Materials Science and Engineering I

Chapter 6

Mechanical Properties Of Metals - I

Outline

Processing of Metals and alloys

◆Casting of Metals and Alloys

◆Hot and Cold Rolling of Metals and Alloys

◆Extrusion of Metals and Alloys

◆Other Metal-forming Process es

Stress and Strain in metals

◆Elastic and Plastic deformation

◆Engineering Stress and Engineering Strain

◆Shear Stress and Shear Strain

Tensile test and Engineering Stress-strain Diagram

◆Mechanical property data Obtained from the tensile test and engineering stress-strain Diagram

◆Comparison of Engineering Stress-Strain Curves for selected Alloys

◆True Stress and True Strain

◆Hardness and Hardness testing

Outline

Plastic deformation of Metal single crystals

◆Slipbands and Slip line on the surface of metal crystals.

◆Plastic Deformation in Metal Crystals by the slip Mechanism

◆Slip System

◆Critical resolved shear stress for metal single cyrstals

◆Schmid's Law

◆Twinning

Plastic deformation of polycrystalline metals

◆Effect of grain boundaries on the strength of metals

◆Effect of plastic deformation on grain shape and dislocation arrangements

◆Effect of cold plastic deformation on increasing the strength of metal

Solid-Solution Strengthening of Metals

Recovery and Recrystallization of Plastically deformed metals

◆Recovery

◆Recrystallization

Superplasticity in Metals

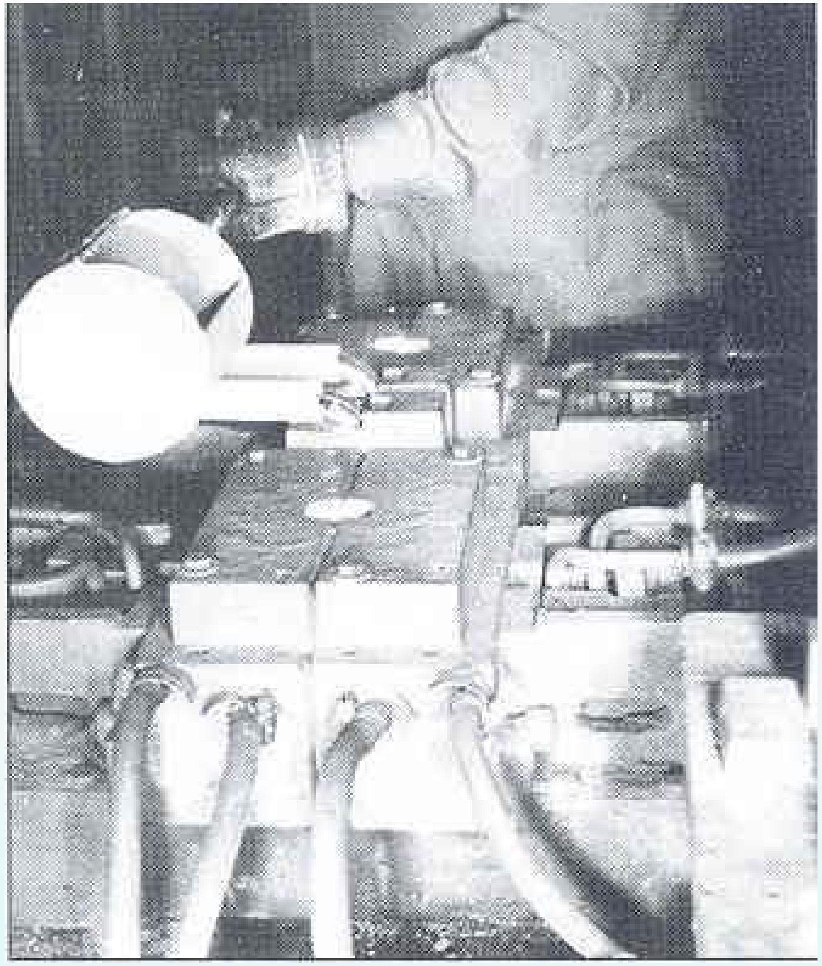
Nanocrystalline metals

Processing of Metals - Casting

- Most metals are first melted in a furnace.
- Alloying is done if required.
- Large ingots are then cast.
- Sheets and plates are then produced from ingots by rolling → Wrought alloy products.
- Channels and other shapes are produced by extrusion.
- Some small parts can be cast as final product.

Example :- Automobile Piston.

Casting (Cont..)



Casting Process

Figure 5.3 a

Casting mold

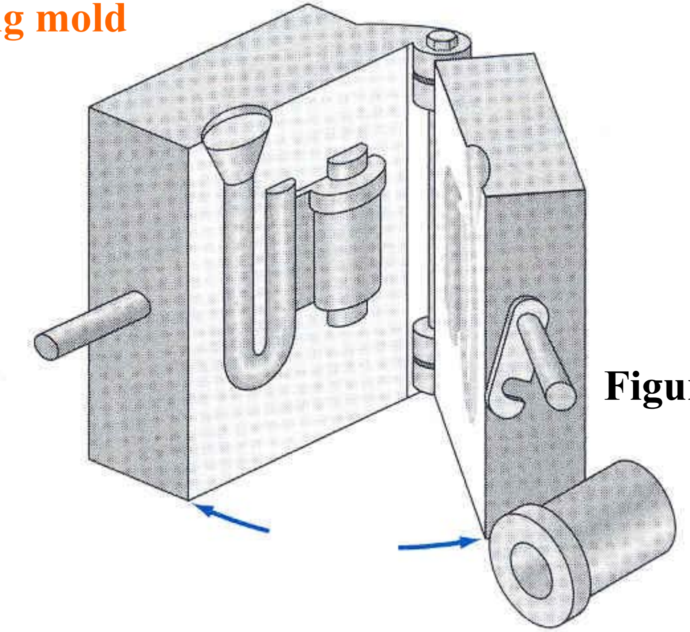


Figure 5.2

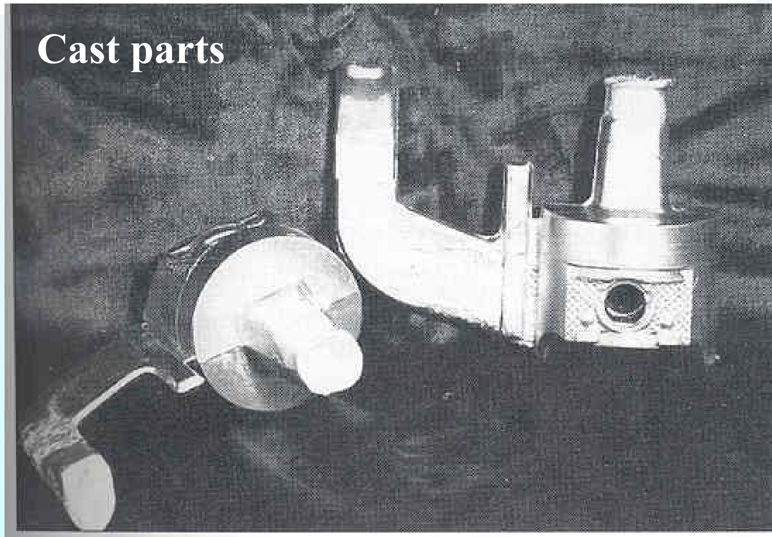
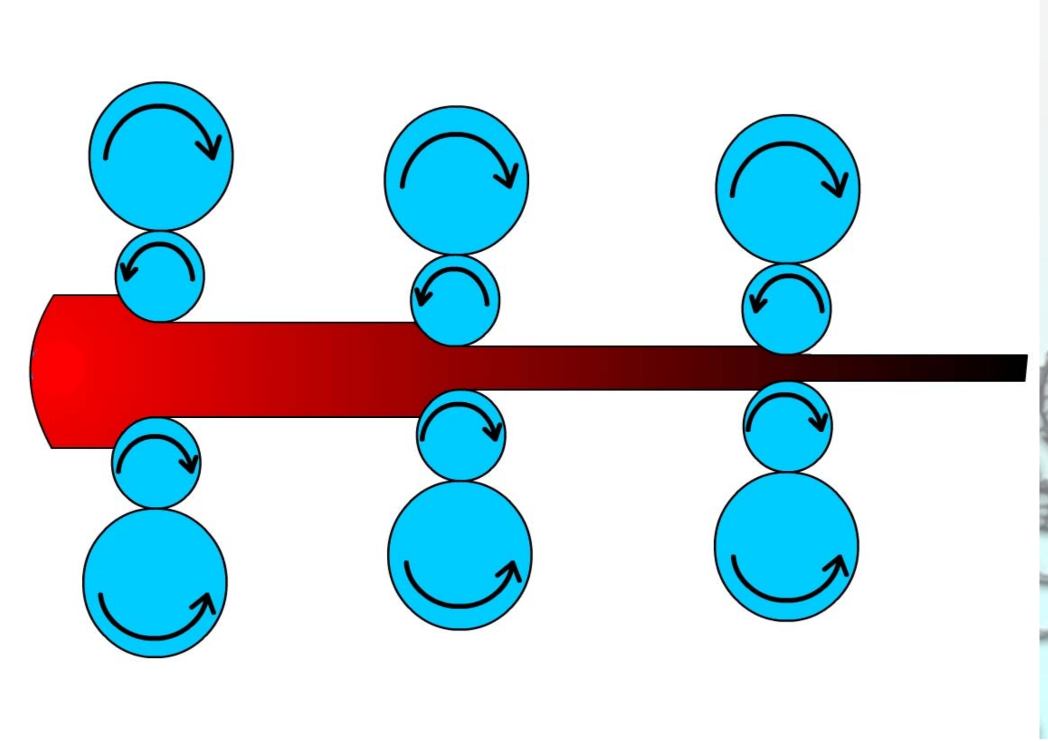


Figure 5.3 b

Hot Rolling of Steel

- Hot rolling → Greater reduction of thickness in a single run.
- Rolling carried out at above *recrystallization temperature*.
- Ingots preheated to about 1200^0C.
- Ingots reheated between passes if required.
- Usually, series of 4 high rolling mills are used.



Example Problem 6.1

Calculate the percent cold reduction in cold rolling an aluminum sheet alloy from 3.0 to 1.0 mm.

■ **Solution**

$$\% \text{ cold reduction} = \frac{\text{initial thickness} - \text{final thickness}}{\text{initial thickness}} \times 100\%$$

$$= \frac{3.0\text{ mm} - 1.0\text{ mm}}{3.0\text{ mm}} \times 100\% = \frac{2.0\text{ mm}}{3.0\text{ mm}} \times 100\%$$

$$= 66.7\%$$

Cold Rolling of Metal Sheet

- Cold rolling is rolling performed below recrystallization temperature.
- This results in strain hardening.
- Hot rolled slabs have to be annealed before cold rolling.
- Series of 4 high rolling mills are usually used.
- Less reduction of thickness.
- Needs high power.

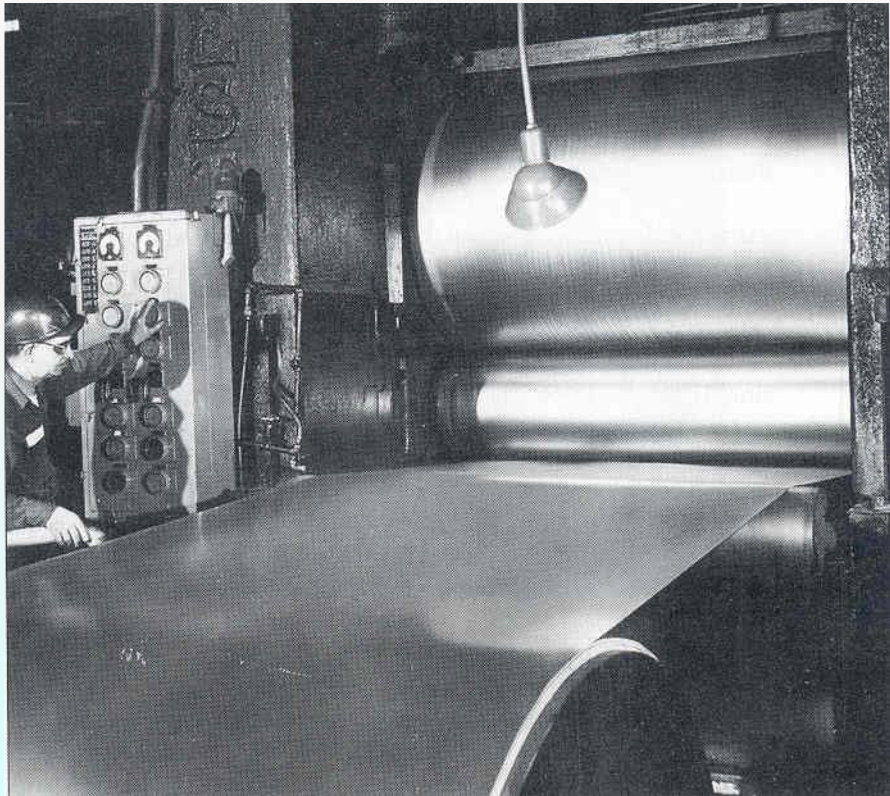


Figure 5.8

Cold Rolling (Cont..)

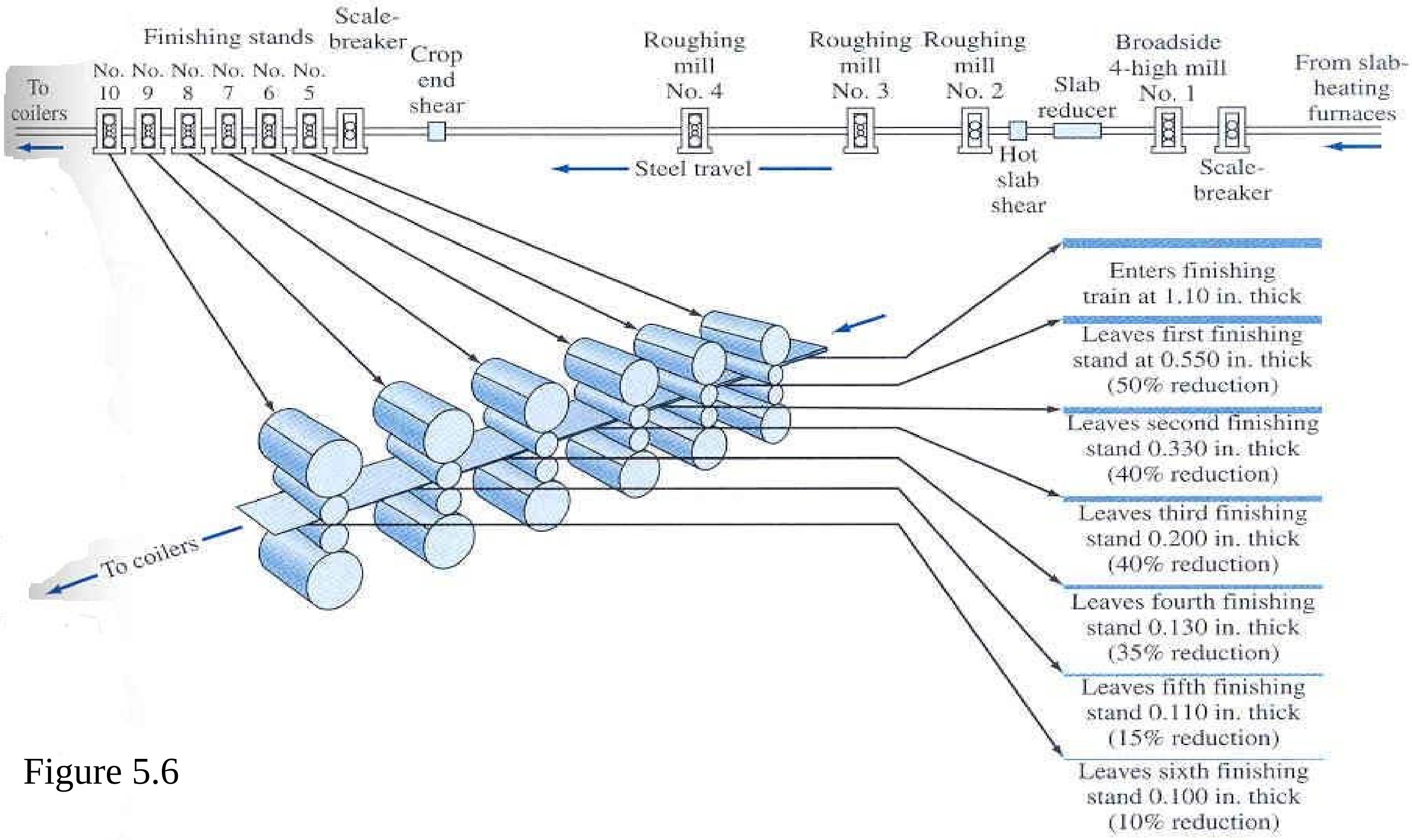


Figure 5.6

$$\text{\% Cold work} = \frac{\text{Initial metal thickness} - \text{Final metal thickness}}{\text{Initial metal thickness}} \times 100$$

Example Problem 6.2

A sheet of a 70% Cu–30% Zn alloy is cold-rolled 20 percent to a thickness of 3.00 mm. The sheet is then further cold-rolled to 2.00 mm. What is the total percent cold work?

■ Solution

We first determine the starting thickness of the sheet by considering the first cold reduction of 20 percent. Let x equal the starting thickness of the sheet. Then,

$$\frac{x - 3.00\ \text{mm}}{x} = 0.20$$

or

$$x - 3.00\ \text{mm} = 0.20x$$
$$x = 3.75\ \text{mm}$$

We can now determine the *total* percent cold work from the starting thickness to the finished thickness from the relationship

$$\frac{3.75\ \text{mm} - 2.00\ \text{mm}}{3.75\ \text{mm}} = \frac{1.75\ \text{mm}}{3.75\ \text{mm}} = 0.466 \text{ or } 46.6\%$$

Extrusion

- Metal under high pressure is forced through opening in a die.
- Common Products are cylindrical bar, hollow tubes from copper, aluminum etc.
- Normally done at high temperature.
- Indirect extrusion needs less power however has limit on load applied

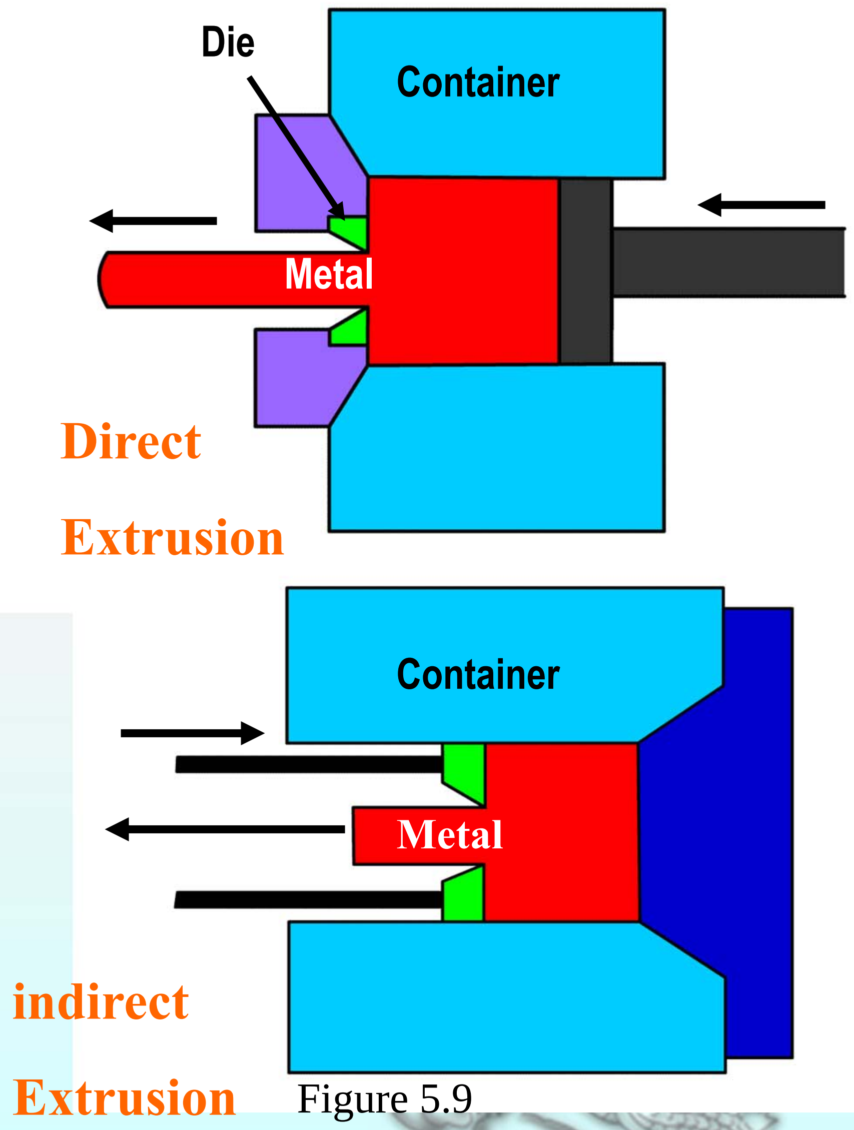


Figure 5.9

Forging

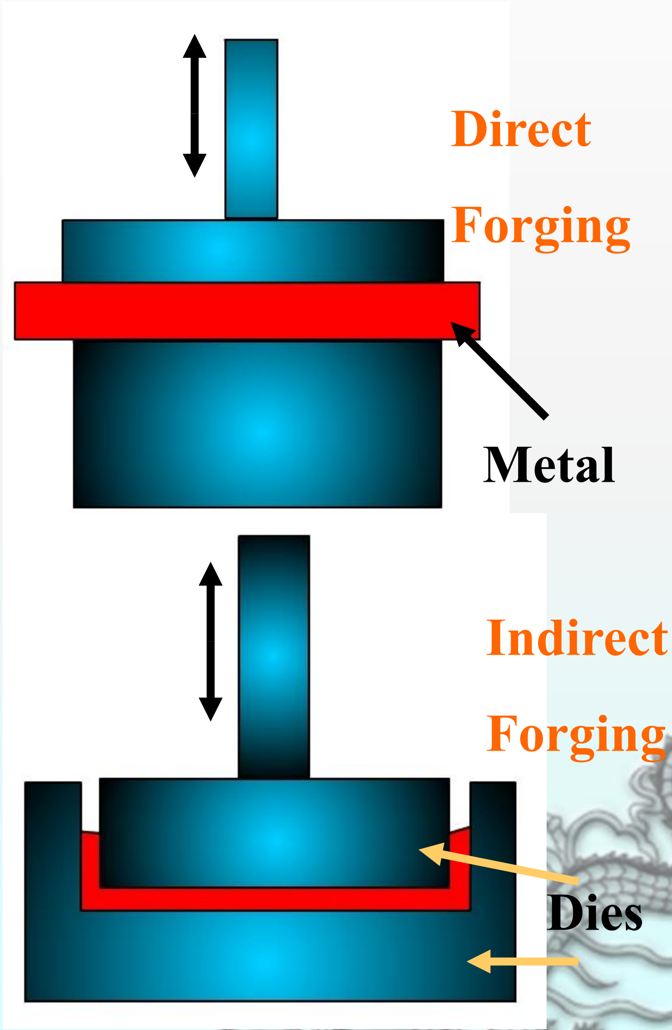
◆ Metal, usually hot, is hammered or pressed into desired shape.

◆ Types:-

- **Open die:** Dies are flat and simple in shape
  * Example products: Steel shafts

- **Closed die:** Dies have upper and lower impresion
  * Example products: Automobile engine connection rod.

◆ Forging increases structural properties, removes porosity and increases homogeneity.

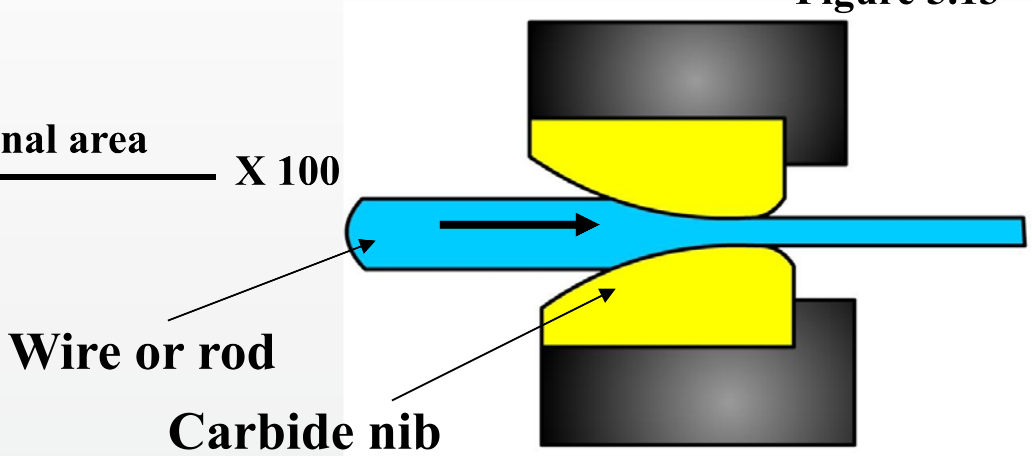


Drawing

- **Wire drawing :- Starting rod or wire is drawn through several drawing dies to reduce diameter.**

Figure 5.13

$$\text{\% cold work} = \frac{\text{Change in cross-sectional area}}{\text{Original area}} \times 100$$



- **Deep drawing:- Used to shape cup like articles from flats and sheets of metals**

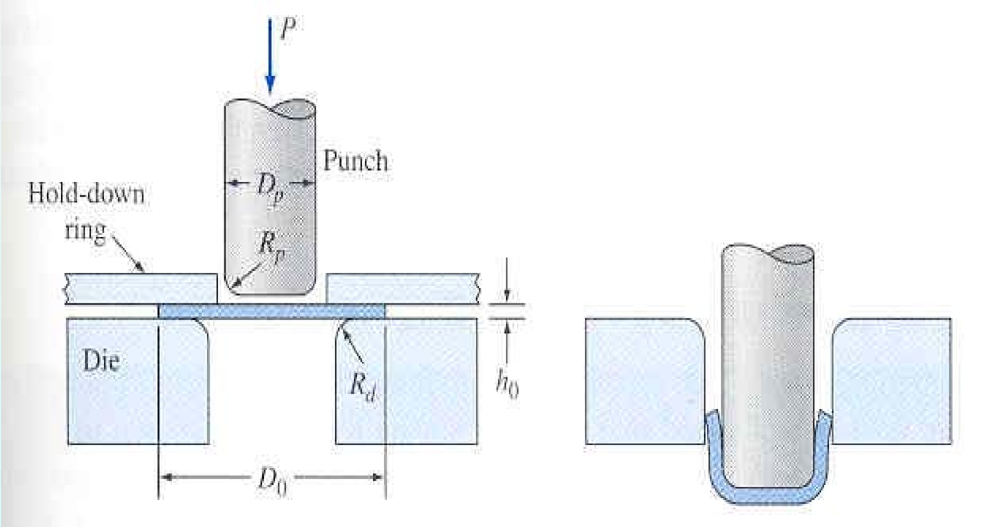


Figure 5.14

Example Problem 6.3

Calculate the percent cold reduction when an annealed copper wire is cold-drawn from a diameter of 1.27 mm to a diameter of 0.813 mm.

■ Solution

$$\% \text{ cold reduction} = \frac{\text{change in cross-sectional area}}{\text{original area}} \times 100\% \qquad \textbf{(6.2)}$$

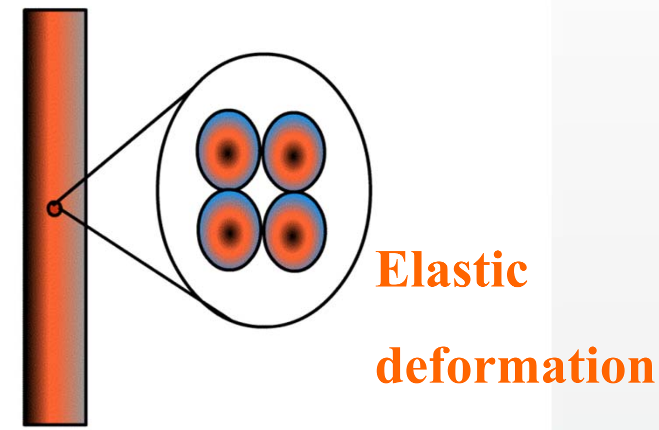
$$= \frac{(\pi/4)(1.27 \text{ mm})^2 - (\pi/4)(0.813 \text{ mm})^2}{(\pi/4)(1.27 \text{ mm})^2} \times 100\%$$

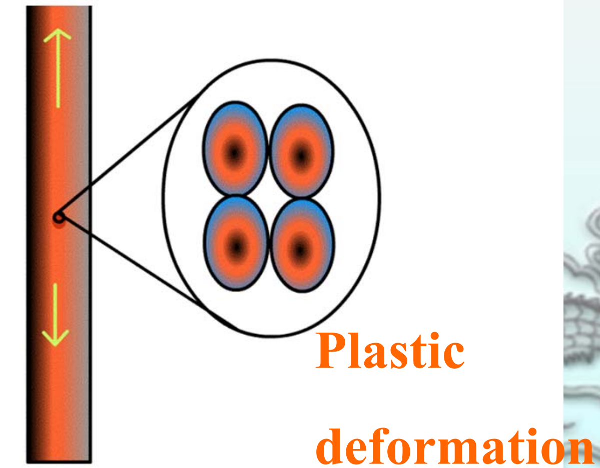
$$= \left[1 - \frac{(0.813)^2}{(1.27)^2}\right](100\%)$$

$$= (1 - 0.41)(100\%) = 59\% \blacktriangleleft$$

Stress and Strain in Metals

- Metals undergo deformation under uniaxial tensile force.
- **Elastic deformation:** Metal returns to its original dimension after tensile force is removed.
- **Plastic deformation:** The metal is deformed to such an extent such that it cannot return to its original dimension





Engineering Stress and Strain

$$\frac{F \text{ (Average uniaxial tensile force)}}{A_0 \text{ (Original cross-sectional area)}}$$

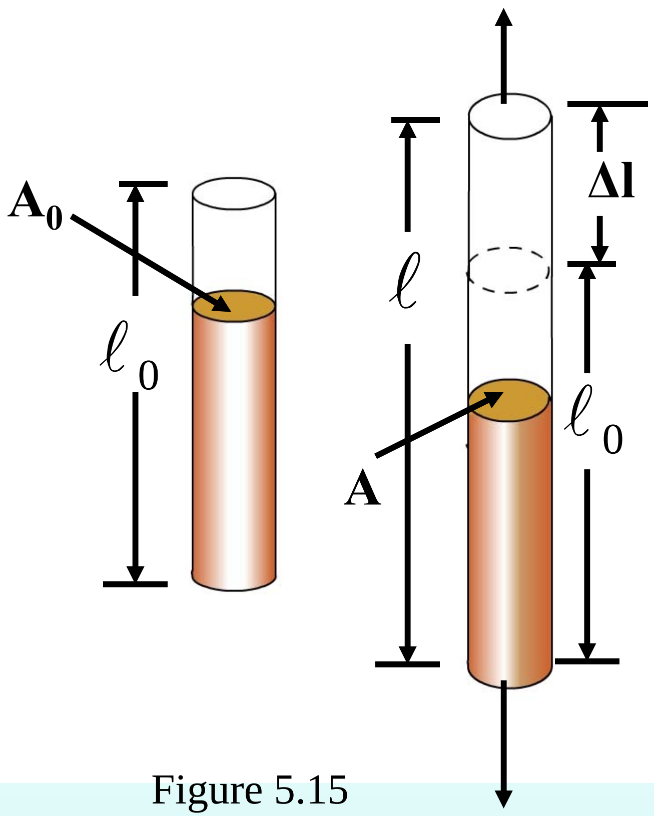


Figure 5.15

Units of Stress are PSI or N/M^2 (Pascals)

1 PSI = 6.89×10^3 Pa

Engineering strain = ε = $\dfrac{\text{Change in length}}{\text{Original length}}$

$$= \frac{\ell - \ell_0}{\ell_0} = \frac{\Delta \ell}{\ell}$$

Units of strain are in/in or m/m.

Example Problem 6.4

A 0.5-cm-diameter aluminum bar is subjected to a force of 500 N. Calculate the engineering stress in MPa on the bar.

■ **Solution**

$$\sigma = \frac{\text{force}}{\text{original cross-sectional area}} = \frac{F}{A_0}$$

$$= \frac{500\ \text{N}}{(\pi/4)(0.005\ \text{m})^2} = 2.55 \times 10^7\ \text{Pa}$$

$$= (2.55 \times 10^7\ \text{Pa})\left(\frac{1\ \text{MPa}}{10^6\ \text{Pa}}\right) = 25.5\ \text{MPa} \blacktriangleleft$$

Example Problem 6.5

A 1.25-cm-diameter bar is subjected to a load of 2500 kg. Calculate the engineering stress on the bar in megapascals (MPa).

■ **Solution**

The load on the bar has a mass of 2500 kg. In SI units, the force on the bar is equal to the mass of the load times the acceleration of gravity (9.81 m/s^2), or

$$F = ma = (2500\ \text{kg})(9.81\ \text{m/s}^2) = 24{,}500\ \text{N}$$

The diameter d of the bar = 1.25 cm = 0.0125 m. Thus, the engineering stress on the bar is

$$\sigma = \frac{F}{A_0} = \frac{F}{(\pi/4)(d^2)} = \frac{24{,}500\ \text{N}}{(\pi/4)(0.0125\ \text{m})^2}$$

$$= (2.00 \times 10^8\ \text{Pa})\left(\frac{1\ \text{MPa}}{10^6\ \text{Pa}}\right) = 200\ \text{MPa} \blacktriangleleft$$

Example Problem 6.6

A sample of commercially pure aluminum 1.27 cm wide, 0.1 cm thick, and 20.3 cm long that has gage markings 5.1 cm apart in the middle of the sample is strained so that the gage markings are 6.7 cm apart (Fig. 6.14). Calculate the engineering strain and the percent engineering strain elongation that the sample undergoes.

■ **Solution**

$$\text{Engineering strain } \epsilon = \frac{l - l_0}{l_0} = \frac{6.7\text{ cm} - 5.1\text{ cm}}{5.1\text{ cm}} = \frac{1.6\text{ cm}}{5.1\text{ cm}} = 0.31 \blacktriangleleft$$

$$\%\text{ elongation} = 0.31 \times 100\% = 31\% \blacktriangleleft$$

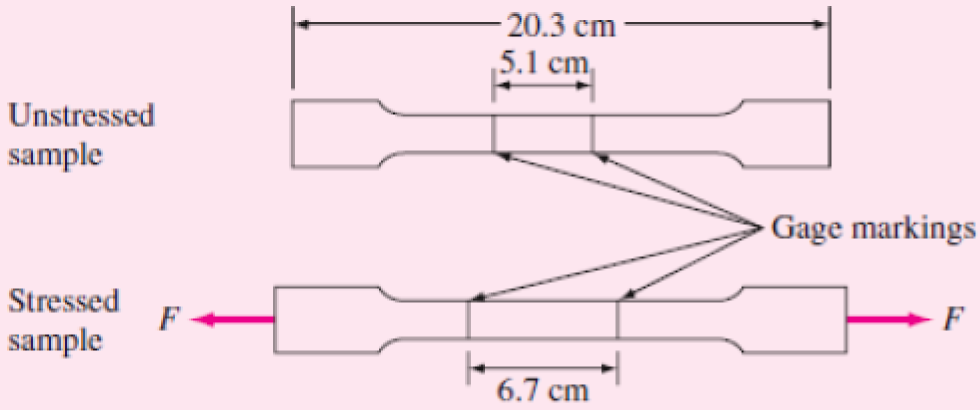


Figure 6.14
Flat tensile specimen before and after testing.

Poisons Ratio

Poisons ratio = $\nu = -\dfrac{\varepsilon(lateral)}{\varepsilon(longitudinal)} = -\dfrac{\varepsilon_y}{\varepsilon_z}$

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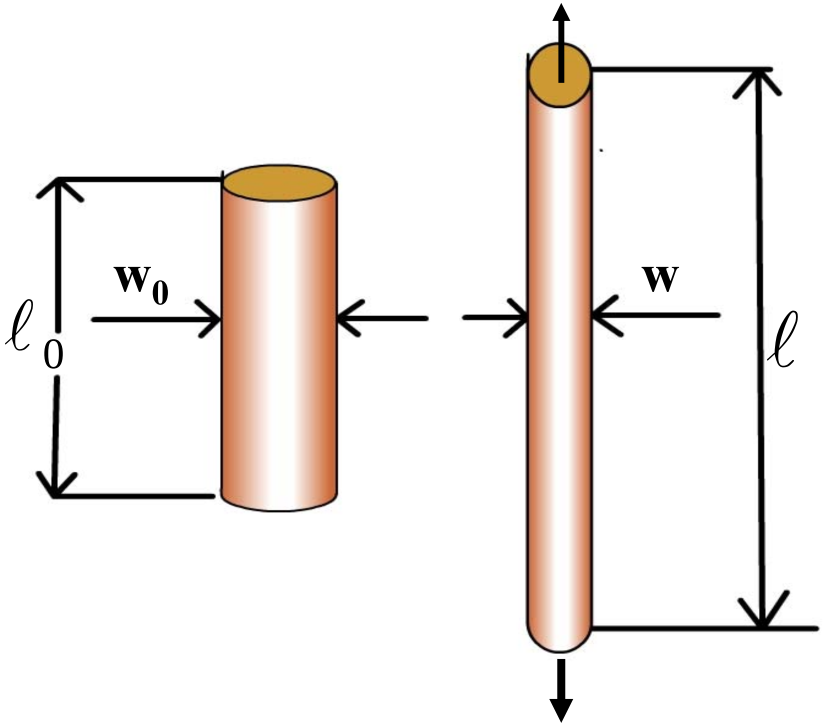


$$\nu = -\frac{w - w_0}{\ell - \ell_0}$$

Usually poisons ratio ranges from

0.25 to 0.4.

Example: Stainless steel → 0.28

Copper → 0.33

Shear Stress and Shear Strain

$$\tau = \text{Shear stress} = \frac{\text{S (Shear force)}}{\text{A (Area of shear force application)}}$$

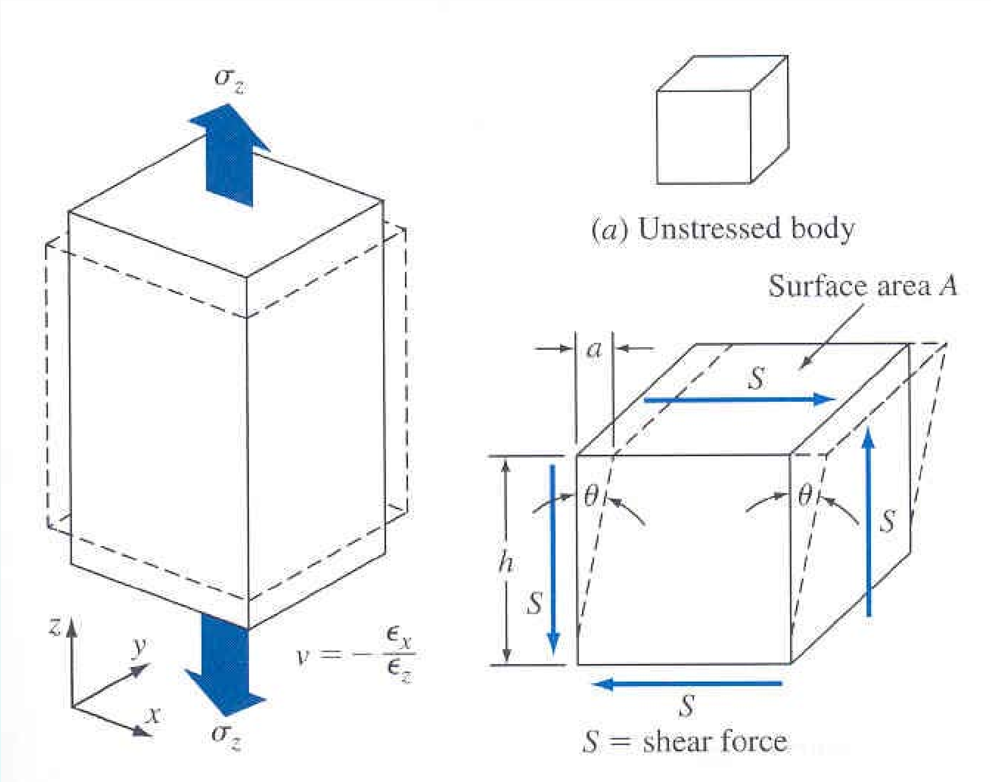


Figure 5.17

$$\text{Shear strain } \gamma = \frac{\text{Amount of shear displacement}}{\text{Distance 'h' over which shear acts.}}$$

$\tau = G\gamma$ G:Elastic Modulus

Tensile test

◆ **Strength of materials can be tested by pulling the metal to failure.**

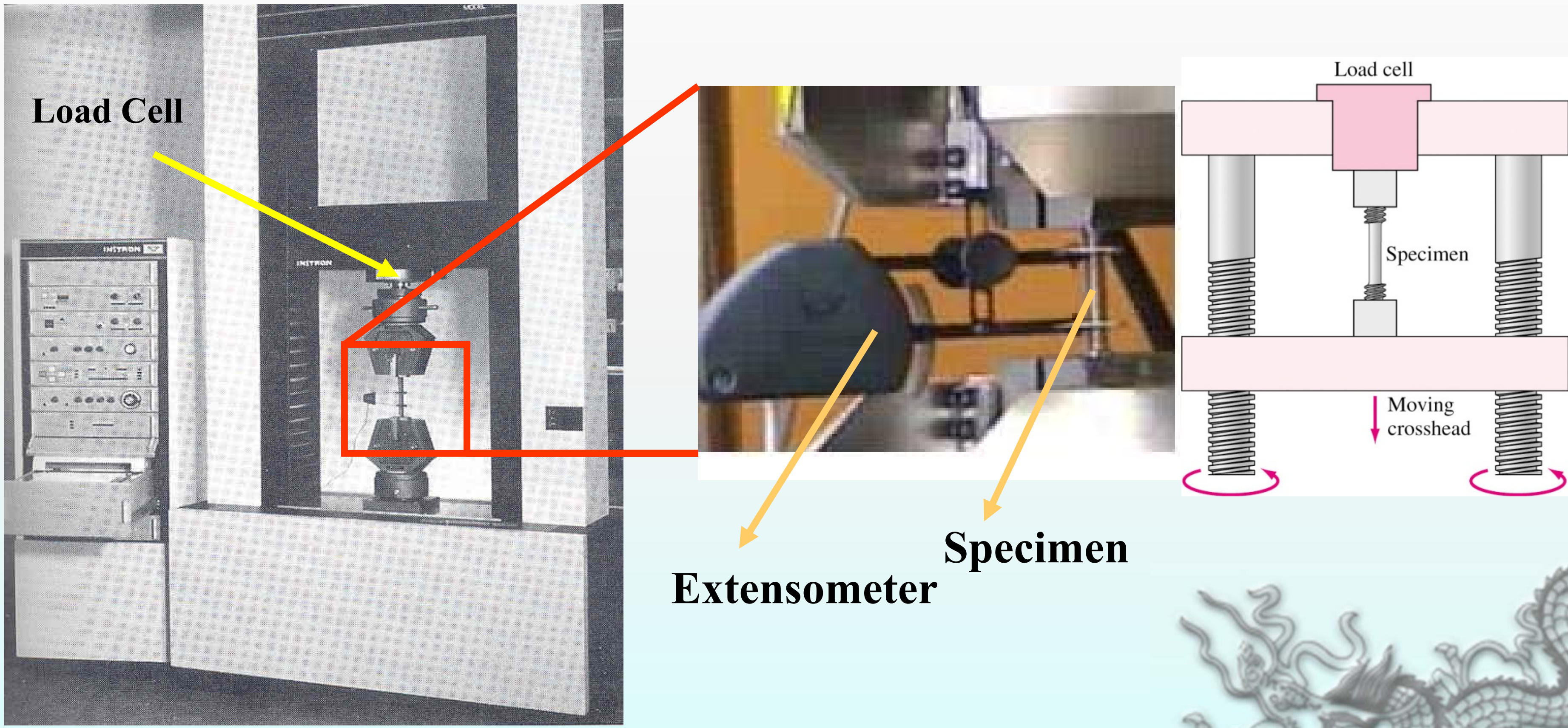


Figure 5.18

Force data is obtained from Load cell

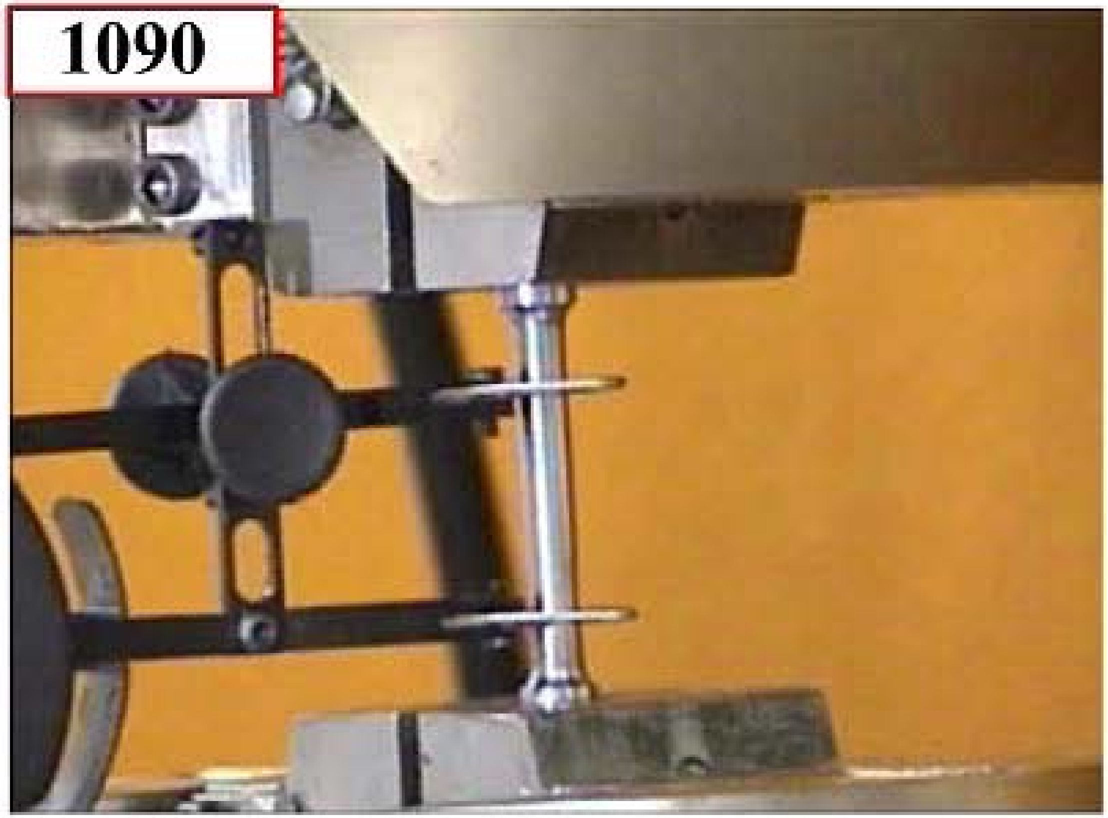
Strain data is obtained from Extensometer.

Tensile Test – 1018 Steel (Low Carbon)

Tensile strength = 440 Mpa Modulus of Elasticity = 205 Gpa

Reduction in area = 40%, Elongation = 15%

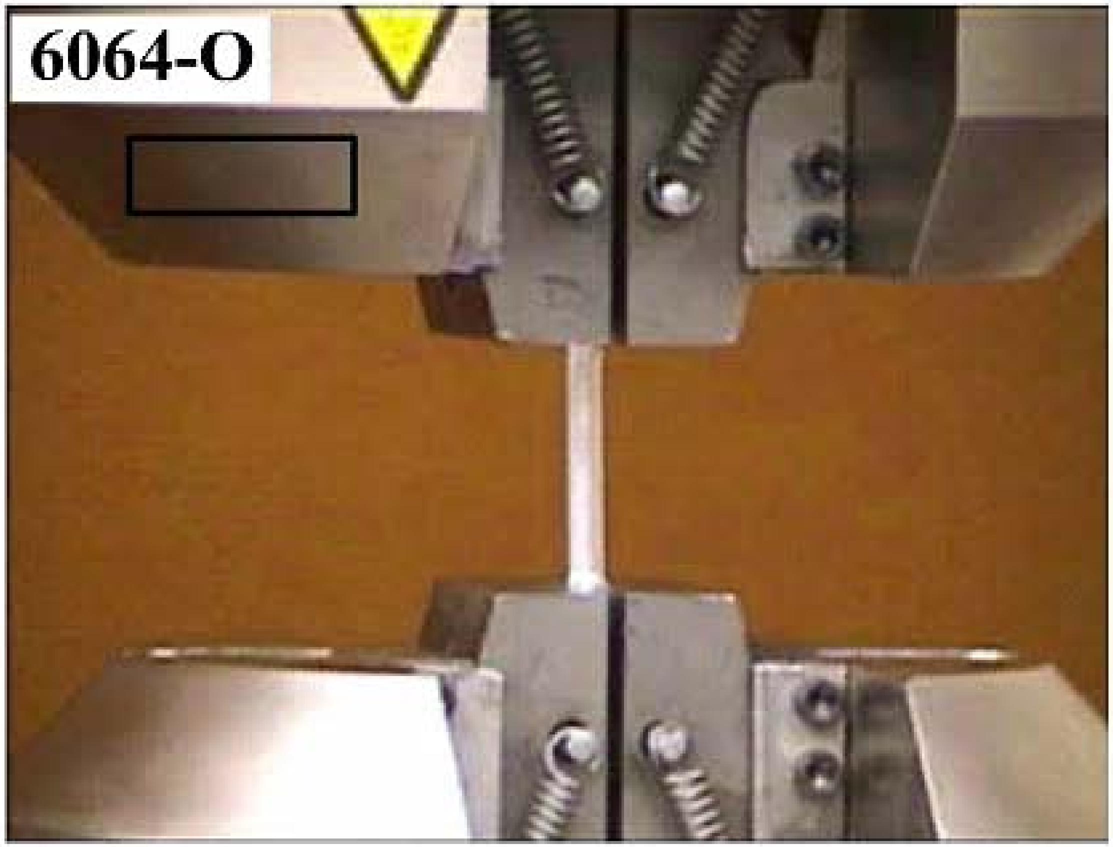
Tensile Test 1090 Steel (High Carbon)



Tensile Strength = 696 Mpa, Elastic Modulus = 207 Gpa

Area reduction = 40%, Elongation = 10%

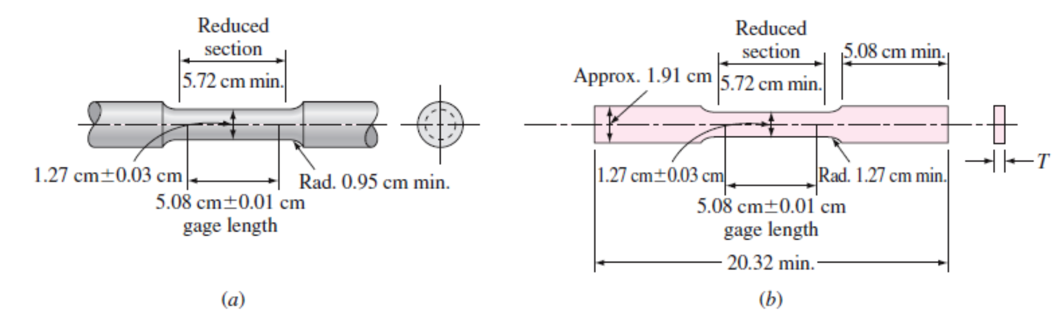
Tensile Test – 6064-O Aluminum (Annealed)



Ultimate tensile strength = 89 MPa, Modulus of elasticity = 69 Gpa

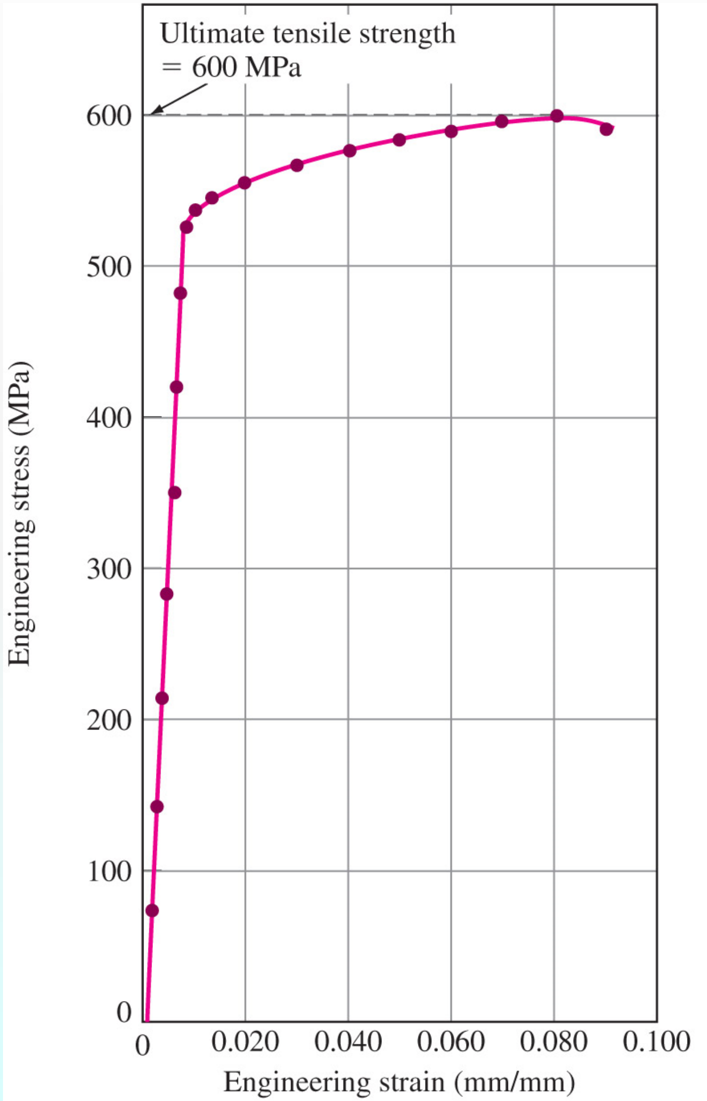
Reduction in area = 68%, Elongation = 28%

Tensile Test (Cont)



Commonly used Test specimen

- ❑ Modulus of elasticity.
- ❑ Yield strength at 0.2 % percent offset.
- ❑ Ultimate tensile Strength
- ❑ Percent elongation at fracture
- ❑ Percent reduction in area at fracture.

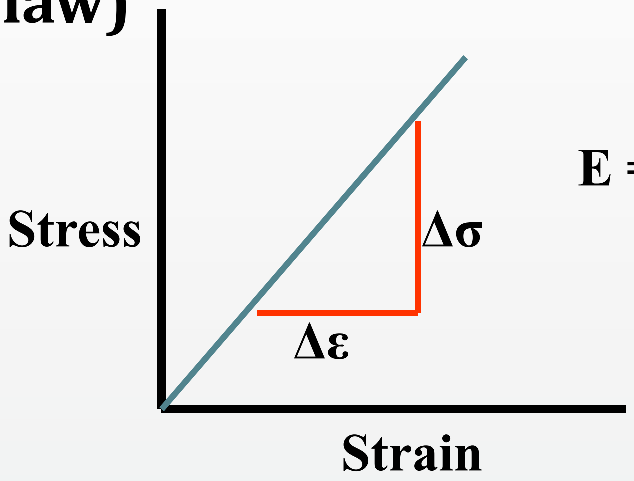


Typical Stress-strain curve

Mechanical Properties

- **Modulus of elasticity (E) : Stress and strain are linearly related in elastic region. (Hooks law)**

$$E = \frac{\sigma \text{ (Stress)}}{\varepsilon \text{ (Strain)}}$$



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

Linear portion of the stress strain curve

- **Higher the bonding strength, higher is the modulus of elasticity.**

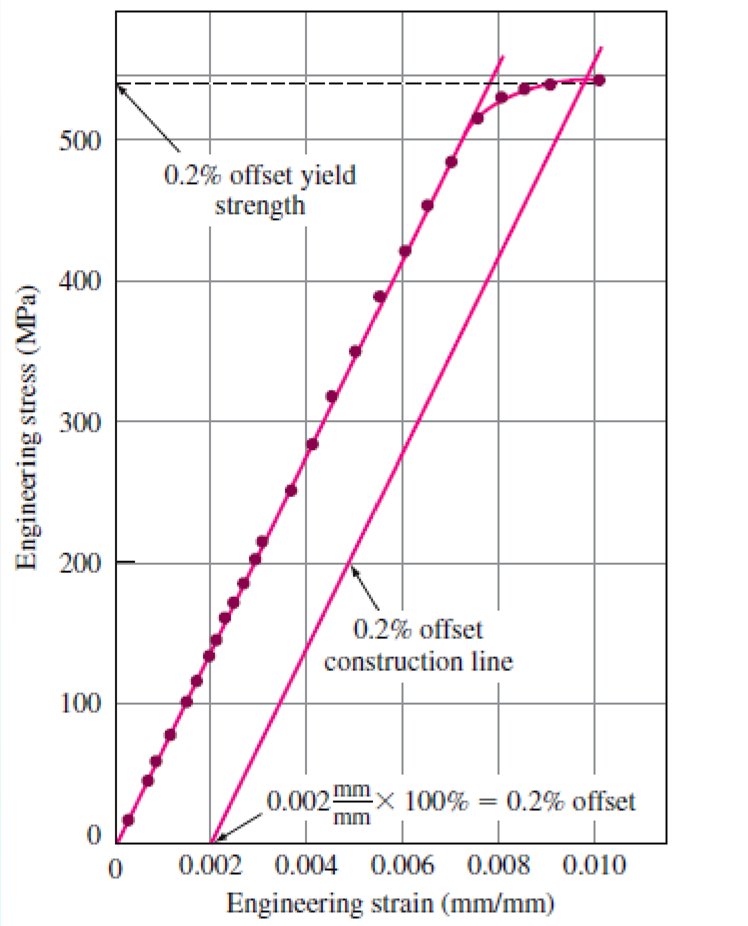
- **Examples: Modulus of elasticity of steel is 207 Gpa.**
  Modulus of elasticity of Aluminum is 76 Gpa

Yield Strength

- Yield strength is strength at which metal or alloy show significant amount of plastic deformation.

- *0.2% offset yield strength* is that strength at which 0.2% plastic deformation takes place.

- Construction line, starting at 0.2% strain and parallel to elastic region is drawn to find 0.2% offset yield strength.



Ultimate tensile strength

- Ultimate tensile strength (UTS) is the maximum strength reached by the engineering stress strain curve.
- Necking starts after UTS is reached.

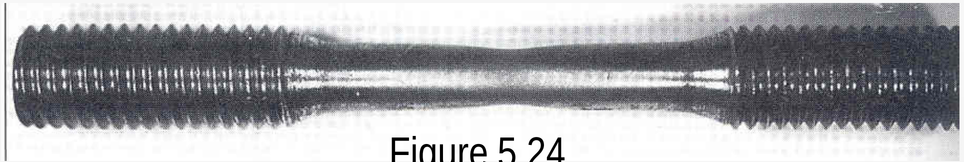
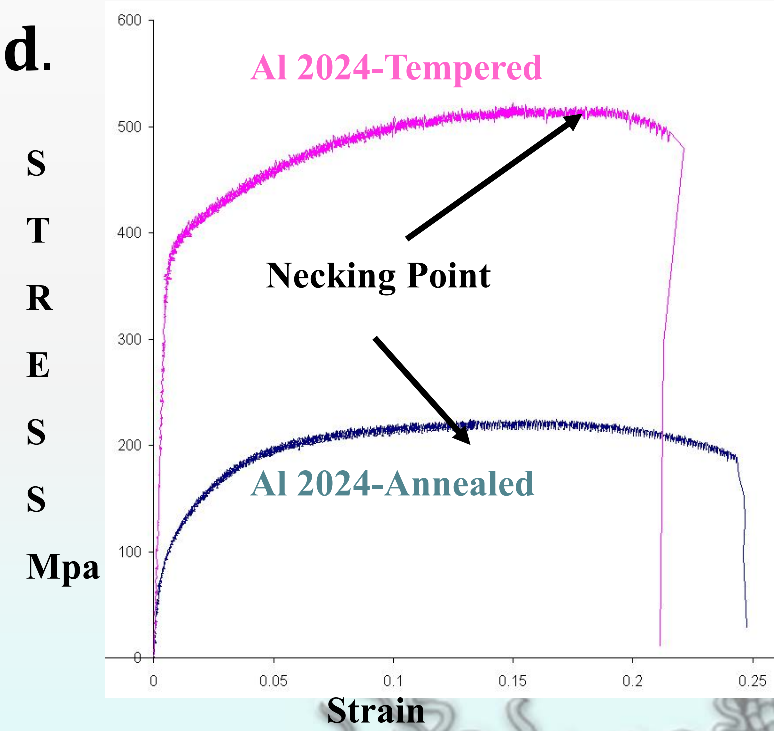


Figure 5.24

- More ductile the metal is, more the necking can be formed before failure.



Stress strain curves of Al 2024 With two different heat treatments. Ductile annealed sample necks more

- Stress **increases** till failure. Drop in stress strain curve is due to stress calculation based on original area.

Percent Elongation

- Percent elongation is a measure of ductility of a material.
- It is the elongation of the metal before fracture expressed as percentage of original length.

$$\% \text{ Elongation} = \frac{\text{Final length} - \text{initial Length}}{\text{Initial Length}}$$

- Example:- Percent elongation of pure aluminum is 35%

For 7076-T6 aluminum alloy it is 11%

Percent Reduction in Area

- Percent reduction area is also a measure of ductility.
- The diameter of fractured end of specimen is measured using caliper.

$$\%\ \text{Reduction Area} = \frac{\text{Initial area} - \text{Final area}}{\text{Final area}}$$

- Percent reduction in area in metals decreases in case of presence of porosity.

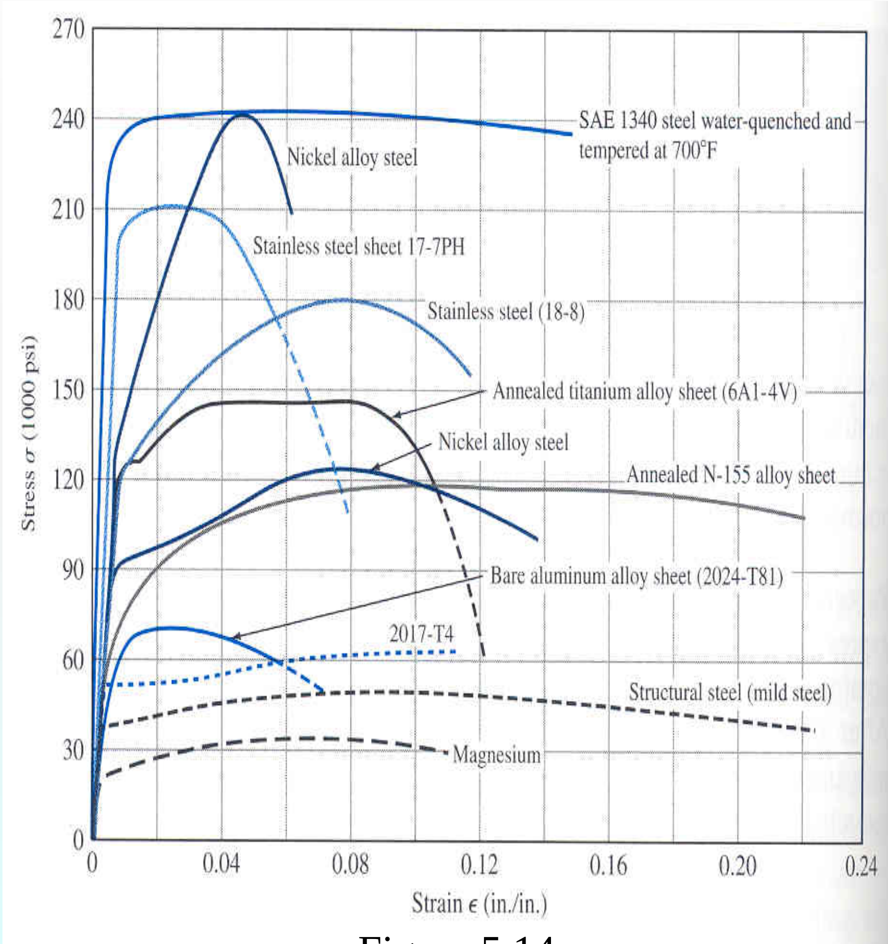


Figure 5.14
Stress-strain curves of different metals

Example Problem 6.7

A 12.7-mm-diameter round sample of a 1030 carbon steel is pulled to failure in a tensile testing machine. The diameter of the sample was 8.7 mm at the fracture surface. Calculate the percent reduction in area of the sample.

■ **Solution**

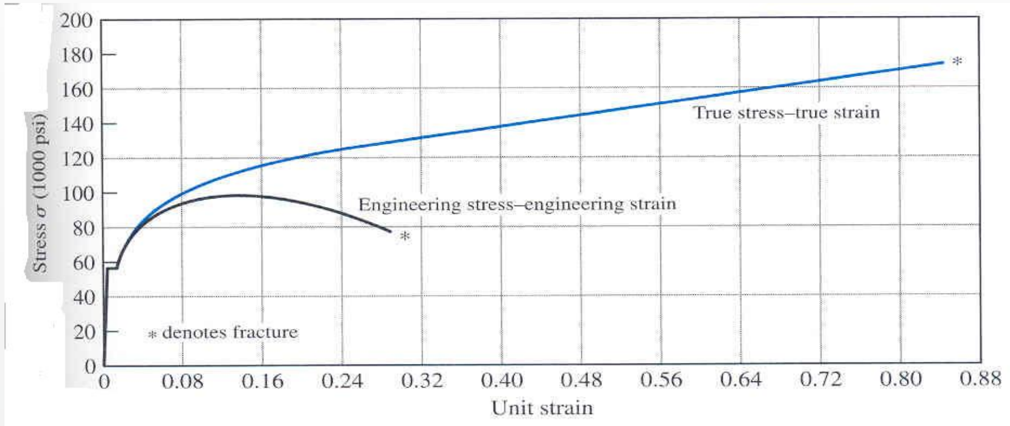
$$\% \text{ reduction in area} = \frac{A_0 - A_f}{A_0} \times 100\% = \left(1 - \frac{A_f}{A_0}\right)(100\%)$$

$$= \left[1 - \frac{(\pi/4)(8.7\text{ mm})^2}{(\pi/4)(12.7\text{ mm})^2}\right](100\%)$$

$$= (1 - 0.47)(100\%) = 53\% \blacktriangleleft$$

True Stress – True Strain

- True stress and true strain are based upon instantaneous cross-sectional area and length.



- True Stress = $\sigma_t = \dfrac{F}{A_i \text{ (instantaneous area)}}$

- True Strain = $\varepsilon_t = \displaystyle\int_{\ell_0}^{\ell_i} \frac{d\ell}{\ell} = Ln\frac{l_i}{l_0} = Ln\frac{A_0}{A_i}$

- True stress is always greater than engineering stress.

Relation of true stress/strain and engineering stress/strain

Constant Volume

$A_0L_0=A_iL_i$

$A_0/A_i=L_i/L_0$

e(Engineering strain)$=(L_i-L_0)/L_0$

$=(L_i/L_o)-1$

$\varepsilon=\ln L_i/L_0=\ln(e+1)$

$\sigma_t=F/A=F/Ao*Ao/A$

$=\sigma_e\,(1+e)$

Example Problem 6.8

Compare the engineering stress and strain with the true test and strain for the tensile test of a low-carbon steel that has the following test values.

Load applied to specimen = 69,000 N Initial specimen diameter = 1.27 cm

Diameter of specimen under 69,000 N load = 1.20 cm

■ **Solution**

$$\text{Area at start } A_0 = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.0127\text{ m})^2 = 0.0001267\text{ m}^2$$

$$\text{Area under load } A_i = \frac{\pi}{4}(0.012\text{ m})^2 = 0.0001131\text{ m}^2$$

Assuming no volume change during extension, $A_0 l_0 = A_i l_i$ or $l_i/l_0 = A_0/A_i$.

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{69{,}000\text{ N}}{0.0001267\text{ m}^2} = 544.6\text{ MPa} \blacktriangleleft$$

$$\text{Engineering strain} = \frac{\Delta l}{l} = \frac{l_i - l_0}{l_0} = \frac{A_0}{A_i} - 1 = \frac{0.0001267\text{ m}^2}{0.0001131\text{ m}^2} - 1 = 0.12$$

$$\text{True stress} = \frac{F}{A_i} = \frac{69{,}000\text{ N}}{0.0001131\text{ m}^2} = 610\text{ MPa} \blacktriangleleft$$

$$\text{True strain} = \ln\frac{l_i}{l_0} = \ln\frac{A_0}{A_i} = \ln\frac{0.0001267\text{ m}^2}{0.0001131\text{ m}^2} = \ln 1.12 = 0.113$$

Hardness and Hardness Testing

- **Hardness is a measure of the resistance of a metal to permanent (plastic) deformation.**
- **General procedure:**

Press the indenter that is harder than the metal Into metal surface.

↓

Withdraw the indenter

↓

Measure hardness by measuring depth or width of indentation.

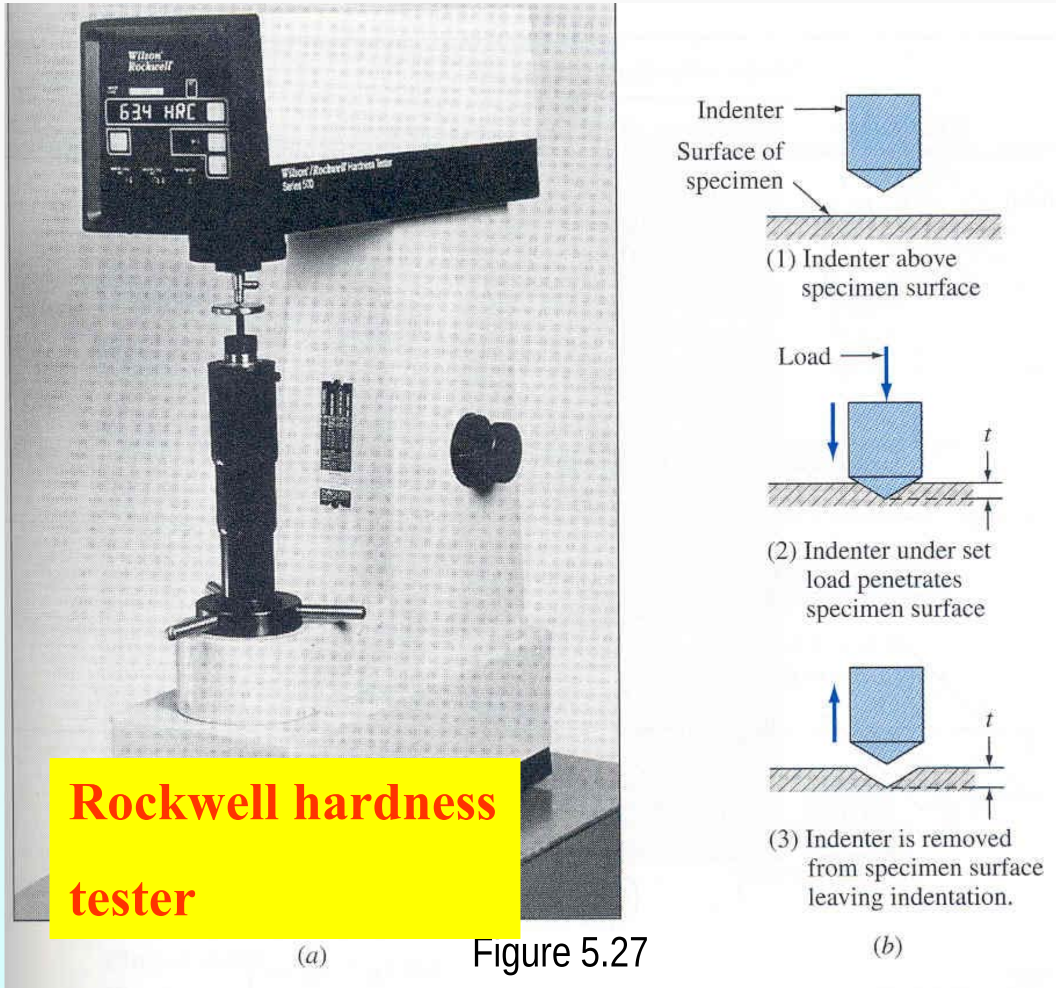
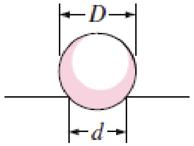
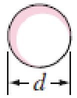
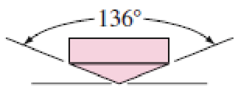
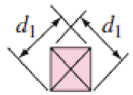
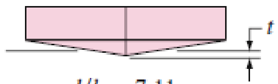
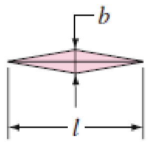
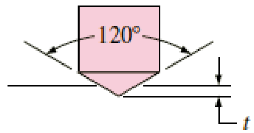
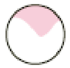
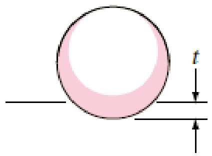
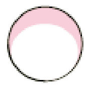


Figure 5.27

Hardness Tests

Table 6.2 Hardness tests

Test	Indenter	Shape of indentation: Side view	Shape of indentation: Top view	Load	Formula for hardness number
Brinell	10 mm sphere of steel or tungsten carbide			P	$\text{BHN} = \dfrac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$
Vickers	Diamond pyramid			P	$\text{VHN} = \dfrac{1.72P}{d_1^2}$
Knoop microhardness	Diamond pyramid	 $l/b = 7.11$ $b/t = 4.00$		P	$\text{KHN} = \dfrac{14.2P}{l^2}$
Rockwell					
A, C, D	Diamond cone			60 kg 150 kg 100 kg	$R_A =$ $R_C =$ $R_D =$ } $100–500f$
B, F, G	1.6-mm-diameter steel sphere			100 kg 60 kg 150 kg	$R_B =$ $R_F =$ $R_G =$ } $130–500f$
E	3.2-mm-diameter steel sphere			100 kg	$R_E =$ } $130–500f$

Source: After H.W. Hayden, W.G. Moffatt, and J. Wulff, "The Structure and Properties of Materials," vol. III, Wiley, 1965, p. 12.

Plastic Deformation in Single Crystals

- Plastic deformation of single crystal results in **step markings** on surface ⟹ **slip bands.**
- Atoms on specific crystallographic planes (slip planes) slip to cause slip bands.

Slip bands

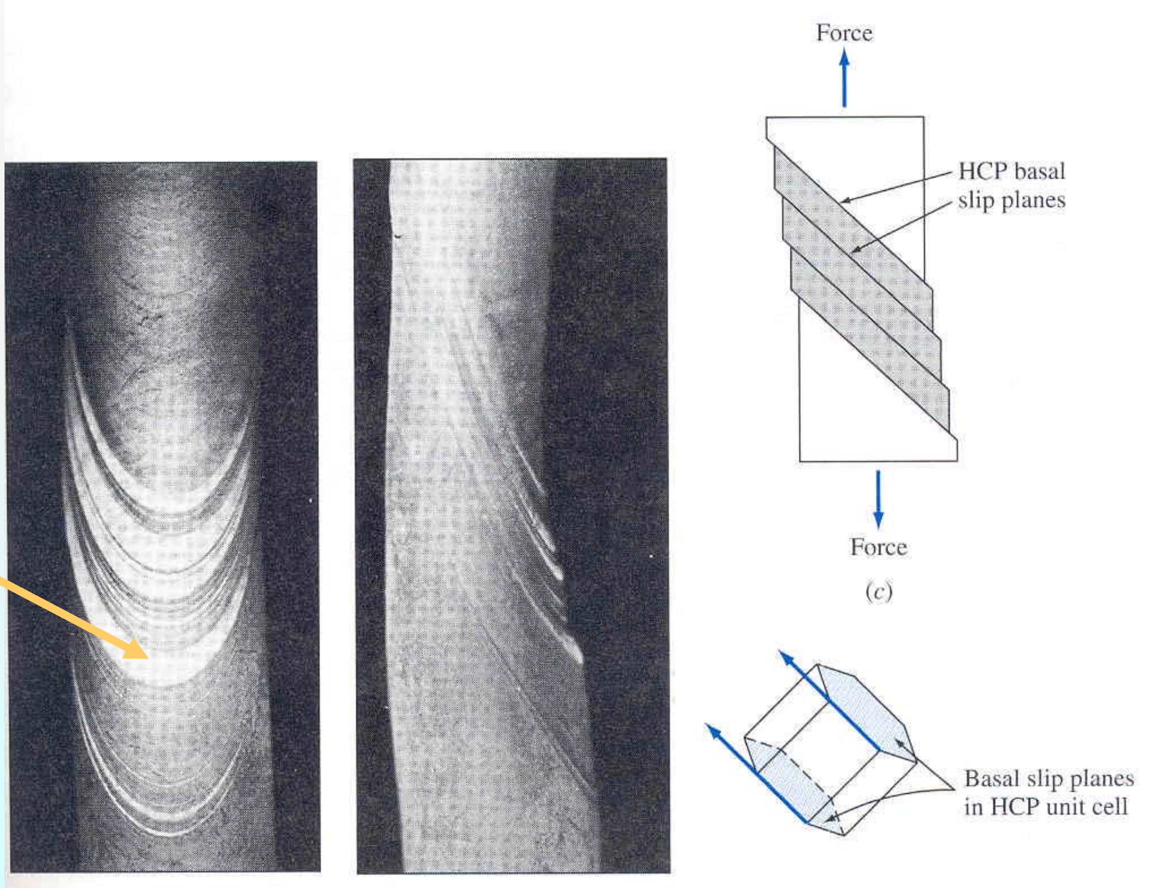


Figure 5.28

Slip Bands and Slip Planes

- Slip bands in ductile metals are uniform (occurs in many slip planes).
- Slip occurs in many *slip planes* within slip bands.
- Slip planes are about 200A thick and are offset by about 2000A

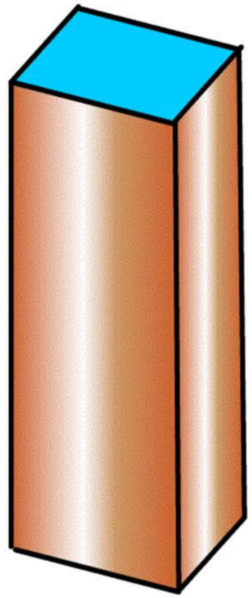


Figure 5.30

Slip Mechanism

- During shear stress, atoms do not slide over each other.
- The slip occurs due to movement of dislocations.

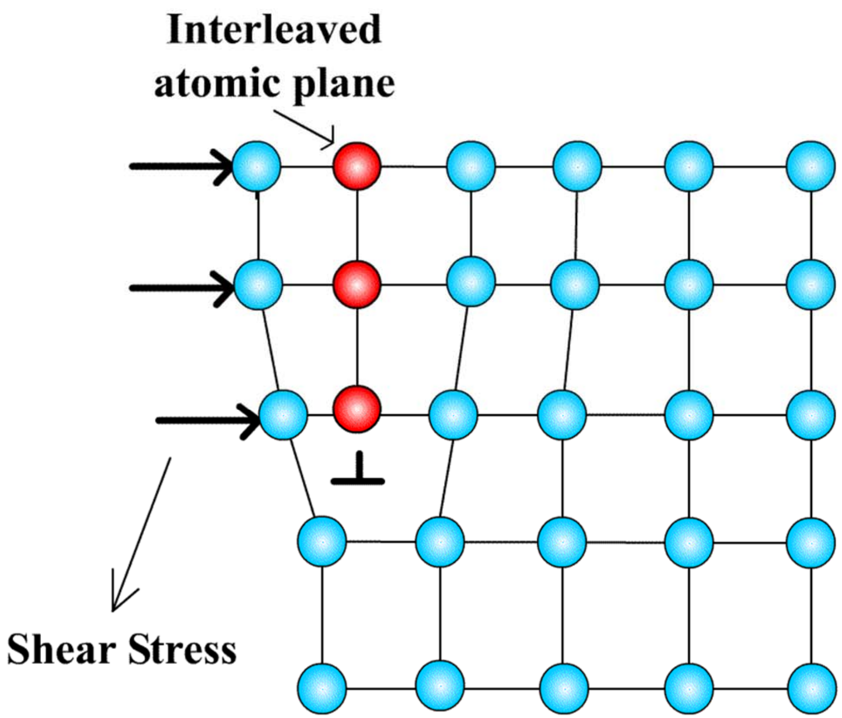


Figure 5.32

Wall of high dislocation density

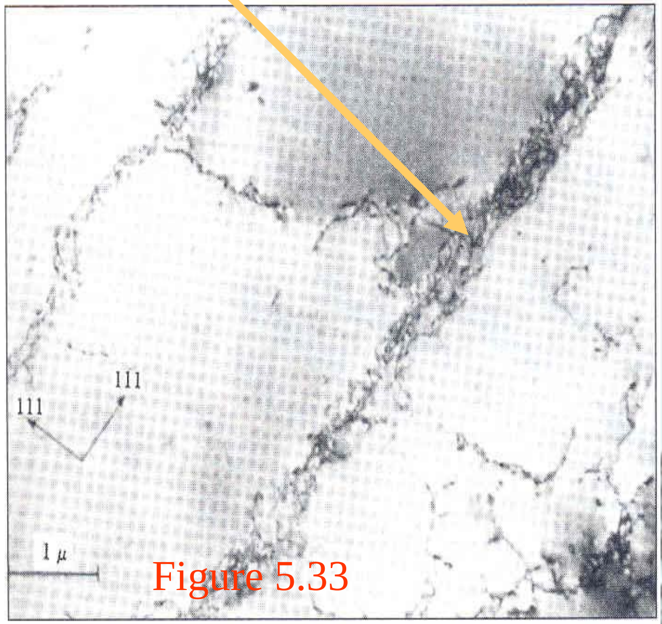


Figure 5.33

Dislocation cell structure in lightly deformed Aluminum

Slip in Crystals

- Slip occurs in densely or close packed planes.
- Lower shear stress is required for slip to occur in densely packed planes.
- If slip is restricted in close planes, then less dense planes become operative.
- Less energy is required to move atoms along denser planes.

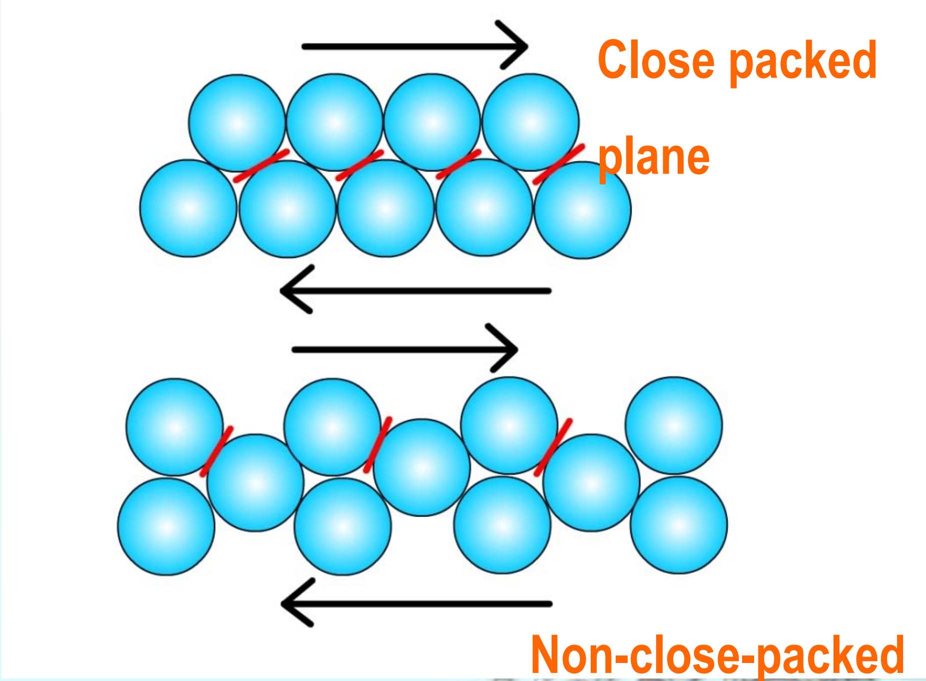


Figure 5.34

Slip Systems

- Slip systems are combination of slip planes and slip direction.
- Each crystal has a number of characteristic slip systems.
- In FCC crystal, slip takes place in {111} octahedral planes and <110> directions.

4 (111) type planes and 3 [110] type directions.

4 x 3 = 12 slip systems.

Structure	Slip plane	Slip direction	Number of slip systems
FCC: Cu, Al, Ni, Pb, Au, Ag, γFe, . . .	{111}	$\langle 1\bar{1}0 \rangle$	$4 \times 3 = 12$

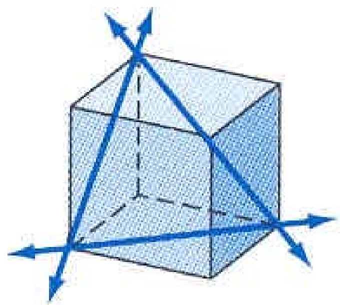
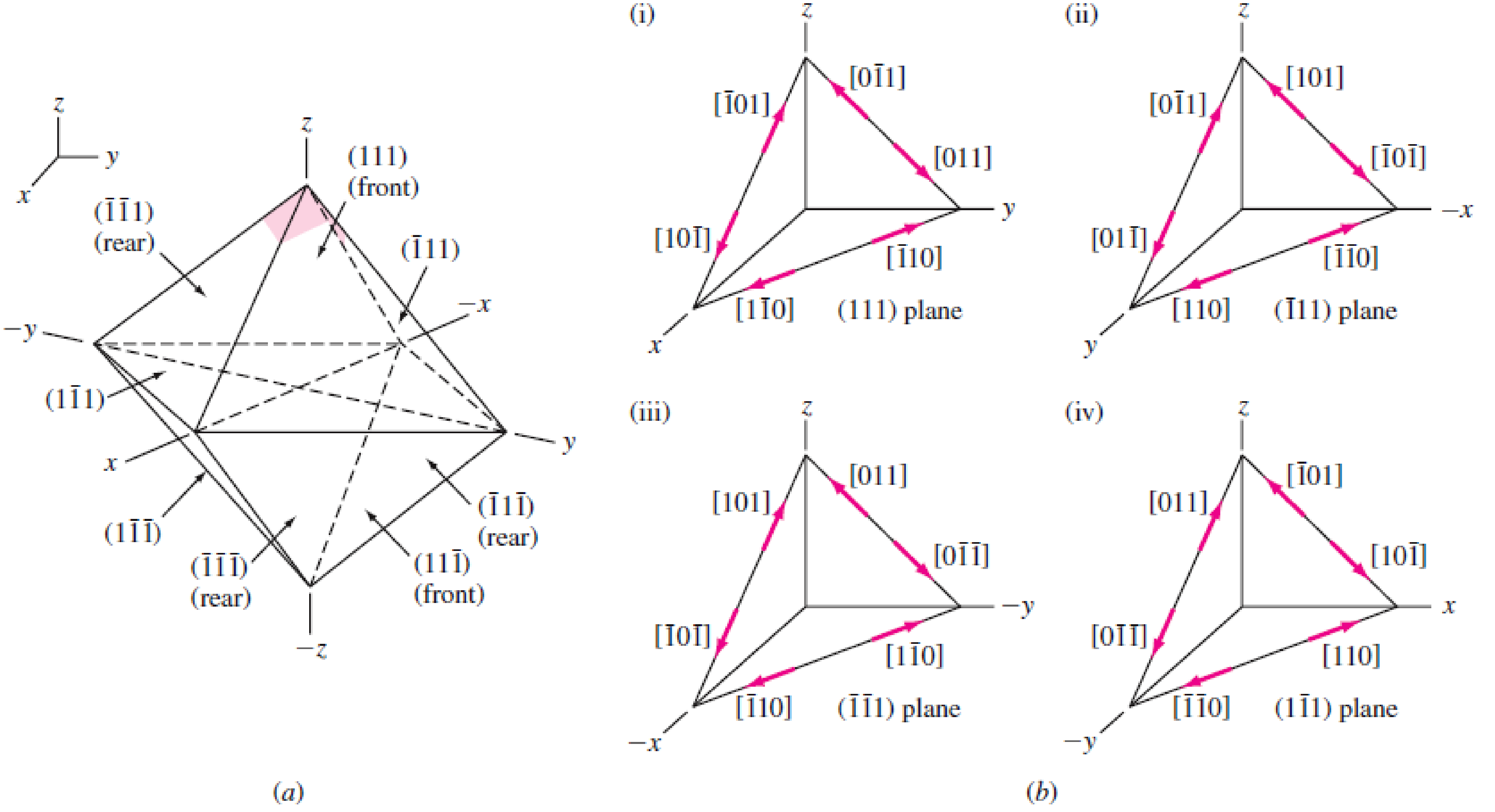


Table 5.3



z
y
x
(111) (front)
$(\bar{1}\bar{1}1)$ (rear)
$(\bar{1}11)$
−x
−y
$(1\bar{1}1)$
x
y
$(1\bar{1}\bar{1})$
$(\bar{1}\bar{1}\bar{1})$ (rear)
$(11\bar{1})$ (front)
$(\bar{1}1\bar{1})$ (rear)
−z
(a)
(i)
$[\bar{1}01]$
$[0\bar{1}1]$
$[011]$
$[10\bar{1}]$
$[\bar{1}10]$
$[1\bar{1}0]$
(111) plane
(ii)
$[0\bar{1}1]$
$[101]$
$[\bar{1}0\bar{1}]$
$[01\bar{1}]$
$[\bar{1}\bar{1}0]$
$[110]$
$(\bar{1}11)$ plane
(iii)
$[101]$
$[011]$
$[0\bar{1}\bar{1}]$
$[\bar{1}0\bar{1}]$
$[1\bar{1}0]$
$[\bar{1}10]$
$(\bar{1}\bar{1}1)$ plane
(iv)
$[011]$
$[\bar{1}01]$
$[10\bar{1}]$
$[0\bar{1}\bar{1}]$
$[110]$
$[\bar{1}\bar{1}0]$
$(1\bar{1}1)$ plane
(b)

Slip Systems in BCC Crystal

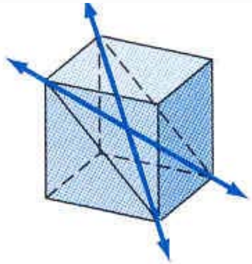
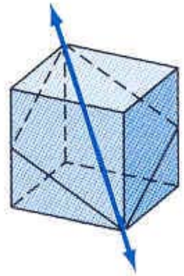
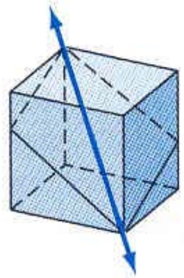
BCC: αFe, W, Mo, β brass	{110}	$\langle\bar{1}11\rangle$	$6 \times 2 = 12$	
αFe, Mo, W, Na	{211}	$\langle\bar{1}11\rangle$	$12 \times 1 = 12$	
αFe, K	{321}	$\langle\bar{1}11\rangle$	$24 \times 1 = 24$	

Table 5.3

- **BCC crystals are not close packed. The slip predominantly occurs in {110} planes that has highest atomic density.**

Slip Systems in HCP Crystal

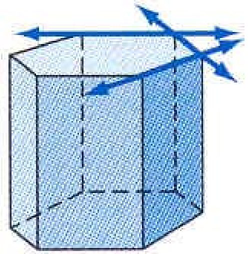
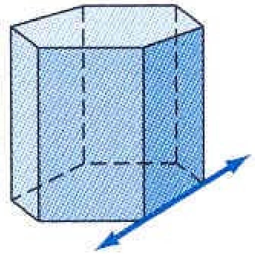
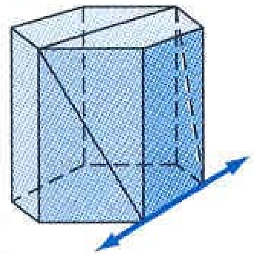
HCP: Cd, Zn, Mg, Ti, Be, . . .	$\{0001\}$	$\langle 11\bar{2}0\rangle$	$1 \times 3 = 3$	
Ti (prism planes)	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	$3 \times 1 = 3$	
Ti, Mg (pyramidal planes)	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	$6 \times 1 = 6$	

Table 5.3

◆ **If HCP crystals have high c/a ratio, slip occurs along basal planes {0001}. For crystals with low c/a ratio, slip also occurs in $\{10\bar{1}0\}$ and $\{10\bar{1}1\}$ planes.**

Critical Resolved Shear Stress

- Critical resolved shear stress is the stress required to cause slip in pure metal single crystal.
- Depends upon
  - Crystal Structure
  - Atomic bonding characteristics
  - Temperature
  - Orientation of slip planes relative to shear stress
- Slip begins when shear stress in slip plane in slip direction reaches critical resolved shear stress.
- This is equivalent to yield stress.
- Example :-

Zn	HCP	99.999% pure	0.18MPa
Ti	HCP	99.99% pure	13.7 MPa

Table 6.4 Room-temperature slip systems and critical resolved shear stress for metal single crystals

Metal	Crystal structure	Purity (%)	Slip plane	Slip direction	Critical shear stress (MPa)
Zn	HCP	99.999	(0001)	$[11\bar{2}0]$	0.18
Mg	HCP	99.996	(0001)	[1120]	0.77
Cd	HCP	99.996	(0001)	$[11\bar{2}0]$	0.58
Ti	HCP	99.99	(1010)	$[11\bar{2}0]$	13.7
		99.9	(1010)	$[11\bar{2}0]$	90.1
Ag	FCC	99.99	(111)	$[1\bar{1}0]$	0.48
		99.97	(111)	$[1\bar{1}0]$	0.73
		99.93	(111)	$[1\bar{1}0]$	1.3
Cu	FCC	99.999	(111)	$[1\bar{1}0]$	0.65
		99.98	(111)	$[1\bar{1}0]$	0.94
Ni	FCC	99.8	(111)	$[1\bar{1}0]$	5.7
Fe	BCC	99.96	(110)	$[\bar{1}11]$	27.5
			(112)		
			(123)		
Mo	BCC	. . .	(110)	$[\bar{1}11]$	49.0

Source: After G. Dieter, "Mechanical Metallurgy," 2nd ed., McGraw-Hill, 1976, p. 129.

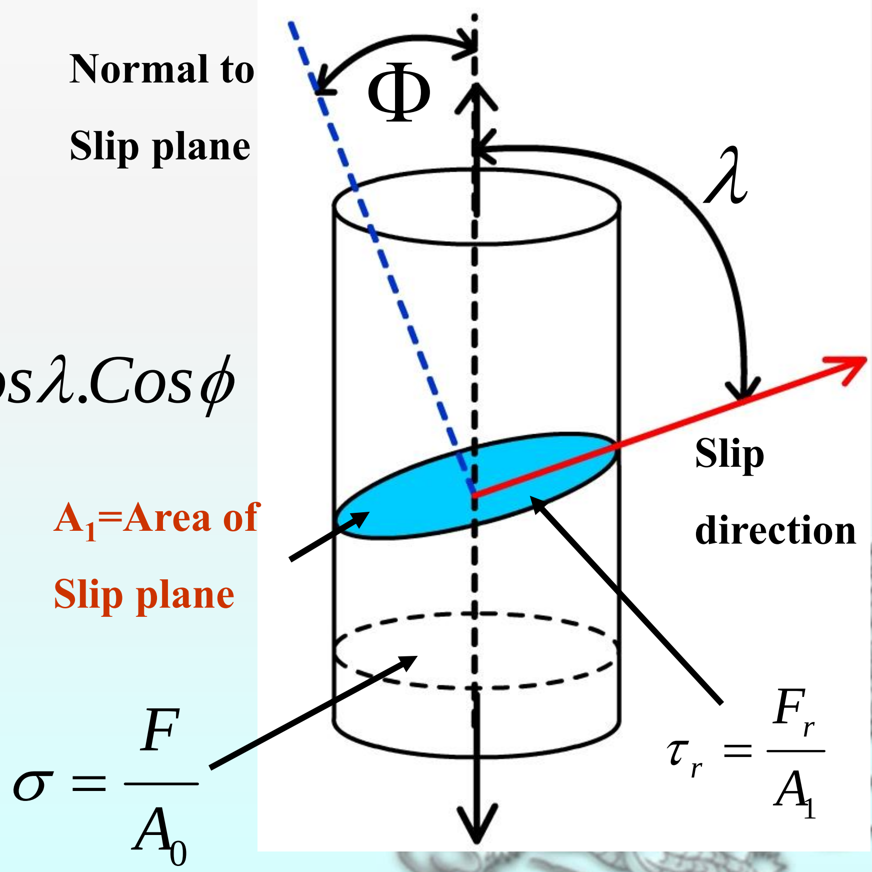
Schmid's Law

- The relationship between uniaxial stress action on a single cylinder of pure metal single crystal and resulting resolved shear stress produced on a slip system is give by

$$\tau_r = \frac{\text{Shear Force}}{\text{Shear Area}}$$

$$= \frac{F_r}{A_1} = \frac{F.Cos\lambda}{A_0 / Cos\Phi} = \frac{F}{A_0} Cos\lambda.Cos\phi$$

$$= \sigma.Cos\lambda.Cos\Phi$$



Example Problem 6.9

Calculate the resolved shear stress on the (111) $[0\bar{1}1]$ slip system of a unit cell in an FCC nickel single crystal if a stress of 13.7 MPa is applied in the [001] direction of a unit cell.

■ Solution

By geometry, the angle λ between the applied stress and the slip direction is 45°, as shown in Fig. EP6.9*a*. In the cubic system, the direction indices of the normal to a crystal plane are the same as the Miller indices of the crystal plane. Therefore, the normal to the (111) plane that is the slip plane is the [111] direction. From Fig. EP6.9*b*,

$$\cos\phi = \frac{a}{\sqrt{3}a} = \frac{1}{\sqrt{3}} \qquad \text{or} \qquad \phi = 54.74°$$

$$\tau_r = \sigma\cos\lambda\cos\phi = (13.7\text{ MPa})(\cos 45°)(\cos 54.74°) = 5.6\text{ MPa} \blacktriangleleft$$

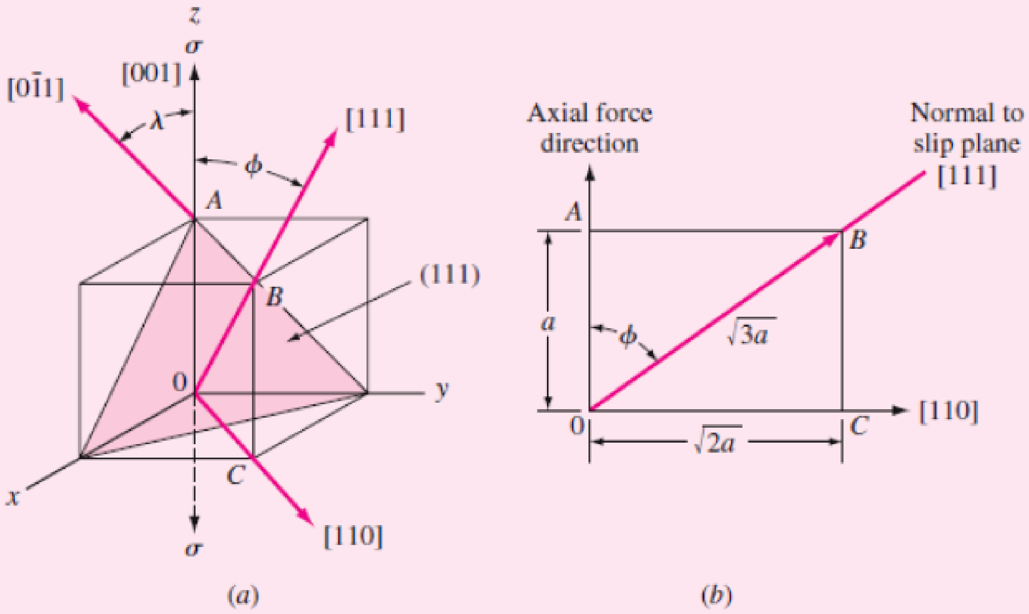
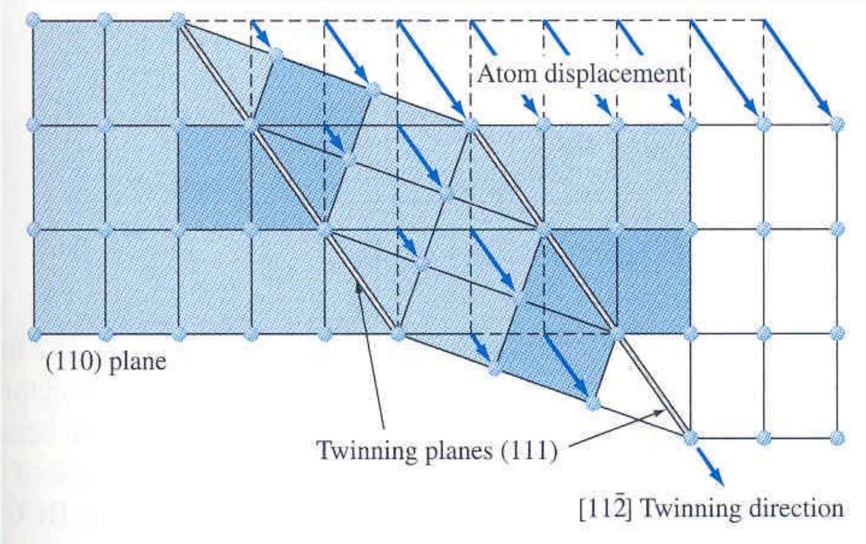


Figure EP6.9
An FCC unit cell is acted upon by a [001] tensile stress producing a resolved shear stress on the (111) $[0\bar{1}1]$ slip system.

Twinning

- In twinning, a part of atomic lattice is deformed and forms *mirror image* of lattice next to it.
- Distance moved by atoms is proportional to their distance from twinning plane.



- Deformation from twinning is small.
- Twinning reorient the slip system.
- Twining is most important in HCP crystals due to lesser slip planes.
- Twining is found in the BCC metals such as Fe, Mo, W, Ta, and Cr in crystals that were deformed at very low temperature/high

Difference between twin and slipband

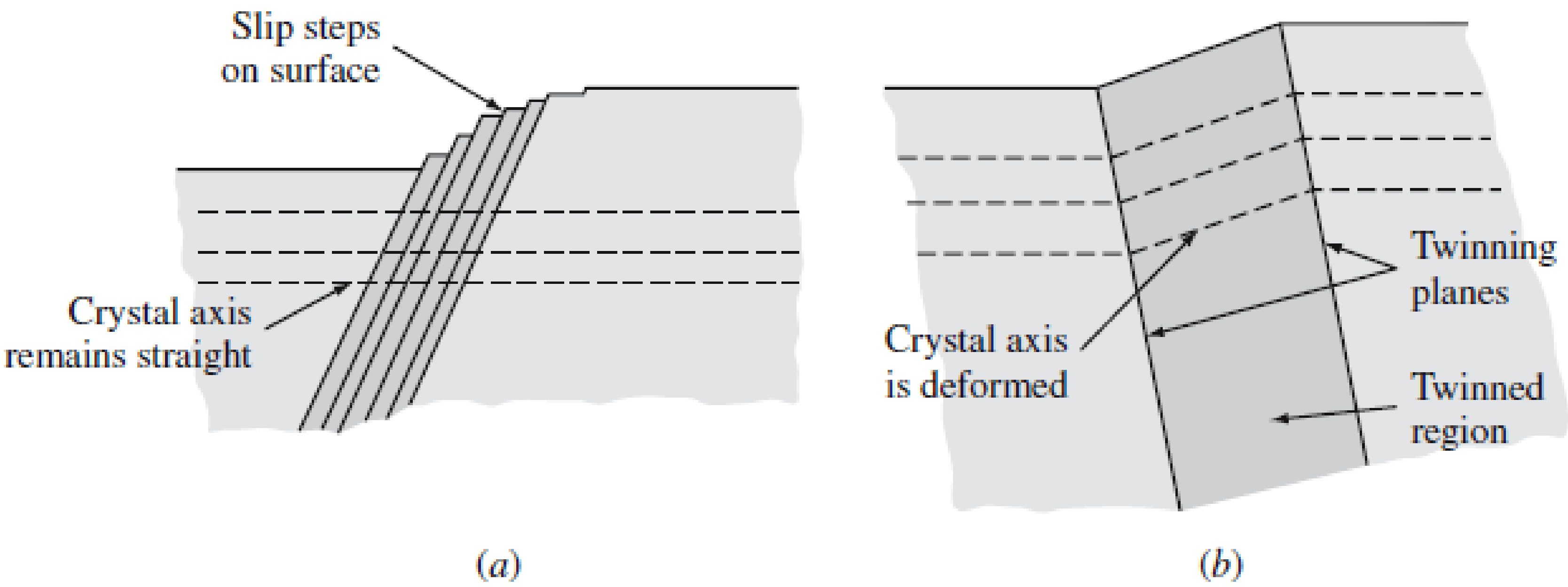


Figure 6.36
Schematic diagram of surfaces of a deformed metal after (*a*) slip and (*b*) twinning.

Effects of Grain Boundaries on Strength

- Grain boundaries stop dislocation movement and hence strengthen the metals.
- Fine grain size is desirable, and hence metals are produced with finer grains.

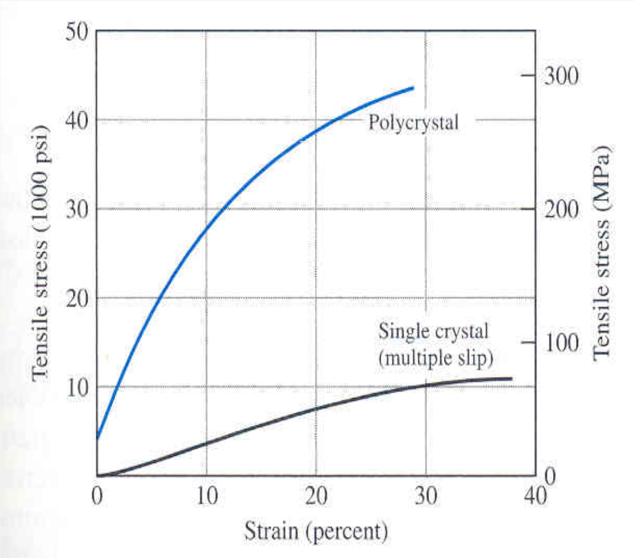


Figure 5.40
Stress-strain curve of single and polycrystalline copper

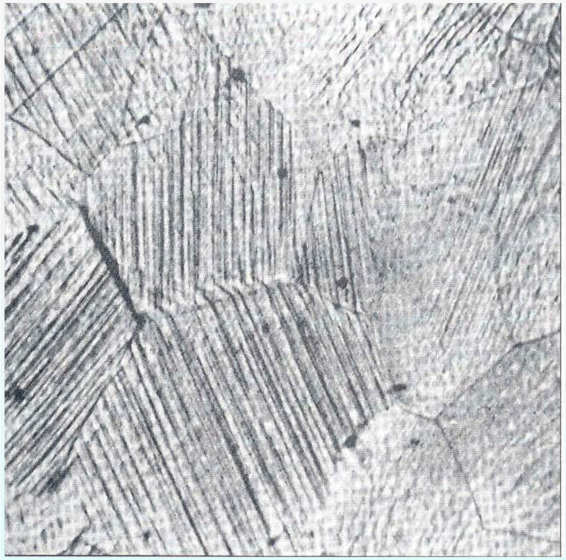


Figure 5.40
Slip bands in polycrystalline aluminum grains

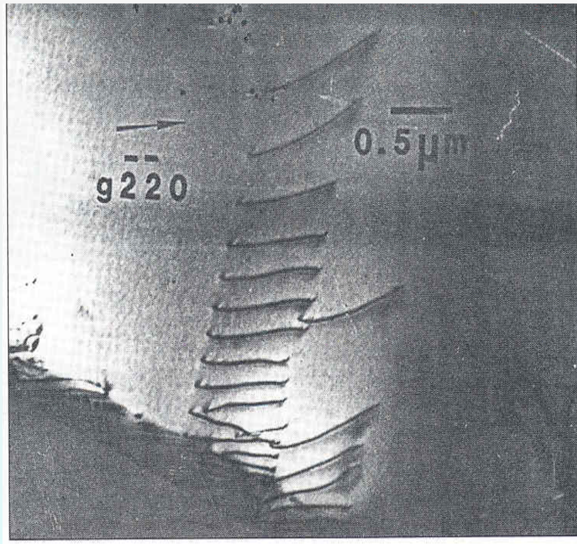


Figure 5.40
Dislocations piled up against grain boundaries in stainless steel

Hall Petch Equation

- Finer the grains, superior are the mechanical properties (at room temperature).
  - More isotropic properties
  - Less resistant to corrosion and creep

Hall-Petch equation - Empirical

$s_y = s_o + k\,/\,(d)^{1/2}$

s_y = Yield strength
d = average grain diameter

s_o and k are **constants** for a metal.

s_o = 70 Mpa and k = 0.74 Mpam$^{1/2}$ for mild steel.

Can not apply to :

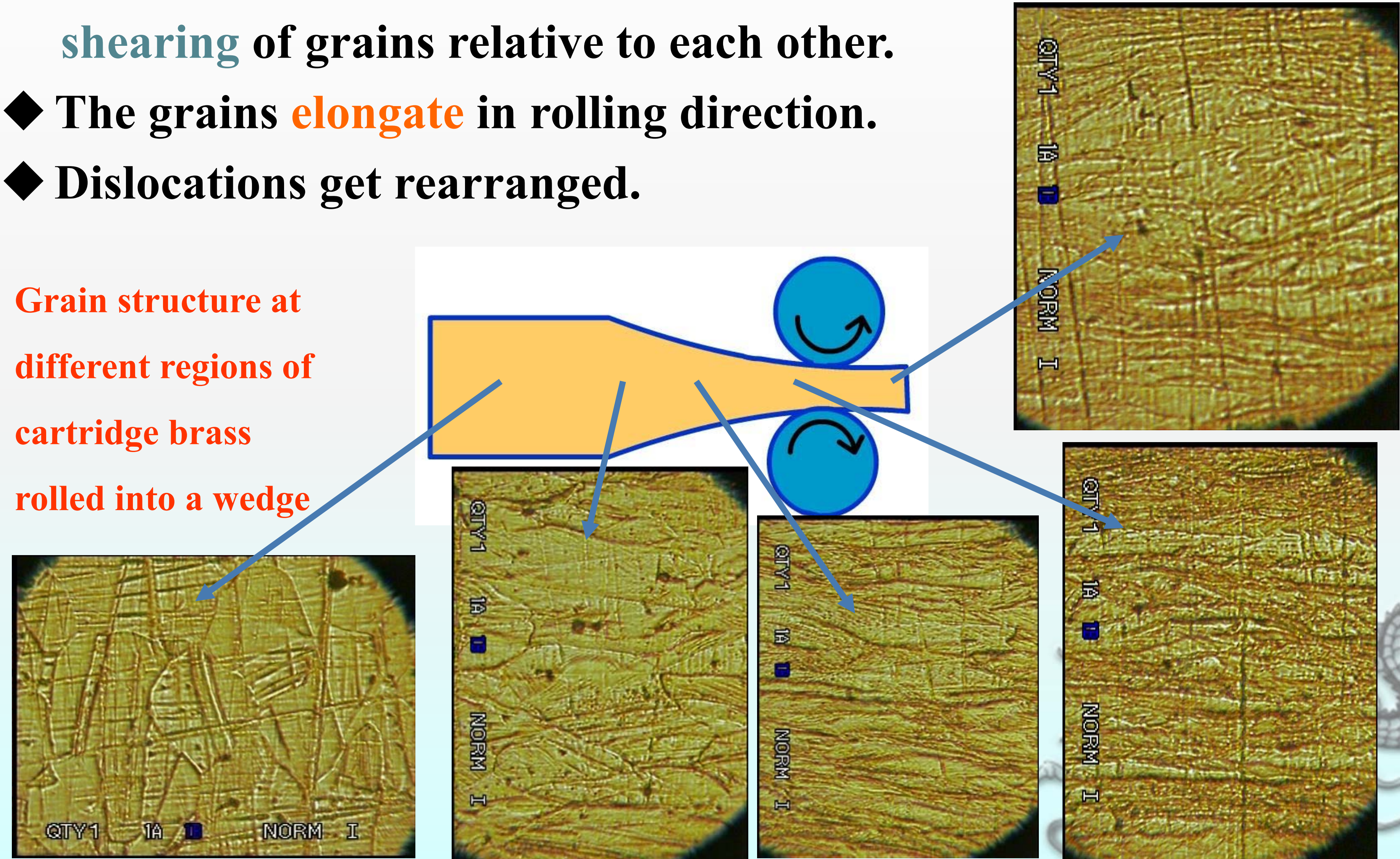
Extremely coarse or extremely fine grain size

Metal used at elevated temperatures

Effects of Plastic Deformation

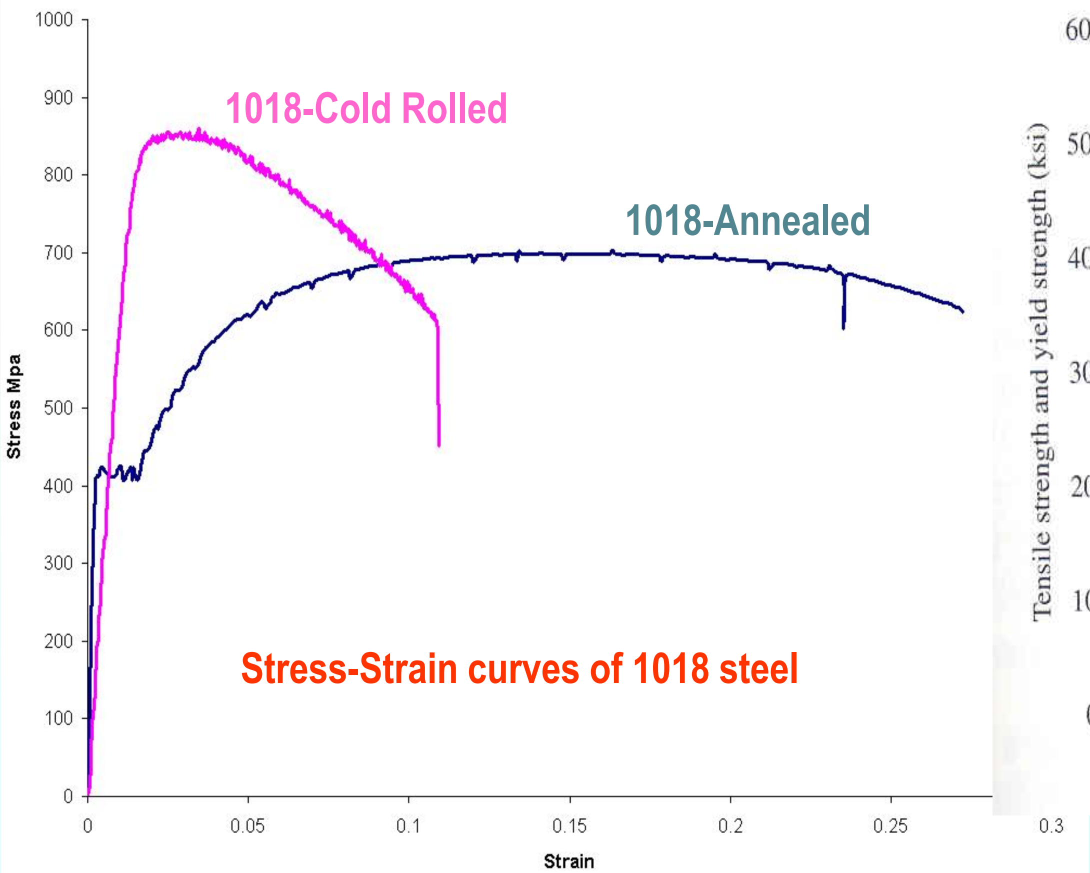
- Plastic deformation results in **shearing** of grains relative to each other.
- The grains **elongate** in rolling direction.
- Dislocations get rearranged.

Grain structure at different regions of cartridge brass rolled into a wedge



Effect of Cold Work on Tensile Strength

- Number of dislocations are increased by cold work.
- Dislocation movements are hindered by both grain boundaries and other dislocations → **Strain Hardening**



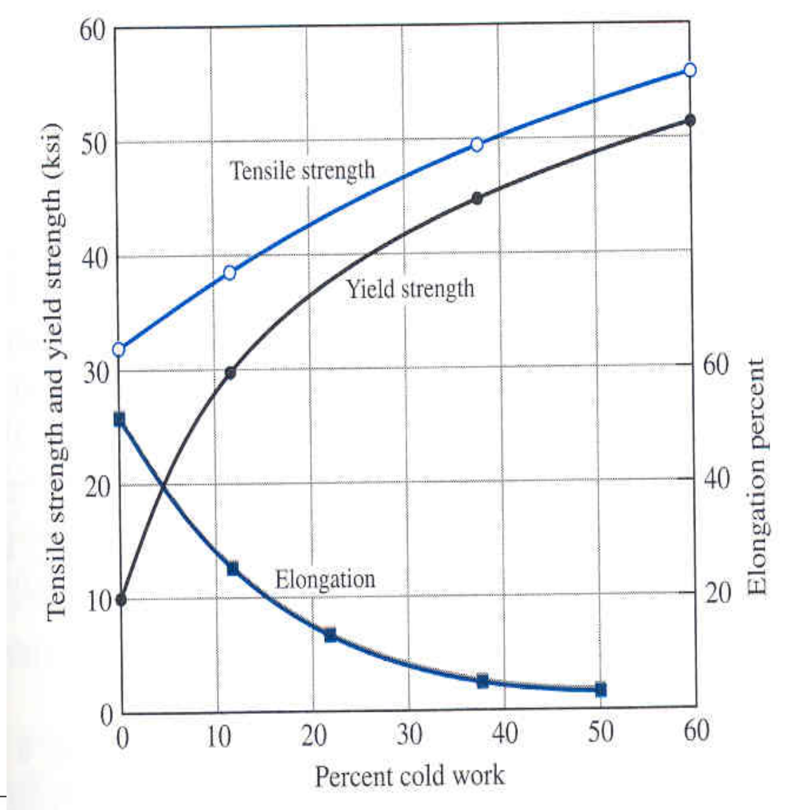


Figure 5.45

Example Problem 6.10

We wish to produce a 1.0-mm-thick sheet of oxygen-free copper with a tensile strength of 310 MPa (45 ksi). What percent cold work must the metal be given? What must the starting thickness of the metal be before cold rolling?

■ **Solution**

From Fig. 6.43, the percent cold work must be 25 percent. Thus, the starting thickness must be

$$\frac{x - 1.0\text{ mm}}{x} = 0.25$$

$$x = 1.33\text{ mm} \blacktriangleleft$$

Solid Solution Strengthening

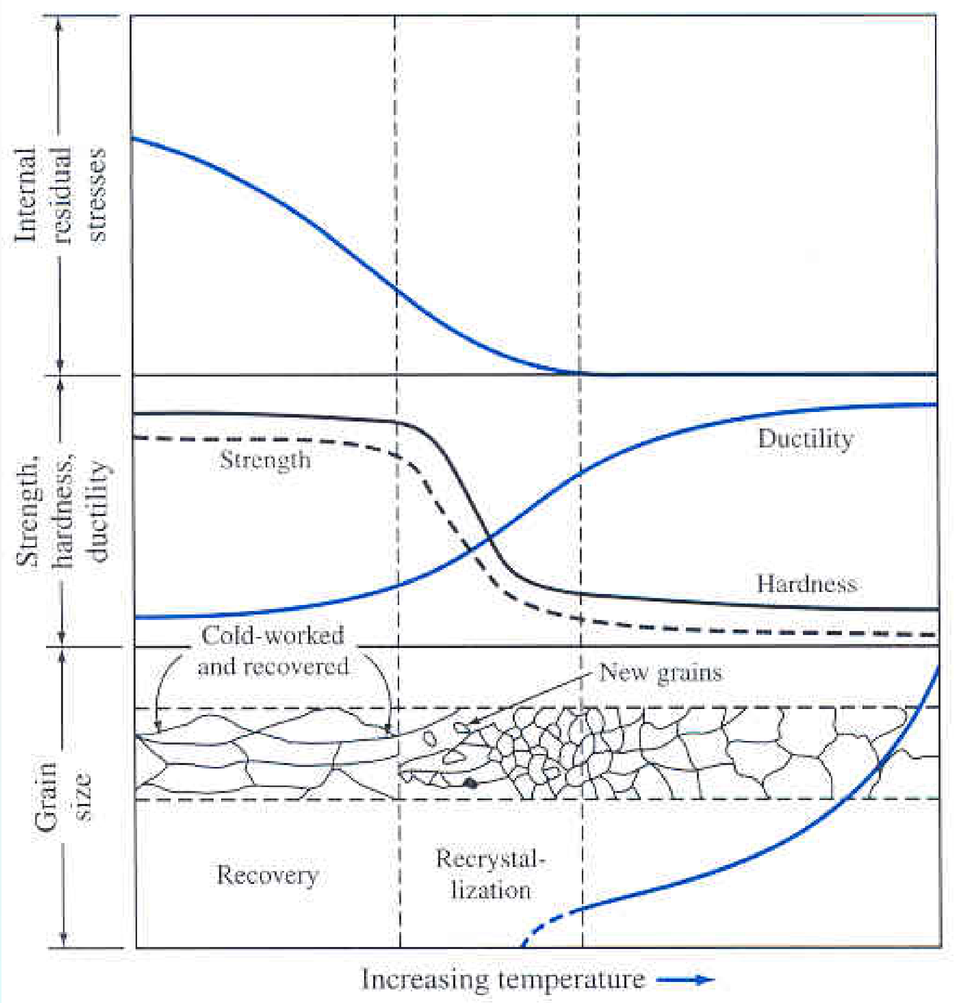
- Addition of one or more metals can increase the strength of metals.
- Solute atoms, on case of substitutional solid solution, create *stress*ation movement.
- Distortion *fields* around themselves and hinder the dislocof lattice and clustering of like atoms also impede dislocation movement.
- Two important factors:

  -Relative-size factors: Different in atomic size of solute and solvent atoms can affect the amount of solid-solution.

  -Short-rang order order: dislocation movement is impeded by different binding structure.
- Example: Solid solution of 70 wt % Cu & 30 wt % Zn (cartridge brass) has tensile strength of 500 MPa. Tensile strength of unalloyed copper is 330 MPa

Recovery and Recrystallization

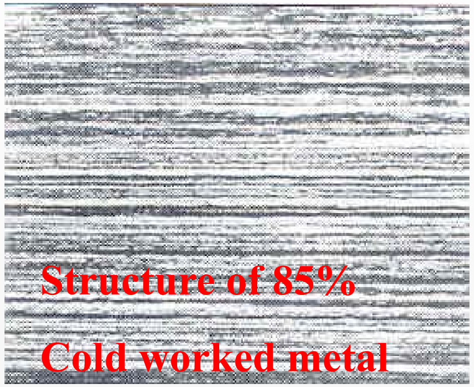
- Cold worked metals become brittle.
- Reheating, which increases ductility results in recovery, recrystallization and grain growth.
- This is called *annealing* and changes material properties.
- Partial and full annealing:
  different degree of softening.

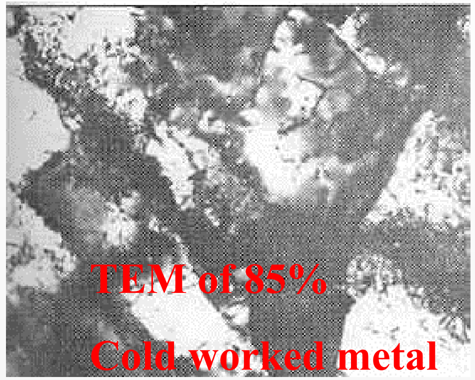


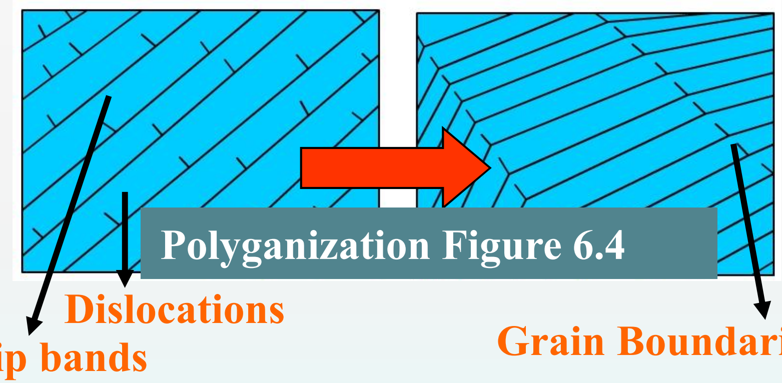
(Adapted from Z.D. Jastrzebski, "The Nature and Properties of Engineering Materials," 2d ed., Wiley, 1976, p.228.)

Structure of Cold Worked Metals

- **Strain energy of cold work is stored as dislocations.**
- **Heating to recovery temperature relieves internal stresses (Recovery stage).**
- ***Polygonization* (formation of sub-grain structure) takes place.**
- **Dislocations are moved into lower energy configuration.**







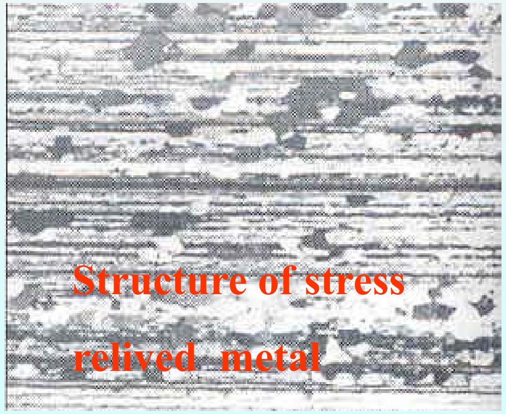
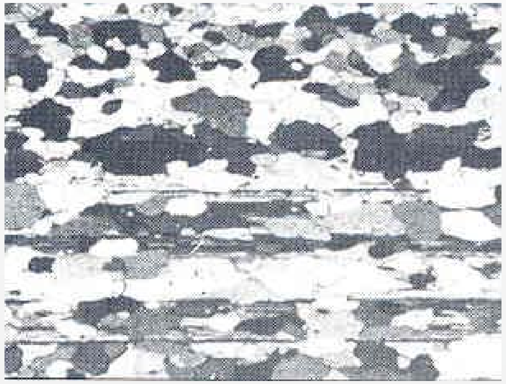


Figure 6.2 and 6.3

(After “Metals Handbook,” vol 7, 8th ed., American Society of Metals, 1972, p.243)

Recrystallization

- If metal is held at recrystallization temperature long enough, cold worked structure is completely replaced with recrystallized grain structure.
- Two mechanisms of recrystallization
  - Expansion of nucleus
  - Migration of grains.



Structure and TEM of Recrystallized metal

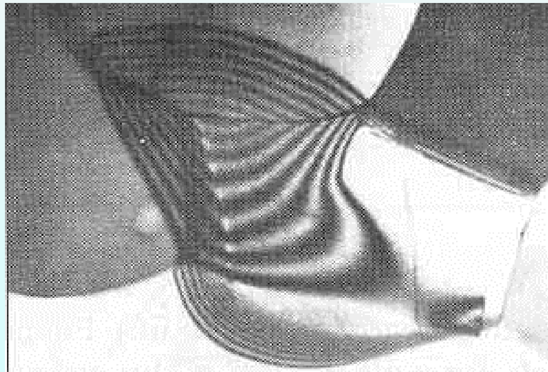


Figure 6.2 and 6.3

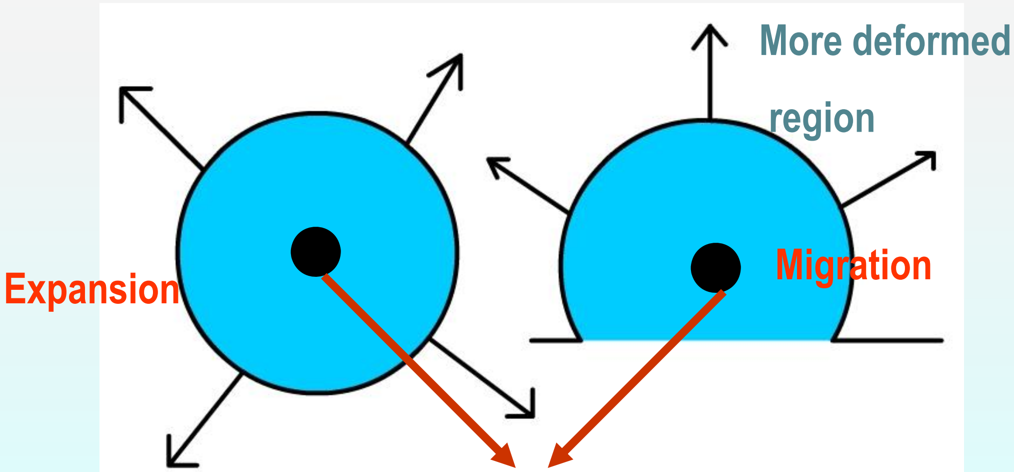


Figure 6.5

(After "Metals Handbook," vol 7, 8th ed., American Society of Metals, 1972, p.243)

Effects on Mechanical Properties

- **Annealing decreases tensile strength, increases ductility.**
- **Example:**

85% Cu & 15% Zn

50% cold rolled → Tensile strength 75 KSI, Ductility 3%

Annealed 1 h 400^0C → Tensile strength 45 KSI, Ductility 38 %

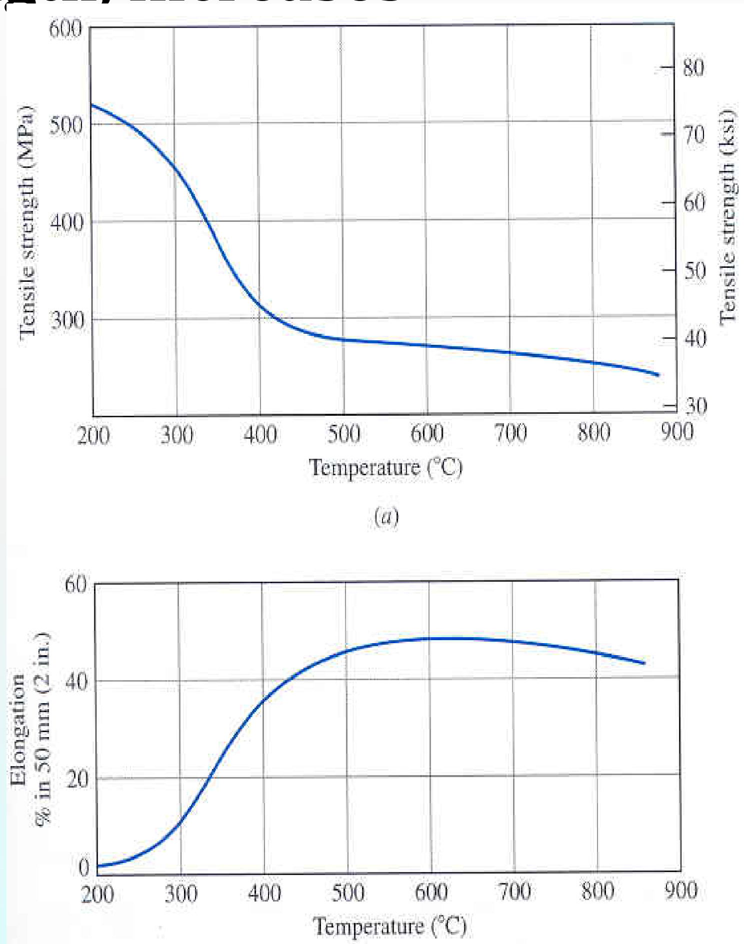


Figure 6.6

- **Factors affecting recrystalization:**
  - Amount of prior deformation
  - Temperature and time
  - Initial grain size
  - Composition of metal

(After "Metals Handbook," vol 2, 9th ed., American Society of Metals, 1979, p.320)

Facts About Recrystallization

- A minimum amount of deformation is needed.
- Smaller the deformation, higher the recrystallization temperature.
- Higher the temperature, lesser is the time required.
- Greater the degree of deformation, smaller are the recrystallized grains.
- Recrystallization temperature decreases with purity of metals.

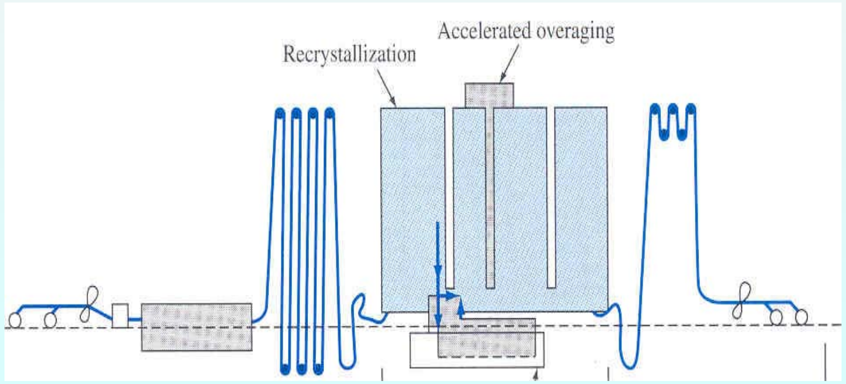


Figure 6.7b

Continuous annealing

(After W.L. Roberts, “Flat Processing of steel,” Marcel Dekker, 1988.)

Example Problem 6.11

If it takes 9.0×10^3 min to recrystallize a piece of copper at 88°C and 200 min at 135°C, what is the activation energy for the process, assuming the process obeys the Arrhenius rate equation and the time to recrystallize $= Ce^{-Q/RT}$, where $R = 8.314$ J/(mol · K) and T is in kelvins?

■ **Solution**

$$t_1 = 9.0 \times 10^3 \text{ min};\ T_1 = 88°\text{C} + 273 = 361 \text{ K}$$

$$t_2 = 200 \text{ min};\ T_2 = 135°\text{C} + 273 = 408 \text{ K}$$

$$t_1 = Ce^{Q/RT_1} \quad \text{or} \quad 9.0 \times 10^3 \text{ min} = Ce^{Q/R(361\text{ K})} \tag{6.17}$$

$$t_2 = Ce^{Q/RT_2} \quad \text{or} \quad 200 \text{ min} = Ce^{Q/R(408\text{ K})} \tag{6.18}$$

Dividing Eq. 6.17 by 6.18 gives

$$45 = \exp\left[\frac{Q}{8.314}\left(\frac{1}{361} - \frac{1}{408}\right)\right]$$

$$\ln 45 = \frac{Q}{8.314}(0.00277 - 0.00245) = 3.80$$

$$Q = \frac{3.80 \times 8.314}{0.000319} = 99{,}038 \text{ J/mol or } 99.0 \text{ kJ/mol} \blacktriangleleft$$

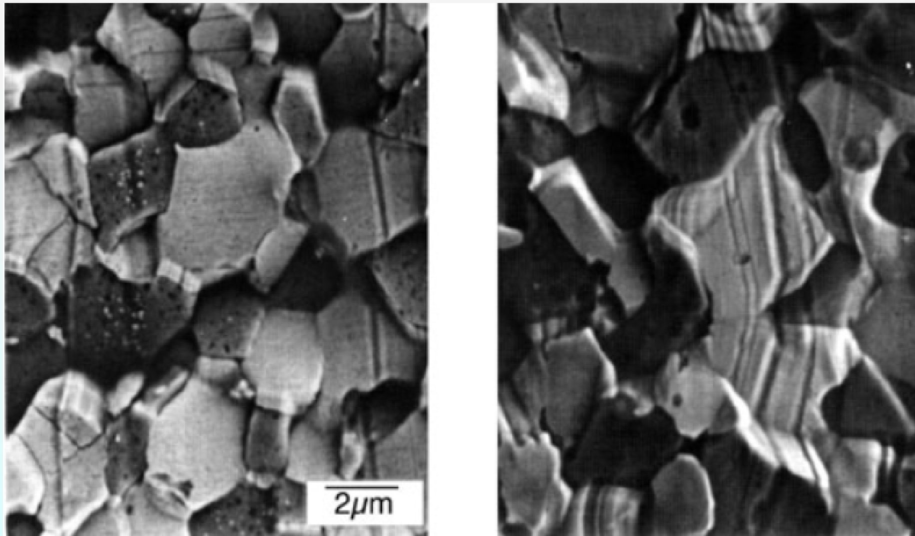
Superplasticity in Metals

- At elevated temperature and slow loading, some alloys deform 2000%.
- Annealed Ti alloy
    - Elongates 12% at room temperature
    - Elongates up to 1170% at 870^{o}C and 1.3x10^{-4}/s loading rate.

- Conditions: Very fine grain size (5-10 microns) (Very difficult to achieve)
    * Highly strain sensitive
    * Temperature above 0.5 Tm
    * Slow strain rate (0.01 to 0.001 S^{-1})

Mechanism of Superplasticity

- Very limited dislocation activity
- Deformation mechanism:
  - Grain boundary sliding
  - Grain boundary diffusion
  - Sliding and rotation of individual grains.
- Applications: Metal forming operations.
  - Blow forming to produce automobile hoods.



Grains before and after deformation

Nanocrystalline Metals

- Average grain diameter < 100 nm
- Results in high strength and hardness, and Superplasticity
- If grain diameter reduces from 10 microns to 10 nm, yield strength of copper increases 31 times.
- Very difficult to produce nanocrystalline metals.
- If d < 5 nm, elastic modulus drops as more atoms are in grain boundary
- Hall-Petch equation is invalid in lower nanocrystalline range.