Chapter 12 - Rate and Temperature Dependent Mechanical Properties

Mechanical properties of materials can become very sensitive to loading rate and temperature, if temperature in question is near the material's melting point.

\[ \text{Strength, ductility, etc.} = f(\dot{\varepsilon}, T) \]

creep
stress relaxation (viscoelasticity)

\[
\text{homologous temperature (°K)} = \frac{\text{temperature (°K) of interest}}{\text{materials melt temperature (°K)}}
\]
Stress - Strain Relation (Holloman)

* The portion of the true stress-strain curve (from the onset of yielding to the maximum load) may be described empirically by:

\[ \sigma = K \varepsilon^m \]

where:

- \( \sigma \) - true stress
- \( \varepsilon \) - true strain
- \( m \) - strain hardening coefficient (work-hardening index)
- \( K \) - material constant \( \rightarrow \) the true stress at a true strain of 1.0

\( \sigma = K \varepsilon^m \) (beyond \( \sigma_y \))
* Ideally when plotted \( \log \sigma \) vs. \( \log \varepsilon \), straight line relation obtained \( \Rightarrow \):
\[
\sigma = K \varepsilon^m
\]
where \( m \) being the slope

\( \sigma \) - referred to as the flow stress

\( m \) - its magnitude reflects the ability of the material to resist further deformation

\( 0 \leq m \leq 1 \)

\( m = 0 \) ideally elastic

\( m = 1 \) ideally elastic

* \( m \) values for metals are sensitive to thermo-mechanical treatment:

- generally larger for materials in the annealed condition and smaller in the cold-worked state

\[ \downarrow \]

* initially soft materials tend to work harden faster
Selected Strain Hardening Coefficients:

<table>
<thead>
<tr>
<th>Material</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1015 steel, normalized, 80 Bhn</td>
<td>0.26</td>
</tr>
<tr>
<td>1045 steel, Q+T (650°C), 225 Bhn</td>
<td>0.13</td>
</tr>
<tr>
<td>1045 steel, Q+T (180°C), 595 Bhn</td>
<td>0.07</td>
</tr>
<tr>
<td>ferritic stainless steel</td>
<td>0.16-0.23</td>
</tr>
<tr>
<td>austenitic stainless steel</td>
<td>0.40-0.55</td>
</tr>
<tr>
<td>copper</td>
<td>0.35-0.50</td>
</tr>
<tr>
<td>brass (70-30)</td>
<td>0.45-0.60</td>
</tr>
<tr>
<td>aluminum alloys</td>
<td>0.20-0.30</td>
</tr>
</tbody>
</table>

Strain Rate Sensitivity

* If materials are tested at various ε and T, their σ vs. ε curves change. For example:
Thus, modifying the Holloman relation:

\[ \sigma = K \varepsilon^n \]

letting:

\[ K = C \dot{\varepsilon}^m \]

where:

- \( m \) - strain rate sensitivity
- \( C \) - material constant

of \( K @ \dot{\varepsilon} = 1.0 \)

Substituting:

\[ \sigma = C \dot{\varepsilon}^m \varepsilon^n \]

strain rate - \( f(T) \)

Sensitivity, \( m \) - low @ low \( T \), \( m \uparrow T \uparrow \)

- low for work hardened, high strength metals @ low \( T \)
\[ C = f(T) \]
\[ - C \downarrow T \uparrow \]
\[ - \text{varies with } \exp \left\{ \frac{1}{T} \right\} \]

Thus, general form of flow stress/strain relation:

\[ \sigma = K_0 \exp \left\{ \frac{1}{T} \right\} \varepsilon^m \leq \varepsilon \]

**Creep in Metals**

Creep — the time-dependent permanent deformation that occurs under stress at elevated temperatures.

\[ \varepsilon \text{ vs. } t \text{ plotted at test temperature} \]

Three stages of creep identified (Fig. 8.36, 8.37)
Mechanisms of High Temperature Deformation in Metals:

- vacancy motion (particularly along grain boundaries)
- dislocation climb (assisted by vacancies)
- grain rotation
- void formation
- metallurgical changes

**Figure 8.36** Typical creep curve of strain versus time at constant stress and constant elevated temperature. The minimum creep rate $\Delta \varepsilon / \Delta t$ is the slope of the linear segment in the secondary region. Rupture lifetime $t_r$ is the total time to rupture.

**Figure 8.37** Influence of stress $\sigma$ and temperature $T$ on creep behavior.
Alloy Selection for High Temperature Application:

- high melting point metal
- metal with large Young's modulus
- metal with large grain size
- metal that is metallurgically stable and oxidation resistant