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
Objectives

• This chapter provides the understanding of deformation and fracture behaviour of material at high temperature.

• Creep and stress rupture tests will be compared such that the interpretation of test data will be discussed for engineering applications. This will lead to the selection of metal and alloys for desired uses at high temperature.
Introduction

High temperature applications

Subjected to high stress at high temperature

Steam power plant

Steam turbine used in power plant

Oil refinery

Process plant

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High temperature materials problem

- 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.

High temperature materials/alloys

- Improved high temperature strength.
- Good oxidation resistance.
What is creep?

Creep occurs when a metal is subjected to a constant tensile load at an elevated temperature. → Undergo a time-dependent increase in length.

At which temperature that 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.
The **creep test** is carried out by applying a **constant load** to a tensile specimen maintained at a **constant temperature**, (according to ASTM E139-70).

**Typical creep curve**

**Schematic creep test**
The creep curve

A typical creep curve shows three distinct stages with different creep rates. After an initial rapid elongation $\varepsilon_0$, the creep rate decreases 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.

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

- $\varepsilon_0$ 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.
The stress rupture test

<table>
<thead>
<tr>
<th>Creep test</th>
<th>Stress rupture test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Low load</td>
</tr>
<tr>
<td>Creep rate</td>
<td>minimum creep rate</td>
</tr>
<tr>
<td>Test period</td>
<td>2000-10000 h</td>
</tr>
<tr>
<td>Total strain</td>
<td>0.5%</td>
</tr>
<tr>
<td>Strain gauge</td>
<td>Good strain measuring devices</td>
</tr>
</tbody>
</table>

The **rupture test** is 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.

- **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

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 inhomogeneity 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.

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

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

Simplified deformation mechanism map.

**Note:** $G$ is the shear modulus
Activated energy for steady-state creep

• Steady-state creep deformation predominates at temperatures above 0.5\(T_m\).

• Steady state creep can be expressed by

\[
\dot{\epsilon}_s = Ae^{-Q/RT}
\]

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.

\[
A = \dot{\epsilon}_1 e^{Q/RT_1} = \dot{\epsilon}_2 e^{Q/RT_2}\\
Q = \frac{R \ln(\dot{\epsilon}_1/\dot{\epsilon}_2)}{1/T_2 - 1/T_1}
\]

Eq. 2
Superplasticity

• **Superplasticity** is the ability to withstand very large deformation in tension without necking.

• Give elongation > 1000%.

• Materials with high **strain rate sensitivity** \((m)\) at high temperature 
\((T > 0.5T_m) \rightarrow \text{superplasticity}\)

• Materials characteristics: **fine grain size** (<10 \(\mu\)m) with the presence of **second phase of similar strength to the matrix** to inhibit grain growth and to avoid extensive internal cavity formation.

• Grain boundary should be **high angle** and **mobile** to promote grain boundary sliding and to avoid the formation of local stress concentration respectively.
The *superplastic flow* is given by

\[
\dot{\varepsilon} = 10^8 \left( \frac{\sigma}{E} \right)^2 \frac{bD_{gb}}{\bar{L}^3}
\]

Eq.3 For grain boundary diffusion

\[
\dot{\varepsilon} = 2 \times 10^9 \left( \frac{\sigma}{E} \right)^2 \frac{D_o}{\bar{L}^2}
\]

Eq.3 For lattice self-diffusion

Where \( \bar{L} \) is the mean linear intercept measure of grain size.

in this case \( n = 2, \rightarrow m = 0.5 \)

The predominant mechanism for superplasticity deformation is *grain-boundary sliding* accommodated by slip.
Fracture at elevated temperature

**Transgranular fracture**
- Slip planes are weaker than grain boundaries

**Intergranular fracture**
- Grain boundaries are weaker than slip planes.

*Note: at T just below $T_{\text{recrys}}$, ductility drops due to grain boundary sliding → intergranular failure.*

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**Equicohesive temperature**

- Strength of GB = grain at the equicohesive temperature (ECT).

**Strain rate** ↓ **ECT** ↓

Increasing the tendency for intergranular failure

- Below ECT small grain sized material is stronger due to high density of grain boundaries to improve strength.
- Above ECT large grain sized material is stronger due to less tendency for grain boundary sliding.

**Note:** Single crystal structure is therefore appreciable for high temperature applications, i.e., nickel base alloy single crystal turbine blade.

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High temperature alloys

- High temperature alloys are complex in their microstructures to obtain the required properties at service temperatures.
- High melting point alloys normally has high creep resistance.
- Metals with high stacking false energy → easy for slip → creep.
- Fine precipitates having high thermal stability are necessary for high creep resistance (prevent grain growth). Ex: (1) Nickel base alloy containing fine precipitates of intermetallic compounds Ni$_3$Al, Ni$_3$Ti or Ni$_3$(Al,Ti), (2) Creep resistance steels containing fine carbides VC, TiC, NbC, Mo$_2$C or Cr$_{23}$C$_6$.

Drawbacks

- Difficult to fabricate by hot-working, cold working or welding.
- Highly alloyed metals are difficult to produced by precision casting.

Microstructure of nickel base alloy
### Composition of some high temperature alloys

#### Table 13-2 Compositions of some high-temperature alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Co</th>
<th>W</th>
<th>Cb</th>
<th>Ti</th>
<th>Al</th>
<th>Fe</th>
<th>Other</th>
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<td></td>
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<tr>
<td>1.25 Cr-Mo</td>
<td>0.10</td>
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<td>—</td>
<td>0.50</td>
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<td></td>
<td>Bal.</td>
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<tr>
<td>5 Cr-Mo</td>
<td>0.20</td>
<td>5.00</td>
<td>—</td>
<td>0.50</td>
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<td>3.0</td>
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<td>316</td>
<td>0.08</td>
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<td>1.95</td>
<td>0.2</td>
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<td></td>
<td>Nickel-based alloys</td>
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<td>Astroloy</td>
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<td>11.0</td>
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<td>3.2</td>
<td>1.6</td>
<td>2.0</td>
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<tr>
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<td>9.0</td>
<td>Bal.</td>
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<td>12.5</td>
<td>1.0</td>
<td>2.0</td>
<td>5.0</td>
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<tr>
<td>TRW 1900</td>
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<td>Bal.</td>
<td>10.0</td>
<td>9.0</td>
<td>1.5</td>
<td>1.0</td>
<td>6.3</td>
<td></td>
<td>2.0</td>
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<tr>
<td>Udimet 700</td>
<td>0.15</td>
<td>15.0</td>
<td>Bal.</td>
<td>5.2</td>
<td>18.5</td>
<td></td>
<td>3.5</td>
<td>4.25</td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>In-100</td>
<td>0.15</td>
<td>10.0</td>
<td>Bal.</td>
<td>3.0</td>
<td>15.0</td>
<td></td>
<td>4.7</td>
<td>5.5</td>
<td>1.0 V</td>
<td></td>
<td>2.0 ThO₂</td>
</tr>
<tr>
<td>TD Nickel</td>
<td>—</td>
<td>—</td>
<td>Bal.</td>
<td></td>
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<td></td>
<td>2.0</td>
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<tr>
<td></td>
<td>Cobalt-based alloys</td>
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<tr>
<td>Vitallium</td>
<td>0.25</td>
<td>27.0</td>
<td>3.0</td>
<td>5.0</td>
<td>Bal.</td>
<td>1.0</td>
<td></td>
<td></td>
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<tr>
<td>(HS-21)</td>
<td>0.40</td>
<td>20.0</td>
<td>20.0</td>
<td>4.0</td>
<td>Bal.</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>S-816</td>
<td>0.25</td>
<td>27.0</td>
<td>3.0</td>
<td>5.0</td>
<td>Bal.</td>
<td>1.0</td>
<td></td>
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</tr>
</tbody>
</table>
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 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.
**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.

\[
1\% \text{ creep in } 1000\text{h} = 10^{-5} \text{ h}^{-1} = \frac{10^{-5}}{3600} \text{ s}^{-1} = 2.8 \times 10^{-9} \text{ s}^{-1}
\]

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

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Creep strength, MPa</th>
<th>Working stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>600°C</td>
<td>210</td>
<td>70</td>
</tr>
<tr>
<td>800°C</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>
Example: For the stress-minimum creep rate curve, determine the activation energy for creep at a stress of 100 MPa.

\[
\begin{align*}
\text{at } T_2 &= 700^\circ C = 973K; \quad \varepsilon_2 = 10^{-8} s^{-1} \\
\text{at } T_2 &= 800^\circ C = 1073K; \quad \varepsilon_1 = 10^{-5} s^{-1}
\end{align*}
\]

From Eq.2

\[
Q = \frac{R \ln(\varepsilon_1/\varepsilon_2)}{(1/T_2 - 1/T_1)} = \frac{(8.3Jmol^{-1}K^{-1}) \ln(10^3)}{1/973 - 1/1073} = 599kJmol^{-1}
\]
Reference