Lecture 15 – High Temperature Deformation of Crystalline Materials

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Introduction

- $T > 0.5 \ T_{mp}$ : CREEP deformation occurs.
  $\sigma < \sigma_{ys}$ : Permanent deformation occurring by CREEP over long periods of time.

CREEP = time-dependent permanent deformation
YIELDING = time-independent permanent permanent deformation

Deformation Mechanism Maps (DMM) [Ashby]
Steady-State Creep Rate

When long life is necessary and dimensional tolerances are critical (Ex. Jet engine turbine blade)

\[ \dot{\varepsilon}_{ss} = A \sigma^n e^{-Q/RT} \]

A & n are material constants
Q is the creep activation energy

Dorn relation :
When \( T \geq 0.5T_{mp} \), Q : activation energy for self-diffusion
Generalized form of the Creep Equation

\[ \dot{\varepsilon} = \frac{ADGb}{kT} \left( \frac{\sigma}{G} \right)^n \left( \frac{b}{d} \right)^p, \text{ where } D = D_0 \exp(-Q/\kappa T) \]

- $D$ = diffusion coefficient
- $d$ = grain size
- $b$ = Burgers vector
- $k$ = Boltzmann’s constant
- $T$ = the absolute temperature (degrees Kelvin)
- $G$ = the shear modulus
- $\sigma$ = applied stress
- $n$ = stress exponent
- $p$ = inverse grain size exponent
- $A$ = a dimensionless constant.

This form of the Dorn equation applies for all creep mechanisms.
**Dislocation Glide Creep**

**Low T or High \( \sigma \)**

- \( \perp \) motion is assisted by thermal activation.
- Crystals always contain defects.
- Certain point defects, vacancies, can promote plastic deformation by helping \( \perp \)'s overcome obstacles. This is “vacancy assisted climb”.

\[
\dot{\varepsilon}_{dg} \approx \frac{ADGb}{kT} \left( \frac{\sigma}{G} \right)^5
\]
Nabarro-Herring Creep

- Occurs solely by diffusional mass transport.
- Is important for much higher $T$ and lower $\sigma$ than was the case for dislocation glide creep.
- Can occur in crystalline and amorphous materials.

\[
\dot{\varepsilon}_{NH} \approx \frac{A_{NH} D_L G b}{kT} \left( \frac{b}{d} \right)^2 \left( \frac{\sigma}{G} \right)
\]

$A_{NH} \approx 10-15$

$D_L =$ lattice diffusion coefficient
Coble Creep

- Also driven by stress-induced vacancy concentration gradient.
- Diffusion/mass transport occurs along:
  
  **Grain boundaries in polycrystalline materials**
  **Surfaces in single crystals**

\[
\dot{\varepsilon}_C \approx \frac{A_C D_{GB} Gb}{kT} \left( \frac{\delta}{b} \right) \left( \frac{b}{d} \right)^3 \left( \frac{\sigma}{G} \right)
\]

\[A_C \approx 30-50\]

\[D_{GB} = \text{grain boundary diffusion coefficient}\]

\[\delta = \text{effective width of grain boundary}\]
Vacancy Flow According to NH and Coble Creep Mechanisms

\[ \varepsilon_{NH} \approx \frac{A_{NH} D_L G b}{kT} \left( \frac{b}{d} \right)^2 \left( \frac{\sigma}{G} \right) \]

\[ \varepsilon_C \approx \frac{A_C D_{GB} G b}{kT} \left( \frac{\delta}{b} \right) \left( \frac{b}{d} \right)^3 \left( \frac{\sigma}{G} \right) \]
The creep rate of a material can be greatly reduced by the incorporation of a fine dispersion of non-deforming particles at grain boundaries. The particles effectively inhibit grain boundary sliding.

**ROLE OF PARTICLES:** they “pin” grain boundaries.
COMBINED CREEP MECHANISMS

DIFFUSION CREEPS

\[ \dot{\varepsilon}_{\text{diffusion}} = \dot{\varepsilon}_{\text{NH}} + \dot{\varepsilon}_C \]

- NH: \( \dot{\varepsilon} \propto d^{-2} \)
- Coble: \( \dot{\varepsilon} \propto d^{-3} \)

\( \therefore \) grain size is more important.
COMBINED CREEP MECHANISMS

DIFFUSION & DISLOCATION CREEP

In this case, $\sigma$ is critical for determining the relative proportion that each mechanism contributes to the overall creep rate.

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{diffusion} + \dot{\varepsilon}_{GC}$$
### ESTIMATES OF CREEP LIFE

<table>
<thead>
<tr>
<th>Design Lives:</th>
<th>Jet turbine ......................... 10,000 hr (1 year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stationary turbine .....................................~10 years</td>
</tr>
<tr>
<td></td>
<td>Nuclear reactor ........................................~40 years</td>
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</tbody>
</table>

**MUST:** be able to **extrapolate** properties measured over short (accelerated) time to predict performance over extended time.

### LARSON-MILLER METHOD

\[
m = LM = T(\log t_f + C)
\]

LM or \( m \): Larson-Miller constant varied with stress  
C : Material constant  
\( t_f \): Time to rupture
ESTIMATES OF CREEP LIFE

Now, if we keep stress constant, \( m = \text{constant} \).
We can change \( T \) and can calculate the time to rupture (failure).

![Graph showing log \( t_r \) vs. \( 1/T \) with lines \( \sigma_1 \) and \( \sigma_2 \), and determination of \( t_r \) and \( T \).]

Experimentally, the LM approach gives optimistic life predictions.
It has been observed that some materials when heated above 0.5Tmp can elongate to extremely large strains (e.g., ~5000%). We take advantage of this phenomenon to form complex shapes that cannot normally be obtained by forging, extrusion, or other metalworking processes. This is called “superplasticity”.

Microstructural Requirements:

1. Grain size ≤ 10 μm
   This grain size must not change during straining!
2. Grain shape remains equiaxed during superplastic forming.
   Grains “slide” under stress.
Superplasticity

Strain Rate Sensitivity:

As $m$ increases, the material becomes more resistant to necking.

In the neck, $\dot{\varepsilon}_{\text{neck}} > \dot{\varepsilon}_{\text{non-neck}}$

$\therefore$ flow stress of the neck $>$ flow stress in non-necked region

$\therefore$ deformation stops in the neck.

We can determine $m$ from strain rate change and/or stress relaxation tests.