Creep and stress rupture

Subjects of interest

- Objectives / Introduction
- The high temperature materials problem
- Temperature dependent mechanical behaviour
- Creep test
- Stress rupture test
- Structural change during creep
- Mechanisms of creep deformation
- Fracture at elevated temperature
- High temperature alloys

INTRODUCTION

High temperature applications

Steam Power Plants

Subjected to high stress at high temperature

Oil Refineries

Steam Turbine Used in Power Plants

High temperature materials problem

TEMP ↑

- Atoms move faster **diffusion controlled process.**

  This affects mechanical properties of materials.
- Greater mobility of dislocations (climb).
- Increased amount of vacancies.
- Deformation at grain boundaries.
- Metallurgical changes, i.e., phase transformation,precipitation, oxidation, recrystallisation.

What is creep?

Creep occurs when a metal is subjected to a constant tensile load at an elevated temperature. In materials science, creep is the tendency of a solid material to slowly move or deform permanently under the influence of stresses.

At which temperature will material will creep?

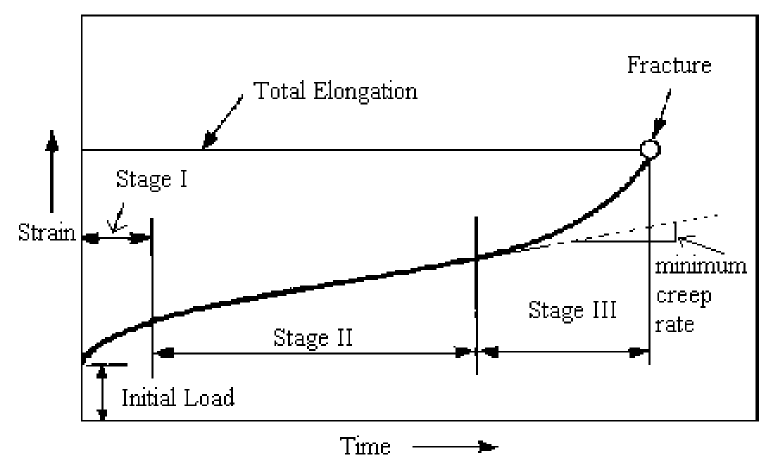
- Since materials have its own different melting point, each will creep when the homologous temperature > 0.5.

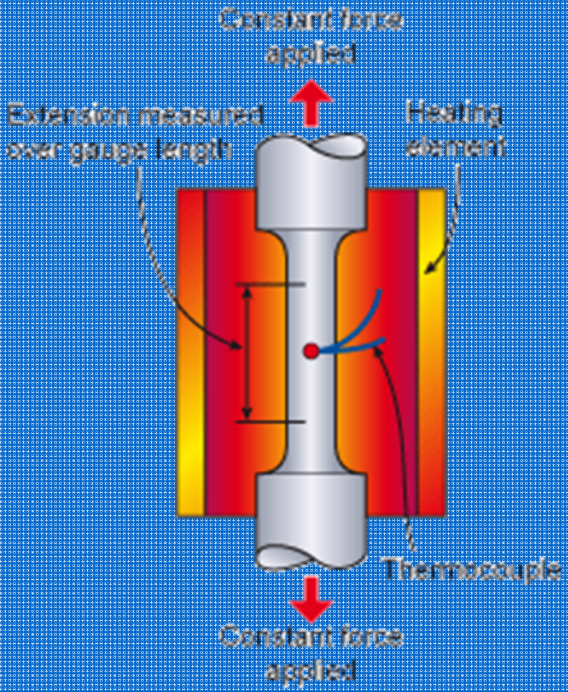
$$\text{Homologous temp} = \frac{\text{Testing temperature}}{\text{Melting temperature}} > 0.5$$

- The creep test measure *the dimensional changes* which occur when subjected to high temperature.
- The rupture test measures the effect of temperature on the long-time load bearing characteristics.

Creep Test

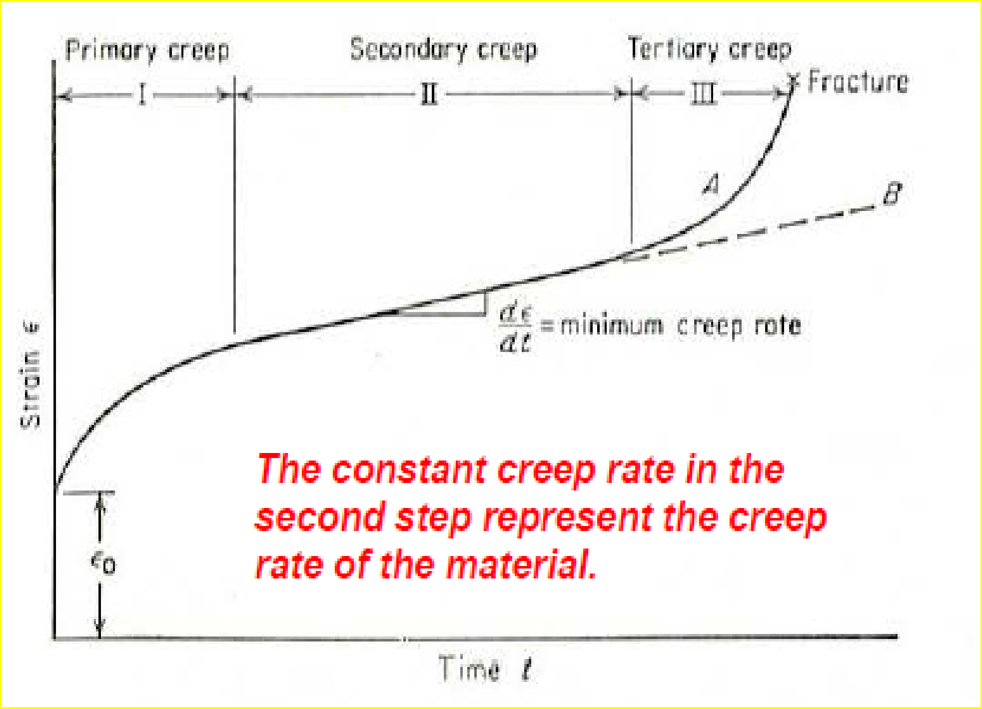
The creep test is carried out by applying a constant load to a tensile specimen maintained at a constant temperature





Schematic creep testing machine

The creep curve



The constant creep rate in the second step represent the creep rate of the material.

Typical creep curve showing three stages of creep

Notes: B curve is obtained when the stress rather than the load is maintained.

A ***typical creep curve*** shows three distinct stages with different creep rates. After an initial rapid elongation ε_o, the creep rate decrease with time until reaching the steady state.

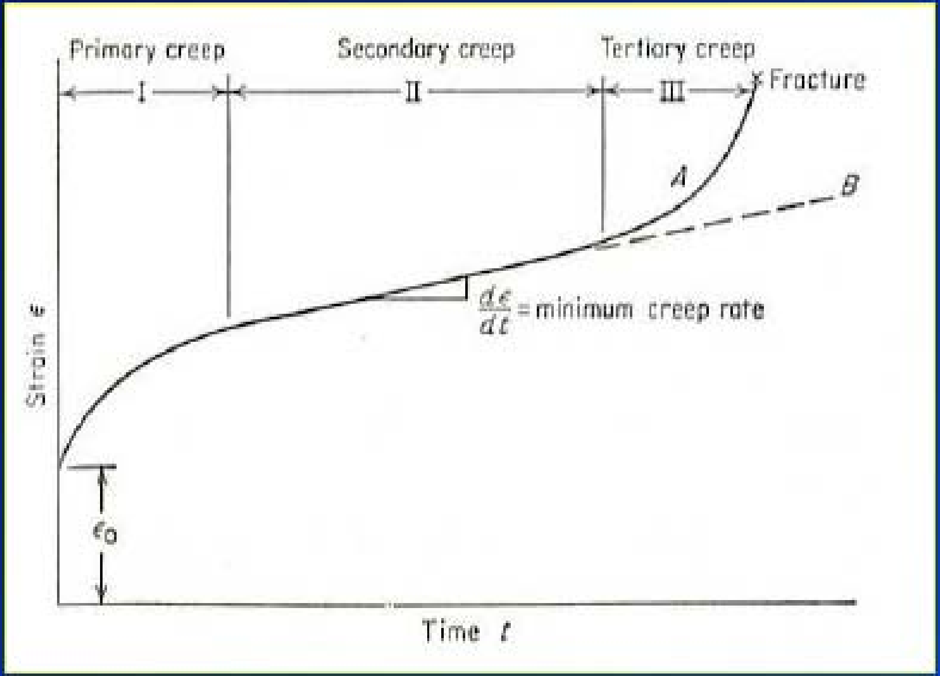
1) ***Primary creep*** provides decreasing creep rate.

2) ***Secondary creep*** gives the representing constant creep rate.

3) ***Tertiary creep*** yields a rapid creep rate till failure.

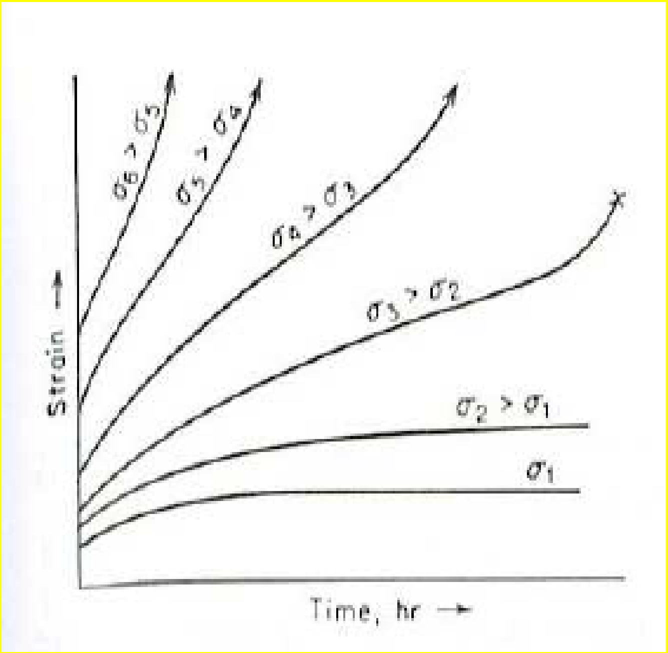
ε_o is instantaneous strain on loading which is partly ***recoverable*** with time (anelastic) and partly ***nonrecoverable*** with time (plastic).

Three stages of creep



1) ***Primary creep*** is a period of transient creep. The creep resistance of the material increases due to material deformation. Predominate at low temperature test such as in the creep of lead at RT.
2) ***Secondary creep*** provides a nearly constant creep rate. The average value of the creep rate during this period is called the ***minimum creep rate***.
3) ***Tertiary creep*** shows a rapid increase in the creep rate due to effectively reduced cross-sectional area of the specimen.

Effect of stress on creep curves at constant temperature



The shape of creep curve will slightly change according to the *applied stress* at a constant temperature.

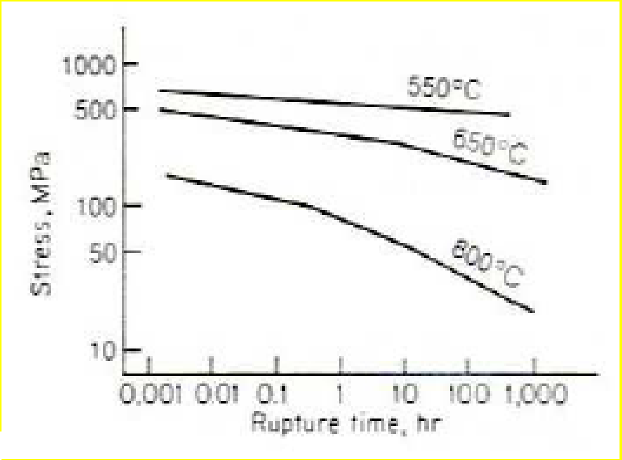
Applied stress ⬆ **Strain** ⬆

Temp ⬆ **Creep rate** ⬆

The stress rupture test

	Creep test	Stress rupture test
Load	Low load	high load
Creep rate	minimum creep rate	high creep rate
Test period	2000-10000 h	1000 h
Total strain	0.5%	50%
Strain gauge	Good strain measuring devices	Simpler strain measuring devices

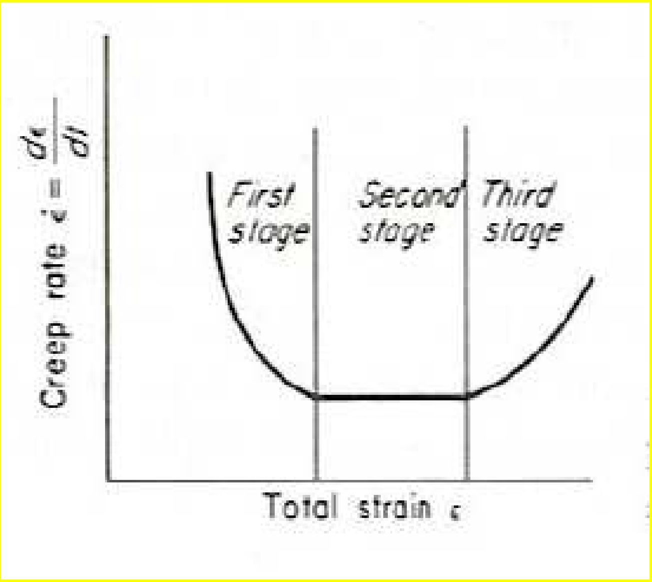
The ***rupture test*** in carried out in a similar manner to the ***creep test*** but at a ***higher stress level*** until the specimen fails and the ***time at failure*** is measured.



Stress rupture- time data on log-log scale

- ***Rupture strength*** and ***failure time*** are plotted, normally showing a ***straight line***.
- ***Changing of the slope*** indicates ***structural changes in the material***, i.e., transgranular → intergranular fracture, oxidation, recrystallisation, grain growth, spheroidization, precipitation.
- Direct application in ***design***.

Structural changes during creep



Creep rate and total strain relationship

Different creep rates result from ***changes in internal structure*** of the materials with creep rate and time.

There are ***three principal deformation processes*** at elevated temperature.

1) Deformation by slip

- More slip systems operate at high temperature
- Slip bands are coarser and widely spaced.

2) Subgrain formation

- Creep deformation produces imhomoginiety especially around grain boundaries, allowing dislocations to arrange themselves into a low-angle grain boundary. Easy for metals with high stacking false energy.

3) Grain boundary sliding

- Produced by shear process and promoted by increasing temperature/or decreasing strain rate.
- Results in grain boundary folding or grain boundary migration

Mechanisms of creep deformation

The chief creep deformation mechanisms can be grouped into;

1) **Dislocation glide**

   Involves dislocation moving along slip planes and overcoming barriers by thermal activation. Occurs at high stress.

2) **Dislocation creep**

   Involves dislocation movement to overcome barriers by diffusion of vacancies or interstitials.

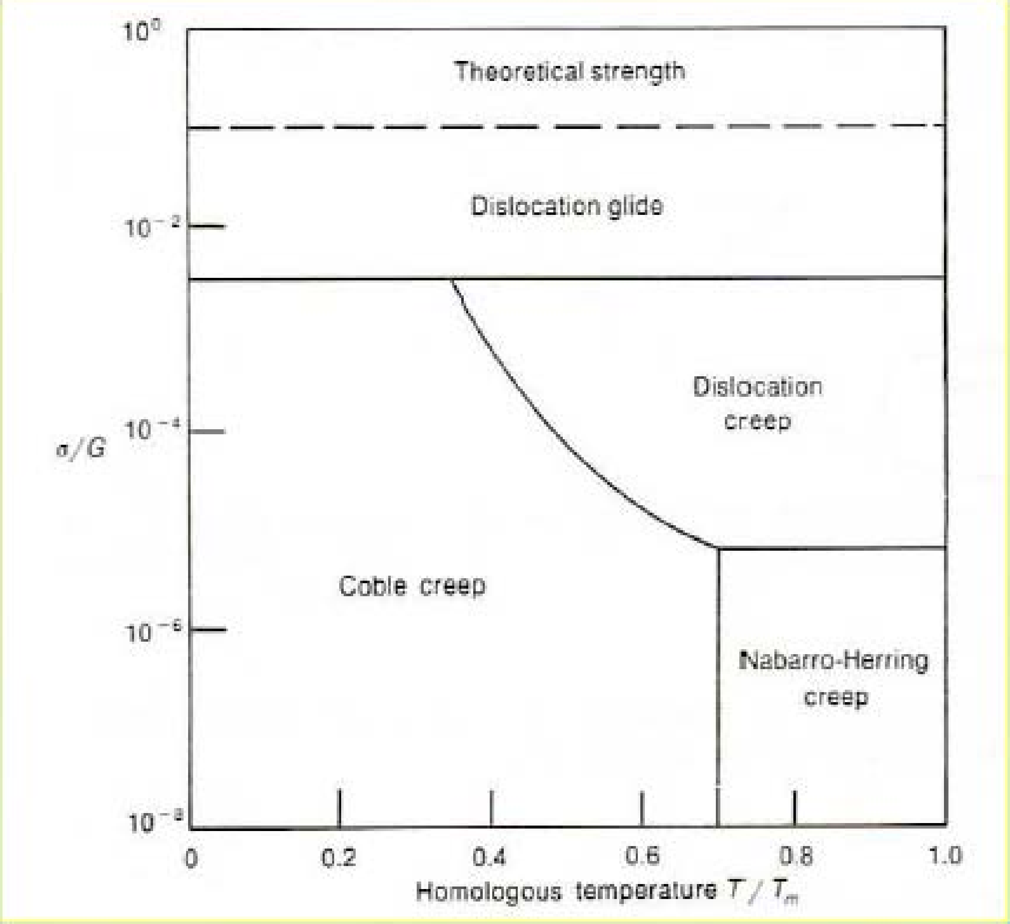
3) **Diffusion creep**

   Involves the flow of vacancies and interstitials through a crystal under the influence of applied stress.

4) **Grain boundary sliding**

   Involves the sliding of grains past each other.

Deformation mechanism maps



Simplified deformation mechanism map.

- *The various regions of the map indicate the* ***dominant deformation mechanism*** *for the combination of stress and temperature.*
- *At the* ***boundary****, two mechanisms occur.*

Note: *G is the shear modulus*

Activated energy for steady-state creep

- ***Steady-state creep deformation** predominates at temperatures above 0.5T_m.*

- Steady state creep can be expressed by

$$\dot{\varepsilon}_s = Ae^{-Q/RT} \qquad \textit{Eq.1}$$

Where **Q** = the activated energy for the rate-controlling process
A = the material structural constant
T = the absolute temperature
R = the universal gas constant

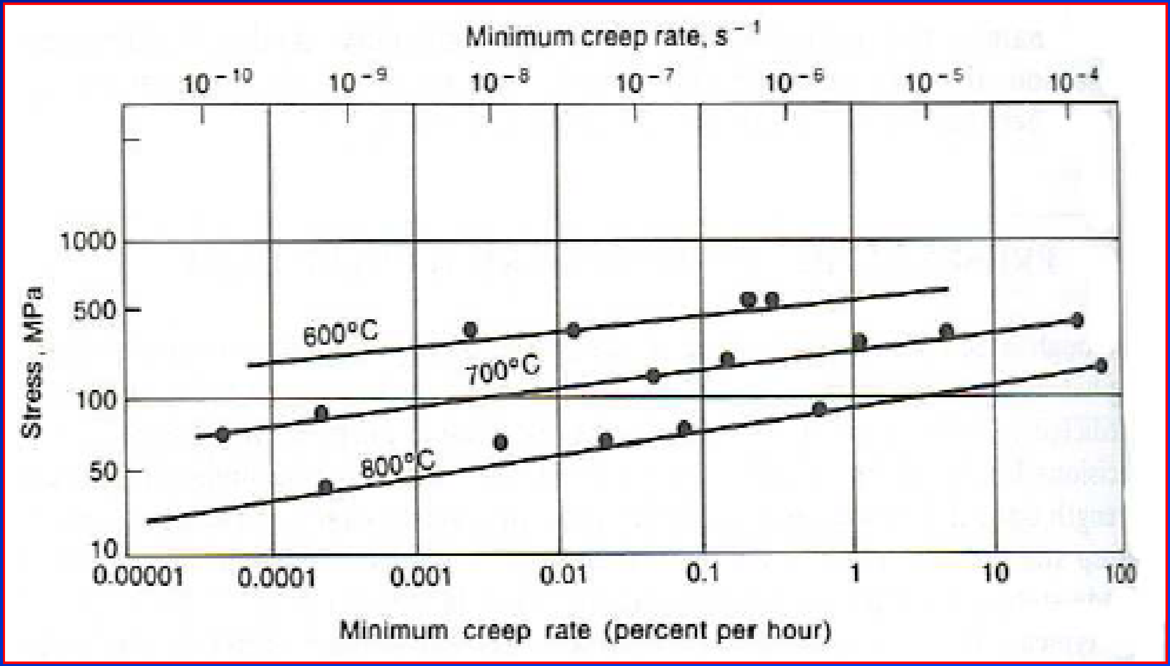
- The ***activated energy*** **Q** can be calculated by assuming the temperature interval is small so that the creep mechanisms is not expected to change.

$$A = \dot{\varepsilon}_1 e^{Q/RT_1} = \dot{\varepsilon}_2 e^{Q/RT_2}$$

$$Q = \frac{R\ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)}{(1/T_2 - 1/T_1)} \qquad \textit{Eq.2}$$

Presentation of engineering creep data

Creep strength is defined as the stress at a given temperature, which produces a ***steady-state creep rate*** (10^{-11} to 10^{-8} s^{-1}.)



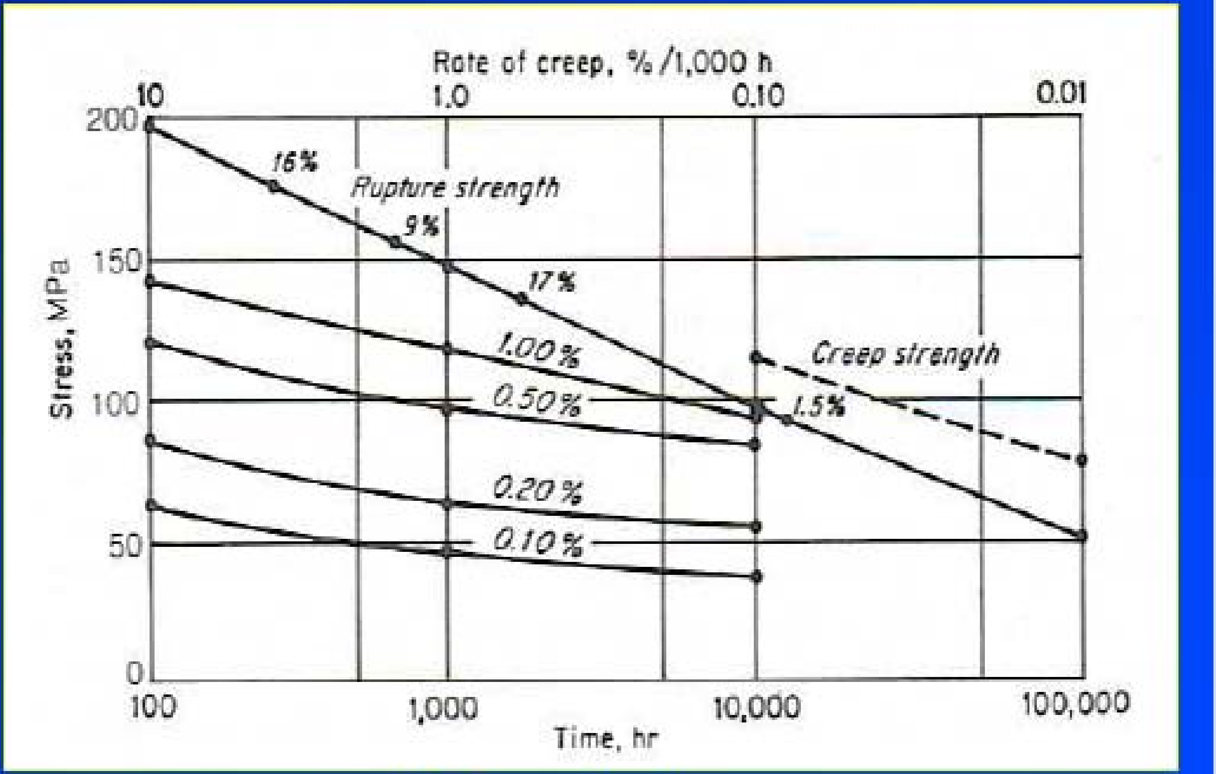
Stress vs minimum creep rate

- ***Log-log plot*** is used so that the extrapolation of one log-cycle represents a ***tenfold change***.

Creep data

Creep data can also be presented as ***a plot of stress and time*** to produce different amounts of total strain.

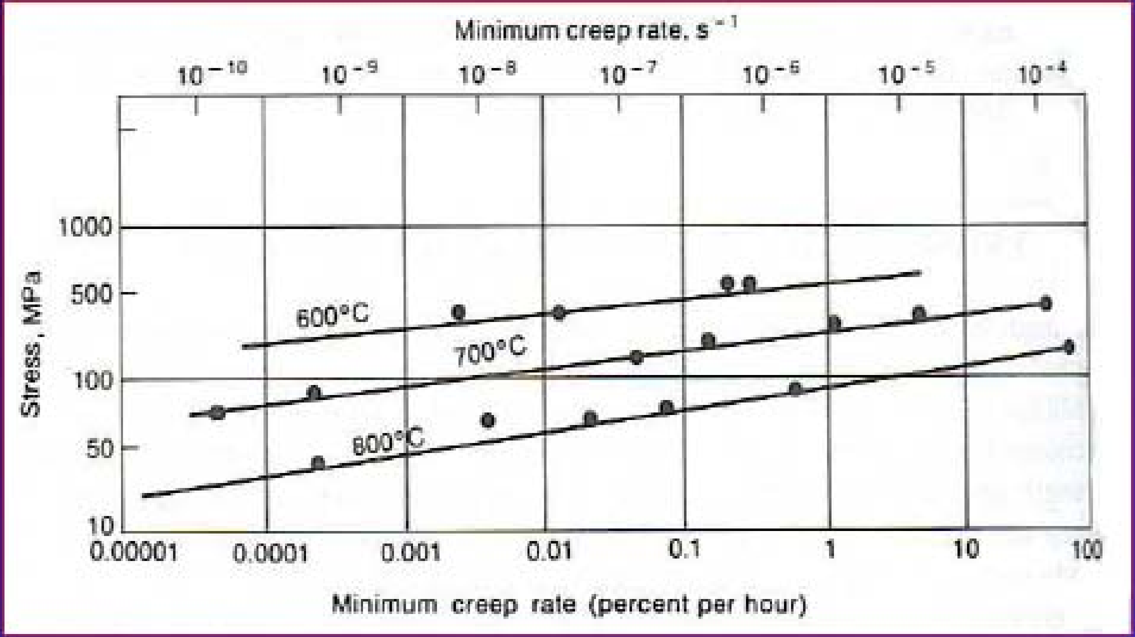
- The upper most curve is the ***stress rupture curve***.
- The percentage beside each data point is the ***percentage reduction at failure***.



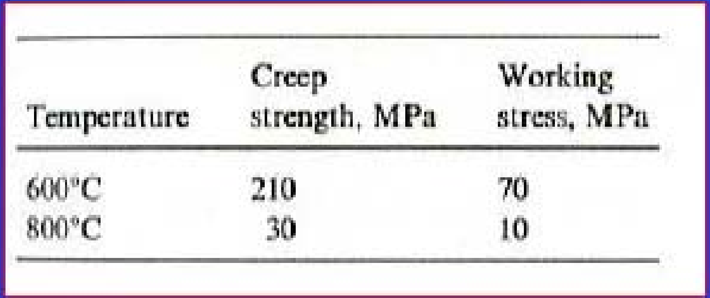
Deformation time curve

Example: *Determine the working stress at 600°C and 800°C for type 316 stainless steel if the design criterion is a creep strength based on 1 percent extension in 1000 hr. Use a factor of safety of 3.*

1% creep in 1000h $= 10^{-5} h^{-1} = \dfrac{10^{-5}}{3600} s^{-1} = 2.8 \times 10^{-9} s^{-1}$



From stress and minimum creep rate curve, the ***working stress*** *using the safety factor of 3 can be obtained in the table below.*



Temperature	Creep strength, MPa	Working stress, MPa
600°C	210	70
800°C	30	10