Chapter 3. A Survey of Engineering Materials

Mechanical Strengths and Behavior of Solids

Contents

3.1 Introduction

- **Become familiar with the 4 major classes of materials :**
  Metals and alloys, Polymers, Ceramics and glasses, Composites

- **Gain a general knowledge of the characteristics, internal structure, behaviors, and processing methods for 4 major classes of materials**

- **Learn typical materials, naming systems, common uses, and develop an appreciation for how uses of materials are related to their properties**

- **Apply a general method for selecting a material for a given engineering component**

3.2 Alloying and Processing of Metals

- **Metal : Approximately 80 % of the elements in the periodic table**
  - **Iron** : The most widely used engineering metal. iron-based alloy, steel **Aluminum, Copper, Titanium, Magnesium, …**
  - **Zinc, Lead, Tin, Silver** : Where stresses are quite low. Ex.) Solder joint
  - **Molybdenum, niobium, tantalum** : Refractory metal, melting temperature much higher than that of iron (1538°C).
  - Metal alloy is usually a melted-together combination of two or more chemicals.

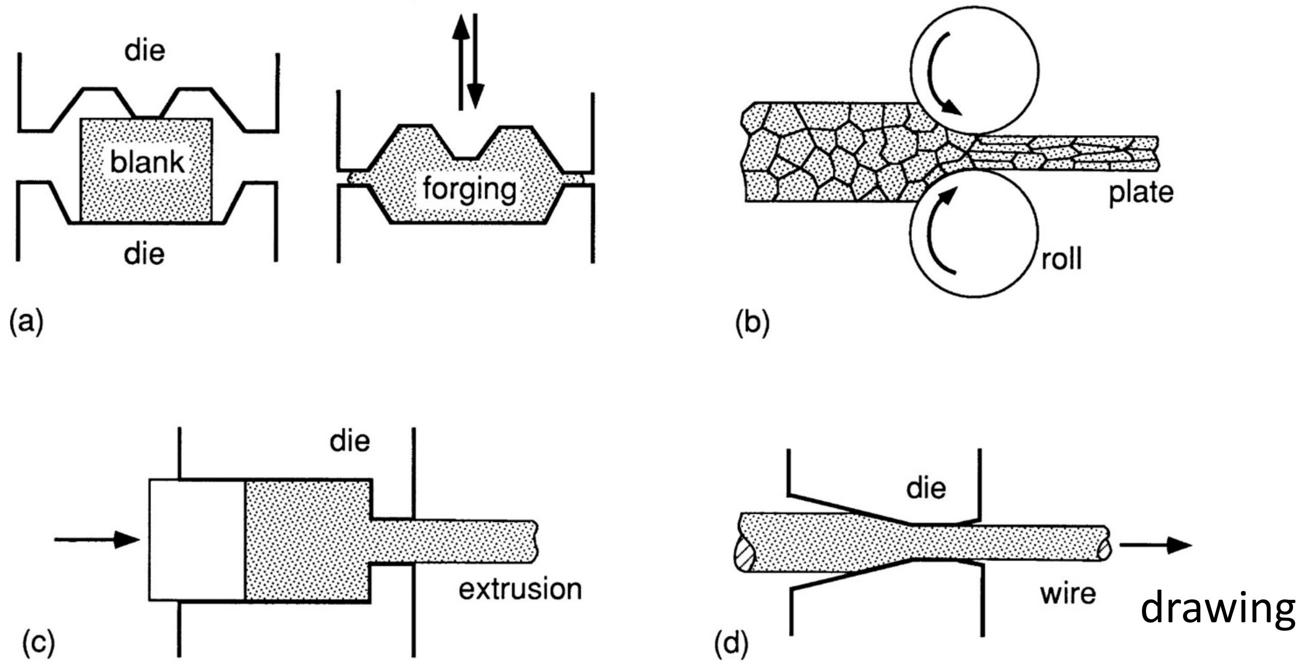
Table 3.1 Properties and Uses for Selected Engineering Metals and their Alloys

Metal	Melting Temp.	Density	Elastic Modulus	Typical Strength	Uses; Comments
	T_m °C (°F)	ρ g/cm^3 (lb/ft^3)	E GPa (10^3 ksi)	σ_u MPa (ksi)	
Iron (Fe) and steel	1538 (2800)	7.87 (491)	212 (30.7)	200 to 2500 (30 to 360)	Diverse: structures, machine and vehicle parts, tools. Most widely used engineering metal.
Aluminum (Al)	660 (1220)	2.70 (168)	70 (10.2)	140 to 550 (20 to 80)	Aircraft and other lightweight structure and parts.
Titanium (Ti)	1670 (3040)	4.51 (281)	120 (17.4)	340 to 1200 (50 to 170)	Aircraft structure and engines; industrial machine parts; surgical implants.
Copper (Cu)	1085 (1985)	8.93 (557)	130 (18.8)	170 to 1400 (25 to 200)	Electrical conductors; corrosion-resistant parts, valves, pipes. Alloyed to make bronze and brass.

3.2 Alloying and Processing of Metals

- **Processing : The properties are further affected by the processing methods.**
  - **Heat treatment** : A metal is subjected to heating, cooling, …
  - **Deformation** : forcing a piece of material to change its thickness or shape.

    Ex.) forging , rolling , extruding , …
  - **Casting** : pouring of melted metal into a mold



3.2 Alloying and Processing of Metals

- **Plastic deformation is due to the motion of dislocation. (Chap.2)**
- By processing of metals, **yield strength** of a metal or alloy can usually be **increased** by introducing **tangles of dislocation, grain boundaries, distorted crystal structure, …**

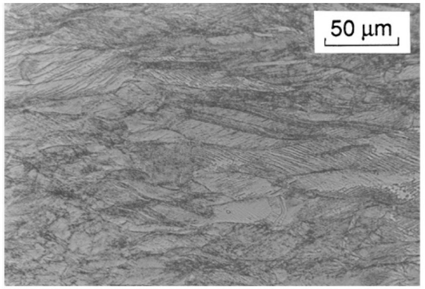
Table 3.2 Strengthening Methods for Metals and Alloys

Method	Features That Impede Dislocation Motion
Cold work	High dislocation density causing tangles
Grain refinement	Changes in crystal orientation and other irregularities at grain boundaries
Solid solution strengthening	Interstitial or substitutional impurities distorting the crystal lattice
Precipitation hardening	Fine particles of a hard material precipitating out of solution upon cooling
Multiple phases	Discontinuities in crystal structure at phase boundaries
Quenching and tempering	Multiphase structure of martensite and Fe_3C precipitates in BCC iron

3.2.1 Cold Work and Annealing

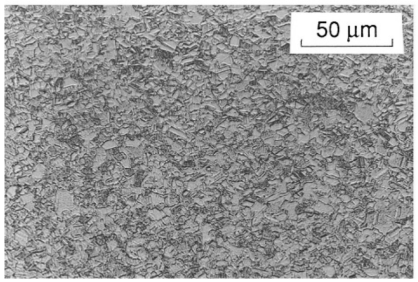
- **Cold work**
  - **Severe deforming** of a metal at **ambient temperature**, often by rolling or drawing.
  - **Large number of dislocation** form dense **tangles** → Strengthening
- **Annealing**
  - **Heating** the metal to a high temperature, **maintaining**, and then **cooling**.
  - **Formation of new crystal** form within the solid material, **grain refinement**

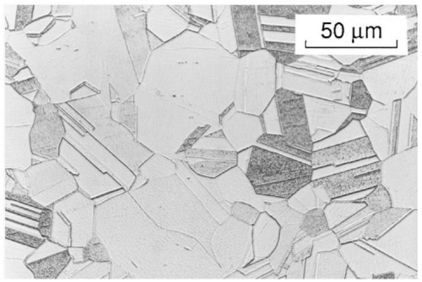
    → loss of strength, gain in ductility



Cold worked
Yield strength ↑
Ductility ↓

Annealed one hour at 375°C (bottom left)



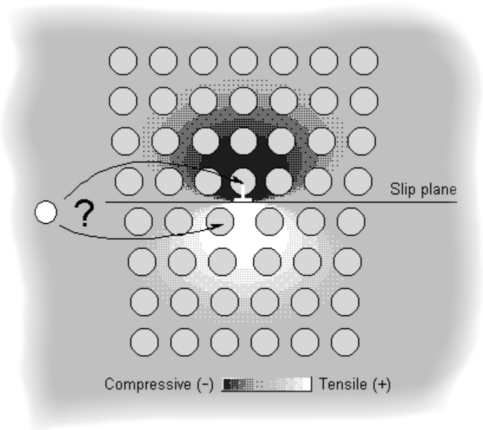


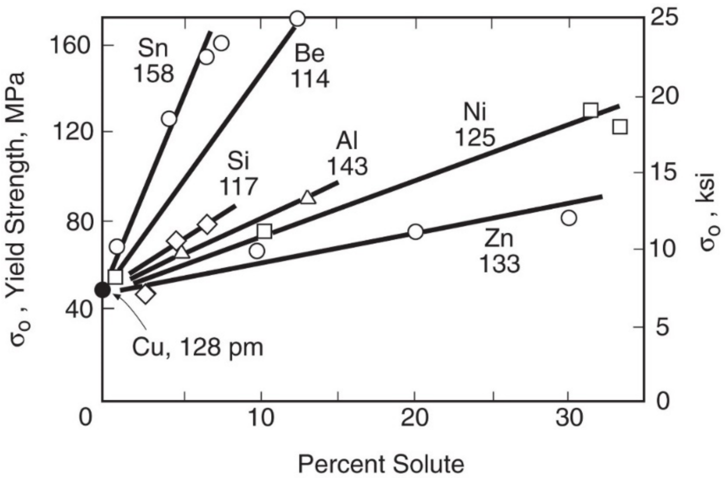
Annealed one hour at 500°C (bottom right)

- Microstructures of 70% Cu, 30% Zn brass in three conditions -

3.2.2 Solid Solution Strengthening

- **Solid Solution Strengthening**
  - The technique works by adding atoms of **one element (the alloying element)** to the crystalline lattice of **another element (the base metal)**.
  - **Impurity atoms distort the crystal lattice** and makes dislocation difficult
  - The effect of impurity is greater if the atomic size differs more from that of the major constituent
  - Impurity atoms of smaller size : interstitial impurity
  - Impurity atoms of larger size : substitutional impurity





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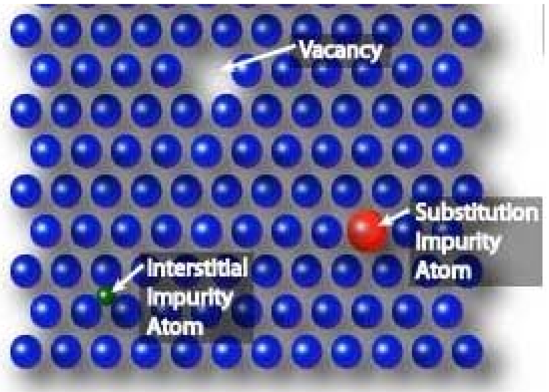
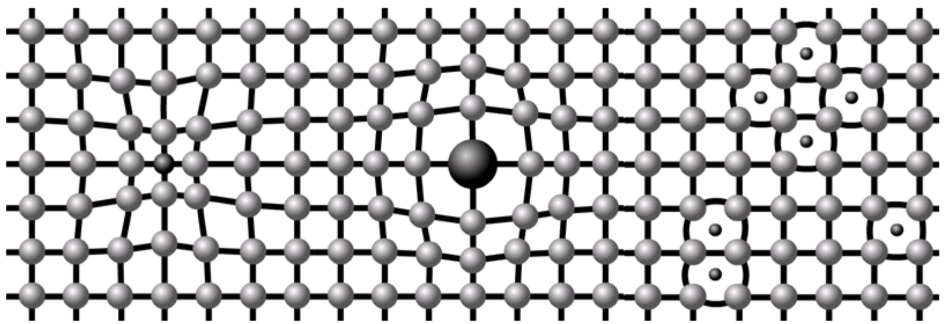
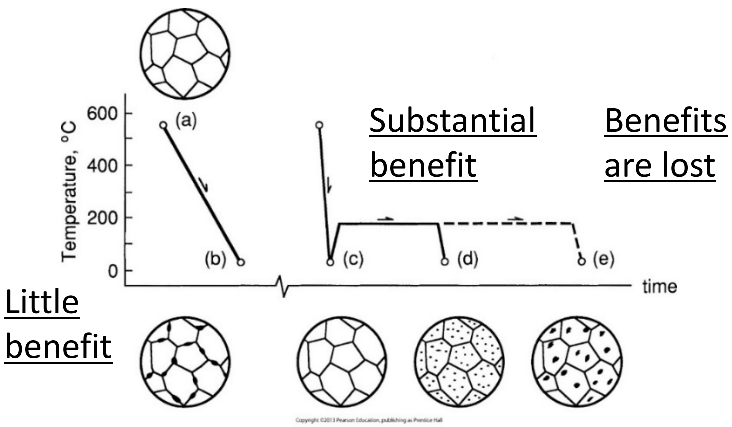
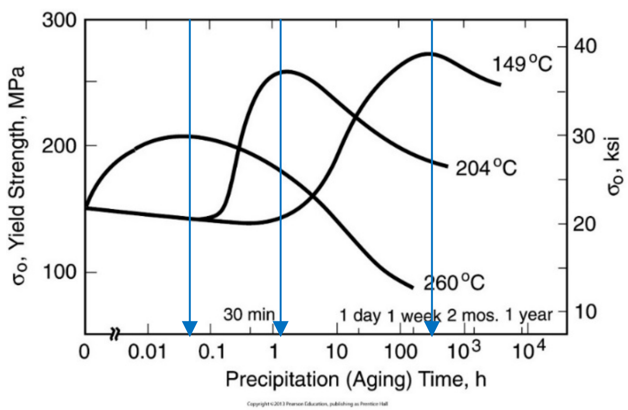




3.2.3 Precipitation Hardening and Other Multiple Phase Effects

- **Precipitation Hardening (석출경화)**
  - Limited solubility of two elements with dissimilar properties
    → Upon cooling, the impurity precipitate out of solution
  - The precipitated state has a hard crystal structure and precipitate particles are coherent with parent metal -> high strength
  - Supersaturate → aging at a moderate temp. gives fine precipitates but overaging does coarse precipitates.
- **Multiple Phase Effects**
  - Needlelike or layered microstructural features, or crystal grains of more than one type→ Increased strength because the discontinuities at the phase boundaries make dislocation motion more difficult.





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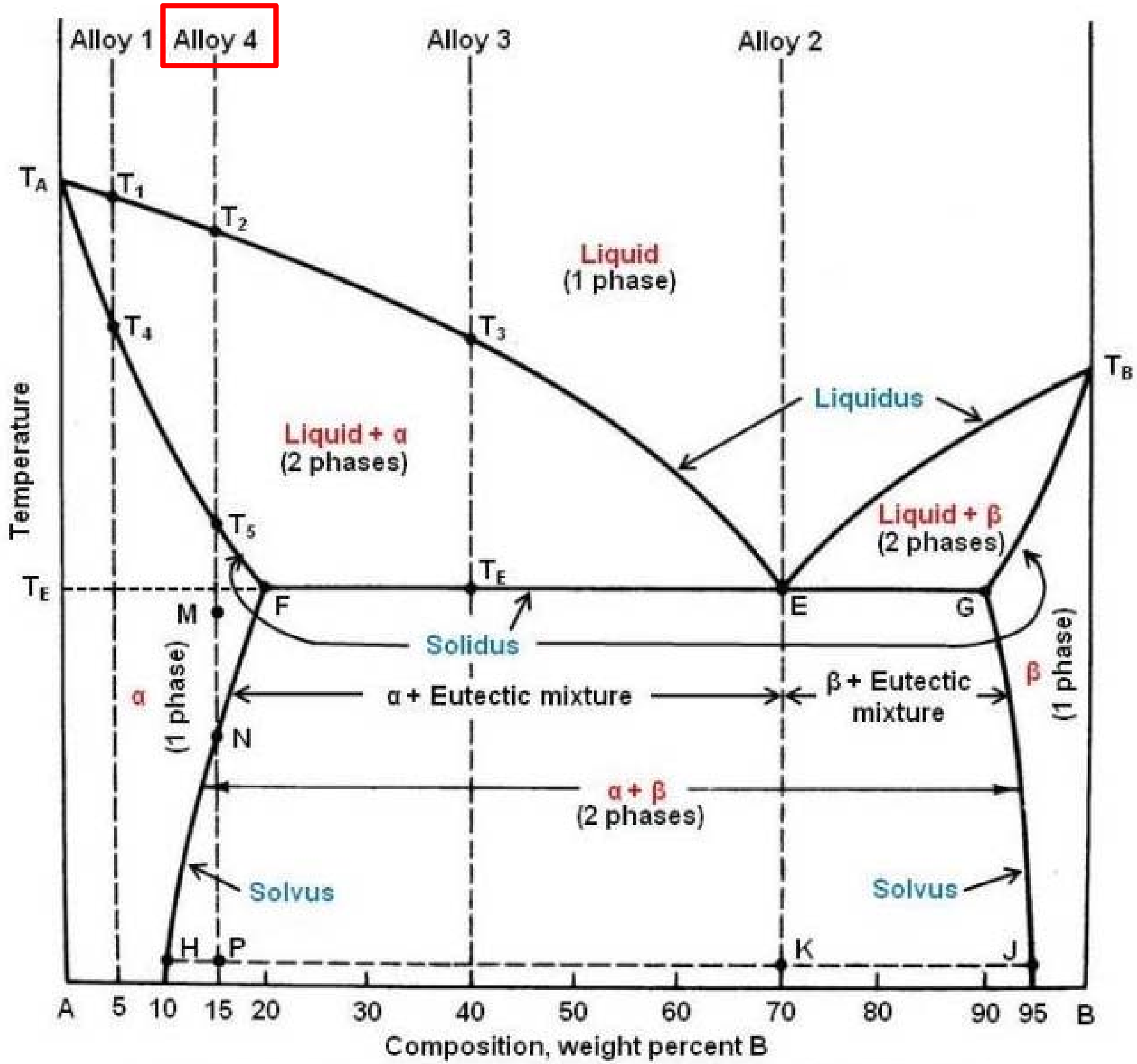
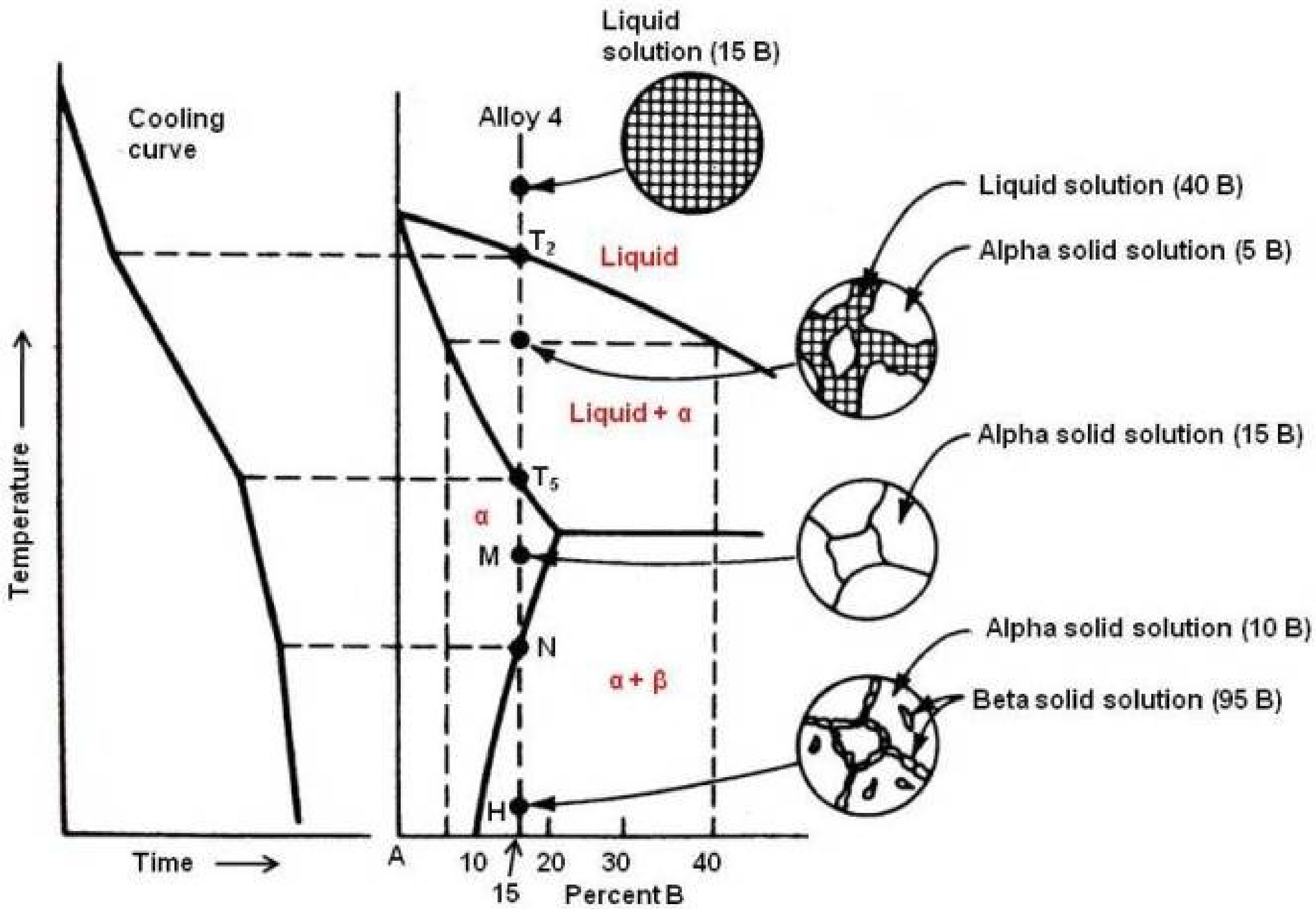


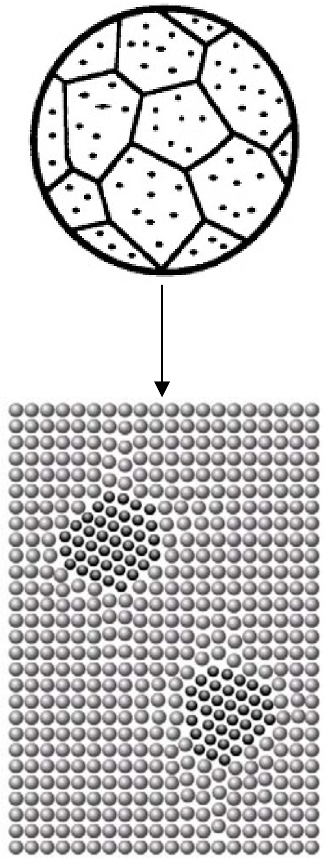
Phase Diagram of Two Metals only Partly Soluble in the Solid State

3.2.3 Precipitation Hardening and Other Multiple Phase Effects



Solidification of Alloy4 (85A-15B)

Precipitation



Precipitation at Grain boundaries

Several reasons explain why precipitation at grain boundaries occurs preferentially compared to precipitation within the crystals:

- First, a thermodynamic reason is the decrease of the energy barrier of the heterogeneous nucleation with respect to its value for homogeneous nucleation. Nucleation at grain boundaries is especially favoured when the chemical driving force is low and, simultaneously, the ratio between the grain boundary energy and that of the "nucleus/bulk" interface is high.
- Then, the self-diffusion coefficient at any grain boundary is generally higher than in the volume; this allows the solute atoms to rapidly migrate towards any new phase nucleus within the grain boundary.
- Finally, a strong segregation yields solute atom saturation in the grain boundary, then formation of second-phase nuclei. For example, garnet (YAG) precipitates appear just after yttrium saturation of grain boundaries in yttria-doped alumina polycrystals (Fig. 7.1) [1]. Grain growth leads to redistribution of yttrium atoms in grain boundaries; the average boundary yttrium concentration increases until saturation followed by formation of intergranular YAG particles. The critical size for which the "segregation/precipitation" transition occurs decreases with the global yttrium content in alumina.

Priester, Louisette. *Grain boundaries: from theory to engineering*. Vol. 172. Springer, 2012.

3.3 Irons and Steels

- **Iron-based alloys, ferrous alloys**
  - Include cast irons (more than 2% carbon and 1 to 3% silicon)
  - Steel : iron and some carbon and manganese, …
  - A wide variation in properties for steels
  - Pure iron is quite weak, but is strengthened considerably by the addition of carbon

Table 3.3 Commonly Encountered Classes of Irons and Steels

Class	Distinguishing Features	Typical Uses	Source of Strengthening
Cast iron	More than 2% C and 1 to 3% Si	Pipes, valves, gears, engine blocks	Ferrite-pearlite structure as affected by free graphite
Plain-carbon steel	Principal alloying element is carbon up to 1%	Structural and machine parts	Ferrite-pearlite structure if low carbon; quenching and tempering if medium to high carbon
Low-alloy steel	Metallic elements totaling up to 5%	High-strength structural and machine parts	Grain refinement, precipitation, and solid solution if low carbon; otherwise quenching and tempering
Stainless steel	At least 10% Cr; does not rust	Corrosion resistant piping and nuts and bolts; turbine blades	Quenching and tempering if < 15% Cr and low Ni; otherwise cold work or precipitation
Tool steel	Heat treatable to high hardness and wear resistance	Cutters, drill bits, dies	Quenching and tempering, etc.

3.3 Irons and Steels

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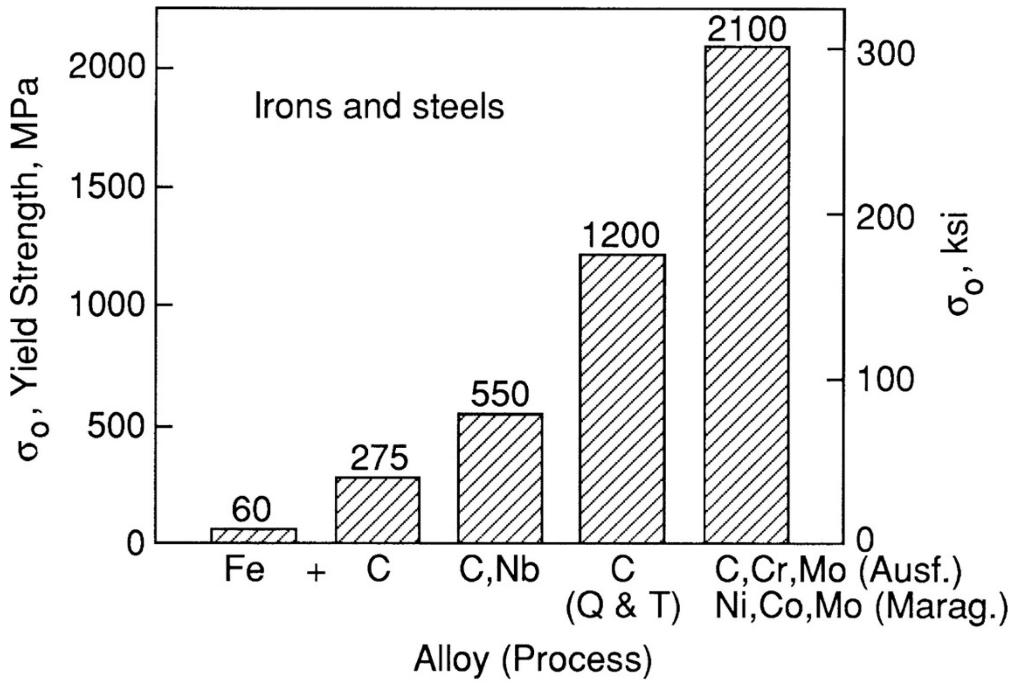

3.3.1 Naming Systems for Irons and Steels

- **Naming Systems for Irons and Steels**
  - Usually 4-digit number
  - The first two digits specify the alloy content other than carbon
  - The second two specify the carbon content in hundredth of a percent

Table 3.5 Summary of the AISI–SAE Designations for Common Carbon and Low-Alloy Steels

Designation[1]	Approx. Alloy Content, %	Designation	Approx. Alloy Content, %
Carbon steels		*Nickel–molybdenum steels*	
10XX	Plain carbon	46XX	Ni 0.85 or 1.82; Mo 0.25
11XX	Resulfurized	48XX	Ni 3.50; Mo 0.25
12XX	Resulfurized and rephosphorized		
15XX	Mn 1.00 to 1.65		
Manganese steels		*Chromium steels*	
13XX	Mn 1.75	50XX(X)	Cr 0.27 to 0.65
		51XX(X)	Cr 0.80 to 1.05
		52XXX	Cr 1.45

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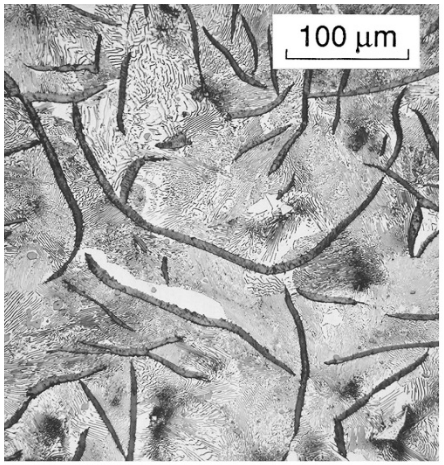
Designation[1]	Approx. Alloy Content, %	Designation	Approx. Alloy Content, %
Molybdenum steels		*Chromium–vanadium steels*	
40XX	Mo 0.25	61XX	Cr 0.6 to 0.95; V 0.15
44XX	Mo 0.40 or 0.52		
Chromium–molybdenum steels		*Silicon–manganese steels*	
41XX	Cr 0.50 to 0.95; Mo 0.12 to 0.30	92XX	Si 1.40 or 2.00; Mn 0.70 to 0.87; Cr 0 or 0.70
Nickel–chromium–molybdenum steels		*Boron steels*[2]	
43XX	Ni 1.82; Cr 0.50 or 0.80; Mo 0.25	YYBXX	B 0.0005 to 0.003
47XX	Ni 1.45; Cr 0.45; Mo 0.20 or 0.35		
81XX	Ni 0.30; Cr 0.40; Mo 0.12		
86XX	Ni 0.55; Cr 0.50; Mo 0.20		
87XX	Ni 0.55; Cr 0.50; Mo 0.25		
94XX	Ni 0.45; Cr 0.40; Mo 0.12		

Notes: [1]Replace “XX” or “XXX” with carbon content in hundredths of a percent, such as AISI 1045 having 0.45% C, or 52100 having 1.00% C. [2]Replace “YY” with any two digits from earlier in table to indicate the additional alloy content.

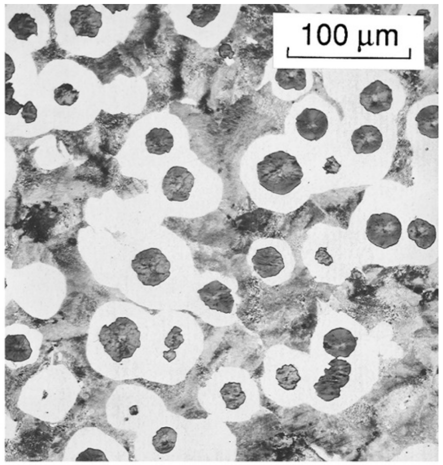
3.3.2 Cast Irons

- **Cast Irons**
  - Have been used for more than 200 year. Inexpensive and useful
  - 2-4% of carbon by weight, 1 to 3% silicon
  - In most cast irons, carbons that exceed 2% are present in the form of graphite.
  - Gray iron : Graphite in the form of flakes. Relatively weak and brittle in tension.
    Higher strength and ductility in compression than those in tension.
  - Ductile iron (=nodular iron) : contains graphite in spherical form of nodules (결정). Greater strength and ductility in tension than gray iron
  - White iron, malleable iron, …

Gray iron :



Ductile iron :

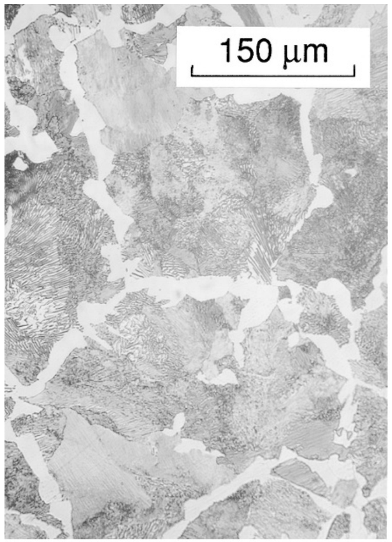


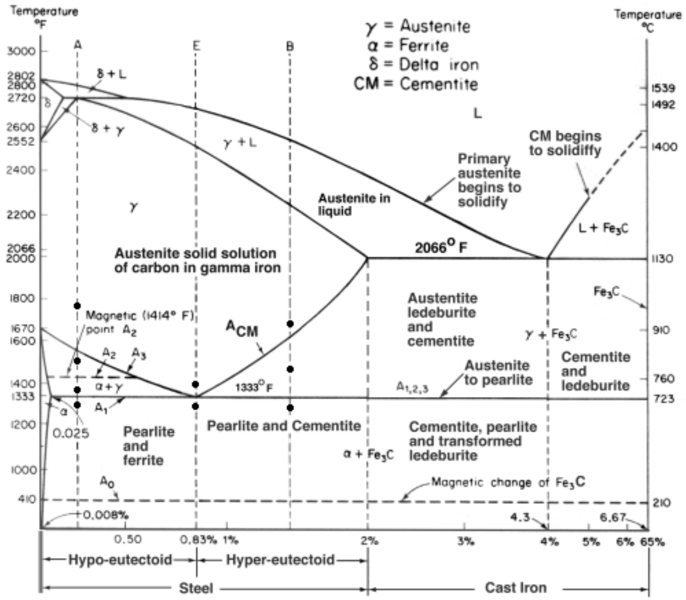
3.3.3 Carbon Steels

- **Plain-carbon steel**
  - less than 1 % carbon, limited amounts of manganese, …
  - Low-carbon steel (or mild steel) : a carbon content of less than 0.25%
  - Low strength, but excellent ductility
  - Structure : combination of BCC iron, called α-iron or ferrite, and pearlite
  - Medium-carbon steel : a carbon content around 0.3 to 0.6%
  - High-carbon steel : a carbon content around 0.7 to 1%

Ferrite-pearlite structure in AISI 1045 steel :

Ferrite : light-colored areas
Pearlite : striated regions

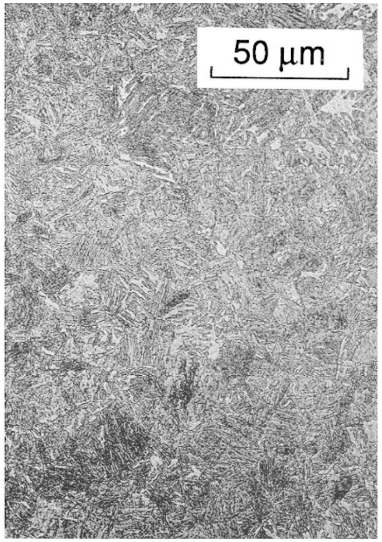




3.3.3 Carbon Steels

- **Heat treatment of Plain-carbon steel**
  - Strength can be achieved while accompanied by loss of ductility (brittle)
  - Heated to about 850°C so that irons changes to FCC, γ-iron or austenite.
  - Supersaturated solution of carbon in BCC by rapid cooling, **quenching**.
  - After quenching, martensite, which has a BCC lattice distorted by interstitial carbon atoms, appears.
  - Martensite exists either as groupings of parallel thin crystals or randomly thin plate → very hard and brittle due to the two phase states, the distorted crystal structure and a high dislocation density.
  - Tempering lowers the strength, but increases the ductility. Tempering is thus needed to obtain a useful material.

Quenched and tempered structure in AISI 4340 steel:



3.3.4 Low-Alloy Steels & 3.3.5 Stainless Steels

- **Low-Alloy Steels**
  - Small amounts of alloying elements totaling no more than about 5%
  - Sulfur : improves machinability
  - Molybdenum and vanadium : promote grain refinement

- **Stainless Steels**
  - Steels containing at least 10% chromium, good corrosion resistance
  - Precipitation-hardening stainless steels : Applications where resistance to corrosion and high temperature are needed.

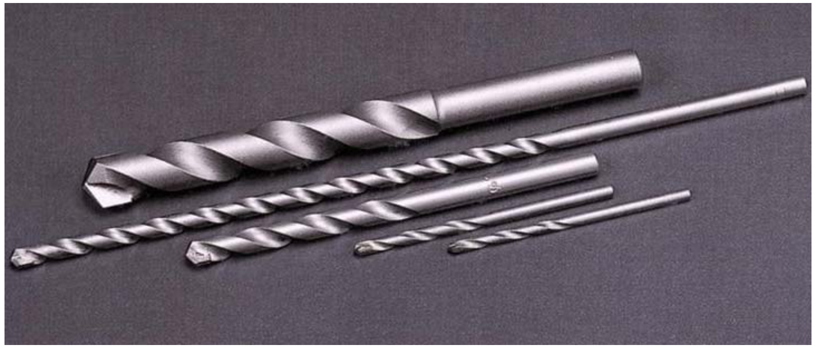
4130 Steel

Stainless Steels

3.3.6 Tool Steels and Other Special Steels

- **Tool Steels (드릴, 칼, 낫 등)**
  - High hardness and wear resistance for use in cutting tools
  - Strengthening generally involves quenching and tempering
  - Ausforming process (열처리+가공): deform the steel at a high temperature within the range where FCC crystal exist and then cold works that yield high dislocation density and fine precipitatation

- **Other Special Steels**
  - Nonstandard trade names
  - 300M, D-6a, Maraging steels, …



Tool steels

Maraging steels

3.4 Nonferrous Metals & 3.4.1 Aluminum Alloys

- **Strengthening of Nonferrous Metals**
  - Quenching and tempering is the most effective means of strengthening in steels as they produce a martensitic structure.
  - In nonferrous metals, martensite may not occur -> Precipitation hardening is performed
- **Aluminum Alloys**
  - Annealed pure aluminum can be strengthened by additions and processing
  - Naming system : 4 digits + processing codes

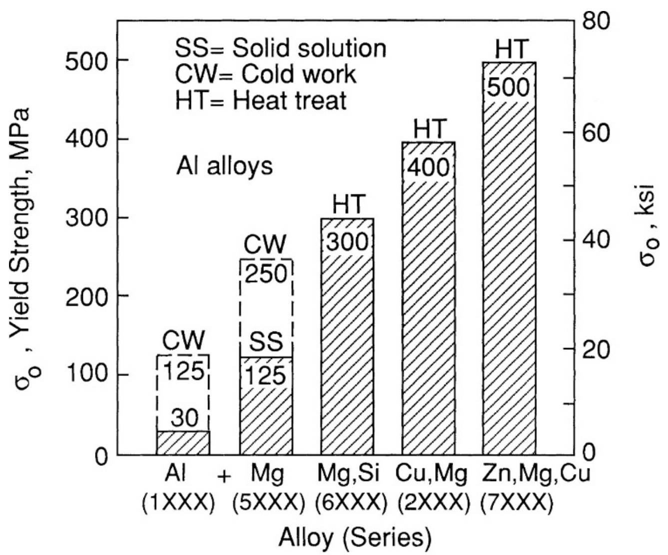


Table 3.7 Some Typical Wrought Aluminum Alloys

		Principal Alloying Elements, Typical % by Weight					
Identification	UNS No.	Cu	Cr	Mg	Mn	Si	Other
1100-O	A91100	0.12	—	—	—	—	—
2014-T6	A92014	4.4	—	0.5	0.8	0.8	—
2024-T4	A92024	4.4	—	1.5	0.6	—	—
2219-T851	A92219	6.3	—	—	0.3	—	0.1 V, 0.18 Zr
3003-H14	A93003	0.12	—	—	1.2	—	—
4032-T6	A94032	0.9	—	1.0	—	12.2	0.9 Ni
5052-H38	A95052	—	0.25	2.5	—	—	—
6061-T6	A96061	0.28	0.2	1.0	—	0.6	—
7075-T651	A97075	1.6	0.23	2.5	—	—	5.6 Zn

3.4.2 Titanium alloys & 3.4.3 Other Nonferrous Metals

- **Titanium alloys**
  - The density of titanium is greater than aluminum, but 60 % of steel
  - Melting temperature is greater than steel, far greater than aluminium.
  - High strength-to-weight ratio → Aerospace application
- **Other Nonferrous Metals**
  - Copper alloy : electrical conductivity, corrosion resistance, and attractiveness
  - Easily alloyed with various other metals, zinc(brass), tin(bronze), …
  - Magnesium alloy : melting temperature near aluminum, density of 65%
  - Superalloy : heat-resisting alloy above 550°C from nickel, cobalt, …

Titanium alloys (SR-71 Blackbird)

Nickel superalloy in jet engine turbine blade

3.5 Polymers

- **Polymers**
  - Materials consisting of long-chain formed by Carbon-to-Carbon bonds.
  - Ex.) Plastics, Rubbers, Fibers, cellulose, …
  - Thermoplastics, Thermosetting plastics, Elastomers
  - Characteristics : light weight, low strength
- **Thermoplastics (열가소성)**
  - When heated, thermoplastics softens and usually melts.
  - If cooled, it returns to its original solid condition
- **Thermosetting plastics (열경화성)**
  - When heated, thermosetting plastics changes chemically
- **Elastomers**
  - Capable of rubbery behaviors.
  - Can be deformed by large amounts.

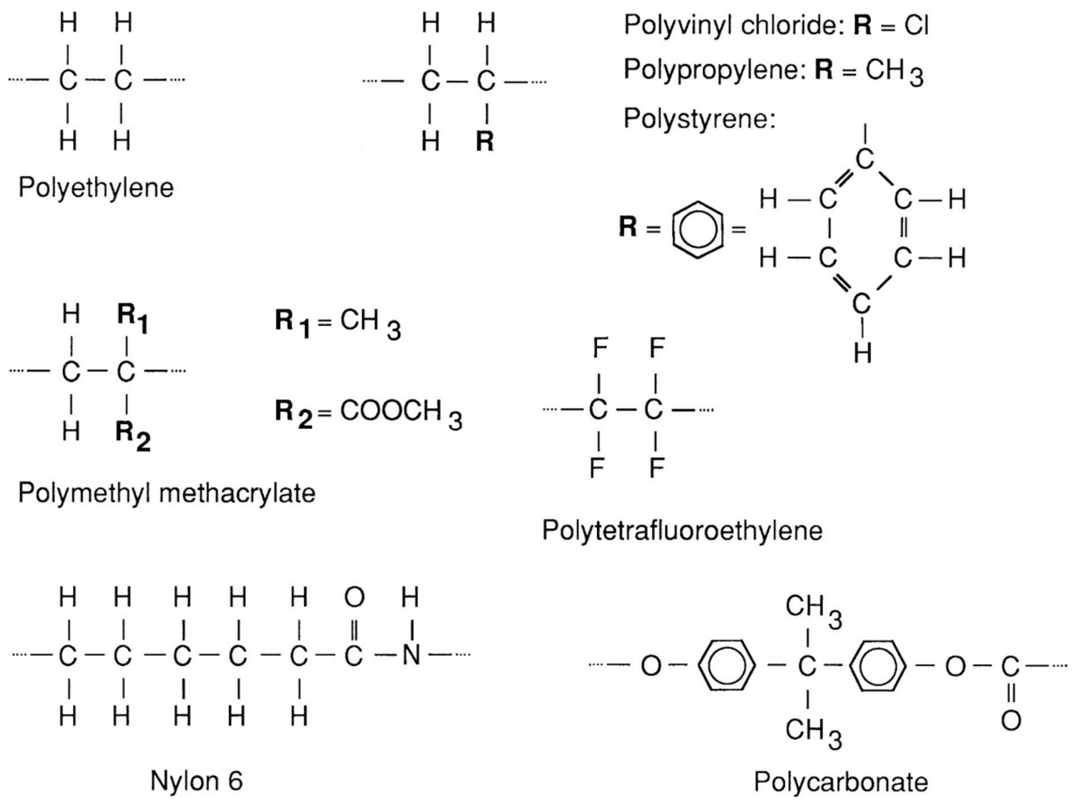
3.5 Polymers

Table 3.8 Classes, Examples, and Uses of Representative Polymers

Polymer	Typical Uses
(a) Thermoplastics: ethylene structure	
Polyethylene (PE)	Packaging, bottles, piping
Polyvinyl chloride (PVC)	Upholstery, tubing, electrical insulation
Polypropylene (PP)	Hinges, boxes, ropes
Polystyrene (PS)	Toys, appliance housings, foams
Polymethyl methacrylate (PMMA, Plexiglas, acrylic)	Windows, lenses, clear shields, bone cement
Polytetrafluoroethylene (PTFE, Teflon)	Tubing, bottles, seals
Acrylonitrile butadiene styrene (ABS)	Telephone and appliance housings, toys
(b) Thermoplastics: others	
Nylon	Gears, tire cords, tool housings
Aramids (Kevlar, Nomex)	High-strength fibers
Polyoxymethylene (POM, acetal)	Gears, fan blades, pipe fittings
Polyetheretherketone (PEEK)	Coatings, fans, impellers
Polycarbonate (PC)	Safety helmets and lenses
(c) Thermosetting plastics	
Phenol formaldehyde (phenolic, Bakelite)	Electrical plugs and switches, pot handles
Melamine formaldehyde	Plastic dishes, tabletops
Urea formaldehyde	Buttons, bottle caps, toilet seats
Epoxies	Matrix for composites
Unsaturated polyesters	Fiberglass resin

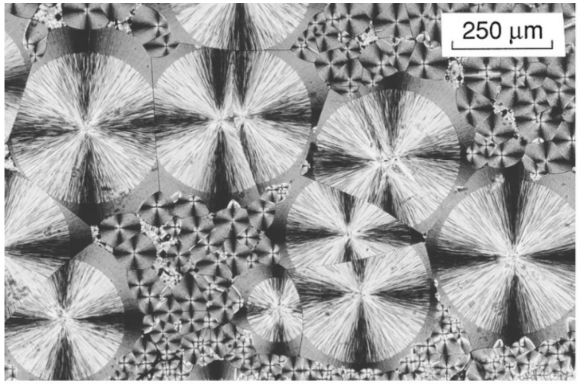
3.5.1 Molecular Structure of Thermoplastics

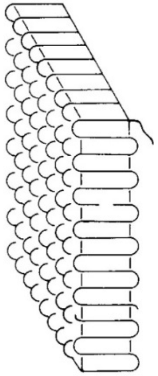
- **Molecular Structure**
  - Structure related to C_2H_4. Ex.) PE, PVC, PP, PS, …
  - High strength can be obtained by complex structure. Ex.) Nylon 6, PC, …



3.5.2 Crystalline Versus Amorphous Thermoplastics

- **Crystalline versus Amorphous**
  - Some thermoplastics are composed of orderly crystalline structures
  - Less brittle than amorphous, stiffness and strength do not drop dramatically beyond the glass transition temperature (T_g)
  - Ex.) PP, PTFE, nylon, POM, PEEK, …
  - Amorphous : Chain molecules are arranged in a random manner
  - Above T_g, elastic modulus decreases rapidly and creep effects become pronounced (see Fig. 3.15)
  - Ex.) PVC, PMMA, PC, …



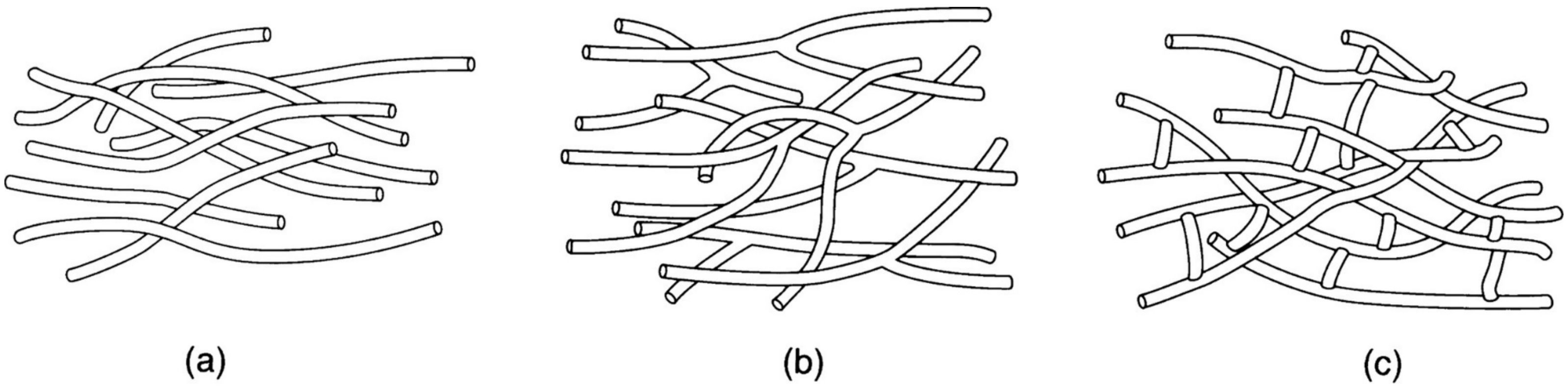


- Crystal structure of PE -

3.5.3 Thermosetting Plastics

- **Thermosetting Plastics**
  - The molecular structure of a thermosetting plastic consist of 3-D network, called cross-links, which is formed by frequent covalent bonds.
  - The cross-linking (thermosetting) chemical reaction occurs during the final stage of processing, typically compression molding at elevated temperature.

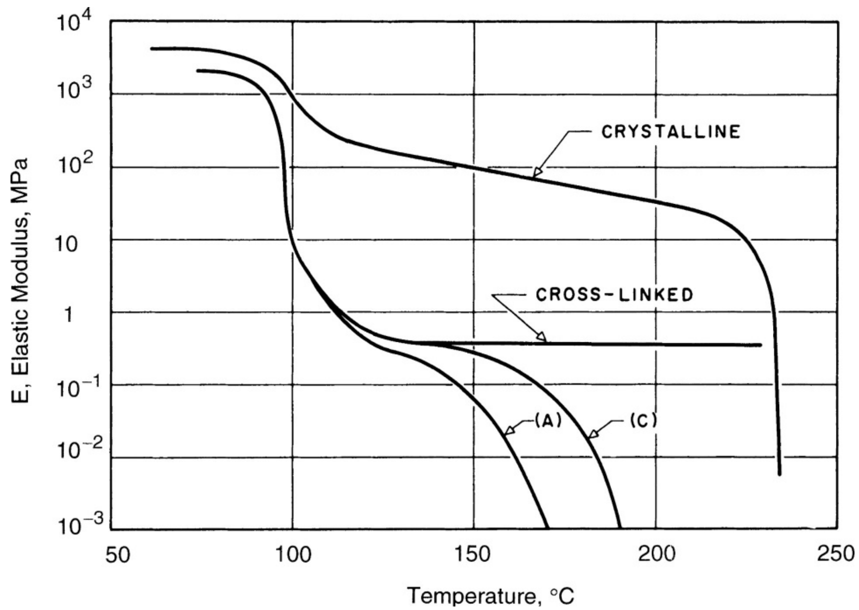
    → Resulting solid will neither soften nor melt, but decompose or burn.



- Polymer chain structures that are (a) linear, (b) branched, or (c) cross-linked-

3.5.3 Thermosetting Plastics

- **Thermoplastics (Amorphous, Crystalline) and Thermosetting Plastics**
  - Thermoplastics : Decrease of E above T_g.
    - ✓ Crystalline : Moderate decrease of E
    - ✓ Amorphous : Drastic decrease of E
  - Thermosetting Plastics : Constant E above T_g



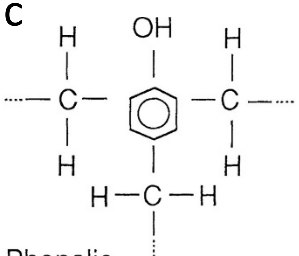
Polystyrene
T_g : 100°C

Elastic modulus versus temperature for amorphous, lightly cross-linked, and crystalline polystyrene. For amorphous samples (A) and (C), the chain lengths correspond to average molecular weights of 2.1×10^5 and 3.3×10^5

3.5.4 Elastomers

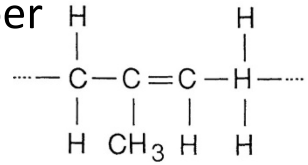
- **Elastomers**
  - Typified by natural rubber. Also synthetic polymers with similar behaviors.
  - Vulcanization : chemical process for converting natural rubber or related polymers into more durable materials via the addition of sulfur or other equivalent curatives or accelerators

Thermosetting plastic

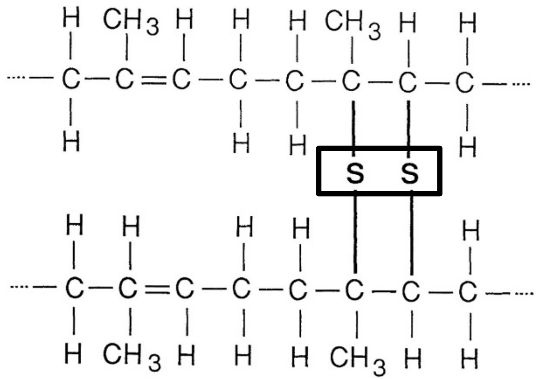


Phenolic

rubber



Cis-polyisoprene

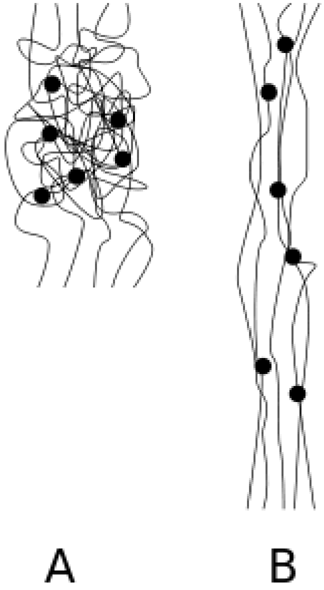


Cross-links in polyisoprene

3.5.4 Elastomers

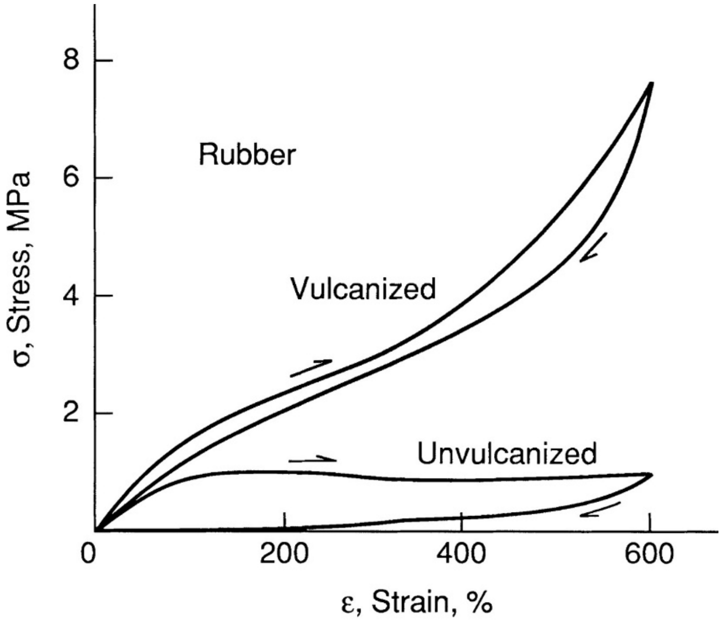
- **Flexibility**
  - Geometry at the carbon-to-carbon double bond cause a bend in the chain, which has a cumulative effect over long length.
  - Low E value at initial state, Stiffening as the chains straighten.

• : Cross-link



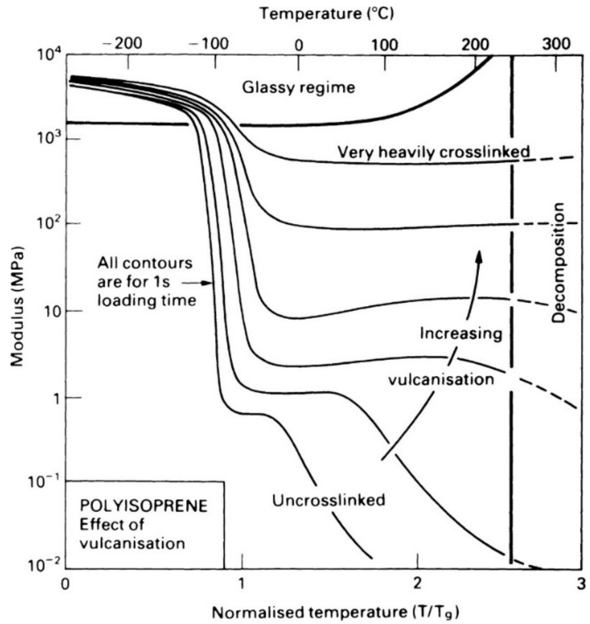
unstressed

Under stress



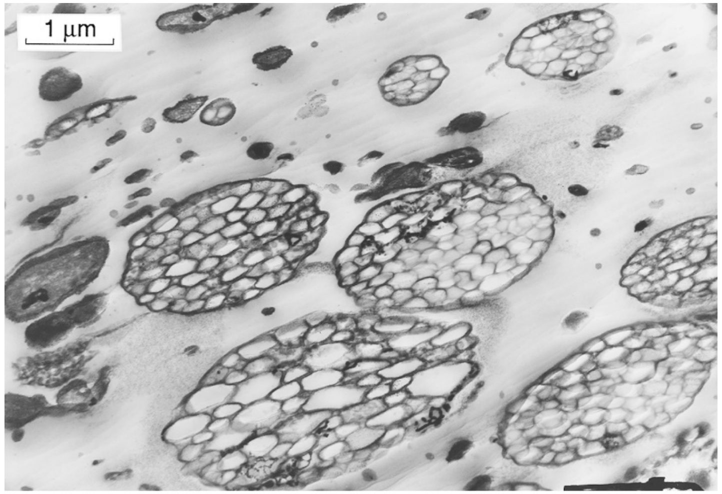
3.5.5 Strengthening Effects (Optional)

- **Strengthening Effects**
  – Any molecular structure of retarding relative sliding between chainlike molecules increases the stiffness and strength.
  – LDPE (low density polyethylene): significant degree of chain branching → Degree of crystallinity about : 65% → Flexible
  – HDPE (high density polyethylene): less branching → Degree of crystallinity about : 90% → Stronger and Stiffer



3.5.6 Combining and Modifying Polymers (Optional)

- **Alloying (=Blending)**
  - Involves melting two or more polymers
  - Copolymerization : Chains are composed of two types of repeating units.
  - Plasticizers : Non-polymer substances added to polymers.
- **Modifying (=filling)**
  - Add other materials in the form of particles of fibers.
  - Reinforcement : Added substances have the specific purpose of increasing strength



Microstructure of **rubber modified polystyrene**, in which the dark-colored particles and networks are rubber, and all light-colored areas inside and outside of particles are polystyrene. The originally equiaxial particles were elongated somewhat when cut to prepare the surface.

3.6 Ceramics and Glasses

- **Ceramics and Glasses**
  - Neither metallic nor organic (carbon-chain based) materials.
  - Ceramic : Clay products like china and brick, natural stone and concrete
  - Engineering ceramic : Ceramics used in high-stress applications.
  - Strong covalent or ionic-covalent chemical bonding

    → Highly resistant to corrosion and wear, high melting temperature.
  - High E and light in weight, crystalline. Produced by binding the particles.
  - Glass : Amorphous. Produced by melting silica (SiO_2), sand
- **Brittleness**
  - Strong and directional nature of covalent bonding and complex crystal structure

    → Slip of crystal plane does not occur, brittleness
  - Grain boundaries are relatively weaker.
  - Appreciable degree of porosity in ceramics. These discontinuities promote macroscopic cracking and contribute to brittle behavior.
  - The processing and uses of ceramics are strongly influenced by their brittleness. Recent efforts thus involves various means of reducing brittleness.

3.6 Ceramics and Glasses

Table 3.10 Properties and Uses for Selected Engineering and Other Ceramics

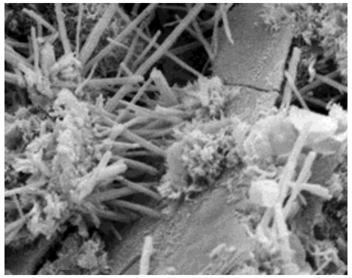
Ceramic	Melting Temp.	Density	Elastic Modulus	Typical Strength		Uses
	T_m °C	ρ g/cm^3	E GPa	σ_u, MPa (ksi)		
	(°F)	(lb/ft^3)	(10^3 ksi)	Tension	Compression	
Soda-lime glass	730 (1350)	2.48 (155)	74 (10.7)	≈ 50 (7)	1000 (145)	Windows, containers
Type S glass (fibers)	970 (1780)	2.49 (155)	85.5 (12.4)	4480 (650)	—	Fibers in aerospace composites
Zircon porcelain	1567 (2850)	3.60 (225)	147 (21.3)	56 (8.1)	560 (81)	High-voltage electrical insulators
Magnesia, MgO	2850 (5160)	3.60 (225)	280 (40.6)	140 (20.3)	840 (122)	Refractory brick, wear parts
Alumina, Al_2O_3 (99.5% dense)	2050 (3720)	3.89 (243)	372 (54)	262 (38)	2620 (380)	Spark plug insulators, cutting tool inserts, fibers for composites
Zirconia, ZrO_2	2570 (4660)	5.80 (362)	210 (30.4)	147 (21.3)	2100 (304)	High-temperature crucibles, refractory brick, engine parts
Silicon carbide, SiC (reaction bonded)	2837 (5140)	3.10 (194)	393 (57)	307 (44.5)	2500 (362)	Engine parts, abrasives, fibers for composites

3.6.1 Clay Products, Natural Stone, and Concrete

- **Clay Products**
  - Consist of various silicate minerals with sheetlike crystalline structure, Kaolin, Al_2O_3-$2SiO_2$-$2H_20$
- **Natural Stone**
  - Used without processing other than cutting
  - Limestone , Igneous rocks
- **Concrete**
  - Combination of crushed stone, sand, and a cement paste
  - Modern cement paste, Portland cement
  - Firing a mixture of limestone and clay at 1500°C
  - When water is added, a hydration occurs
    → Water is bound to minerals by being incorporated into crystal structure. Interlocking needlelike crystals form that bind the cement particles to each other and to the stone and sand.
- **All are used in large stationary structures**
  - Strength: poor in tension but reasonable in compression

Kaoiln

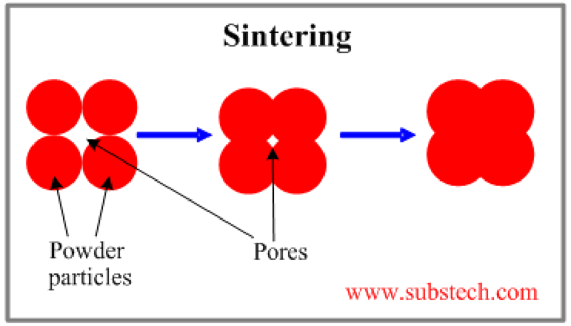
Limestone



Hydrated cement paste

3.6.2 Engineering Ceramics

- **Processing of Engineering ceramics**
  - Obtain the compound → Compounds are ground to a fine powder.
  - Compacted into a useful shape by cold or hot pressing.
  - The ceramic in this states is said to be in a green state with little strength
  - **Sintering** : Heating the green ceramic about 70 % of melting T. This causes the particles to fuse and form a solid.
  - Improvement of properties from minimizing the porosity
  - Hot isostatic pressing (HIP) : One variation on the sintering process
  - Enclosing the ceramic in a sheet metal closure and pressurizing with a hot gas.
  - Engineering ceramics : high stiffness, light weight, high strength in compression



HIP :

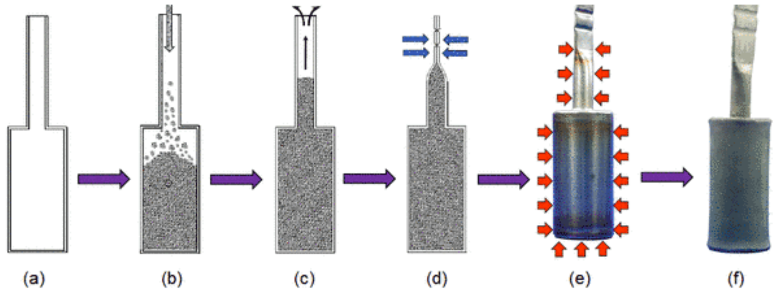
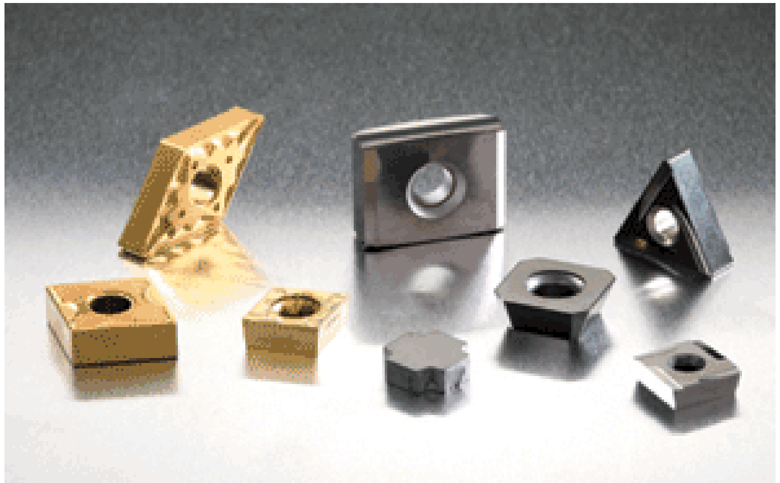


Fig.1: HIP process; (a) Capsule production; (b) Filling powder; (c) Evacuation; (d) Sealing capsule; (e) Apply high temperature 1150°C and high pressure 110 MPa; (f) Full density hipped component

3.6.3 Cermets; Cemented Carbides (Optional)

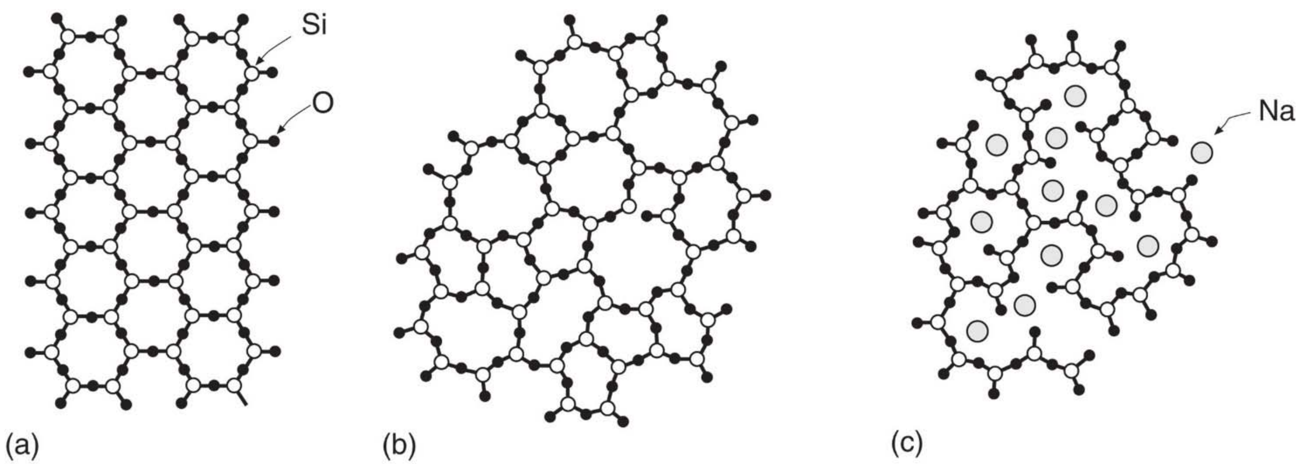
- **Cermet**
  - Made from powders of a ceramic and a metal by sintering
  - The metal surrounds the ceramic particles and bind them
    → High hardness and wear resistance
  - Cemented Carbides : the most important cermets used in cutting tools



- Cemented Carbides -

3.6.4 Glasses

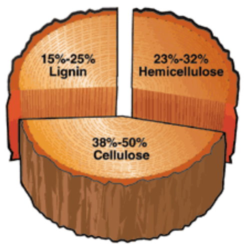
- **Glasses**
  - Silica (SiO_2) in quartz crystal is solidified from a molten state, an amorphous solid results.
  - In processing, glasses are heated so that they can be formed for plate glass (rolling) or bottles (blowing).
  - Network modifiers (i.e., Na_2O, K_20, CaO) lower the temperatures for forming, as metal ions forms the non-directional ionic bond with oxygens, resulting in terminal ends in the structure (Fig. 3.22(c)).

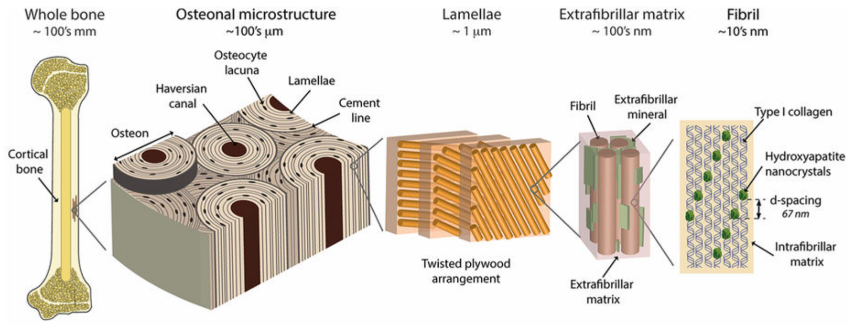


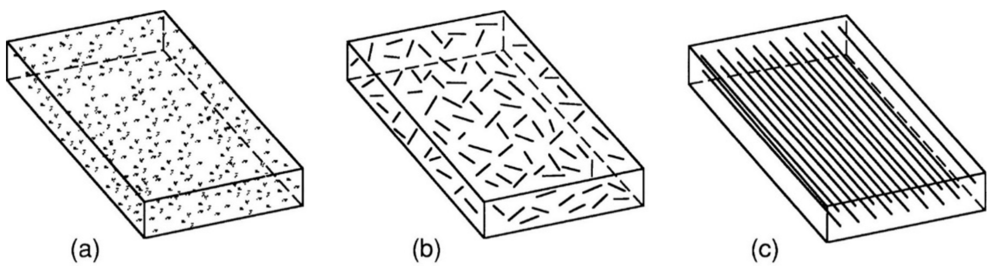
(a) quartz crystal (melting at 1,800°C), (b) glass, and (c) glass with a network modifier (melting in between 800 and 1,000°C)

3.7 Composite Materials

- **Composite**
  - Made by combining two or more materials that are insoluble each other
  - Combination of matrix and reinforcement
  - Biological materials : Wood with cellulose by lignin and hemicellulose, Bone with collagen with hydroxylapatite, …
  - Man-made composites can be tailored to meet special needs such as high strength and stiffness, …







Composites reinforced by a) particles, (b) chopped fibers or whiskers, and (c) continuous fibers

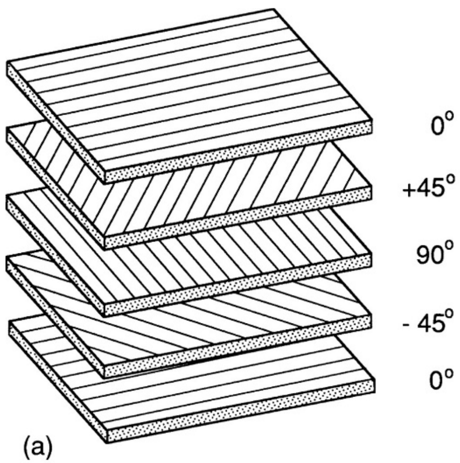
Table 3.12 Representative Types and Examples of Composite Materials

Reinforcing Type	Matrix Type	Example	Typical Use
(a) Particulate composites			
Ductile polymer or elastomer	Brittle polymer	Rubber in polystyrene	Toys, cameras
Ceramic	Ductile metal	WC with Co metal binder	Cutting tools
Ceramic	Ceramic	Granite, stone, and silica sand in Portland cement	Bridges, buildings
(b) Short-fiber, whisker composites			
Strong fiber	Thermosetting plastic	Chopped glass in polyester resin	Auto body panels
Ceramic	Ductile metal	SiC whiskers in Al alloy	Aircraft structural panels
(c) Continuous-fiber composites			
Ceramic	Thermosetting plastic	Graphite in epoxy	Aircraft wing flaps
Ceramic	Ductile metal	Boron in Al alloy	Aircraft structure
Ceramic	Ceramic	SiC in Si_3N_4	Engine parts
(d) Laminated composites			
Stiff sheet	Foamed polymer	PVC and ABS sheets over ABS foam core	Canoes
Composite	Metal	Kevlar in epoxy between Al alloy layers (ARALL)	Aircraft structure

3.7.1 Particulate Composites & 3.7.2 Fibrous Composites

- **Particulate Composite**
  - Ductile particles added to a brittle matrix → increase toughness
  - Hard and stiff particles added to a ductile matrix → increase strength and stiffness
  - Dispersion hardening : Sintering the metal in powder form with ceramic particles
    → desirable strengthening effect similar to that of precipitation hardening

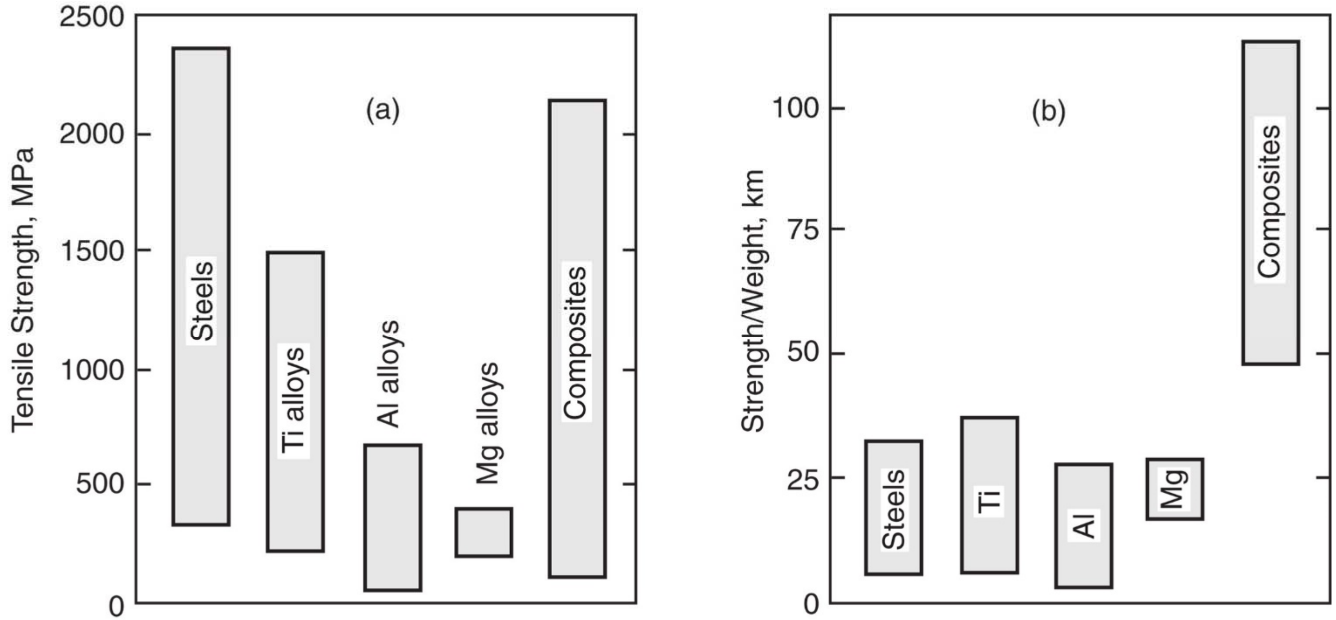
- **Fibrous Composites**
  - Strong and stiff fibers are embedded in a matrix of a ductile material.
    → Strong, stiff and tough
  - Short, randomly chopped fibers and Long fibers
  - Whisker : Special class of short fiber that consists of tiny, elongated, single crystal
  - Long fibers can be woven into a cloth or made into a mat of intertwined strands
  - Prepregs : Composites with a thermosetting plastic matrix assembled in a different orientation.
    → high strength and stiffness in transverse direction



- Prepregs -

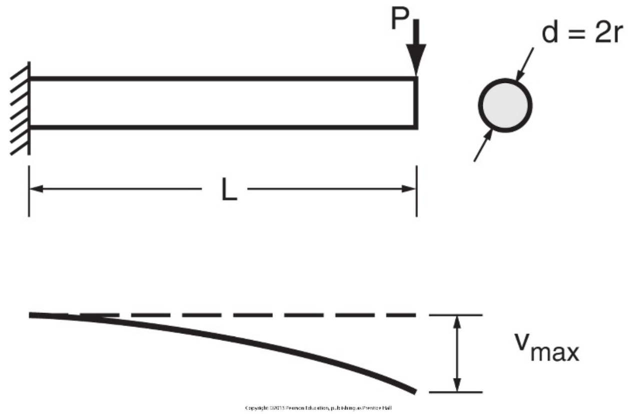
3.7.3 Laminated Composites

- **Laminated Composites**
  - Laminate : A material made by combining layers. ex) Plywood, Windshieds
  - Unidirectional composites sheets are usually laminated.



3.8 Materials Selection for Engineering Components (Reading homework)

- **Materials Selection**
  - Major concern : Elastic modulus (E), Yield strength (σ_o), …
  - Systematic analysis that provides a ranking of materials.



- **Selection Procedure**

① Classify the variables

1. Requirements : *L, P, X*
2. Geometrical variable : *r*
3. Material properties : ρ, σ_c
4. Quantity to minimize : *m*

② Express quantity *Q* to be minimized or maximized

$$Q = f_1(Requirements)f_2(Materials)$$

$$m = f_1(L, P, X)f_2(\rho, \sigma_c)$$

③ Apply each candidate to *Q*

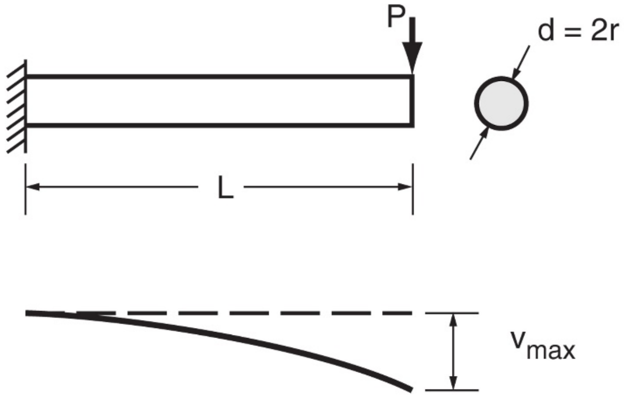
Example

- **Example 3.1**

(a) Perform the material selection for minimum mass

(b) Calculate the beam radius r that is required for each material.

(P=200N, L=100mm, X=2)



Sol) objective : minimize $m = (\pi r^2 L)\rho$

→ substitute *r* with other expression

$$\sigma = \frac{M_{max} r}{I_z} = \frac{4PL}{\pi r^3} = \frac{\sigma_c}{X}$$

$$(I_z = \frac{\pi r^4}{4}, Mmax = PL)$$

- $m = \pi L (\frac{4PLX}{\pi \sigma_c})^{2/3}$

$$= [f_1][f_2] = [\pi \left(\frac{4PX}{\pi}\right)^{\frac{2}{3}} L^{\frac{5}{3}}][\frac{\rho}{\sigma_c^{2/3}}]$$

- All the quantities in f_1 are fixed, minimized by f_2

Table E3.1

Material	$\frac{\rho}{\sigma_c^{2/3}}$	Rank for Min. Mass	Radius r, mm	$\frac{C_m \rho}{\sigma_c^{2/3}}$	Rank for Min. Cost
Structural steel	0.194	8	5.81	0.194	2
Low-alloy steel	0.0740	6	3.59	0.222	3
Aluminum alloy	0.0447	5	4.77	0.268	4
Titanium alloy	0.0402	4	3.50	1.81	7
Polymer	0.0766	7	9.37	0.383	6
Wood	0.0258	2	8.33	0.0387	1
Glass–epoxy	0.0381	3	5.12	0.381	5
Graphite–epoxy	0.0168	1	3.80	3.36	8

Notes: Units are g/cm^3 for ρ and MPa for σ_c. The strength σ_c is the yield strength for metals, and the ultimate strength for wood, glass, and composites. Ranks are 1 = best, etc., for minimum mass or cost.

Summary

- **Pure metals** in bulk form yield at quite low stress

  → Processing (cold work, solid-solution strengthening, precipitation hardening, …) or alloying

  - Irons and Nonferrous metals and their alloys

- **Polymers** : lack in strength, stiffness, and temperature but advantages in light weight and corrosion resistance

  - Thermoplastics, Thermosetting plastics, elastomers.

- **Ceramics** : nonmetallic and inorganic crystalline solids. Brittle but light weight, high stiffness, high compressive strength, …

- **Composite :** Combinations of two or more materials that are insoluble each other