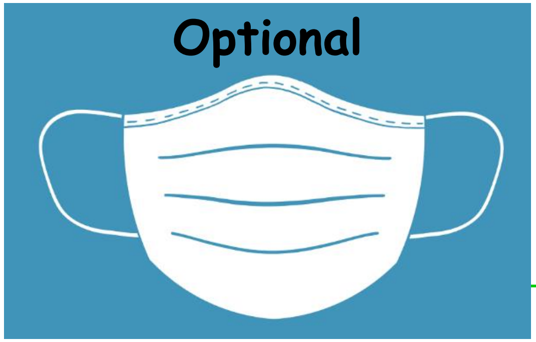
WORCESTER POLYTECHNIC INSTITUTE
MECHANICAL ENGINEERING DEPARTMENT

DESIGN OF MACHINE ELEMENTS
ME-3320, B'2025

Lecture 02

October 2025



DO NOTE:

Watch the following short videos before coming to class

Tensile test:

https://www.youtube.com/watch?v=D8U4G5kcpcM HERE

Poisson's ratio:

https://www.youtube.com/watch?v=M_7Prst1Ysc HERE

Fatigue test:

https://www.youtube.com/watch?v=LhUclxBUV_E HERE

Brinell Hardness test

https://www.youtube.com/watch?v=RJXJpeH78iU HERE

Charpy impact test:

https://www.youtube.com/watch?v=tpGhqQvftAo HERE

Material properties

Conventional tensile test

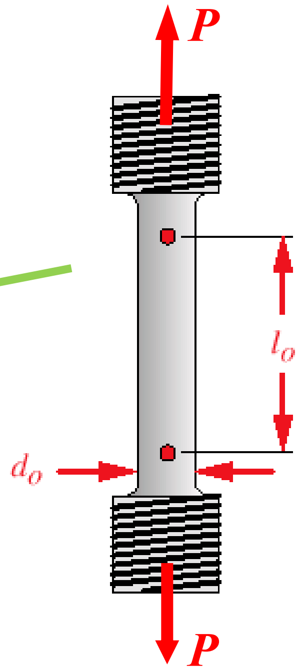


FIGURE 2-1

A Tensile Test Specimen

ASTM standards

Stress: $\sigma = \dfrac{P}{A_o}$

(Average normal stress)

Strain: $\varepsilon = \dfrac{l - l_o}{l_o}$

Modulus of elasticity:

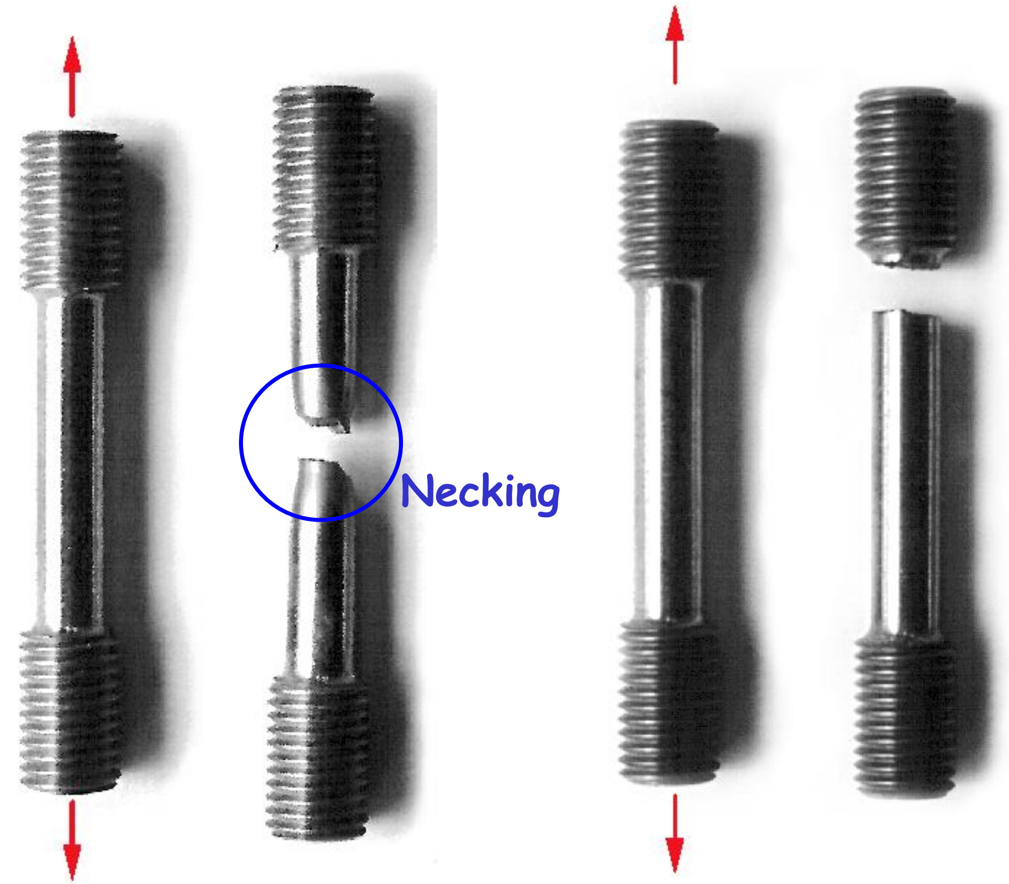
$$E = \frac{\sigma}{\varepsilon}$$

Average normal stress in an axially loaded bar

Tensile test

Typical results

Ductile material **Brittle material**



Average normal stress in an axially loaded bar: Poisson's ratio

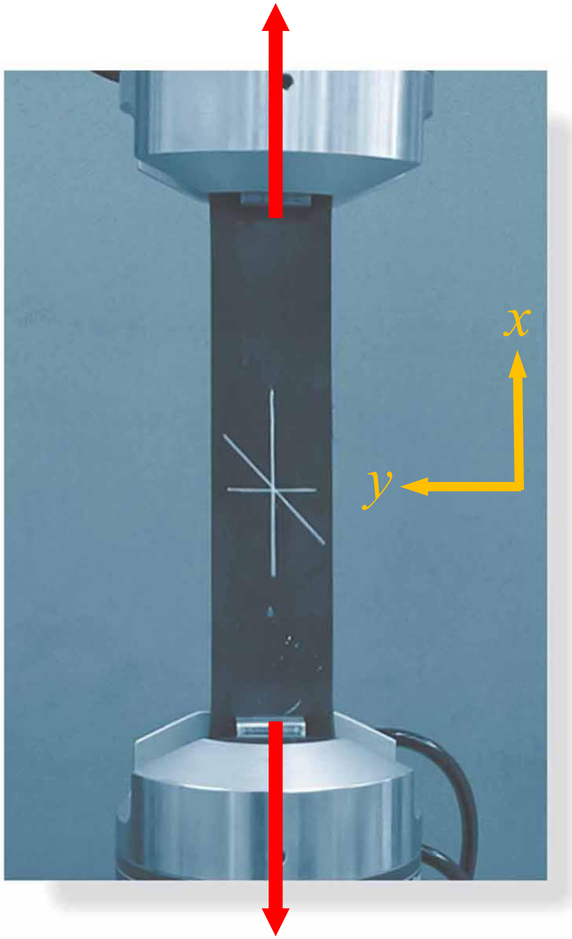


Figure: 02-01-A-UN
Note the before and after positions of three different line segments on this rubber membrane which is subjected to tension.The vertical line is lengthened, the horizontal line is shortened, and the inclined line changes its length and rotates.

Poisson's ratio:

$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$

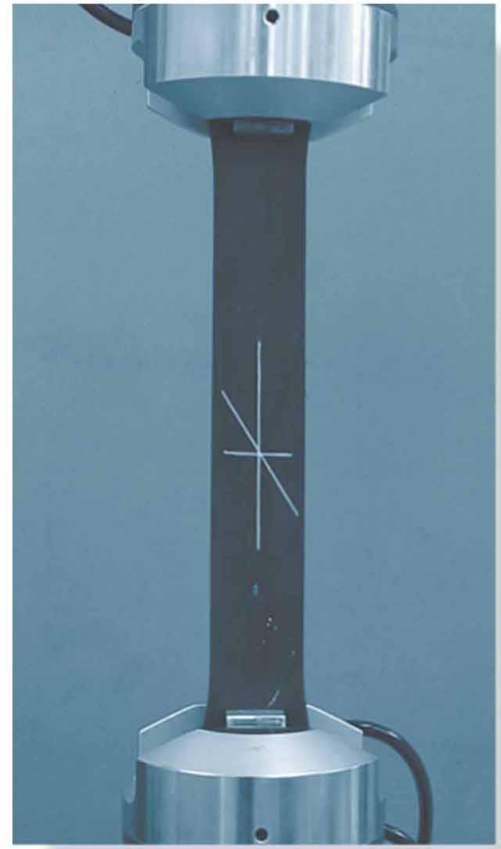
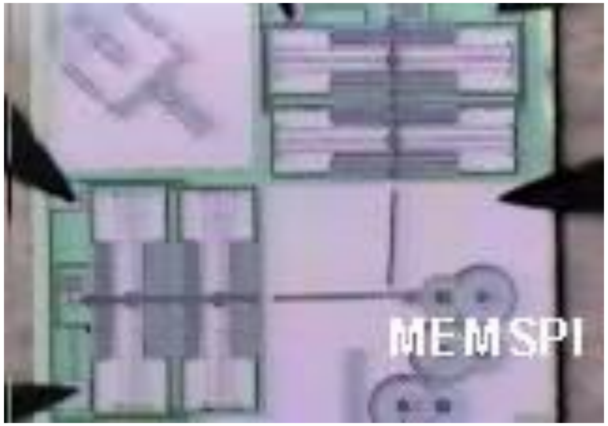
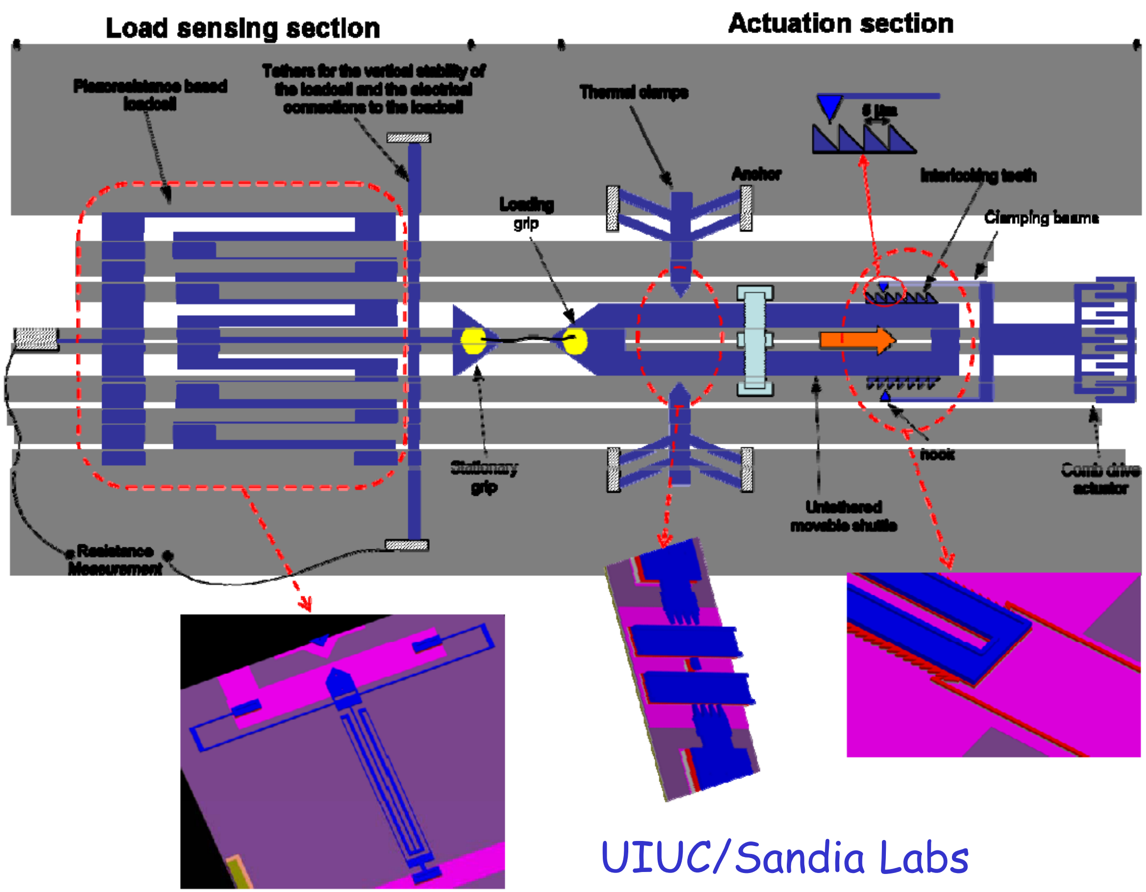


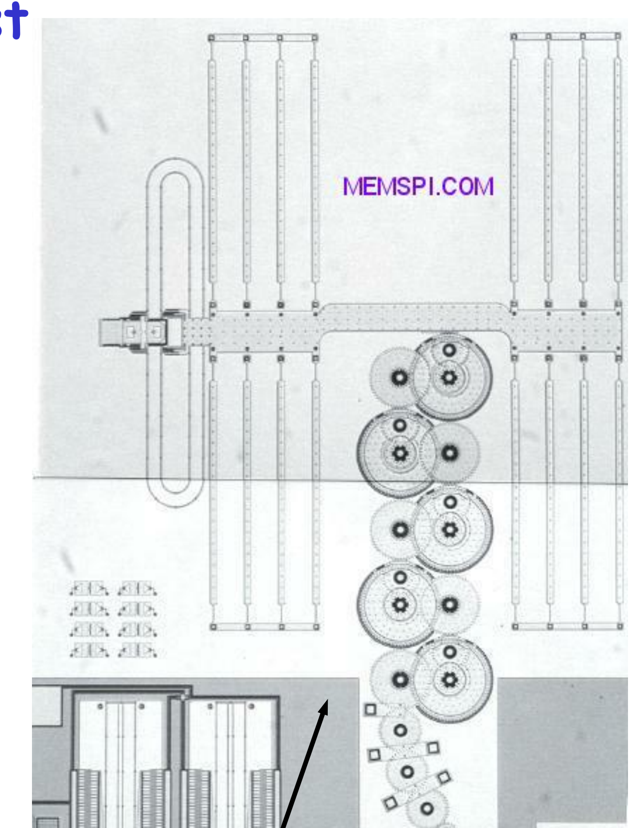
Figure: 02-01-B-UN
Note the before and after positions of three different line segments on this rubber membrane which is subjected to tension.The vertical line is lengthened, the horizontal line is shortened, and the inclined line changes its length and rotates.

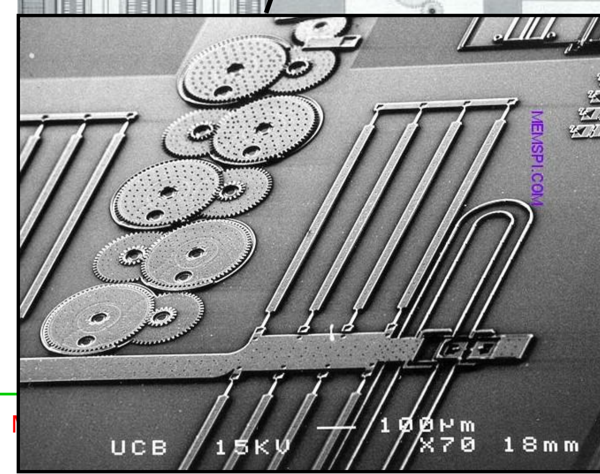
Material properties

Microscale tensile test





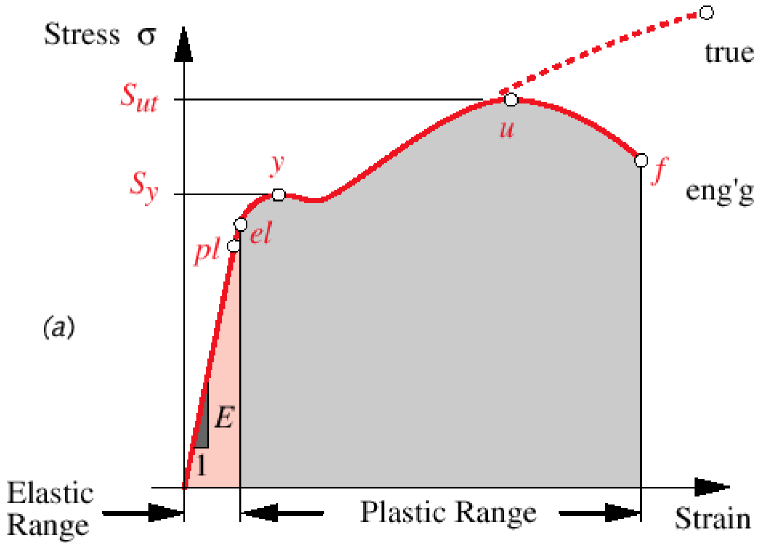


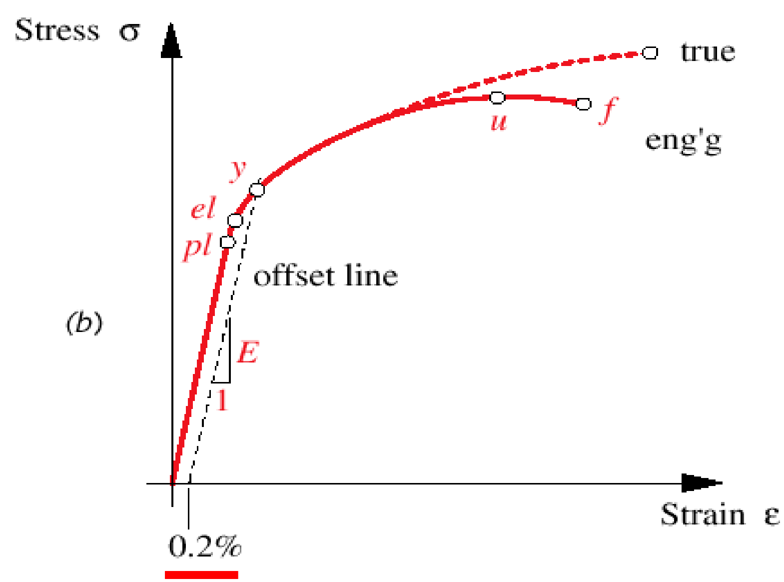


UIUC/Sandia Labs

Material properties

Stress-strain diagrams: yield behavior





Material properties

Tensile test

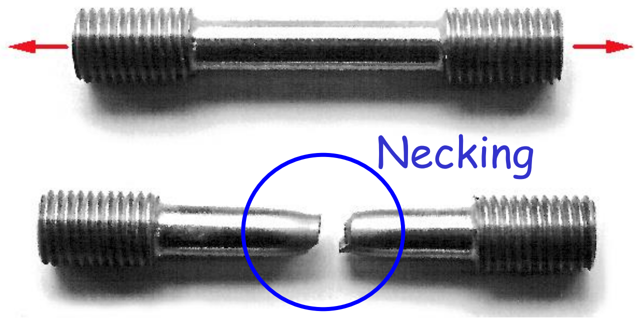


FIGURE 2-3

A Tensile Test Specimen of Mild, Ductile Steel After Fracture

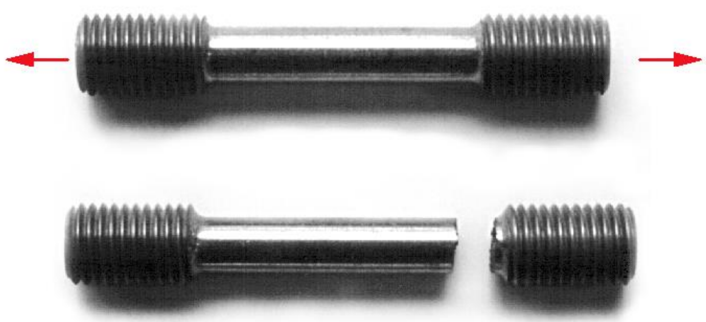


FIGURE 2-5

A Tensile Test Specimen of Brittle Cast Iron After Fracture

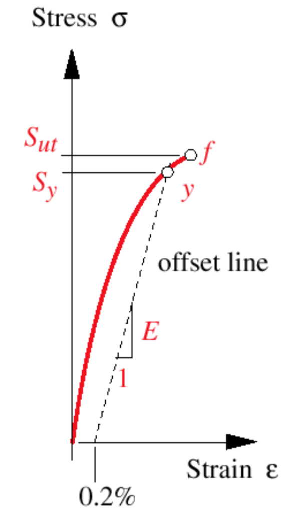


FIGURE 2-4

Stress-Strain Curve of a Brittle Material

Material properties

Compression test

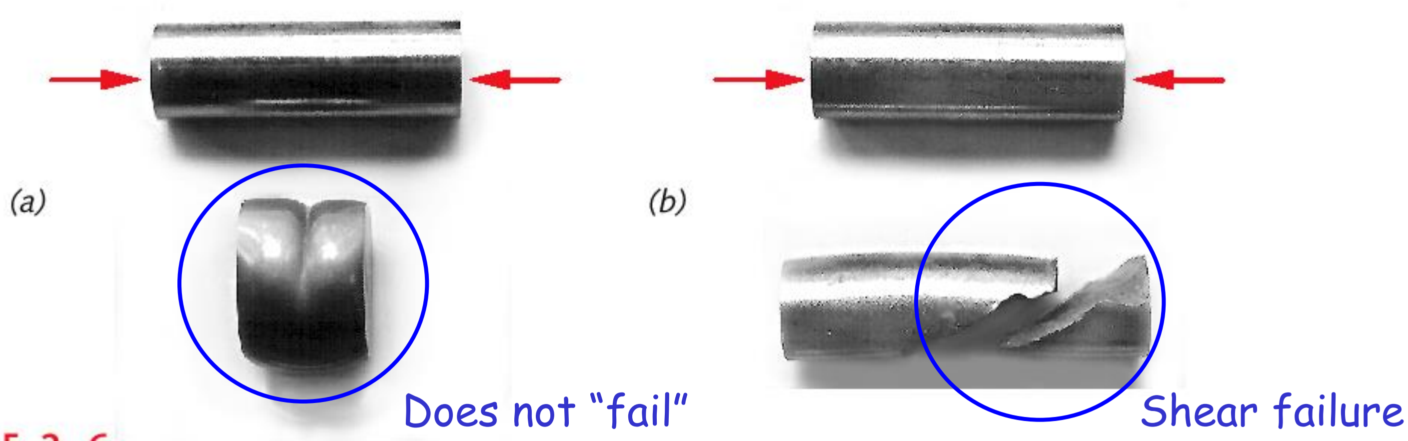


FIGURE 2-6

Compression Test Specimens After Failure *(a)* Ductile Steel *(b)* Brittle Cast Iron

Even materials: same behavior in tension as in compression.

Material properties

Bending test: three-point bending

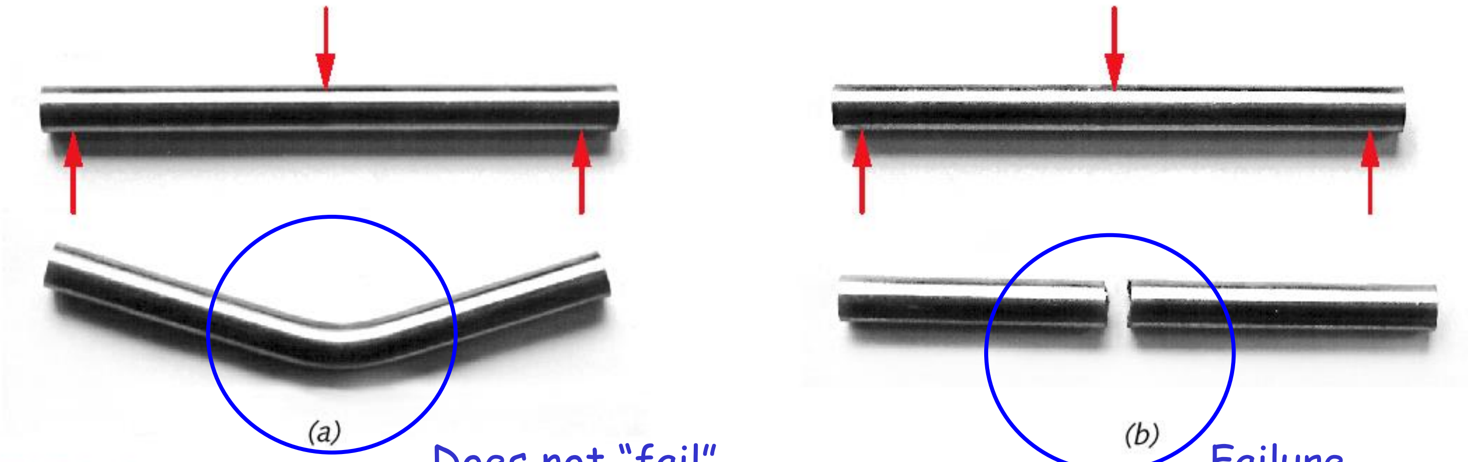


FIGURE 2-7

Bending Test Specimens After Failure *(a)* Ductile Steel *(b)* Brittle Cast Iron

Material properties

Torsion test

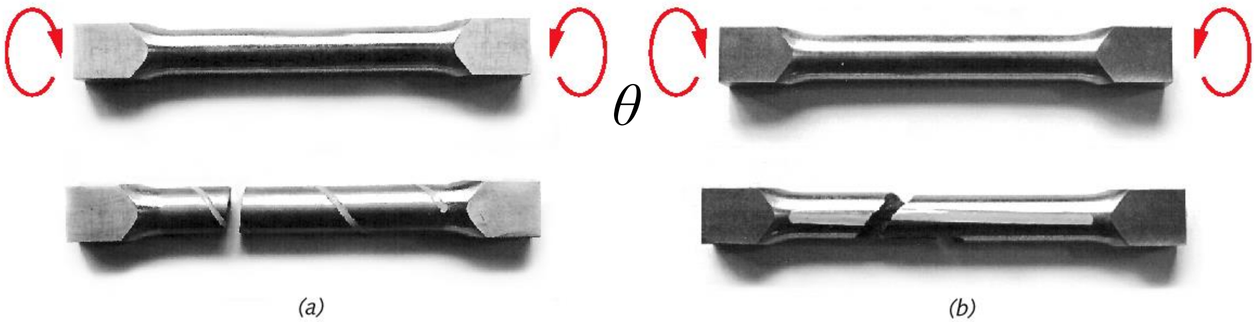


FIGURE 2-8

Torsion Test Specimens After Failure (a) Ductile Steel (b) Brittle Cast Iron

Steels: $S_{us} = 0.80\, S_{ut}$

Other ductile mtls.: $S_{us} = 0.75\, S_{ut}$

Note: $S_{sy} = 0.58\, S_y$

Stress-strain relation (torsion):

$$\tau = \frac{Gr\theta}{l_o}$$

Modulus of rigidity:

$$G = \frac{E}{2(1+\nu)}$$

Table 2-1

Poisson's Ratio ν

Material	ν
Aluminum	0.34
Copper	0.35
Iron	0.28
Steel	0.28
Magnesium	0.33
Titanium	0.34

Ultimate shear strength (torsion):

$$S_{us} = \frac{T_{(break)}r}{J}$$

Not uniform stress distribution; (in some cases, thin-walled tubes are preferred for this test, why?)

Material properties

Fatigue strength S_f and endurance limit S_e

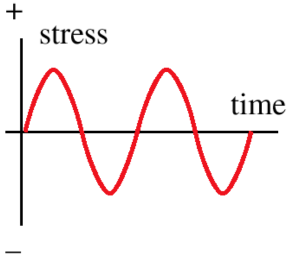
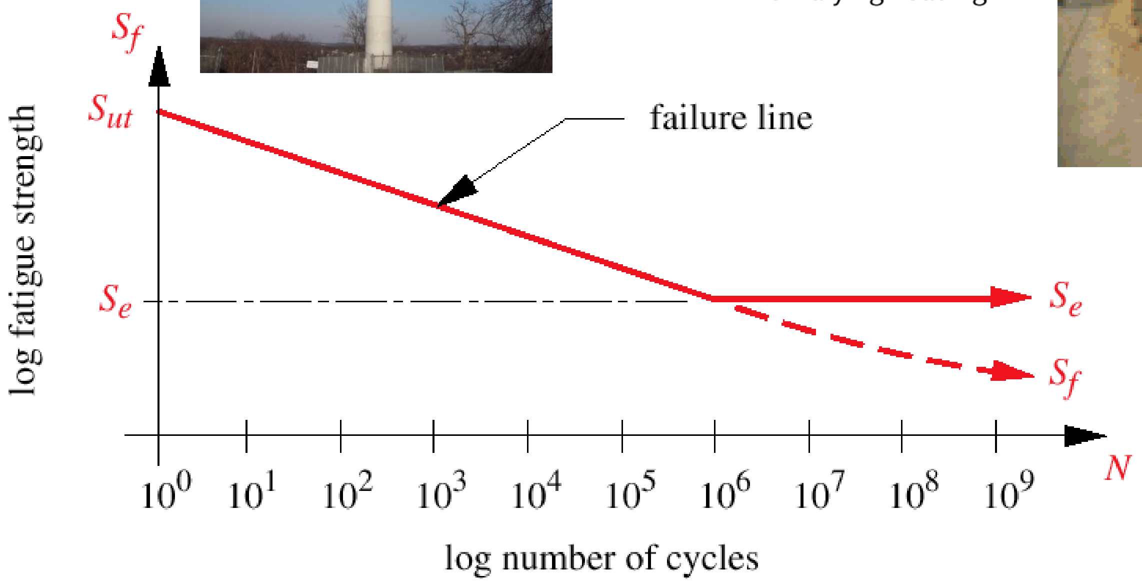


FIGURE 2-9

Time-Varying Loading

Testing of wind turbine blades



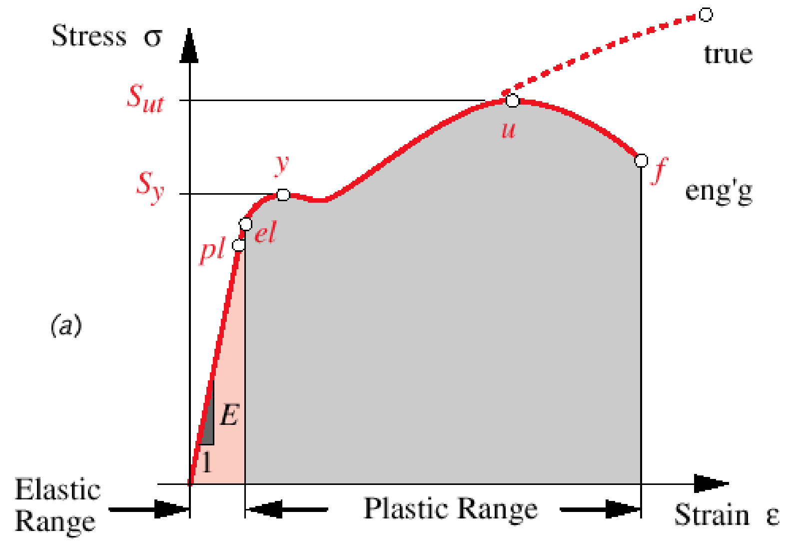
An endurance limit S_e exists for some ferrous metals and titanium alloys. Other materials show no endurance limit.

FIGURE 2-10

Wohler Strength-Life or *S-N* Diagram Plots Fatigue Strength Against Number of Fully Reversed Stress Cycles

Material properties

Resilience and toughness: impact load



Resilience: $$U_R = \int_0^{\varepsilon_{el}} \sigma \, d\varepsilon$$

Toughness: $$U_T = \int_0^{\varepsilon_f} \sigma \, d\varepsilon$$

Material properties

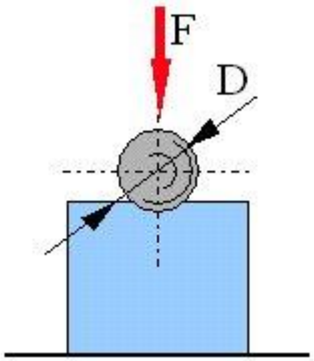
Resilience and toughness: impact load

Wind turbine test set-up on the UCSD-NEES Outdoor Shake Table at UCSD's Jacobs School of Engineering. The Table is capable of creating realistic simulations of the most devastating earthquakes ever recorded. The facility is part of the National Science Foundation's George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES).

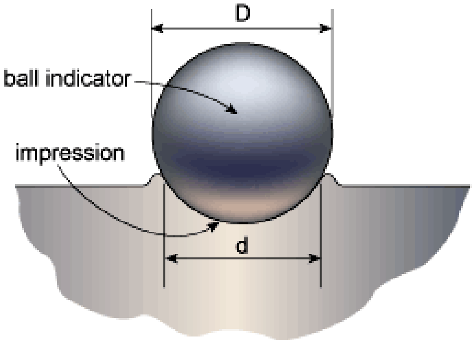
Reference:
http://www.jacobsschool.ucsd.edu/

Material properties

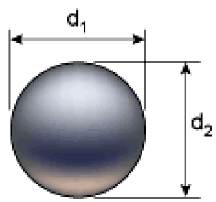
Hardness: Brinell, Rockwell, and Vickers test



Brinell test



(a) Brinell indentation



(b) measurement of impression diameter

$$H_B = \frac{F}{\frac{\pi}{2} D \cdot (D - \sqrt{D^2 - d^2})}$$

Table 2-3 Approximate Equivalent Hardness Numbers and Ultimate Tensile Strengths for Steels

Brinell	Vickers	Rockwell		Ultimate, σ_u	
HB	HV	HRB	HRC	MPa	ksi
627	667	—	58.7	2393	347
578	615	—	56.0	2158	313
534	569	—	53.5	1986	288
495	528	—	51.0	1813	263
461	491	—	48.5	1669	242
429	455	—	45.7	1517	220
401	425	—	43.1	1393	202
375	396	—	40.4	1267	184
341	360	—	36.6	1131	164
311	328	—	33.1	1027	149
277	292	—	28.8	924	134
241	253	100	22.8	800	116
217	228	96.4	—	724	105
197	207	92.8	—	655	95
179	188	89.0	—	600	87
159	167	83.9	—	538	78
143	150	78.6	—	490	71
131	137	74.2	—	448	65
116	122	67.6	—	400	58

Note: Load 3000 kg for HB.

Source: Table 5-10, p.185, in N. E. Dowling, *Mechanical Behavior of Materials*, Prentice Hall, Englewood Cliffs, N.J., 1993, with permission.

S_{ut} estimation using Brinell hardness number:

$$S_{ut} \cong 500 H_B \pm 30 H_B , \quad \text{psi}$$

$$S_{ut} \cong 3.45 H_B \pm 0.2 H_B , \text{MPa}$$

Material properties

Heat treatment

- **Quenching:** transformation temperature (steels ≈ 700 °C); rapid cooling; formation of martensite
- **Tempering:** quenching; reheated (200 - 700 °C -- lower than transformation temperature); cool slowly
- **Annealing:** reverses quenching and tempering; slow cooling rate
- **Normalizing**: similar to annealing, but faster cooling rate

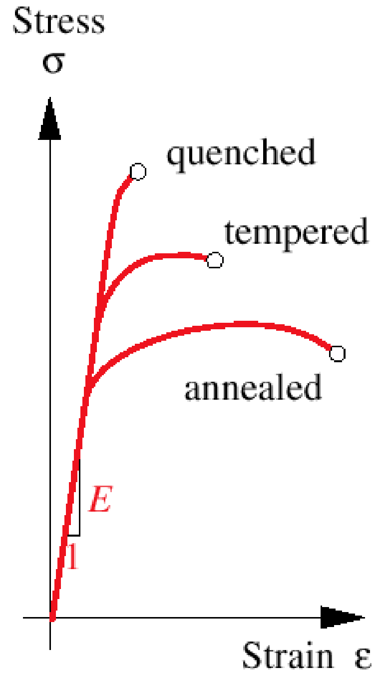


FIGURE 2-12

Stress-Strain Curves for Annealed, Quenched, and Tempered Steel

Material properties

Cold working

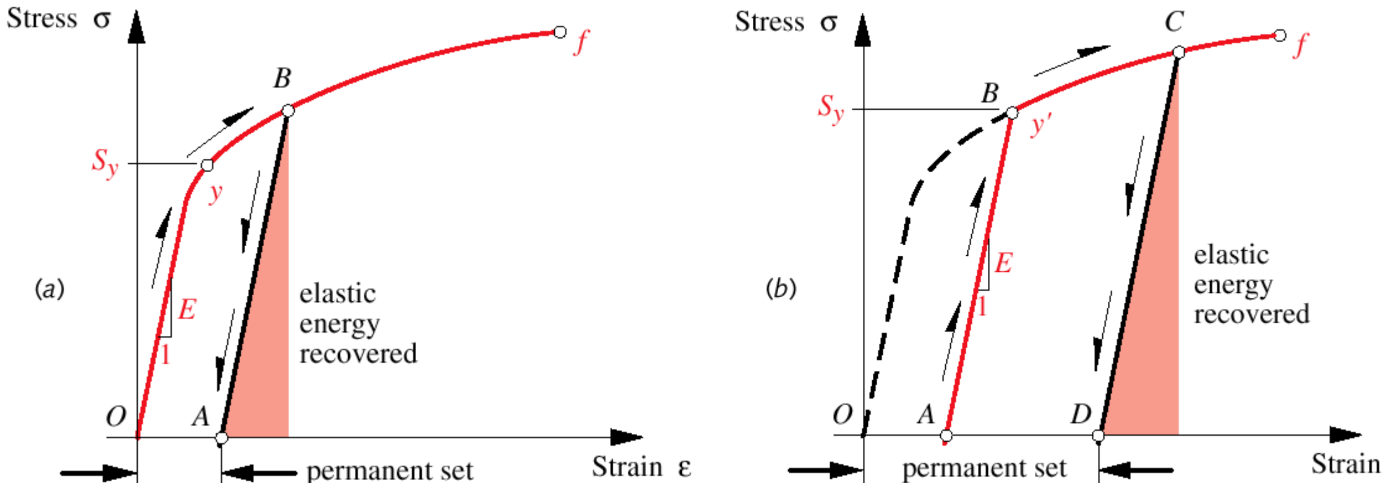


FIGURE 2-13

Strain Hardening a Ductile Material by Cold Working (*a*) First Working (*b*) Second Working

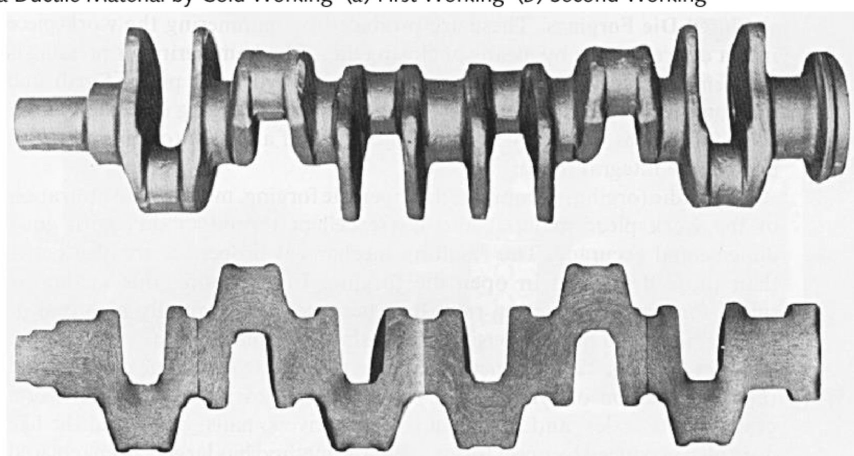


FIGURE 2-14

Forged Steel Crankshaft for a Diesel-Truck Engine - *Courtesy of Wyman-Gordon Corp, Grafton, MA*

Material properties

Coatings and surface treatments: surface protection (wear resistance, corrosion, etc.)

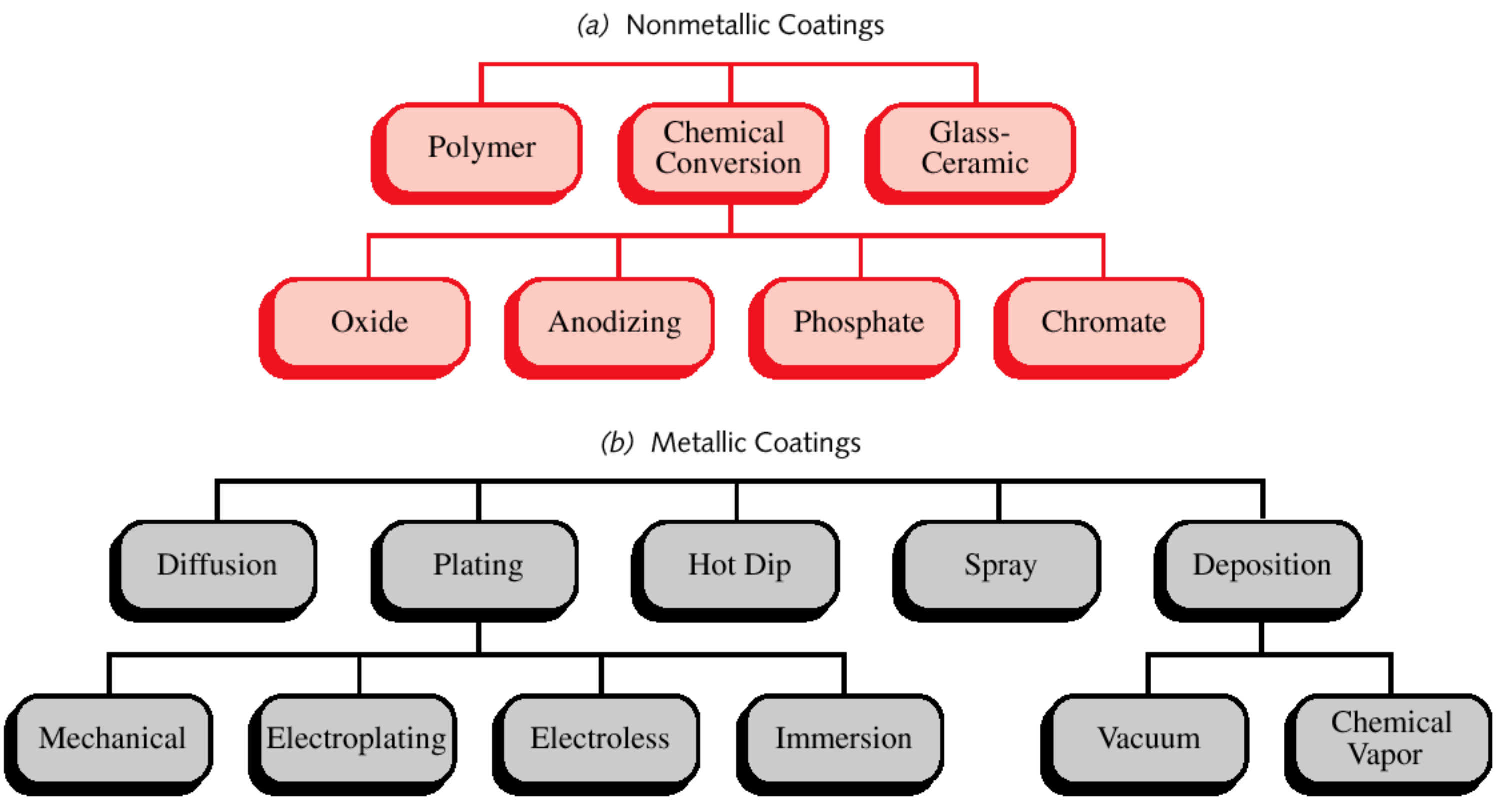


FIGURE 2-16

Coating Methods Available for Metals

Material properties

AISI/SAE designation of steel alloys

Table 2-5 AISI/SAE Designations of Steel Alloys
A partial list - other alloys are available - consult the manufacturers

(represent hundredths of a percent of carbon present)

Type	AISI/SAE Series	Principal Alloying Elements
Carbon Steels		
Plain	10xx	Carbon
Free-cutting	11xx	Carbon plus Sulphur (resulphurized)
Alloy Steels		
Manganese	13xx	1.75% Manganese
	15xx	1.00 to 1.65% Manganese
Nickel	23xx	3.50% Nickel
	25xx	5.00% Nickel
Nickel-Chrome	31xx	1.25% Nickel and 0.65 or 0.80% Chromium
	33xx	3.50% Nickel and 1.55% Chromium
Molybdenum	40xx	0.25% Molybdenum
	44xx	0.40 or 0.52% Molybdenum
Chrome-Moly	41xx	0.95% Chromium and 0.20% Molybdenum
Nickel-Chrome-Moly	43xx	1.82% Nickel, 0.50 or 0.80% Chromium, and 0.25% Molybdenum
	47xx	1.45% Nickel, 0.45% Chromium, and 0.20 or 0.35% Molybdenum
Nickel-Moly	46xx	0.82 or 1.82% Nickel and 0.25% Molybdenum
	48xx	3.50% Nickel and 0.25% Molybdenum
Chrome	50xx	0.27 to 0.65% Chromium
	51xx	0.80 to 1.05% Chromium
	52xx	1.45% Chromium
Chrome-Vanadium	61xx	0.60 to 0.95% Chromium and 0.10 to 0.15% Vanadium minimum

Material properties

General properties

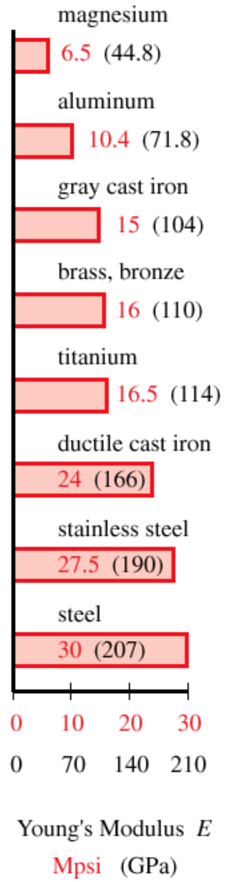


FIGURE 2-17
Young's Moduli for Various Metals

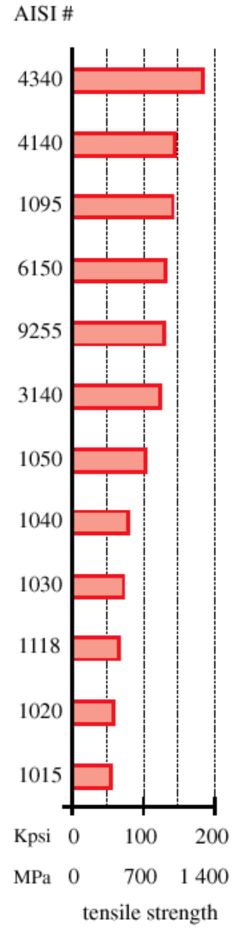


FIGURE 2-18
Approximate Ultimate Tensile Strengths of Some Normalized Steels

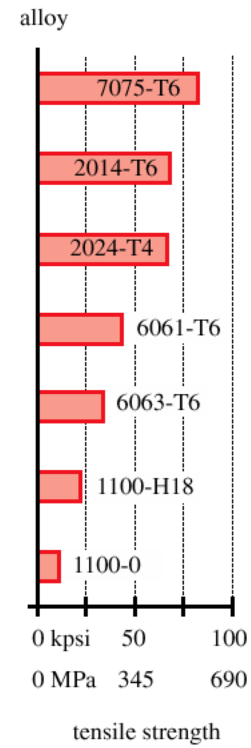


FIGURE 2-20
Ultimate Tensile Strengths of Some Aluminum Alloys

(AISI - American Iron & Steel Institute)

Reading assignment

- Chapter 2 of textbook
- Review notes and text: ES2001

Homework assignment

- Author's: Refer to website of our course
- Solve: Refer to website of our course