Mechanics In Design and Manufacturing

Structure and Properties of Materials

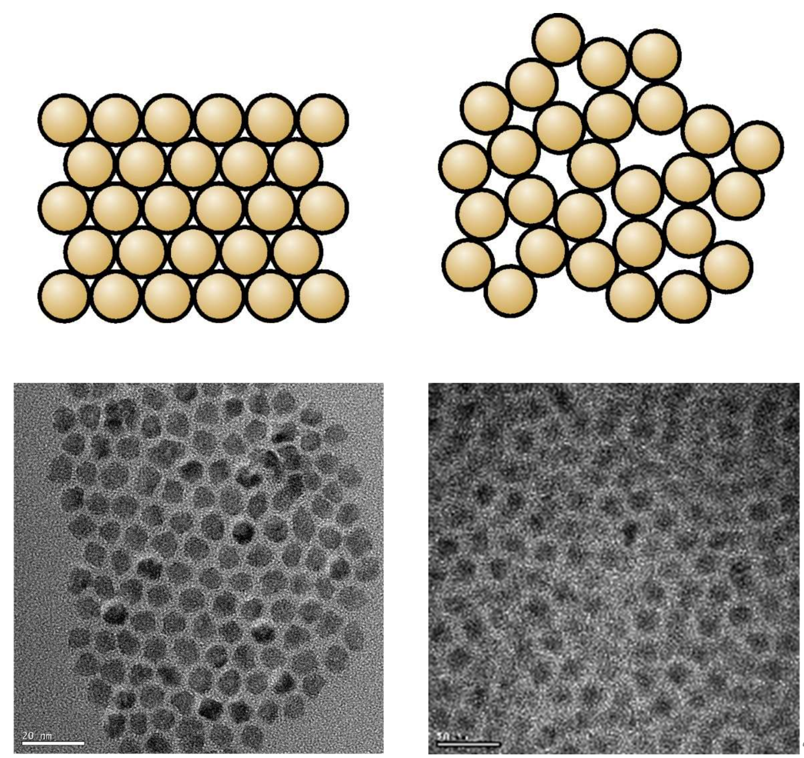
Readings:

Structure

- Atoms and molecules are the building blocks of a more macroscopic structure of matter
- When materials solidify from the molten state, they pack tightly, into one of two structures:
    -
    -

Noncrystalline Structures

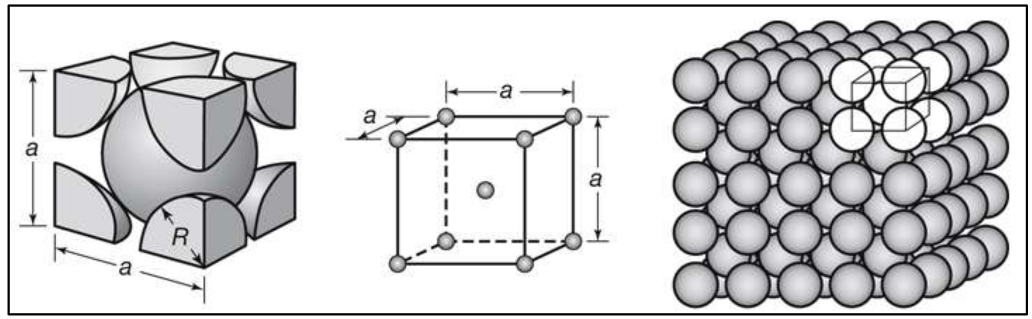
- Sometimes called "Amorphous"
- Water and air have noncrystalline structures
- Melting ->
- Some engineering materials have noncrystalline forms in their solid state

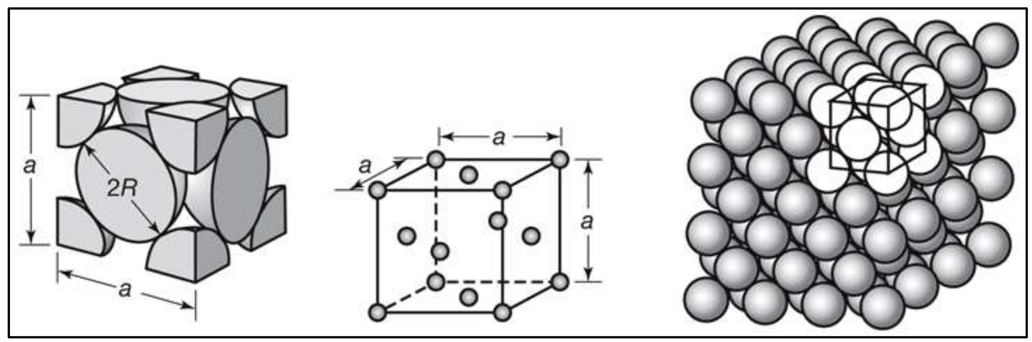


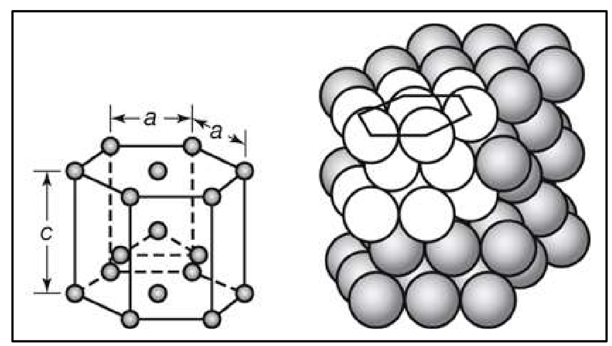
http://www.temwindows.com/Articles.asp?ID=133

Crystalline

- Metals are most useful to us in crystalline state







Deformation – Slip is the key

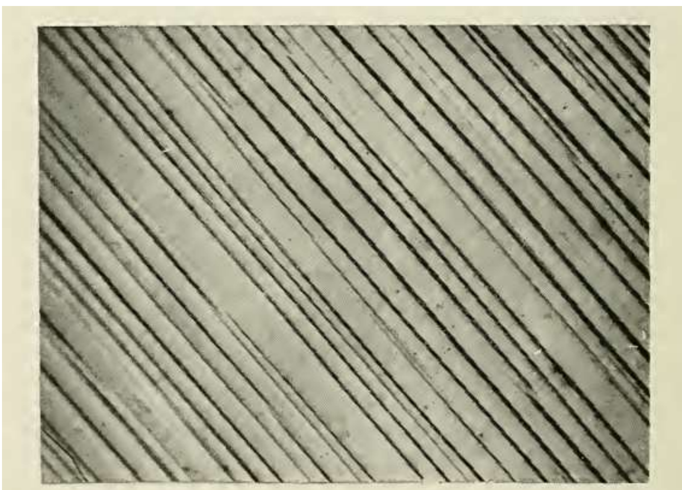
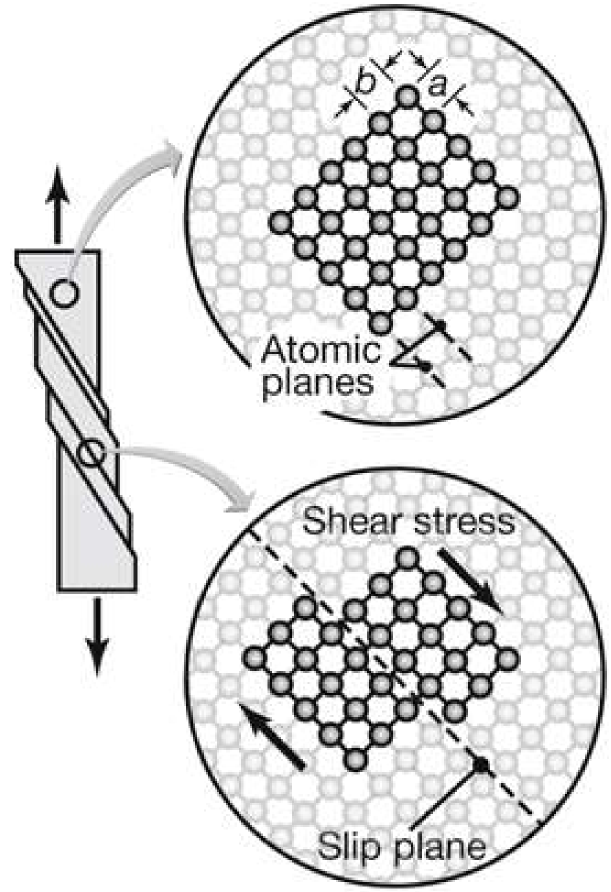
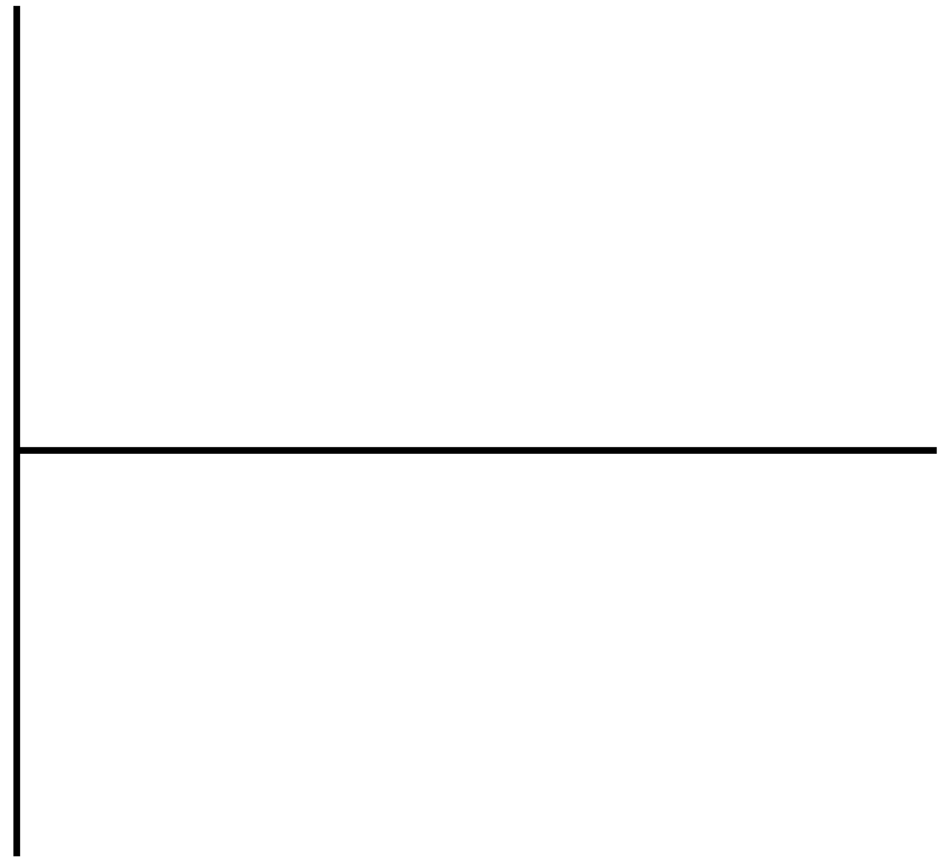


Fig. 4-12. Straight slip lines in copper, 500×. (*Courtesy W. L. Phillips.*)

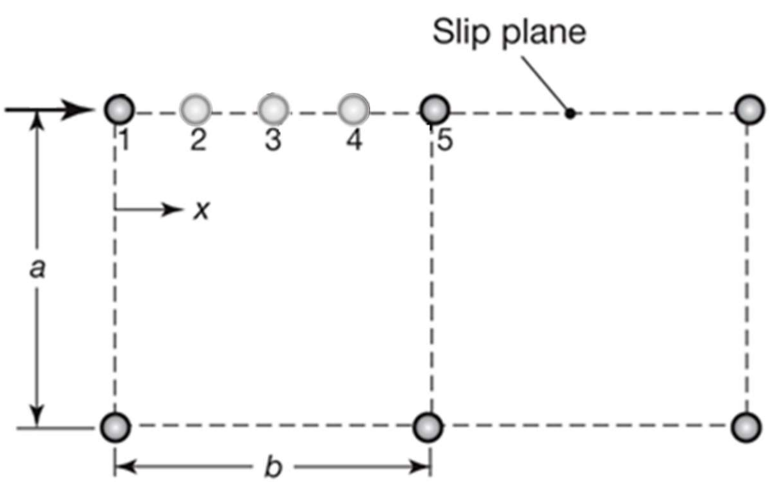


Slip forces

- Consider: two atoms separated by a distance r



Slip in a Perfect Lattice – Maximum Theoretical Shear Stress

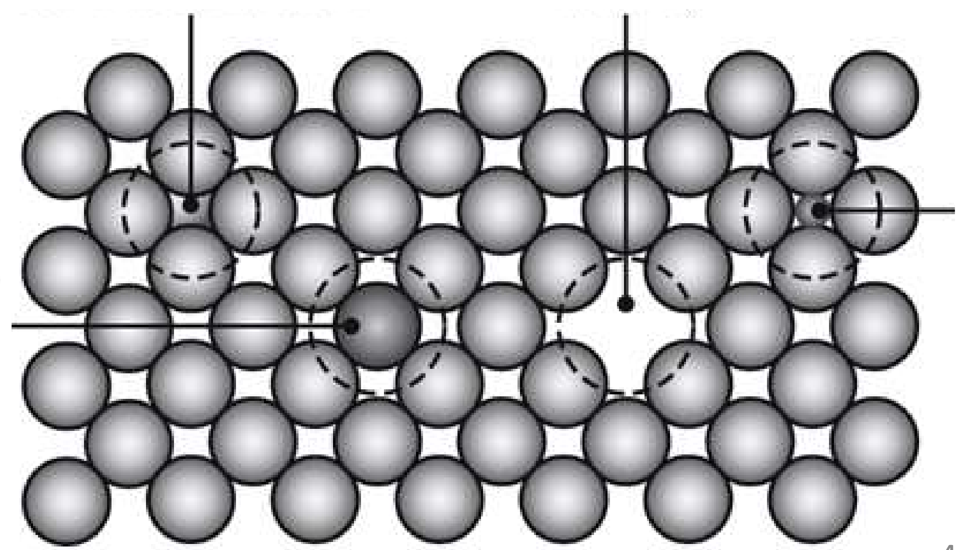


Slip Systems

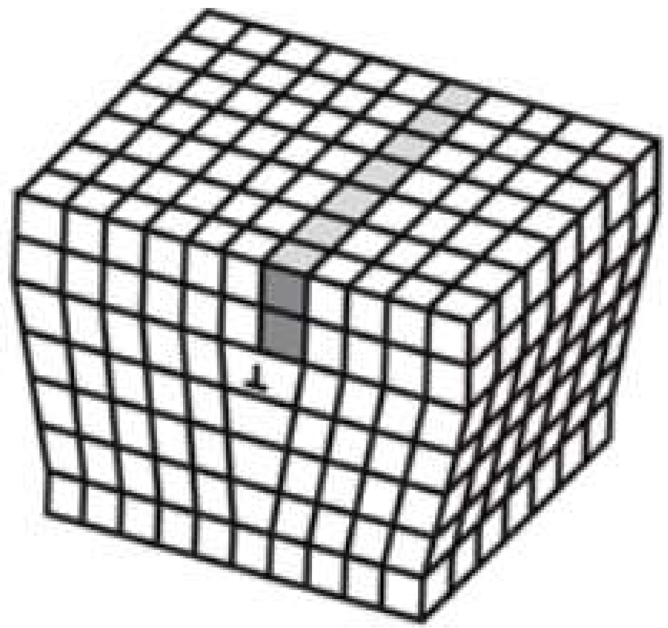
- BCC
- FCC
- HCP

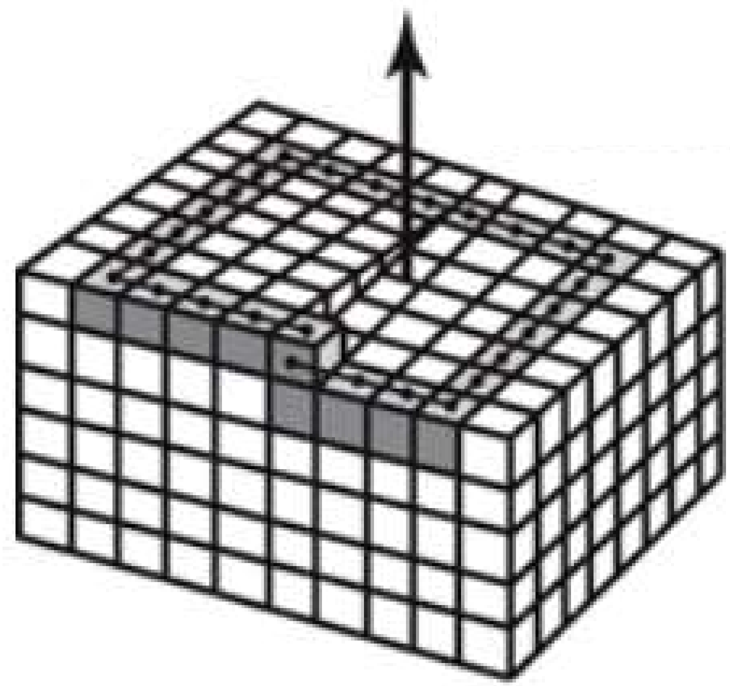
Point Defects

- Imperfections in crystal structure can involve either a single atom or multiple atoms

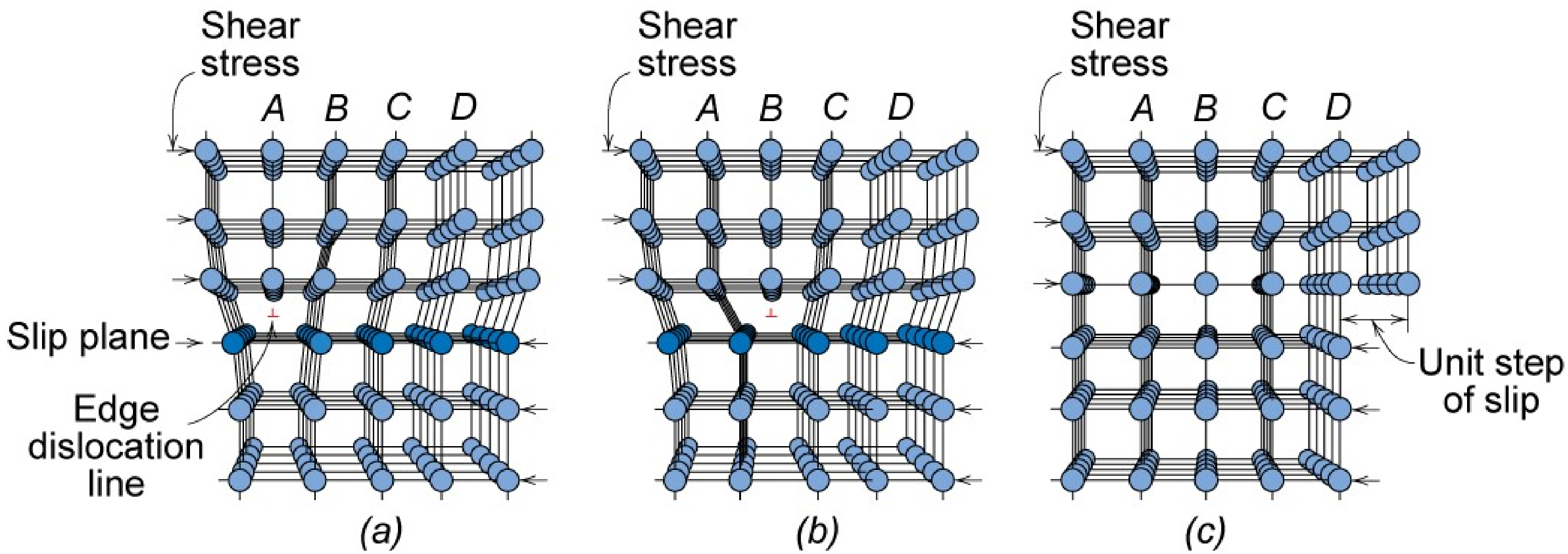


Linear Defects – Dislocations

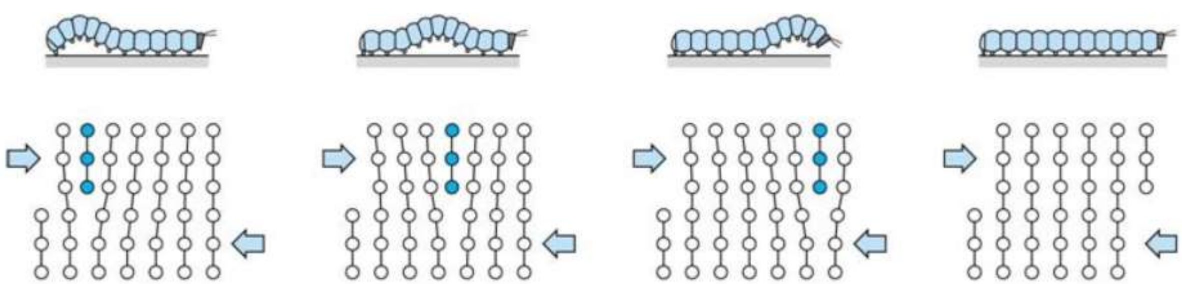


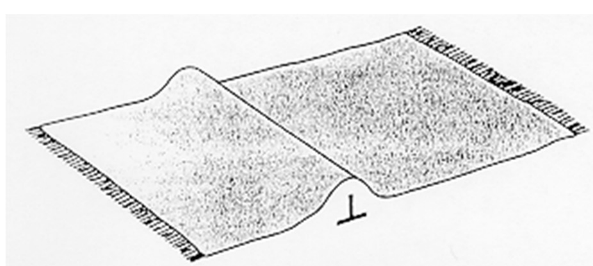


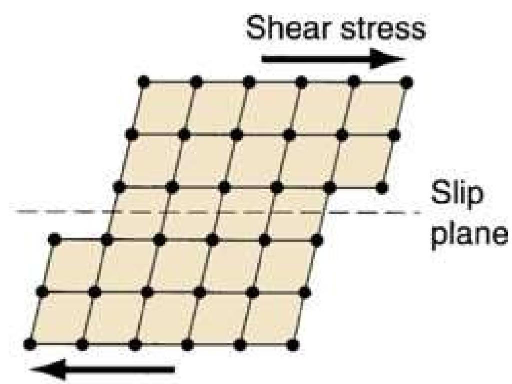
Crystal Deformation



Adapted from Fig. 7.1, *Callister 7e.*

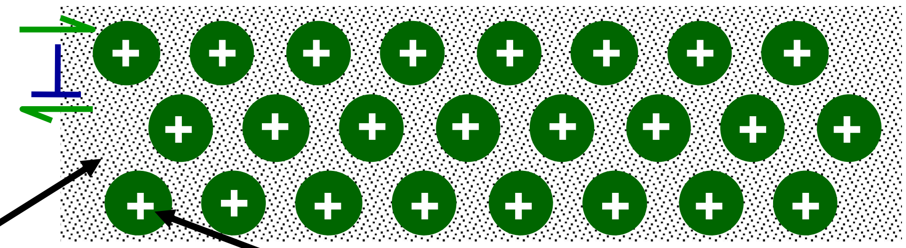




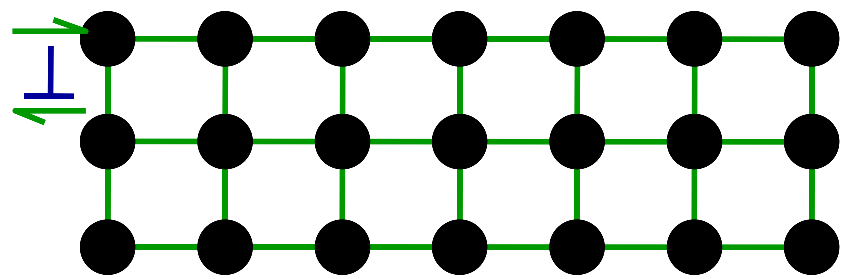


Dislocation Motion in Material Types

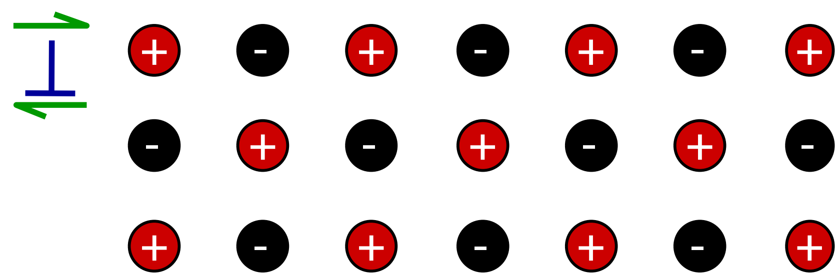
- Metals: Dislocation motion easier.



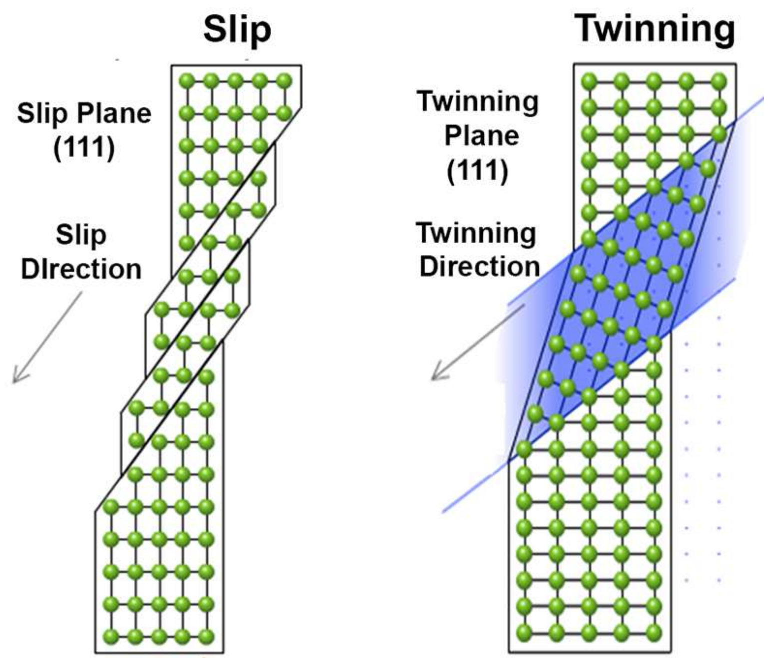
- Covalent Ceramics



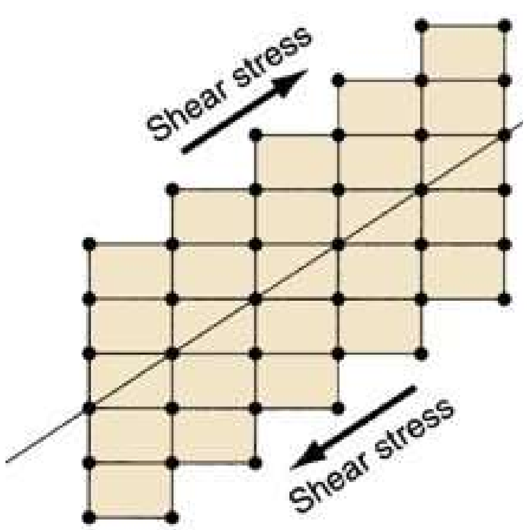
- Ionic Ceramics

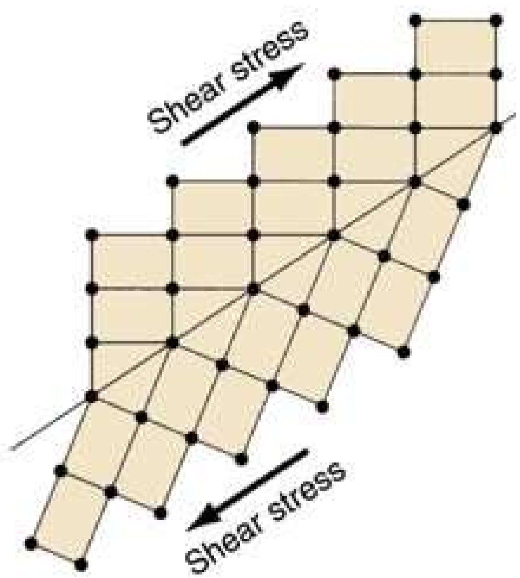


Twins

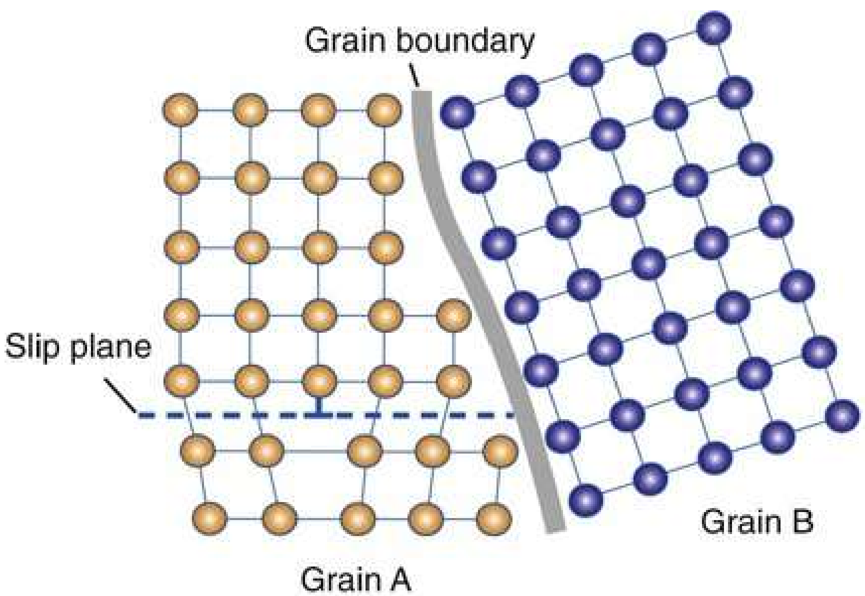


Bourne, N.K., "Unexpected Twins" Physics Viewpoint, 9, 19 (2016)





Planar Defects - Grains and Grain Boundaries

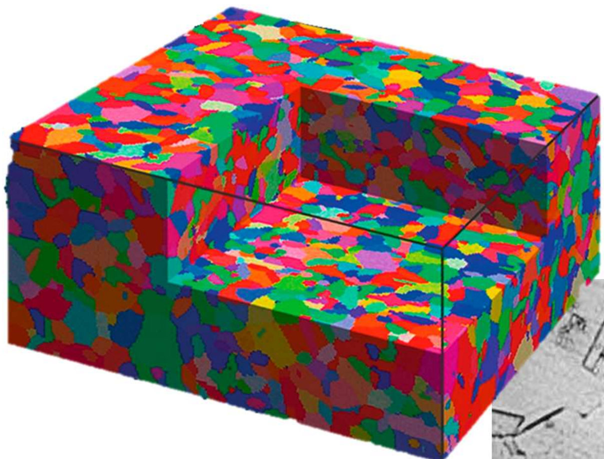


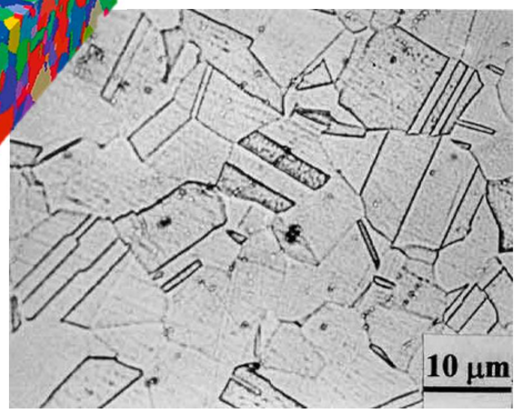
- A block of material may contain millions of individual crystals
- Such a structure is called *polycrystalline*
  - Each grain

1.

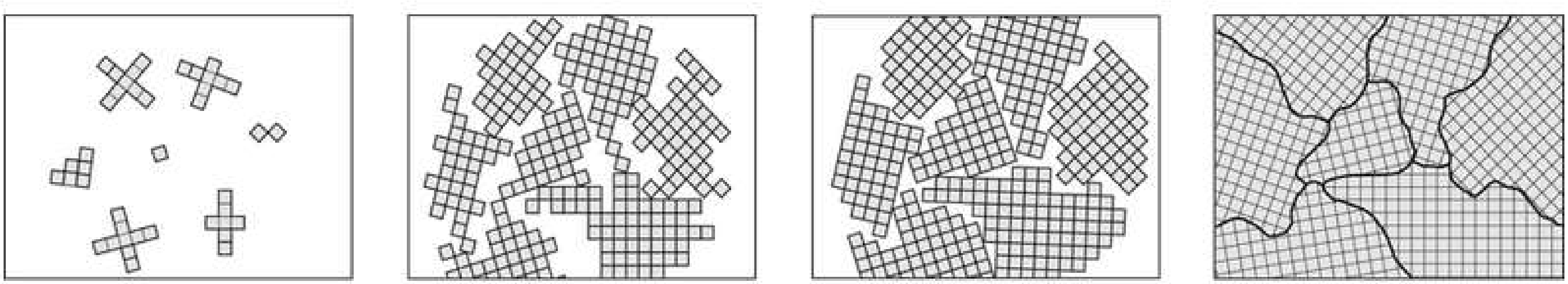
2.

How do grain boundaries form?



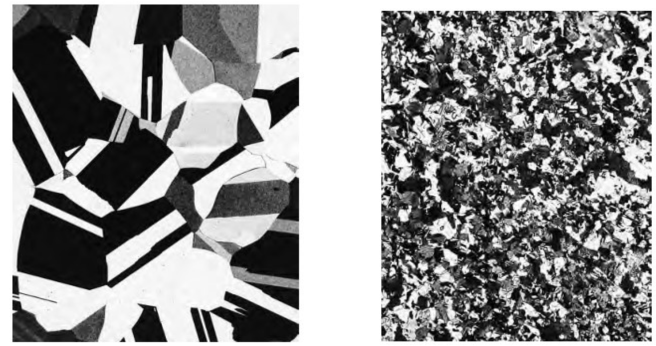


- As a material solidifies, individual crystals nucleate at random positions and orientations throughout the liquid

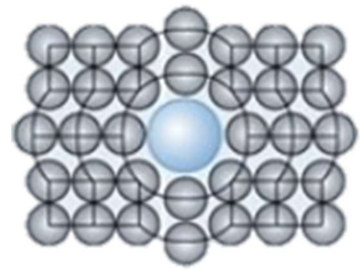


Making Crystalline Materials Stronger

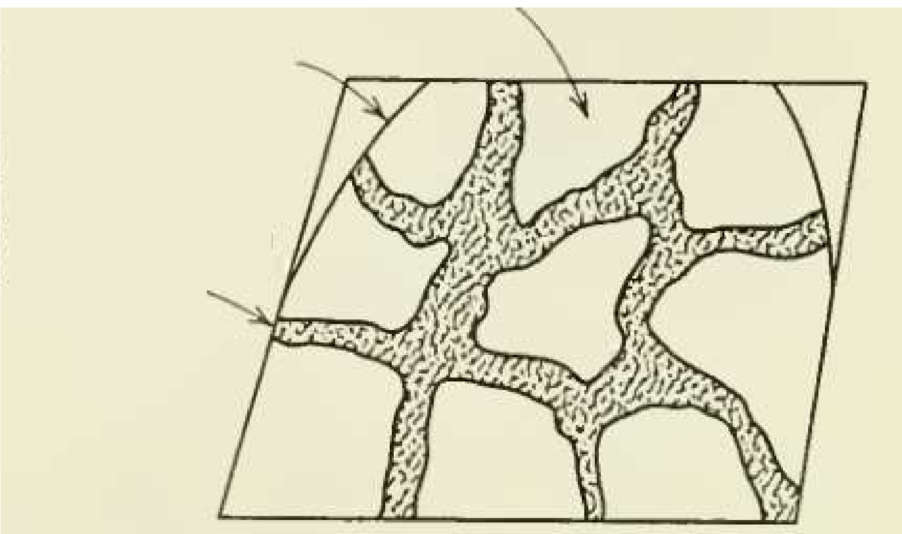
Four strengthening mechanisms

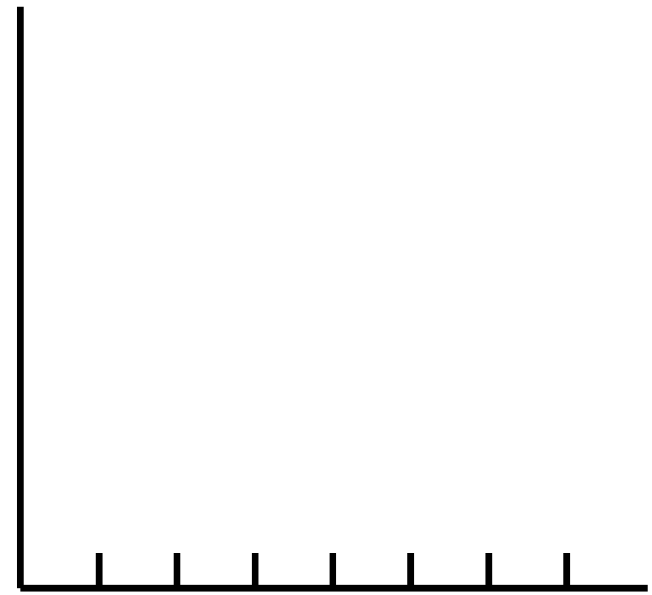


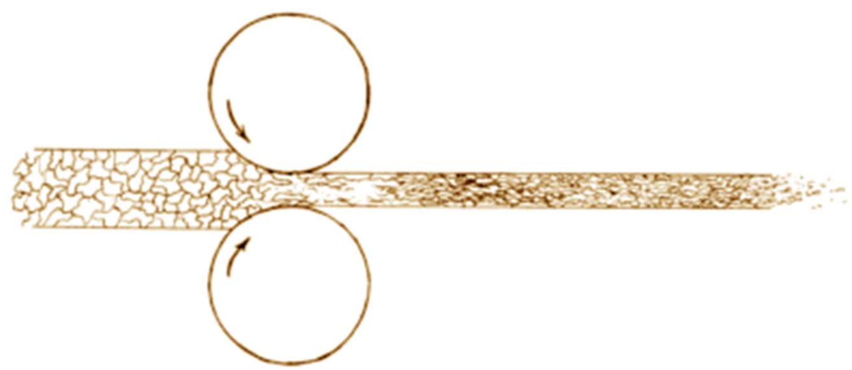
Adapted from *Callister 7e.*



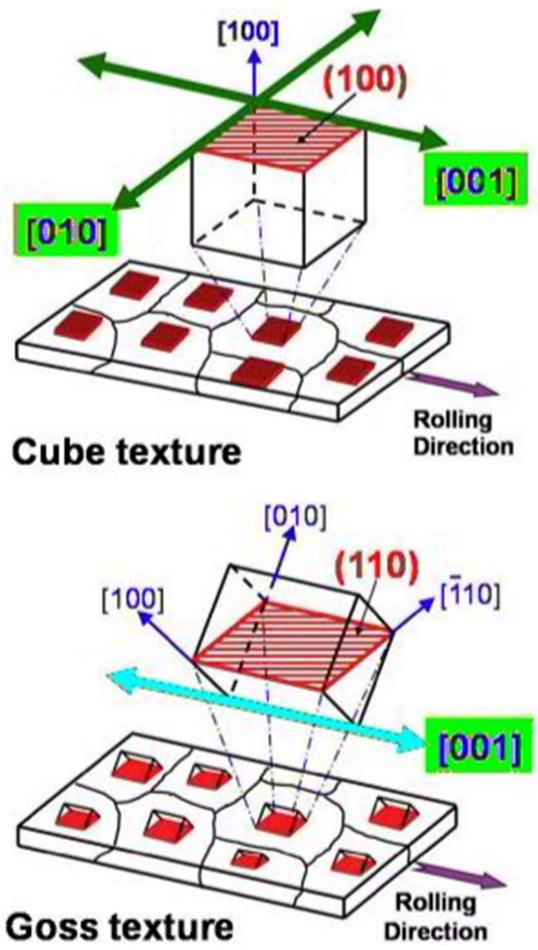
Strain Hardening/Cold Work

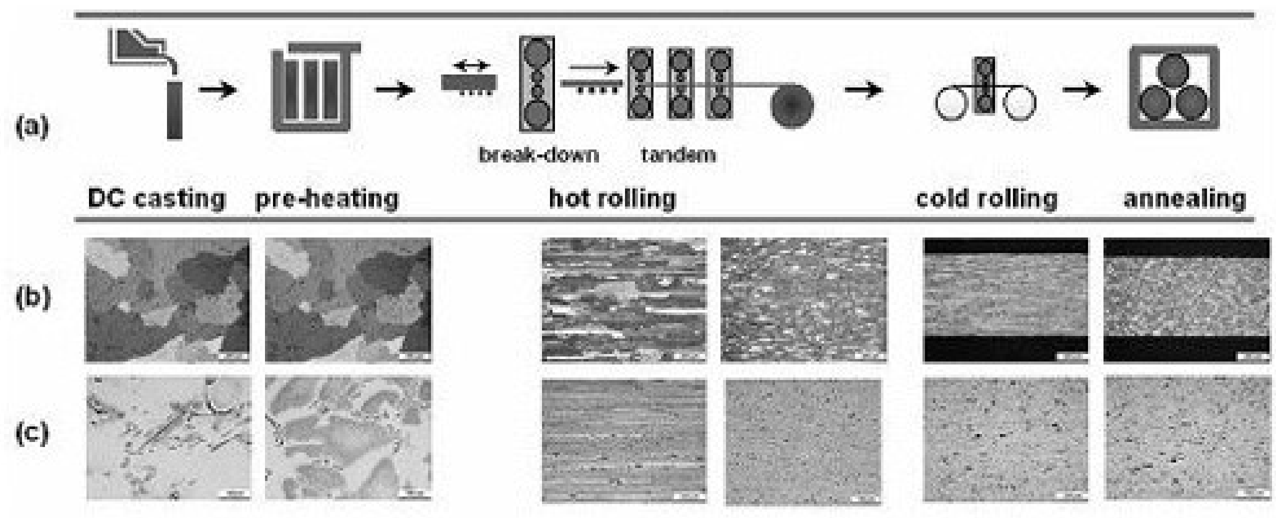






Crystallographic Texture





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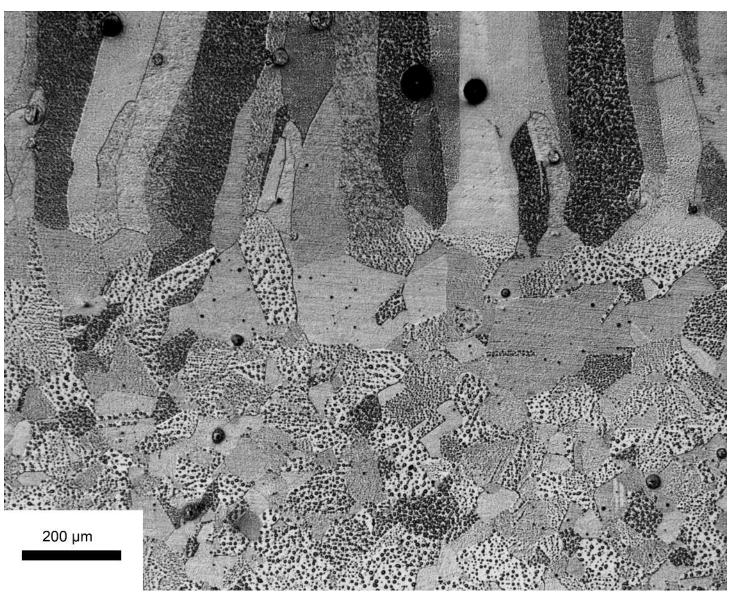
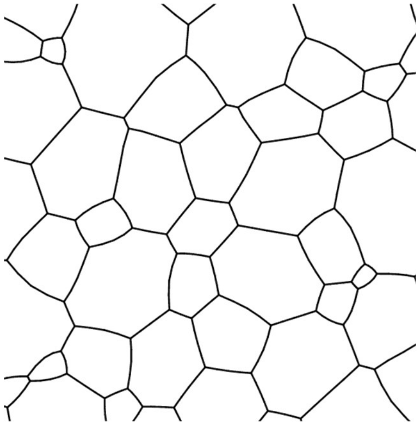
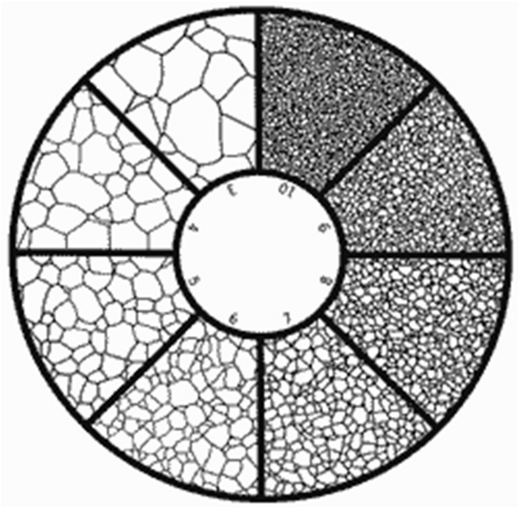


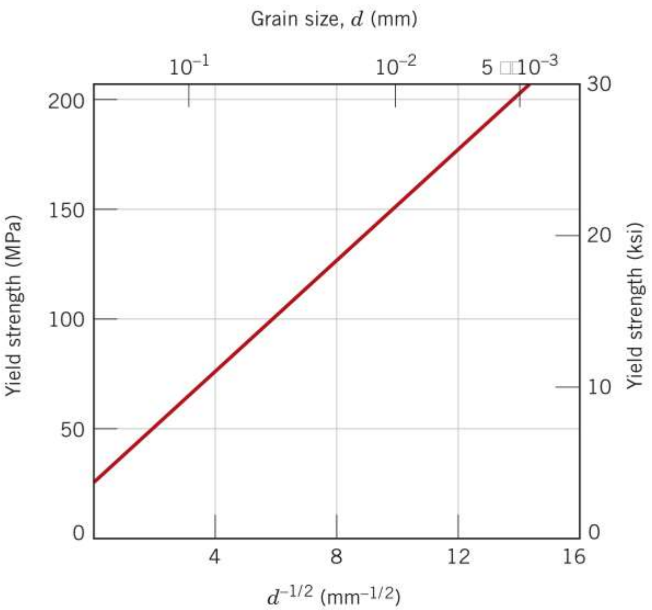
Grain size

- Line intercept and ASTM

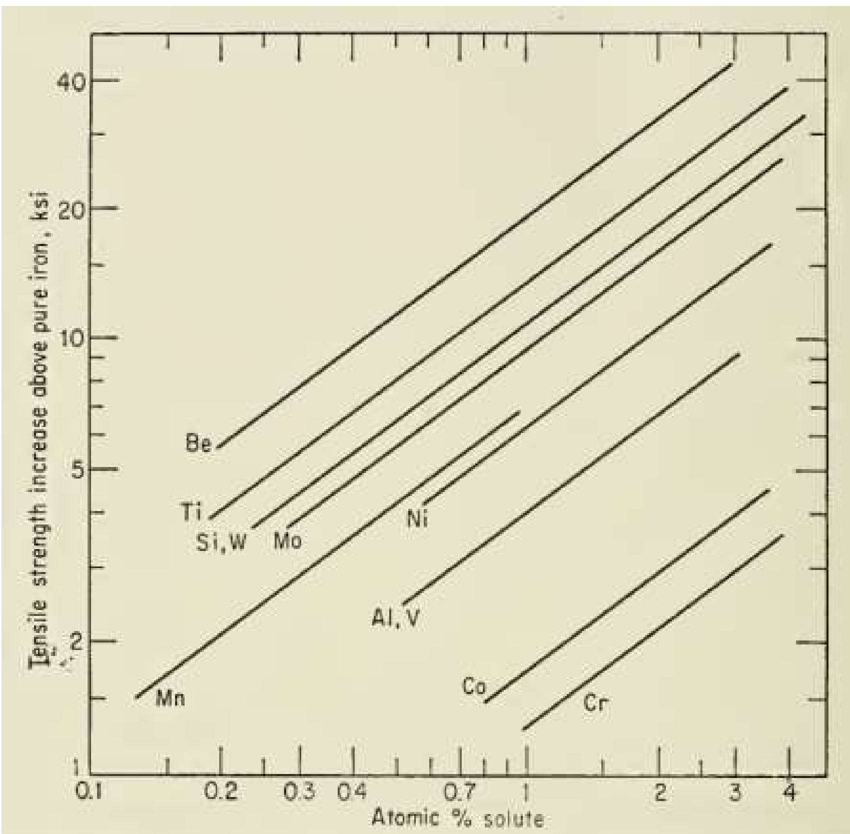


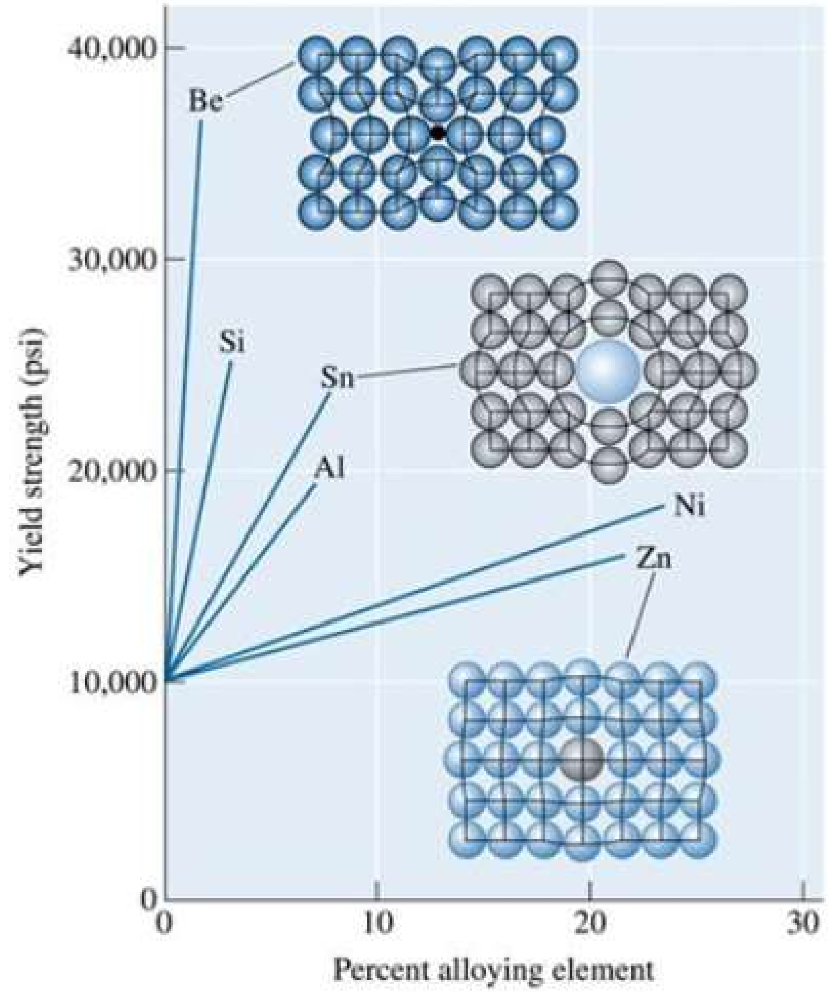


- Hall-Petch Equation



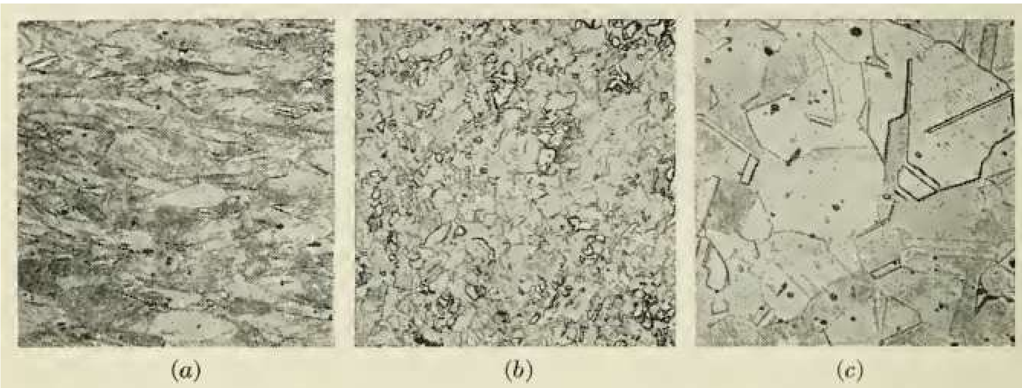
Solid-solution strengthening

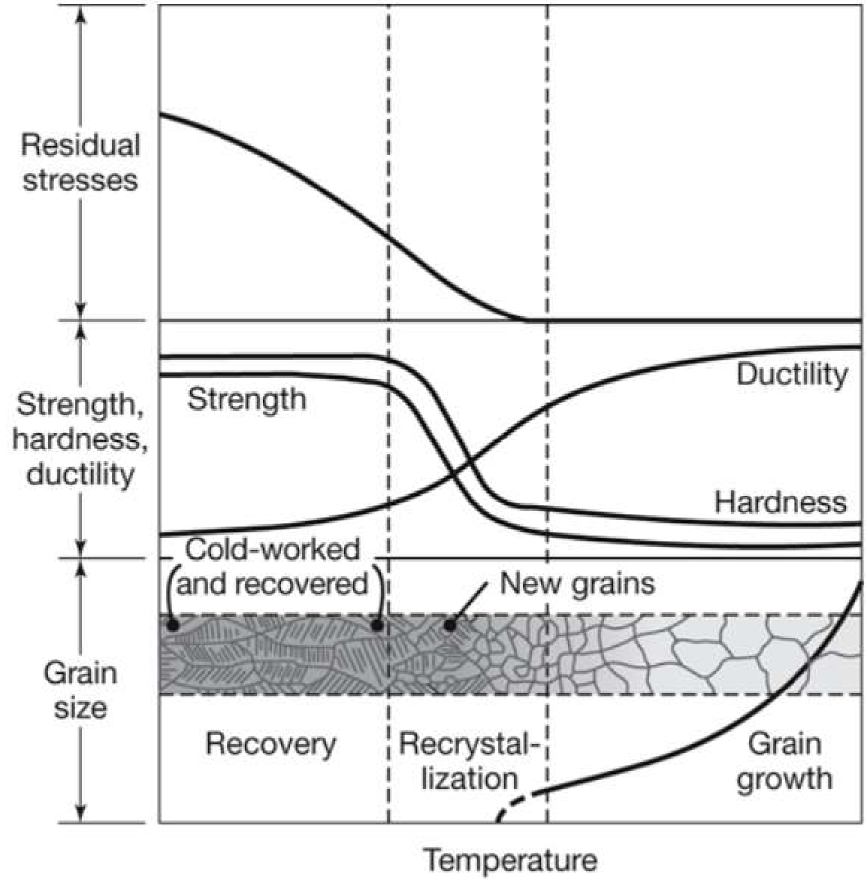




Askeland and Phule

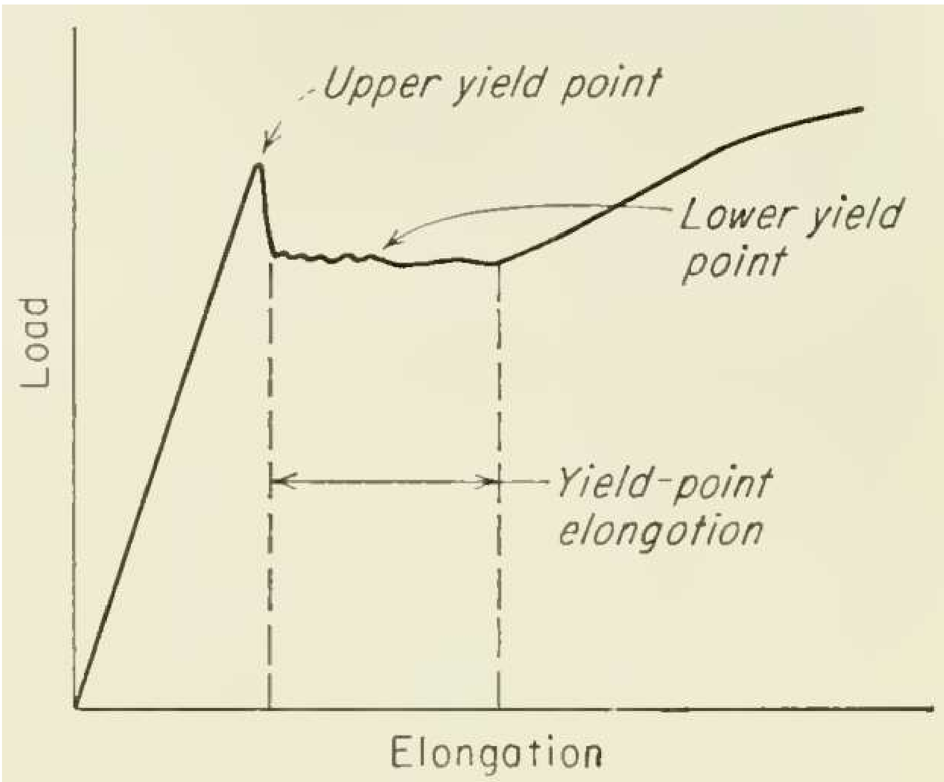
Recovery, Recrystallization, and Grain Growth

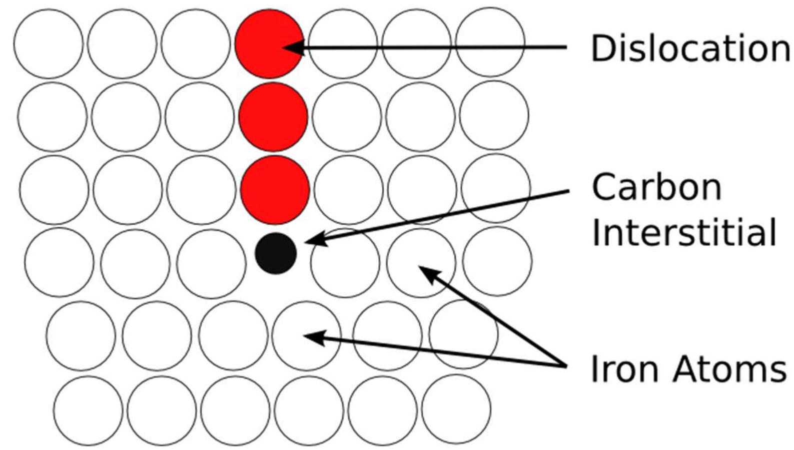




Influence of Time and Temperature on Strength

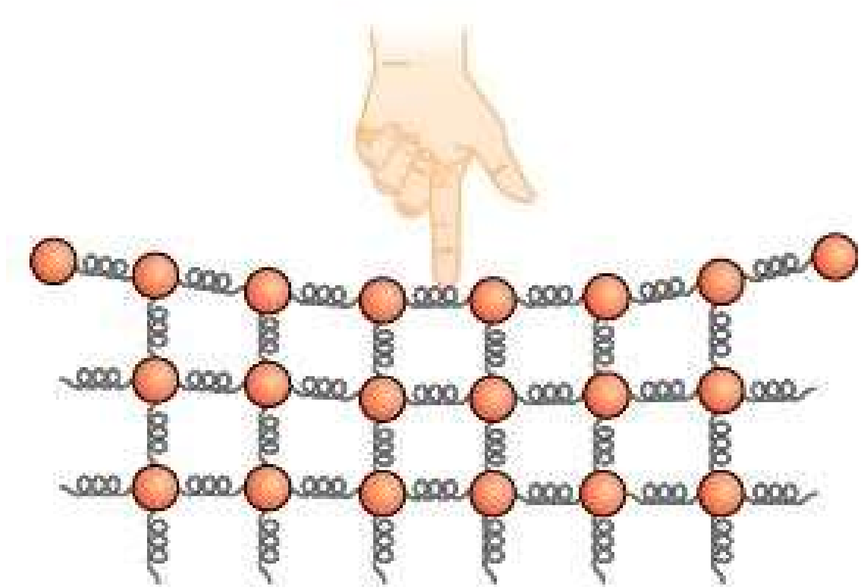
Upper/Lower Yield





Influence of Structure

- Material deformation is dependent on defects



<u>Dependent on structure</u>

-
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<u>Independent of structure</u>

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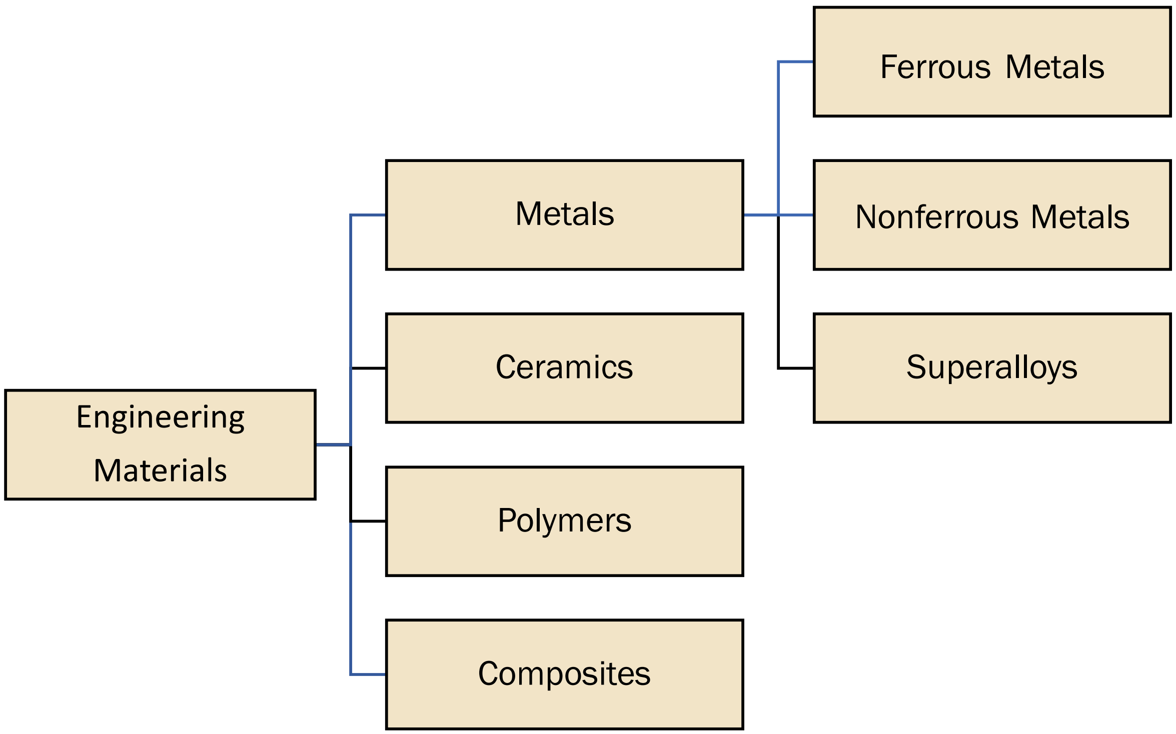
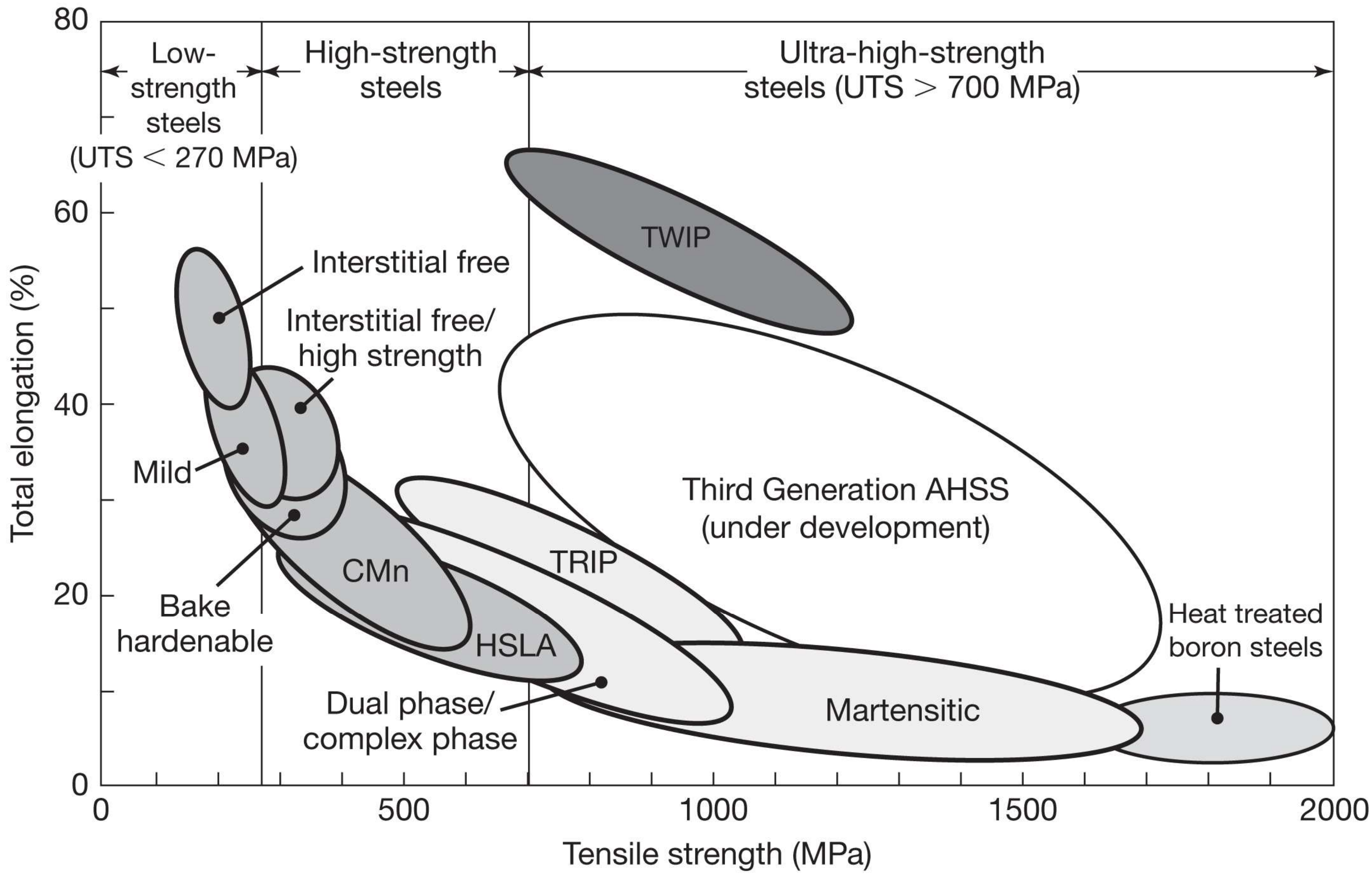
Materials



Engineering Materials
Metals
Ceramics
Polymers
Composites
Ferrous Metals
Nonferrous Metals
Superalloys

Steel Comparison



Steels: AISI-SAE Designation Scheme

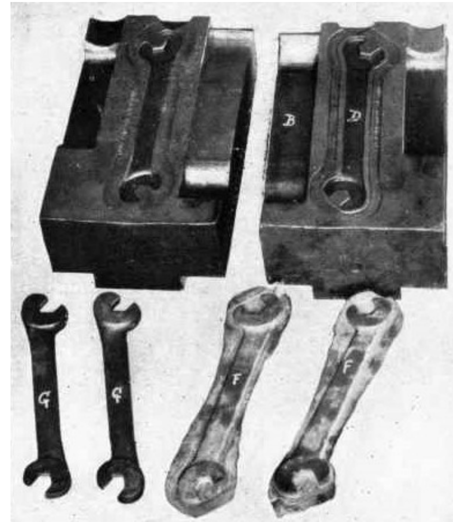
- Four digit number
- Alloying elements
  - 10XX – Carbon only
  - 13XX - Manganese steel
  - 20XX - Nickel steel
  - 31XX - Nickel-chrome steel
  - 40XX - Molybdenum steel
  - 41XX - Chrome-molybdenum steel

$$\overbrace{X\ X}\,\underbrace{X\ X}$$

Stainless Steels

- Type 302 – Austenitic SS
  - 18% Cr, 8% Ni, 2% Mn, 0.15% C
- Type 430 – Ferritic SS
  - 17% Cr, 0% Ni, 1% Mn, 0.12% C
- Type 440 – Martensitic SS
  - 17% Cr, 0% Ni, 1% Mn, 0.65% C

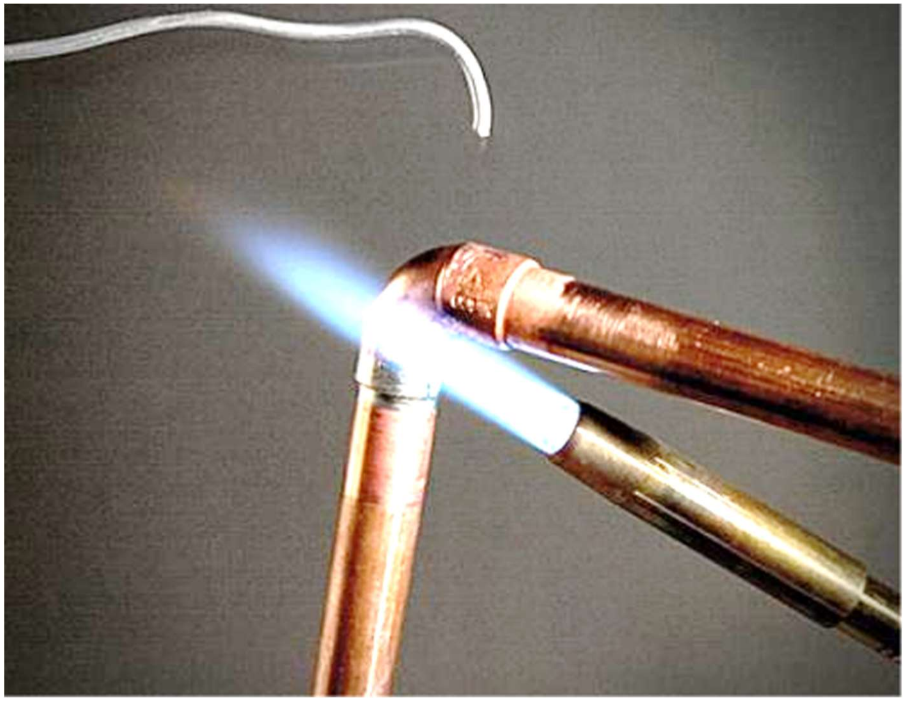
Tool Steels



Defining property	AISI-SAE grade	Significant characteristics
Water-hardening	W	
Cold-working	O	Oil-hardening
	A	Air-hardening; medium alloy
	D	High carbon; high chromium
Shock resisting	S	
High speed	T	Tungsten base
	M	Molybdenum base
Hot-working	H	H1–H19: chromium base H20–H39: tungsten base H40–H59: molybdenum base
Plastic mold	P	
Special purpose	L	Low alloy
	F	Carbon tungsten

Adapted from *Oberg, et al. 2004*

Nonferrous Alloys



- Iron/Steel Limitations

Copper

Table 11.6 Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys

Alloy Name	UNS Number	Composition (wt%)[a]	Condition	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [% EL in 50 mm (2 in.)]	Typical Applications
				Wrought Alloys			
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	965–1205 (140–175)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed	300 (44)	75 (11)	68	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
			Cold-worked (H04 hard)	525 (76)	435 (63)	8	
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed	325 (47)	130 (19)	64	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
			Cold-worked (H04 hard)	560 (81)	515 (75)	10	
Copper–nickel, 30%	C71500	30 Ni	Annealed	380 (55)	125 (18)	36	Condenser and heat-exchanger components, saltwater piping
			Cold-worked (H02 hard)	515 (75)	485 (70)	15	
				Cast Alloys			
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

[a] The balance of the composition is copper.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* 1990. Reprinted by permission of ASM International, Materials Park, OH.

Aluminum

Table 11.7 Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys

Aluminum Association Number	UNS Number	Composition (wt%)[a]	Condition (Temper Designation)	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications/ Characteristics
Wrought, Nonheat-Treatable Alloys							
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
Wrought, Heat-Treatable Alloys							
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat-treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat-treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
Cast, Heat-Treatable Alloys							
295.0	A02950	4.5 Cu, 1.1 Si	Heat-treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat-treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
Aluminum–Lithium Alloys							
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat-treated, cold-worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat-treated, cold-worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

[a] The balance of the composition is aluminum.

Source: Adapted from *ASM Handbook,* Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* 1990. Reprinted by permission of ASM International, Materials Park, OH.

Magnesium

Table 11.8 Compositions, Mechanical Properties, and Typical Applications for Six Common Magnesium Alloys

ASTM Number	UNS Number	Composition (wt%)[a]	Condition	Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Wrought Alloys							
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
Cast Alloys							
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

[a] The balance of the composition is magnesium.

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Titanium

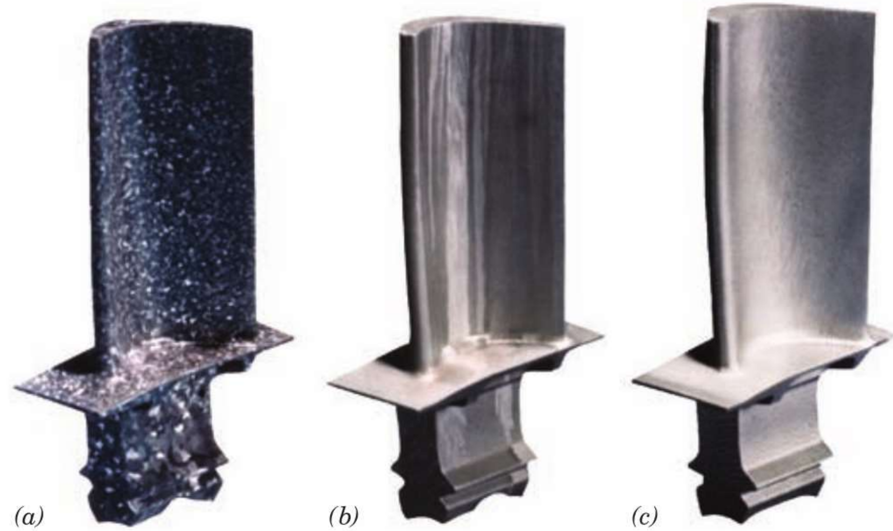
Table 11.9 Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys

Alloy Type	Common Name (UNS Number)	Composition (wt%)	Condition	Average Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Commercially pure	Unalloyed (R50250)	99.5 Ti	Annealed	240 (35)	170 (25)	24	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
α–β	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
α–β	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

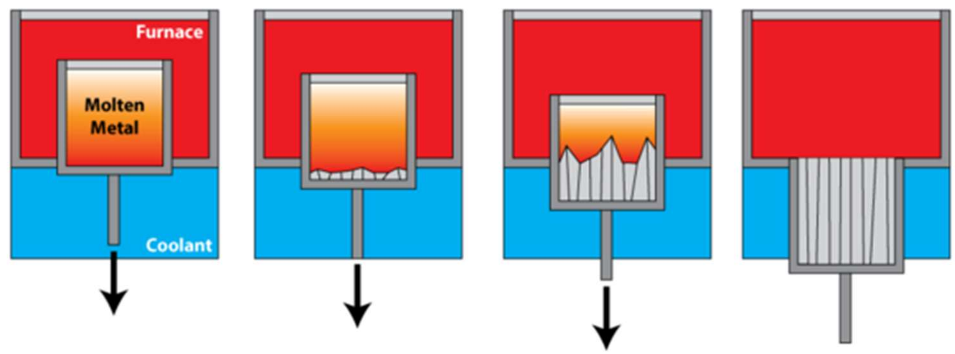
Superalloys

- Most used for turbine blades



Conventional casting Columnar grain Single crystal

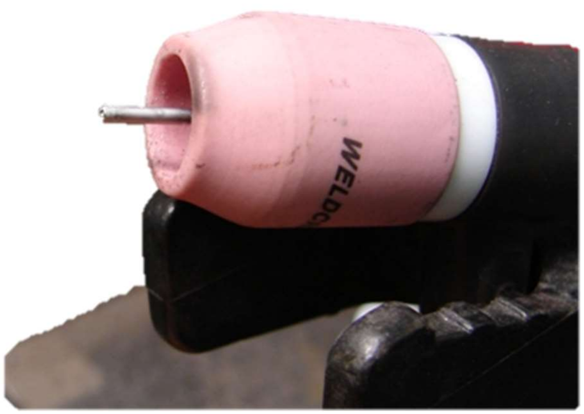
Adapted from *Callister 8e.*



wikipedia

Other Metals

- Niobium
- Molybdenum
- Tungsten
- Tantalum



- Gold
- Platinum
- Palladium
- Rhodium
- Ruthenium
- Iridium
- Osmium

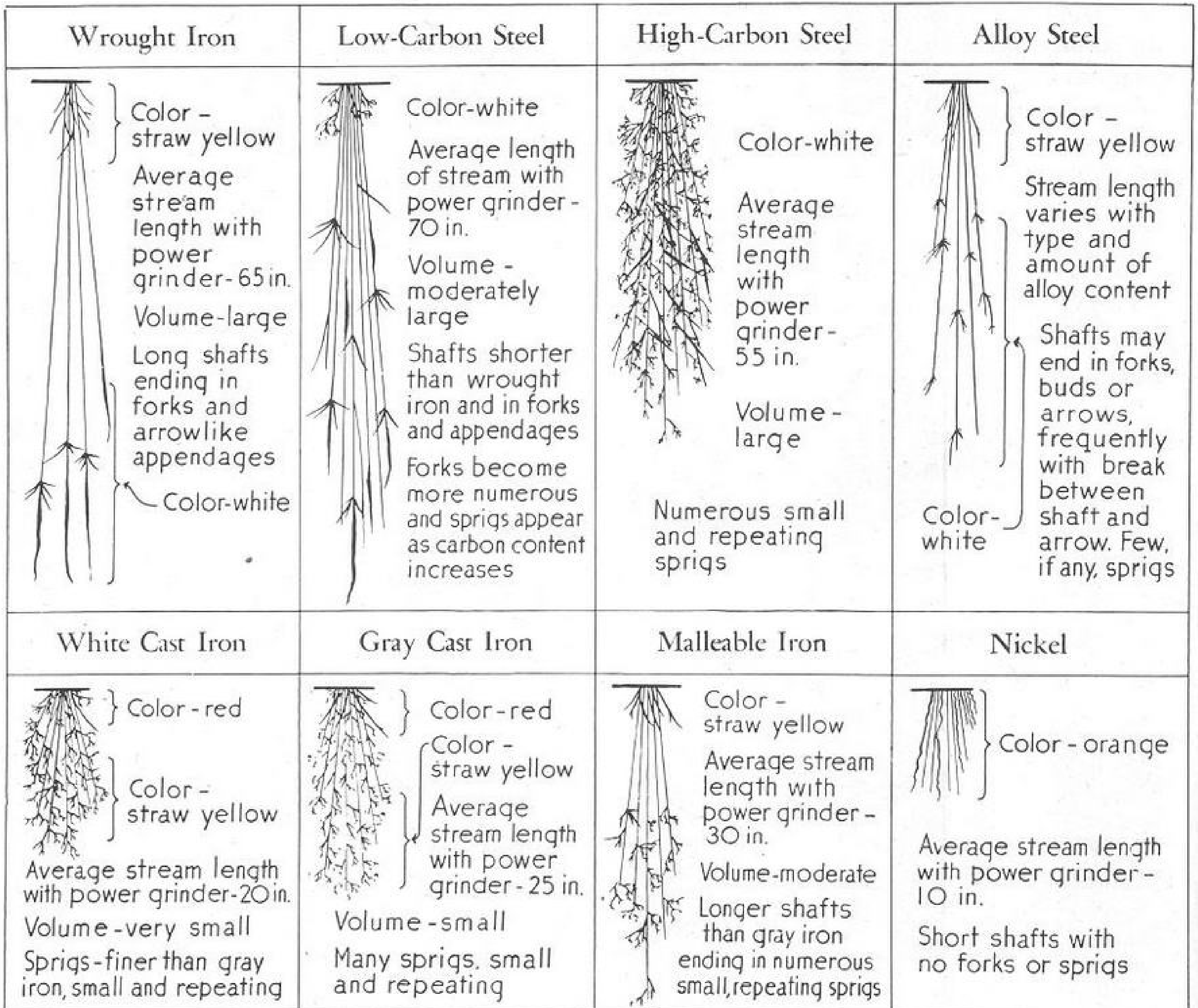


Fig. 18–12. Identification of sparks from various types of metal. (Linde Air Products Co.)