Notes on Chapter 3: Structure and Manufacturing Properties

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Based on notes by Prof. Junlan Wang

Crystal Structures of Metals

Metals are characterized by the metallic bond

- A complete outer shell can not be formed by electron sharing or transfer
- Positive ions are surrounded by wandering, universally shared valence electrons
- Electrons are highly mobile
- High electrical and thermal conductivity
- Bond strength, material strength, and melting point vary
- Positive ions can move within the structure without the breaking of discrete bonds

Metals solidify into crystalline structures

Some metals can exist in the solid state in two or more lattice forms (allotropic
polymorphic)

The change from one lattice form to another is called an allotropic transformati

Common Crystal Structures for Metals

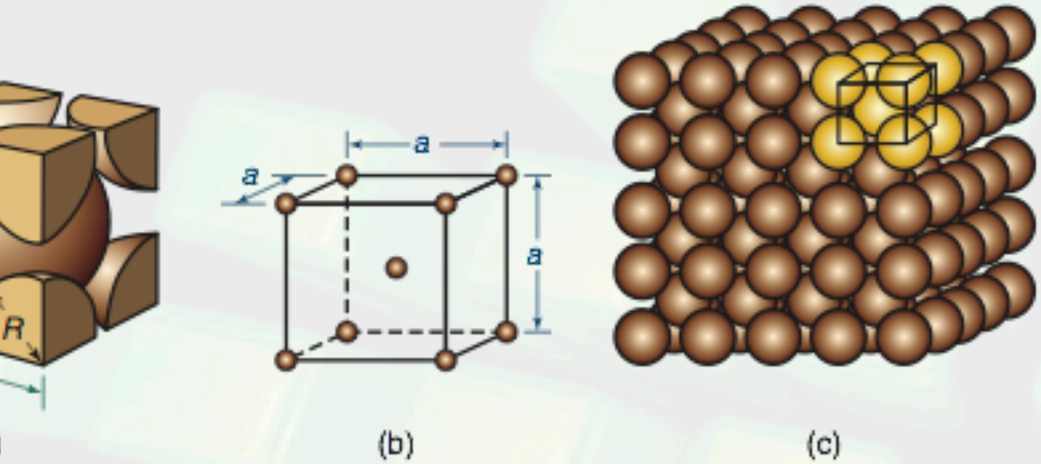


FIGURE 3.2 The **body-centered cubic (b**
structure: (a) hard-ball model; (b) unit cell; and
crystal with many unit cells. Common bcc met
chromium, titanium, and tungsten. *Source:* After W.G

High strength, moderate ductility

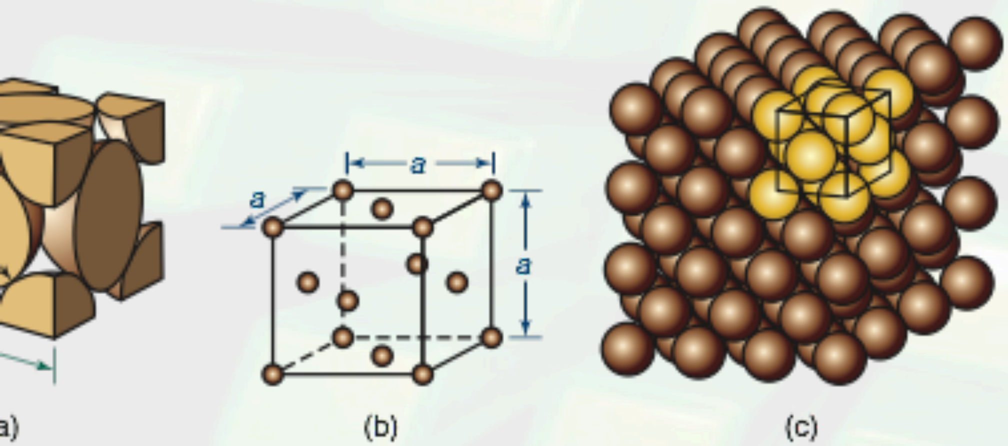


FIGURE 3.3 The **face-centered cubic (fc**
structure: (a) hard-ball model; (b) unit cell; and
crystal with many unit cells. Common fcc met
aluminum, copper, gold and silver. *Source:* After W.G.

Low strength, high ductility

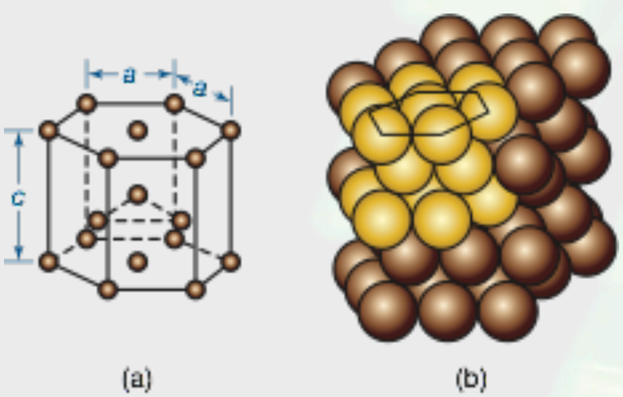
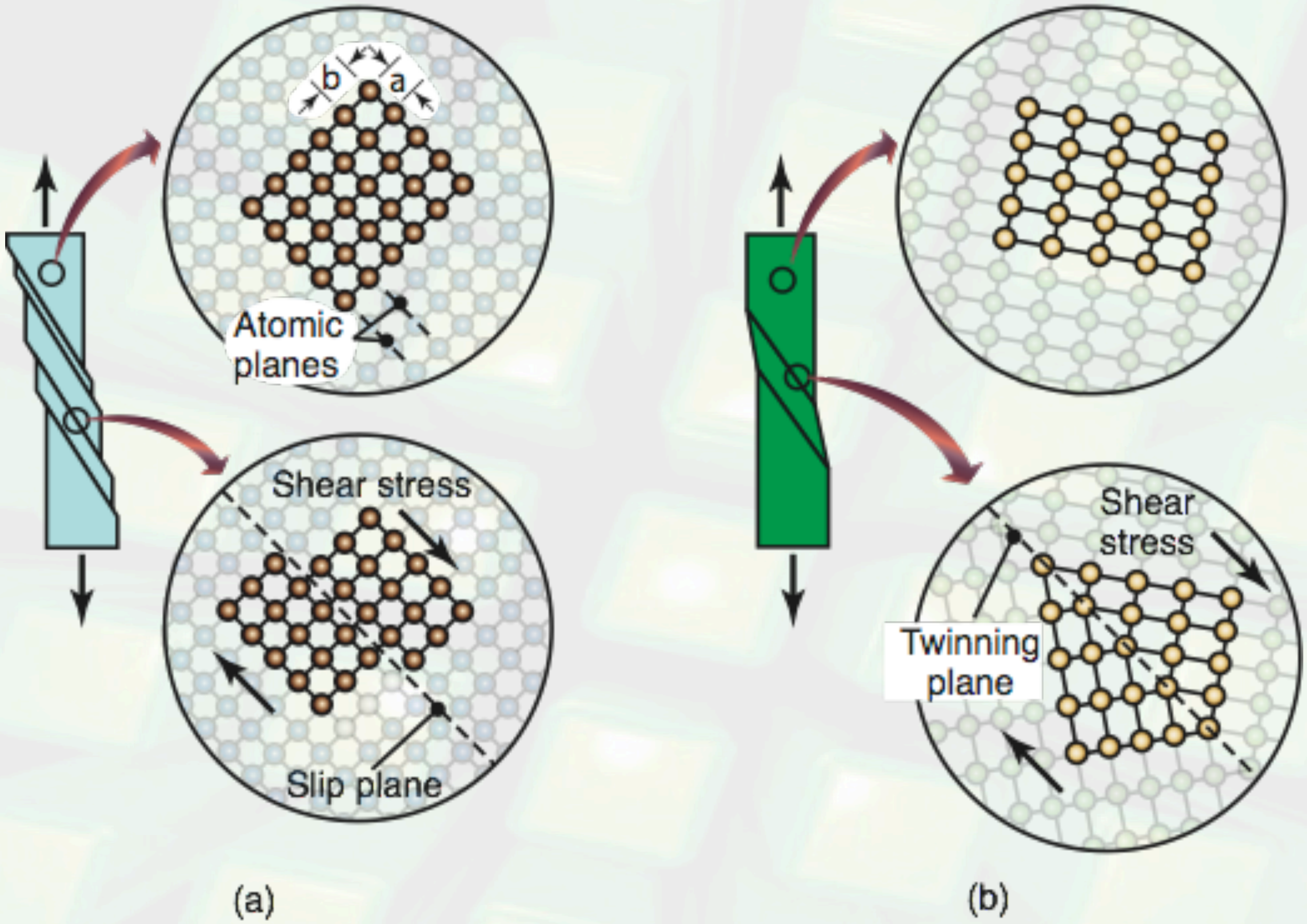


FIGURE 3.4 The **hexagonal close-packed (h**
structure: (a) unit cell; and (b) single crystal with
cells. Common hcp metals include zinc, magnesium
Source: After W.G. Moffatt.

Low ductility, Brittle

Plastic Deformation in Crystals



Permanent deformation of a single crystal under a tensile load. The highlighted grid of atoms emphasizes
within the lattice.(a) Deformation by **slip**. The *b*/*a* ratio influences the magnitude of the shear stress requi
that the slip planes tend to align themselves in the direction of pulling. (b) Deformation by **twinnin**
of a "twin" around a line of symmetry subjected to shear. Note that the tensile load results in a shear stress

Crystal Defects

Point

Linear

Planar (GB, phase boundary)

Volume or bulk

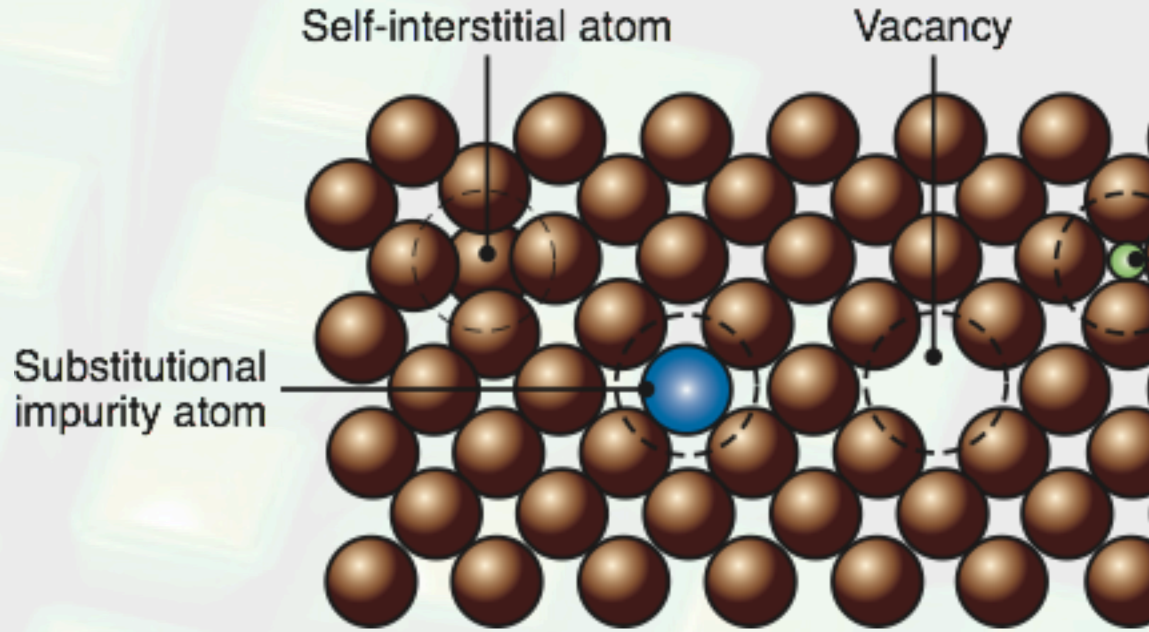


FIGURE 3.9 Various defects in a single-crystal lattice. *Source:* After W.G. Moffatt.

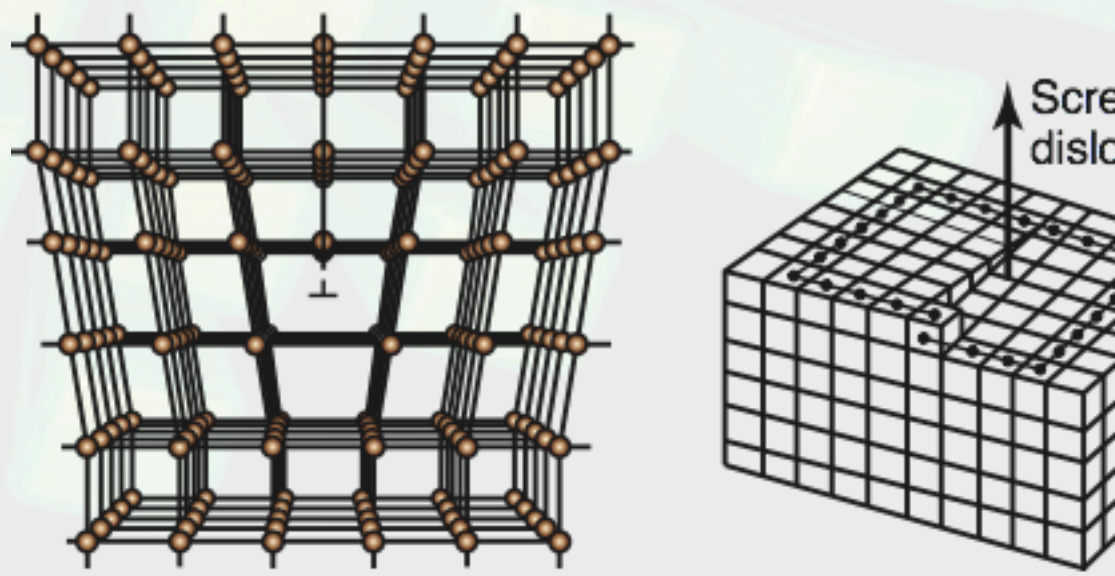


FIGURE 3.10 (a) Edge dislocation, a linear defect at the edge of an extra plane of atoms. (b) Screw dislocation, a helical defect in a three-dimensional lattice of atoms. Screw dislocations are so named because the atomic planes form a spiral ramp.

Movement of Edge Dislocation

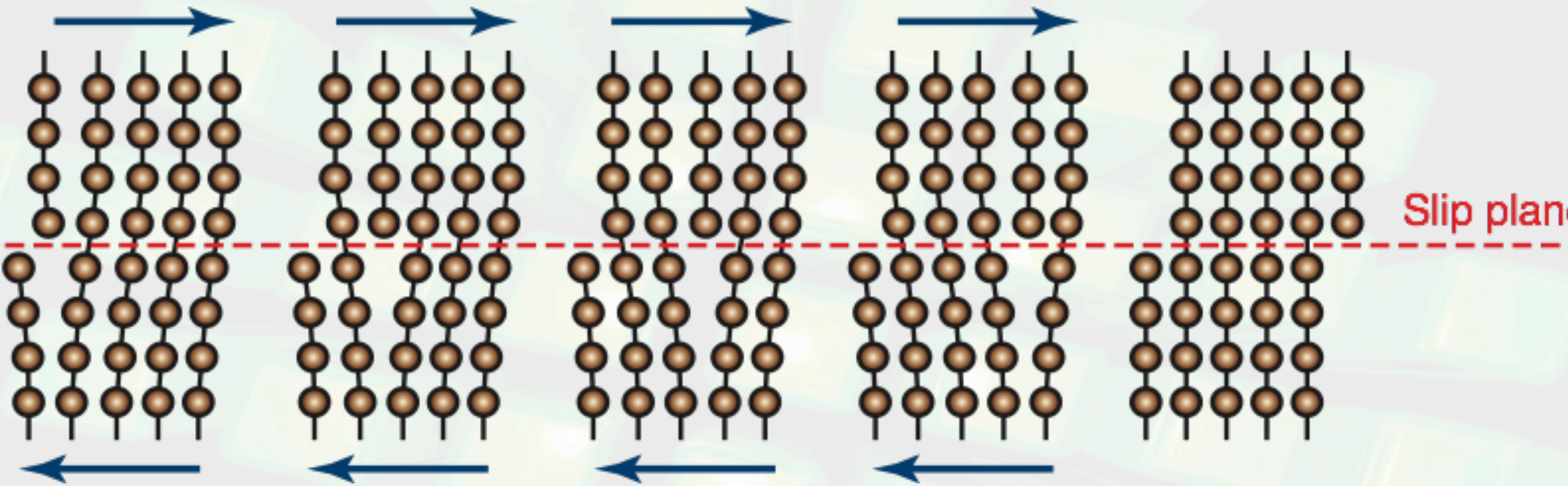


FIGURE 3.11 Movement of an edge dislocation across the crystal lattice under a shear stress. Dislocations help explain why the actual strength of metals is much lower than that predicted by atomic theory.

Hardening

Very pure single crystals: $0 - 10^3\ \mathrm{mm}^{-2}$

Annealed single crystals: 10^5 - 10^6

Annealed polycrystals: 10^7 - 10^8

Highly cold-worked metals: 10^{11} - 10^{12}

in-hardening: increase of overall strength c
dislocation entanglement and impediments
ers (GB, impurities, inclusions, etc).

Development of Grain Structure

A small particle of solid forms from the liquid, as the metal solidifies

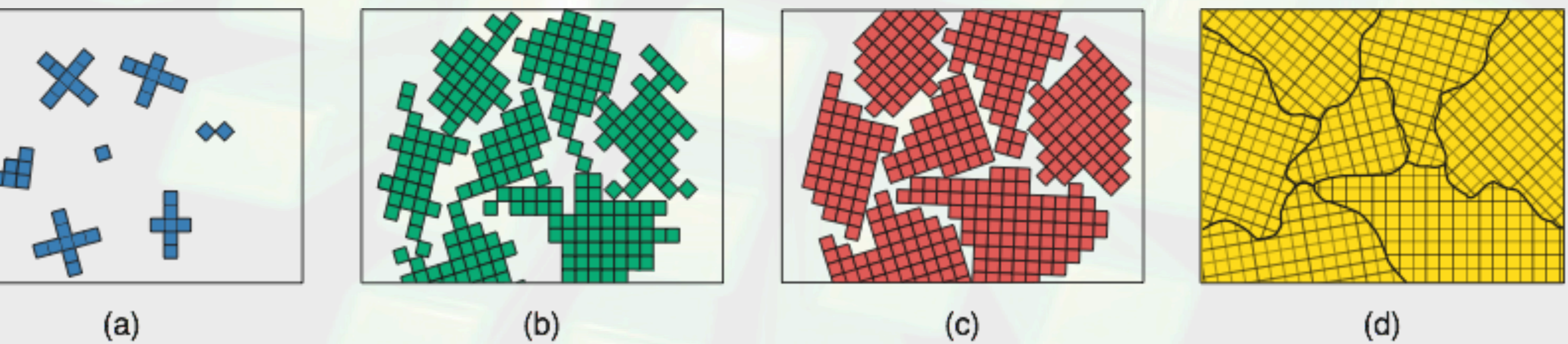
Lattice structure that forms is characteristic of a given material

Metal solidifies as atoms attach themselves to the small particle (nucleation and growth)

Basic crystalline unit is called a unit cell and is repeated throughout the material

Grains are small continuous volumes of solid

Surfaces that divide grains are called grain boundaries



RE 3.12 Schematic illustration of the various stages during solidification of molten metal. Each small squa
sents a unit cell. (a) Nucleation of crystals at random sites in the molten metal. Note that the crystallograph

Grains

Smallest unit in a metal that can be observed by a light microscope

Grain structure impacts mechanical and physical properties

- Hall-Petch Equation

$$Y = Y_i + kd^{-1/2}$$

Grain size number is important for a design engineer

- ASTM grain size specification
  - $N=2^{n-1}$
  - N is the number of grains per square inch at 100X

Summary

Crystal structures of Metals

- Metallic bonding
- Three crystal lattices
  - FCC, BCC, HCP
- Ideal shear and tensile strength of metals

Plastic deformation of metals

- Slip vs twinning
- Mechanisms of strain hardening

Grain formation during solidification

- Grain size characterization

Manufacturing Properties of Metals

Outline

Polycrystalline metals

- Tensile strength, GB effect, plastic deformation

Cold, hot, warm working and recrystallization

Fracture and Failure of metals

Physical and chemical properties

Categories of metals and alloys

- Ferrous, Nonferrous, Superalloys, Refractory, others

Tensile Stress in Polycrystalline Material

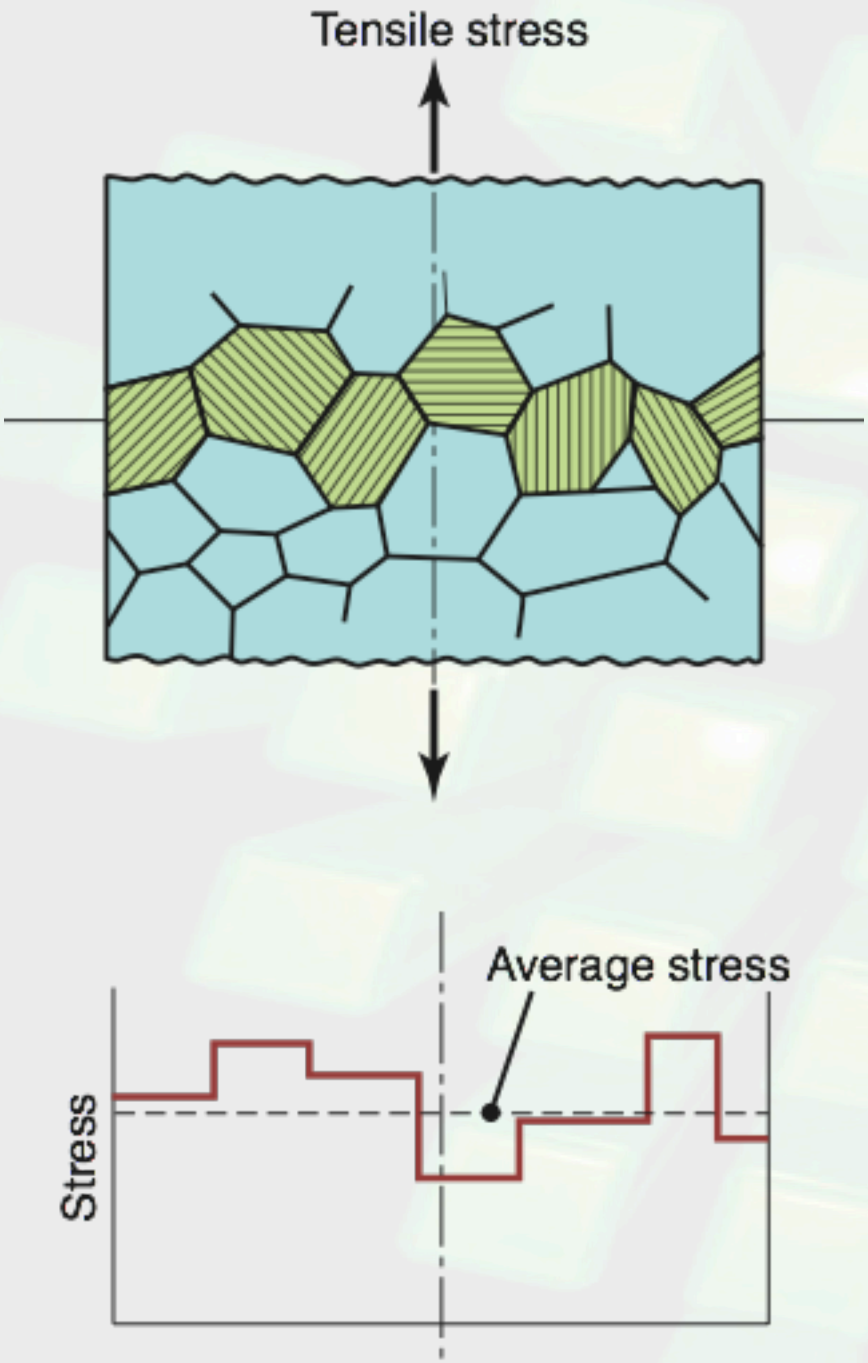


FIGURE 3.13 Variation of tensile stress across a p
polycrystalline metal specimen subjected to t
Note that the strength exhibited by each grain c
on its orientation.

Grain Boundary Effect

Interfere with dislocation movement

Grain boundary sliding→creep

Grain boundary embrittlement

Corrosion

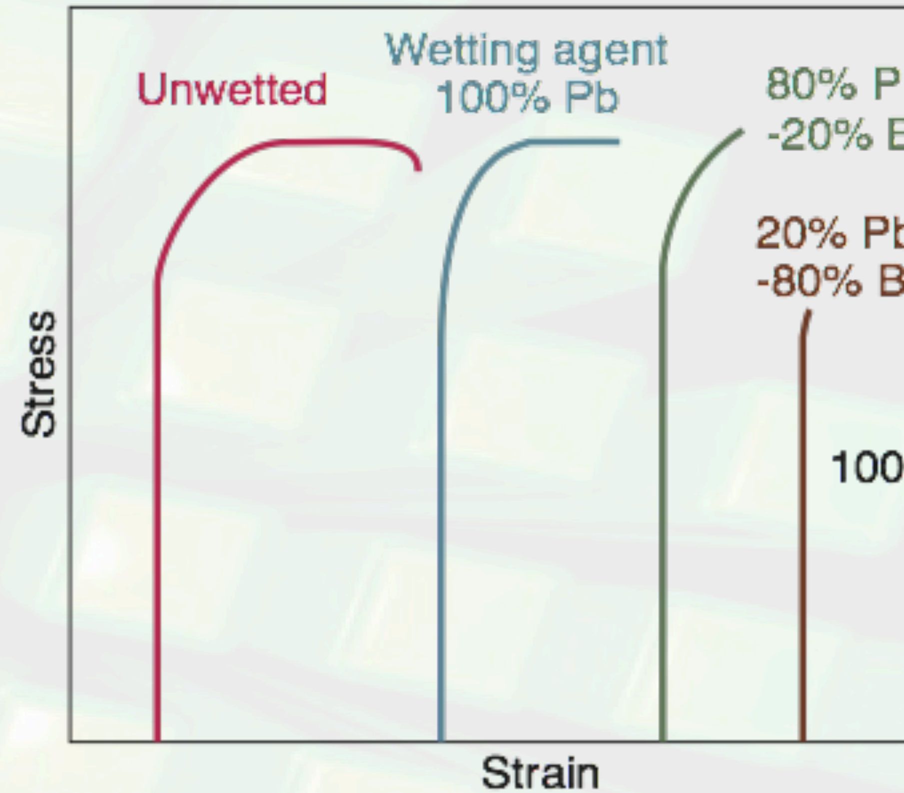


FIGURE 3.14 Embrittlement of copper by lea
bismuth at 350°C (660°F). Embrittlemen
important effects on the strength, ductility
toughness of materials. *Source:* After W. Rostok

Plastic Deformation

Deformation of grain

Increasing strength with increasing deformation

Anisotropy (texture)

- Preferred orientation
- Mechanical fibering
  - Alignment of impurities, inclusions, voids

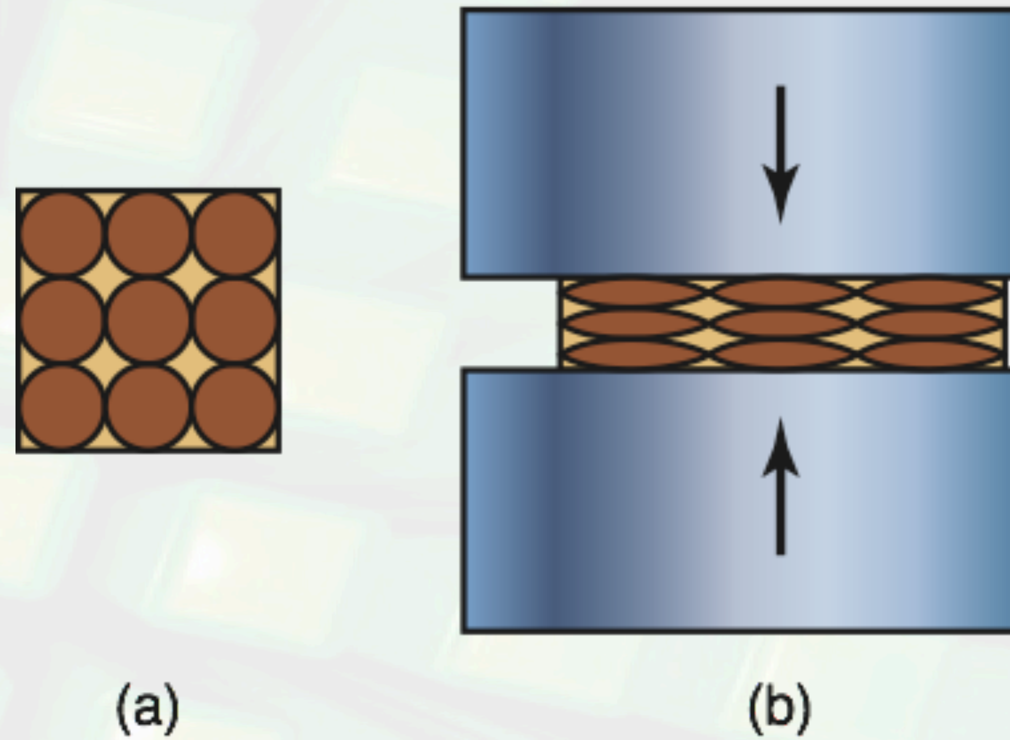


FIGURE 3.15 Plastic deformation of idealized (equ grains in a specimen subjected to compression, suc done in rolling or forging of metals: (a) deformation; and (b) after deformation. Note alignment of grain boundaries along a horizontal dire

Grain Growth

Recovery

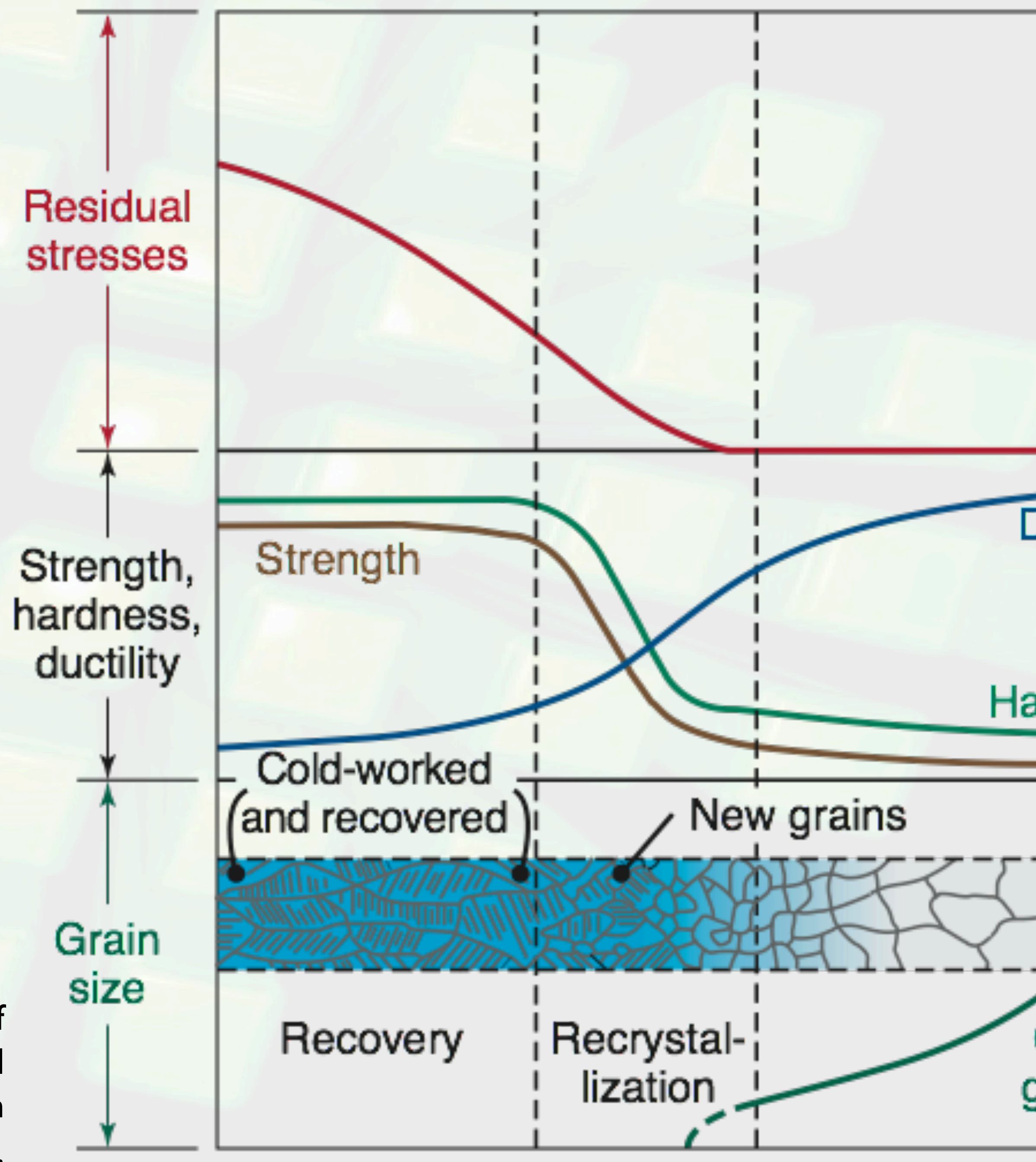
- Stress relieve in highly deformed region

Recrystallization

- Formation of equi-axed, stress-free grains
- 0.3-0.5 *Tm*
- Decrease dislocation density
- Lowers metal strength, increase ductility
- Depends on prior cold work

Grain Growth

- Adverse effect on mechanical properties
- Orange-peel effect (rough surface)



3.17 Schematic illustration of the effects of y, recrystallization, and grain growth on mechanical es and shape and size of grains. Note the formation new grains during recrystallization. *Source:* After G.

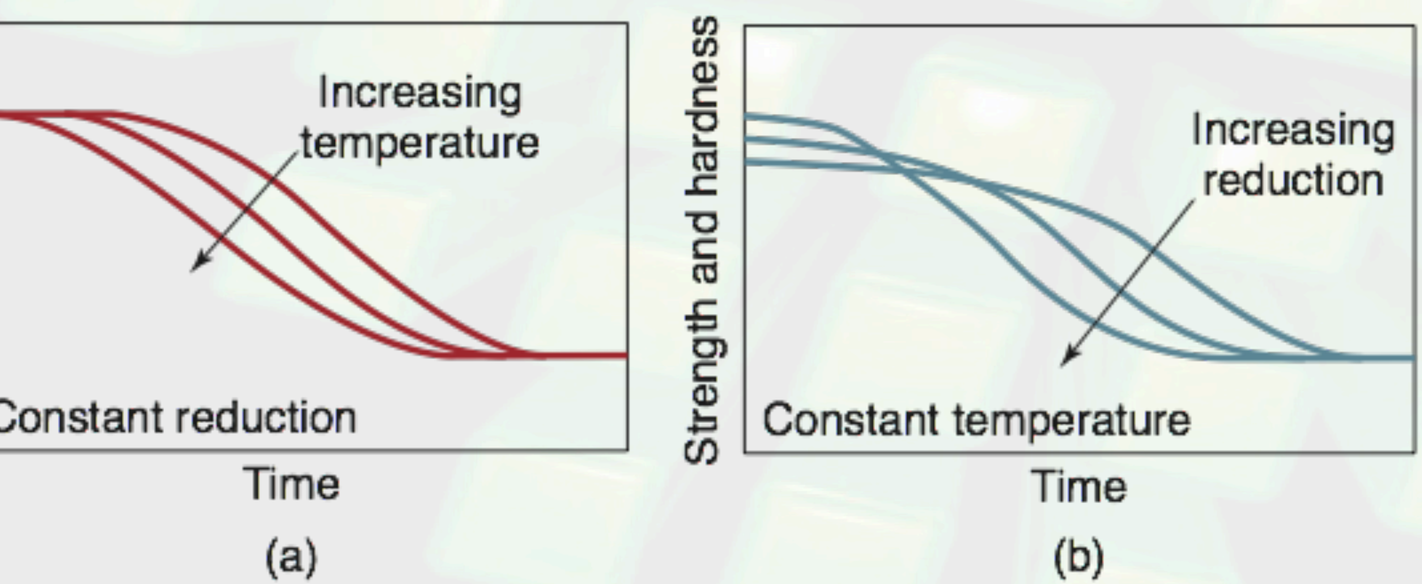
Recrystallization vs Prior Cold Work

Under same cold work, less time with increasing temperature

More prior cold work, lower temperature for recrystallization

Higher amount of deformation, smaller resulting grain size duirng recrystallizatio

Anisotropy due to preferred orientation persists during recrystallization; require higher temperature to remove



URE 3.18 Variation of strength and hardness with recrystallization perature, time, and prior cold work. Note that the more a metal is cold

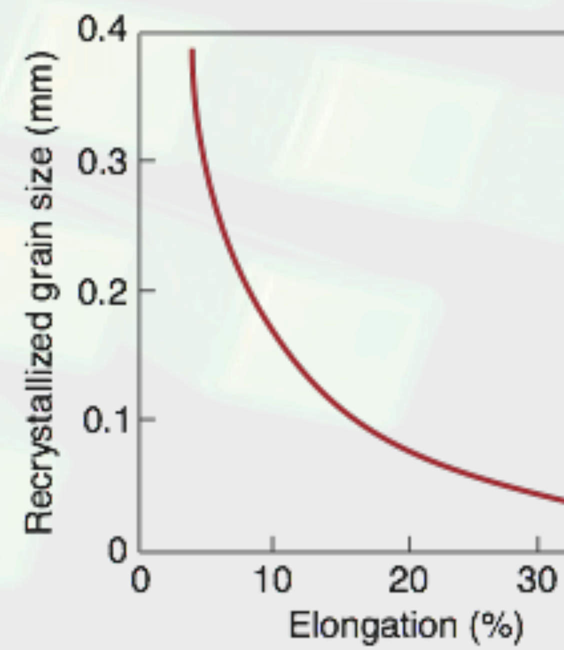


FIGURE 3.19 The effect of prior co recrystallized grain size of alpha

Surface Roughness due to Grain Growth

Orange peel effect

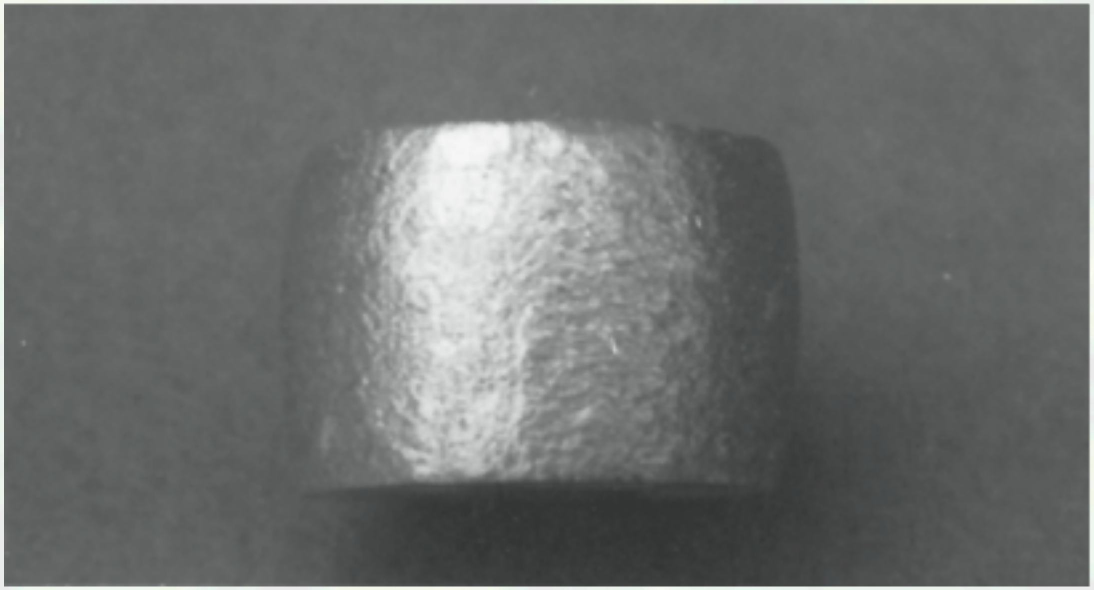


FIGURE 3.20 Surface roughness on the cylindrical surface of an aluminum specimen subjected to compression. *Source:* A. Mulc and S. Kalpakjian.

Cold, Warm, Hot Working

lot working: above recrystallization temperature
old working: below recrystallization temperature
Varm working: intermediate temperature

Process	T/T_m
Cold working	< 0.3
Warm working	0.3 to 0.5
Hot working	> 0.6

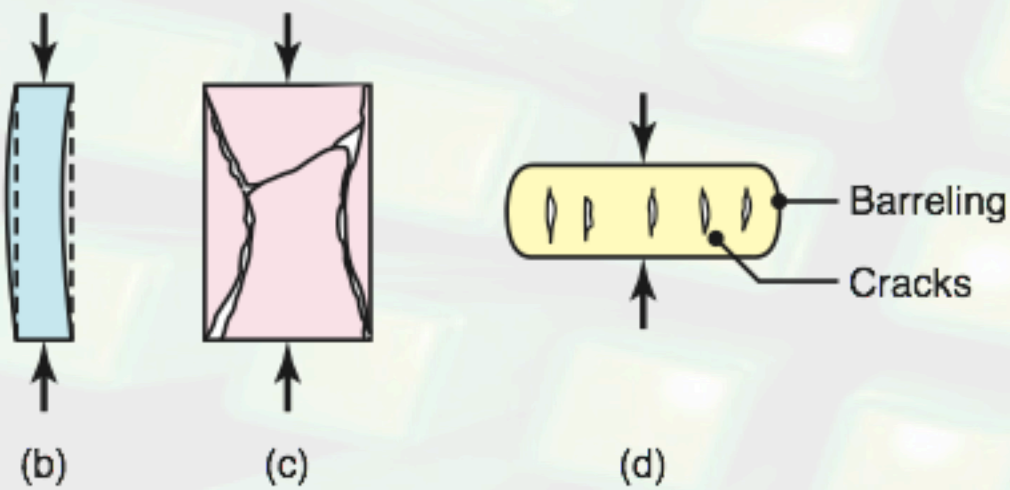
TABLE 3.2 Homologous Temperature Ranges for Various Processes.

Iot worked product:

- Less dimensional accuracy
  - Uneven thermal expansion/contraction
- Rougher surface appearance and finish
  - Oxidation layer

Failure

vo types of Failure: Fracture (brittle, ductile) and Buckling



E 3.21 Schematic illustration of types of failure in als: (a) necking and fracture of ductile materials; ckling of ductile materials under a compressive) fracture of brittle materials in compression; (d) g on the barreled surface of ductile materials in ession. (See also Fig. 6.1b)

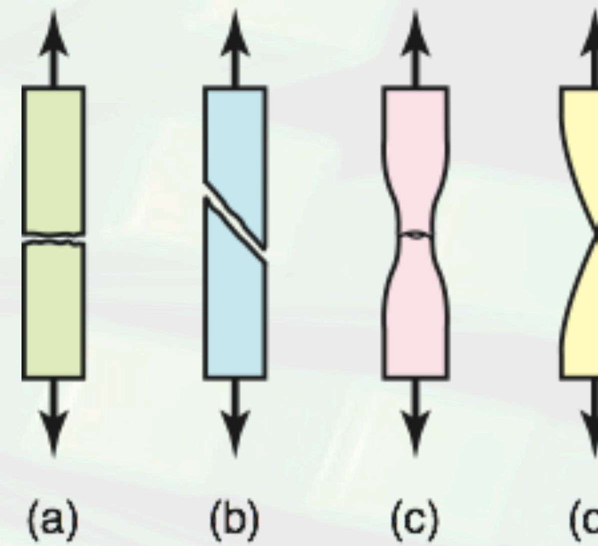


FIGURE 3.22 Schematic illustration of th fracture in tension: (a) brittle fracture in po metals; (b) shear fracture in ductile single c also Fig. 3.5a); (c) ductile cup-and-cone polycrystalline metals (see also Fig. 2.2); (c ductile fracture in polycrystalline metals, reduction of area.

Ductile Fracture Surface

Fibrous pattern with dimples

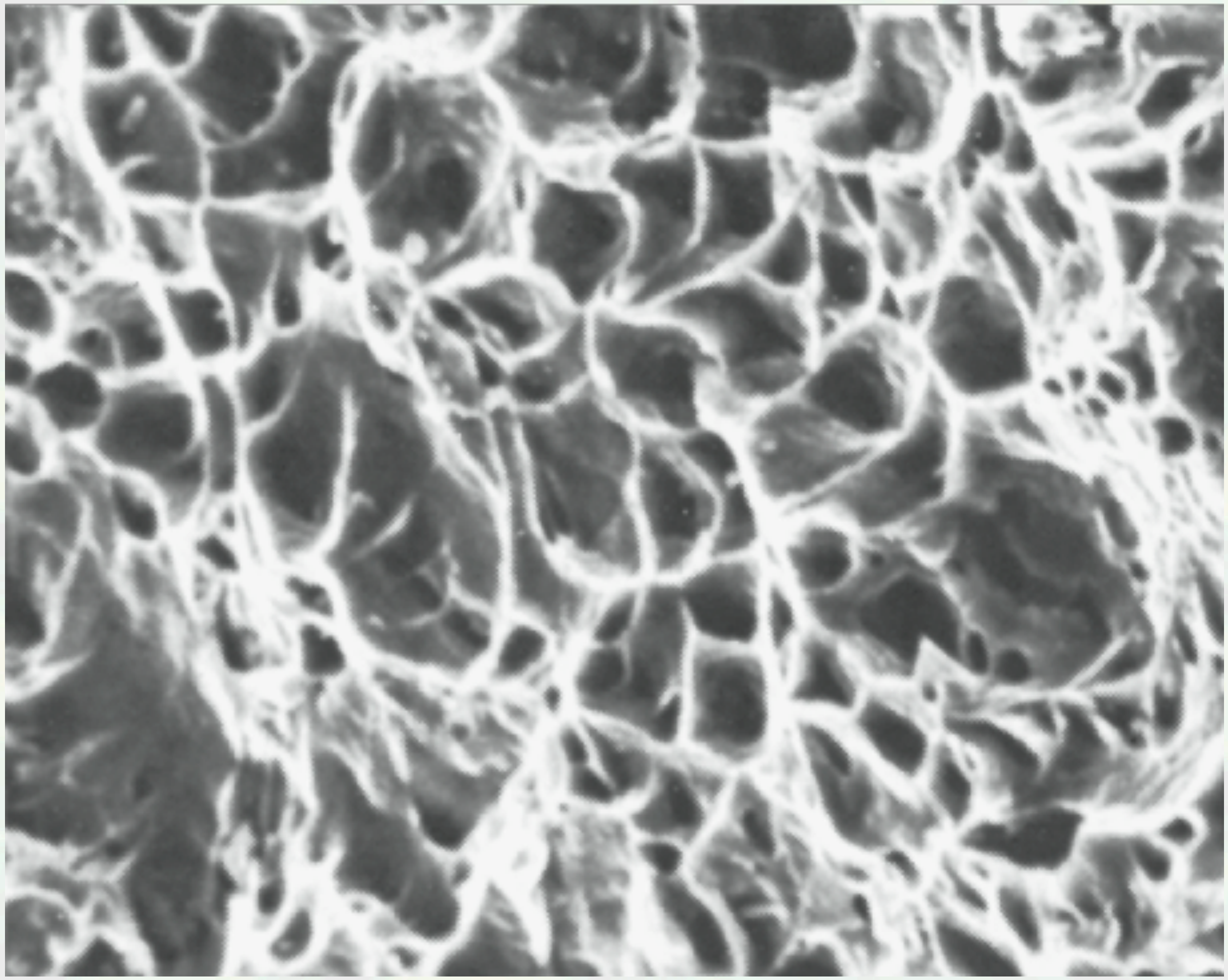
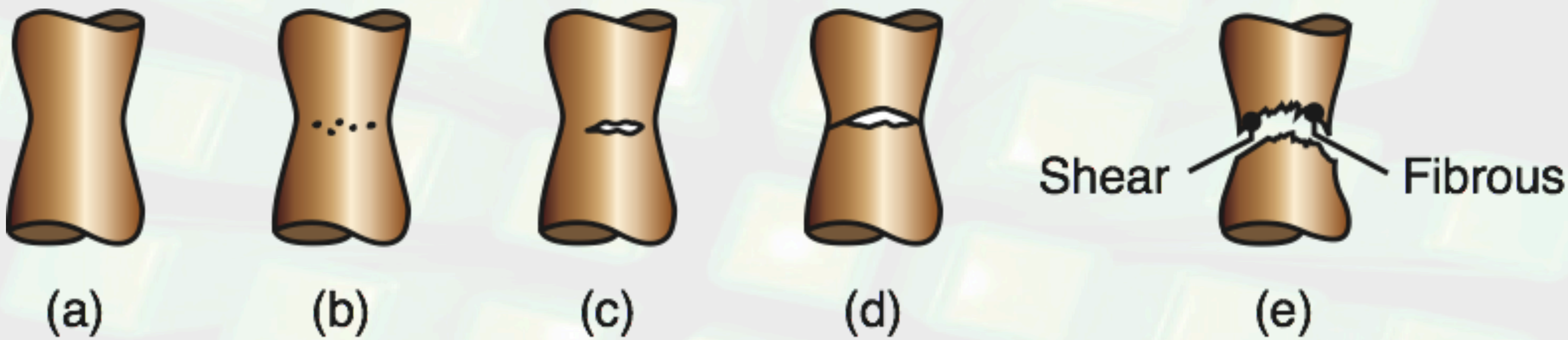


FIGURE 3.23 Surface of ductile fracture in low-carbon steel, showing dimples. Fracture is usually initiated at impurities, inclusions, or preexisting voids in the metal. *Source:* K.-H. Habig and D. Klaffke. Photo courtesy of BAM, Berlin, Germany.

Sequence in Necking and Ductile Fracture



GURE 3.24 Sequence of events in necking and fracture of a tensile-test specimen: (a) early stage of necking; (
nall voids begin to form within the necked region; (c) voids coalesce, producing an internal crack; (d) rest
oss-section begins to fail at the periphery by shearing; (e) final fracture surfaces, known as **cup**-(top fractu
rface) **and-cone** (bottom surface) **fracture**.

Effect of Inclusions on Void Nucleation

Bond strength between inclusion and matrix

Hardness of inclusion

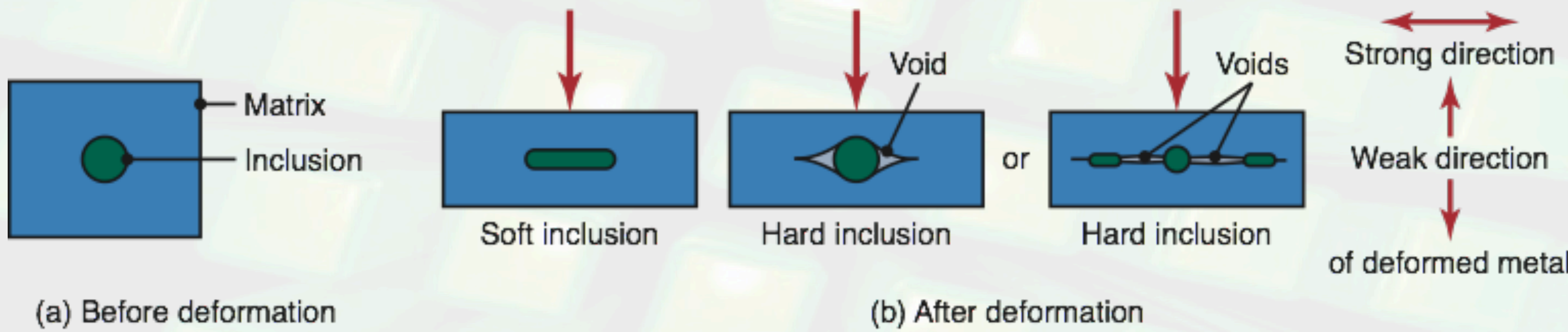


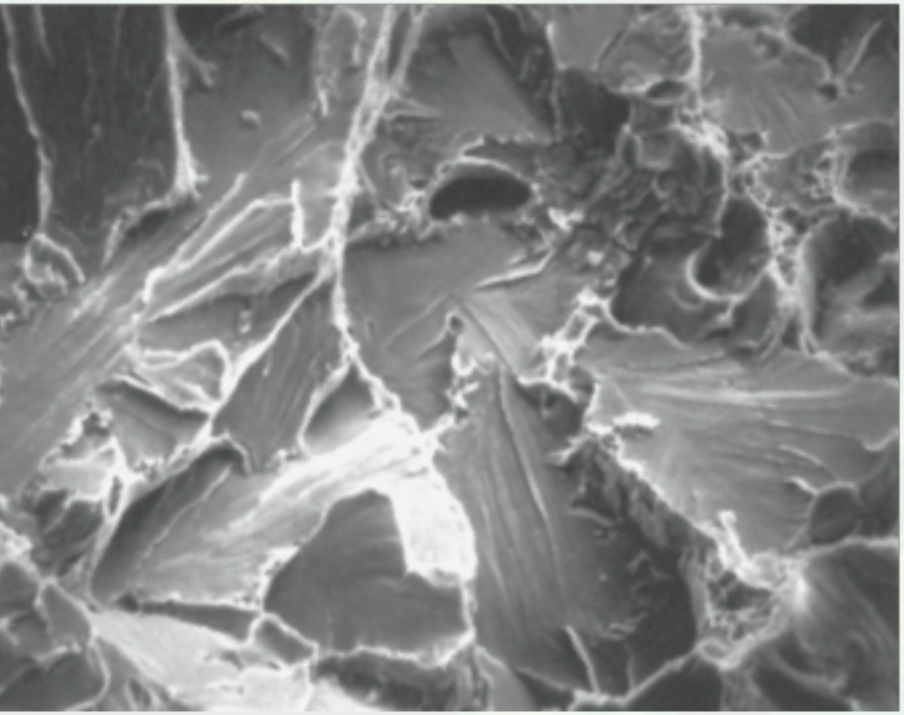
FIGURE 3.25 Schematic illustration of the deformation of soft and hard inclusions and their effect on void formation in plastic deformation. Note that hard inclusions, because they do not comply with the overall deformation of the ductile matrix, can cause voids.

Brittle and Intergranular Fracture

Little or no plastic deformation

Happens along a crystallographic plane (cleavage plane) where normal stress is highest

BCC and hcp metals



RE 3.28 Typical fracture surface of steel that
iled in a brittle manner. The fracture path is
granular (through the grains). Compare this
e with the ductile fracture surface shown in

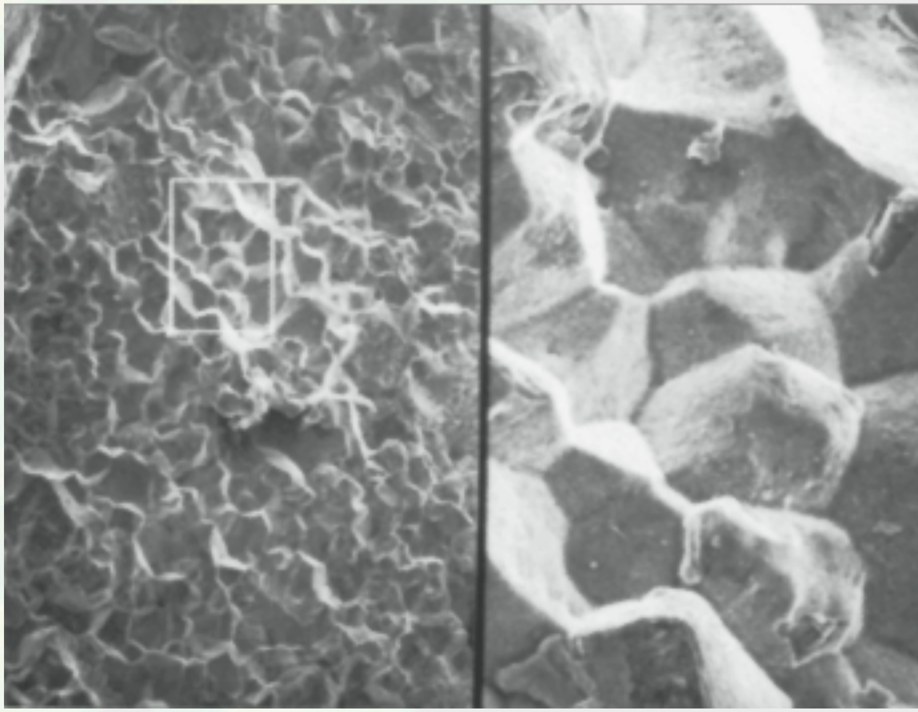


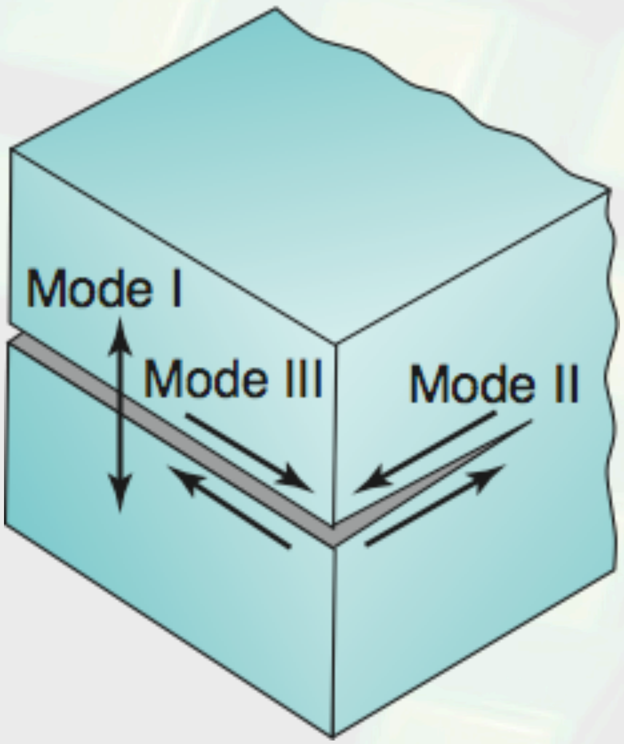
FIGURE 3.29 Intergranular fracture, at two
magnifications. Grains and grain boundaries are
visible in this micrograph. The fracture path is a
grain boundaries. *Source:* Courtesy of Packer Engin

Defects, Fracture Mode & Fatigue Fracture

fect of defect

$$\sigma \propto \frac{1}{\sqrt{Crack\ length}}$$

Fracture mode



E 3.30 Three modes of fracture. Mode I has tudied extensively, because it is the most nly observed in engineering structures and nents. Mode II is rare. Mode III is the tearing s; examples include opening a pop-top can,

- Fatigue fracture
  - Characteristics: bench mark
  - Improving fatigue strength
    - Introduce compressive residual stress
    - Surface hardening
    - Fine surface finishing
    - Materials free of inclusions, voids, imp

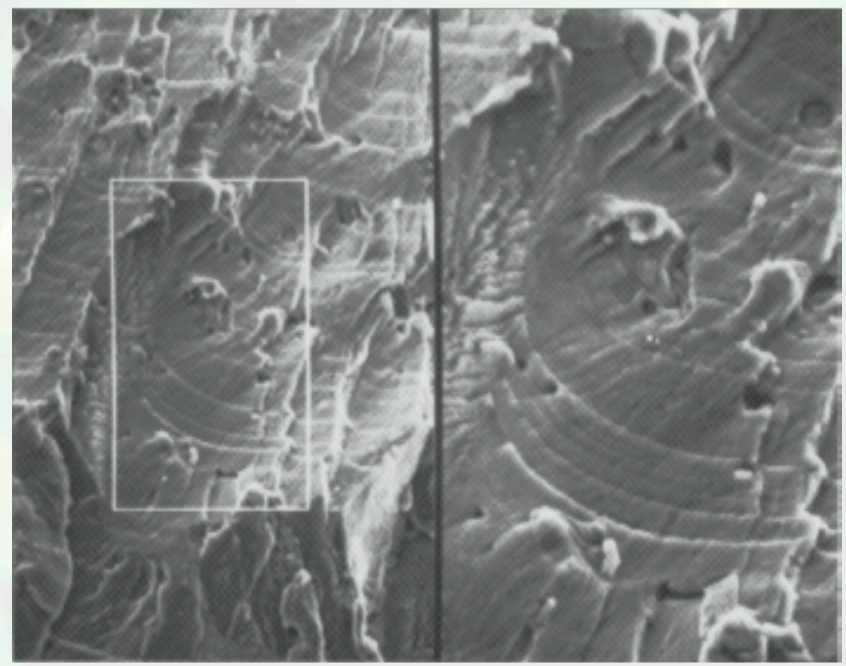


FIGURE 3.31 Typical fatigue fracture surface on m showing **beach marks**. Most components in mac

Density: depends on atomic weight, atomic radius and packing (little dependence on alloying elements)

Melting point: strong dependence on alloying elements

Specific heat: little dependence on alloying elements

Thermal conductivity: significant effect from alloying elements

Thermal expansion coefficient (CTE): $\propto \frac{1}{T_m}$, minor alloying eff

Electrical and magnetic properties: strong alloying effect

- Electrical conductivity, resistivity, piezoelectricity
- Magnetostriction

Oxidation and corrosion resistance

Physical Properties of Materials

	Density (kg/m^3)	Melting Point (°C)	Specific Heat (J/kg K)	Thermal Conductivity (W/m K)	Coefficient of Thermal Expansion ($\mu m/m°C$)
METAL					
Aluminum	2700	660	900	222	23.6
Aluminum alloys	2630-2820	476-654	880-920	121-239	23.0-23.6
Beryllium	1854	1278	1884	146	8.5
Columbium (niobium)	8580	2468	272	52	7.1
Copper	8970	1082	385	393	16.5
Copper alloys	7470-8940	885-1260	337-435	29-234	16.5-20
Gold	19300	1063	129	317	19.3
Iron	7860	1537	460	74	11.5
Steels	6920-9130	1371-1532	448-502	15-52	11.7-17.3
Lead	11,350	327	130	35	29.4
Lead alloys	8850-11,350	182-326	126-188	24-46	27.1-31.1
Magnesium	1745	650	1025	154	26.0
Magnesium alloys	1770-1780	610-621	1046	75-138	26.0
Molybdenum alloys	10,210	2610	276	142	5.1
Nickel	8910	1453	440	92	13.3
Nickel alloys	7750-8850	1110-1454	381-544	12-63	12.7-18.4
Silicon	2330	1423	712	148	7.63
Silver	10,500	961	235	429	19.3
Tantalum alloys	16,600	2996	142	54	6.5
Titanium	4510	1668	519	17	8.35
Titanium alloys	4430-4700	1549-1649	502-544	8-12	8.1-9.5
Tungsten	19,290	3410	138	166	4.5
NONMETALLIC					
Ceramics	2300-5500	—	750-950	10-17	5.5-13.5
Glasses	2400-2700	580-1540	500-850	0.6-1.7	4.6-70
Graphite	1900-2200	—	840	5-10	7.86
Plastics	900-2000	110-330	1000-2000	0.1-0.4	72-200
Wood	400-700	—	2400-2800	0.1-0.4	2-60

General Properties of Ferrous Alloys

Alloys with iron as base metal

Carbon and alloy steels

- Carbon steels
- Alloy steels

Stainless steels

- High corrosion resistance, high strength and ductility, high Cr content

Tool and die steels

- High speed, hot-worked, cold-worked, shock resisting

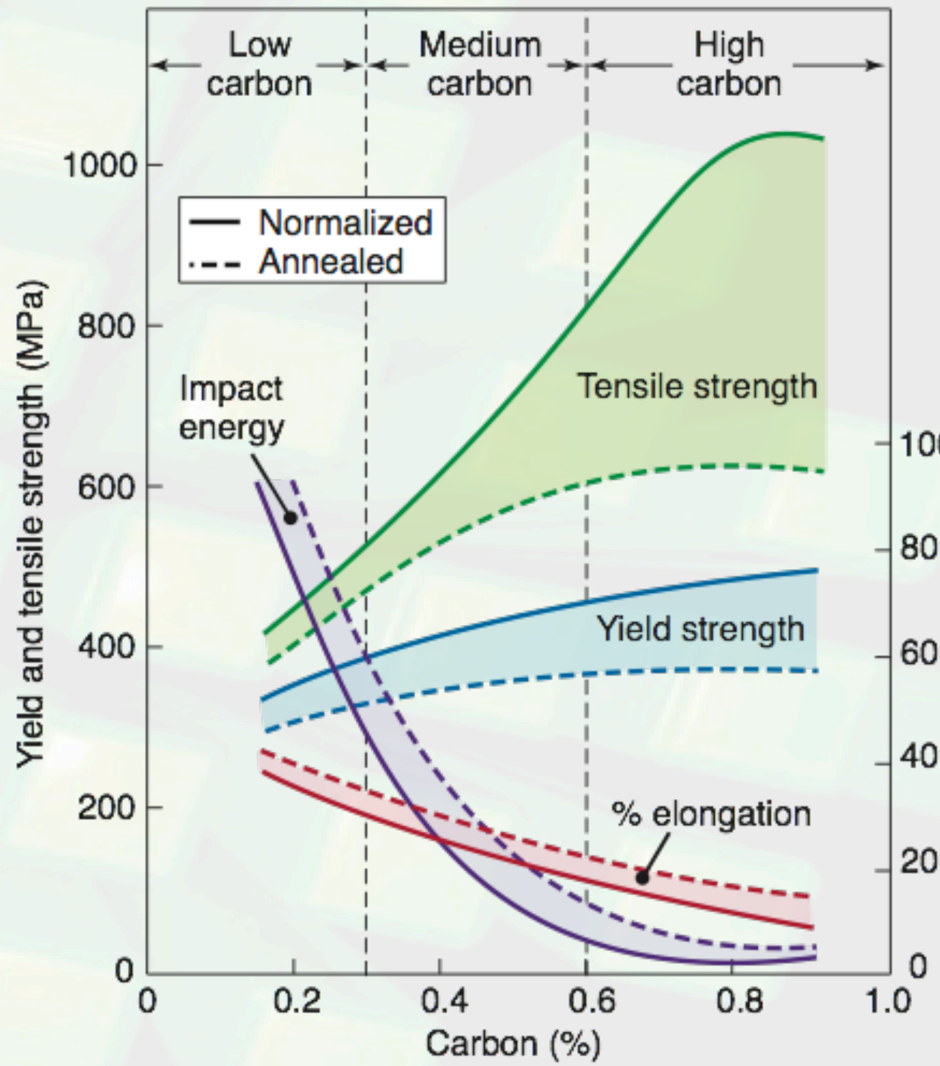


FIGURE 3.33 Effect of carbon content on mechanical properties of carbon steel.

Metals

Al and Al alloys

- High strength-to-weight ratio, resistance to corrosion, high thermal and elec conductivity, non toxicity, reflectivity, appearance
- Alloy elements: copper, zinc, magnesium, silicon, manganese and lithium
- Wrought aluminum alloys (4 figure number), cast (5 figure number)

Mg and Mg alloys

- Lightest engineering metal available
- Light-weight applications, minimize inertial forces
- Low strength – use as alloys with other metals
- Potential fire hazard

Non-ferrous Metals and Alloys (cont.)

Cu and Cu alloys

- Superior conductor of electricity and heat, resistance to corrosion
- Easy processing: machining, forming, casting, joining..
- Most common Cu alloys: Brass (Cu+Zn), Bronze (Cu+Sn)

Ni and Ni alloys

- High strength, toughness, corrosion resistance
- Important alloying element in stainless steel and Ni-based alloys
- High temperature applications

Super alloys: Heat-resistance or high-temperature alloys

- Iron base, Ni base, Co base
- Service temperature>1000 °C

Ti and Ti alloys

- High strength-to-weight ration
- High corrosion resistance under room and high temperature
- Alloying elements: Al, V, Mo, Mg, … for strength, workability

Refractory Metals

- High melting point metals: Mo, Nb, W ($T_m = 3410\ ^oC$), Ta ($T_m = 3000$

Others

- Low melting point metals – Pb, Zn, Sn
- Precious metals: Au, Ag, Pt

Special Metals and Alloys

- SMA: shape-memory alloys, eg.. Ni(55%)/Ti (45%) alloy
- Amorphous alloys ~ Metallic glass (Fe, Ni, Cr with C, P, B, Si)
- Nanomaterials
- Metal foams

Summary

GB effect of polycrystalline metals

Recovery, recrystallization, grain growth

- Cold, hot, warm working

Failure and fracture

- Ductile vs brittle

Physical properties and their importance

General properties and applications of most common Ferrous and N
ferrous metals and alloys

- Strength, toughness, hardness, ductility, creep, resistance to temperature anc
oxidation