From last time… deformation behaviour

- Tensile strength $\sigma_{TS}$
- Yield strength $\sigma_y$

Diagram showing:
- Stress vs. Strain
- Points 2, 3, and 5
- Fracture
- Necking
- Plastic strain
From last time... yield strength and necking

Leaf spring

Aircraft Fuselage

Metal Rolling

Necking
At room temperature

\[ \varepsilon = f(\sigma) \]

At room temperature

\[ \varepsilon = f(\sigma, t, T) \]

As the temperature is raised, loads that give no permanent deformation at room temperature cause materials to *creep*.
A tungsten lamp filament which has sagged under its own weight owing to creep → reason that lamps burn out
Turbine blades in aircraft

Turbine Blade cracked due to creep
Can creep happen at room temperature?

Lead pipes often creep noticeably over the years

Source: M.F. Ashby
The temperature at which materials start to creep depend on their melting point

As a general rule, creep start when

\[ T > 0.3 \text{ to } 0.4 \, T_M \text{ for metals} \]
\[ T > 0.4 \text{ to } 0.5 \, T_M \text{ for ceramics} \]
Designing against creep

The material must carry the design loads, without failure, for the design life at design temperature

• **Displacement-limited applications**
  - Precise dimensions or small clearance must be maintained
  - Disc and blades of gas turbines

• **Rupture-limited applications**
  - Dimensional tolerance is relatively unimportant, but fracture must be avoided such as pressure piping
Designing against creep

The material must carry the design loads, without failure, for the design life at design temperature

- **Stress relaxation-limited applications**
  - Pre-tensioning of Bolts get loosen

- **Buckling-limited applications**
  - Structural steelwork exposed to fire
Creep testing and Creep curve

### Creep Curve

- **Furnace windings**

- **Creep test** usually applied in tension at constant load and at constant temperature.

### 3 Stages of Creep

1. **Primary creep**
   - Time, \( t_f \)
   - Initial elastic strain

2. **Steady-state creep**
   - Strain rate, \( \dot{\epsilon}_{ss} \)

3. **Tertiary creep**
   - Fracture

- **In steady-state creep**, strain increases steadily with time.
- **In designing**, steady-state creep concerns us most.
Variation of creep rate with stress

\[ \dot{\varepsilon}_{ss} = B \sigma^n \]

- \( n \) is creep exponent

Two regime of creep

1. Power-law creep
2. Diffusional creep

Diagram:
- Slope \( n \approx 3 \) to 8
- Low \( \sigma \) tail, \( n \approx 1 \)
Variation of creep rate with temperature

\[ \dot{\varepsilon}_{ss} = C e^{-\left(\frac{Q}{RT}\right)} \]

*Q* is Activation Energy (J/mol)
*R* is Universal gas constant (8.31 J/mol/K)

**Rate of steady-state creep**

\[ \dot{\varepsilon}_{ss} = A \sigma^n e^{-\left(\frac{Q}{RT}\right)} \]

*A, Q and n* characterise the creep of a material
Creep damage and creep fracture

During creep, damage accumulates in the form of internal cavities.
Creep rupture diagram

$T_3 > T_2 > T_1$

$log \sigma$

$log t_f$

$T_1$

$T_2$

$T_3$
Creep rates follow Arrhenius law

Rate of steady-state creep

\[ \dot{\varepsilon}_{SS} = A \sigma^n e^{-\left(\frac{Q}{RT}\right)} \]

Arrhenius law

- Creep rate increases exponentially with temperature
- The time for a given amount of creep decreases exponentially with temperature
Diffusion

Dropped Potassium Permanganate into water

@ T = 18°C

Elapsed time ≈ 0 minutes. Ring radius = 2.6 mm.
Diffusion

The movement of Potassium permanganate ions by random exchanges with water molecules

Elapsed time = 57 minutes. Ring radius = 30.3 mm.
**Diffusion**

The ions/atoms move from concentrated regions to less concentrated regions, *i.e.* The ions/atoms move down the *concentration gradient*.

\[
J = -D \frac{dc}{dx}
\]

**Fick’s first law of diffusion**

- *J* represents the number of atoms diffusing down the concentration gradient per second per unit area, called flux of atoms.
- *D* is the diffusion coefficient (m²/s).
- *c* represents the concentration.

![Diagram](image-url)
Diffusion of atoms

Diffusion requires atoms to cross the energy barrier.

Number of atoms actually jump from A to B per second
\[ \frac{v}{6} n_A e^{-Q/RT} \]

Number of atoms actually jump from B to A per second
\[ \frac{v}{6} n_B e^{-Q/RT} \]

Net number of atoms climbing over barrier per second
\[ \frac{v}{6} (n_A - n_B) e^{-Q/RT} \]
Diffusion of atoms

Net flux of atoms

\[ J = \frac{v}{6l_1l_2} (n_A - n_B) e^{-Q/RT} \]

Concentrations

\[ c_A = \frac{n_A}{l_1l_2r_0}, \quad c_B = \frac{n_B}{l_1l_2r_0} \]

Net flux of atoms

\[ J = -D_0 e^{-Q/RT} \left( \frac{dc}{dx} \right) \]

where

\[ \frac{dc}{dx} = \frac{c_B - c_A}{r_0} \]

\[ D_0 = \frac{vr_0^2}{6} \]
Diffusion of atoms

Net flux of atoms

\[ J = -D_0 e^{-\frac{Q}{RT}} \left( \frac{dc}{dx} \right) \]

Fick’s first law of diffusion

\[ J = -D \frac{dc}{dx} \]

Diffusion coefficient (Diffusivity)

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

The diffusion coefficient is exponentially dependence on temperature

Compared with \[ \dot{\epsilon}_{ss} = A\sigma^n e^{-\left(\frac{Q}{RT}\right)} \] so diffusion may be related to creep
Diffusion in the bulk of a crystal can occur by two mechanisms:

- **Interstitial Diffusion**: Small atoms diffuse interstitially to spaces between atoms.

- **Vacancy Diffusion**: When atoms are comparable in size, an atom has to wait and diffuse to the missing atom (vacancy) next to it.
Diffusion Mechanisms

Fast diffusion paths

Diffusion rate is much greater than in the bulk

**Grain-boundary Diffusion**

- Grain boundary = fast diffusion corridor
- Channel width $\delta \approx 2$ atom diameters

**Dislocation-core Diffusion**

- “Core” of dislocation
- Dislocation “line”

When grains are small or dislocations numerous, their contributions become important
Creep mechanisms

Creep mechanisms in metals and ceramics

• Dislocation creep (power-law creep)
  • Core diffusion
  • Bulk diffusion
• Diffusion creep (linear-viscous creep)
  • Grain-boundary diffusion
  • Bulk diffusion

Creep mechanisms in polymers

• Viscous flow
Dislocation creep (power-law creep)

The stress required to make a crystalline material to deform plastically is that needed to make the dislocations in it move.

How an edge dislocation moves (glide) through a crystal
Dislocation creep (power-law creep)

The movement of dislocation is restricted by (a) intrinsic lattice resistance and (b) obstructing effect of obstacles (e.g. solute atoms and precipitates)
Dislocation creep (power-law creep)

\[ \dot{\varepsilon}_{ss} = A \sigma^n e^{-\left(\frac{Q}{RT}\right)} \]

Higher \( \sigma \) the higher the climb force so more dislocations become unlock.
Diffusion creep (linear-viscous creep)

• When the stress is reduced, the rate of power-law creep falls quickly. Creep does not stop!
• Instead creep takes place by diffusion (dislocations are not involved)

• At high $T/T_M$ : Bulk diffusion
• At low $T/T_M$ : Grain-boundary diffusion
Deformation Mechanism Diagram

\[ \frac{\tau}{G} \]

\( T/T_M \)

Conventional plastic flow

Yield strength

Elastic deformation only

Dislocation creep

Core diffusion

Diffusional flow

Boundary diffusion

Bulk diffusion

Bulk diffusion
Creep in polymer

- Example of creep in polymer: plastic clips slowly lose their grip
- Glass transition temperature ($T_G$) is a criterion of creep resistance
- Glass transition temperature increases with degree of cross-linking so cross-linked polymers are more creep-resistant at room temperature than less cross-linked polymers
- Crystalline polymers are more creep-resistant than glassy polymers
- Creep rate is reduced by filling them with glass or silica powder
Creep-limited design

High Temperature Materials for Turbines
Efficiency VS Inlet temperature

An increase in combustion temperature in a turbofan engine will generate an increase in engine efficiency.
Power VS Inlet temperature

Power output of engine increases linearly with temperature
Ni-based Superalloys

• A superalloy is a metallic alloy which can be used at high temperatures, often up to $0.8 \ T_m$
• Exceptional heat resistance, creep resistance, and corrosion resistance

Typical composition of creep-resistant blade (e.g. Nimonic)

<table>
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<th>Metals</th>
<th>Wt.%</th>
<th>Metals</th>
<th>Wt.%</th>
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<tr>
<td>Fe</td>
<td>0.25</td>
<td>Pb</td>
<td>&lt;0.0005</td>
</tr>
</tbody>
</table>
Ni-based Superalloys

The effect of temperature on the tensile strength of several nickel-based alloys
Ni-based Superalloys

Simple reasons for complicated alloying addition

- to have as many atoms in **solid solution** as possible (the cobalt, the tungsten, and the chromium)
- to form stable, **hard precipitates** of compounds such as Ni₃Al, Ni₃Ti, MoC, TaC to obstruct the dislocations
- to form a **protective surface oxide** film of Cr₂O₃ to protect the blade itself from attack by oxygen
Ni-based Superalloys

Three strengthening mechanisms are used in Ni Superalloys

- Solid solution hardening
- Coherent precipitate hardening
- Carbide phases on grain boundaries
Investment casting of turbine blades. This produces a fine-grained material which may undergo a fair amount of diffusion creep, and which may fail rather soon by cavity formation.
Microstructure of Superalloys in Turbine Blades

- **Equiaxed Crystal Structure**
- **Directionally Solidified Structure**
- **Single Crystal**

*Increasing Resistance to Creep Deformation*
Directional solidification (DS) of turbine blades.

Slow withdrawal of mold from furnace

Furnace windings
Molten alloy
Solid alloy

No shear stress in boundaries (no sliding). No tensile stress at right angles to boundaries (no cavities)

Grain boundaries

\( \sigma \)
Single crystal (SX) of superalloy blade
Deformation Mechanism Diagram

Effect of grain size on diffusion creep

![Deformation Mechanism Diagram](image)
Improved manufacturing method

The high-temperature capability of Superalloys has increased with improvements in manufacturing methods.
Active cooling

A turbine blade designed for active cooling by a gas
Temperature evolution and materials trends in turbine blades

- With cooling and thermal barriers
- Inlet temp.
- Blade cooling
- DS nickel alloys
- Nickel alloys (investment cast)
- Single crystal (SX)
- Thermal barrier coatings
- Maximum flame temperature (function of fuel used and gas composition) limits performance


Temperature (°C): 500, 1000, 1500, 2000, 2500