CREEP

1. Introduction: The mechanical strength of metals decreases with increasing temperature and the properties become much more time dependent. In the past the operating temperatures in applications like steam power plant, chemical plant and oil refineries seldom exceeded 500^{o}C, but since the development of the gas turbine in the 1940's successive designs have pushed this temperature up to typically 1000 ^{o}C. Developments in high temperature alloys with improved high temperature strength and oxidation resistance have had to keep pace with these demands, and applications like rocket engines present greater problems.

The strength of **viscoelastic materials** like polymers is very dependent at room temperature on the time factor, i.e. the strain rate applied. This is not so true for metals at low temperatures, but at high temperatures the time factor becomes increasingly important. Metals subjected to a constant load at elevated temperatures will undergo **'creep'**, a time dependent increase in length. The terms 'high' and 'low' temperature in this context are relative to the absolute melting temperature of the metal. At **homologous temperatures** of more than 0.5, creep is of engineering significance. Table 1 below illustrates this point.

Table 1: Homologous temperature of 0.5 for lead and tungsten.

Metal	Melting Temperature		0.5 X Melting Temperature	
	^{0}C	^{0}K	^{0}K	^{0}C
Lead	327	600	300	27
Tungsten	3407	3680	1840	1567

For a low melting point metal like lead, creep becomes significant at about 27^{0}C, i.e. on a hot day. This may cause drainage piping made from lead to sag between its supports or lead plates to creep in a battery. For a high melting point metal like tungsten, temperatures above 1500^{0}C would be needed to produce creep. Tungsten light bulb filaments operate at over 2000^{0}C and do in fact creep under their own weight, with a creep life to rupture of about 1000 hours.

2. Effect of High Temperature on Metals: Alloys developed for successful use at high temperatures must cope with the following effects:

(i) Lower strength.
(ii) Greater atomic and dislocation mobility, assisting dislocation climb and diffusion.
(iii) Higher equilibrium concentration of vacancies.
(iv) New deformation mechanisms, such as new slip systems or grain boundary sliding.
(v) Recrystallisation and grain growth.
(vi) Age hardened alloys will overage by particle coarsening and lose strength.
(vii) Oxidation and intergranular penetration.

3. High Temperature Mechanical Tests: Different tests may be required to evaluate high temperature properties, based on the time scale of the service requirements. These might include the following:-

(i) High Temperature Tensile Test: Similar to a short term room temperature test, i.e completed in a few minutes and producing stress versus strain curves at specific temperatures. Provides useful data for short term applications such as rocket parts.

(ii) Creep Test: Measures dimensional changes accurately at constant high temperature and constant load or stress. Useful for long term applications which are strain limited, such as turbine blades. The specimen will have a parallel waisted section, like a tensile specimen, but with screwed ends to avoid slippage in the grips. It is mounted inside a furnace with a sensitive strain measuring device attached, such as an inductance gauge.

(iii) Stress Rupture Test: Measures time to failure at specified stress and temperature. Useful for applications where some strain can be tolerated but failure must be avoided, such as large furnace housings.

Table 2 below illustrates the essential differences between the latter two tests.

Table 2: Comparison of Creep and Stress Rupture Tests.

Creep Test	**Stress Rupture Test**
Measures strain versus time at constant temperature and load or stress.	Measures stress versus time to rupture at constant temperature.
Relatively low loads and creep rates.	Higher loads and creep rates.
Long duration, 2,000 to 10,000 hours. Not always to fracture.	Shorter duration, less than 1,000 hours typically. Always to fracture.
Strain measured accurately using sensitive equipment (inductance gauges) to determine creep rate. Strains typically less than 0.5%.	Simpler less sensitive strain measuring equipment (dial gauges). Time and strain to fracture measured. Strains typically up to 50%.

The figures below illustrate typical results from these types of tests:

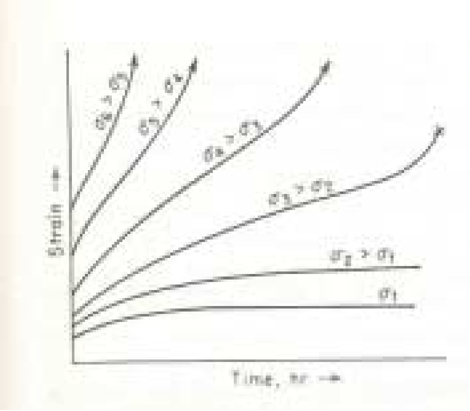

Figure 1: Typical creep curves.

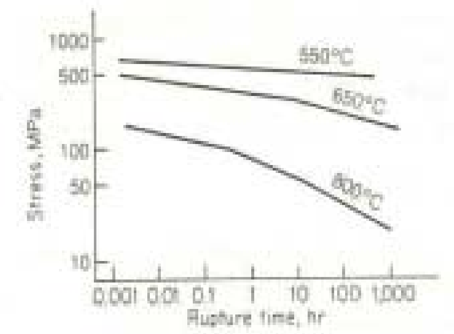

Figure 2: Typical stress-rupture curves.

4. The Creep Curve: Creep in metals is defined as time dependent plastic deformation at constant stress (or load) and temperature. The form of a typical creep curve of strain versus time is shown in Figure 3. The slope of this curve is the **creep rate** $\frac{d\varepsilon}{dt}$**.** The curve may show the instantaneous elastic and plastic strain that occurs as the load is applied, followed by the plastic strain which occurs over time. Three stages to the creep curve may be identified:

Primary creep: in which the creep resistance increases with strain leading to a decreasing creep strain rate.

Secondary (Steady State) creep: in which there is a balance between work hardening and recovery processes, leading to a minimum constant creep rate.

Tertiary creep: in which there is an accelerating creep rate due to the accumulating damage, which leads to creep rupture, and which may only be seen at high temperatures and stresses and in constant load machines.

The minimum secondary creep rate is of most interest to design engineers, since failure avoidance is required and in this region some predictability is possible. In the USA two Standards are commonly used: (i) The stress to produce a creep rate of 0.0001% per hour (1% in 10,000 hours). (ii) The stress to produce a creep rate of 0.00001% per hour (1% in 100,000 hours or approximately 11.5 years). The first requirement would be typical of that for gas turbine blades, while the second for steam turbines. Constant load machines simulate real engineering situations more accurately, but as the specimen extends its cross section area reduces, leading to a rising stress. Machines designed to reduce the load to compensate for the reduced area and maintain constant stress may produce an extended steady state region.

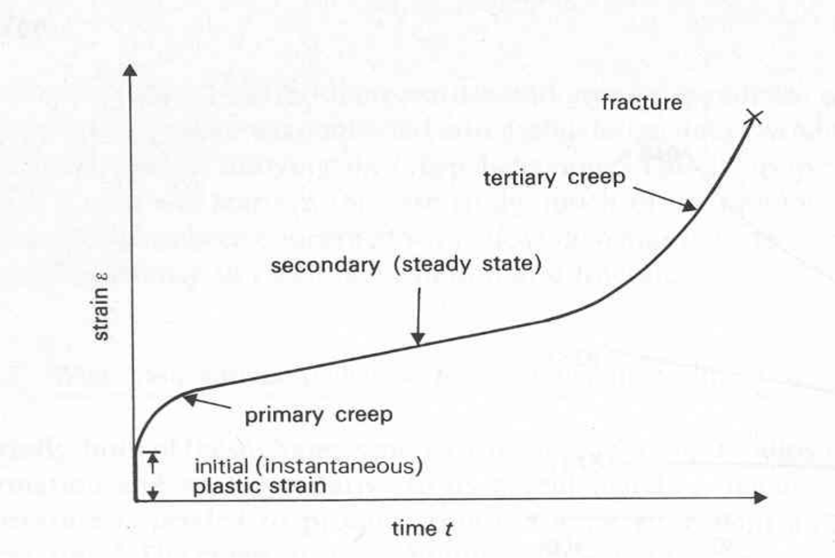

Figure 3: Stages in a typical creep curve.

5. Models for Creep Curves: There have been several empirical models proposed for creep curves. Andrade (1914) considered the superposition of a transient term and a viscous creep term, thus:

Strain, $\varepsilon = \varepsilon_0 \left(1 + \beta t^{1/3}\right) . \exp(\kappa t)$ ...(1), where t is time and β, κ are constants.

Wyatt (1953), using data on polycrystalline copper, produced:

Strain, $\varepsilon = a \log t + b t^n + c t$ ...(2), where a, b, c are constants and $n \cong \frac{1}{3}$.

Secondary creep, which occurs as a linear function of time, is strongly dependent on temperature and stress. Since creep is a **thermally activated process**, the minimum secondary creep rate can be described by a fundamental **Arrhenius equation** of the form:

Secondary creep rate, $\frac{d\varepsilon}{dt} = A \exp - \left(\frac{Q_0 - v\sigma}{RT} \right)$ ...(3), where A, v are constants, σ is applied stress, Q_0 is activation energy for creep in Joules per mole, R is the gas constant and T is the absolute temperature. An alternative expression, which separates the stress and temperature terms, is:

Secondary creep rate, $\frac{d\varepsilon}{dt} = A \sigma^n \exp - \left(\frac{Q_0}{RT} \right)$ ...(4), where $n \cong 3 \to 8$ except at low stress where it is approximately 1. Hence the term **'power law creep'**.