MT-124: Metallurgy and Materials

LECTURE NOTES

Chapter 3: Properties of Materials

INTRODUCTION

- Successful products begin with the appropriate materials
  - Materials rarely come in the right shape, size, and quantity for use
  - Parts and components are produced by subjecting engineering materials to one or more processes
- Manufacturing requires knowledge in several areas

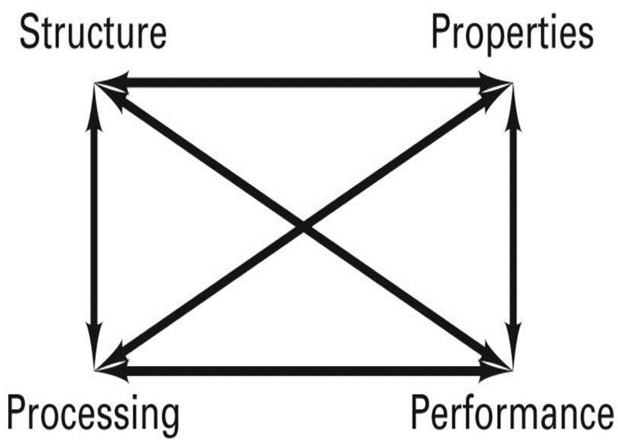


Figure 3-1: The manufacturing relationships among structure, properties, processing, and performance.

REQUIREMENTS FOR DESIGN

- Material requirements must be determined:
  - Strength
  - Rigidity
  - Resistance to fracture
  - Ability to withstand vibrations or impacts
  - Weight
  - Electrical properties
  - Appearance
  - Ability to operate under temperature extremes
  - Corrosion resistance

METALLIC AND NONMETALLIC MATERIALS

- Metallic materials
  - Iron, steel, copper, aluminum, magnesium, etc.
  - General properties
    - Luster, high thermal conductivity, high electrical conductivity, ductile
- Nonmetallic materials
  - Wood, brick, concrete, glass, rubber, plastic, etc.
  - General properties
    - Weaker, less ductile, less dense

METALLIC AND NONMETALLIC MATERIALS

- Metals have historically been the more important of the two groups
- Recently, advanced ceramics, composite materials, and engineered plastics have become increasingly important
- If both a metal and nonmetal are capable for a certain product, cost is often the deciding factor
- Other factors that are considered:
  - Product lifetime
  - Environmental impact
  - Energy requirements
  - Recyclability

PHYSICAL AND MECHANICAL PROPERTIES

- Physical properties:
  - Density, melting point, optical properties, thermal properties, electrical properties, magnetic properties
- Mechanical properties:
  - A property that dictates how a material responds to applied loads and forces
  - Determined through specified testing
  - It is important to take the testing methodology

STRESS AND STRAIN

- Strain is the distortion or deformation of a material from a force or a load
- Stress is the force or the load being transmitted through the material's cross sectional area
- Stress and strain can occur as tensile, compressive or shear

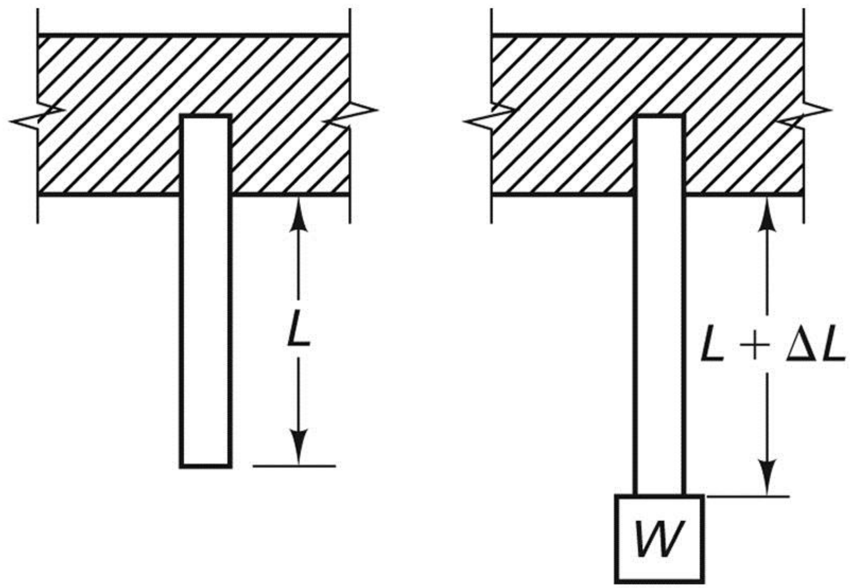
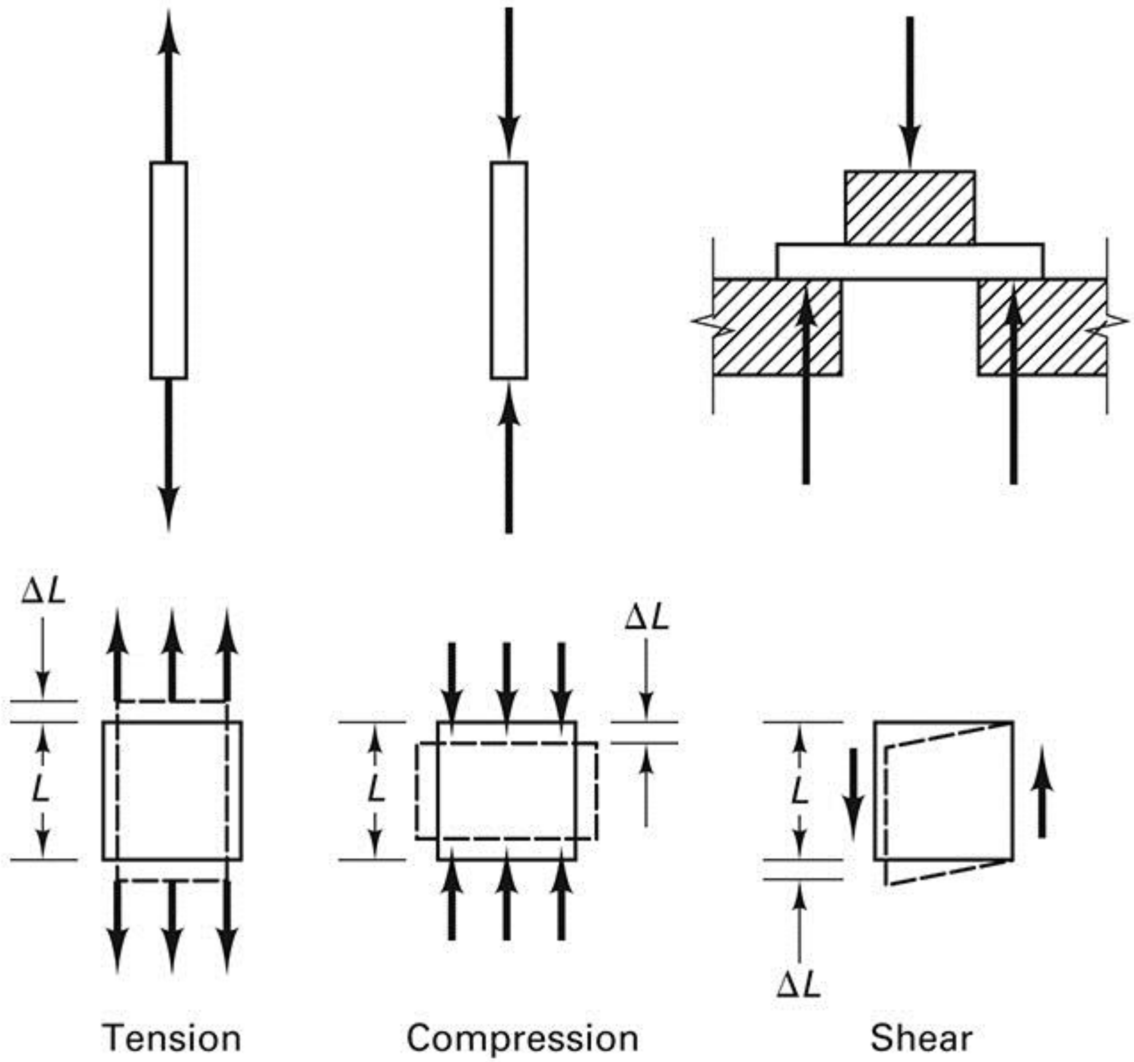


Figure 3-2: Tension loading and the resultant elongation.

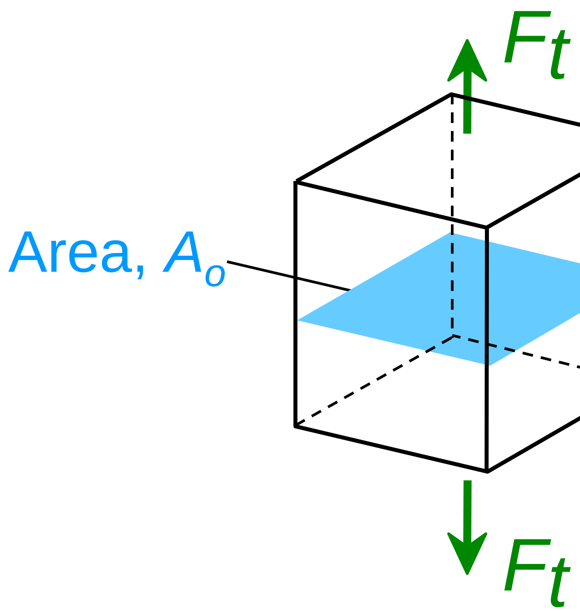
TENSION, COMPRESSION AND SHEAR LOADING

Figure 3-3: Examples of tension, compression, and shear loading, and their response.



TENSION, COMPRESSION AND SHEAR LOADING

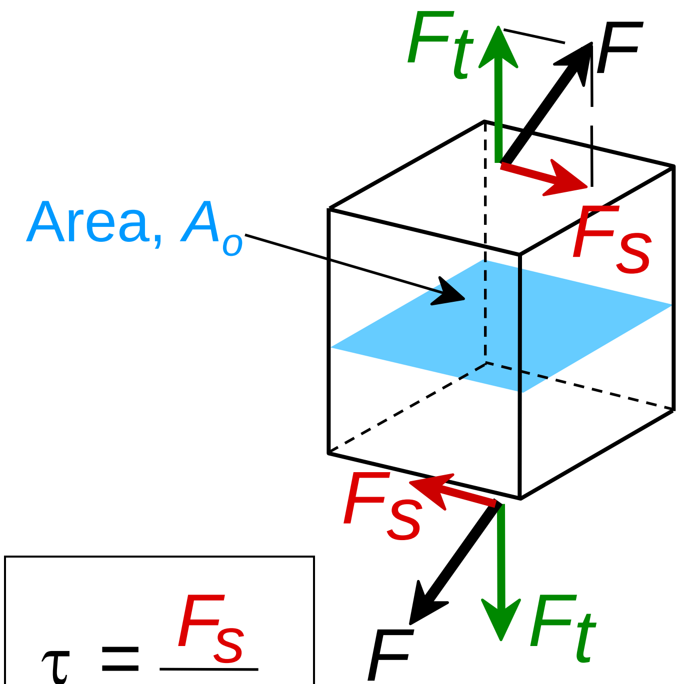
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{\mathrm{lb_f}}{\mathrm{in}^2} \text{ or } \frac{\mathrm{N}}{\mathrm{m}^2}$$

original area before loading

- Shear stress, τ:

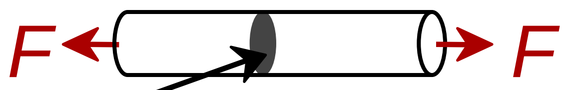


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units: N/m^2 or lb_f/in^2

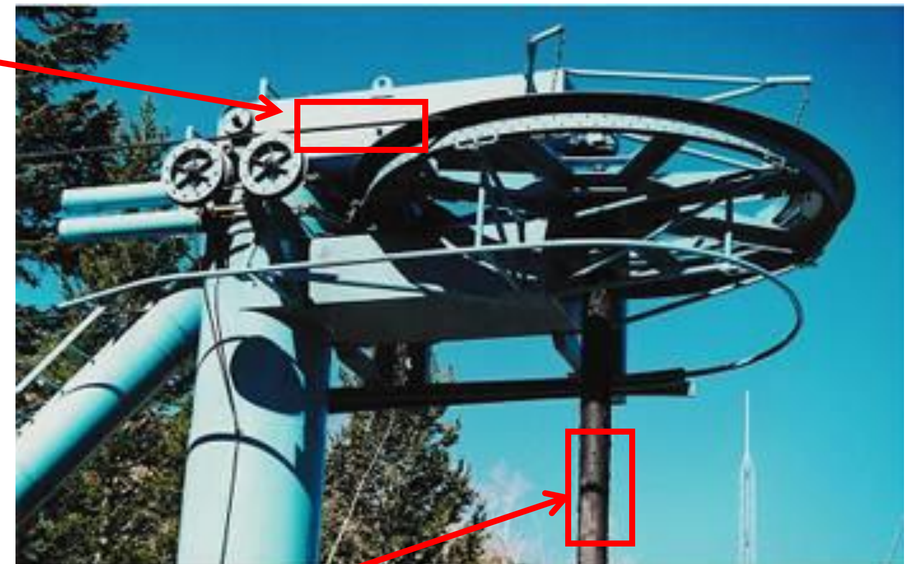
COMMON STATES OF STRESS

- **Simple tension: cable**



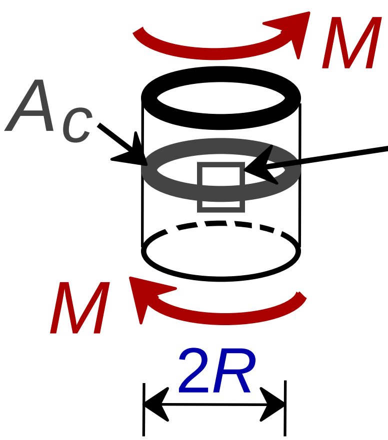
A_o = cross sectional area (when unloaded)

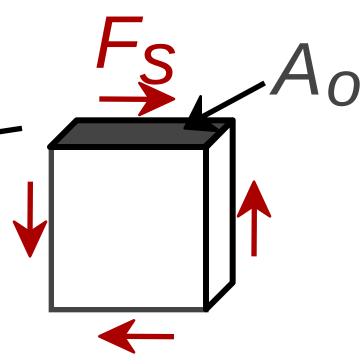
$$\sigma = \frac{F}{A_o}$$



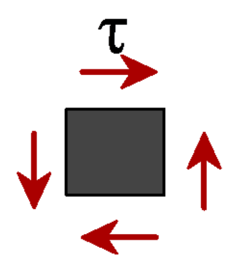
Ski lift (photo courtesy P.M. Anderson)

- **Torsion (a form of shear): drive shaft**





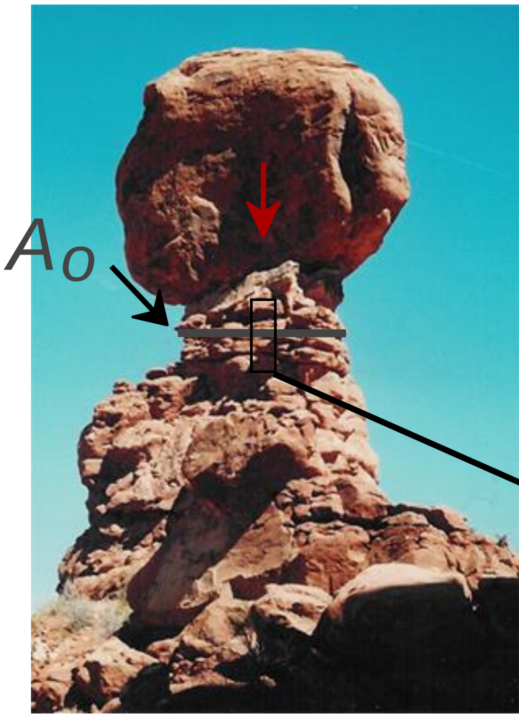
$$\tau = \frac{F_s}{A_o}$$



Note: $\tau = M/A_cR$ here.

COMMON STATES OF STRESS

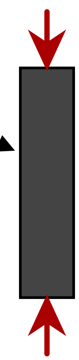
- **Simple compression:**



Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)

Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

$$\sigma = \frac{F}{A_o}$$



Note: compressive structure member ($\sigma < 0$ here).

STATIC PROPERTIES

- Constant force on a material is called a static force
- Strength of a material is important
  - Elastic stretching or deflection of a material is related to Young's Modulus
- A number of tests have been developed to determine these static properties of materials

STATIC TESTING

- Tensile test
  - Uniaxial test
  - Generates an engineering stress-strain curve
- Compression test
  - Difficult to test compression
  - Similar results to that of the tensile testing

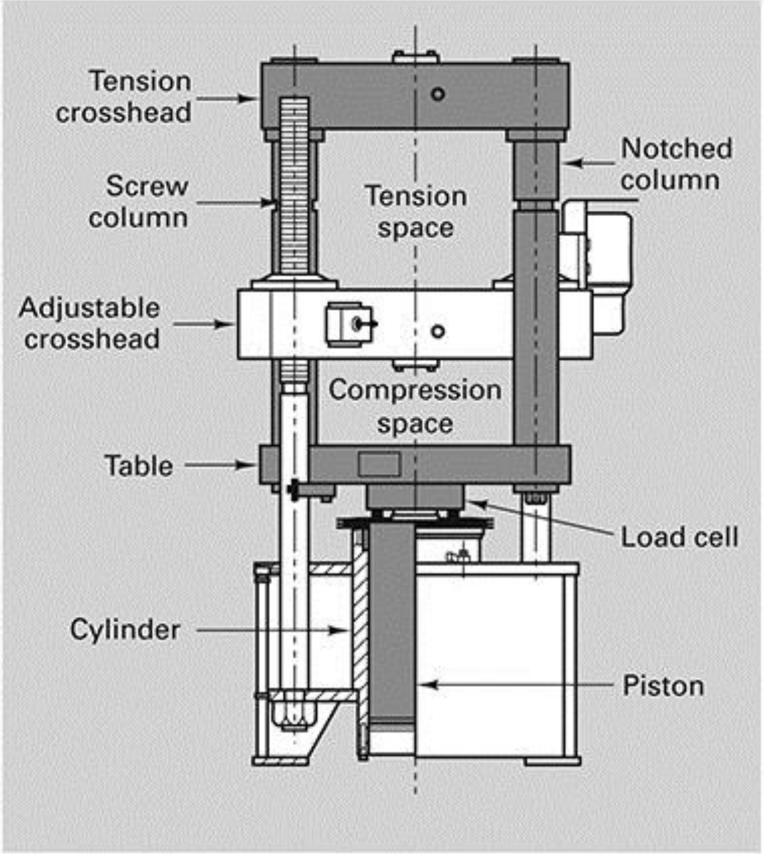
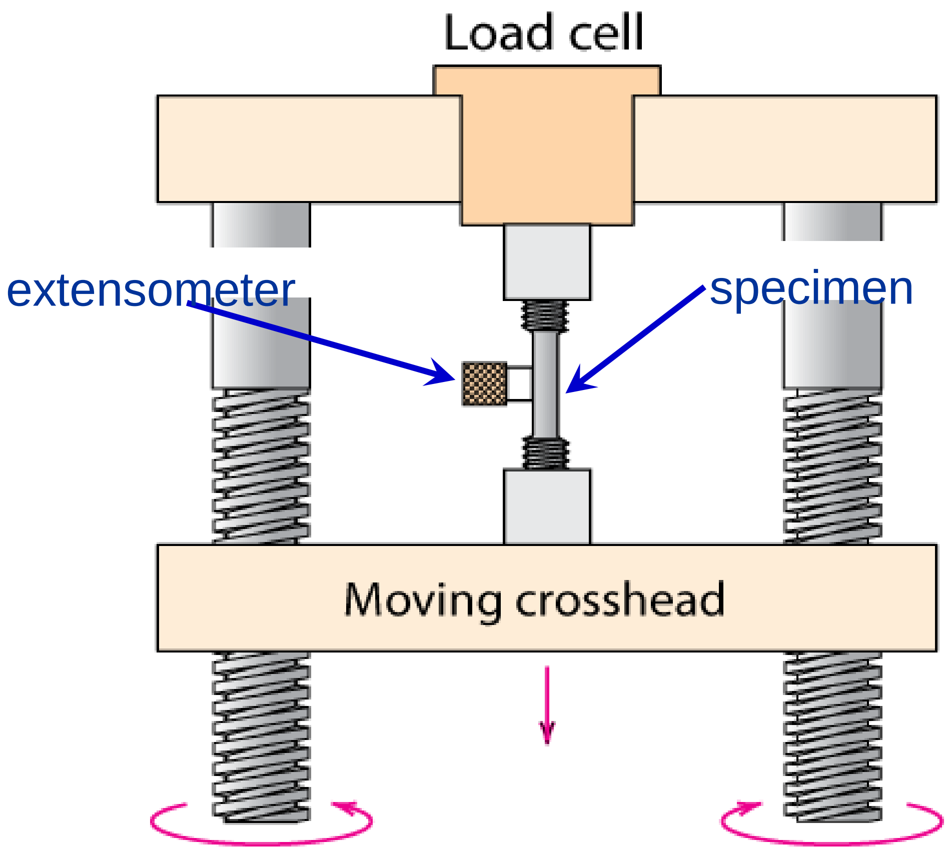


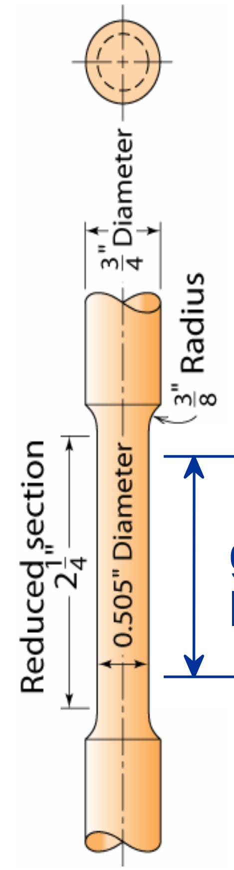
Figure 3-5b: Schematic of the load frame showing how upward motion of the darkened yoke can produce tension or compression with respect to the stationary (white) crosspiece. (Courtesy of Satec Systems, Inc., Grove City, PA.)

STRESS-STRAIN TESTING

- **Typical tensile test machine**



- **Typical tensile specimen**



Adapted from Fig. 6.2, *Callister & Rethwisch 8e.*

ENGINEERING STRESS-STRAIN CURVE

- Key features
  - Proportional limit (below this limit, the strain is directly proportional to stress)
  - Ratio of stress to strain is Young’s Modulus
    - Measures stiffness
    - Designated by E
  - Ultimate Strength
    - Stress at which the load-bearing ability peaks

ENGINEERING STRESS-STRAIN CURVE

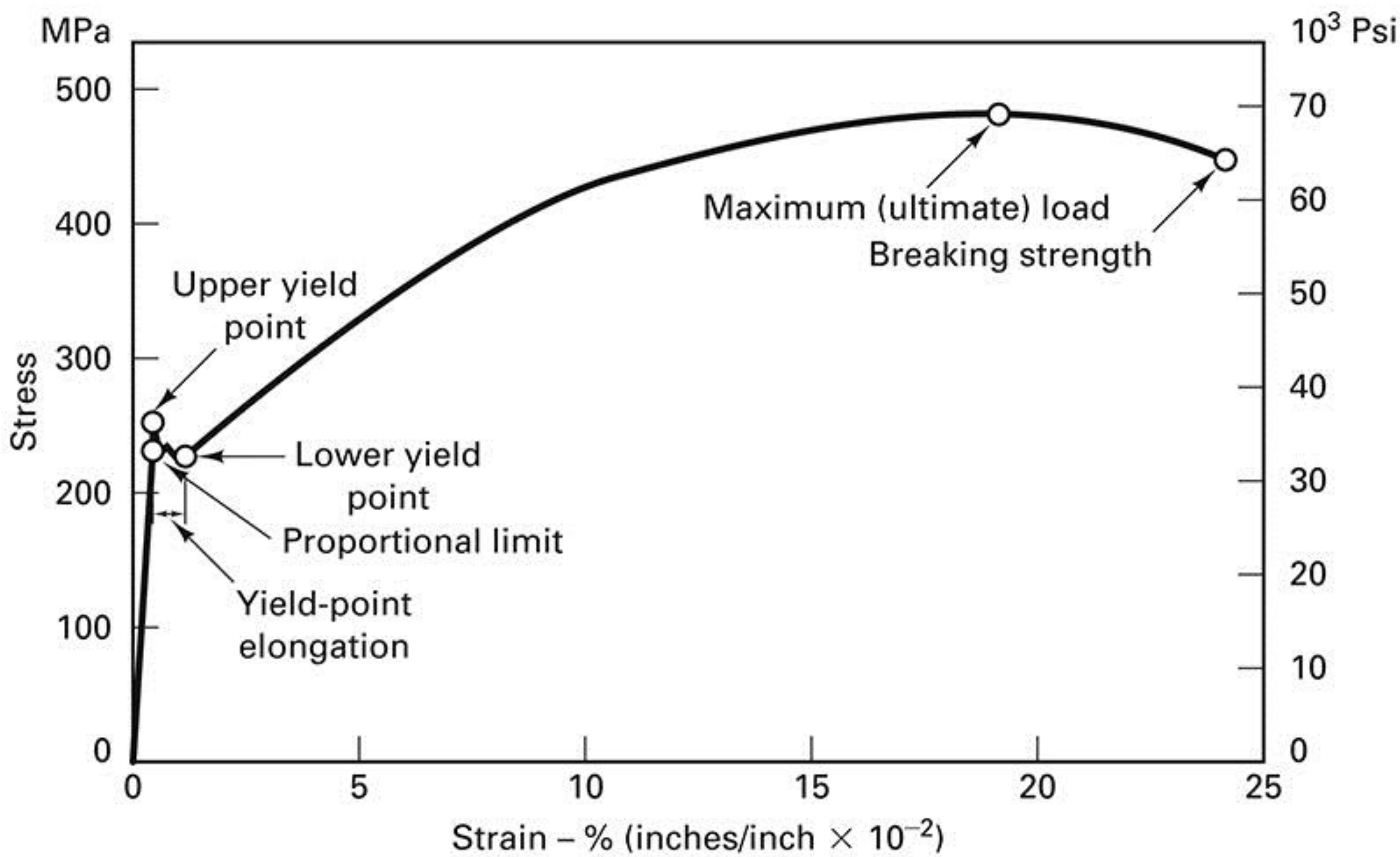


Figure 3-6: Engineering stress-strain diagram for a low-carbon steel.

ADDITIONAL PROPERTIES FROM THE STRESS-STRAIN CURVE

- Modulus of resilience- amount of energy per unit volume that a material can absorb
- Plastic deformation- permanent change in shape due to a load that exceeded the elastic limit
- Yield point- stress value where additional strain occurs without an increase in stress
- Offset yield strength- the stress required to produce an allowable amount of permanent strain

DUCTILITY AND BRITTLENESS

- Necking is a localized reduction in cross sectional area
- For ductile materials, necking occurs before fracture
- For brittle materials, fracture ends the stress strain curve before necking
- Percent elongation is the percent change of a material at fracture
- Material failure is the onset of localized deformation or necking

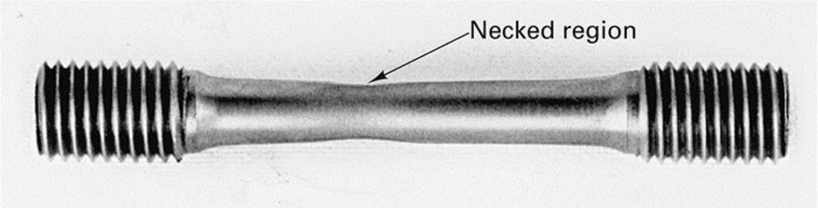


Figure 3-8: A standard 0.505-in diameter tensile specimen showing a necked region developed prior to failure.

Percent Reduction in Area:

$$R.A. = \frac{A_0 - A_f}{A_0} \times 100\%$$

TRUE STRESS-STRAIN CURVE

- Toughness- work per unit volume to fracture a material
  - Total area under the stress-strain curve
- True stress-strain curve
  - Instantaneous stress versus the summation of the incremental strain

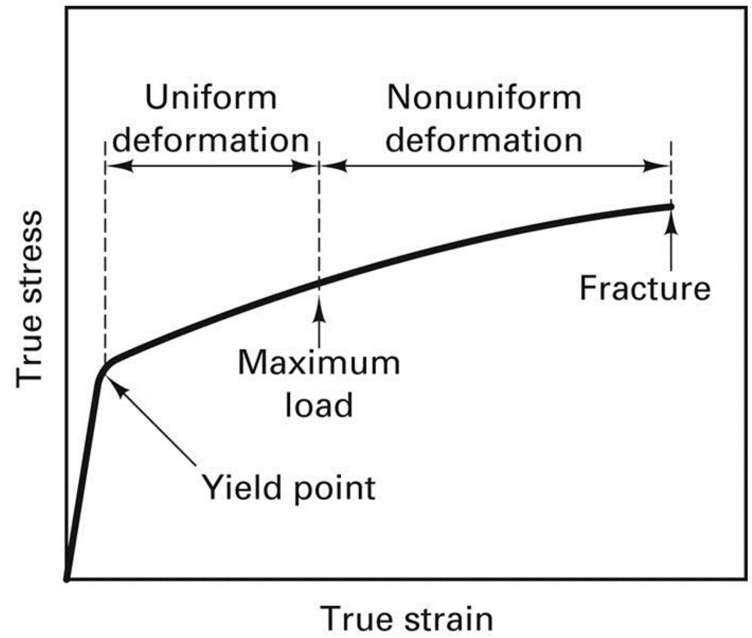


Figure 3-10: True stress-strain curve for an engineering metal.

STRAIN HARDENING

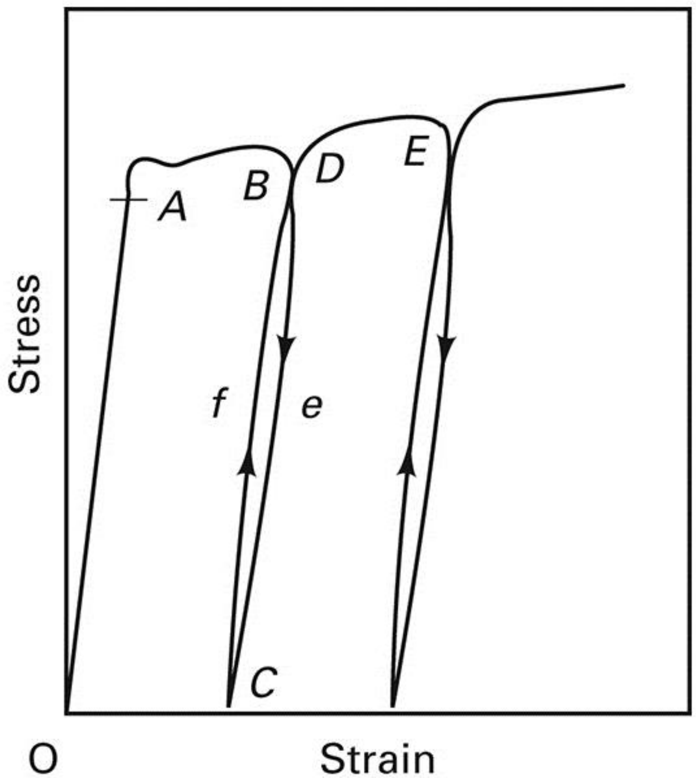


Figure 3-12: Stress-strain diagram obtained by unloading and reloading a specimen.

- Loading and unloading within the elastic region will result in cycling up and down the linear portion of the stress strain curve
- When metals are plastically deformed, they become harder and stronger (strain hardening)

HARDNESS TESTING

- Hardness is the resistance to permanent deformation in the form of penetration or indentation
  - Brinell Hardness Test
    - Measures the indentation of a steel ball
    - Yields a Brinell hardness number based on diameter of indentation
  - Rockwell Test
    - Small steel ball or diamond tip cone (called a brale) causes an indentation
    - Indentation is measured based on depth
  - Vickers Hardness Test
  - Knoop Hardness Test
  - Microhardness Test
- Hardness testing can provide a close approximation of tensile strength (~500 times the Brinell hardness number for psi)

HARDNESS TESTING

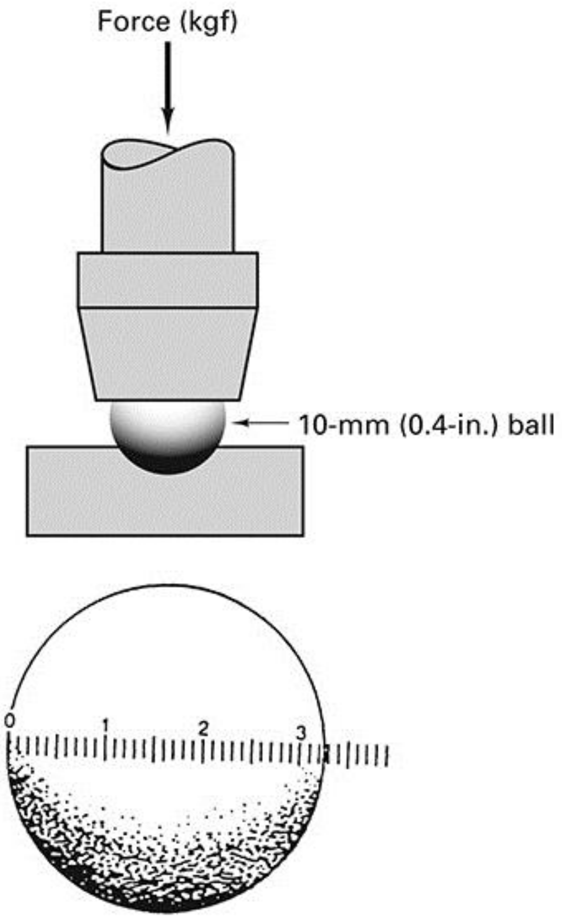


Figure 3-14b: Brinell test sequence showing loading and measurement of the indentation under magnification with a scale calibrated in millimeters.

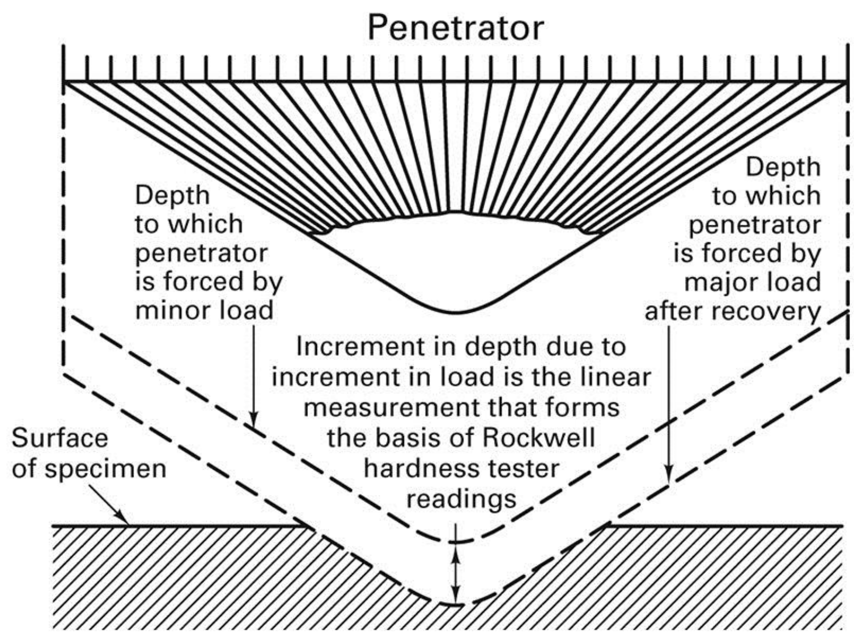
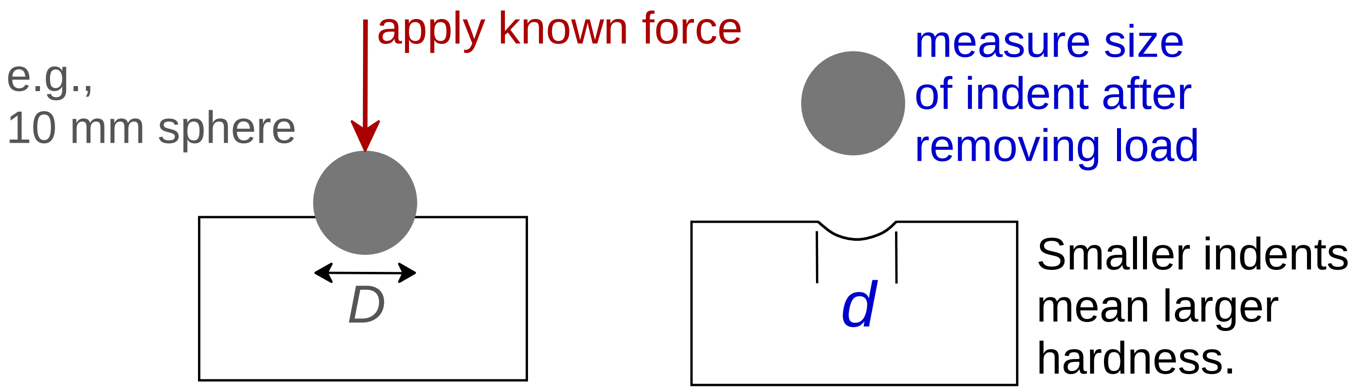
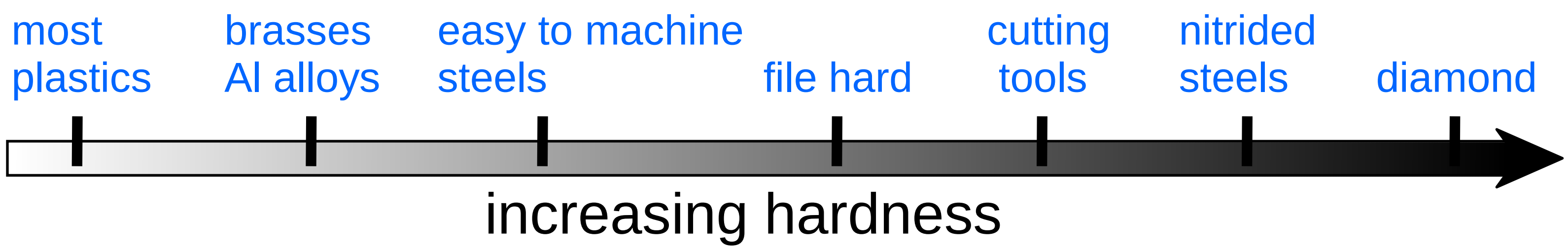


Figure 3-15a: Operating principle of the Rockwell hardness tester. (Courtesy of Wilson Instruments Division, Instron Corp., Norwood, MA.)

HARDNESS TESTING





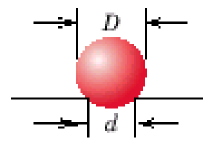
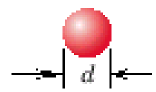
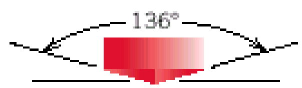
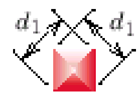
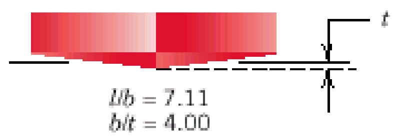
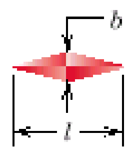
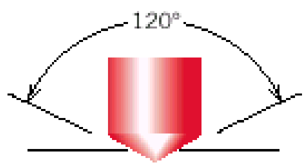
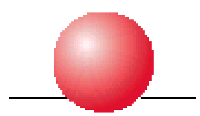
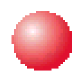
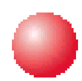
HARDNESS MEASUREMENT

- Rockwell
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Minor load 10 kg
  - Major load 60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond

- HB = Brinell Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

HARDNESS MEASUREMENT

Table 6.4 Hardness Testing Techniques

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg (Rockwell); 15 kg, 30 kg, 45 kg (Superficial Rockwell)	

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials,* Vol. III, *Mechanical Behavior.* Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

HARDNESS MEASUREMENT

TABLE 3-1 Some Common Rockwell Hardness Tests

Scale Symbol	Penetrator	Load (kg)	Typical Materials
A	Brale	60	Cemented carbides, thin steel, shallow case-hardened steel
B	$\frac{1}{16}$-in. ball	100	Copper alloys, soft steels, aluminum alloys, malleable iron
C	Brale	150	Steel, hard cast irons, titanium, deep case-hardened steel
D	Brale	100	Thin steel, medium case-hardened steel
E	$\frac{1}{8}$-in. ball	100	Cast iron, aluminum, magnesium
F	$\frac{1}{16}$-in. ball	60	Annealed coppers, thin soft sheet metals
G	$\frac{1}{16}$-in. ball	150	Hard copper alloys, malleable irons
H	$\frac{1}{8}$-in ball	60	Aluminum, zinc, lead

HARDNESS MEASUREMENT

TABLE 3-2 Hardness Conversion Table for Steels

Brinell Number	Vickers Number	Rockwell Number C	Rockwell Number B	Scleroscope Number	Tensile Strength ksi	Tensile Strength MPa
	940	68		97	368	2537
757[a]	860	66		92	352	2427
722[a]	800	64		88	337	2324
686[a]	745	62		84	324	2234
660[a]	700	60		81	311	2144
615[a]	655	58		78	298	2055
559[a]	595	55		73	276	1903
500	545	52		69	256	1765
475	510	50		67	247	1703
452	485	48		65	238	1641
431	459	46		62	212	1462
410	435	44		58	204	1407
390	412	42		56	196	1351
370	392	40		53	189	1303
350	370	38	110	51	176	1213
341	350	36	109	48	165	1138
321	327	34	108	45	155	1069
302	305	32	107	43	146	1007

(continued)

HARDNESS MEASUREMENT

Brinell Number	Vickers Number	Rockwell Number C	Rockwell Number B	Scleroscope Number	Tensile Strength ksi	Tensile Strength MPa
285	287	30	105	40	138	951
277	279	28	104	39	34	924
262	263	26	103	37	128	883
248	248	24	102	36	122	841
228	240	20	98	34	116	800
210	222	17	96	32	107	738
202	213	14	94	30	99	683
192	202	12	92	29	95	655
183	192	9	90	28	91	627
174	182	7	88	26	87	600
166	175	4	86	25	83	572
159	167	2	84	24	80	552
153	162		82	23	76	524
148	156		80	22	74	510
140	148		78	22	71	490
135	142		76	21	68	469
131	137		74	20	66	455
126	132		72	20	64	441
121	121		70		62	427
112	114		66		58	

[a] Tungsten, carbide ball; others, standard ball.

DYNAMIC PROPERTIES

- Bending impacts
  - Charpy and Izod tests
- Tension impacts
- Fatigue and endurance limit
  - Materials can fail if they are subjected to repeated applications of stress
  - Fatigue is cyclic repetition of a load
  - Stress versus number of cycles curves are useful in determining endurance limits
    - Endurance limit is the stress below which the material will not fail regardless of the number of cycles
    - Fatigue strength is the maximum stress that can be sustained for a number of loading cycles

FATIGUE FAILURES

- Fatigue resistance is sensitive to sharp corners, surface cracks, gouges, etc.
- Fatigue life can be affected by changes in the environment (corrosion)
- Residual stresses can negatively impact fatigue life
- Crack growth continues with each successive application of the load until failure

FATIGUE FAILURES

TABLE 3-3 Ratio of Endurance Limit to Tensile Strength for Various Materials

Material	Ratio
Aluminum	0.38
Beryllium copper (heat-treated)	0.29
Copper, hard	0.33
Magnesium	0.38
Steel	
AISI 1035	0.46
Screw stock	0.44
AISI 4140 normalized	0.54
Wrought iron	0.63

TEMPERATURE EFFECTS

- Temperatures effect the mechanical properties of materials
- Ductile-brittle transition temperature is the temperature at which the response of the material goes from high energy absorption to low energy absorption
- Creep is failure of a material due to long term exposure to elevated temperature

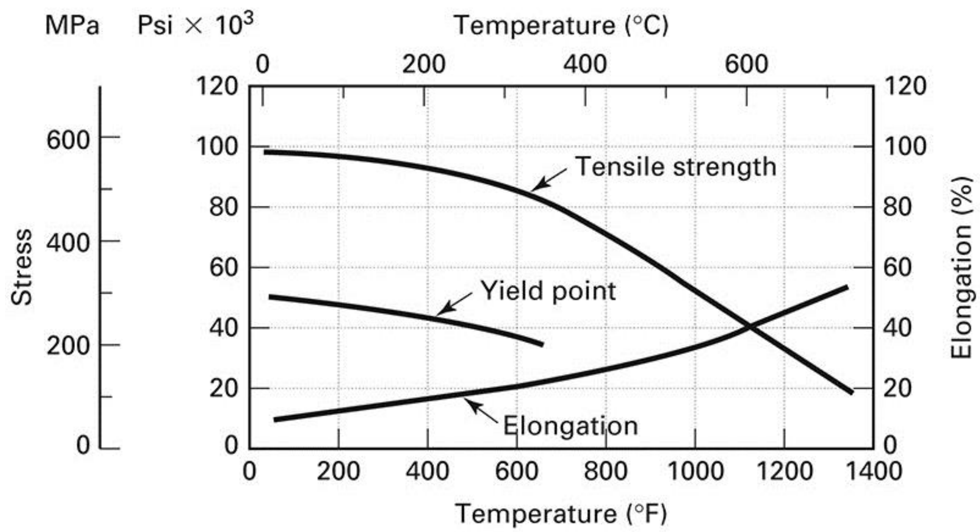


Figure 3-30: The effects of temperature on the tensile properties of a medium-carbon steel.

MACHINABILITY, FORMABILITY, AND WELDABILITY

- Machinability, formability, and weldability are the ways in which a material responds to a specific process
- Both the process and the machine dictate how the material will respond to manufacturing processes
- Each characteristic must be evaluated individually (i.e. there is no necessary relationship between machinability, formability, and weldability)

FRACTURE TOUGHNESS

- All materials contains flaws or defects
- Material defects:
  - Pores
  - Cracks
  - Inclusions
- Manufacturing or Design defects
  - Abrupt section changes
  - Excessively small fillets
  - Small holes

FRACTURE MECHANICS

- Identify the conditions under which defects will grow
  - Size of the largest or most critical flaw
  - Applied stress
  - Fracture toughness
- Dormant defects are those whose size remains unchanged through the lifetime of the part
- Dynamic defects change through the life of the part

PHYSICAL PROPERTIES

- Include thermal, electrical, magnetic, and optical characteristics
- Heat capacity is extremely important in casting because heat must be removed for solidification
- Thermal conductivity measures the rate at which heat can be transported through a material
- Thermal expansion is the measure of contraction or expansion of a material due to heating or cooling
  - Dimensions must be adjusted to compensate
- Electrical conductivity, electrical resistance, and magnetic response may be significant considerations for manufacturing
- Optical properties
  - Transmission, absorption, and reflection
- Density
- Melting and boiling point

TESTING STANDARDS AND CONCERN

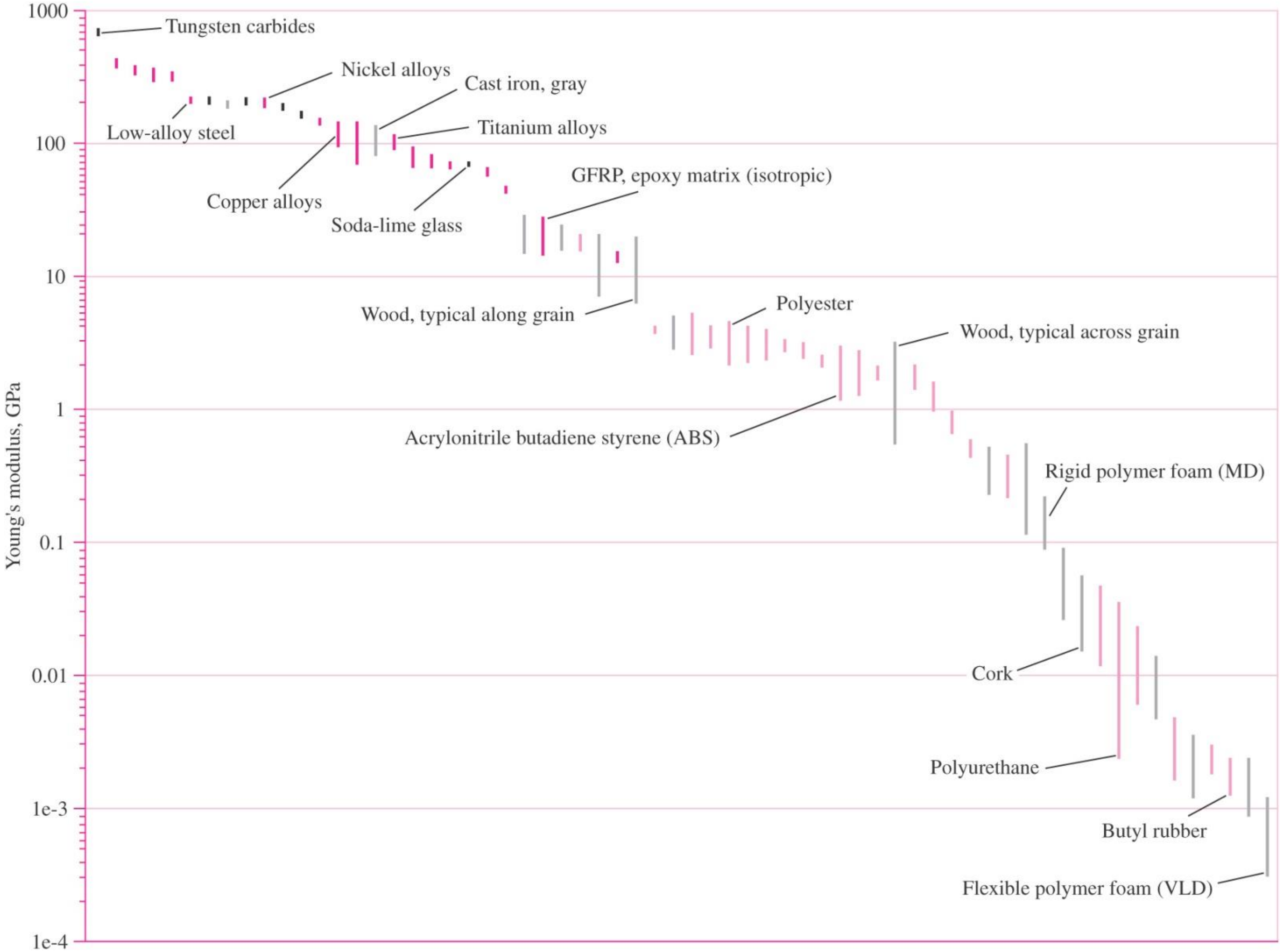
- American Society of Testing and Materials (ASTM) has standardized the testing methodologies for determining physical and mechanical properties
- Important that the tests are standardized and reproducible
- ASTM maintains and updates testing standards

CONSTANT PHYSICAL PROPERTIES OF MATERIALS

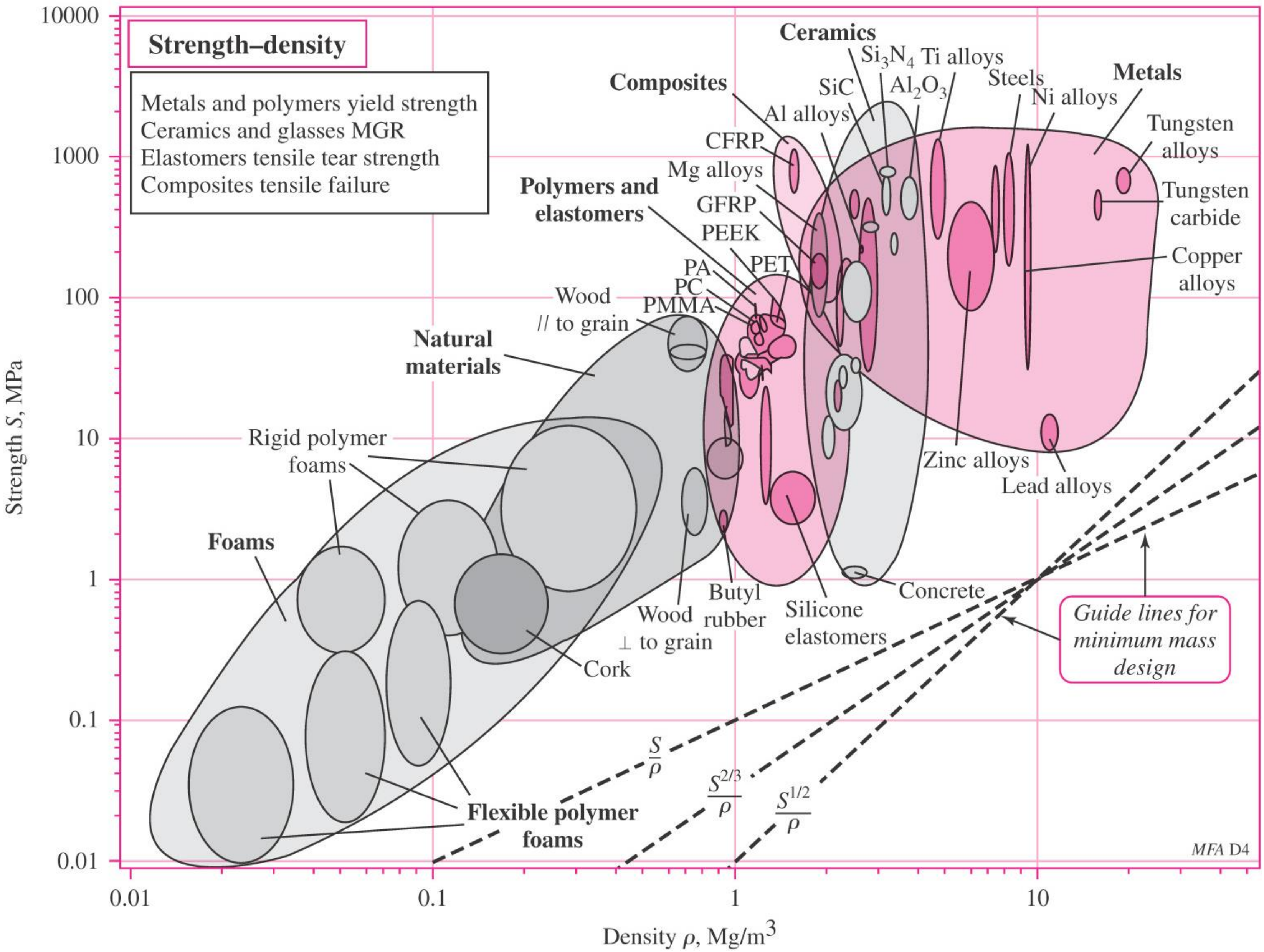
Physical Constants of Materials

Material	Modulus of Elasticity E, Mpsi	Modulus of Elasticity E, GPa	Modulus of Rigidity G, Mpsi	Modulus of Rigidity G, GPa	Poisson's Ratio ν	Unit Weight w, lbf/in^3	Unit Weight w, lbf/ft^3	Unit Weight w, kN/m^3
Aluminum (all alloys)	10.4	71.7	3.9	26.9	0.333	0.098	169	26.6
Beryllium copper	18.0	124.0	7.0	48.3	0.285	0.297	513	80.6
Brass	15.4	106.0	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30.0	207.0	11.5	79.3	0.292	0.282	487	76.5
Cast iron (gray)	14.5	100.0	6.0	41.4	0.211	0.260	450	70.6
Copper	17.2	119.0	6.49	44.7	0.326	0.322	556	87.3
Douglas fir	1.6	11.0	0.6	4.1	0.33	0.016	28	4.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Inconel	31.0	214.0	11.0	75.8	0.290	0.307	530	83.3
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.350	0.065	112	17.6
Molybdenum	48.0	331.0	17.0	117.0	0.307	0.368	636	100.0
Monel metal	26.0	179.0	9.5	65.5	0.320	0.319	551	86.6
Nickel silver	18.5	127.0	7.0	48.3	0.322	0.316	546	85.8
Nickel steel	30.0	207.0	11.5	79.3	0.291	0.280	484	76.0
Phosphor bronze	16.1	111.0	6.0	41.4	0.349	0.295	510	80.1
Stainless steel (18-8)	27.6	190.0	10.6	73.1	0.305	0.280	484	76.0
Titanium alloys	16.5	114.0	6.2	42.4	0.340	0.160	276	43.4

YOUNG'S MODULUS OF VARIOUS MATERIALS



STRENGTH VS. DENSITY



SUMMARY

- Material selection is extremely important to a successful product
  - Desired material properties must be determined
- Stress strain curve is a valuable engineering tool that demonstrates a material's behavior as loads are applied
- Variety of testing methodologies to determine material properties
  - Method in which they are tested is important to understand

CASE STUDY

Separation of Mixed Materials

Because of the amount of handling that occurs during material production, within warehouses, and during manufacturing operations, along with loading, shipping, and unloading, material mix-ups and mixed materials are not an uncommon occurrence. Mixed materials also occur when industrial scrap is collected, or when discarded products are used as new raw materials through recycling. Assume that you have equipment to perform each of the tests described in this chapter (as well as access to the full spectrum of household and department store items and even a small machine shop). For each of the following material combinations, determine one or more procedures that would permit separation of the mixed materials. Use standard data-source references to help identify distinguishable properties.

1. Steel and aluminum cans that have been submitted for recycling
2. Stainless steel sheets of Type 430 ferritic stainless and Type 316 austenitic stainless.
3. 6061-T6 aluminum and AZ91 magnesium that have become mixed in a batch of machine shop scrap.
4. Transparent bottles of polyethylene and polypropylene (both thermoplastic polymers) that have been collected for recycling.
5. Hot-rolled bars of AISI 1008 and 1040 steel.
6. Hot-rolled bars of AISI 1040 (plain-carbon) steel and 4140 steel (a molybdenum-containing alloy)
7. Mixed plastic consisting of recyclable thermoplastic polyvinylchloride (PVC) and nonrecyclable polyester—as might occur from automotive dashboards, consoles, and other interior components.