Introduction to Plasticity

- After a high enough stress is reached, the strain is not fully recovered upon unloading
- The remaining permanent strain is the "plastic" strain
- Additional plastic strains may be accumulated upon subsequent loading and unloading

Schematic of Plastic Strain After Unloading
Objectives of This Class

- This class will present an introduction to plasticity in different classes of materials
  - ceramics
  - metals
  - intermetallics
  - polymers

- This will be followed by a detailed description of what happens during a tensile test

- Basic definitions of true stress and true strain will be presented along with \( \sigma - \varepsilon \) behavior
Plasticity in Ceramics

- Most ceramics undergo elastic deformation before the onset of catastrophic failure at room temperature.

- Most ceramists report flexural properties obtained under 3- or 4-point bending.

- Ceramics are stronger in compression than in tension/flexure – why?

**Strength Properties of Selected Ceramic Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive Strength [MPa (ksi)]</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Flexural Strength [MPa (ksi)]</th>
<th>Modulus of Elasticity [GPa (10^6 psi)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina (85% dense)</td>
<td>1620 (235)</td>
<td>125 (18)</td>
<td>295 (42.5)</td>
<td>220 (32)</td>
</tr>
<tr>
<td>Alumina (99.8% dense)</td>
<td>2760 (400)</td>
<td>205 (30)</td>
<td>345 (50)</td>
<td>385 (56)</td>
</tr>
<tr>
<td>Alumina silicate</td>
<td>275 (40)</td>
<td>17 (2.5)</td>
<td>62 (9)</td>
<td>55 (8)</td>
</tr>
<tr>
<td>Transformation</td>
<td>1760 (255)</td>
<td>335 (51)</td>
<td>635 (92)</td>
<td>200 (29)</td>
</tr>
<tr>
<td>Toughened zirconia</td>
<td>1860 (270)</td>
<td>690 (100)</td>
<td>205 (30)</td>
<td></td>
</tr>
<tr>
<td>Partially stabilized zirconia</td>
<td>1860 (270)</td>
<td>690 (100)</td>
<td>205 (30)</td>
<td></td>
</tr>
<tr>
<td>Zirconia + 9% MgO</td>
<td>138 (20)</td>
<td>24 (3.5)</td>
<td>69 (10)</td>
<td>115 (17)</td>
</tr>
<tr>
<td>Cast Si₃N₄</td>
<td>3450 (500)</td>
<td>860 (125)</td>
<td>860 (125)</td>
<td></td>
</tr>
</tbody>
</table>

Factors that Control the Strength of Ceramics

- The strength of ceramic materials are controlled by pre-existing defects such as cracks

- Also, ceramics have large slip vectors that are unfavorable for plastic deformation

- Deformation is limited to small strains (typically < 0.1 – 1%) except at high temperatures

- Some fine-grained ceramics may be superplastic ($\varepsilon > 100$-$1000\%$) elevated temperature
The Effects of Microcracking on Ceramics

- Microcrack generally results in a reduction in Young’s modulus, $E$
- $E$ is a global/scalar measure of damage
- The scalar damage variable is given by
  $$D = 1 - \frac{E}{E_0}$$
- Damage tensors may also be used (Lemaitre, 1991)

Schematic of Young’s Modulus Reduction Due to Damage
Plasticity in Ceramics: Possible Causes

- Plasticity in ceramics may occur by
  - stress induced phase transformations e.g. in zirconia alloyed with CaO, Y_2O_3 or CeO
  - microcracking mechanisms

Three Stages of Deformation in Material Undergoing Stress-Induced Phase Transformation
Plasticity in Metals and Their Alloys

- In contrast to ceramics, plastic deformation in metals/alloys is associated with large strains.

- Typical plastic strains to failure can vary between 5 and 100% in ductile metals/alloys.

- However, elastic strains are typically less than ~ 0.1 to 1%.

**Stress-Strain Behavior in Al Alloy**
The Three Types of Stress-Strain Response

Strain Hardening

Elastic-Perfectly Plastic

Strain Softening
Reasons for Strain Hardening in Metals/Alloys

- Strain hardening occurs largely as a result of dislocation interactions with defects
  - point defects (vacancies, solutes, interstitials)
  - line defects (dislocations)
  - surface defects (grain boundaries & stacking faults)
  - volume defects (precipitates)
Reasons for Strain Softening

- Strain localization on a particular microstructural feature such as a precipitate

- Once the initial shear stress is overcome
  - material may offer decreasing resistance to increasing displacement
  - this may give rise ultimately to strain softening

\[
\text{Strain Softening}
\]
Portevin Le Chatelier Effect

- Since dislocations interact with solute clouds, serrated yielding phenomena may be observed in stress-strain behavior.

- Different types of stress-strain behavior associated with possible dislocation/solute interactions.

- Phenomenon referred to as Portevin Le Chatelier effect (Portevin and Le Chatelier, 1923).

- Effective at certain strain rate/temperature ranges.
Figure 5.6 - Types of Serrated Yielding Phenomena: (a) Type A; (b) Type B; (c) Type C, and (d) Type S (Types A-C After Brindley and Worthington, 1970 - Reprinted with permission from Metall. Rev.; Type S After Pink, 1994 - Reprinted with permission from Scripta Met.).
Anomalous Yielding Phenomena

- Anomalous double yield point phenomena observed in some plain carbon steels
- Upper yield point (UYP) corresponds to the unpinning of dislocations for interstitials
- Load drops to lower yield point (LYP) upon unpinning
- Luders bands (shear bands inclined at $\sim 45^\circ$ to loading axes) then observed to propagate across gauge section

Anomalous Yielding in 1018 Plain Carbon Steel
Some Note on Lűder’s Band

- Strain is relatively constant in the Luder’s strain regime
- Serrations may be observed with sensitive instrumentation
- The strain at the end of this regime is known as the Lűder’s strain
- Slip bands have spread completely across the gauge at the Lűder’s strain – which is followed by conventional stress-strain behavior
Plasticity in Intermetallics

- Intermetallics are compounds between metals and non-metals
- They generally have ordered or partially ordered crystal structures
- They also tend to have partially ionic or covalently bonded structures
- Usually exhibit limited ductility at room-temperature
  - iron aluminides (Fe$_3$Al-xB) – 10-20% ductility
  - gamma titanium aluminides (TiAl) – 1-2 % ductility
  - nickel aluminides (Ni$_3$Al-xB) – 10-50 ductility
  - nickel aluminides (NiAl) < 1%
  - niobium aluminides (Nb$_3$Al-xTi) – 1-30% ductility
Plasticity in Polymeric Materials

- Plasticity in polymers is not associated with dislocation motion
- Instead, plasticity in polymers associated with sliding of polymer chains
- Chain sliding occurs readily in linear polymers
- Chain sliding is hindered by side groups and other steric hindrances

Chain Structure of Polymeric Materials
Plasticity in Polymeric Materials

- Plasticity in Polymeric Materials
- Plasticity in polymers can result in strain levels between 10 and 1000%
- Such large strains associated with sliding, unkinking and uncoiling
- Unloading may be time-dependent (viscoelastic or viscoplastic)

Deformation of Rubber  Viscoelasticity of Rubbery Polymer
Elastic-Plastic Behavior in Materials

- Generic stress-strain behavior shows "elastic" and "plastic" regimes
- Linear behavior occurs up to the proportional limit
- Linear elasticity persists up to the elastic limit
- 0.2% offset yield stress defined (corresponds to 0.002 strain)
- Specifications for tensile testing in the ASTM E-8 code

Schematic of Stress-Strain Behavior
Stages of Elastic-Plastic Deformation

[Diagram showing stages of deformation with labels TS, M, and F, and axes for Stress and Strain]
Hardening Versus Geometric Instability

(a) $\varepsilon < \varepsilon_{pu}$

(b) $\varepsilon = \varepsilon_{pu}$

(c) $\varepsilon > \varepsilon_{pu}$
Types of Tensile Specimen Geometries

Cylindrical

Dog-Bone (Wedge Grips)

Dog-Bone (Pin-Loaded)
Basic Definitions of Stress and Strain

- The engineering stress is given by:

\[
\sigma_E = \text{Engineering Stress} = \frac{\text{Applied load}}{\text{Original Cross - Sectional Area}} = \frac{P}{A_0}
\]

The true stress is given by

\[
\sigma_T = \text{True Stress} = \frac{\text{Applied load}}{\text{Actual Cross - Sectional Area}} = \frac{P}{A}
\]

- The engineering strain is given by

\[
\varepsilon_E = \frac{\delta \ell}{\ell_0} = \frac{\ell - \ell_0}{\ell_0}
\]

- The true strain is given by

\[
\varepsilon_T = \int \frac{d\ell}{\ell} = \ln \left( \frac{\ell}{\ell_0} \right)
\]
Relationships Between Stress and Strain

- The engineering and true strains are given by

\[ \varepsilon_E = \frac{\ell}{\ell_0} - \varepsilon = \frac{A_0}{A} - \ell \]

and

\[ \varepsilon_T = \ln \left( \frac{\ell}{\ell_0} \right) = \ln \left( \frac{A_0}{A} \right) = \ln (\ell + \varepsilon_E) \]

- Similarly, the true stress may be expressed in terms of the engineering stress, since:

\[ \sigma_T = \frac{P}{A} = \frac{P}{A_0} \cdot \frac{A_0}{A} = \sigma_E \cdot \frac{A_0}{A} = \sigma_E \cdot \frac{1}{\ell_0} = \sigma_E (1 + \varepsilon_E) \]
Comparison of Engineering and True Stress-Strain Behavior

A schema showing the relationship between tensile true stress-true strain (dotted line) and engineering stress-engineering strain (solid line). For engineering strains less than $\varepsilon_{\text{eu}}$, $\sigma_T > \sigma_E$ and $\varepsilon_T < \varepsilon_E$. The necking point ($\sigma_E = \text{T.S.}$) has no particular significance in the true stress-true strain curve. At some strain greater than $\varepsilon_{\text{eu}}$, $\varepsilon_T$ (when calculated on the basis of neck area) becomes greater than $\varepsilon_E$, although $\sigma_T$ remains greater than $\sigma_E$. 