Introduction

- Tensile properties are used in selecting materials for various applications. Material specifications often include minimum tensile properties to ensure quality. Tensile tests must be made to ensure that materials meet these specifications. The tensile stress-strain curves can be used to predict a material’s behavior under loading forms other than the uni-axial tension.
Tensile-testing Machine

- A modern tensile-testing machine allows users to select force, strain, strain rate, stroke motion that can be enforced upon a test specimen. Linear variable differential transformers (LVDTs) are used to measure displacements accurately.

![Diagram of a tensile-testing machine with labels for Load Cell, Extensometer, and LVDT.](image)

Standard Test Methods

- The measured values of materials properties require that everyone who makes these measurements does so in a consistent way; therefore, the safety and reliability of engineering materials can be defined quantitatively.
- The American Society for Testing and Materials (ASTM)
- International Organization for Standardization (ISO)
- Japanese Industrial Standards (JIS)
- CNS


![Diagram showing typical grips for a tension test.](image)
Tensile Specimens

- The figure below shows a typical tensile specimen. The cross-sectional area of the gauge section is less than that of the shoulders and grip section, so the deformation will occur in the gauge section. According to St. Venant’s principle, the gauge section should be long compared to the diameter (typically four times). The transition between the gauge section and the shoulders should be at least as great as the diameter so that the larger ends do not constrain the deformation in the gauge section.

![Figure 3.1. Typical tensile specimen with a reduced gauge section and larger shoulders.](image)

Tensile Specimens

- The figure below shows various ways of gripping specimens. The gripping system should ensure that the maximum load can be applied without slippage or appreciable deformation in the grip section, i.e., bending near the grip should be avoided.

![Image of various gripping methods](image)
Stress-Strain Curves

• A tension test involves mounting a specimen in a machine, extending it, and recording how the tensile force changes as the specimen is elongated.
• The onset of plastic deformation is usually associated with the first deviation of the stress-strain curve from linearity.

Typical *engineering* stress-engineering strain curve for ductile materials.

Yield Strength

• For low carbon steels and some linear polymers, their engineering stress-strain curves have an initial maximum followed by a lower stress. This indicates that, after the initial maximum, at any given instant all of the deformation occurs within a relatively small region.
Necking Formation

As long as the engineering stress-strain curve passes the lower yield strength and rises, the deformation will occur uniformly along the length. For a ductile material, the stress will reach a maximum well before fracture. When the maximum is reached, deformation localizes, forming a neck.

The tensile strength (or ultimate strength) is defined as the highest value of the engineering stress.

The Tensile Strength

For ductile materials, the tensile strength corresponds to the point at which necking starts. Less ductile materials fracture before they neck. In this case, the fracture stress is the tensile strength. Very brittle materials fracture before they yield. Such materials have tensile strengths, but no yield stresses.
Ductility

- Two common parameters are used to describe the ductility of a material.
  1. The percent elongation
     \[ \%E_l = \frac{(L_f - L_o)}{L_o} \times 100\% \]
     where \( L_o \) is the initial gauge length and \( L_f \) is the length of the gauge section at fracture.
  2. The percent reduction of area
     \[ \%R_A = \frac{(A_o - A_f)}{A_o} \times 100\% \]
     where \( A_o \) is the initial cross-sectional area and \( A_f \) is the cross-sectional area of the fracture.

Related Properties

- The ability of a material to absorb energy when deformed elastically and to return it when unloaded is called “resilience.”
- The “toughness” of a material is its ability to absorb energy in the plastic range. The toughness of a material enables the material to withstand stresses above its yield stress without fracturing.

<table>
<thead>
<tr>
<th>Material</th>
<th>E, GPa</th>
<th>( v ), MPa</th>
<th>Modulus of resilience, ( U_{c}, ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-carbon steel</td>
<td>207</td>
<td>140</td>
<td>232</td>
</tr>
<tr>
<td>High-carbon spring steel</td>
<td>207</td>
<td>965</td>
<td>2250</td>
</tr>
<tr>
<td>Duratitan</td>
<td>72</td>
<td>124</td>
<td>107</td>
</tr>
<tr>
<td>Copper</td>
<td>110</td>
<td>29</td>
<td>5.5</td>
</tr>
<tr>
<td>Rubber</td>
<td>0.0040</td>
<td>2.1</td>
<td>2140</td>
</tr>
<tr>
<td>Acrylic polymer</td>
<td>3.4</td>
<td>14</td>
<td>28</td>
</tr>
</tbody>
</table>
Example

- A 13 mm diameter tensile specimen has a 50 mm gage length. The load corresponding to the 0.2% offset is 6800 kg and the maximum load is 8400 kg. Fracture occurs at 7300 kg. The diameter after fracture is 8 mm and the gage length at fracture is 65 mm. Calculate the standard mechanical properties (such as the ultimate tensile strength, 0.2% offset yield strength, fracture strength, elongation, and the reduction of area).

\[
A_0 = \frac{\pi}{4} (13)^2 = 132.7 \text{ mm}^2 = 132.7 \times 10^{-6} \text{ m}^2 \\
A_f = \frac{\pi}{4} (8)^2 = 50.3 \text{ mm}^2 = 50.3 \times 10^{-6} \text{ m}^2
\]

- Ultimate tensile strength
  - \( \varepsilon_u = \frac{P_u}{A_0} \times \frac{132.7 \times 10^{-6}}{132.7} = 620 \text{ MPa} \)
  - 0.2% Offset Yield Strength
  - \( \varepsilon_y = \frac{P_y}{A_0} \times \frac{132.7 \times 10^{-6}}{132.7} = 502 \text{ MPa} \)
  - Breaking Stress
  - \( \varepsilon_r = \frac{P_r}{A_0} \times \frac{132.7 \times 10^{-6}}{132.7} = 539 \text{ MPa} \)
  - Elongation
  - \( \varepsilon_f = \frac{L_f - L_0}{L_0} \times \frac{65 - 50}{50} = 30 \text{ percent} \)
  - Reduction of Area
  - \( q = \frac{A_0 - A_f}{A_0} \times \frac{132.7 - 80.3}{132.7} = 62 \text{ percent} \)

**True Stress and True Strain**

<table>
<thead>
<tr>
<th>True stress and true strain</th>
<th>( \sigma_t = \frac{F}{A} )</th>
<th>( \varepsilon = \ln \left( \frac{L}{L_0} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering stress and engineering strain</td>
<td>( \sigma = \frac{F}{A_0} )</td>
<td>( \varepsilon = \frac{\Delta L}{L_0} )</td>
</tr>
</tbody>
</table>

![True stress-strain and Engineering stress-strain graph](image-url)
Other Factors

- State of stress changes from uniaxial to triaxial after neck formation: The Bridgman correction for the stress distribution at the neck.

- Local temperature rise (especially at high strain rate)
- Anisotropic material property (especially for specimen with sample geometry different from axial symmetric "rod" shape, e.g. sheet shape).
- Measurement of force and strain.
- Axial alignment
- Effect of strain rate and testing temperature

Effect of Strain Rate

- Strain rate is defined as $d\varepsilon/dt$, and has a profound influence on the flow stress measured. Increasing strain rate increases flow stress, as shown in the figure below. Moreover, the strain-rate dependence of strength increases with increasing temperature.

$$\sigma = (\text{const.}) (\dot{\varepsilon})^m$$

Table 8-5: Spectrum of strain rate

<table>
<thead>
<tr>
<th>Range of strain rate</th>
<th>Condition or type test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$ to $10^{-1}$ s$^{-1}$</td>
<td>Creep testing at constant load or stress</td>
</tr>
<tr>
<td>$10^{-1}$ to $10^{-2}$ s$^{-1}$</td>
<td>&quot;Static&quot; tension tests with hydraulic or water driven machines</td>
</tr>
<tr>
<td>$10^{-2}$ to $10^{-3}$ s$^{-1}$</td>
<td>Dynamic tension or compression tests</td>
</tr>
<tr>
<td>$10^{-3}$ to $10^{-4}$ s$^{-1}$</td>
<td>High-speed testing using impact bars (must consider wave propagation effects)</td>
</tr>
<tr>
<td>$10^{-4}$ to $10^{-5}$ s$^{-1}$</td>
<td>High-speed impact testing on gases or explosively driven projectiles (shock wave propagation)</td>
</tr>
</tbody>
</table>
Testing-Temperature Effect

- In addition to the “local” temperature effect, the stress-strain curve also depends on the testing temperature. In general, strength decreases and ductility increases as the test temperature is increased. However, structural changes such as precipitation, strain aging or recrystallization may occur in certain temperature range to alter the general behavior.

Yield strength varies with temperature for mild steels (BCC materials).

\[
\sigma = (\text{const.})e^{-Q/RT}
\]

Yield strength varies with temperature for mild steels (BCC materials).

Testing-Temperature Effect

- For FCC metals flow stress is not strongly dependent on temperature but the strain-hardening exponent decreases with increasing temperature. This explains why bcc metals often exhibit brittle fracture at low temperatures.

BCC metal: Ta, W, Mo, Fe
FCC metal: Ni
Summary

- Tension test is one of the mechanical tests used to evaluate materials properties. Tensile properties can be used in engineering design and as a basis for comparing and selecting materials.
- For a given stress-strain relationship, you need to know how to determine the yield strength, ultimate tensile strength, residual strain after unloading over the plastic region, elastic modulus, etc.
- Engineering stress-strain curve vs. true stress-strain curve.
- Factors that ought to be considered for an accurate measurement, e.g., alignment of mechanical system and sample, strain rate, temperature, necking, etc.