per the dimensions were rejected.

The specimens were carefully screwed to the loading system and mounted onto the creep set up (the furnace) ready for heating and load application.

The heating system was switched on and desired temperature set using the control knob (simmer switch). The temperature level was checked by use of the pyrometer.

The dial gauge was set to zero while making contact with the loading pan.

The desired load was then placed on the pan attached to the loading system holding the specimen. The initial extension was noted and the stop watch started.
Extensions were measured against time and consequently, strains were obtained. This was done till rupture. The readings of extension against time were recorded for the various specimens as shown in appendix I.

The creep test was done by varying the temperature and loads for the different specimens for the different materials.

3.3 CHALLENGES AND CONSEQUENT MODIFICATIONS ON THE CREEP TESTING MACHINE

Various challenges were faced while undertaking the project which included:

3.3.1 SPECIMENS

Some specimens produced were not to the specifications and thus we ended up rejecting them. Furthermore, some had scratches and curves. These could not be used for the purposes of accurate creep test results.

3.3.2 LOADING SYSTEM

We discovered that the creep specimens could not fit exactly into the loading system when screwed. We thus had to re-thread the grooves of the loading system to accommodate the specimens.

3.3.3 TEMPERATURE CONTROL

Temperature control was a major setback as it kept on fluctuating unpredictably for the preliminary tests. After several tests, we decided to replace the switch that was available with a simmer switch which gave automatic temperature control rather than the manual temperature control system that was available. Obtaining the simmer switch posed a great problem at the beginning but eventually we managed to secure one which could achieve our objective of automatic temperature control.

3.3.4 THE STRAIN MEASUREMENT

As we settled for the project, we realized that the digital strain gauge indicator that had been used previously was not consistent in its functionality. The attempts to repair the indicator bore no fruits.
as it was taking long to get it to shape and time was also of the essence. We thus decided to use the available method to record extensions. We hence decided to use dial gauge which has an accuracy of 0.01 mm to record extensions.

3.3.5 HEAT LOSS CONTROL
The furnace was initially losing a lot of heat thus could not achieve desired temperatures. We improved the furnace efficiency by packing extra fiber glass to reduce heat loss. Asbestos was also used at the top and bottom of the furnace to prevent direct heat loss.
CHAPTER FOUR

4.0 EXPERIMENTAL RESULTS
This section deals with raw data obtained from the experiments carried out. The findings are presented in form of tables and graphs for the various tests performed, i.e. the tensile and the creep test.

4.1 THE TENSILE TEST RESULTS
These are the results giving the mechanical properties of various materials tested.

Sample dimensions and calculations;

Gauge Length ($L_0$) = 25.54mm

Diameter $(D)$ = 4.54mm

Area $(A)$ = $\pi D^2/4$

$= \pi (0.00454)^2/4$

$=1.612 \times 10^{-5}$ m$^2$

Stress $(\sigma)$ = Force $/(F)$ Area $/(A)$

Strain $(\epsilon)$ = Extension $/(\varepsilon)$ Original Length $/(L_0)$
Table 4.1: Mechanical Properties of Metals

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$\sigma_{ults}$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>%elongation</th>
<th>%Area Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRASS</td>
<td>385</td>
<td>363</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>COPPER</td>
<td>404</td>
<td>345.8</td>
<td>15</td>
<td>70</td>
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<tr>
<td>MILD STEEL</td>
<td>624</td>
<td>598</td>
<td>13</td>
<td>42</td>
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<tr>
<td>ALUMINIUM</td>
<td>494.4</td>
<td>367.3</td>
<td>12</td>
<td>64</td>
</tr>
</tbody>
</table>
4.2 CREEP TEST RESULTS

The raw data for creep test are recorded in tables. The extensions and time are monitored continuously until the specimen ruptures or to a given set predetermined time period. From the extensions obtained from the raw data, strains and strain rates can be calculated.

4.2.1 TABLES OF STRAIN AGAINST TIME

Strain is obtained by finding the ration of the extension to the original length of the specimen. These are then tabulated as shown in the appendix I

4.2.2 GRAPHS OF STRAIN AGAINST TIME

These are graphs of strain obtained against the time taken until rupture. These are shown for different materials as shown below;

4.2.2.1 Creep curves for copper:

Figure 4.1; Stress=42.1 MPa Temperature=700°C
Figure 4.2; Stress=40.27 MPa Temperature=650°C

Figure 4.3; Stress=34.2 MPa; Temperature=500°C
Figure 4.4; Temperature=550°C; Stress=33.5 MPa

Figure 4.5; Temperature=610°C; Stress=40.2 MPa
4.2.2.2 Creep curves for aluminium

**Figure 4.6; Stress=22.4 MPa ; Temperature=450°C**

![Graph showing creep curve with strain on the Y-axis and time in seconds on the X-axis.]

**Figure 4.7; Temperature=500°C; Stress=28.1 MPa**

![Graph showing creep curve with strain on the Y-axis and time in seconds on the X-axis.]
**Figure 4.8;** Temperature=350°C; Stress= 44.6 MPa

![Graph showing strain over time for Temperature=350°C; Stress= 44.6 MPa.]

**Figure 4.9;** Temperature=400°C; Stress=33.48 MPa

![Graph showing strain over time for Temperature=400°C; Stress=33.48 MPa.]

You created this PDF from an application that is not licensed to print to novaPDF printer (http://www.novapdf.com)
**Figure 4.10;** Temperature = 510°C; Stress = 23.04 MPa

![Creep Curve for Brass](image1)

**4.2.2.3 Creep Curves for brass**

**Figure 4.11;** Temperature = 500°C; Stress = 42.84 MPa

![Creep Curve for Brass](image2)
Figure 4.12; Temperature=500°C; Stress=27.33 MPa

Figure 4.13; Temperature=500°C; Stress=25.94 MPa
**Figure 4.14:** Temperature=550°C; Stress= 30.1 MPa

**Figure 4.15:** Temperature=550°C; Stress=34.2 MPa
4.2.2.4 Creep curves for steel

Figure 4.16; Temperature = 740°C; Stress = 49.09 MPa

Figure 4.17; Temperature = 740°C; Stress = 45.983 MPa
Figure 4.18: Temperature = 700°C; Stress = 40 MPa
4.3 LARSON MILLER PARAMETER ANALYSIS

4.3.1 SAMPLE CALCULATIONS FOR LARSON MILLER CREEP PARAMETER (L.C.M.P)

In general, Larson-Miller Creep Parameter, L.C.M.P = T (ln t + C)

Where T= Temperature in Kelvins

C= Material constant

t=Time of rapture in Hours

4.3.1.1 COPPER

<table>
<thead>
<tr>
<th>SPECIMEN 1</th>
<th>SPECIMEN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress = 42.085 MPa</td>
<td>Stress = 40.24 MPa</td>
</tr>
<tr>
<td>Temperature (T) = 973° K</td>
<td>Temperature (T) = 943° K</td>
</tr>
<tr>
<td>Time of rapture (t) = 2.457 Hours</td>
<td>Time of rapture (t) = 0.6018 Hours</td>
</tr>
</tbody>
</table>

Obtain the constant C

L.C.M.P = 973(ln 2.457 + C)

L.C.M.P = 943 (ln 0.6018 + C)

Solving the two simultaneously, the value of C becomes

C= 45.13

Thus for specimen 1, the L.C.M.P = 973 (ln 2.4577 + 45.13)

= 44786.47
4.3.1.2 ALUMINIUM

SPECIMEN 1
Stress = 22.42 MPa
Temperature (T) = 723° K
Time of rapture (t) = 5.38667 Hours

SPECIMEN 2
Stress = 40.24 MPa
Temperature (T) = 773° K
Time of rapture (t) = 0.6125 Hours

Obtain the constant C

\[ \text{L.C.M.P} = 723 (\ln 5.38667 + C) \]
\[ \text{L.C.M.P} = 773 (\ln 0.6125 + C) \]

Solving the two simultaneously, the value of C becomes

\[ C = 41.93 \]

Thus for specimen 1, the L.C.M.P = 723(\ln 5.38667 + 41.93)

\[ = 31532.87 \]

4.3.1.3 BRASS

SPECIMEN 1
Stress = 30.1 MPa
Temperature (T) = 823° K
Time of rapture (t) = 2.7025 Hours

SPECIMEN 2
Stress = 42.085 MPa
Temperature (T) = 873° K
Time of rapture (t) = 0.2886 Hours

Obtain the constant C

\[ \text{L.C.M.P} = 823 (\ln 2.7025 + C) \]
\[ \text{L.C.M.P} = 873 (\ln 0.2886 + C) \]
Solving the two simultaneously, the value of C becomes

\[ C=38.062 \]

Thus for specimen 1, the L.C.M.P = 823(ln 2.7025 + 38.062)

\[ = 32143.23 \]

4.3.1.4 Steel

<table>
<thead>
<tr>
<th>SPECIMEN 1</th>
<th>SPECIMEN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress = 45.983 MPa</td>
<td>Stress = 40.1 MPa</td>
</tr>
<tr>
<td>Temperature (T) =1013° K</td>
<td>Temperature (T) = 973° K</td>
</tr>
<tr>
<td>Time of rapture (t) = 3.306 Hours</td>
<td>Time of rapture (t) = 15.823 Hours</td>
</tr>
</tbody>
</table>

Obtain the constant C

L.C.M.P = 1013(ln3.30556 + C)

L.C.M.P = 973 (ln 15.82333 + C)

Solving the two simultaneously, the value of C becomes

\[ C=36.9 \]

Thus for specimen 1, the L.C.M.P = 1013(ln 3.30556+ 36.9)

\[ = 38511.18 \]
Table 4.3.1: TABLE SUMMARY FOR THE MATERIAL CONSTANTS

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>L.C.M.P CONSTANT (C)</th>
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<tr>
<td>COPPER</td>
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<tr>
<td>ALUMINIUM</td>
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<td>BRASS</td>
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<tr>
<td>STEEL</td>
<td>36.9</td>
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The L.C.M.P values for the different materials at various temperatures and stresses are summarized in the table below;

Table 4.3.2

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<thead>
<tr>
<th>MATERIAL</th>
<th>TEMP(K)</th>
<th>STRESS (MPa)</th>
<th>LOG STRESS</th>
<th>RUPTURE TIME(Hrs)</th>
<th>L.M.C.P</th>
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<p>|         | 50   |      |        |         |          |</p>
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</table>

**Key**

- **2009 Report**
- **2008 Report**

---

9 Serem Anderson and Ouma Abraham report
10 Korir Charles and Muhoro Frances Report
4.4 THE LARSON MILLER MASTER CREEP CURVES

Figure 4.4.1: L.M.C.P for copper

Figure 4.4.2: L.M.C.P for copper-comparison
**Figure 4.4.3:** L.M.C.P for aluminium

![Graph of L.M.C.P for Aluminium](image1)

**Figure 4.4.4:** L.M.C.P for aluminium-comparison

![Graph comparing L.M.C.P for Aluminium](image2)
Figure 4.4.5: L.M.C.P for brass

Figure 4.4.6: L.M.C.P for brass-comparison
**Figure 4.4.7**: L.M.C.P for steel

**Figure 4.4.8**: L.M.C.P for steel-comparison
CHAPTER FIVE

5.0 DISCUSSION OF RESULTS

5.1 TENSILE TEST RESULTS
The tensile tests were carried out to establish the material properties of the various materials, including their yield strength, ultimate tensile strength and the percentage elongation and percentage area change.

Generally, the material properties of any material are affected by the microstructure, the composition, specimen dimensions, heat treatment and manufacturing methods.

For each material, the variation noted in their properties obtained could be attributed to the variation of specimen dimensions during machining, reading errors due to parallax and computational errors. There is also a possibility of inadequate control of the material properties by the manufacturer.

The various properties are as discussed below;

5.1.1 Copper
The yield strength was obtained to be 345.8 MPa with ultimate tensile strength of 403.5 MPa. It also exhibited a 15% elongation and 70% area reduction. It failed after a remarkable plastic deformation. The material failed by ductile fracture.

5.1.2 Aluminium
The yield strength for aluminium was found to be 367.3 MPa with ultimate tensile strength of 494.42 MPa. The percentage elongation was 12% with a 64% reduction in cross-sectional area. The material had no defined yield strength but had considerable plastic deformation. This is due to the ductility of aluminium.

5.1.3 Mild steel
This showed yield strength of 598 Mpa with 624 Mpa as the ultimate tensile strength. It recorded a percentage elongation of 13% with a 42% reduction in the cross-sectional area. The specimen failed by ductile fracture forming cup and cone fibrous surface.
5.1.4 Brass
This material exhibited yield strength of 363 Mpa and ultimate tensile strength of 385 Mpa. It had 10% elongation and 30% area reduction. The material failed by brittle fracture.

5.2 Creep Test Results
Generally, the materials exhibited the three creep stages including the primary, secondary and tertiary stages. An instantaneous strain was recorded for all the four materials when the load was applied due to elasticity in the initial stages. In the primary creep stage, the materials showed decelerating creep rate which can be attributed to progressive work hardening which makes the materials resistant to deformation.

In the secondary creep stage, also known as the steady state creep stage, the materials exhibited constant creep rate. This is attributed to the recovery of the material as the balance between work hardening and annealing effects occurs. The bulk of the creep life of all the material occurred at the secondary stage, with the stage being longer at lower temperatures and stresses. For high temperatures and stresses, the secondary stage was observed to be short and at even higher values of stresses and temperatures, there was direct transition from primary to tertiary stage of creep.

The third stage is the tertiary stage that precedes the secondary stage. This is a period of accelerating creep rate that leads to final fracture of the material. This is attributed to necking-reduction in area of the specimen and thus the increased stress in the neck region. Possible cracking or formation of internal voids, over-aging and instability also contributes greatly to this stage as the materials become less resistant to creep. This stage however takes a very short time before fracture and at very high temperatures, it is almost unnoticeable.

5.2.1 Creep in copper
At temperature of 700°C and stress of 42.085 MPa, it experienced an instantaneous strain of 0.009. The primary stage lasted about 17 minutes. The bulk of the creep life was spent in the secondary stage which took about 134 minutes. The tertiary stage however was short lasting about 4 minutes. The steady state creep rate was obtained to be $1.526 \times 10^{-6}$ sec$^{-1}$. The specimen ruptured after 2.46 hours.
At temperature of 650°C and stress of 40.3 MPa, the instantaneous strain was 0.006. The primary stage lasted for about 20 minutes with the bulk of the creep life occurring in the secondary stage lasting about 145 minutes with a steady creep rate of $4.98 \times 10^{-6}$ sec$^{-1}$. The tertiary creep stage took least time of about 13 minutes.

At temperature of 610°C and stress of 40.2 MPa, the specimen experienced instantaneous strain of 0.00822 and ruptured after 2.83 hours. The primary stage lasted for about 30 minutes; the secondary stage lasted about 1.786 hours while the tertiary stage took 33 minutes. The steady state creep rate was $9.91975 \times 10^{-7}$ sec$^{-1}$. The graphs of strain against time are shown from figures 4.1 to 4.5

It can be observed that as the temperature increases, the strain rate increases while the secondary creep duration decreases. This is due to diffusion controlled mechanisms that are dependent on temperature. As the temperature increase, the diffusion rate also increases thus the increase in the creep strain rate.

### 5.2.2 Creep in Aluminium

At temperature of 450°C and stress of 22.4 MPa, the aluminum specimen experienced instantaneous strain of 0.006 with a rupture time of 5.37 hours. The steady state creep rate was $2.13 \times 10^{-6}$ sec$^{-1}$. The primary stage lasted about 33 minutes, the secondary stage about 292 minutes while the tertiary stage lasted for about 28 minutes before it finally fractured, with the overall time taken to rupture being 5.37 hours.

At temperature of 500°C and stress of 28.07 MPa, the instantaneous strain was 0.008 with the duration of the primary, secondary and tertiary stages being 17, 69 and 11 minutes respectively. The steady state creep rate recorded was $9.33 \times 10^{-6}$ sec$^{-1}$. The specimen ruptured after 1.61 hours.

At temperature of 510°C and stress of 23.04 MPa, the specimen experienced an instantaneous strain of 0.007 with the duration of the primary, secondary and tertiary stages being 33, 107 and 10 minutes respectively. The rupture time was 2.505 hours.
At temperature of 450°C and stress of 33.597 MPa, the instantaneous strain experienced by the specimen was 0.0083 with the primary, secondary and tertiary stages durations being 7.5, 59 and 14.2 minutes respectively. The steady state creep rate recorded was $5.1813 \times 10^{-6}$ sec$^{-1}$. The specimen ruptured after 1.352 hours.

The graphs of strain against time are shown from figures 4.6 to 4.10

An increase in stress thus leads to an increase in instantaneous strain and steady state creep rate but a decrease in the duration of secondary creep stage. This is due to stress induced diffusion.

An increase in temperature leads to a reduction in rupture time at constant stress. High temperature also leads to reduced primary, secondary and tertiary creep lives.

The Aluminum specimen failed after a remarkable plastic deformation (elongation) and there was also large reduction in the cross-sectional area.

5.2.3 Creep in Brass
at temperature of 500°C and stress of 42.84 MPa, the instantaneous strain was 0.010963 with the primary, secondary and tertiary stages durations being 35, 64 and 15 minutes respectively. The steady state creep rate was recorded as $5.79 \times 10^{-6}$ sec$^{-1}$. Rupture time was 1.91 hours.

At temperature of 500°C and stress of 27.33 MPa, the instantaneous strain recorded was 0.00822 with the primary, secondary and tertiary durations being 38, 193 and 7 minutes respectively. The steady state creep rate recorded was $2.63 \times 10^{-6}$ sec$^{-1}$. The rupture time was 3.95 hours.

At temperature of 500°C and stress of 25.94 MPa, the instantaneous strain was 0.007246 with the primary, secondary and tertiary stages durations being 38, 420 and 22 minutes respectively. The steady state creep rate was found to be $1.176 \times 10^{-6}$ sec$^{-1}$. Time to rupture was 7.95 hours.

At temperature of 550°C and stress level of 30.1 MPa, the instantaneous strain recorded was 0.008614 with a steady state creep rate of $3.45 \times 10^{-6}$ sec$^{-1}$. The durations of the primary, secondary and tertiary stages were 27, 130 and 7 minutes respectively. The specimen ruptured after 2.7 hours.
At 550°C and stress level of 34.2 MPa, the instantaneous strain was 0.012 MPa with steady state creep rate of $3.64 \times 10^{-6} \text{sec}^{-1}$. The primary, secondary and tertiary stage durations were 8, 225 and 0.82 minutes respectively. It took 3.897 hours for the specimen to rupture.

The graphs of strain against time are shown from figures 4.11 to 4.15

Like other metals, increase in stress has the effect of increasing instantaneous strain and decreasing the rupture time. The primary, secondary and tertiary creep stages also reduce in their duration during the creep test with the bulk of the creep life experienced at the secondary stage of creep.

Brass failed with little plastic deformation as well as necking. This is due to low ductility of Brass, that is, brittle. The highest strain rate experienced at high temperature and stress for instance at temperature of 550°C and stress of 34.2 MPa. The shortest tertiary stage recorded at high temperature and stress.

5.2.4 Creep in Steel
At temperature of 740°C and stress level of 49.01 MPa, the instantaneous strain recorded was 0.012 with steady state creep rate of $7.5 \times 10^{-6} \text{sec}^{-1}$. The durations of the creep deformation stages were 15, 95 and 15 minutes respectively for primary, secondary and tertiary creep stages. The specimen ruptured after 2.081 hours.

At temperature of 740°C and stress of 45.983 MPa, the specimen experienced an instantaneous strain of 0.018 with steady state creep rate of $1.61 \times 10^{-6} \text{sec}^{-1}$. The primary, secondary and tertiary creep stages took 56, 110 and 33 minutes respectively. The rupture time was 3.3056 hours.

At temperature of 700°C and stress level of 40 MPa, the instantaneous strain recorded was 0.014961 with steady state creep rate of $4.23 \times 10^{-7} \text{sec}^{-1}$. The durations of the primary, secondary and tertiary creep stages were 0.82, 14.7 and 0.3 hours respectively. The specimen ruptured after 15.82 hours.

The graphs of strain against time are shown from figures 4.16 to 4.18
When stress is increased at constant temperature, the secondary creep rate increases while the creep life at this stage reduces. The increased stress provides a driving force for dislocation movement and diffusion of atoms. As the stress is increased, the rate of deformation also increases. The increase in stress and temperature increases strain rates.

For steel, the rupture strains were large attributed to improved ductility of mild steel at high temperatures. The secondary creep stage took the longest times compared with other specimens.

5.3 OBSERVATIONS ON THE FRACTURED CREEP SPECIMENS

5.3.1 Aluminum
The specimen failed by ductile fracture after remarkable plastic deformation due to its high ductility. The surface of the specimen remained shiny as before the test because of excellence in corrosion resistance resulting from the formation of a protective alumina coating on the surface.

5.3.2 Brass
The material failed by ductile fracture with almost unnoticeable necking. There was virtually no change in the cross-sectional area. Brass being a good corrosive resistant material, the color of the specimen remained as before.

5.3.3 Copper
The specimen failed indicating no necking therefore very little change in the cross-sectional area. A black coating was observed on the surface of the fractured specimen due to oxidation of copper at high temperatures.

5.3.4 Mild Steel
Mild steel exhibited a remarkable necking, reduction in cross-sectional area and in the overall strain indicating its high ductility. The specimen underwent oxidation which was witnessed by dark brown scales on its surface. This is due to low corrosion resistance of mild steel and therefore it reacted with oxygen in the furnace.
5.4 LARSON- MILLER CURVES

These are obtained by using stress, temperature and rupture times for the different materials specimens. These curves are important in predicting creep rupture time of a given material through extrapolation hence aid in design. Different materials portrayed different trends as depicted in diagrams.

5.4.1 Copper

LCMP values increase with increasing temperature. The LMCP values obtained were 35727, 44786, 40771.47, 41907.75 and 37663.35 for 973°K (32.19MPa), 723°K (42.08 MPa), 883°K (40.2 MPa), 923°K (40.276 MPa) and 823°K (33.5 MPa) respectively. The values obtained for constant stress showed an increase in LMCP as temperature increases.

The plots of the log of Stress against LMCP\textsuperscript{11} showed little scatter with the plots concentrated.

The plots however showed much scatter for Copper compared with the other reports of 2008 and 2009\textsuperscript{12}.

5.4.2 Aluminium

The LMCP values obtained were 31532.87, 29143.26, 33559.85, 26126.87 and 33530 for 723°K (22.42 MPa), 673°K (33.48 MPa), 823°K (24.48 MPa), 623°K (44.62 MPa) and 783°K (23.04 MPa) respectively.

The values portrayed less scatter thus a curve could easily be drawn\textsuperscript{13} which indicates an increase in LMCP value as stress decreases. On comparison with the 2008 and 2009 reports\textsuperscript{14}, there was consistency as the LMCP values obtained was almost the same. Furthermore, there was less scatter of the data just like the previous reports.

\textsuperscript{11} The plots are shown in figure 4.4.1
\textsuperscript{12} Comparison shown in figure 4.4.2
\textsuperscript{13} Plots shown in figure 4.4.3
\textsuperscript{14} Comparison for Aluminium shown in figure 4.4.4
5.4.3 Brass
The LMCP values obtained for brass were 32143.23, 31024.97, 30483.65, 29923, 31755 for 823K (30.1 MPa), 773⁰K (25.94 MPa), 773⁰K (27.33 MPa), 773⁰K (42.844 MPa) and 873⁰K (52 MPa) respectively. The data showed consistency and the values converged to a particular LMCP. A linear of best fit gave a linear trend depicting increase of LMCP values for decreasing stresses. On comparison with data from other reports, the values converged at almost the same LMCP value and less scatter of the data plots.

5.4.4 Steel
At temperature of 923⁰K and stress of 40 MPa, the LMCP was obtained as 40177.1 for a rupture time of 15.823 Hours. At temperature of 1013⁰K and stress of 45.983 MPa, the LMCP was 38511.8 for a rupture time of 3.31 Hours. With stress changed to 49.01MPa at temperature of 1013⁰K shifting the rupture time to 2.08 Hours, the LMCP obtained was 38122.4.

The plots of Log stress against LMCP values gave a slight scatter. Nevertheless, curve that gave a trend was obtained. From this trend, LMCP values decrease as stress increases. The data obtained showed consistency with the 2009 (Serem and Ouma) Report though the LMCP values were higher.

\footnote{Comparison on figure 4.4.6}
CHAPTER SIX

6: CONCLUSION
The creep properties of metals were established as per the objectives of the project hence successful. The following conclusions can be drawn from the entire project;

1) Creep is time dependent deformation that is prevalent at temperatures higher than 50% of the melting point of each material.

2) Creep failure is manifested in three stages; the primary, secondary (steady state creep) and tertiary stages. The secondary stage takes the bulk of the creep life of the material with the primary and tertiary stages taking shorter time with the tertiary stage being the shortest that culminates into fracture. At higher temperatures and stresses, the duration of each of the stages is reduced.

3) Temperature has great effect on creep rate as a slight increase or decrease leads to a greater change in the creep rate as can be observed in the steady state stage of creep.

4) Different materials have different creep resistance with steel having the highest resistance as it recorded the highest rapture times.

5) Mild steel and aluminium portrayed pronounced plastic deformation before rupture while copper and brass registered very little deformation as the cross-sectional area remained almost the same after the experiment. This is attributed induced brittleness at high temperatures.

6) The Larson-Miller Creep Parameter constants obtained are 38.06, 41.93, 45.12 and 36.9 for brass, aluminium, copper and mild steel respectively. This is in agreement with the acceptable values of the constants that range between 35 and 60.
RECOMMENDATIONS

To improve on the standards and the accuracy of creep testing and creep data, we recommend the following on test apparatus and methodology;

1. The test specimens should be prepared with great accuracy to avoid production of tapering weak threaded specimens. This will ensure application of equal stresses on all parts of specimen and that it does not slip as the experiment goes on.

2. A loading mechanism that prevents disturbance to the test specimen should be devised. This calls for loading at once as opposed to progressive loading to achieve the desired stress level.

3. The temperature control system had problems as temperatures kept on fluctuating therefore calling for complete attention. This can be stopped by installing a more sensitive and an automatic temperature control system.

4. The functionality of the heating coil at low and high temperatures should be ensured before the start of the project. This will prevent its failure in the process of the experiments hence avoiding time and specimen wastage.

5. Complete overhaul and repair of the creep testing equipment\(^{16}\) and the equipment in figure 2.5.2 is hereby proposed for consideration that would ensure no disturbance to the specimen due to loading and even during the experiments.

6. Incorporation of data logger that would record all data once the set-up is set so that it would not be necessary to be near the set up all the time as the case has been to minimize the risks involved during the experiment as due to the long duration taken by the experiments.

7. Temperature measurement equipment that is very sensitive to temperature change should be used as the pyrometer used presented much difficulty in stabilizing to read the exact temperature portrayed by the thermocouple. This is in line with discovery that creep deformation is greatly affected by temperature changes

\(^{16}\) Refer to figure 2.5.2
REFERENCES


