Mechanical Properties & Strengthening of Metals

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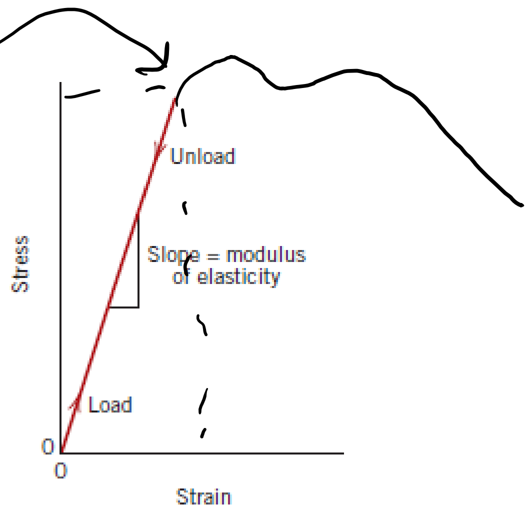
EGR 235

Elastic and Plastic Deformation

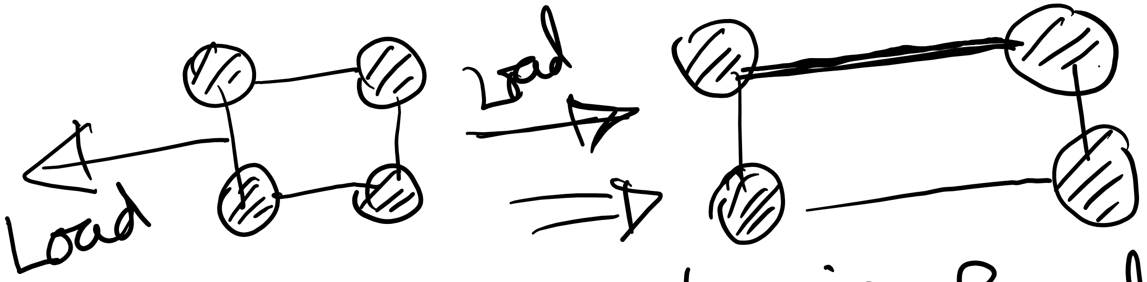
On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds. As a consequence, the magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces. Furthermore, this modulus is proportional to the slope of the interatomic force–separation curve (Figure 2.8*a*) at the equilibrium spacing:

$$E \propto \left(\frac{dF}{dr}\right)_{r_0} \tag{6.6}$$

Elastic Limit



- Strain represents-
  - Changes in interatomic spacing
  - Stretching of Interatomic bond
- Modulus-
  - Slope of Inter-atomic Separation
  - Modulus is Material Property



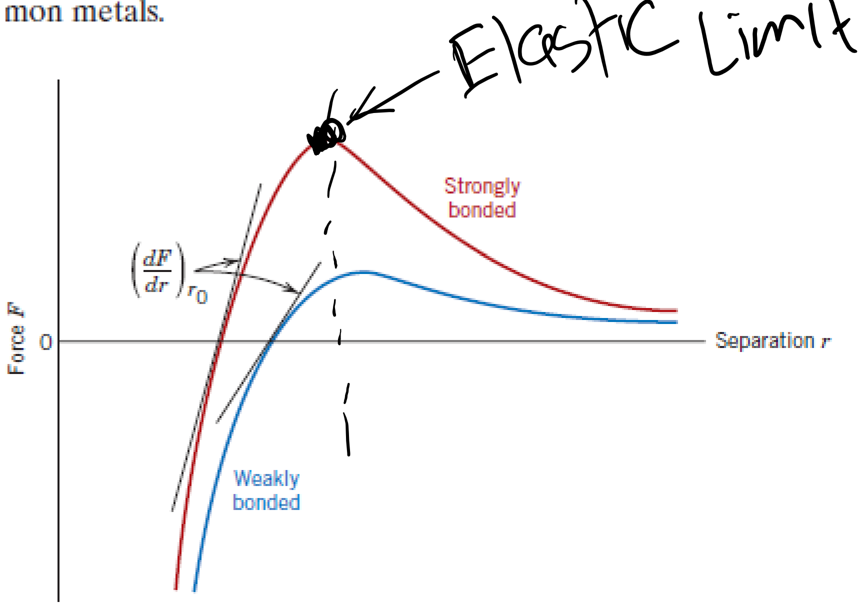
Plastic deformation = Permanent deformation

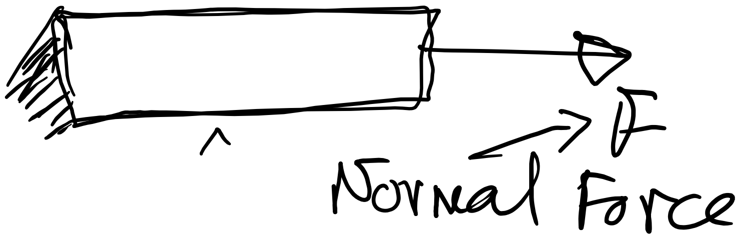
Interatomic Bonding plays a role in deformation

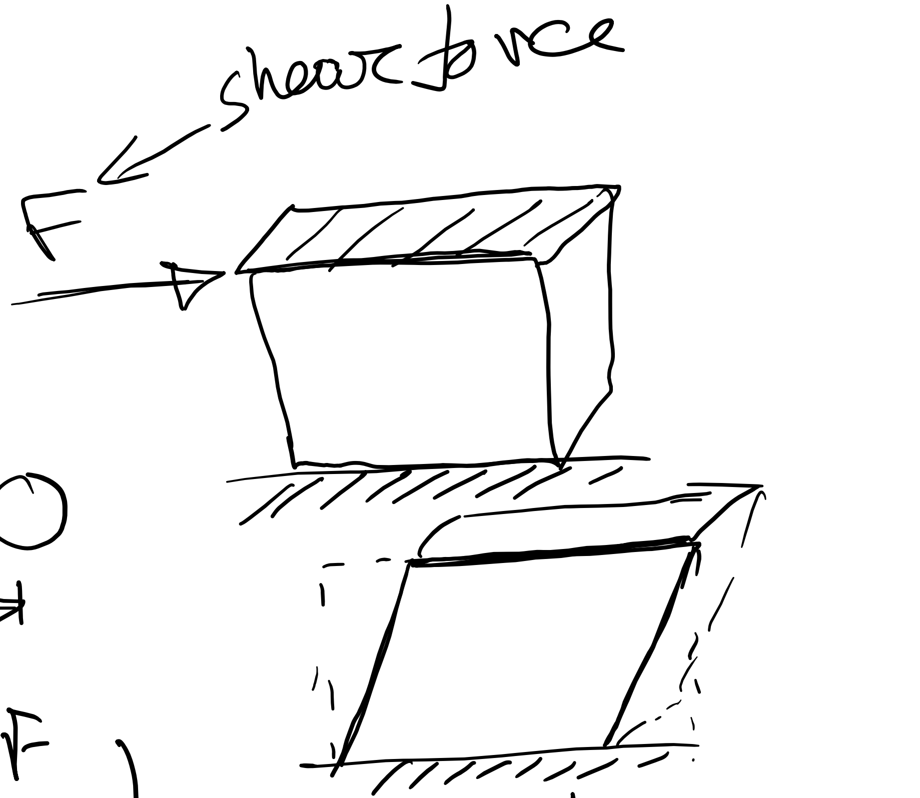
Shear Modulus

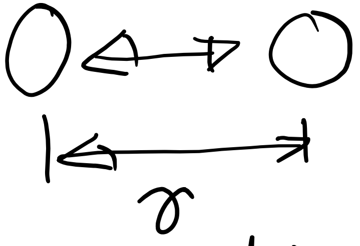
$$\tau = G\gamma \qquad (6.7)$$

where G is the *shear modulus*, the slope of the linear elastic region of the shear stress–strain curve. Table 6.1 also gives the shear moduli for a number of the common metals.









$$G = \left(\frac{dF}{dr}\right)$$

$$G = \frac{\text{shear stress}}{\text{shear strain}}$$

Elastic and shear Modulus Values

E = Youngs modulus

$E = 2G(1+\nu)$

$\nu = \frac{E}{2G} - 1$

$= \frac{69}{2*25} - 1$

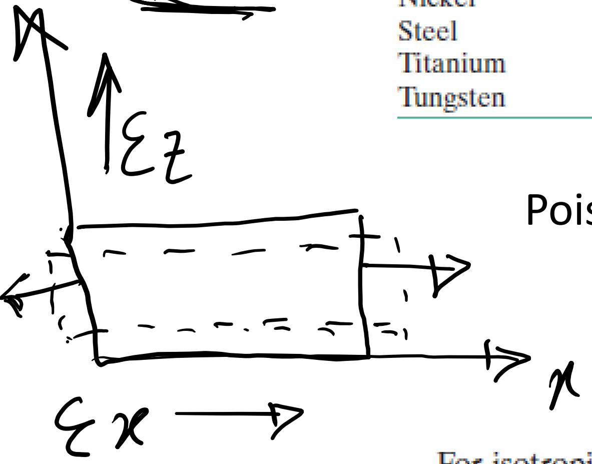
$= 0.38$

Table 6.1 Room-Temperature Elastic and Shear Moduli and Poisson's Ratio for Various Metal Alloys

	Modulus of Elasticity		Shear Modulus		
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*10^6 psi*	*Poisson's Ratio*
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

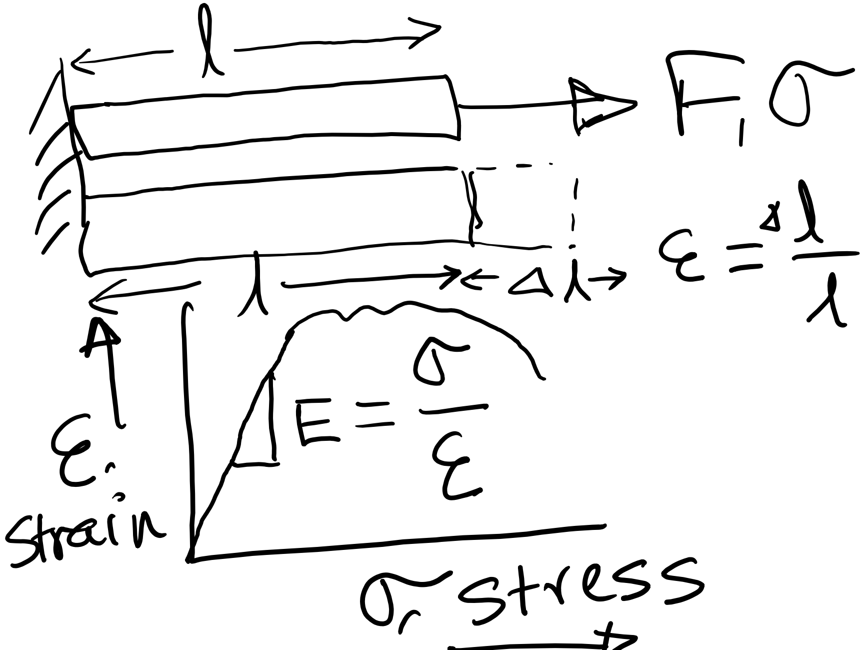
- Neu, ν=Ποισσον’σ Ρατιο

$\nu \rightarrow$ Neu, Nu



Poisson's Ratio- Ratios of strains in two axes

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z} \qquad (6.8)$$



For isotropic materials, shear and elastic moduli are related to each other and to Poisson's ratio according to

$$E = 2G(1+\nu) \qquad (6.9)$$

Lateral change due to longitudinal loading

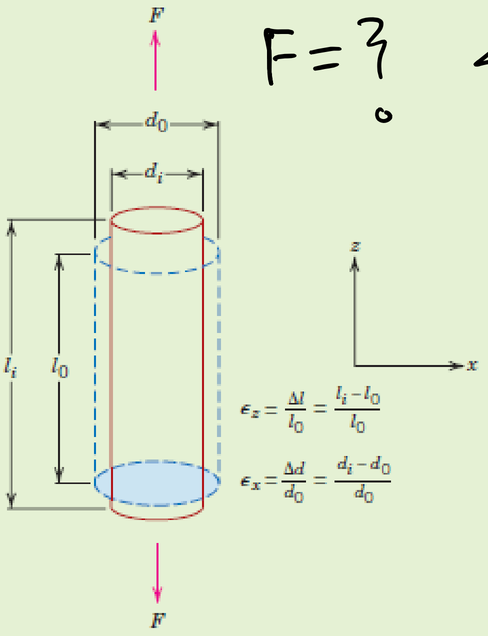
EXAMPLE PROBLEM 6.2

Computation of Load to Produce Specified Diameter Change

A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm (0.4 in.). Determine the magnitude of the load required to produce a 2.5×10^{-3} mm (10^{-4} in.) change in diameter if the deformation is entirely elastic.

Solution

This deformation situation is represented in the accompanying drawing.



F=? $\Delta d = -2.5 \times 10^{-3}$ mm

$d_0 = 10$mm

$\nu = 0.34$

$E = \frac{\sigma_z}{\varepsilon_z}$

known

$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi}{4}(d^2)}$

When the force F is applied, the specimen will elongate in the z direction and at the same time experience a reduction in diameter, Δd, of 2.5×10^{-3} mm in the x direction. For the strain in the x direction,

$$\epsilon_x = \frac{\Delta d}{d_0} = \frac{-2.5 \times 10^{-3}\ \cancel{\text{mm}}}{10\ \cancel{\text{mm}}} = -2.5 \times 10^{-4}$$

which is negative, because the diameter is reduced.

It next becomes necessary to calculate the strain in the z direction using Equation 6.8. The value for Poisson's ratio for brass is 0.34 (Table 6.1), and thus

$$\boxed{\epsilon_z = -\frac{\epsilon_x}{\nu} =} -\frac{(-2.5 \times 10^{-4})}{0.34} = 7.35 \times 10^{-4}$$

The applied stress may now be computed using Equation 6.5 and the modulus of elasticity, given in Table 6.1 as 97 GPa (14×10^6 psi), as

$$\sigma = \epsilon_z E = (7.35 \times 10^{-4})(97 \times 10^3 \text{ MPa}) = 71.3 \text{ MPa}$$

Finally, from Equation 6.1, the applied force may be determined as

$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi$$

$$= (71.3 \times 10^6 \text{ N/m}^2)\left(\frac{10 \times 10^{-3} \text{ m}}{2}\right)^2 \pi = 5600 \text{ N} (1293 \text{ lb}_f)$$

E=σ / ε

$\sigma =$ F/A

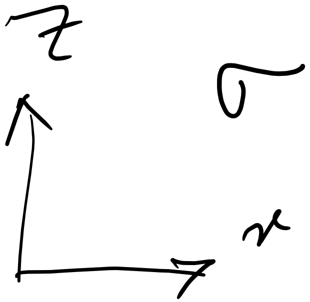
A=Sectional Area

If, F=7 KN, Find the change in diameter. Find Δd, 10min

$\simeq \Delta d = 3.1 \times 10^{-3}$ mm

Solution:—

$$F = 7\,kN = 7000\,N$$



$$\sigma = \frac{F}{A} = \frac{7000\,N}{78.54\,mm^2} = 89.1\,MPa$$

$$\varepsilon_z = \frac{\sigma}{E} = \frac{89.1\,MPa}{97\times10^{3}\,MPa} = 9.2\times10^{-4}$$

$$\nu = \frac{-\varepsilon_x}{\varepsilon_z} \qquad \underline{\underline{\varepsilon_x}} = -\nu * \varepsilon_z = 9.2\times10^{-4} * 0.34 = -3.128\times10^{-4}$$

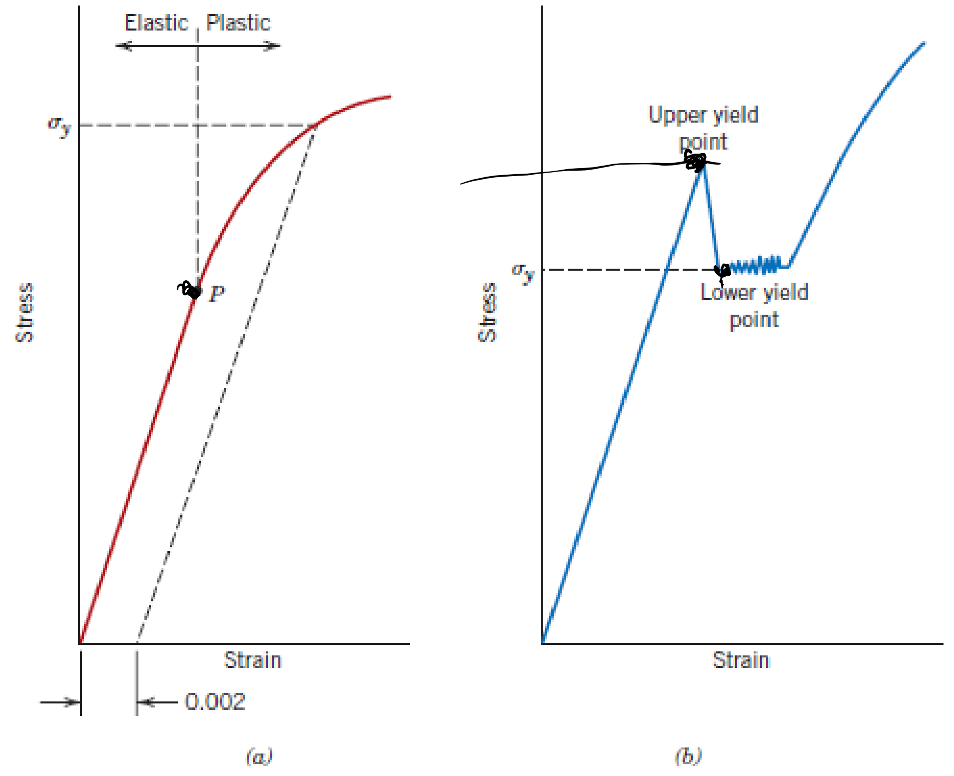
$$\varepsilon_x = \frac{-\Delta d}{d_o} \Rightarrow \Delta d = \varepsilon_x * d_o$$

$$= 3.128\times10^{-4} * 10\,mm$$

$$= \underline{\underline{3.128\times10^{-3}}}\,mm$$

Plastic Deformation

Figure 6.10
(*a*) Typical stress–strain behavior for a metal showing elastic and plastic deformations, the proportional limit *P*, and the yield strength σ_y, as determined using the 0.002 strain offset method. (*b*) Representative stress–strain behavior found for some steels demonstrating the yield point phenomenon.



- Yield Strain, $\in$
- Yield Stress, σ_y
- Yield strength varies from 35 MPa (Low strength Al) to 1400 MPa (high Strength steel)

Mechanical Property Determination

Mechanical Property Determinations from Stress–Strain Plot

From the tensile stress–strain behavior for the brass specimen shown in Figure 6.12, determine the following:

(a) The modulus of elasticity

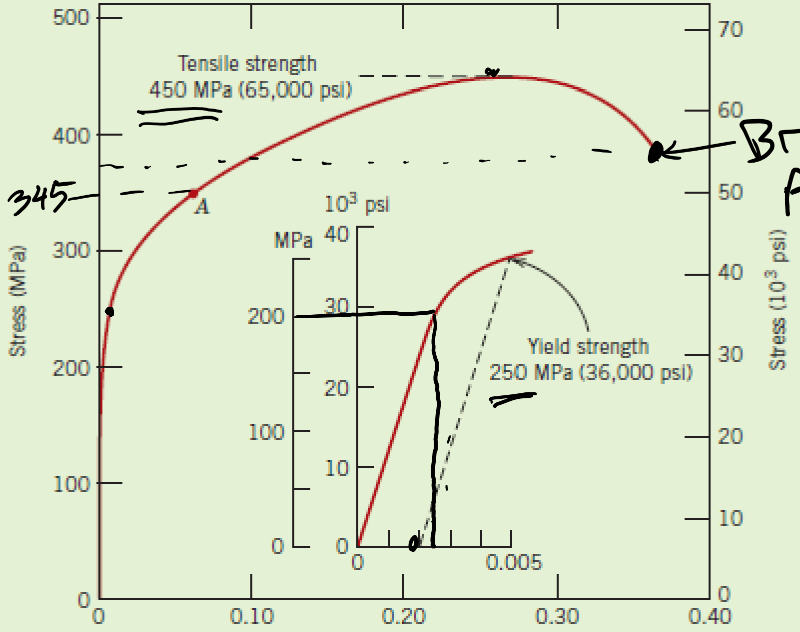
(b) The yield strength at a strain offset of 0.002

(c) The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.)

(d) The change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi)

Solution

(a) The modulus of elasticity is the slope of the elastic or initial linear portion of the stress–strain curve. The strain axis has been expanded in the inset, Figure 6.12, to facilitate this computation. The slope of this linear region is the



How much Load can it take before yield →

Find yield Load = Load at yield stress

$F_y = \sigma_y * A_0$

$= 250*10^6 * 1.2\times10^{-4}$

$= 35000$ N

rise over the run, or the change in stress divided by the corresponding change in strain; in mathematical terms,

$$E = \text{slope} = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{6.10}$$

Inasmuch as the line segment passes through the origin, it is convenient to take both σ_1 and ϵ_1 as zero. If σ_2 is arbitrarily taken as 150 MPa, then ϵ_2 will have a value of 0.0016. Therefore,

$$E = \frac{(150 - 0)\text{ MPa}}{0.0016 - 0} = 93.8 \text{ GPa } (13.6 \times 10^6 \text{ psi})$$

which is very close to the value of 97 GPa (14×10^6 psi) given for brass in Table 6.1.

(b) The 0.002 strain offset line is constructed as shown in the inset; its intersection with the stress–strain curve is at approximately 250 MPa (36,000 psi), which is the yield strength of the brass.

(c) The maximum load that can be sustained by the specimen is calculated by using Equation 6.1, in which σ is taken to be the tensile strength, from Figure 6.12, 450 MPa (65,000 psi). Solving for F, the maximum load, yields

$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi \rightarrow \frac{\pi d^2}{4}$$

$$= (450 \times 10^6 \text{ N/m}^2)\left(\frac{12.8 \times 10^{-3}\text{ m}}{2}\right)^2 \pi = 57{,}900 \text{ N } (13{,}000 \text{ lb}_f)$$

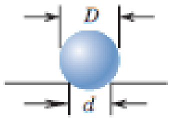
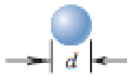
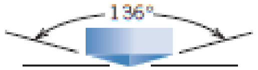
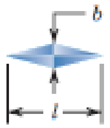
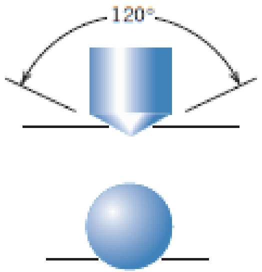
(d) To compute the change in length, Δl, in Equation 6.2, it is first necessary to determine the strain that is produced by a stress of 345 MPa. This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Inasmuch as $l_0 = 250$ mm, we have

$$\Delta l = \epsilon l_0 = (0.06)(250 \text{ mm}) = 15 \text{ mm } (0.6 \text{ in.})$$

Hardness

Hardness is Materials Resistance to Plastic Deformation

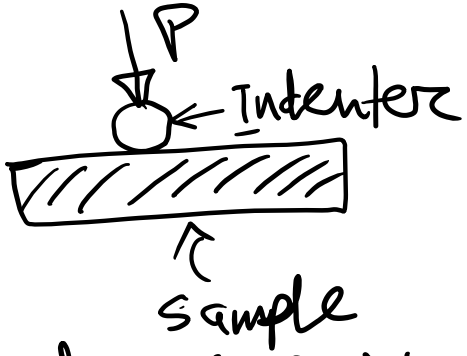
Table 6.5 Hardness-Testing Techniques

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	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
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, whereas 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.

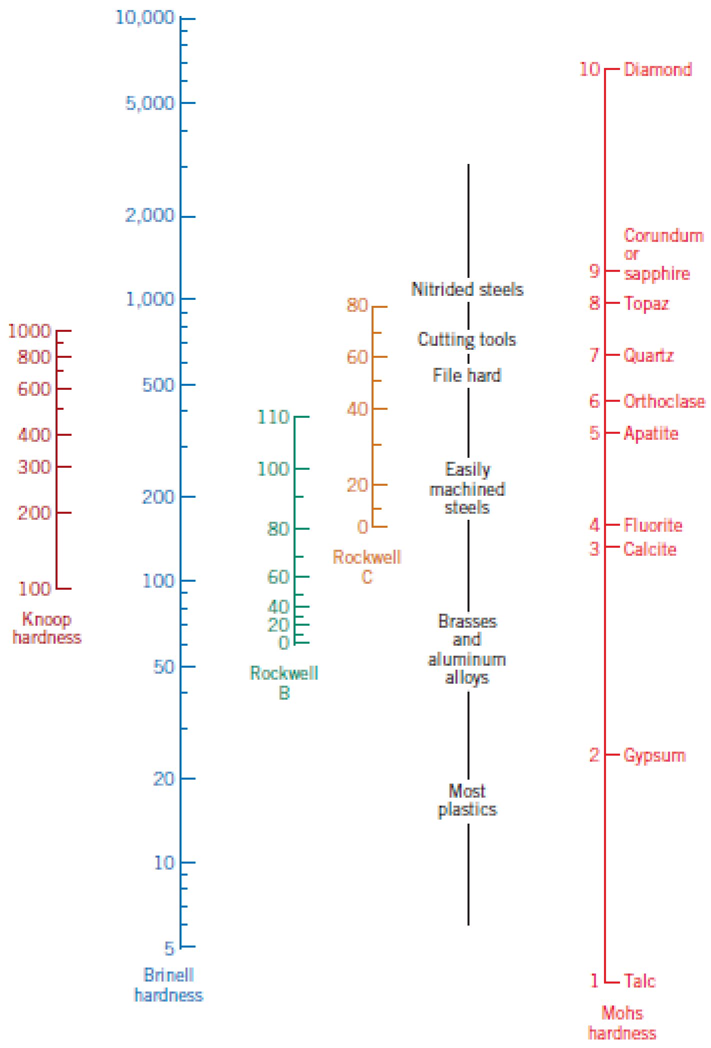
- Brinell
- Vickers
- Knoop
- Rockwell



Hardness is Resistance to plastic deformation

Hardness Conversion

Figure 6.18 Comparison of several hardness scales. (Adapted from G. F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202. Copyright © 1957 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



- ASTM E 140- Standard Hardness Conversion Tables for Metals

Hardness Correlation with Tensile Strength

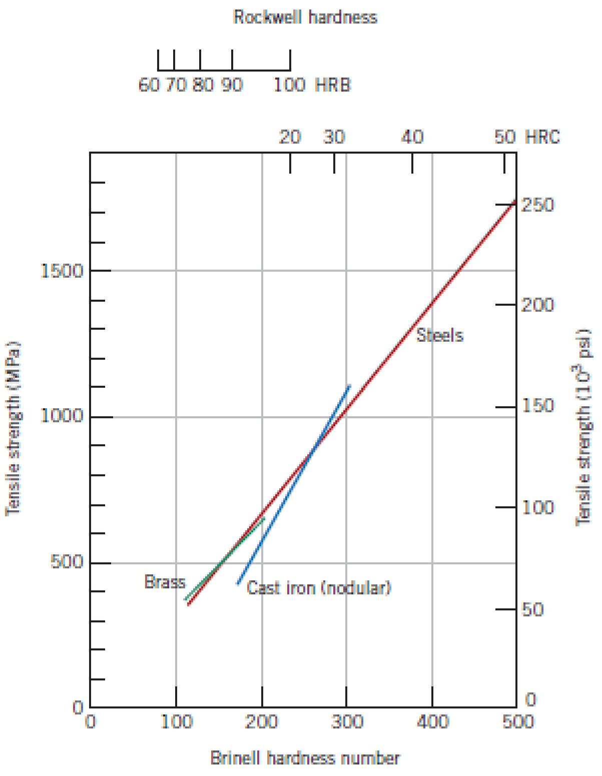


Figure 6.19 Relationships between hardness and tensile strength for steel, brass, and cast iron. [Data taken from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), American Society for Metals, 1978, pp. 36 and 461; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), American Society for Metals, 1979, p. 327.]

- TS(Mpa)=3.45*HB
- PS(psi)=500*HB

Equation Summary

Equation Summary

Equation Number	Equation	Solving For	Page Number
6.1	$\sigma = \frac{F}{A_0}$	Engineering stress	154
6.2	$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$	Engineering strain	154
6.5	$\sigma = E\epsilon$	Modulus of elasticity (Hooke's law)	156
6.8	$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$	Poisson's ratio	160
6.11	$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$	Ductility, percent elongation	166
6.12	$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$	Ductility, percent reduction in area	167

Lets Solve the Elasticity Related Problem

A cylindrical specimen of aluminum having a diameter of 19 mm (0.75 in.) and length of 200 mm (8.0 in.) is deformed elastically in tension with a force of 48,800 N (11,000 lb_f). Using the data in Table 6.1, determine the following:

(a) The amount by which this specimen will elongate in the direction of the applied stress.

(b) The change in diameter of the specimen. Will the diameter increase or decrease?

Given

$d = 19\ mm$

$l = 200\ mm$

$F = 48800\ N$

$E_{Al} = 69\ GPA$

$\nu = 0.33$

a) $\Delta l = ?$

b) $\Delta d = ?$

Solve it

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Part 1 End

Hardness Related Problem

6.51 (a) A 10-mm-diameter Brinell hardness indenter produced an indentation 1.62 mm in diameter in a steel alloy when a load of 500 kg was used. Compute the HB of this material.

(b) What will be the diameter of an indentation to yield a hardness of 450 HB when a 500-kg load is used?

If HB of steel is 241
What is the value in Rockwell B Scale?

Use-Hardness Conversion Table

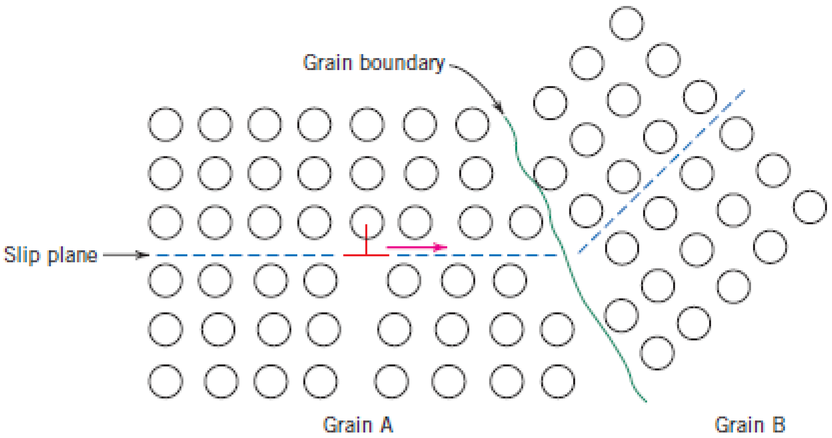
Strengthening of Metals

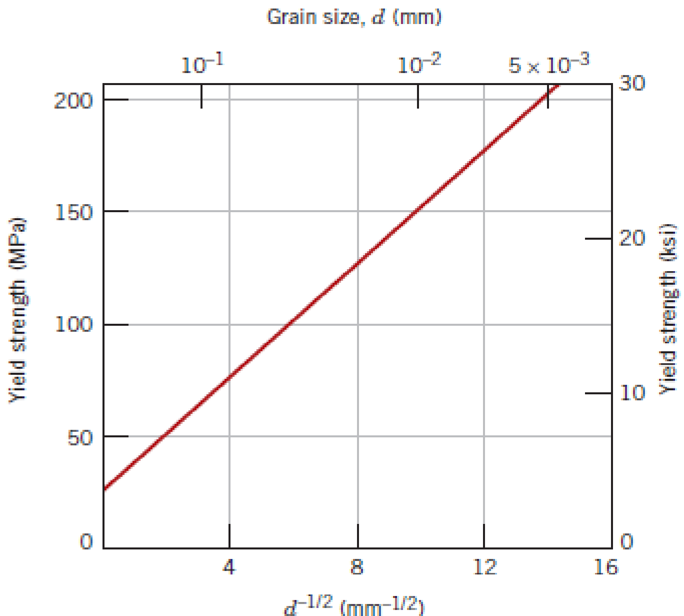
Is Metals strength constant? N
Is Metal Modulus Constant? Y
Is it possible to Improve Strength? Y

- Primary things to keep in mind-
  - Plastic Deformation
  - Number of Dislocations in the structure.
- Macroscopic plastic deformation/strain depends on the ability of dislocations to move
  - Bond Breaking and Re-bonding Process
- Reduction the ability of dislocation movement , means increase in hardness and strength
  - Pure Aluminum is Weaker and Softer Than Al 6061
  - Pure Iron is Weaker and Softer Steel

Strengthening by Grain size reduction

Figure 7.14 The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary. (From *VAN VLACK, TEXTBOOK MATERIALS TECHNOLOGY, 1st, © 1973.* Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)

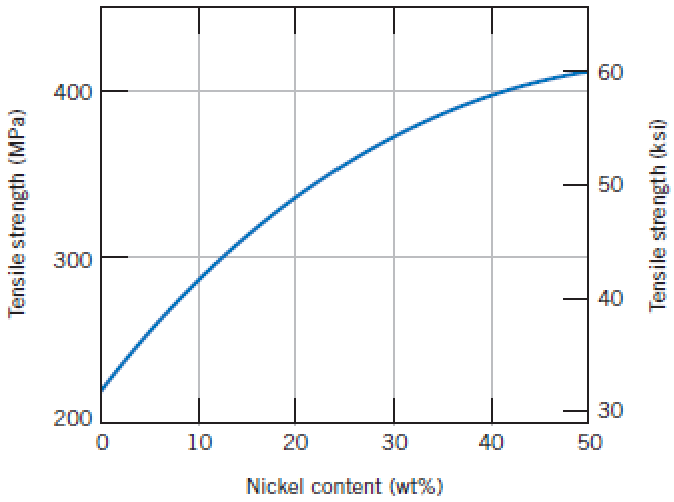




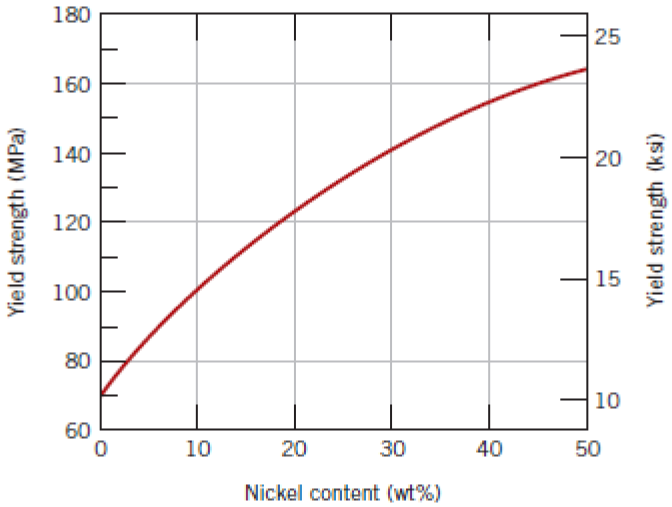
Hall-Petch Equation

- Poly-crystalline Metals
  - Poly-Grain Metals
  - Multiple Grain Boundary
- Crystal-→ Grain→ Grain Boundary
- Smaller Grain Means More Boundaries
- More Slip Resistance
  - Dislocation Pile Up
- Higher Strength

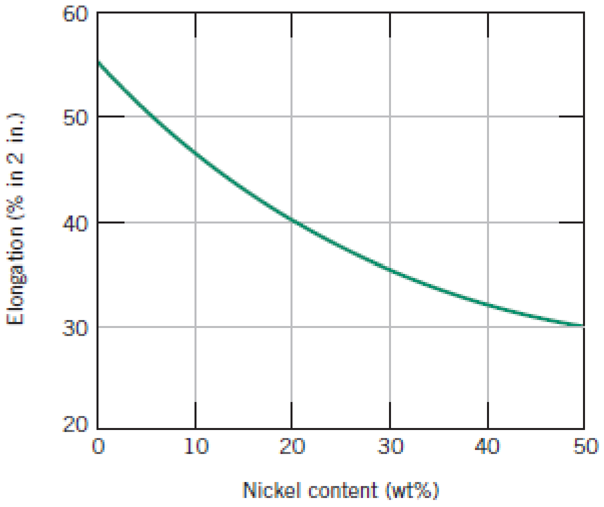
Solid Solution Strengthening



(a)



(b)



(c)

24 Karat Weaker than 18 Karat

- Adding Alloy element
  - Solid Solution
- Increasing impurity
  - Increase strength
  - 22 Karat Gold
    - 22 Part Au, 2 Part Cu
- Cu in Ni
  - Solubility Limit Restricts the content of impurity

Hume- Rothery Rules

Lattice Strain

Diameter of Ni < Diameter of Cu

- Dislocations impeded by substitutional Impurity
- Depends on solute atom size
- Smaller atom
  - Creates Tensile strain
- Larger atom
  - Creates Compressive strain

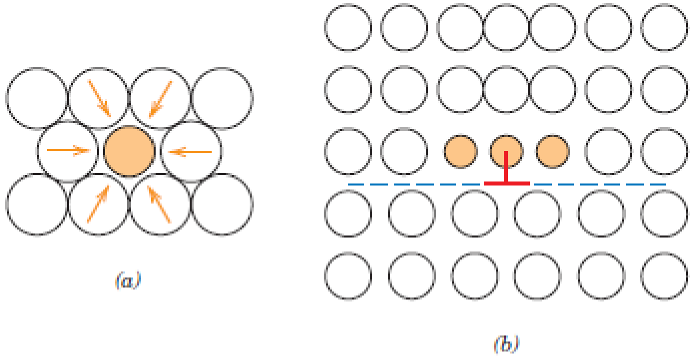


Figure 7.17 (*a*) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom. (*b*) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

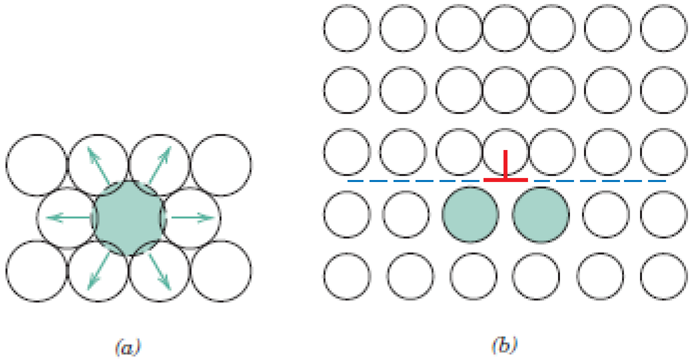


Figure 7.18 (*a*) Representation of compressive strains imposed on host atoms by a larger substitutional impurity atom. (*b*) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

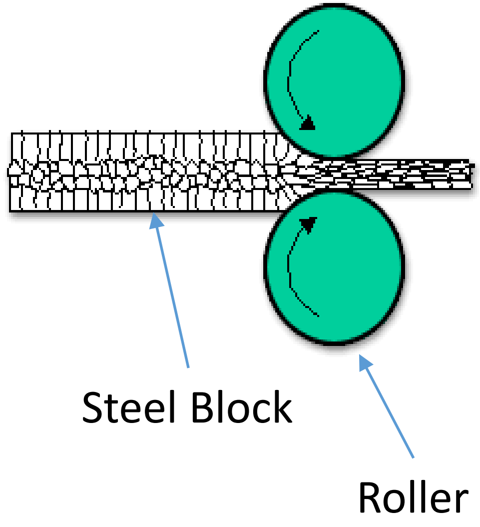
Strain Hardening

- Cold Work Hardening
- Cold Rolling Process

It is sometimes convenient to express the degree of plastic deformation as *percent cold work* rather than as strain. Percent cold work (%CW) is defined as

$$\%\mathrm{CW} = \left(\frac{A_0 - A_d}{A_0}\right) \times 100 \qquad (7.8)$$

where A_0 is the original area of the cross section that experiences deformation and A_d is the area after deformation.



Several Examples of Cold -Hardening

Rolled Steel coils

Rolled Steel Bars

If , Steel 1040 Rod is cold Rolled from 1 in to 0.75 in Dia, Determine %EL and Tensile Strength. Also determine, elongation (Delta l) of a 2 ft long cylindrical bar.

Example

EXAMPLE PROBLEM 7.2

Tensile Strength and Ductility Determinations for Cold-Worked Copper

Compute the tensile strength and ductility (%EL) of a cylindrical copper rod if it is cold worked such that the diameter is reduced from 15.2 mm to 12.2 mm (0.60 in. to 0.48 in.).

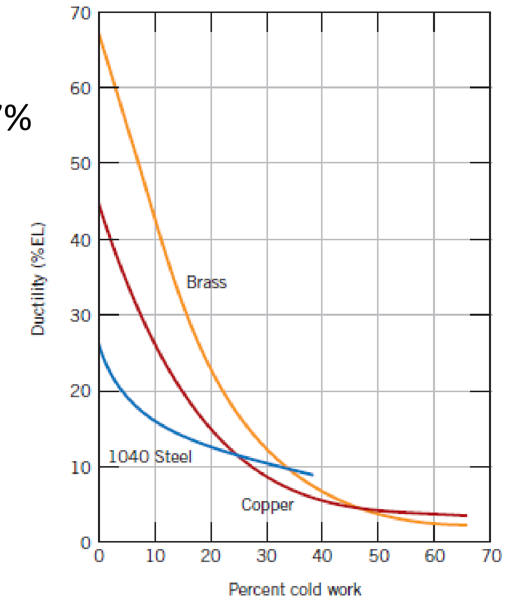
Solution

It is first necessary to determine the percent cold work resulting from the deformation. This is possible using Equation 7.8:

$$\%CW = \frac{\left(\frac{15.2\text{ mm}}{2}\right)^2 \pi - \left(\frac{12.2\text{ mm}}{2}\right)^2 \pi}{\left(\frac{15.2\text{ mm}}{2}\right)^2 \pi} \times 100 = 35.6\%$$

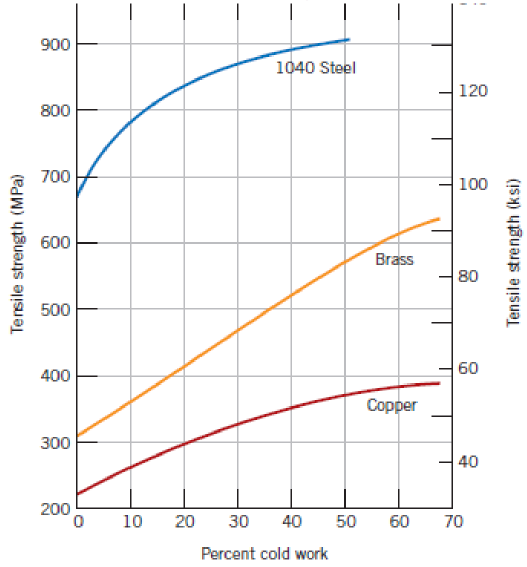
The tensile strength is read directly from the curve for copper (Figure 7.19*b*) as 340 MPa (50,000 psi). From Figure 7.19*c*, the ductility at 35.6%CW is about 7%EL.

Ans: %CW=(.5^2-.375^)*100/.5^2=43.7%
Sy=900 Mpa
%EL=6%
If l=2ft, Delta l= .06*2 ft=.12 ft=1.44 in
Final Length =2ft+1.44 in

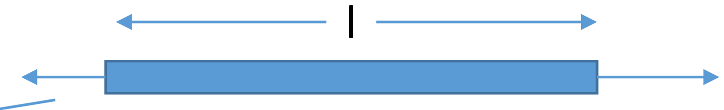


(*c*)

Spend
15 minutes



(*b*)

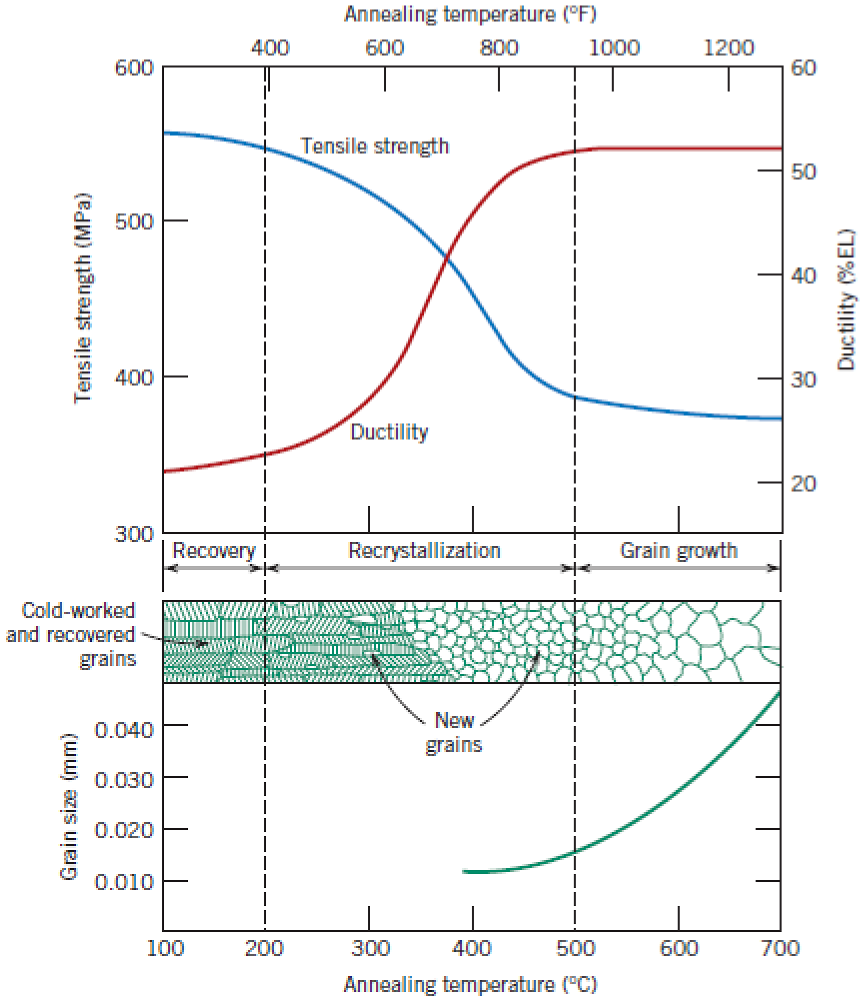


%EL=(Delta l/l)x100

Cylindrical bar

Recovery, Recrystallization and Grain Growth

Figure 7.22 The influence of annealing temperature (for an annealing time of 1 h) on the tensile strength and ductility of a brass alloy. Grain size as a function of annealing temperature is indicated. Grain structures during recovery, recrystallization, and grain growth stages are shown schematically. (Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)



- Hot Work Process
- Typical is Hot work after cold rolling
- Physical Strain Hardening
  - Distortion
  - Deformation- Results in Crack
- Heat Treatment Process
- Recovery
  - Internal strain Removed
- Re-Crystallization
  - New Crystal formed
- Grain Growth

If Fy goes down then why hot work needed?
Because, Hot work increase ductility or formability.

Re-Crystallization and Temperature

Table 7.2 Recrystallization and Melting Temperatures for Various Metals and Alloys

	Recrystallization Temperature		*Melting Temperature*	
Metal	*°C*	*°F*	*°C*	*°F*
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

Grain Growth

For many polycrystalline materials, the grain diameter d varies with time t according to the relationship

$$d^n - d_0^n = Kt \tag{7.9}$$

where d_0 is the initial grain diameter at $t = 0$, and K and n are time-independent constants; the value of n is generally equal to or greater than 2.

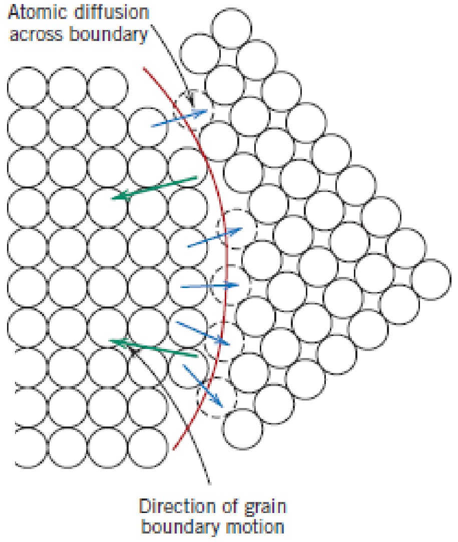


Figure 7.24 Schematic representation of grain growth via atomic diffusion. (From *VAN VLACK, L. H., ELEMENTS OF MATERIALS SCIENCE AND ENGINEERING, 6th, © 1989.* Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)

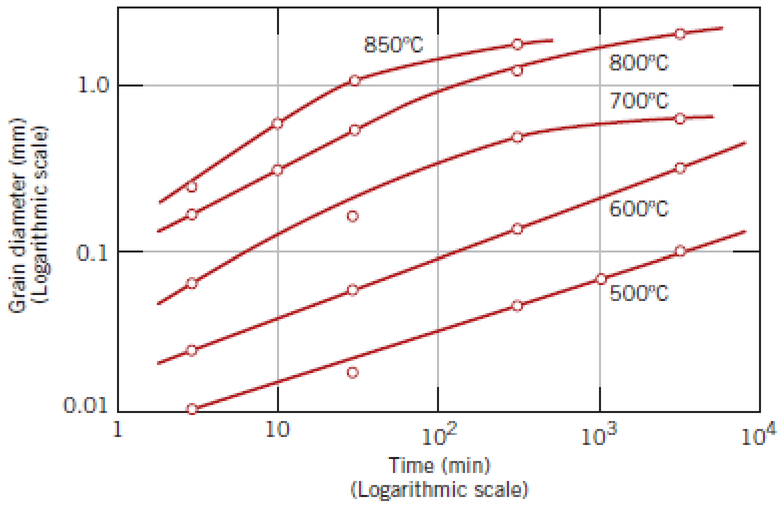


Figure 7.25 The logarithm of grain diameter versus the logarithm of time for grain growth in brass at several temperatures. (From J. E. Burke, "Some Factors Affecting the Rate of Grain Growth in Metals." Reprinted with permission from *Metallurgical Transactions,* Vol. 180, 1949, a publication of The Metallurgical Society of AIME, Warrendale, Pennsylvania.)

Equations

7.2	$\tau_R = \sigma \cos \phi \cos \lambda$	Resolved shear stress
7.4	$\tau_{crss} = \sigma_y(\cos \phi \cos \lambda)_{max}$	Critical resolved shear stress
7.7	$\sigma_y = \sigma_0 + k_y d^{-1/2}$	Yield strength (as a function of average grain size)—Hall–Petch equation
7.8	$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$	Percent cold work
7.9	$d^n - d_0^n = Kt$	Average grain size (during grain growth)

List of Symbols

Symbol	*Meaning*
A_0	Specimen cross-sectional area prior to deformation
A_d	Specimen cross-sectional area after deformation
d	Average grain size; average grain size during grain growth
d_0	Average grain size prior to grain growth
K, k_y	Material constants
t	Time over which grain growth occurred
n	Grain size exponent—for some materials has a value of approximately 2
λ	Angle between the tensile axis and the slip direction for a single crystal stressed in tension (Figure 7.7)
ϕ	Angle between the tensile axis and the normal to the slip plane for a single crystal stressed in tension (Figure 7.7)
σ_0	Material constant
σ_y	Yield strength

Assignment

Q1. Explore various strengthening mechanism in engineering materials

- Identify types of strengthening
- List the material names
- List application
- List as many Materials as you can (Minimum 10)
- Use a Table like the following -

Strengthening Mechanism (e.g. Solid Solution)	Metal/ Material Combination (e.g. iron+Carbon)	Industrial Grade (e.g. Steel 1040)	Application (e.g. Sheet Metal)

Q.2.

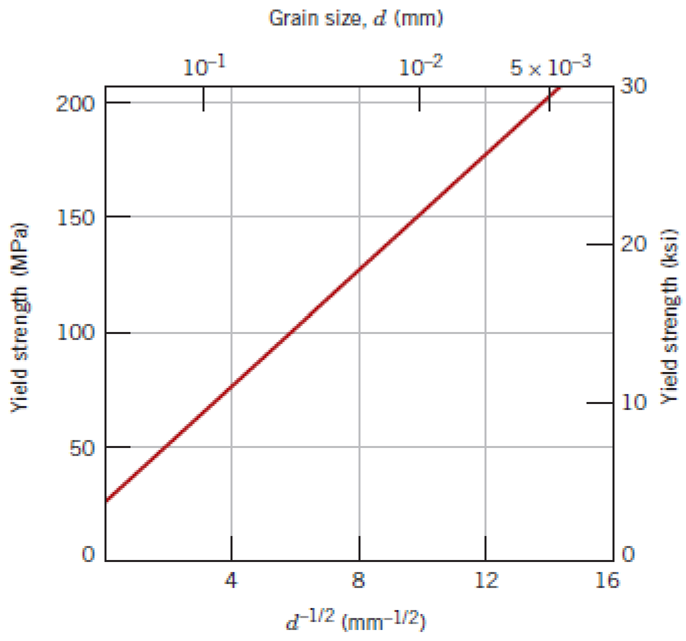


Figure 7.15 The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear. (Adapted from H. Suzuki, "The Relation between the Structure and Mechanical Properties of Metals," Vol. II, *National Physical Laboratory, Symposium No. 15,* 1963, p. 524.)

- From the plot of yield strength-grain diameter for a 70Cu-30 Zn cartridge brass, determine values for the constants σ_0 and Ky.

Submit Q1, Q2- in one file