Mechanical Properties
Hardness can be defined as resistance to deformation or indentation or resistance to scratch.

- Indentation hardness is of particular interest to engineers and is most commonly used.
- Indentation hardness can be measured by different methods.
- Classified based on how it is measured.
## Mohs scale of hardness

<table>
<thead>
<tr>
<th>Mohs hardness</th>
<th>Mineral</th>
<th>Chemical formula</th>
<th>Absolute hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Talc</td>
<td>Mg$_3$Si$<em>4$O$</em>{10}$(OH)$_2$</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Gypsum</td>
<td>CaSO$_4$·2H$_2$O</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Calcite</td>
<td>CaCO$_3$</td>
<td>9</td>
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<tr>
<td>4</td>
<td>Fluorite</td>
<td>CaF$_2$</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>Apatite</td>
<td>Ca$_5$(PO$_4$)$_3$(OH$^-$,Cl$^-$,F$^-$)</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>Orthoclase</td>
<td>KAlSi$_3$O$_8$</td>
<td>72</td>
</tr>
<tr>
<td>7</td>
<td>Feldspar</td>
<td></td>
<td></td>
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<tr>
<td>8</td>
<td>Quartz</td>
<td>SiO$_2$</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>Topaz</td>
<td>Al$_2$SiO$_4$(OH$^-$,F$^-$)$_2$</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>Corundum</td>
<td>Al$_2$O$_3$</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Diamond</td>
<td>C</td>
<td>1600</td>
</tr>
</tbody>
</table>
Rockwell Hardness

➢ In this type of test, depth of indentation at a constant load is taken as the measure of Hardness.
➢ A minor load of 10 kg is first applied for good contact between the indenter and the sample surface.
➢ The major load is then applied and the depth of indentation is recorded on a dial gage in terms of an arbitrary number.
➢ The dial consists of 100 divisions, each division representing a penetration depth of 0.002 mm.
Rockwell Hardness

Indenter and Hardness Scale

- **Two types of indenters** – 120° diamond cone called Brale indenter and 1.6 and 3.2 mm diameter steel balls
- Combination of indenter and major load gives rise to different hardness scales.
  - **C - Scale** – Brale indenter + 150 kg load, designated as $R_C$. Range is $R_C \, 20 - R_C \, 70$. Used for hard materials like hardened steels.
  - **B-Scale** – Steel ball indenter + 100 kg load, written as $R_B$. Range is $R_B \, 0$ to $R_B \, 100$.
  - Minor loads in $R_C$ and $R_B$ scales are 10 kg and 3 kg respectively.
Brinell Hardness

- Indentation is done with 10 mm diameter steel ball.
- A load of 3000 kg (500 kg for softer materials) is applied for 10 – 30 s.
- Dia of the indentation is measured to obtain the hardness (Brinell Hardness No.) from the relationship

\[ BHN = \frac{P}{\pi D t} \left( \frac{\pi D}{2} \right) \left( D - \sqrt{D^2 - d^2} \right) \]

\[ \text{(kgf/m}^2) \]

\( P = \text{Applied load} \)
\( D = \text{Diameter of ball} \)
\( d = \text{Dia of indentation} \)
\( t = \text{Depth of impression} \)
Brinell Hardness

BHN varies with load. \( P/D^2 \) value needs to be kept constant according to eqn. (2). \( P_1/D_1^2 = P_2/D_2^2 = P_3/D_3^2 \)

\[
BHN = \frac{P}{\left(\frac{\pi}{2}\right) D^2 (1 - \cos \phi)} \quad (2)
\]

\[d = D \sin \phi\]
Vickers Hardness

- Vickers test uses a square-base diamond pyramid indenter having an angle of $136^\circ$ between the opposite faces. This angle approximates the ideal $d/D$ ratio (0.375) in Brinell test (Fig. a).
- The hardness, called DPH or VHN (Diamond pyramid hardness no. or Vickers Hardness no.), is obtained by dividing the load ($1 – 120$ kg) with the surface area of the indentation.
- The surface area is calculated from the diagonals length of the impression.

$$DPH(VHN) = \frac{2P \sin(\theta/2)}{L^2} = \frac{1.854P}{L^2}$$
Microhardness

- Sometime hardness determination is needed over a very small area.
- For example, hardness of carburised steel surface, coatings or individual phases or constituents of a material.
- The load applied is much smaller compared to macrohardness.
- The indentation is very small. An optical microscope is used to observe it. Sample preparation is needed.
- Two methods are used for microhardness testing.
Microhardness

Knoop Indentation

- Knoop indenter is a diamond pyramidal indenter. Produces diamond shaped indentation with long and short diagonal lengths in the ratio of 7:1.
- The hardness is called Knoop Hardness number (KHN) and is obtained by dividing the load (25 - 300 g) with the projected surface area of the indentation.

\[
KHN = \frac{P}{A_p} = \frac{P}{L^2 C} \quad \text{(kgf/m}^2\text{)}
\]

- \(A_p\) = Projected area of indentation
- \(L\) = Longer diagonal length
- \(C\) = Indenter specific constant
Microhardness

Vickers Microhardness

- This is same as Vickers hardness except that the applied load is much smaller so as to cover a small area.
- The applied load range is 1 – 100 g.
Tensile Properties

Stress and Strain

Stress, \( s = \frac{P}{A} \) -------------- (1)
where \( P \) is the applied load and \( A \) is the original area of the cross section of the sample.

Strain, \( e = \frac{\Delta L}{L_o} = \frac{L - L_o}{L_o} \) ----------- (2)

\( L_o = \) Original length
\( L = \) Final length
\( \Delta L = L - L_o \) is the elongation

These are called engineering stress and engineering strain.
Elastic and Plastic behavior

- All materials deform when subjected to an external load.
- Up to a certain load the material will recover its original dimensions when the load is released. This is known as elastic behavior.
- The load up to which the materials remains elastic is the elastic limit. The deformation or strain produced within the elastic limit is proportional to the load or stress. This is known as **Hook’s Law**, Stress \( \propto \) Strain or Stress = \( E \times \) Strain. \( E \) is known as the Elastic Modulus.
- When the load exceeds the elastic limit, the deformation produced is permanent. This is called plastic deformation. Hook’s law is no longer valid in the plastic region.
Tensile Testing

- Load is applied uniaxially in a tensile testing frame and the displacement is recorded.
- The stress and strain are derived using equations (1) and (2).
- The stress is plotted against strain to generate the stress-strain curve.
- Different properties are calculated from this curve.
Tensile Testing

(a) Stress vs. Strain graph showing different stages:
- Elastic
- Uniform strain
- Necking
- Fracture

(b) Stress vs. Strain graph:
- Curve 1
- Curve 2
- Yield Strength (YS)
- Ultimate Tensile Strength (UTS)
- Elongation (er)
Tensile Properties

- $E_L = \text{Elastic limit}$, up to which Hook's Law (Stress $\propto$ Strain) is valid. The material comes back to original shape when the load is released.

- Elastic limit is difficult to determine. The proportional limit, $P_L$, the load at which the curve deviates from linearity, is taken as the elastic portion.

- The slope of the linear region is the Young's Modulus or Elastic Modulus ($E$).

- Loading beyond $P_L$ produces permanent or plastic deformation. The onset point of plastic deformation is known as Yield stress ($YS$).

- In some materials like mild steel the yield point is prominent (Curve 1 in Fig. b)
Tensile Properties

- In many other metals and alloys the yield point is not distinct (Curve 2, Fig. b). In such cases, a line parallel to the linear region is drawn at a strain = 0.002 (0.2%) and its intercept on the plastic region is taken as the yield stress (Fig. b). This is called 0.2% Proof stress.

- The stress at the maximum load is called ultimate tensile strength (UTS).

- The strain up to UTS is the uniform plastic strain. Beyond this the cross sectional area reduces and necking takes place.

- The fracture strain \( e_f = (L_f - L_o)/L_o \), where \( L_f \) is the length after fracture, is taken as the measure of Ductility.
Tensile Properties

Resilience:
The ability of a material to absorb energy in the elastic region. This is given by the strain energy per unit volume

\[ U_0 = \frac{1}{2} s_0 e_0 = \frac{s_0^2}{2E} \]

which is the area of the elastic region

Toughness:
Ability to absorb energy in the plastic range. This is given by the total area under the stress-strain curve.

High resilience is a property required in spring steels whereas structural steels have high toughness but lower resilience.
Ductile Vs. Brittle Fracture

- The fracture strain $e_f = (L_f - L_o)/L_o$, or reduction of area at fracture, $q = (A - A_o)/A_o$, is taken as the measure of Ductility.
- A ductile material exhibits high fracture strain, that is, it undergoes significant plastic deformation before fracture.
- A brittle material is the one which exhibits little or no plastic deformation before fracture.

![Stress vs. Strain Diagram]

The diagram shows the stress-strain curve for both ductile and brittle materials. The ductile material exhibits a higher strain at fracture, indicating more plastic deformation before failure, whereas the brittle material fails at a lower strain with less plastic deformation.
True Stress and Strain

- The engineering stress and strain are based on the original sample dimensions which change during the test.
- True stress and strain on the other hand are based on the actual or instantaneous dimensions and hence, are better representation of the deformation behavior of the material.

True strain, \( \varepsilon = \sum \frac{L_1 - L_o}{L_o} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} \) ....

\[ \varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0} = \ln \left( \varepsilon + 1 \right) \]

Engineering stress, \( s = \frac{P}{A_o} \)
True stress, \( \sigma = \frac{P}{A} = \left( \frac{P}{A_o} \right) \left( \frac{A_o}{A} \right) = s \left( \frac{A_o}{A} \right) \)
Volume, \( AL \), remains constant, \( A_o L_o = AL \rightarrow A_o / A = L / L_o = (\varepsilon + 1) \)
\( \sigma = s \left( \varepsilon + 1 \right) \)
True Stress-Strain Curve

- Since the engineering stress-strain curve is based on original area, it descends after maximum load as the load bearing ability of the sample decreases due to reduction in area.
- The true stress-strain curve (blue) however, continues to go up till fracture as it is based on the actual area.
The Flow Curve

The true stress-strain curve is also known as flow curve. The plastic region of the flow curve can be described as

$$\sigma = K\varepsilon^n$$

$n$ is known as strain-hardening exponent and $K$ is the strength coefficient. A log-log plot up to maximum load will yield a straight line. The slope of the line is $n$. $K$ is the true stress at $\varepsilon = 1$. $n = 0$, perfectly plastic solid, $n = 1$, elastic solid. For most metals $n = 0.1 – 0.5$
Poisson’s ratio

A tensile force in the $x$ direction produces an extension along that axis while it produces contraction along the transverse $y$ and $z$ axis.

The ratio of the lateral to axial strain is the Poisson's ratio, $\nu$. For most metals it is around 0.33

$$
\nu = - \frac{\varepsilon_y}{\varepsilon_x} = - \frac{\varepsilon_z}{\varepsilon_x}
$$
Shear Stress and Strain

The deformation in a body may also result in change in the initial angle between any two lines. The angular change is known as the shear strain, $\gamma$, which is produced by a shear stress, $\tau$.

$$\gamma = \frac{a}{h} = \tan \theta = \theta$$

$$\tau = G \gamma$$

$G$ is the shear modulus
Structure-Property Correlation

- **Structure-insensitive:** Elastic modulus
- **Structure-sensitive properties:** Yield stress, UTS, Ductility. These properties vary with the structure of the material.
- For example, the same material having a finer grain size will have higher strength as per the relation -

\[ \sigma_o = \sigma_i + kd^{-1/2} \]

This is known as the **Hall-Petch** equation which relates the yield strength to grain size.

\( \sigma_o \) is the yield strength, \( d \) is the grain size and \( \sigma_i \) and \( k \) are material dependent constants.

- Finer grain size – large grain boundary area/unit volume. As grain boundaries hinder dislocation motion, stress required to move the dislocations increases in the fine grained material and hence the strength increases.
# Mechanical Properties of some commonly used materials

<table>
<thead>
<tr>
<th>Material</th>
<th>E, GPa</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
<th>%Elong.</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>C steel</td>
<td>207</td>
<td>220 - 250</td>
<td>400 - 500</td>
<td>23</td>
<td>0.30</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>193</td>
<td>515</td>
<td>850</td>
<td>10</td>
<td>0.30</td>
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<tr>
<td>Alloy steels</td>
<td>207</td>
<td>860</td>
<td>1280</td>
<td>12</td>
<td>0.30</td>
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<tr>
<td>Al</td>
<td>70</td>
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<td>90</td>
<td>40</td>
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<td>250 - 500</td>
<td>300 - 550</td>
<td>10 - 20</td>
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<td>25 - 40</td>
<td>50 – 60</td>
<td>8 – 10</td>
<td>0.35</td>
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<td>220</td>
<td>290</td>
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<td>148</td>
<td>460</td>
<td>47</td>
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<td>207</td>
<td>517</td>
<td>930</td>
<td>-</td>
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<td>Al$_2$O$_3$</td>
<td>380</td>
<td>550</td>
<td>-</td>
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<td>0.16</td>
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<tr>
<td>PET</td>
<td>2.7 - 4</td>
<td>60</td>
<td>70</td>
<td>30-300</td>
<td>0.39</td>
</tr>
</tbody>
</table>
References

http://www.virginia.edu/bohr/mse209/chapter6.htm
http://web.utk.edu/~prack/mse201/Chapter%206%20Mechanical%20Properties.pdf
http://nptel.iitm.ac.in/courses/IIT-MADRAS/Design_Steel_Structures_I/1_introduction/3_properties_of_steel.pdf

Key words: Mechanical properties; Hardness; True stress; True strain; Strain hardening exponent; Flow curve; Poisson’s ratio; Hall-Petch relationship
Examples

Ex.1. A 15 mm long and 13 mm diameter sample shows the following behavior in a tensile test. Load at 0.2% offset – 6800 kg, maximum load – 8400 kg, fracture occurs at 7300 kg, diameter and length after fracture – 8 mm and 65 mm respectively. Find the standard mechanical properties.

Solution: \( A_o = \pi \frac{(13)^2}{4} = 132.7 \text{ mm}^2 \), \( A_f = \pi \frac{(8)^2}{4} = 50.3 \text{ mm}^2 \)

\( UTS = \frac{P_{max}}{A_o} = \frac{(8400 \times 9.8)}{132.7} = 620 \text{ N/mm}^2 = 620 \text{ MPa} \)

0.2% proof stress = \( \frac{(6800 \times 9.8)}{132.7} = 502 \text{ N/mm}^2 = 502 \text{ Mpa} \)

Breaking stress = \( \frac{(7300 \times 9.8)}{132.7} = 539 \text{ Mpa} \)

\%elongation = \( 100 \times \frac{(L_f - L_o)}{L_o} = 100 \times \frac{(65 - 50)}{50} = 30\% \)

\% area reduction = \( 100 \times \frac{(A_f - A_o)}{L_o} = 100(\frac{132.7 - 50.3}{132.7} = 62\% \)
Examples

Ex. 2. A metal experiences a true strain of 0.16 at a true stress of 500 MPa. What is the strain hardening exponent of the metal? K = 825 MPa. What will be the true strain at a stress of 600 MPa?

Solution: \( n = \frac{\log \sigma - \log K}{\log \varepsilon} = \frac{\log 500 - \log 825}{\log 0.16} = 0.271 \)
\( \sigma = K \varepsilon^n \)
Strain at 600 MPa: \( 600 = 825 (\varepsilon)^{0.271} \), strain \( \varepsilon = 0.3 \)
Quiz

1. Define hardness. What is Mohs scale of hardness?
2. Why it is necessary to specify load-indenter combination in Rockwell hardness test?
3. How is Brinell hardness measured. Show that BHN varies as \( \frac{P}{D^2} \) where \( P \) is the load and \( D \) is the indenter diameter.
4. Why is the included angle between opposite faces of the Vickers indenter 136°?
5. What is microhardness? Why sometime it is necessary?
6. What is engineering stress and strain?
7. What is Hook’s law?
8. What is elastic and proportional limit?
9. How is the elastic modulus measured from the stress-strain curve?
10. What is yield stress?
Quiz

11. What is 0.2% proof stress?
12. How is the ductility measured?
13. What is ductile and brittle behavior?
14. What is resilience? What is toughness?
15. What is true stress and strain. Deduce the relationship between true and engineering stress ad strain.
16. Why does the engineering stress-strain curve peak and drop where as the true stress-strain curve keep on going up?
17. What is a flow curve?
18. What is shear stress and strain
19. What is Poisson's ratio?
20. What are structure-sensitive and structure insensitive properties?
21. What is Poisson's ratio?
Quiz

22. A 15 mm long and 120 mm dia cylindrical rod is subjected to a tensile load of 35 kN. It must not experience either plastic deformation or a diameter reduction of more than 0.012 mm. Which of the listed materials is suitable for such a requirement and why? Al (E= 70 GPa, YS = 250 MPa, ν = 0.33), Ti (E= 105 GPa, YS = 850 MPa, ν = 0.36), Steel (E= 205 GPa, YS = 550 MPa, ν = 0.27), Mg (E= 45 GPa, YS = 170 MPa, ν = 0.35).

23. A metal experiences a true strain of 0.1 at a true stress of 415 MPa. What is the strain hardening exponent of the metal? K = 1035 MPa. What will be the true strain at a stress of 600 MPa?
Quiz

24. The following data were obtained in a tensile test of a low-carbon steel of diameter 12 mm and gage length 50 mm.

<table>
<thead>
<tr>
<th>Load, kN</th>
<th>Elongation, mm</th>
<th>Load, kN</th>
<th>Elongation, mm</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0041</td>
<td>25.2</td>
<td>0.51</td>
</tr>
<tr>
<td>4</td>
<td>0.0082</td>
<td>28</td>
<td>1.52</td>
</tr>
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<td>6</td>
<td>0.0132</td>
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<td>2.03</td>
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<td>8</td>
<td>0.0183</td>
<td>34</td>
<td>3.05</td>
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<tr>
<td>10</td>
<td>0.0226</td>
<td>38.4</td>
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<tr>
<td>12</td>
<td>0.0267</td>
<td>40</td>
<td>6.60</td>
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<td>14</td>
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<td>7.62</td>
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<tr>
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<td>0.0351</td>
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<td>40.2</td>
<td>14.7</td>
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<td>17.8</td>
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<tr>
<td>24</td>
<td>0.0518</td>
<td>32.4</td>
<td>19.3</td>
</tr>
</tbody>
</table>

Plot Engineering and True stress-strain curve and find the tensile properties.