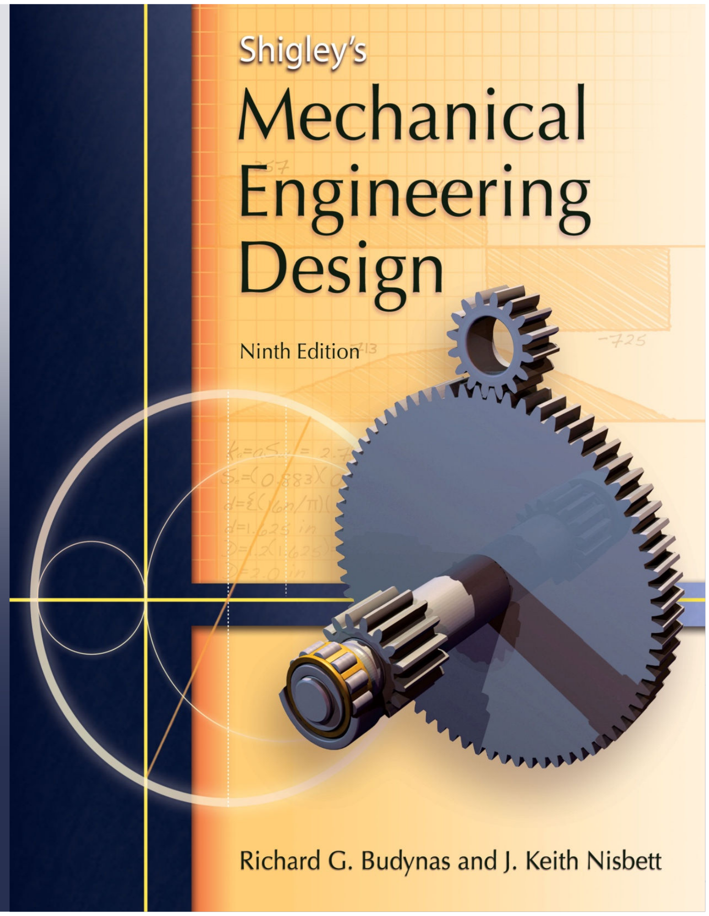
Lecture Slides

Chapter 2

Materials



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Standard Tensile Test

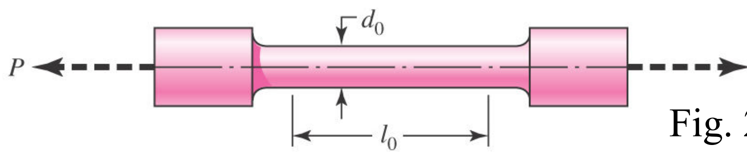


Fig. 2–1

Standard dimensions
for d_0: 2.5, 6.25 and 12.5 mm
for l_0: 10, 25 and 50 mm

- Used to obtain material characteristics and strengths
- Loaded in tension with slowly increasing *P*
- Load and deflection are recorded

Engineering Stress and Strain

The *stress* is calculated from

$$\sigma = \frac{P}{A_0} \qquad (2\text{–}1)$$

where $A_0 = \frac{1}{4}\pi d_0^2$ is the original cross-sectional area.

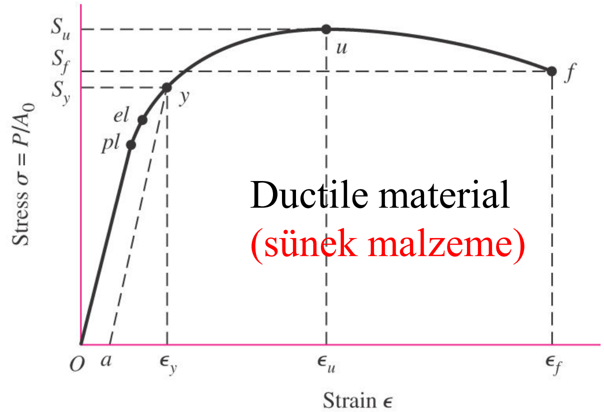
The *normal strain* is calculated from

$$\epsilon = \frac{l - l_0}{l_0} \qquad (2\text{–}2)$$

where l_0 is the original gauge length and l is the current length corresponding to the current *P*.

Engineering Stress-Strain Diagram

- Plot stress vs. normal strain
- Typically linear relation until the *proportional limit, pl*
- No permanent deformation until the *elastic limit, el*
- *Yield strength,* S_y , defined at point where significant plastic deformation begins, or where permanent set reaches a fixed amount, usually 0.2% of the original gauge length
- *Ultimate strength,* S_u , defined as the maximum stress on the diagram



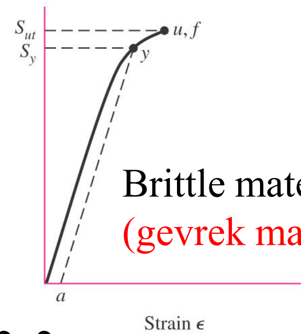


Fig. 2–2

Elastic Relationship of Stress and Strain

- Slope of linear section is *Young's Modulus*, or *modulus of elasticity*, *E*
- *Hooke's law*

$$\sigma = E\epsilon$$

- *E* is relatively constant for a given type of material (e.g. steel, copper, aluminum)
- See Table A-5 for typical values
- Usually independent of heat treatment, carbon content, or alloying

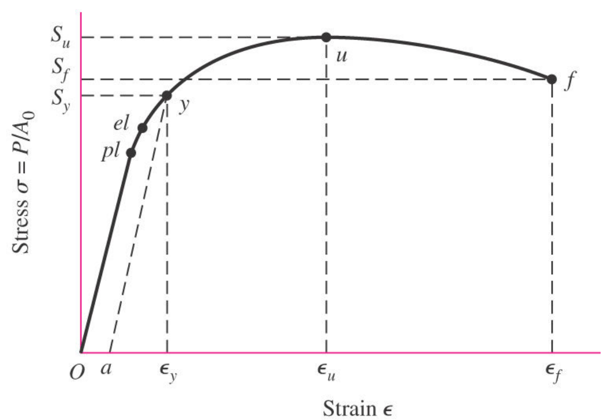
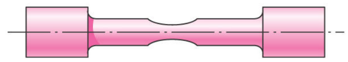
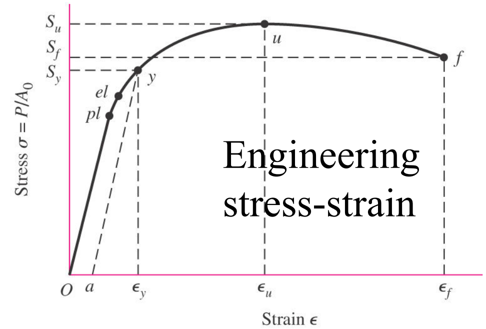


Fig. 2–2 (*a*)

True Stress-Strain Diagram

- *Engineering* stress-strain diagrams (commonly used) are based on original area.
- Area typically reduces under load, particularly during "necking" after point *u*.

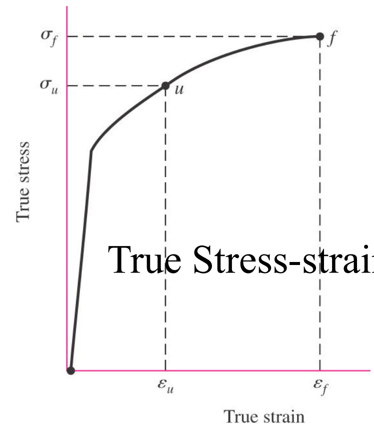




- *True stress* is based on actual area corresponding to current *P*.
- *True strain* is the sum of the incremental elongations divided by the *current* gauge length at load *P*.

$$\varepsilon = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} \qquad (2\text{-}4)$$

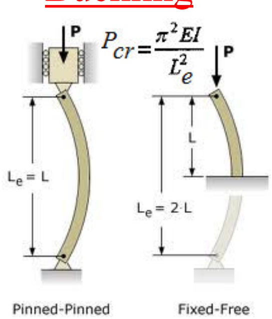
- Note that true stress continually increases all the way to fracture.



Compression Strength

- Compression tests are used to obtain compressive strengths.
- Buckling and bulging can be problematic.
- For ductile materials, compressive strengths are usually about the same as tensile strengths, $S_{uc} = S_{ut}$.
- For brittle materials, compressive strengths, S_{uc} , are often greater than tensile strengths, S_{ut} .

Buckling



Bulging

Torsional Strengths

- Torsional strengths are found by twisting solid circular bars.
- Results are plotted as a *torque-twist diagram*.
- Shear stresses in the specimen are linear with respect to the radial location – zero at the center and maximum at the outer radius.
- Maximum shear stress is related to the angle of twist by

$$\tau_{\max} = \frac{Gr}{l_0}\theta \qquad (2\text{–}5)$$

  - θ is the angle of twist (in radians)
  - r is the radius of the bar
  - l_0 is the gauge length
  - G is the material stiffness property called the *shear modulus* or *modulus of rigidity*.

Torsional Strengths

- Maximum shear stress is related to the applied torque by

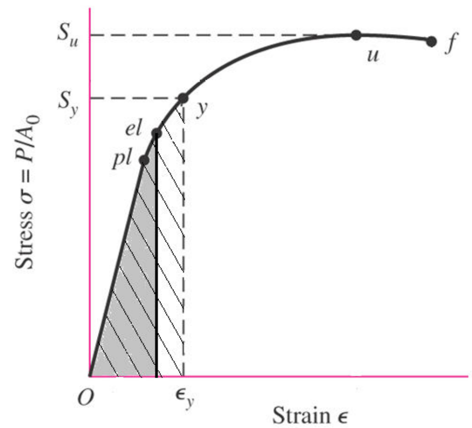
$$\tau_{\max} = \frac{Tr}{J} \qquad (2\text{–}6)$$

  - J is the polar second moment of area of the cross section
  - For round cross section, $J = \frac{1}{2}\pi r^4$
- *Torsional yield strength,* S_{sy} corresponds to the maximum shear stress at the point where the torque-twist diagram becomes significantly non-linear
- *Modulus of rupture*, S_{su} corresponds to the torque T_u at the maximum point on the torque-twist diagram

$$S_{su} = \frac{T_u r}{J} \qquad (2\text{–}7)$$

Resilience

- *Resilience* – Capacity of a material to absorb energy within its elastic range
- *Modulus of resilience, u_R*
  - Energy absorbed per unit volume without permanent deformation
  - Equals the area under the stress-strain curve up to the elastic limit
  - Elastic limit often approximated by yield point



Resilience

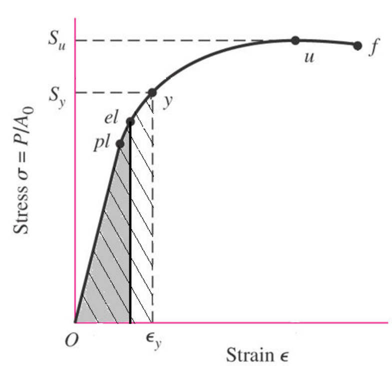
- Area under curve to yield point gives approximation

$$u_R \cong \int_0^{\epsilon_y} \sigma \, d\epsilon \qquad (2\text{–}8)$$

- If elastic region is linear,

$$u_R \cong \frac{1}{2} S_y \epsilon_y = \frac{1}{2}(S_y)(S_y/E) = \frac{S_y^2}{2E} \qquad (2\text{–}9)$$

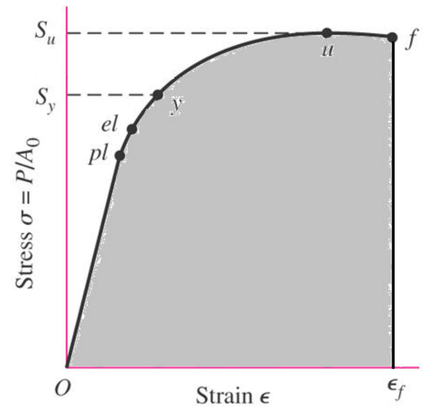
- For two materials with the same yield strength, the less stiff material (lower E) has greater resilience



Toughness

- *Toughness* – capacity of a material to absorb energy without fracture

- *Modulus of toughness, u_T*
  - Energy absorbed per unit volume without fracture
  - Equals area under the stress-strain curve up to the fracture point



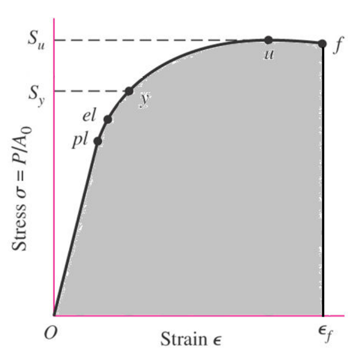
Toughness

- Area under curve up to fracture point

$$u_T = \int_0^{\epsilon_f} \sigma \, d\epsilon \qquad (2\text{–}10)$$

- Often estimated graphically from stress-strain data
- Approximated by using the average of yield and ultimate strengths and the strain at fracture

$$u_T \cong \left(\frac{S_y + S_{ut}}{2}\right)\epsilon_f \qquad (2\text{–}11)$$



Resilience and Toughness

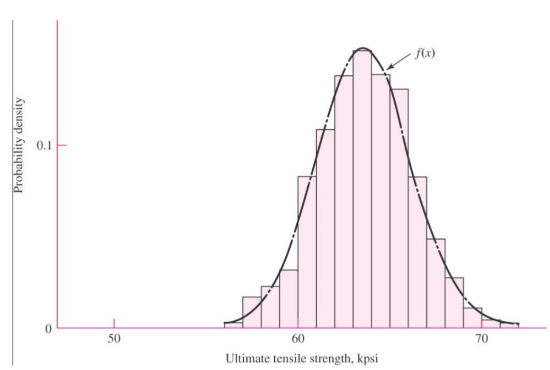
- Measures of energy absorbing characteristics of a material
- Units are energy per unit volume
  - lbf·in/in^3 or J/m^3
- Assumes low strain rates
- For higher strain rates, use impact methods (See Sec. 2-5)

Statistical Significance of Material Properties

- Strength values are obtained from testing many nominally identical specimens.
- Strength is distributional and thus statistical in natüre.
- Example – Histographic report for maximum stress of 1000 tensile tests on 1020 steel

Class Frequency f_i	2	18	23	31	83	109	138	151	139	130	82	49	28	11	4	2
Class Midpoint x_i, kpsi	56.5	57.5	58.5	59.5	60.5	61.5	62.5	63.5	64.5	65.5	66.5	67.5	68.5	69.5	70.5	71.5

- *Probability density* –
  number of occurrences divided by
  the total sample number



Strengths from Tables

- Property tables often only report a single value.
- Important to check if it is mean, minimum, or some percentile.
- Common to use 99% minimum strength, indicating 99% of the samples exceed the reported value.
- Confidence bounds are also placed.
- A-basis value is the value exceeded by 99% of the population with 95% confidence.
- B-basis value is the value exceeded by 90% of the population with 95% confidence.

$$Basis = \bar{X} - k\,s$$

$$k = \frac{z_{1-p} + \sqrt{z_{1-p}^2 - ab}}{a}, \quad a = 1 - \frac{z_{1-\gamma}^2}{2(N-1)}, \quad b = z_{1-p}^2 - \frac{z_{1-\gamma}^2}{N}$$

Cold Work (*Soğuk İşleme*)

- *Cold work* – Process of plastic straining below recrystallization temperature in the plastic region of the stress-strain diagram
- Loading to point i beyond the yield point, then unloading, causes permanent plastic deformation, ϵ_p
- Reloading to point i behaves elastically all the way to i, with additional elastic strain ϵ_e

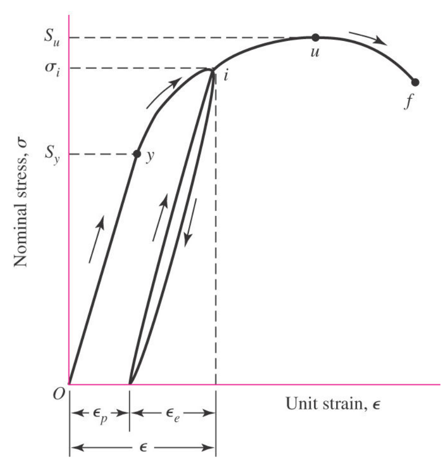


Fig. 2–6 (*a*)

$$\epsilon_e = \frac{\sigma_i}{E} \qquad \epsilon = \epsilon_p + \epsilon_e$$

Cold Work - continued

- The yield point is effectively increased to point *i*
- Material is said to have been *cold worked*, or *strain hardened*
- Material is less ductile (more brittle) since the plastic zone between yield strength and ultimate strength is reduced
- Repeated strain hardening can lead to brittle failure

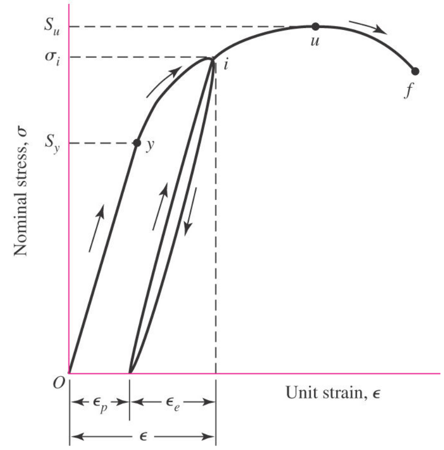


Fig. 2–6 (*a*)

Reduction in Area

- Plot load *P* vs. Area Reduction
- *Reduction in area* corresponding to load P_f at fracture is

$$R = \frac{A_0 - A_f}{A_0} = 1 - \frac{A_f}{A_0} \qquad (2\text{-}12)$$

- *R* is a measure of *ductility*
- Ductility represents the ability of a material to absorb overloads and to be cold-worked

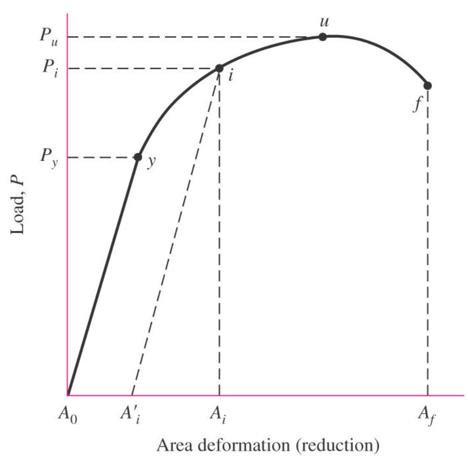


Fig. 2–6 (*b*)

Cold-work Factor

- *Cold-work factor W* – A measure of the quantity of cold work

$$W = \frac{A_0 - A_i'}{A_0} \approx \frac{A_0 - A_i}{A_0} \qquad (2\text{–}13)$$

$$A_i' = A_0(1 - W) \qquad (2\text{–}14)$$

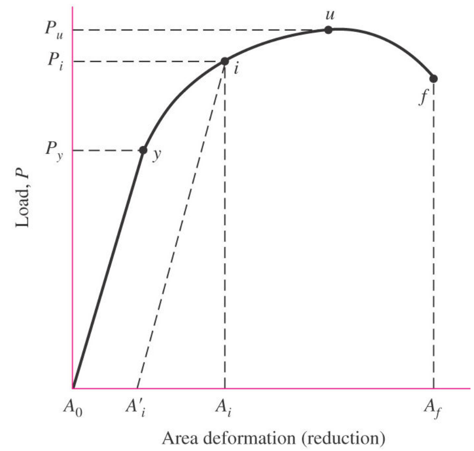


Fig. 2–6 (*b*)

Equations for Cold-worked Strengths

$$\sigma = \sigma_0 \varepsilon^m \qquad (2\text{–}15)$$

$$m = \varepsilon_u \qquad (2\text{–}16)$$

$$\varepsilon = \ln \frac{l}{l_0} = \ln \frac{A_0}{A} \qquad (2\text{–}17)$$

$$S_y' = \frac{P_i}{A_i'} = \sigma_0 \varepsilon_i^m \qquad P_i \le P_u \qquad (2\text{–}18)$$

$$S_u' = \frac{S_u A_0}{A_0(1 - W)} = \frac{S_u}{1 - W} \qquad \varepsilon_i \le \varepsilon_u \qquad (2\text{–}19)$$

$$S_u' \doteq S_y' \doteq \sigma_0 \varepsilon_i^m \qquad \varepsilon_i > \varepsilon_u \qquad (2\text{–}20)$$

Example 2-1

An annealed AISI 1018 steel (see Table A-22) has S_y = 220 MPa, S_u = 341 MPa, σ_f = 628 MPa, σ_0 = 620 MPa, m = 0.25, and ε_f = 1.05 mm/mm.
Find the new values of the strengths if the material is given 15% cold work.

Solution

Example 2-1 (continued)

Hardness

- *Hardness* – The resistance of a material to penetration by a pointed tool

- Two most common hardness-measuring systems
  - Rockwell
  - Brinell

- For many materials, relationship between ultimate strength and Brinell hardness number is roughly linear

- For steels

$$S_u = \begin{cases} 0.5H_B & \text{kpsi} \\ 3.4H_B & \text{MPa} \end{cases}$$

For cast iron

$$S_u = \begin{cases} 0.23H_B - 12.5 \text{ kpsi} \\ 1.58H_B - 86 \text{ MPa} \end{cases}$$

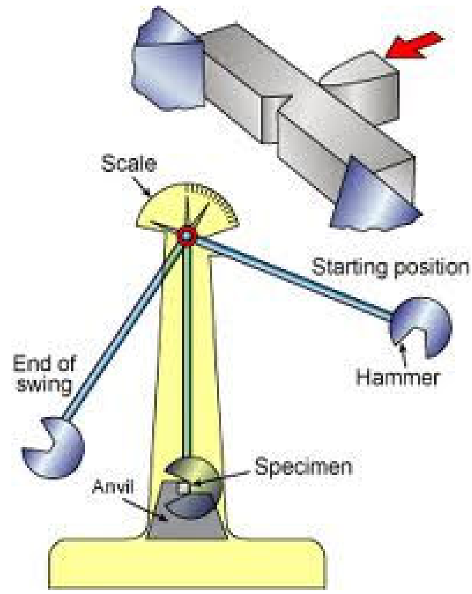
Example 2-2

It is necessary to ensure that a certain part supplied by a foundry always meets or exceeds ASTM No. 20 specifications for cast iron (see Table A–24). What hardness should be specified?

Solution

Impact Properties

- Charpy notched-bar test is used to determine brittleness and impact strength
- Specimen struck by pendulum
- Energy absorbed, called *impact value*, is computed from height of swing after fracture



Effect of Strain Rate on Strengths

- Average strain rate for stress-strain diagram is 0.001 in/(in·s)
- Increasing strain rate increases strengths

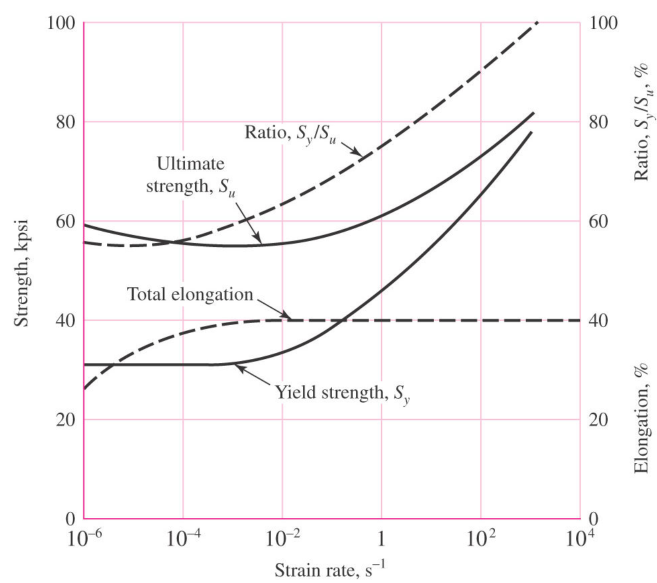


Fig. 2–8

Temperature Effects on Strengths

- Plot of strength vs. temperature for carbon and alloy steels
- As temperature increases above room temperature
  - S_{ut} increase slightly, then decreases significantly
  - S_y decreases continuously
  - Results in increased ductility

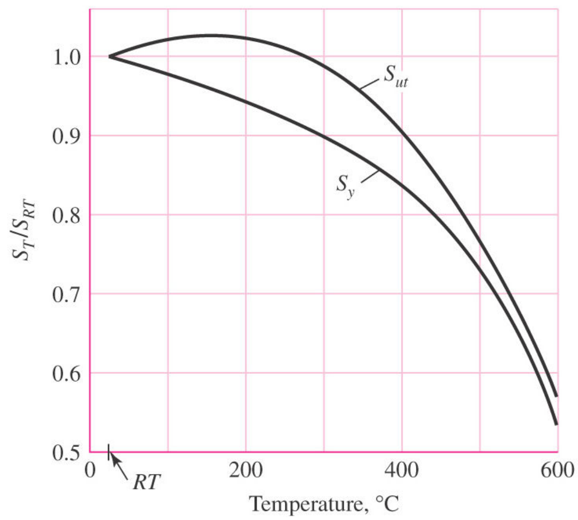


Fig. 2–9

Creep

- *Creep* – a continuous deformation under load for long periods of time at elevated temperatures
- Often exhibits three stages
  - 1^{st} stage: elastic and plastic deformation; decreasing creep rate due to strain hardening
  - 2^{nd} stage: constant minimum creep rate caused by the annealing effect
  - 3^{rd} stage: considerable reduction in area; increased true stress; higher creep rate leading to fracture

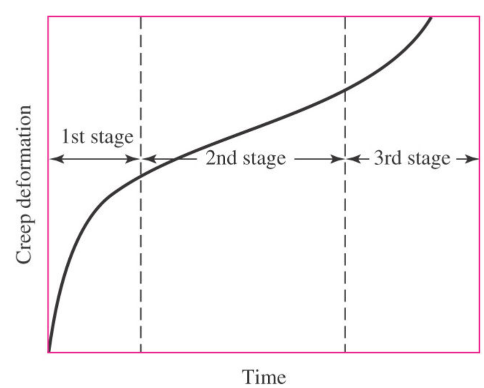


Fig. 2–10

Alloy Steels

- Chromium
- Nickel
- Manganese
- Silicon
- Molybdenum
- Vanadium
- Tungsten

Nonferrous Metals

- Aluminum
- Magnesium
- Titanium
- Copper-based alloys
  - Brass with 5 to 15 percent zinc
    - Gilding brass, commercial bronze, red brass
  - Brass with 20 to 36 percent zinc
    - Low brass, cartridge brass, yellow brass
    - Low-leaded brass, high-leaded brass (engraver's brass), free-cutting brass
    - Admiralty metal
    - Aluminum brass
  - Brass with 36 to 40 percent zinc
    - Muntz metal, naval brass
  - Bronze
    - Silcon bronze, phosphor bronze, aluminum bronze, beryllium bronze

Composite Materials

- Formed from two or more dissimilar materials, each of which contributes to the final properties
- Materials remain distinct from each other at the macroscopic level
- Usually amorphous and non-isotropic
- Often consists of *laminates* of *filler* to provide stiffness and strength and a *matrix* to hold the material together
- Common filler types:

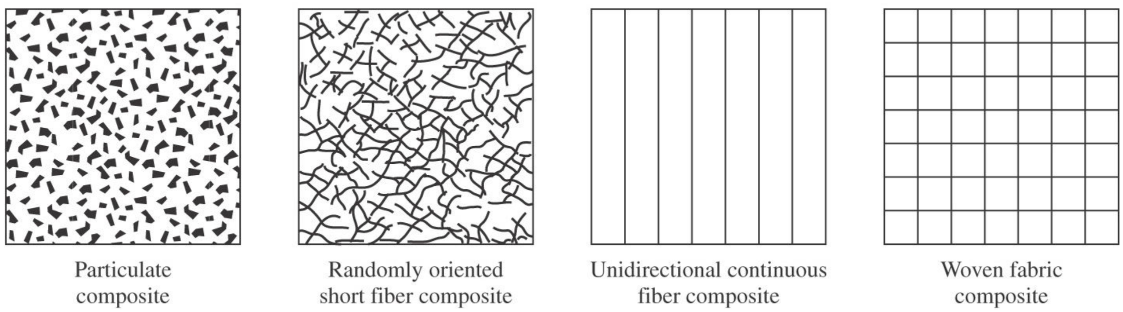


Fig. 2–14

The Performance Metric

The *performance metric* depends on (1) the functional requirements, (2) the geometry, and (3) the material properties.

$$P = \left[\begin{pmatrix}\text{functional}\\ \text{requirements } F\end{pmatrix}, \begin{pmatrix}\text{geometric}\\ \text{parameters } G\end{pmatrix}, \begin{pmatrix}\text{material}\\ \text{properties } M\end{pmatrix}\right]$$

$$P = f(F, G, M)$$

The function is often separable,

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M)$$

$f_3(M)$ is called the *material efficiency coefficient.*

Maximizing or minimizing $f_3(M)$ allows the material choice to be used to optimize P.

Performance Metric – Example #1

- Requirements: light, stiff, **end-loaded cantilever beam** with circular cross section
- Mass m of the beam is chosen as the performance metric to minimize
- Stiffness is functional requirement $k = \frac{F}{\delta}$

Example #1 (continued)

Performance Metric – Example #1

- *M* is called *material index*
- Use guidelines parallel to $E^{1/2}/\rho$
- Increasing *M*, move up and to the left
- Good candidates for this example are certain woods, composites, and ceramics

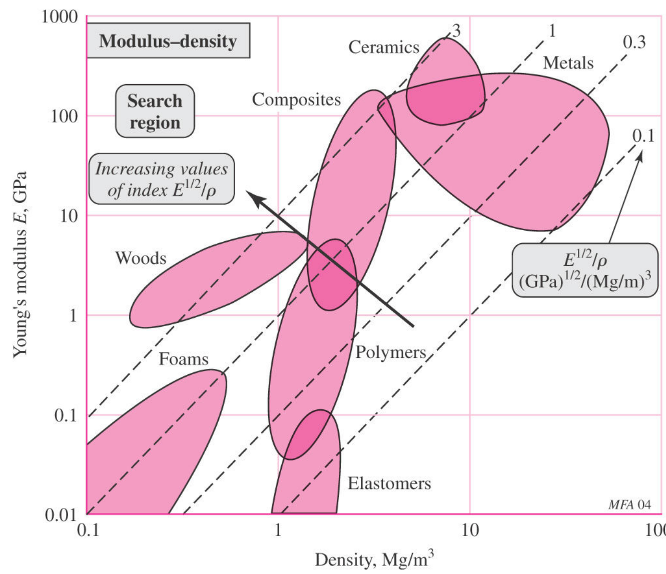


Fig. 2–17

Performance Metric – Example #2

- Requirements: light, stiff, **axially-loaded connecting rod** with circular cross section
- Mass *m* is chosen as the performance metric to minimize
- Stiffness is the functional requirement $k = \dfrac{F}{\delta}$

Example #2 (continued)