Outline

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Torsion - Introduction

- Torsion is a variation of shear occurring in machine axles, drive shafts and twist drills
- From observation, the angle of twist of the shaft is proportional to the applied torque and to the shaft length.
  \[ \phi \propto T \]
  \[ \phi \propto L \]
- When subjected to torsion, every cross-section of a circular shaft remains plane and undistorted, because a circular shaft is axisymmetric.
- Cross-sections of noncircular (non-axisymmetric) shafts are distorted when subjected to torsion.

Torsion - Theory

- Torsional moment
- \[ M_T = \frac{\tau J}{r} \]
- \[ \tau = \frac{M_T r}{J} \]
- Shear stress is zero at centre of bar increasing linearly to max at surface.
- \[ J = \frac{1}{2} \pi r^4 \]
- \[ \tau_{\text{max}} = \frac{2M_T}{\pi c^4} \]
- \[ c_2 = \text{outer radius} \]
- \[ c_1 = \text{inner radius} \]
- Often tests are done on tubular cross sections

Torsion Test

- Not as common in testing as tensile test.
- Torsion test samples (similar to tensile samples).
- But also used on full sized parts such as shafts, axles, drills etc.
- Torsion machines use an electrical motor and gear drive to apply a torque to the specimen
- The specimen is gripped on both ends, with one end remaining stationary and the other rotated by the motor
- Troptometers are used to measure how much the specimen has been twisted.
- Combining this twisting information with the applied torque, we are able to determine the mechanical properties of the specimen.
During test, measure angle of twist, $\theta$, (in radians) and plot against $M_T$.

\[ \gamma = \tan \phi = \frac{r \theta}{L} \]

In elastic region, we can measure shear modulus, $G$:

\[ \tau = G \gamma = \frac{M_T r}{J} \quad \Rightarrow \quad G = \frac{M_T L}{J \theta} \]

Shear stress in plastic region can be calculated using diagram of $M_T$ vs. $\theta'$.

If $r = a$, then:

\[ \tau_a = \frac{1}{2 \pi a} (BC + 3CD) \]

Also the ultimate torsional shear strength (Modulus of Rupture):

\[ \tau_u = \frac{3M_{\max}}{2 \pi a^3} \]

Elements with faces parallel and perpendicular to the shaft axis are subjected to shear stresses only. Normal stresses, shearing stresses or a combination of both may be found for other orientations.

Consider an element at $45^\circ$ to the shaft axis,

\[ F = 2(\tau_{\max} A_0) \cos 45 = \tau_{\max} A_0 \sqrt{2} \]

\[ \sigma_{45^\circ} = \frac{F}{A} = \frac{\tau_{\max} A_0 \sqrt{2}}{A_0 \sqrt{2}} = \tau_{\max} \]

Element $a$ is in .......... shear.

Element $c$ is subjected to a tensile stress on two faces and compressive stress on the other two.

Note that all stresses for elements $a$ and $c$ have the same magnitude.

Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?

These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani: Plastic deformation is due to the motion of a large number of .................
Dislocations

- Dislocations result from solidification from the melt, from mechanical work (e.g., rolling, drawing, compressive impact, tensile or shear stress), or from thermal stresses.
- It is very difficult to prepare a dislocation-free crystal!!!
- 2 Types:
  - ………………………
  - ………………………
  - ………………………

- Think of edge dislocation as an extra half-plane of atoms inserted in a crystal.
- Misalignment of atomic planes due to the extra half plane.

Burger's vector (b) = magnitude + direction of lattice distortion.

Dislocations allow deformation at much lower stress than in a perfect crystal, How?!

Bonds across slip plane break consecutively not simultaneously – less energy is required but with same end result.

The movement of the dislocation (to the right in this sequence) requires the breaking (and formation) of only ONE set of bonds per step.

Dislocations move in ……………… directions within …………………. planes.

Caterpillar or Rug Analogy

- The caterpillar would require a large force (energy) to slide its complete body along
- it is much easier for it to move one part of its body at a time
- this analogous to the shearing of the lattice by movement of an edge dislocation
- another analogy is the sliding of a rug across a floor
Dislocations

- Dislocations are intrinsic defects like vacancies.
- **Dislocation density** is the total dislocation length/unit volume.
  - Units: mm/mm$^3$ or mm$^{-2}$
    - Annealed metal: $10^4$-$10^5$ mm$^{-2}$
    - Deformed: $10^9$-$10^{10}$ mm$^{-2}$
- Atoms above the slip plane are in compression.
- Atoms below the slip plane are in tension.
- It creates a strain field around the dislocation.
- Dislocations contain stored energy.

**Theoretical vs. Experimental Mech properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>G/2π</th>
<th>Experimental Yield Strength</th>
<th>(\tau_{\text{TH}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>12.6</td>
<td>1.83</td>
<td>0.37</td>
</tr>
<tr>
<td>Aluminium</td>
<td>11.3</td>
<td>1.64</td>
<td>0.78</td>
</tr>
<tr>
<td>Copper</td>
<td>19.6</td>
<td>2.84</td>
<td>0.49</td>
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<tr>
<td>Nickel</td>
<td>32</td>
<td>4.64</td>
<td>3.2-7.35</td>
</tr>
<tr>
<td>Iron</td>
<td>33.9</td>
<td>4.92</td>
<td>27.5</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>54.1</td>
<td>7.85</td>
<td>71.6</td>
</tr>
<tr>
<td>Nickel</td>
<td>10.6</td>
<td>2.41</td>
<td>33.3</td>
</tr>
<tr>
<td>Cadmium</td>
<td>9.9</td>
<td>1.44</td>
<td>0.57</td>
</tr>
<tr>
<td>Magnesium</td>
<td>7</td>
<td>1.02</td>
<td>0.39</td>
</tr>
<tr>
<td>Magnesium (basal slip)</td>
<td>7</td>
<td>1.02</td>
<td>39.2</td>
</tr>
<tr>
<td>Magnesium ( prism slip)</td>
<td>16.9</td>
<td>2.45</td>
<td>13.7</td>
</tr>
<tr>
<td>Titanium</td>
<td>49.3</td>
<td>7.15</td>
<td>1.37</td>
</tr>
<tr>
<td>Beryllium</td>
<td>49.3</td>
<td>7.15</td>
<td>52</td>
</tr>
</tbody>
</table>

When compared to experimental shear yield strengths, common metals are 1000 to 10,000 times weaker than theory predicts.

Theoretical Shear Strength, \(\tau_{\text{TH}}\) \approx \frac{G}{2\pi}, to \approx \frac{G}{30} depending on method.

Dislocation Interaction

- Dislocations **interact** during plastic deformation.
- Dislocations can either repel or attract one another.
- Depends on orientation or sign (positive or negative).
- Important since deformation increases dislocation density \(\rightarrow\) work hardening.
- This is a strengthening mechanism.

Movement of Dislocations

Under applied shear stress, dislocations can move by breaking bonds **consecutively** (rather than simultaneously).

 Requires **less energy**, (reason why exp. shear strength is lower).

Deformation by dislocations movement is called **slip**.

- The combination of C-P plane (the slip plane) and C-P direction (the slip direction) is called a …………..

Recall:

**SLIP SYSTEMS DEPEND ON THE CRYSTAL STRUCTURE OF THE MATERIAL!**
The more slip systems available, the easier it is for dislocations to move, which is why (on the average) FCC and BCC metals are more ductile than HCP metals.

Number of slip systems increases with temperature e.g. HCP metals → more ductile at high temperature.
Next time:
Continue Dislocations