

Lecture #19

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Creep in Metals:

- Tests required to evaluate high temperature properties of metals.
- Comparison of Creep and Stress Rupture Tests.
- What is Creep?
- The creep test.
- Correlation and Extrapolation Methods.
- Structural changes during creep.
- Mechanisms of Creep in metals.
- Effect of structure and properties on creep resistance.

References:

- 1- Dieter G. E, 1986, *Mechanical Metallurgy*, 3rd ed., McGraw Hill.
- 2- Meyers M.A & Chawla K.K., 1999 *Mechanical Behavior of Materials*, Prentice Hall.
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Creep in Metals:

The mechanical strength of metals decreases with increasing temperature and the properties become much more time dependent. Effect of high temperature on metals can be summarized as following:

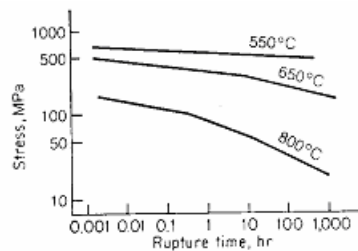
- Lower strength.
- Greater atomic and dislocation mobility, assisting dislocation climb and diffusion.
- Higher equilibrium concentration of vacancies.
- New deformation mechanisms, such as new slip systems or grain boundary sliding.
- Recrystallisation and grain growth.
- Age hardened alloys will overage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

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.

The stress is plotted against the rupture time on a log-log scale.

Changes in the slope of the stress-rupture line are due to structural changes occurring in the material, e.g., changes from transgranular to intergranular fracture, oxidation, recrystallization and grain growth, or other structural changes such as spheroidization, graphitization, or sigma-phase formation. It is important to know about the existence of such instabilities, since serious errors in extrapolation of the data to longer times can result if they are not detected.



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%.

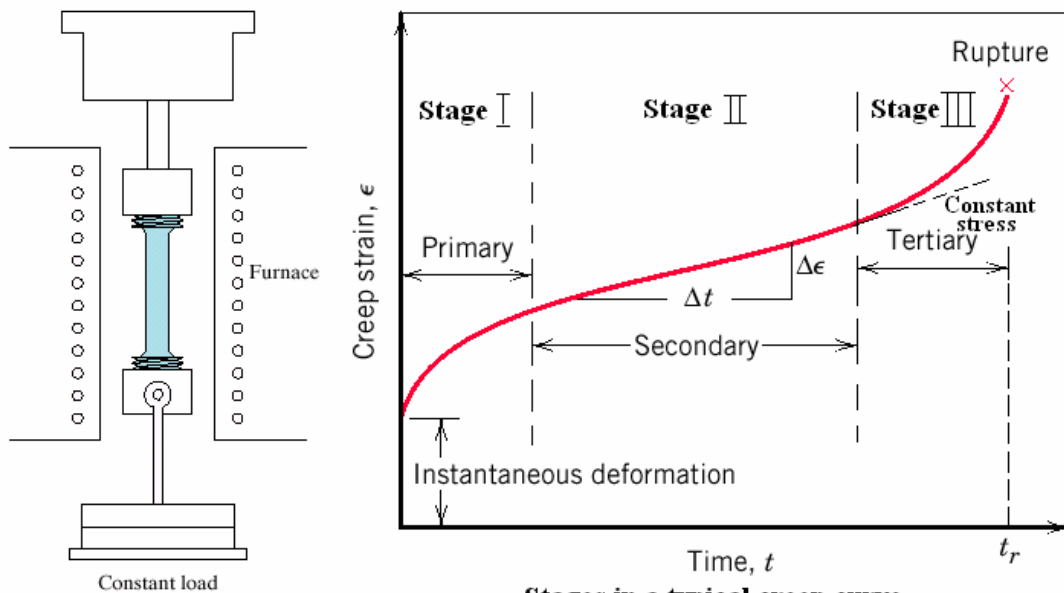
Creep is the tendency of a solid material to slowly deform permanently under the influence of stresses. It occurs as a result of long term exposure to levels of stress that

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 "time-dependent" 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 1567°C would be needed to produce creep, so tungsten light bulb filaments operate at over 2000°C 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 27°C . 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.**

The creep test:

The creep test consists of subjecting a specimen (likes a tensile test specimen) to a constant **load** (or **stress**) and measuring its length as a function of time, at a constant temperature. The figure shows the characteristic creep curve; the ordinate shows the strain and the abscissa shows time.



Stages in a 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 ($d\epsilon/dt$)**. 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.

$$\epsilon_t = \epsilon_0 + \epsilon(1 - e^{-mt}) + \epsilon_s^{\bullet} t \dots\dots\dots(1)$$

where ϵ_0 is the instantaneous strain (the strain at the instant of application of load), ϵ_s^{\bullet} is a linear function of time, depicting stage II, and the term $\epsilon[1 - \exp(-mt)]$ 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**):

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

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

$$\epsilon_s^{\bullet} = \frac{AGbD}{kT} \left(\frac{b}{d}\right)^p \left(\frac{\sigma}{G}\right)^n \dots\dots\dots(3)$$

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:

$$T (\log t_r + C) = m \quad \dots\dots\dots(4)$$

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:

$$(\log t_r - \log t_a)/(T - T_a) = m \quad \dots\dots\dots(5)$$

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.

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

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

$$t_r = 6.7 \times 10^3 \text{ hours.}$$

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, $T_a = 311$ 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 $(\log t_r - \log t_a)/(T - T_a) = m$

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

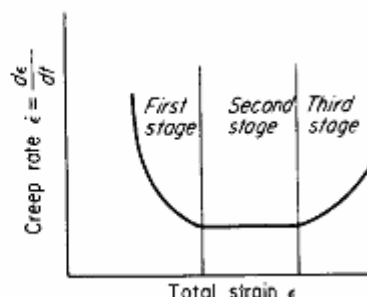
$$\log t_r = 3.924,$$

$$t_r = 8.4 \times 10^3 \text{ hours.}$$

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 processes 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:

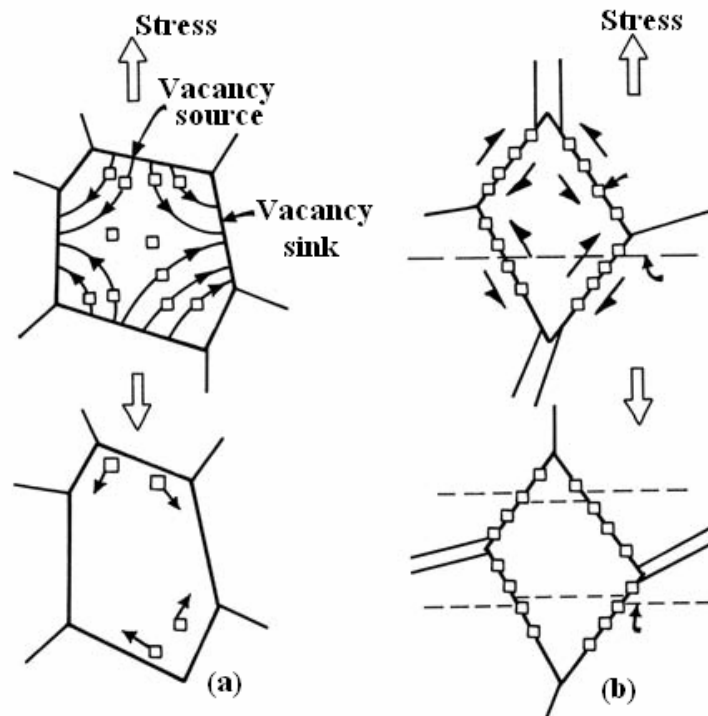
There are three basic mechanisms that can contribute to creep in metals, namely:

- (i) Dislocation slip and climb.
- (ii) Grain boundary sliding.
- (iii) Diffusional flow.

Diffusion Creep ($\sigma/G < 10^{-4}$)

Diffusion creep tends to occur for $\sigma/G \leq 10^{-4}$. (This value depends, to a certain extent, on the metal.) Two mechanisms are considered important in the region of diffusion creep. Nabarro and Herring proposed the mechanism shown.

It involves the flux of vacancies inside the grain. The vacancies move in such a way as to produce an increase in length of the grain along the direction of applied (tensile) stress. Hence, the vacancies move from the top and bottom region in the figure to the lateral regions of the grain. The boundaries perpendicular (or close to perpendicular) to the loading direction are distended and are sources of vacancies. The boundaries close to parallel to the loading direction act as sinks.



Flow of vacancies according to (a) Nabarro-Herring and (b) Coble mechanisms, resulting in an increase in the length of the specimen.

Coble proposed the second mechanism explaining diffusion creep. It is based on diffusion in the grain boundaries instead of in the bulk. This diffusion results in sliding of the grain boundaries. Hence, if a scratch is made on the surface of the specimen prior to creep testing, the scratch will show a series of discontinuities (at the grain boundaries) after testing if Coble creep is operative.

A practical way of having an alloy with high resistance to Nabarro-Herring or Coble creep is to increase the size of the grains. This method is used in superalloys; a fabricating technique called *directional solidification* has been developed to eliminate virtually all grain boundaries perpendicular and inclined to the tensile axis.

Harper and Dorn observed another type of diffusional creep in aluminum. This occurred at high temperatures and low stresses, and the creep rates were over 1,000 times greater than those predicted by Nabarro-Herring. (Also, little Coble creep was observed.) The two researchers concluded that creep occurred exclusively by dislocation climb.

Dislocation slip and climb ($10^{-4} < \sigma/G < 10^{-2}$):

When a polycrystalline metal is deformed many of the grains will have slip planes suitably aligned to the applied stress, and slip will occur when the shear stress exceeds the **critical resolved shear stress**. As the metal is deformed, plastic flow of the metal becomes increasingly more difficult, and more stress has to be applied to accomplish it due to **work hardening**.

In the **primary stage** of a creep test, the stress is constant and these mechanisms lead to a decreasing strain rate. During **secondary or steady state** creep, the increased strain energy stored in the metal due to deformation, together with the high temperature, provides a driving force for the process of **recovery**. There is therefore a **balance between the processes of work hardening and recovery**.

The creep rate, in this case, is controlled by how rapidly the dislocations can overcome obstacles (formed by dislocation that intersect and react) that obstruct their motion. In order for this to happen, dislocations have to climb as well as slip, and this in turn requires atomic movement or **self-diffusion** within the lattice.

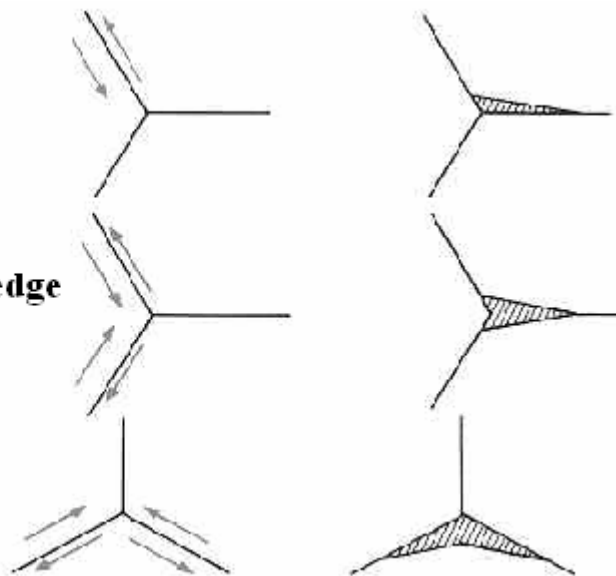
Dislocation Glide ($\sigma/G > 10^{-2}$):

Dislocation glide occurs for $\sigma/G > 10^{-2}$. At a certain stress level, dislocation climb may be replaced by dislocation glide, which does not depend on diffusion, thermally activated dislocation glide is the rate-controlling step; this is the same deformation mode as the one in conventional deformation at ambient temperature.

Grain Boundary sliding:

The onset of tertiary creep is a sign that structural damage has occurred in an alloy. Rounded and wedge shaped voids are seen mainly at the grain boundaries, and when these coalesce creep rupture occurs. The mechanism of void formation involves grain boundary sliding which occurs under the action of shear stresses acting on the boundaries.

The formation of wedge cracks during grain boundary sliding.



The grain boundary sliding may account for 10% to 65% of the total creep strain, the contribution increasing with increasing temperature and stress and reducing grain size. Above about $0.6 T_m$ the grain boundary region is thought to have a lower shear strength than the grains themselves, probably due to the looser atomic packing at grain boundaries. Boundaries lying at about 45° to the applied tensile stress experience the largest shear stress and will slide the most.

Cavitation

Cavitation can lead to fracture during creep. Cavitation occurs by nucleation and growth of voids, particularly at grain boundaries and second-phase particles. A void will grow if its growth lowers the energy of the system.

Effect of structure and properties on creep resistance:

- $\dot{\epsilon}$ \uparrow with: \uparrow applied stress, \uparrow diffusivity (\downarrow activation energy), \downarrow grain size
- For a given application T, use of higher T_{mp} material will \downarrow diffusivity and correspondingly $\downarrow \dot{\epsilon}_{ss}$
- In general:
 - Diffusivities in bcc metals \gg diffusivities in fcc metals
 - if we have a bcc metal and an fcc metal with the same T_{mp} , then
 $\dot{\epsilon}_{bcc} > \dot{\epsilon}_{fcc}$
- \uparrow grain size, $\downarrow \dot{\epsilon}$ for diffusion controlled creep but does not have any influence on the dislocation creep mechanism.
- For dislocation glide mechanism: \uparrow in grain size will $\uparrow \dot{\epsilon}$