Foundations of

Materials Science and Engineering

Lecture Note 1

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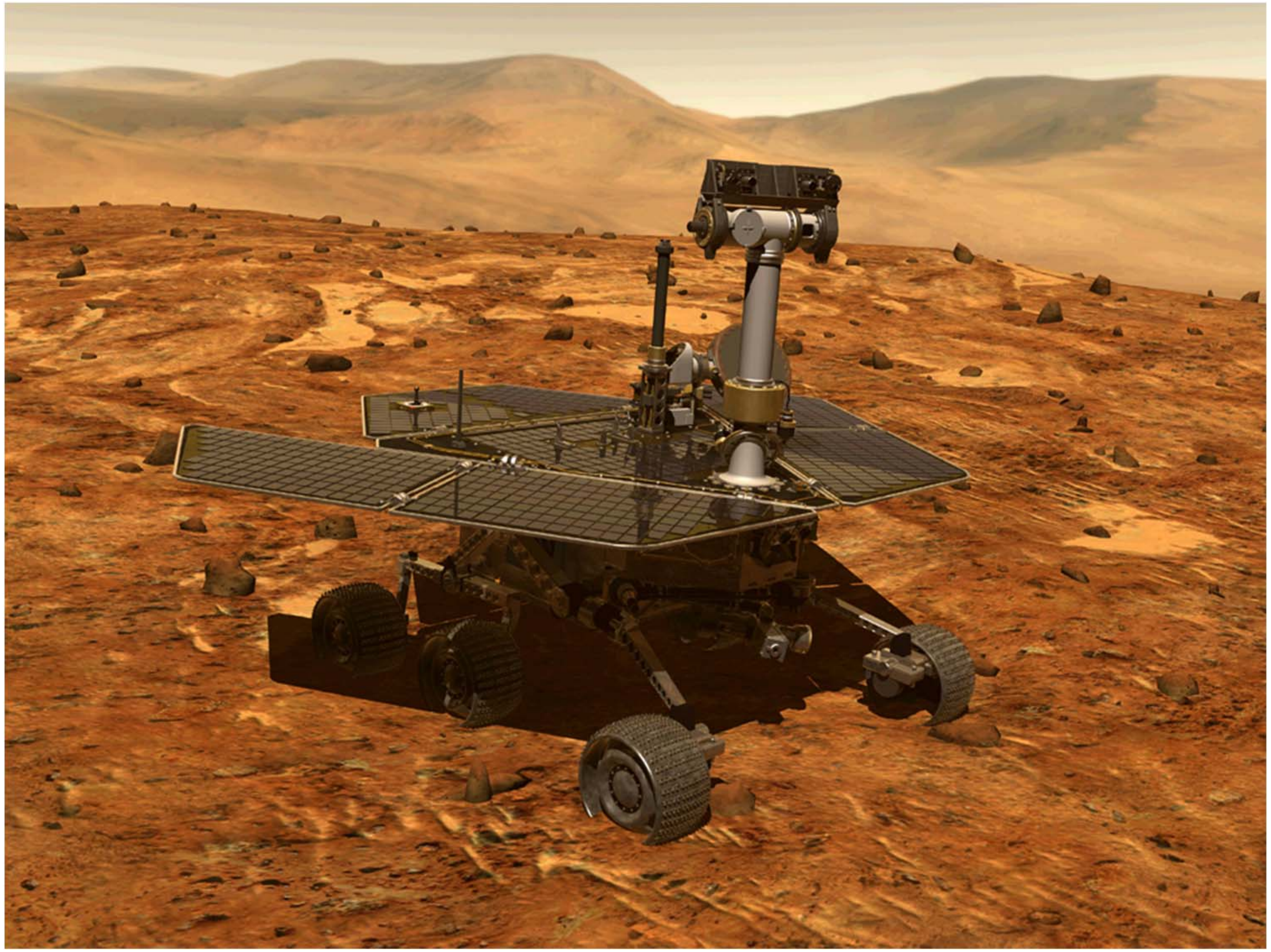
88.91	16.00	14.01	78.96	126.9

The Mars Rovers - Spirit and Opportunity



What are Materials?

- Materials may be defined as substance of which something is composed or made.
- We obtain materials from earth crust and atmosphere.

- *Examples :-*
  - ➢ Silicon and Iron constitute 27.72 and 5.00 percentage of weight of earths crust respectively.
  - ➢ Nitrogen and Oxygen constitute 78.08 and 20.95 percentage of dry air by volume respectively.

Human Civilization and Materials

Materials we use define our social relationship and economic quality.

The materials of the earlier human were probably for tools and weapons. The most popular way of naming the era of human civilization is in terms of materials from which these tools and weapons were made.

The stone age : Starts from 2.5 million years ago.

The pottery age: Before 4,000BC,domestic vessels were made and glass artifacts have been traced back to 4,000BC

The copper age : It is estimated between roughly 4,000BC ~ 3,000BC.

The bronze age : The period from 2,000BC to 1,000BC. Better quality of tools and weapons with the alloy of Cu-Sn.

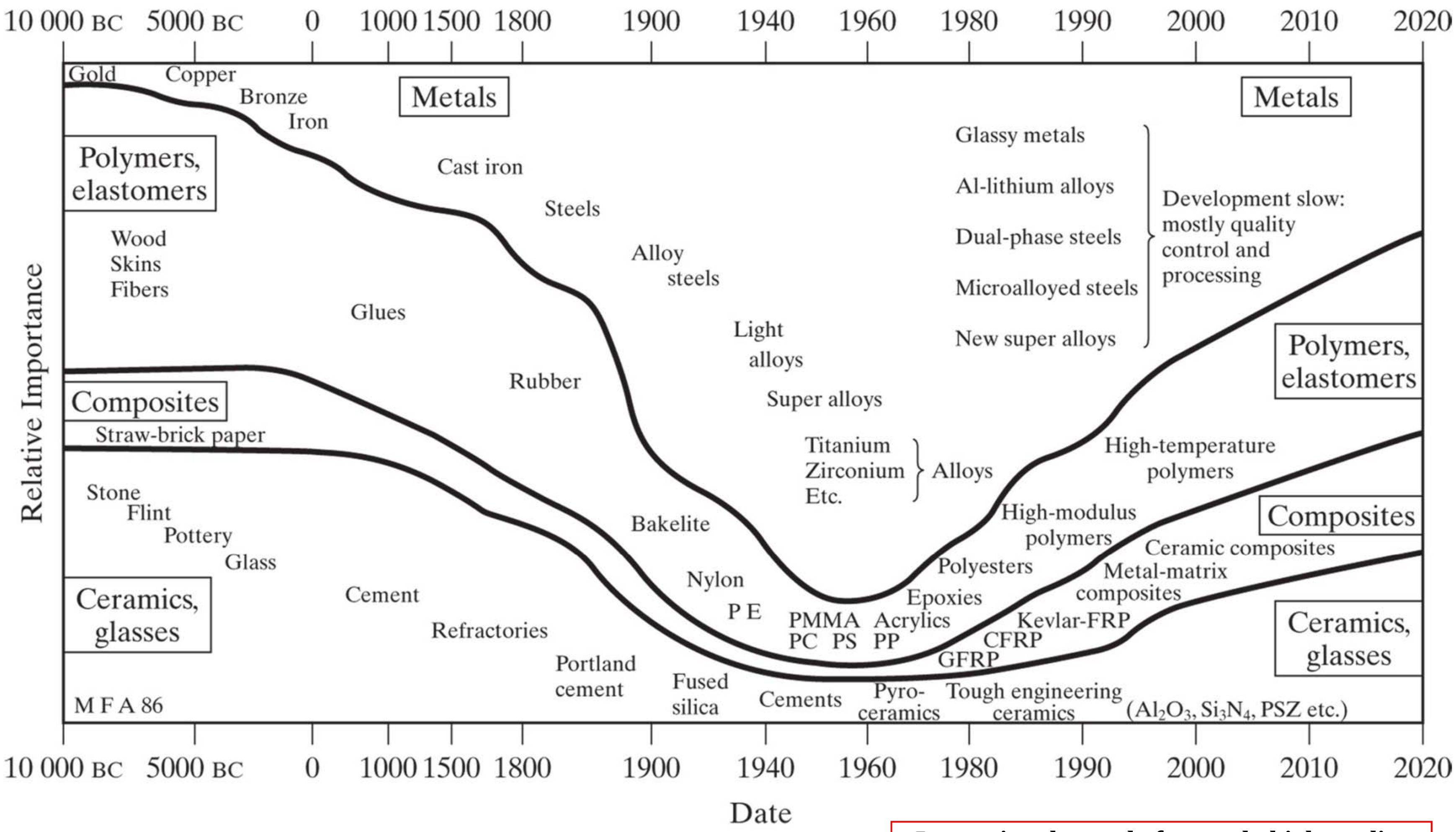
The iron age : The period from 1,000BC to 1BC. By 500BC, iron alloys largely replaced bronze for tool and weapon making in Europe.

Age of Advanced materials: throughout the Iron Age many new types of materials have been introduced (ceramic, semiconductors, polymers, composites…). Understanding of the relationship among structure, properties, processing, and performance of materials. Intelligent design of new materials.

Human Civilization and Materials

The evolution of engineering materials with time.

(From M. F. Ashby, Materials Selection in Mechanical Design, *2nd ed., Butterworth-Heinemann, Oxford, 1999.)*



WW II → **Increasing demand of not only high quality metallic alloys but non-metallic materials.**

Why the Study of Materials is Important?

- Production and processing of materials constitute a large part of our economy.
- Engineers choose materials to suite design.
- New materials might be needed for some new applications.

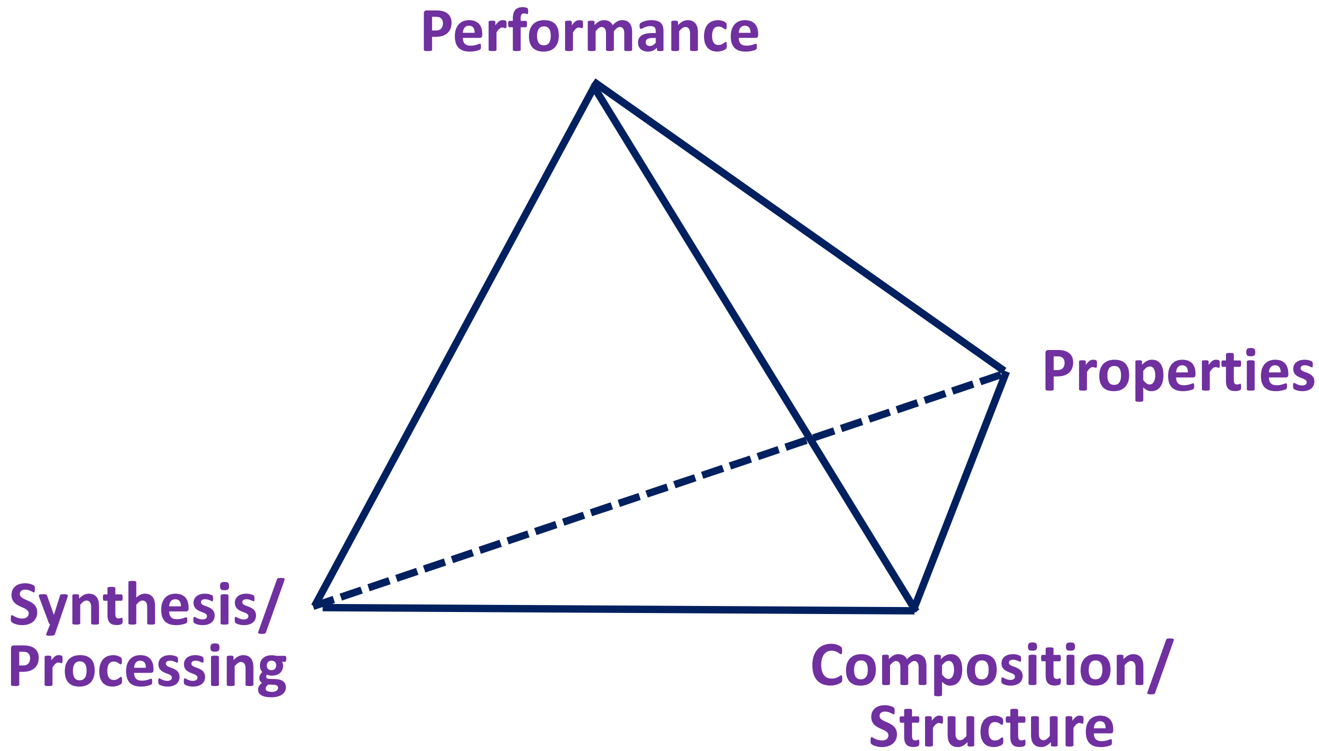
  - ➢ Example :- High temperature resistant materials.
  - ➢ Space station and Mars Rovers should sustain conditions in space.
    - * High speed, low temperature, strong but light.

- Modification of properties might be needed for some applications.

  - ➢ Example :- Heat treatment to modify properties.

Material Science and Engineering (MSE)

"Tetrahedron of Materials Science and Engineering"



Material Science and Engineering (MSE)

Composition means the chemical make-up of a material.

Structure means a description of the arrangements of atoms or ions in a material.

Properties are the way the material responds to the environment and external forces.

Mechanical properties, Electrical and Magnetic properties,
Thermal properties, Optical properties, Chemical stability

Synthesis is the process by which materials are made from naturally occurring or other chemicals.

Processing means different ways for shaping materials into useful components or changing their properties.

Material Science and Engineering (MSE)

Structure means a description of the arrangements of atoms or ions in a material.

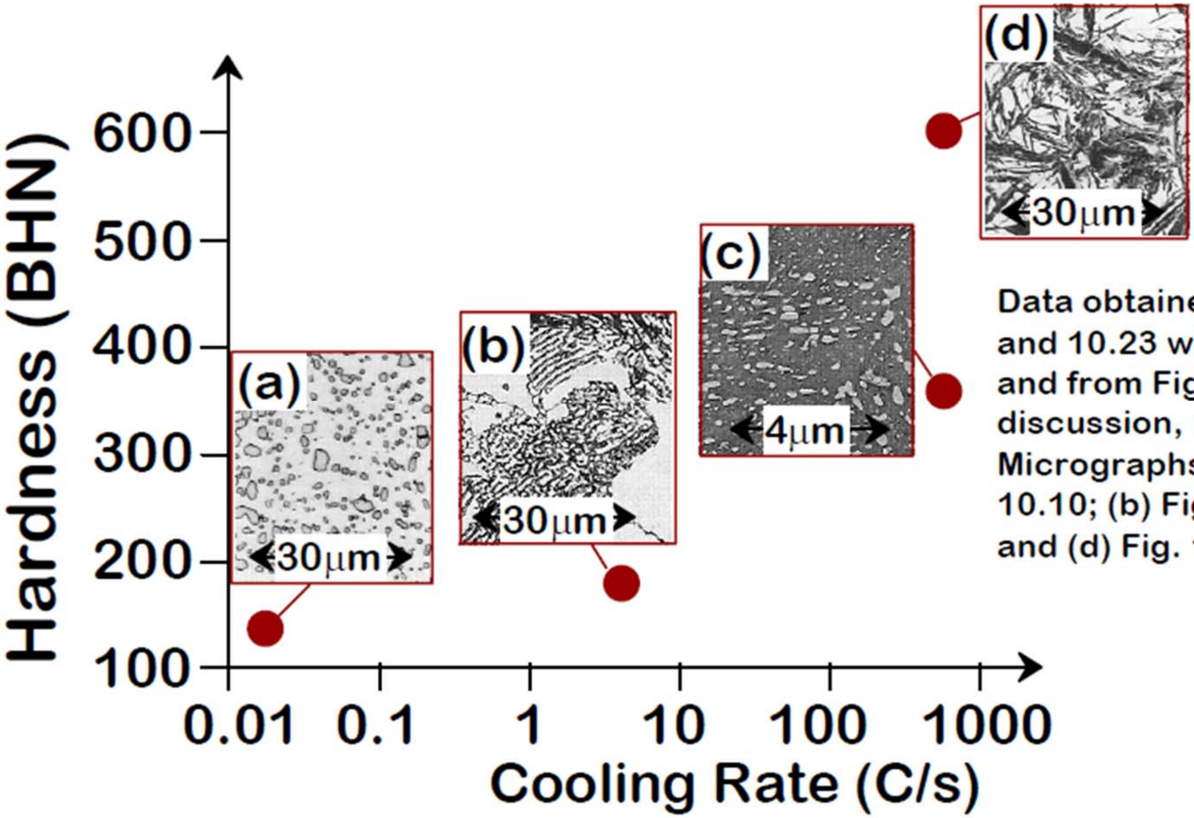
- Subatomic level : Electronic structure of individual atoms that defines interaction among atoms (interatomic bonding).

- Atomic level : Arrangement of atoms in materials (for the same atoms can have different properties, e.g. two forms of carbon: graphite and diamond)

- Microscopic structure : Arrangement of small grains of material that can be identified by microscopy.

Properties depend on structure

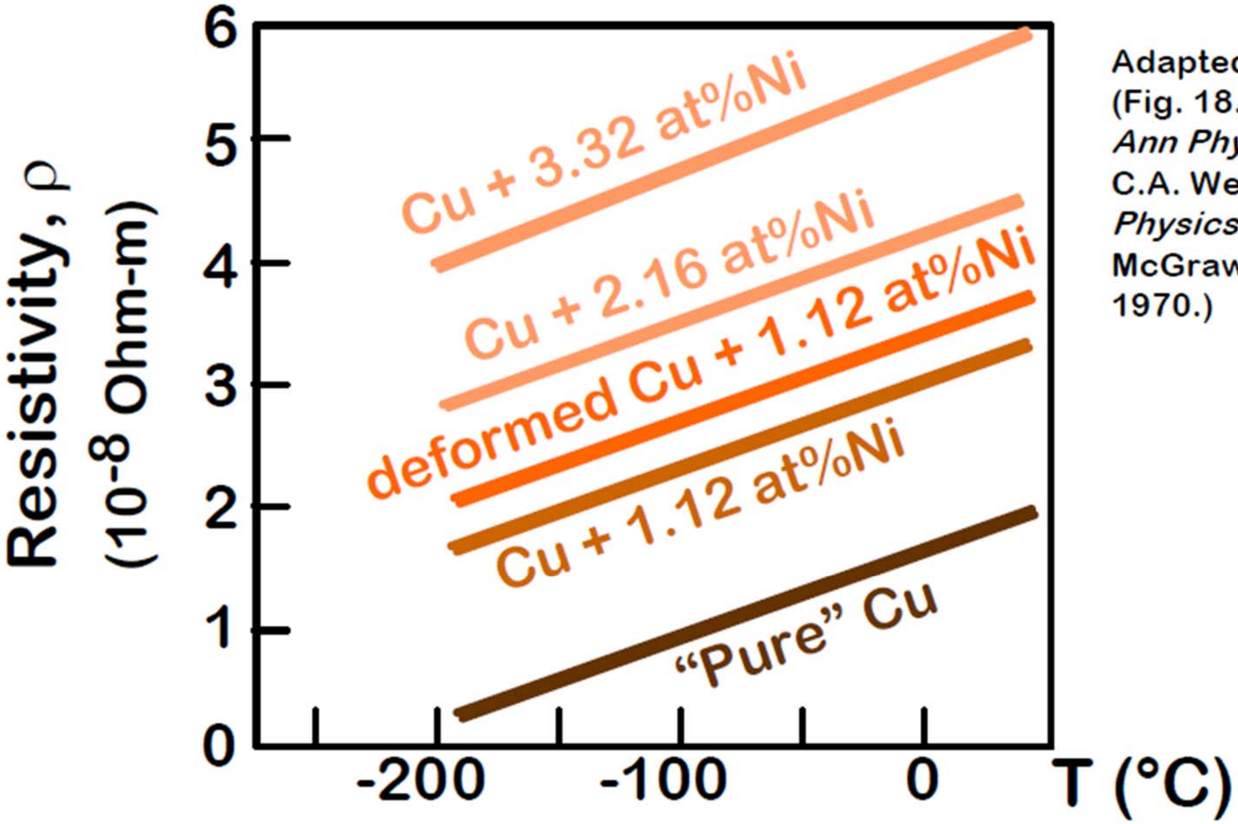
ex: structure vs cooling rate of steel



Data obtained from Figs. 10.21(a) and 10.23 with 4wt%C composition, and from Fig. 11.13 and associated discussion, *Callister 6e*. Micrographs adapted from (a) Fig. 10.10; (b) Fig. 9.27;(c) Fig. 10.24; and (d) Fig. 10.12, *Callister 6e*.

Processing can change structure : hardness vs structure of steel

Electrical Resistivity of Copper:



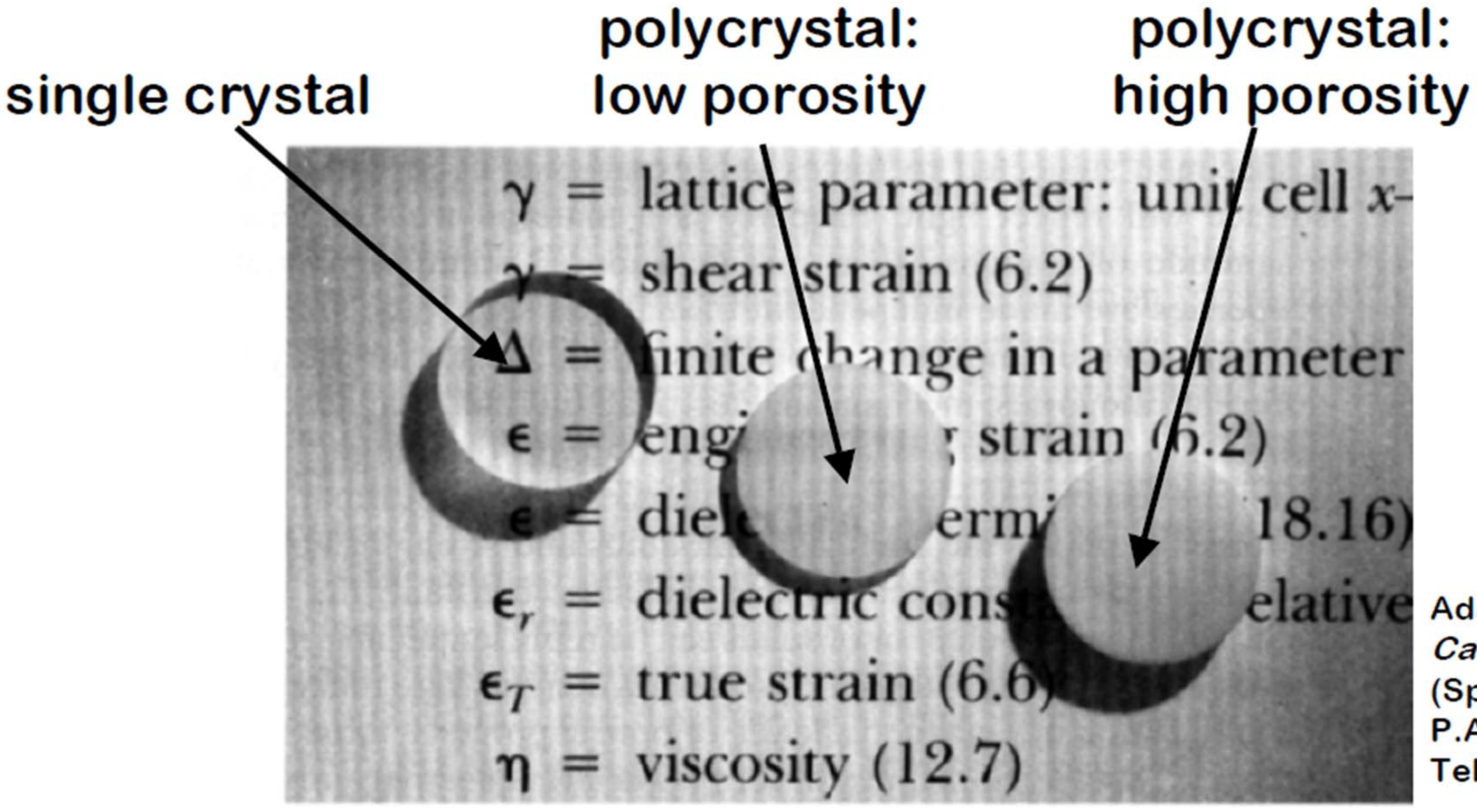
Adapted from Fig. 18.8, *Callister 6e.* (Fig. 18.8 adapted from: J.O. Linde, *Ann Physik* **5**, 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd edition, McGraw-Hill Company, New York, 1970.)

Adding "impurity" atoms to Cu increases resistivity.

Deforming Cu increases resistivity.

Transmittance:

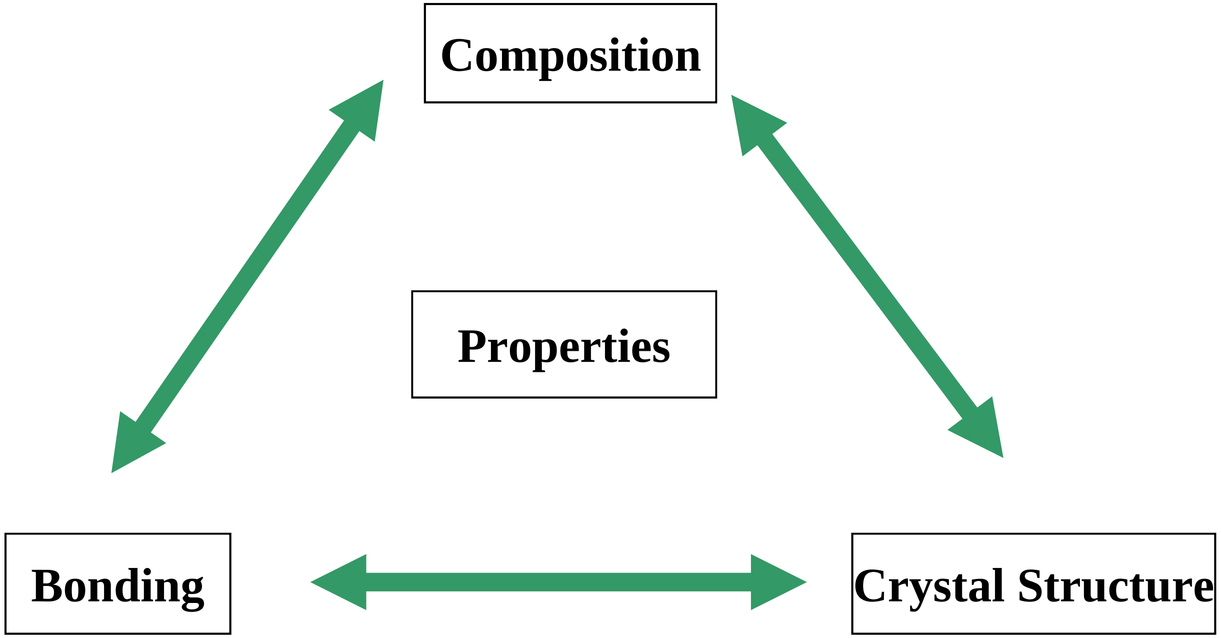
Aluminum oxide may be transparent, translucent, or opaque depending on the material structure.



Adapted from Fig. 1.2, *Callister 6e.* (Specimen preparation, P.A. Lessing; photo by J. Telford.)

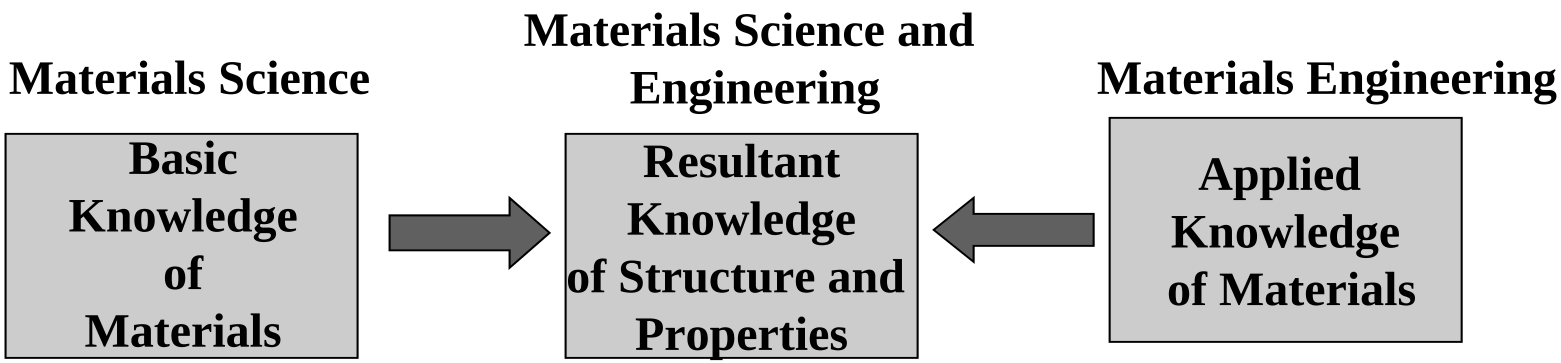
Material Science and Engineering (MSE)

Composition, Bonding, Crystal Structure and Microstructure DEFINE Materials Properties.

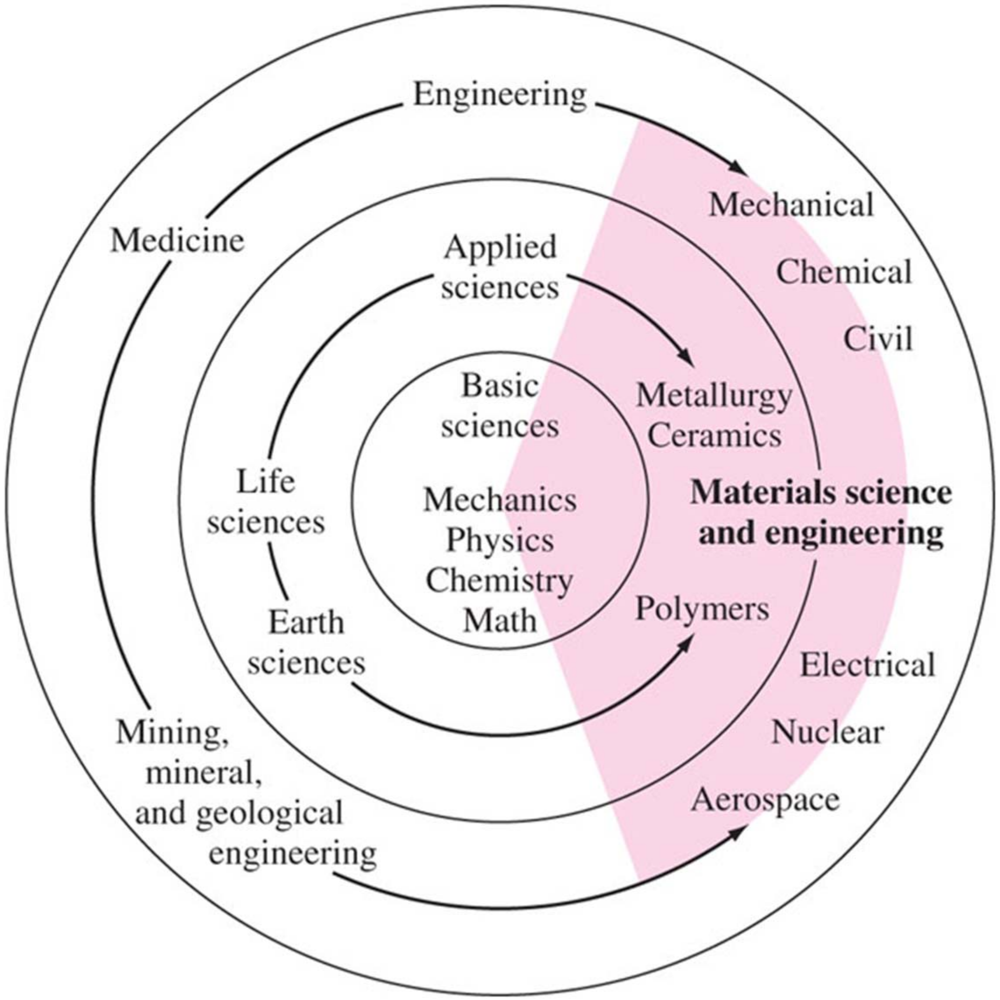


Materials Science and Engineering

- Materials science deals with basic knowledge about the internal structure, properties and processing of materials.
- Materials engineering deals with the application of knowledge gained by materials science to convert materials to products.



Materials Science and Engineering



Types of Materials

Six categories that encompass the materials available to practicing engineers :

1) Metals (crystalline materials, metallic bonding)

2) Ceramics (crystalline materials, ionic bonding)

3) Glasses (mainly non-crystalline materials, ionic bond)

4) Polymers (non-crystalline materials, covalent bonding)

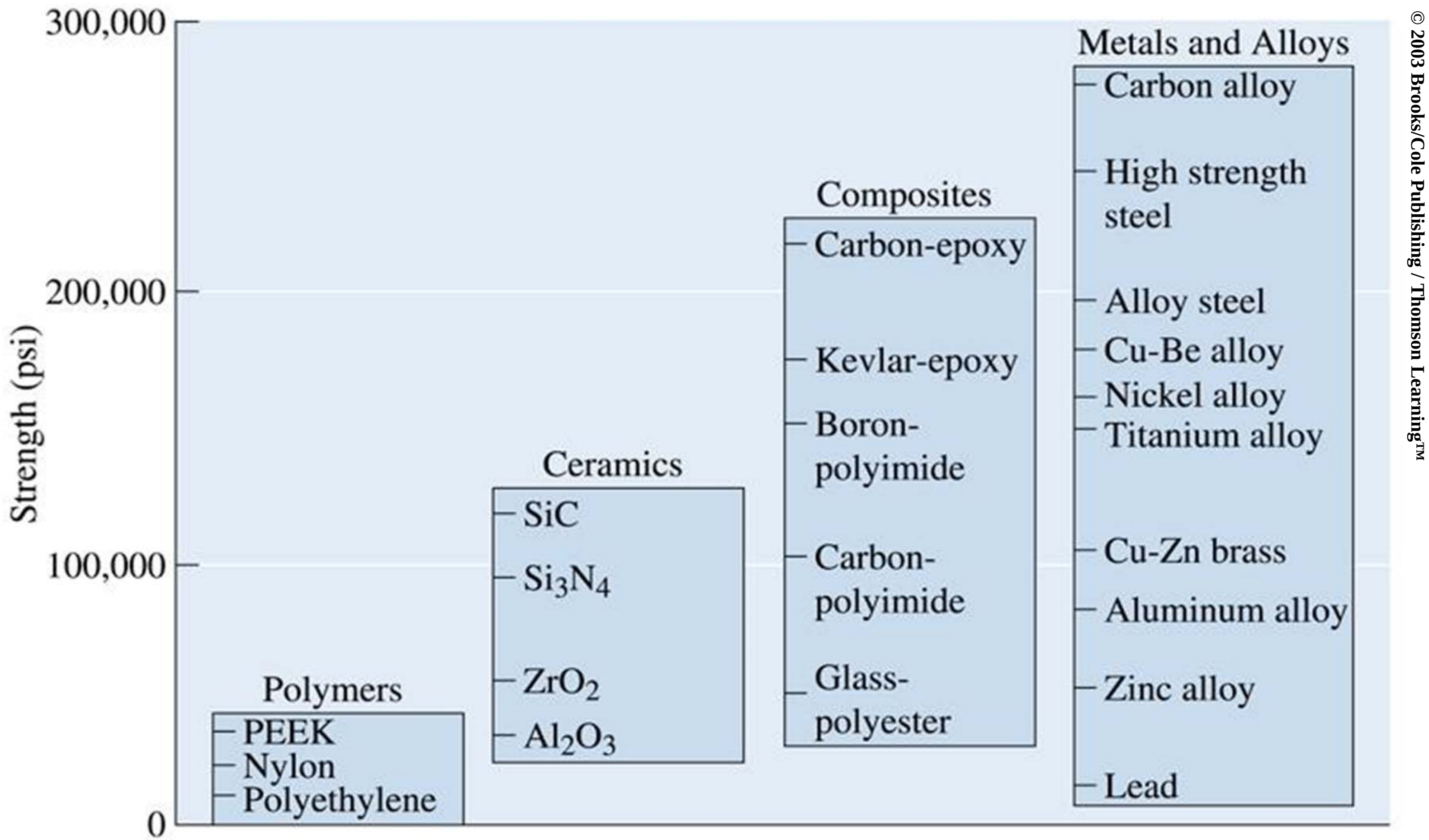
5) Semiconductors (unique electrical conducting behavior)

6) Composites (mixture of above materials)

Types of Materials

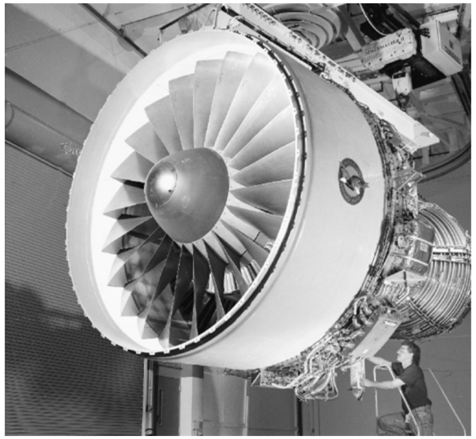
Materials	Example of Applications	Properties
Metals and Alloys		
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration damping
Ceramics and Glasses		
SiO_2-Na_2O-CaO	Window glass	Optically transparent, thermally insulating
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Semiconductors		
Silicon	Transistors	Unique electrical behavior
Composites		
Tungsten carbide -cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance

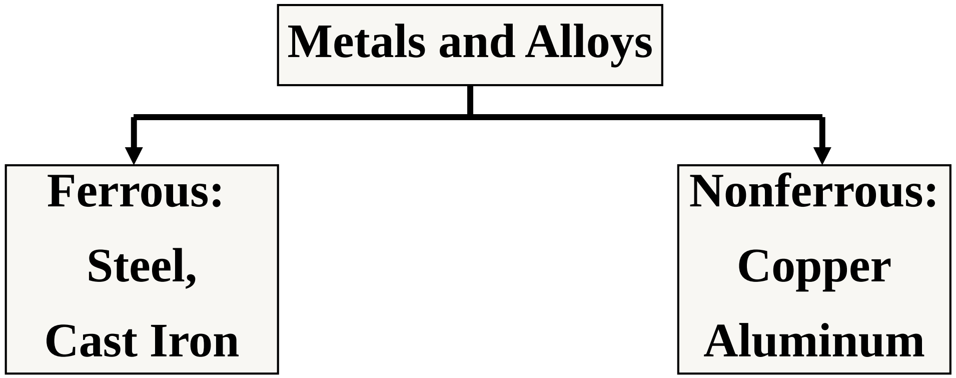
Types of Materials



Representative strengths of various categories of materials

- Metallic Materials
  - ➢ Composed of one or more metallic elements.
  - ❑ *Example:- Iron, Copper, Aluminum.*
  - ➢ Metallic element may combine with nonmetallic elements.
  - ❑ *Example:- Silicon Carbide, Iron Oxide.*
  - ➢ Inorganic and have crystalline structure.
  - ➢ Good thermal and electric conductors.





Types of Materials

Periodic table of the elements. Those elements that are inherently metallic in nature are shown in color.

106-23=83

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	O
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												
		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw		

The shaded elements are inherently metallic and bases of the various engineering alloys, from Fe, Al, Mg, Ti, Ni, Zn, Cu and etc.

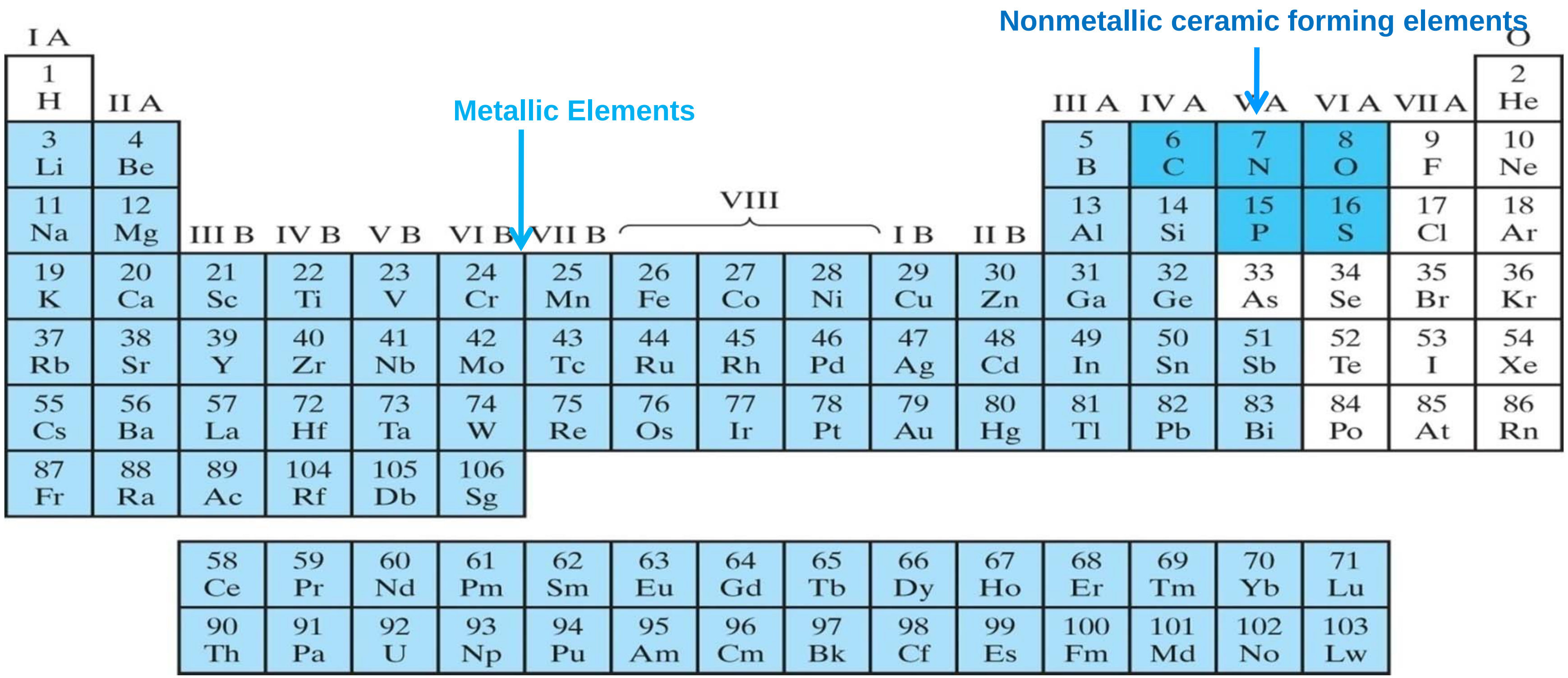
Types of Materials

- Ceramic Materials
  - ➢ Metallic and nonmetallic elements are chemically bonded together.
  - ➢ Inorganic but can be either crystalline, noncrystalline or mixture of both.
  - ➢ High hardness, strength and wear resistance.
  - ➢ Very good insulator. Hence used for furnace lining for heat treating and melting metals.
  - ➢ Also used in space shuttle to insulate it during exit and reentry into atmosphere.
  - ➢ Other applications : Abrasives, construction materials, utensils etc.

  - ➢ *Example:- Porcelain, Glass, Silicon nitride.*

Types of Materials

Periodic table with ceramic compounds indicated by a combination of one or more metallic elements (in light color) with one or more nonmetallic elements (in dark color)

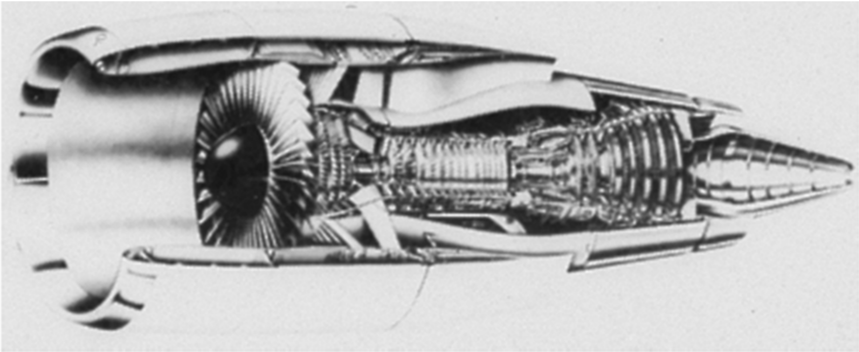


Ceramics are usually oxides. However, silicon nitride (Si_3N_4) is an important nonoxide ceramic used in a variety of structural applications. Some ceramics are chemical compounds made up of one of the five nonmetallic materials, C, N, O, P or S, shaded with dark blue color in figure 1.7. Very many variety of ceramic materials can be formed.

(C, N, P, S are forming none-oxide ceramics with metallic elements.)

(Now, Si and Ge are included as metallic elements in this classification, because they form ceramics.)

Types of Materials



A section through a jet engine. The forward compression section operates at low to medium temperatures, and titanium parts are often used. The rear combustion section operates at high temperatures and nickel-based superalloys are required. The outside shell experiences low temperatures, and aluminum and composites are satisfactory. (Courtesy of GE Aircraft Engines.)

A variety of complex ceramic components, including impellers and blades, which allow turbine engines to operate more efficiently at higher temperatures. (Courtesy of Certech, Inc.)

Types of Materials

Periodic table with the elements associated with commercial polymers in color.

Polymers continued

I A	II A	III B	IV B	V B	VI B	VII B	VIII			I B	II B	III A	IV A	V A	VI A	VII A	O
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

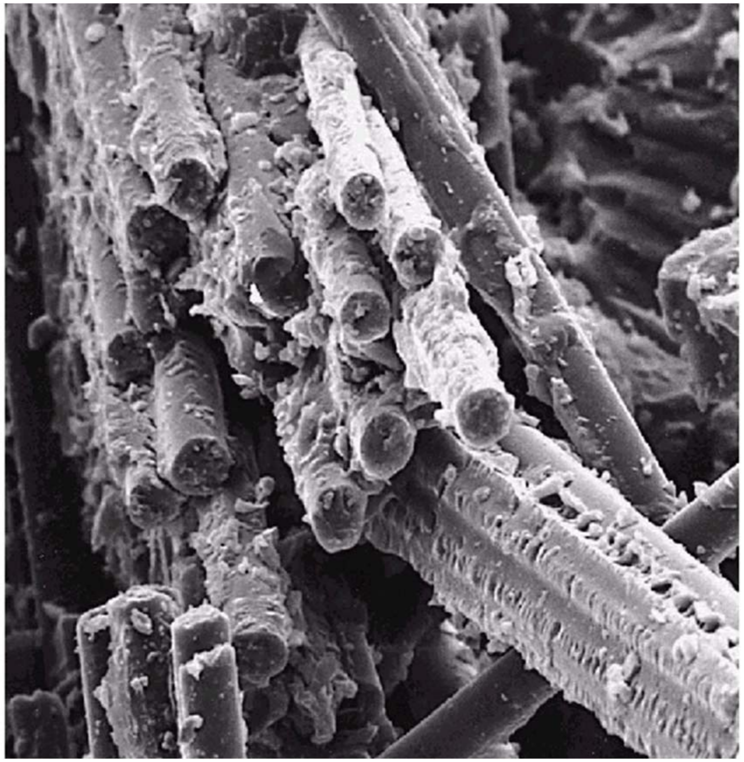
Small number of elements (6 elements) are involved for the formation of commercial polymers and most of polymers are simply compounds of hydrogen and carbon. Some other polymers contain oxygen (e.g., acrylics), nitrogen (nylon), fluorine (fluoroplastics) and silicon (silicones).

Types of Materials

- Polymeric (Plastic) Materials
  - Organic giant molecules and mostly noncrystalline.
  - Some are mixtures of crystalline and noncrystalline regions.
  - Poor conductors of electricity and hence used as insulators.
  - Strength and ductility vary greatly.
  - Low densities and decomposition temperatures.
  - *Examples :- Poly vinyl Chloride (PVC), Polyester.*
  - *Applications :- Appliances, DVDs, Fabrics etc.*

Types of Materials

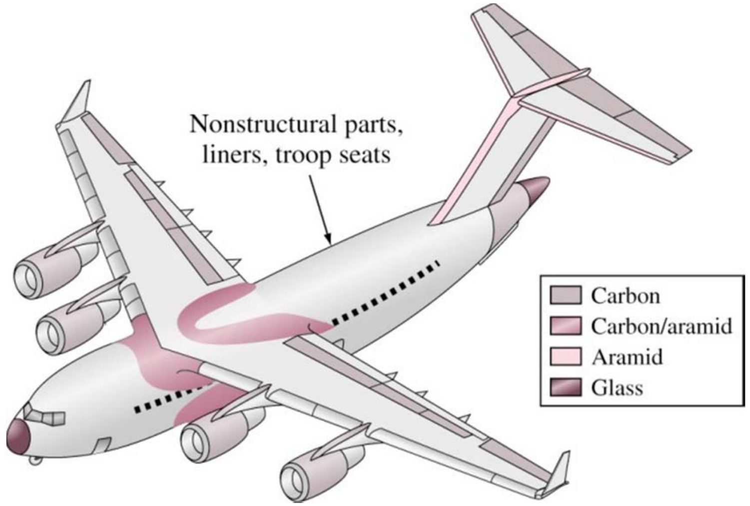
- Composite Materials
  - ➢ Mixture of two or more materials.
  - ➢ Consists of a filler material and a binding material.
  - ➢ Materials only bond, will not dissolve in each other.
  - ➢ Mainly two types :-
  - o Fibrous: Fibers in a matrix
  - o Particulate: Particles in a matrix
  - o Matrix can be metals, ceramic or polymer
  - ➢ *Examples* :-
  - ❑ Fiber Glass (Reinforcing material in a polyester or epoxy matrix)
  - ❑ Concrete (Gravels or steel rods reinforced in cement and sand)
  - ➢ *Applications:*- Aircraft wings and engine, construction.

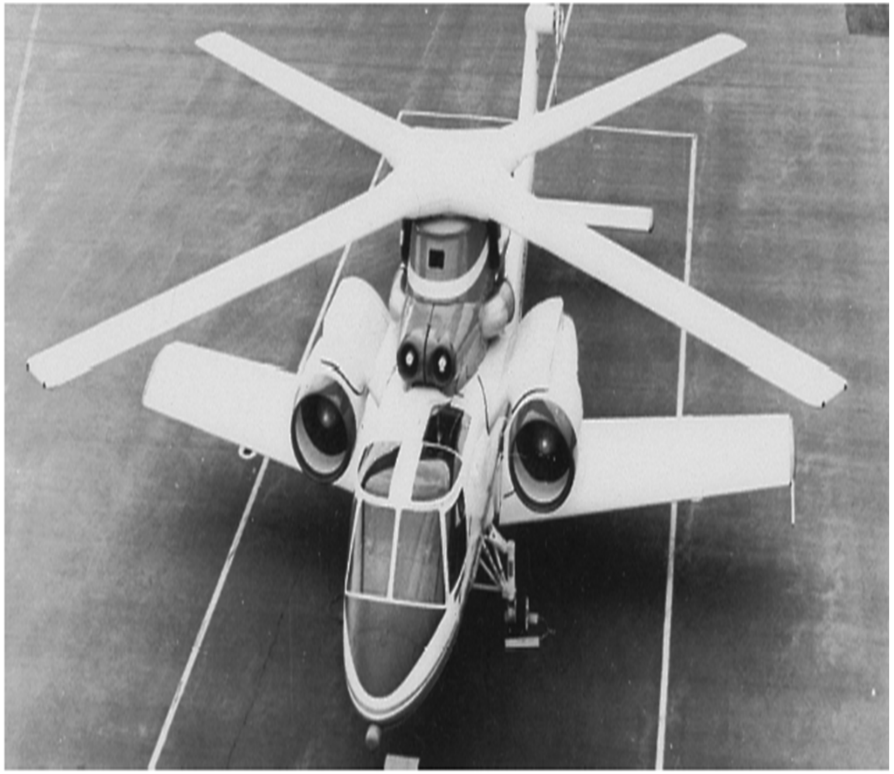


Polymer composite materials:

reinforcing glass fibers in a polymer matrix

Types of Materials





The X-wing for advanced helicopters relies on a material composed of a carbon-fiber-reinforced polymer. (Courtesy of Sikorsky Aircraft Division—United Technologies Corporation.)

Types of Materials

Periodic table with the elemental semiconductors in dark color (Si, Ge, Sn) and those elements that form semiconducting compounds in light color. The semiconducting compounds are composed of pairs of elements from columns III and V (e.g., GaAs) or from columns II and VI (e.g., CdS).

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	O
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

A relatively small group of elements shaded in the above figure 1.16 and their compounds has an important electrical property, *semiconduction*, in which they are neither good electrical conductors nor good insulators. Instead, their ability to conduct electricity is intermediate. These materials are called *semiconductors.*

Types of Materials

- Semiconductor Materials

  - Not Major by volume but very important.
  - Silicon is a common electronic material.
  - Its electrical characteristics are changed by adding impurities.

  - *Examples:*- Silicon chips, transistors
  - *Applications :*- Computers,
    Integrated Circuits,
    Satellites etc.

Types of Materials

Metals: valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together. Strong, ductile, conduct electricity and heat well, are shiny if polished.

Semiconductors: the bonding is covalent (electrons are shared between atoms). Their electrical properties depend strongly on minute proportions of contaminants. Examples: Si, Ge, GaAs.

Ceramics: atoms behave like either positive or negative ions, and are bound by Coulomb forces. They are usually combinations of metals or semiconductors with oxygen, nitrogen or carbon (oxides, nitrides, and carbides). Hard, brittle, insulators. Examples: glass, porcelain.

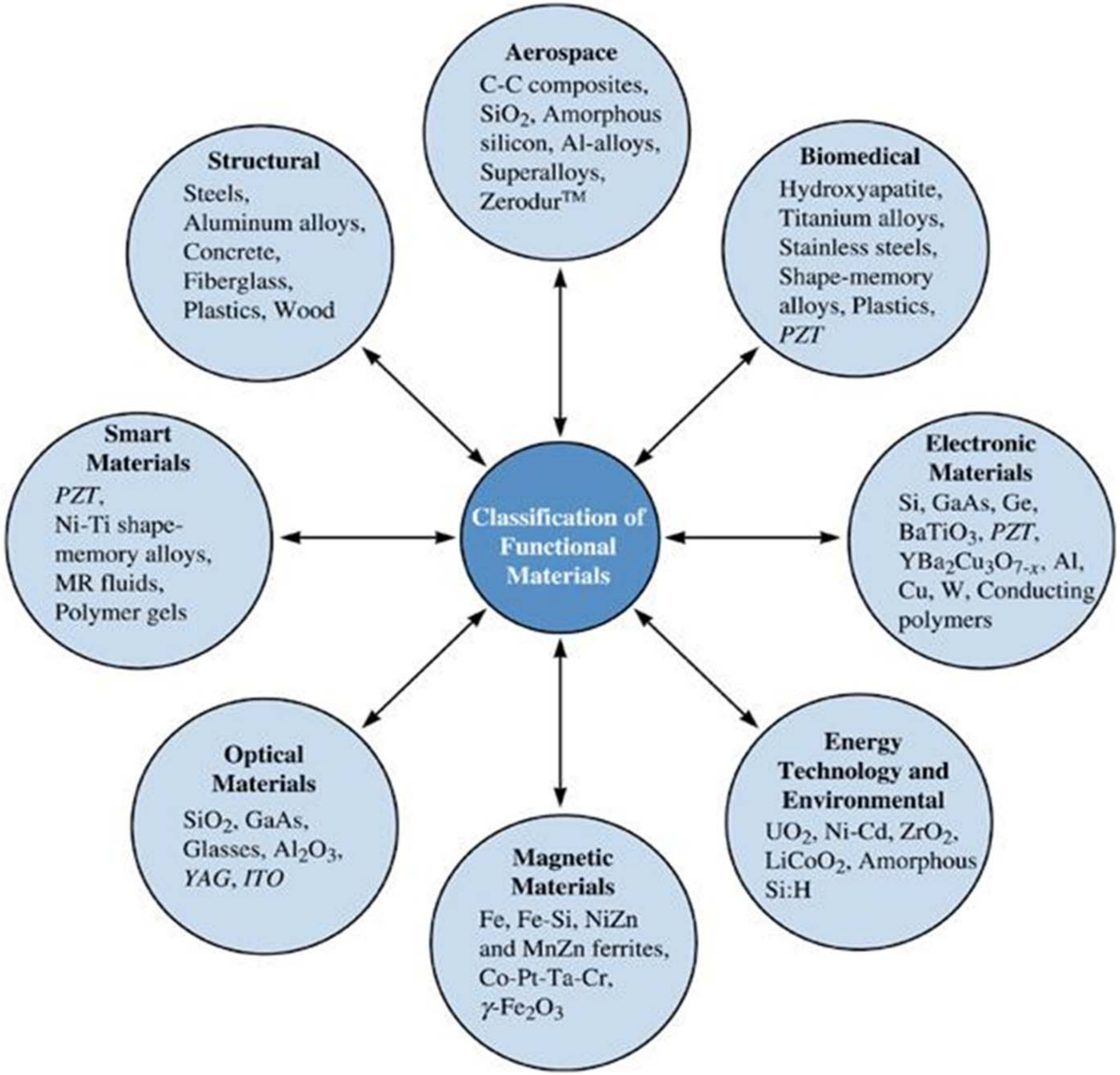
Polymers: are bound by covalent forces and also by weak van der Waals forces, and usually based on C and H. They decompose at moderate temperatures (100 – 400 C), and are lightweight. Examples: plastics rubber.

- .

Functional Classification of Materials

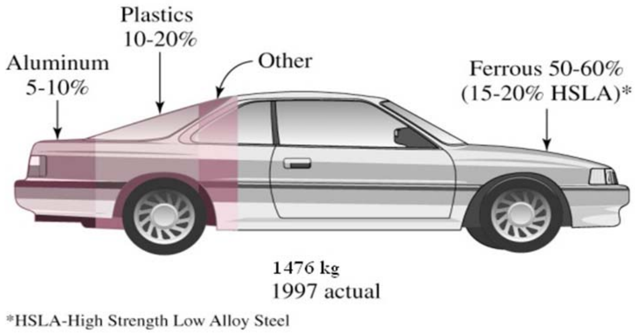
- Aerospace
- Biomedical
- Electronic Materials
- Energy Technology and Environmental Technology
- Magnetic Materials
- Photonic or Optical Materials
- Smart Materials
- Structural Materials

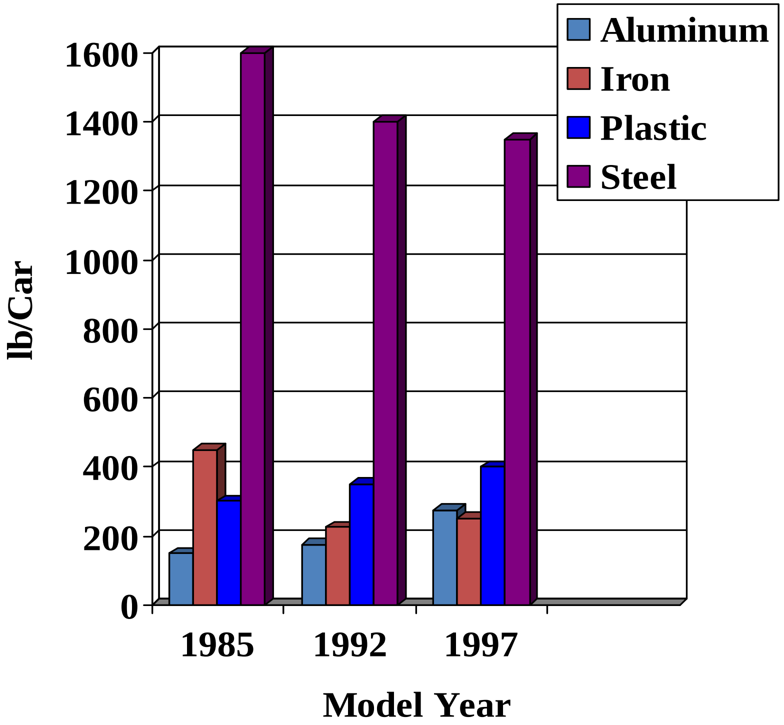
Functional Classification of Materials



Competition Among Materials

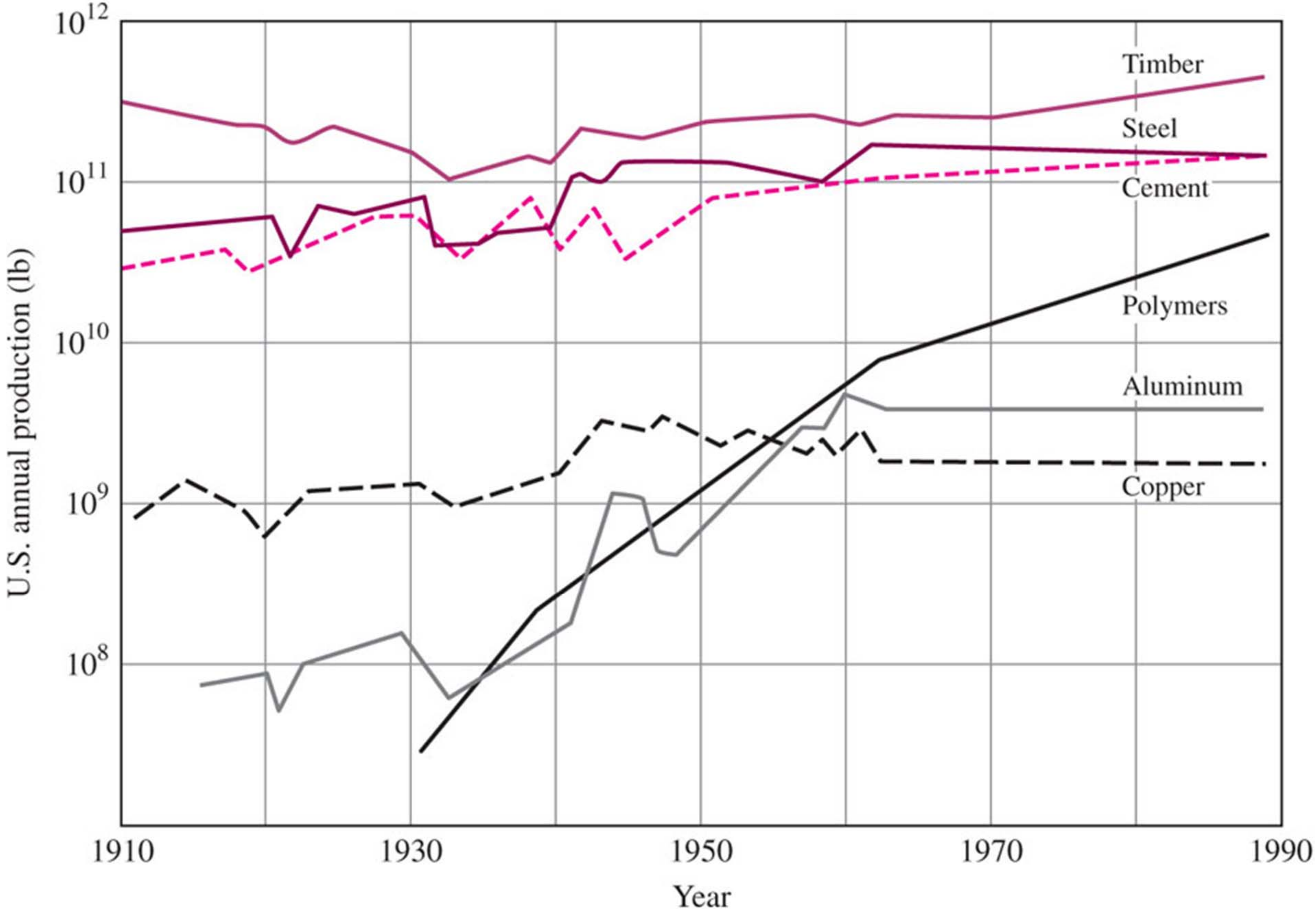
- Materials compete with each other to exist in new market
- Over a period of time usage of different materials changes depending on cost and performance.
- New, cheaper or better materials replace the old materials when there is a breakthrough in technology





Predictions and use of materials in US automobiles.

Competition Among Materials



Competition of 6 major materials produced in the US on a weight basis (1988)

Recent Advances and Future Trends

Design of materials having specific desired characteristics directly from our knowledge of atomic structure.

Nano materials: “Nanostructured" materials, with microstructure that has length scales between 1 and 100 nanometers with unusual properties. Electronic components, materials for quantum computing.

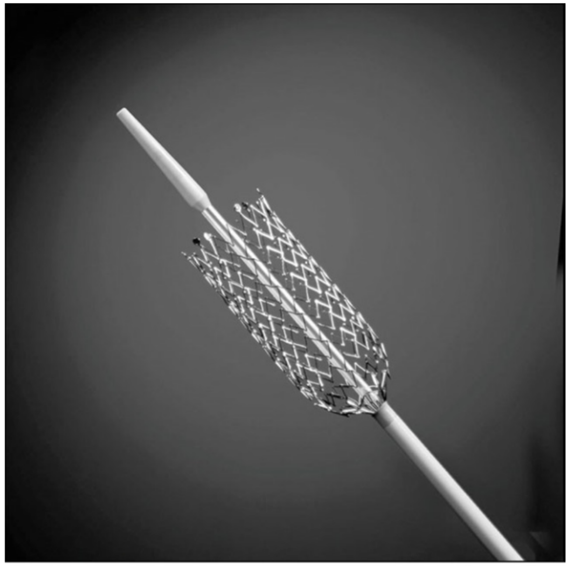
Smart materials: airplane wings that deice themselves, buildings that stabilize themselves in earthquakes…

Environment-friendly materials: biodegradable or photodegradable plastics, advances in nuclear waste processing, etc.

Learning from Nature: shells and biological hard tissue can be as strong as the most advanced laboratory-produced ceramics, molluscs produce biocompatible adhesives that we do not know how to reproduce…

Recent Advances and Future Trends

- Smart Materials
  - ➢ React to environment Stimuli.
  - ➢ Change their properties by sensing external stimulus.
    - ➢ Examples: Shape memory alloys – used in the artery stents.
    - ➢ Microelectromechanical systems (MEMS) devices.



(a)

(b)

Recent Advances and Future Trends

- Nanomaterials
  - ➢ Smaller than 100 nm particle size.
  - ➢ Materials have special properties.
  - ➢ Very hard and strong characteristics.
  - ➢ Research in progress.

Material Selection

Effects of following factors must be accounted for in design to ensure that components do not fail expectedly:

- Temperature
- Corrosion
- Fatigue
- Strain Rate

Material Selection

1. Pick Application Determine required Properties

Properties: mechanical, electrical, thermal, magnetic, optical

2. Properties Identify candidate Material(s)

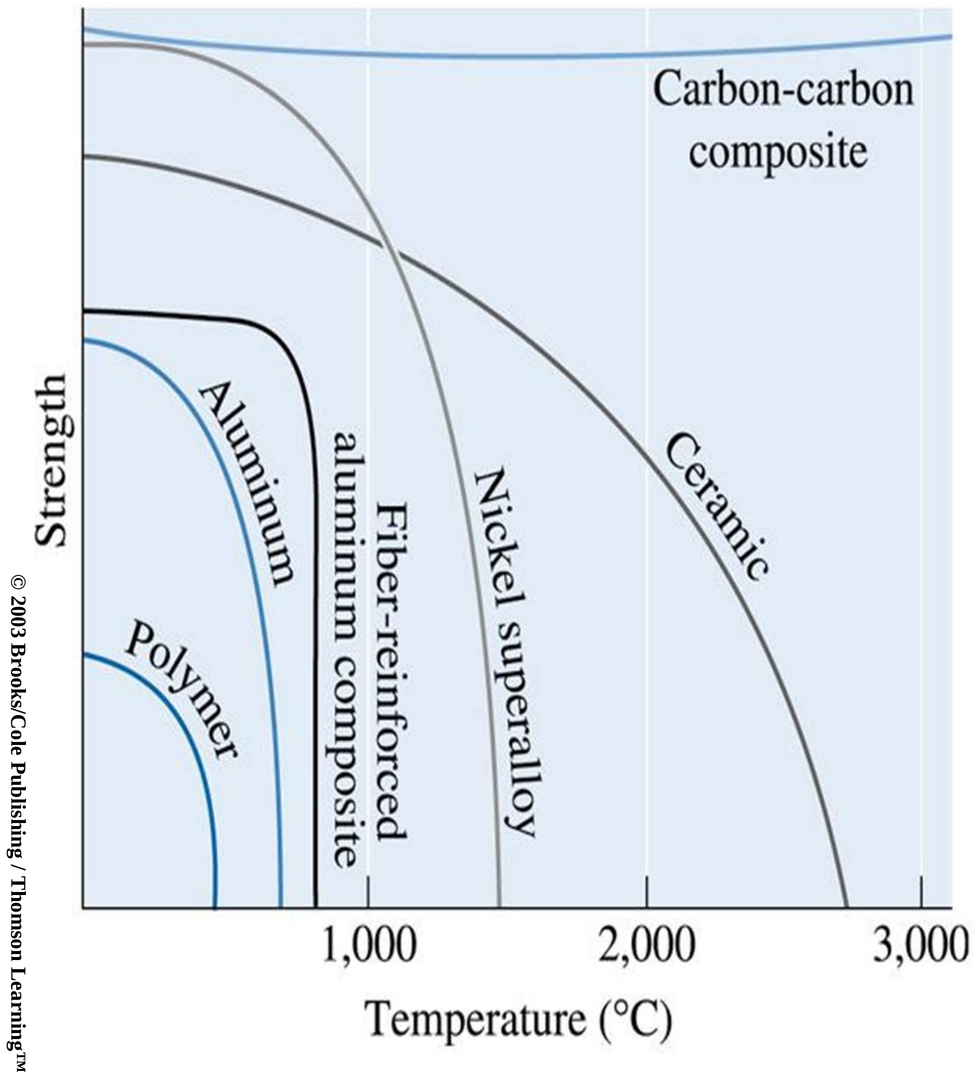
Material: structure, composition

3. Material Identify required Processing

Processing: changes structure and overall shape

ex: casting, sintering, vapor deposition, forming, joining,

Material Selection



Increasing temperature normally reduces the strength of a material. Polymers are suitable only at low temperatures. Some composites, special alloys, and ceramics, have excellent properties at high temperatures

Material Selection

- Density is mass per unit volume of a material, usually expressed in units of g/cm^3 or $lb/in.^3$
- Strength-to-weight ratio is the strength of a material divided by its density; materials with a high strength-to-weight ratio are strong but lightweight.

Material Selection

TABLE 1-2 *Strength-to-weight ratios of various materials*

Material	Strength ($lb/in.^2$)	Density ($lb/in.^3$)	Strength-to-weight ratio (in.)
Polyethylene	1,000	0.030	0.03×10^6
Pure aluminum	6,500	0.098	0.07×10^6
Al_2O_3	30,000	0.114	0.26×10^6
Epoxy	15,000	0.050	0.30×10^6
Heat-treated alloy steel	240,000	0.280	0.86×10^6
Heat-treated aluminum alloy	86,000	0.098	0.88×10^6
Carbon-carbon composite	60,000	0.065	0.92×10^6
Heat-treated titanium alloy	170,000	0.160	1.06×10^6
Kevlar-epoxy composite	65,000	0.050	1.30×10^6
Carbon-epoxy composite	80,000	0.050	1.60×10^6

Material Selection

- Problem: Select suitable material for bicycle frame and fork.