Lecture: Creep of Materials

Lecture: Creep of Materials

Introduction

Creep is the time-dependent deformation of a material under constant load at high temperatures. It is a critical factor in the design of engineering components exposed to elevated service temperatures and static mechanical stresses.

Time-Dependent Deformation

- When a material is loaded below its yield strength and stress is kept constant over time, strain may increase at high temperatures (creep).
- At low temperatures, strain remains constant with time (no creep).

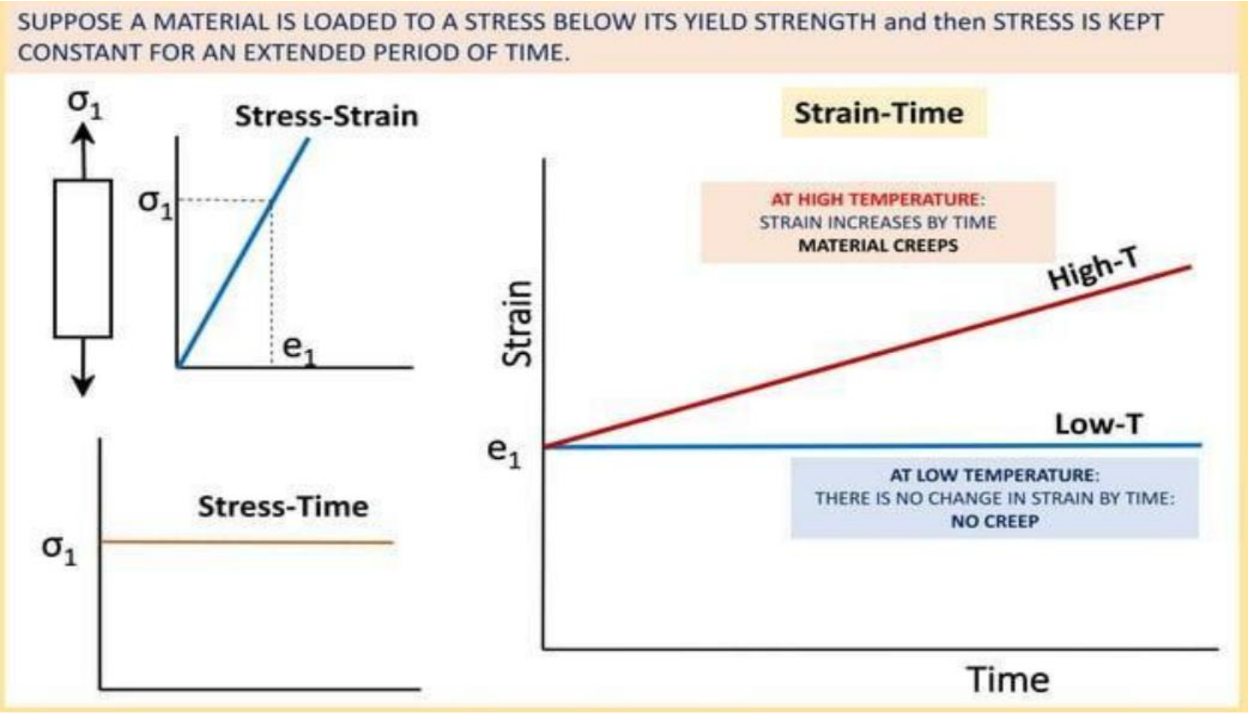
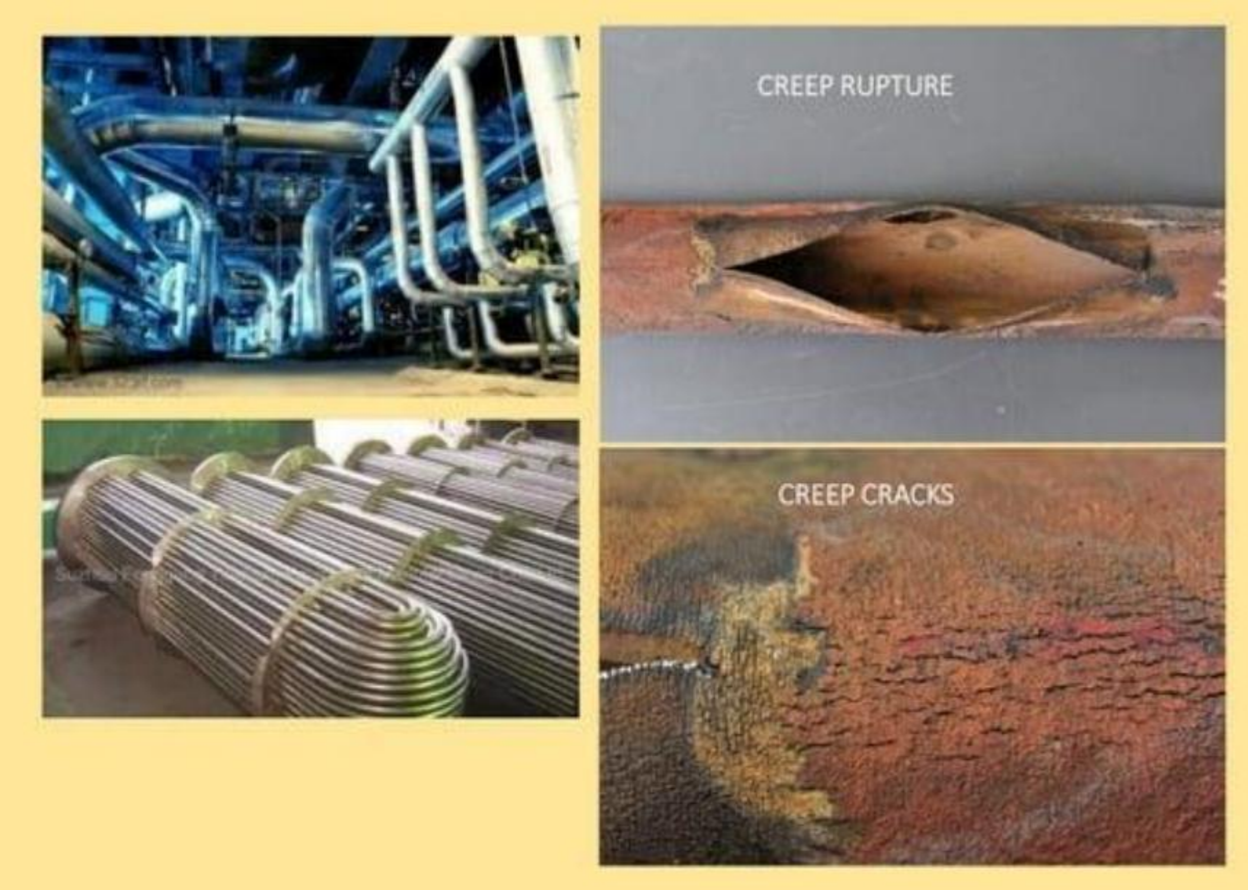


Figure: Stress-Strain-Time Relationship

Creep Failures

Creep failures are commonly observed in:

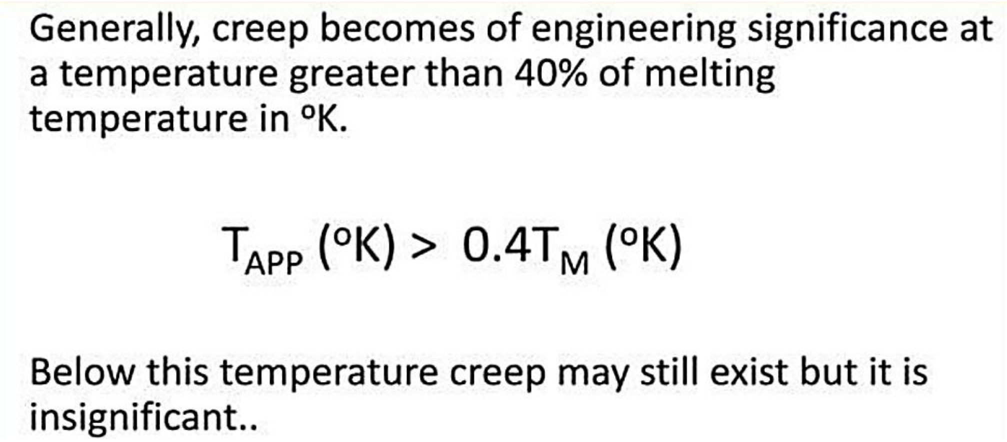
- Rocket engines and motor nozzles
- Turbine rotors of jet engines
- Steam generators and pipelines
- Nuclear power plants
- Gas turbine engines (800-1000 °C)



Figures: Creep Rupture and Cracks

Temperature for Creep

- Creep becomes significant at temperatures greater than 40% of the melting temperature (in Kelvin).



Generally, creep becomes of engineering significance at a temperature greater than 40% of melting temperature in ºK.

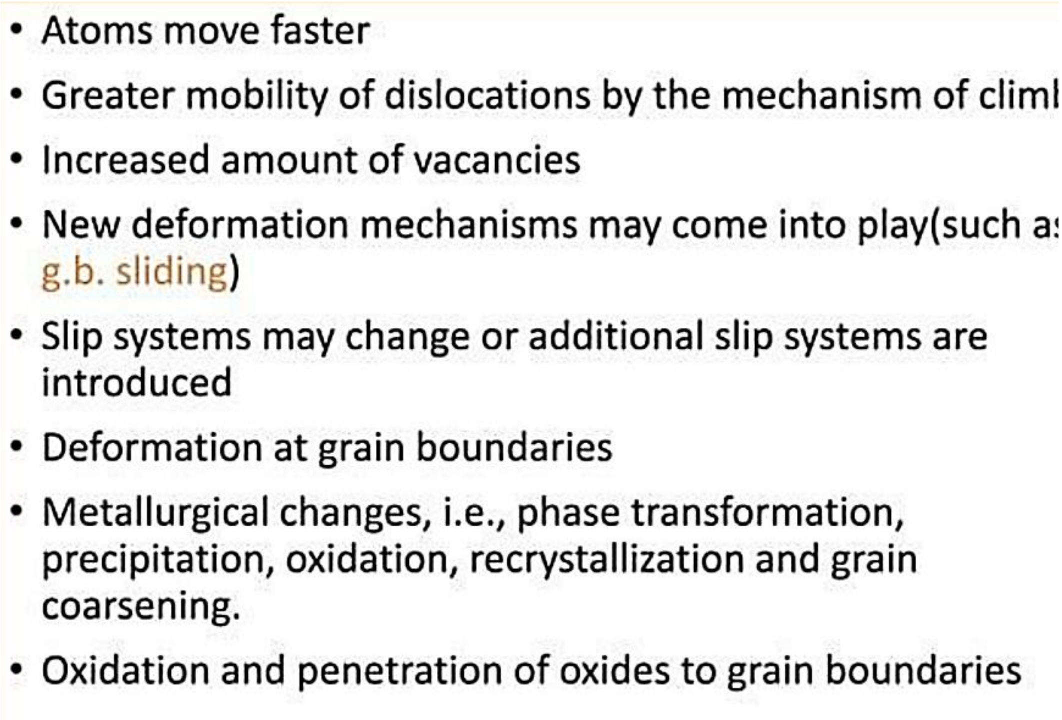
$$T_{APP}\ (^oK) > 0.4T_M\ (^oK)$$

Below this temperature creep may still exist but it is insignificant..

- Example: Iron (Tm = 1812 K) → creep above 451 °C.
- Example: Solder (Pb-Sn alloy, Tm = 456 K) → creep even at room temperature.

Figures: Temperature vs. Creep Behavior

High-Temperature Effects



- Atoms move faster
- Greater mobility of dislocations by the mechanism of climb
- Increased amount of vacancies
- New deformation mechanisms may come into play(such as g.b. sliding)
- Slip systems may change or additional slip systems are introduced
- Deformation at grain boundaries
- Metallurgical changes, i.e., phase transformation, precipitation, oxidation, recrystallization and grain coarsening.
- Oxidation and penetration of oxides to grain boundaries

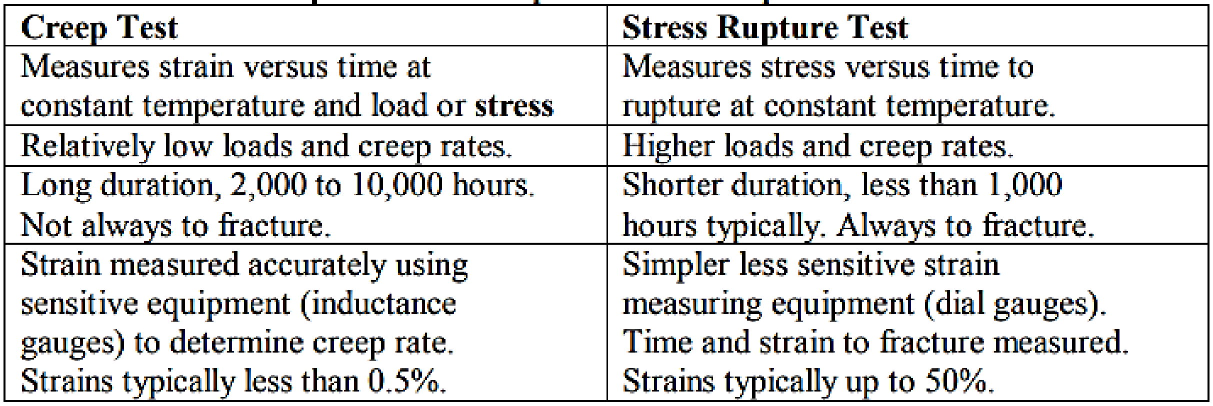
Different tests may be required to evaluate high temperature properties. These might include the following:-

(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.

(iii) Stress Rupture Test (Creep rupture test): Measures time to failure at specified stress and temperature. It is carried out at a constant load. Useful for applications where some strain can be tolerated but failure must be avoided, such as large furnace housings.

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%.

Creep Curve

Stages of creep under constant stress:

1. **Primary Creep**: Decreasing creep rate due to strain hardening.
2. **Secondary Creep**: Constant creep rate (steady-state).
3. **Tertiary Creep**: Increasing creep rate until rupture.

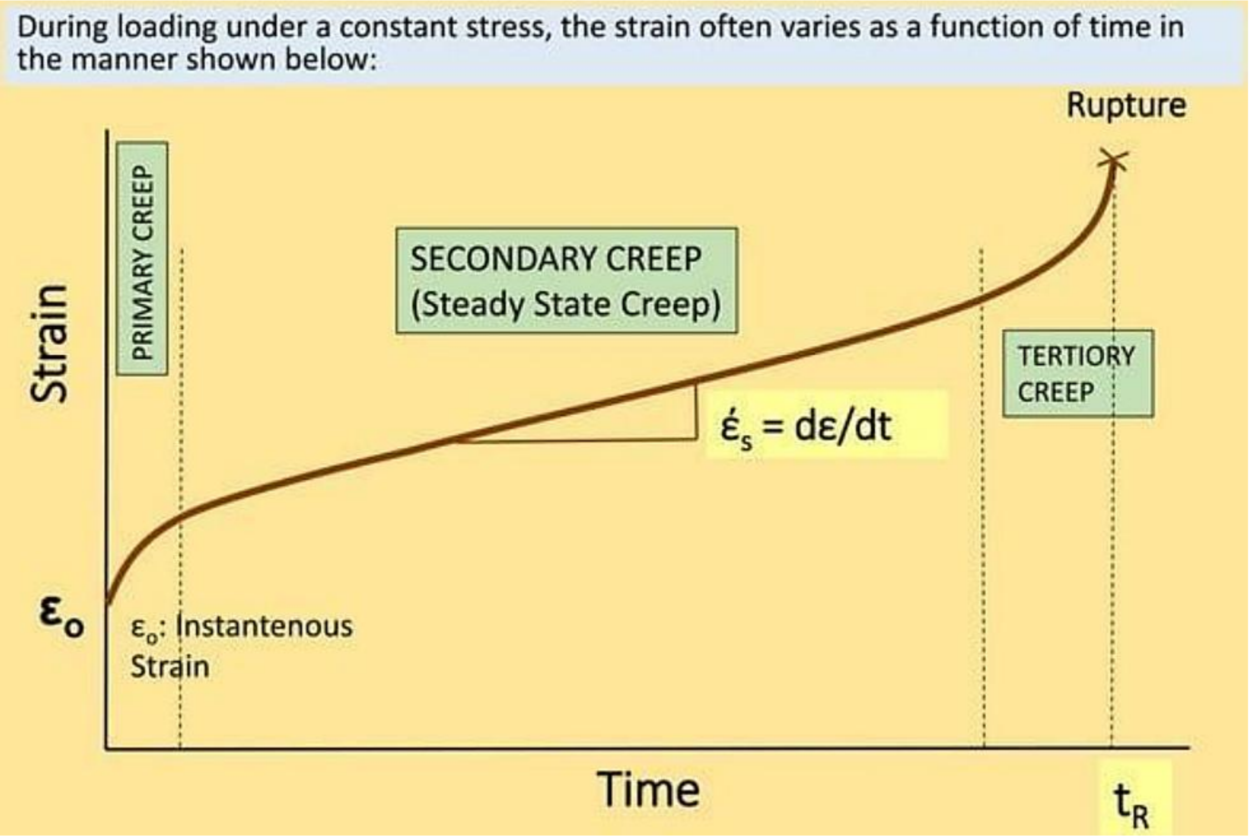

During loading under a constant stress, the strain often varies as a function of time in the manner shown below:

Figure: Typical Creep Curve

The creep curves are usually divided into three stages: I, primary or transient; II, secondary, constant rate, or quasi viscous; and III, tertiary. This division into stages was made by Andrade, one of the pioneers in the study of creep.

The slope of this curve is the **creep rate (dε/dt).** The curve shows the instantaneous deformation (mainly elastic) 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 (made by Andrade, one of the pioneers in the study of creep):

- **Primary or transient:** in which the creep resistance increases with strain leading to a decreasing creep strain rate.
- **Secondary (Steady State), or quasi viscous:** 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 dashed line in the figure represents the constant stress curve. Initially they are identical, and when the specimen increases in length, the stress increases and so does the creep rate, at a constant load. The failure times under constant stress and constant load can be drastically different.

Constant load machines simulate real engineering situations more accurately, but as the specimen extends its cross-sectional 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. From a fundamental point of view, there are **significant differences between the constant-load and constant-stress creep tests**. From an engineering point of view, the creep test at constant load is more important than the one at constant stress because it is the load, not the stress, that is maintained constant in engineering applications. On the other hand, fundamental studies should be conducted as the study of the evolution of the substructure of an alloy under increasing stress would be excessively complex.

$$\varepsilon_t = \varepsilon_0 + \varepsilon\left(1 - e^{-mt}\right) + \varepsilon_s^{\bullet} t \quad \text{....................(1)}$$

where ε_0 is the instantaneous strain (the strain at the instant of application of load), $\varepsilon_s^{\bullet}$ is a linear function of time, depicting stage II, and the term $\varepsilon[1 - \exp(-mt)]$ represents stage I in which m is the exponential time parameter and ε is the limiting transient creep strain (strain at end of that stage minus ε_0).

The minimum creep rate, or slope of **stage II** of creep, is a very important parameter. This stage, is usually represented by the equation (**Mukherjee-Bird-Dorn equation**):

$$\varepsilon_s^{\bullet} = \frac{AGb}{kT} D_0 \exp\left(-Q_c / RT\right)\left(\frac{b}{d}\right)^p \left(\frac{\sigma}{G}\right)^n \quad \text{.......(2)}$$

where A is a dimensionless constant, D_0 is a frequency factor, G is the shear modulus, b is the Burgers vector, k is Boltzmann's constant, T is the absolute temperature, σ is the applied stress, d is the grain size, p is the inverse grain-size exponent, n is the stress exponent, Q_c is the appropriate activation energy, and R is the gas constant. **Note that (at $T > T_m$) the activation energy for diffusion is often equal to the activation energy for creep ($Q_c = Q_D$).** The diffusion coefficient is:

$$D = D_0 \exp\left(-\frac{Q_D}{RT}\right)$$

and

$$\varepsilon_s^{\bullet} = \frac{AGbD}{kT}\left(\frac{b}{d}\right)^p \left(\frac{\sigma}{G}\right)^n \quad \text{................(3)}$$

Essentially, Equations 2 and 3 express the steady-state creep rate as a function of the applied stress, temperature, and grain size.

Correlation and Extrapolation Methods:

Industrial equipment operating at a high temperature is designed to have a certain lifetime (as: jet turbines for 10,000 hours, stationary turbines for 100,000 hours, nuclear reactions for 350,000 hours (40 years)). A great number of advanced alloys are used in such projects, and the engineer does not have on hand the results of lengthy tests. Hence, several extrapolation methods have been developed that seek to predict the performance of alloys based on tests conducted over a shorter period. The three most common are the Larson--Miller, Manson-Haferd, and Sherby-Dorn methods.

In 1952, Larson and Miller proposed a method that correlates the temperature *T* (in kelvins) with the time to failure t_r, at a constant engineering stress σ. The Larson-Miller equation has the form:

$$\mathbf{T\ (\log t_r + C\ ) = m} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where *C* is a constant that depends on the alloy, *m* is a parameter that depends on stress, and rupture time. Hence, if *C* is known for a particular alloy, one can find *m* in a single test. From this result, one can then find the rupture times at any temperature, *as long as the same engineering stress is applied.*

Manson and Haferd proposed the following equation:

$$\mathbf{(\log t_r - \log t_a)/(T - T_a) = m} \qquad \ldots\ldots\ldots\ldots(5)$$

The same extrapolation procedure as that of Larson-Miller is used to obtain rupture times at different times and temperatures. T_a, t_r, and m are parameters to be established for a given material. T_a and t_r are constant, and m depends on the stress.

Another method that has found considerable success is the Orr-Sherby-Dorn method.

$$\log t_r - m = 0.43\frac{Q_c}{kT} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Q, the activation energy, is expressed as energy (joules per atom). If Q is expressed per mole, or atom gram, then R (the gas constant) should be used instead of k (Boltzmann’s constant). The value of R is 8.314 J/(mol K). Table 1 presents estimated values for the parameters of the three equations (4, 5, 6) for a number of engineering alloys.

Table 1 Some Values of Constants for Time-Temperature Parameters

Material	Sherby–Dorn Q, kJ/mol	Larson–Miller C	Manson–Haferd	
			T_a K	log t_a
Various steels and stainless steels	≈400	≈20	-----	-----
Pure aluminum and dilute alloys	≈150	-----	-----	-----
Nimonic 81A (Ni-based)	380	18	311	16
1% Cr–1% Mo–0.25%V steel	460	22	311	18
A-286 stainless steel	380	20	367	16

Example :

Calculate the time to rupture at 650˚C and 100MPa stress for a 1%Cr-1% Mo-0.25%V steel, according to the Larson-Miller , Sherby--Dorn, and Manson--Haferd methods, if this alloy underwent rupture in 20hrs when tested in tension at the same stress level at a temperature of 750˚C.

Solution:

The Larson-Miller equation is $T(\log t_r + C) = m$.

At 750˚C, $T = 750 + 273 = 1{,}023^0$ K and $t_r = 20$ hours. Therefore,

$m = 1023 \times (\log 20 + 22) \approx 2.4 \times 10^4$

At 650˚C, $T = 650 + 273 = 923^0$K, and we have

$923(\log t_r + 22) = 2.4 \times 10^4$, so that $\log t_r = (2.4 \times 10^4/923) - 22$

$t_r = 6.7 \times 10^3$ hours.

The Sherby-Dorn equation is $\log t_r - Q/(kT) = m$. From Table 1, $Q = 460$ kJ/mol. Because Q here involves moles, we must use R instead of k. At 750˚C, $T = 1{,}023^0$ K and $t_r = 20$ hours. Thus, $m = \log 20 - (460 \times 10^3/8.314 \times 1023)$

At 650˚C, $T = 923^0$ K, and we obtain $\log t_r = m + 0.43(Q/kT)$

so that **$t_r = 6 \times 10^3$ hours.**

The Manson-Haferd equation is $(\log t_r - \log t_a)/(T - T_a) = m$. From Table 1, $Ta = 311$ K, and $\log t_a = 18$. At 750˚C, $T = 1{,}023^0$ K, and it follows that $t_r = 20$ hours.

Therefore, $m = (\log 20 - 18)/(1{,}023 - 311) = -0.023$.

At 650˚C, $T = 923^0$ K, and we have $(\log t_r - \log t_a)/(T - T_a) = m$

$(\log t_r - 18)/(923 - 311) = -0.023$,

$\log t_r = 3.924$,

$t_r = 8.4 \times 103$ hours.

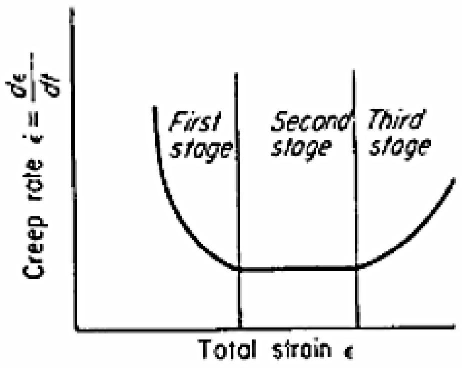
Creep is the tendency of a solid material to slowly deform permanently under the influence of stresses. It occurs as a result of long term exposure to levels of stress that

are below the yield strength of the material. Creep is more severe in materials that are subjected to heat for long periods, and near the melting point. Creep always increases with temperature. The rate of this deformation is a function of the material properties, exposure time, exposure temperature and the applied load. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function — for example creep of a turbine blade will cause the blade to contact the casing, resulting in the failure of the blade.

Creep deformation does not occur suddenly upon the application of stress. Instead, strain accumulates as a result of long-term stress. Creep deformation is "timedependent" deformation.

The temperature range in which creep deformation may occur differs in various materials, it may occur at high or may at low temperature. For a high melting point metal like tungsten, temperatures above 15670C would be needed to produce creep, so tungsten light bulb filaments operate at over 20000C and do in fact creep under their own weight, with a creep life to rupture of about 1000 hours. For a low melting point metal like lead, creep becomes significant at about 270C. This may cause lead plates to creep in a battery. The terms 'high' and 'low' temperature in this context are relative to the absolute melting temperature of the metal. At homologous temperatures (ratio of operating temperature to melting temperature) of more than 0.5, creep is of engineering significance.

Structural changes during creep: A curve of creep rate vs. total strain shows the large change in creep rate during the creep test. Since the stress and temperature are constant, this variation in creep rate is the result of changes in the internal structure of the material with creep strain and time. The principal deformation process at elevated temperature are slip, sub-grain formation, and grain boundary sliding.



Strain rate in creep test as function of total strain.

Mechanisms of Creep in metals: There are three basic mechanisms that can contribute to creep in metals, namely: (i) Dislocation slip and climb. (ii) Grain boundary sliding. (iii) Diffusional flow.