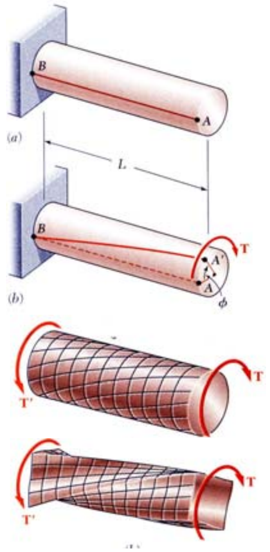
Outline

- Example
- Torsion - introduction
- Torsion test
- Torsional Failure Modes
- Plastic deformation
- Dislocations – introduction
- Edge Dislocation
- Dislocation movements

Torsion - *Introduction*



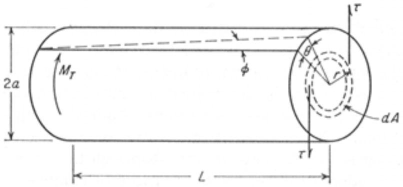
- Torsion is a variation of shear occurring in machine axles, drive shafts and twist drills
- From observation, the angle of twist of the shaft is proportional to the applied torque and to the shaft length.

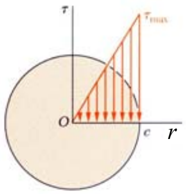
$$\phi \propto T$$

$$\phi \propto L$$

- 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*





$$\tau_{max} = \frac{2M_T}{\pi\ c^3}$$

$$J = \tfrac{1}{2}\pi c^4$$

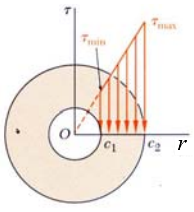
$$M_T = \frac{\tau J}{r} \quad \rightarrow \quad \tau = \frac{M_T r}{J}$$

Shear stress is zero at centre of bar increasing linearly to max at surface.

M_T = Torsional moment
τ = shear stress
r = radial distance from centre
J = Polar moment of inertia

$$\tau_{max} = \frac{2M_T c_2}{\pi(c_2^4 - c_1^4)}$$

c_2 = *outer radius*
c_1 = *inner radius*



$$J = \tfrac{1}{2}\pi\left(c_2^4 - c_1^4\right)$$

Shear Strain:

$$\gamma = \tan\phi = \frac{r\theta}{L}$$

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.

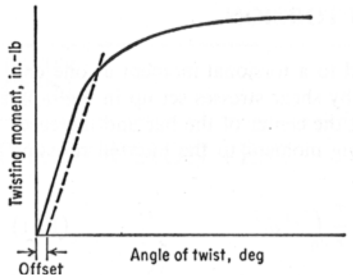
Torsion machine

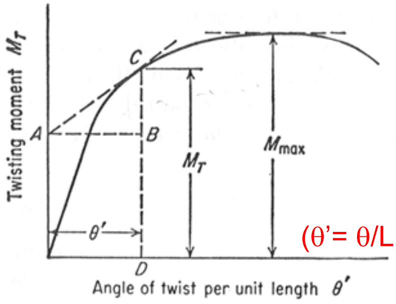
- Torsion machines use an electrical motor and gear drive to apply a torque to the specimen
- The specimen is gripped on both ends, with one end remaining stationary and the other rotated by the motor

Troptometer

- 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.

Torsion Test





(θ'= θ/L)

During test, measure angle of twist, θ, (in radians) and plot against M_T.

$$\gamma = \tan\phi = \frac{r\theta}{L}$$

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

$$\tau = G\gamma = \frac{M_T r}{J} \rightarrow G = \frac{M_T L}{J\theta}$$

Shear stress in plastic region can be calculated using diagram of M_T vs. θ'

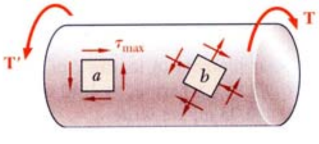
If r = a, then:

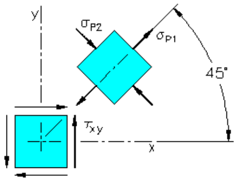
$$\tau_a = \frac{1}{2\pi a^3}(BC + 3CD)$$

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

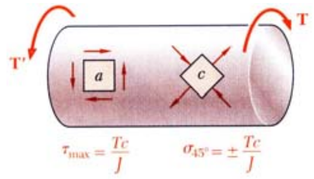
$$\tau_u = \frac{3M_{max}}{2\pi a^3}$$

Torsional Failure Modes





Torsion Stress States



- 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° to the shaft axis,

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

$$\sigma_{45^o} = \frac{F}{A} = \frac{\tau_{max} A_0 \sqrt{2}}{A_0 \sqrt{2}} = \tau_{max}$$

- 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

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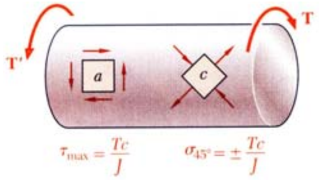
Torsional Failure Modes



- Ductile materials generally fail in shear. Brittle materials are weaker in tension than shear.
- When subjected to torsion, a ductile specimen breaks along a plane of **maximum shear**, i.e., a plane perpendicular to the shaft axis.
- When subjected to torsion, a brittle specimen breaks along planes ……………… to the direction in which tension is a maximum, i.e., along surfaces at 45° to the shaft axis.

Plastic Deformation

❖ Why metals could be plastically deformed?

❖ Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?

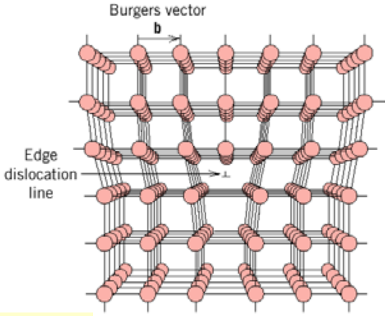
❖ Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?

❖ 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.

Described by ⊥ symbol.

Edge Dislocation

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

Dislocations

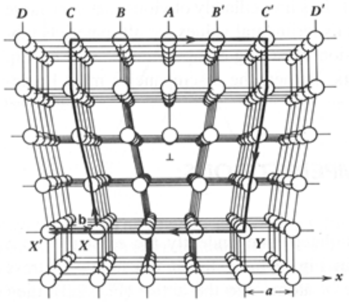


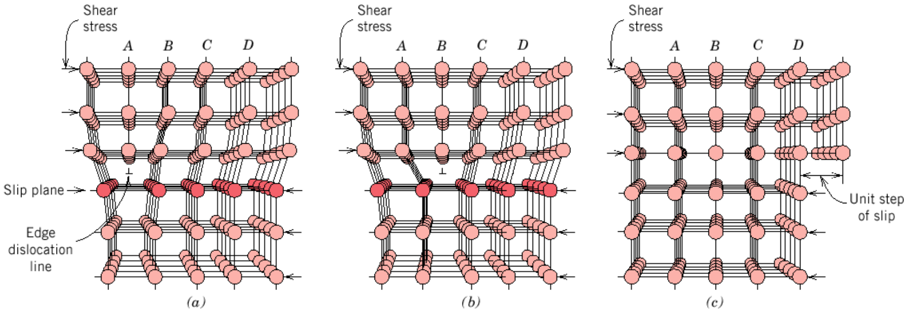
FIGURE 2.3 Lattice defect caused by introduction of an extra half plane of atoms, *A*. Note symmetrical displacement of planes *B*, *B'*, *C*, *C'*, etc. The dislocation line is defined as the edge of the half plane, *A*. The Burgers circuit *XCC'YX'* contains a closure failure *X'X*. (From Guy,[5] *Elements of Physical Metallurgy*, 2nd ed., Addison-Wesley, Reading, MA, 1959.)

"a" is the lattice constant

"b" is the Burgers vector

Burger's vector, b, describes magnitude and direction of ………. Burger's circuit around section of crystal that includes a dislocation shows Burger's vector (a vector needed to close circuit) (*In perfect crystal, however, Burger's circuit closes itself*).

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

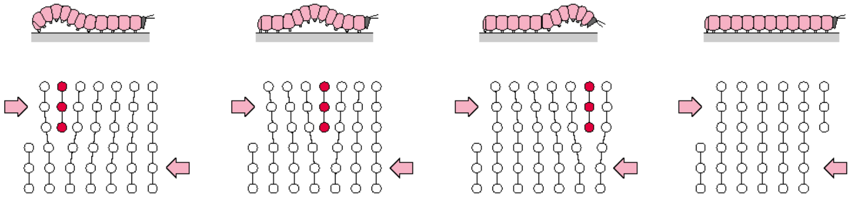


Bonds across slip plane break consecutively **not simultaneously** – less energy is required but with same end result.

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.

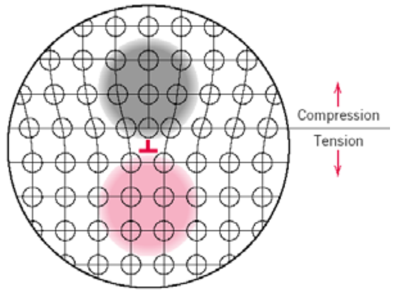
Caterpillar or Rug Analogy



- 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

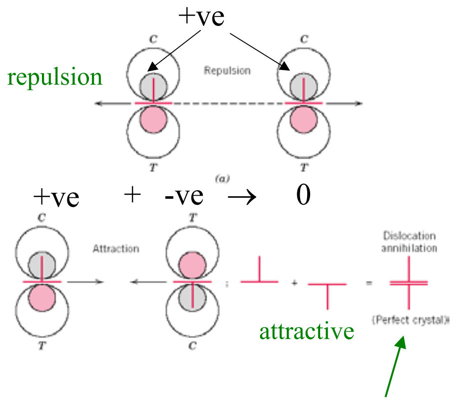
Dislocations

- dislocations are *intrinsic* defects like vacancies
- *dislocation density* is the total dislocation length/unit volume
- units: mm/mm^3 or mm^{-2}
  - annealed metal: 10^5-10^6 mm^{-2}
  - deformed: 10^9-10^{10} mm^{-2}
- atoms above slip plane are in compression
- atoms below slip plane are in tension
- creates a *strain field* around the dislocation
- dislocations contain *stored energy*



Regions of compression (dark) and tension (colored) located around an edge dislocation.

Dislocation Interaction



Two extra half-planes will align and become a complete plane

- dislocations ………. 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 → *work hardening*
- this is a strengthening mechanism

Theoretical vs. Experimental Mech properties

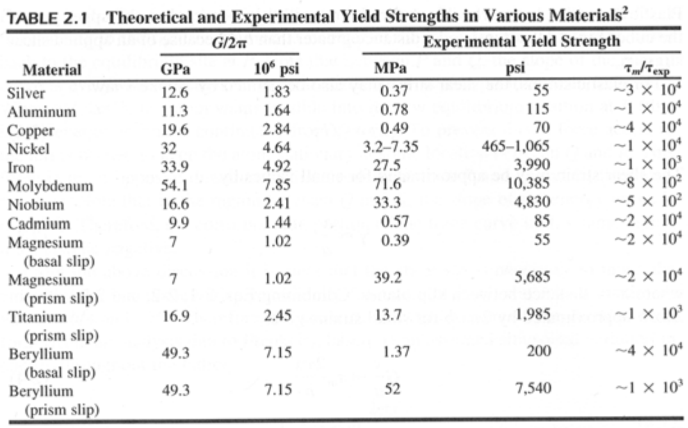


TABLE 2.1 Theoretical and Experimental Yield Strengths in Various Materials[2]

Material	$G/2\pi$ GPa	$G/2\pi$ 10^6 psi	Experimental Yield Strength MPa	Experimental Yield Strength psi	τ_{th}/τ_{exp}
Silver	12.6	1.83	0.37	55	$\sim 3 \times 10^4$
Aluminum	11.3	1.64	0.78	115	$\sim 1 \times 10^4$
Copper	19.6	2.84	0.49	70	$\sim 4 \times 10^4$
Nickel	32	4.64	3.2–7.35	465–1,065	$\sim 1 \times 10^4$
Iron	33.9	4.92	27.5	3,990	$\sim 1 \times 10^3$
Molybdenum	54.1	7.85	71.6	10,385	$\sim 8 \times 10^2$
Niobium	16.6	2.41	33.3	4,830	$\sim 5 \times 10^2$
Cadmium	9.9	1.44	0.57	85	$\sim 2 \times 10^4$
Magnesium (basal slip)	7	1.02	0.39	55	$\sim 2 \times 10^4$
Magnesium (prism slip)	7	1.02	39.2	5,685	$\sim 2 \times 10^4$
Titanium (prism slip)	16.9	2.45	13.7	1,985	$\sim 1 \times 10^3$
Beryllium (basal slip)	49.3	7.15	1.37	200	$\sim 4 \times 10^4$
Beryllium (prism slip)	49.3	7.15	52	7,540	$\sim 1 \times 10^3$

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

Theoretical Shear Strength, $\tau_{TH} \approx G/2\pi$ to $\approx G/30$ depending on method.

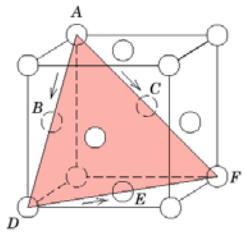
Movement of Dislocations

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

Requires less energy, (reason why expt. 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!

Slip Systems

Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	$\langle \bar{1}11\rangle$	12
α-Fe, W	{211}	$\langle \bar{1}11\rangle$	12
α-Fe, K	{321}	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

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 ………….. with temperature e.g. HCP metals → more ductile at high temperature

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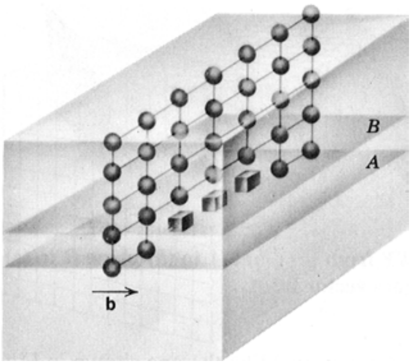
Movement of Dislocations



Dislocation climb involving vacancy (□) diffusion to edge dislocation allowing its movement to climb from plane A to plane B.

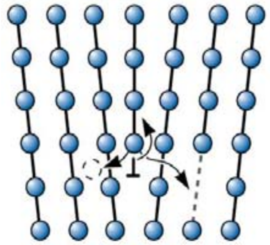
Edge dislocations can move “out” of the slip plane by <u>non-conservative</u> motion.

Requires diffusion of vacancies to bottom of extra 1/2 plane thus dislocation <u>CLIMBS</u> to a higher SLIP plane.

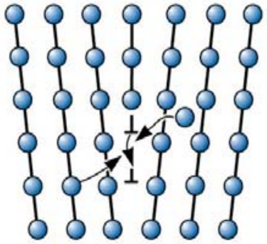
Thermally activated process (diffusion + number of vacancies) so usually only important at high temps. > 0.5 T_m (K)

Movement of Dislocations

Can dislocations climb?



when atoms leave the dislocation line to create interstitials or to fill vacancies



or when atoms are attached to the dislocation line by creating vacancies or eliminating interstitials

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Strength of a perfect Crystals

If we have a material **without** dislocations (i.e. SLIP cannot occur)!!

Is the strength closer to the theoretical value?

TABLE 2.2 Theoretical and Experimental Strengths of Dislocation-Free Crystal (Whiskers)[6]

Material	Theoretical Strength ($G/2\pi$) GPa	Theoretical Strength ($G/2\pi$) 10^6 psi	Experimental Strength GPa	Experimental Strength 10^6 psi	Error
Copper	19.1	2.77	3.0	0.44	~6
Nickel	33.4	4.84	3.9	0.57	~8.5
Iron	31.8	4.61	13	1.89	~2.5
B_4C	71.6	10.4	6.7	0.98	~10.5
SiC	132.1	19.2	11	1.60	~12
Al_2O_3	65.3	9.47	19	2.76	~3.5
C	156.0	22.6	21	3.05	~7

Quite close; only x10 not x10,000.

Next time:

Continue Dislocations