

Properties of Materials

Part I

1- Introduction and Classification of Engineering Materials.

2- Metals and Alloys.

- ✓ **Characteristic property of metals, bonds.**
- ✓ **Crystal systems.**
- ✓ **Representations of planes and directions in crystals, atomic packing in**
- ✓ **Aluminum Alloys, Copper Alloys and Iron Alloys.**
- ✓ **Phase Diagram**

3- Ceramics.

- ✓ **Classification.**
- ✓ **Structures.**
- ✓ **Properties.**

4- Polymers.

- ✓ **Classification.**
- ✓ **Structures.**
- ✓ **Properties.**

5- Composite Materials.

Part II

6- Corrosion

- ✓ **Types of Corrosion.**
- ✓ **Polarization.**
- ✓ **Protections Methods.**
- ✓ **Case Study.**

Part III

7- Mechanics of Materials

- ✓ **Stresses**
- ✓ **Equilibrium**
- ✓ **Centeriod**
- ✓ **Moment of Inertia**

References

- 1- William D. Callister, "*Fundamentals of Materials Science and Engineering*", Fifth Edition, 2001.
- 2- Michael F. Ashby and David R. H. Jones, "*Engineering Materials An Introduction to their Properties and Applications*", Second Edition, 2002.
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I-1 Introduction to Engineering Materials

Materials play an important role for our existence, for our day to day needs, and even for our survival. In the stone age the naturally accessible materials were stone, wood, bone, fur etc.

According to Webster's dictionary, materials are defined as 'substances of which something is composed (formed) or made'

Material Science: Primarily concerned with the search for basic knowledge about internal structure, properties and processing of materials and their complex interactions/relationships

Material Engineering: Mainly concerned with the use of fundamental and applied knowledge of materials, so that they may be converted into products, as needed or desired by the society.

Why Material Science & Engineering is important to technologists ?

- Mechanical engineers search for high temp material so that gas turbines, jet engines etc can operate more efficiently and wear resistance materials to manufacture bearing materials
- Electrical engineers search for materials by which electrical devices or machines can be operated at a faster rate with minimum power losses
- Aerospace & automobile engineers search for materials having high strength-to-weight ratio
- Electronic engineers search for material that are useful in the fabrication of electronic devices
- Chemical engineers search for highly corrosion-resistant materials

I-2 Classifications of Materials

It is the systematic arrangement or division of materials into groups on the basis of some common characteristic

1. According to General Properties.
2. According to Nature of Materials.
3. According to Applications.

1. According to General Properties

(a). Metals (e.g. iron, aluminum, copper, zinc, lead, etc)

Iron as the base metal, and range from plain carbon (> 98 % Fe) to (i). Ferrous: high alloy steel (< 50 % alloying elements), e.g. cast iron, wrought iron, steel, alloys like high-speed steel, spring steel, etc

(ii). Non-Ferrous: Rest of the all other metals and their alloys, e.g. copper, aluminum, zinc lead, alloys like brass, bronze, duralumin, etc

(b). Non-Metals (e.g. leather, rubber, asbestos, plastics, etc)

2. According to Nature of Materials

(a). Metals: e.g. Iron & Steel, Alloys & Super alloys, Intermetallic Compounds, etc

(b). Ceramics: e.g. Structural Ceramics (high-temperature load bearing), Refractories

(corrosion-resistant, insulating), Whitewares (porcelains), Glass, Electrical Ceramics

(capacitors, insulators, transducers), Chemically Bonded Ceramics (cement & concrete)

(c). Polymers: e.g. Plastics, Liquid Crystals, Adhesives

(d). Electronic Materials: e.g. Silicon, Germanium, Photonic materials (solid-state lasers, LEDs)

(e). Composites: e.g. Particulate composites (small particles embedded in a different material), Laminate composites (golf club shafts, tennis rackets), Fiber reinforced composites (fiberglass).

(f). Biomaterials: e.g. Man-made proteins (artificial bacterium), Biosensors, etc

(g). Advanced / Smart Materials: e.g. materials in computers (VCRs, CD Players, etc), fibreoptic systems, spacecrafts, aircrafts, rockets, shape-memory alloys, piezoelectric ceramics, magnetostrictive materials, optical fibres, microelectromechanical (MEMs) devices, electrorheological / magnetorheological fluids, Nanomaterials, etc.

3. According to Applications

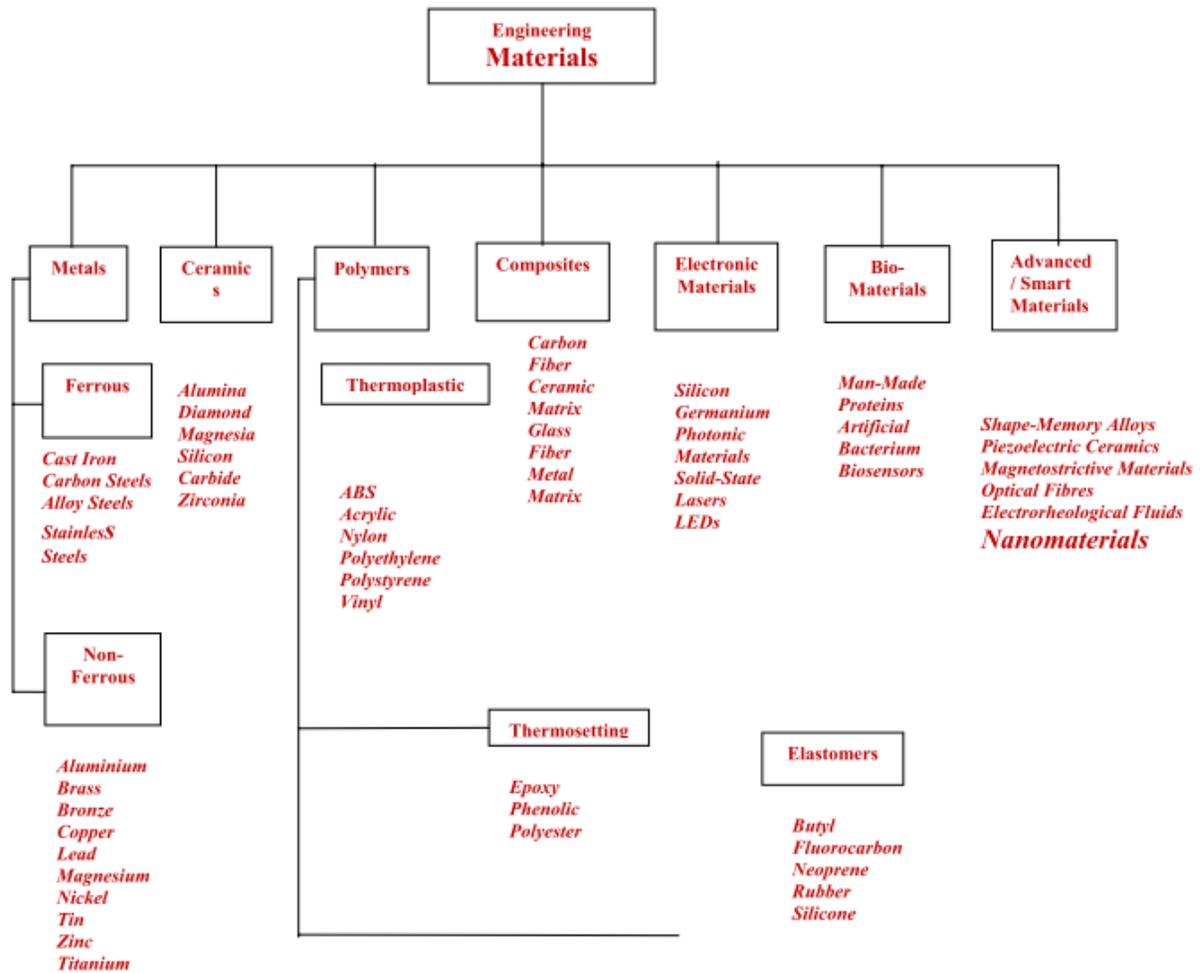
(a). Electrical Materials: e.g. conductors, insulators, dielectrics, etc.

(b). Electronic Materials: e.g. conductors, semi-conductors, etc.

(c). Magnetic Materials: e.g. ferromagnetic, paramagnetic & diamagnetic materials.

(d). Optical Materials: e.g. glass, quartz, etc.

(e). Bio Materials: e.g. man-made proteins, artificial bacterium.



What are the Difference between Metals & Non-Metals ?

Property	Metals	Non-Metals
Structure	Crystalline	Amorphic
State	Generally solids at room temp.	Gaseous & solid at ordinary temp.
Luster	Metallic luster	No metallic luster (except iodine & graphite)
Conductivity	Good conductors of heat & electricity	Bad conductors
Malleability	Malleable	Not malleable
Ductility	Ductile	Not ductile
Hardness	Generally hard	Hardness varies
Electrolysis	Form anions	Form anions
Excitation of valence electron by e.m.f.	Easy	Difficult
Density	High	Low

I-3. Material Properties

- Physical: e.g. appearance, shape, weight, boiling point, melting point, freezing point, density, glass transition temperature, permeability
- Mechanical: e.g. strength (tensile, compressive, shear, torsion, bending), elasticity, plasticity, ductility, malleability, rigidity, toughness, hardness, brittleness, impact, fatigue, creep, strain hardening, strain rate effect, vibration resistance, wear
- Thermal: e.g. thermal conductivity, expansion coefficient, resistivity, thermal shock resistance, thermal diffusivity
- Electrical: e.g. conductivity, resistivity, dielectric strength, thermoelectricity, superconductivity, electric hysteresis
- Magnetic: e.g. ferromagnetism, paramagnetism, diamagnetism, magnetic permeability, coercive force, curie temperature, magnetic hysteresis
- Chemical: e.g. reactivity, corrosion resistance, polymerization, composition, acidity, alkalinity
- Optical: e.g. reflectivity, refractivity, absorptivity, transparency, color.

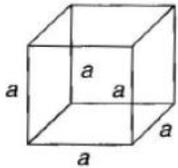
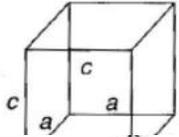
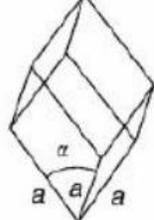
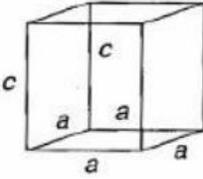
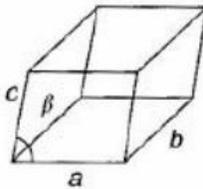
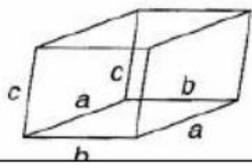
I-4 Introduction to Crystal Geometry

Crystal structure: the manner in which atoms, ions, or molecules are spatially arranged.

Unit cell: small repeating entity of the atomic structure. The basic building block of the crystal structure. It defines the entire crystal structure with the atom positions within.

Lattice Parameters

- ❖ Six lattice parameters $a, b, c, \alpha, \beta, \gamma$
- ❖ Typically in the order of few Angstroms (few tenths of nanometer)

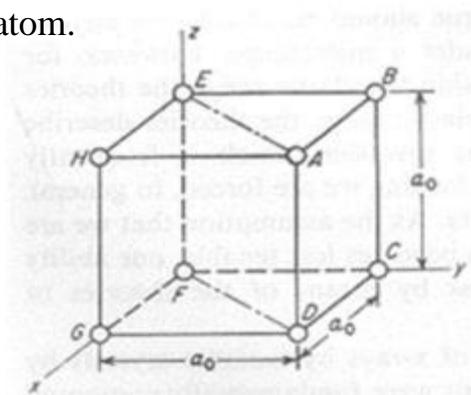
System	Lattice constants and angles	Unit cell geometry
Cubic	$a = b = c, \alpha = \beta = \gamma = 90^\circ$	
Tetragonal	$a = b \neq c, \alpha = \beta = \gamma = 90^\circ$	
Rhombohedral	$a = b = c, \alpha = \beta = \gamma \neq 90^\circ$	
Hexagonal	$a = b \neq c, \alpha = \beta = 90^\circ, \gamma = 120^\circ$	
Monoclinic	$a \neq b \neq c, \alpha = \gamma = 90^\circ, \neq \beta$	
Triclinic	$a \neq b \neq c, \alpha \neq \beta \neq \gamma \neq 90^\circ$	

Cubic System

- ❖ Simple Cubic Lattice (SCL) Structure.
- ❖ Body Centered Cubic (BCC) Structure.
- ❖ Face Centered Cubic (FCC) Structure.

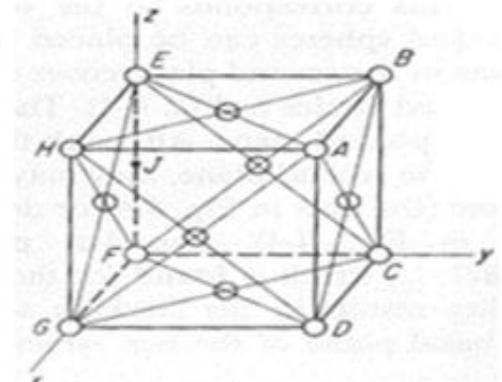
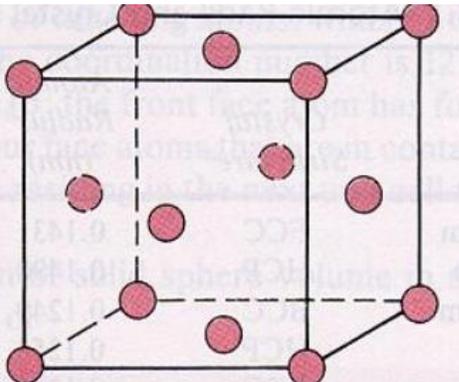
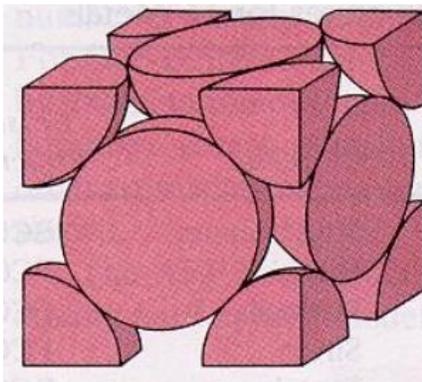
1- Simple Cubic Lattice

- ✓ Most elementary crystal structure with three mutually perpendicular axes arbitrarily placed through one of the corners of a cell.
- ✓ Each corners occupied with one atom.
- ✓ Example: alpha polonium.



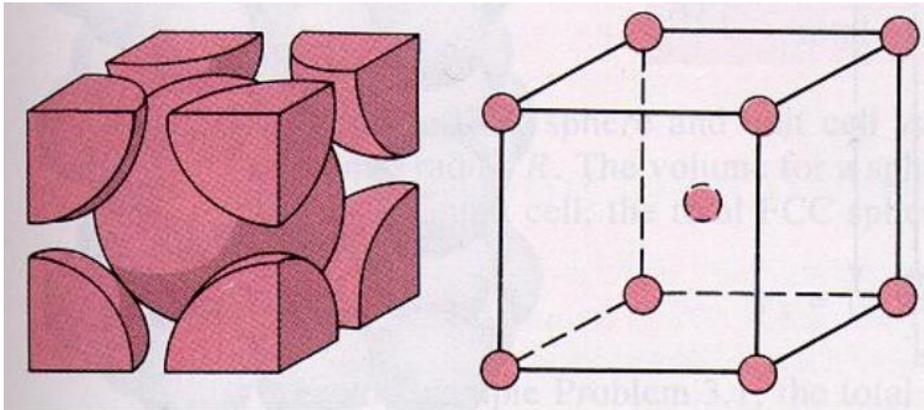
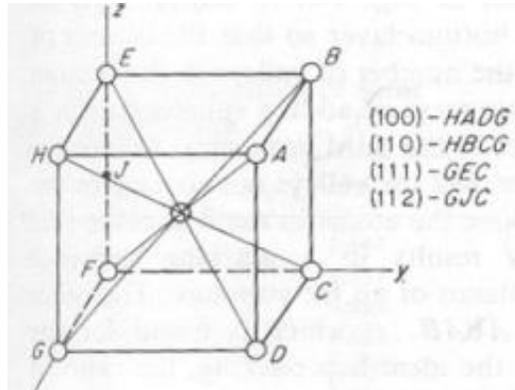
2- Face Centered Cubic (FCC) Structure

- ✓ Atoms at each corner of cube, and in addition there is an atom at the center of each cube's face.
- ✓ Example: aluminum, copper, gold, lead, silver and nickel.

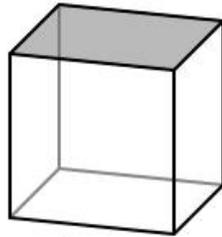


3- Body Centered Cubic (BCC) Structure

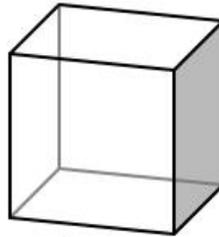
- ✓ BCC cell has an atom at each corner and another atom at body center of cube
- ✓ Each atom at corner is surrounded by eight adjacent atoms
- ✓ Example: alpha iron, chromium, molybdenum & tungsten



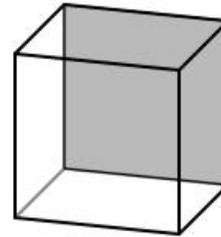
Crystallographic Planes & Directions



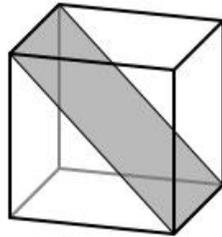
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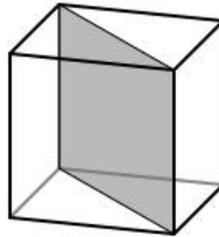
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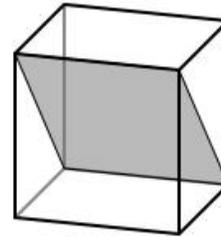
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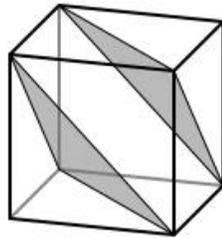
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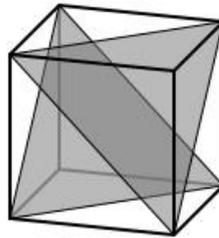
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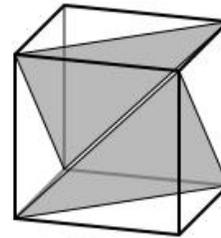
(011)



(111)



(1 $\bar{1}$ 1)



($\bar{1}$ 11)

– Direction 1	1, 0, 0 = [100]
– Direction 2	0, 1, 0 = [010]
– Direction 3	1, 0, 1 = [101]
– Direction 4	1, 1, 1 = [111]
– Direction 5	½, 1, 0 = [120]
– Direction 6	½, ½, 1 = [112]

-- Parallel directions have the same value
 Lowest Integer Value [111] = [222]

I-5 Bonding

1- Primary bonding

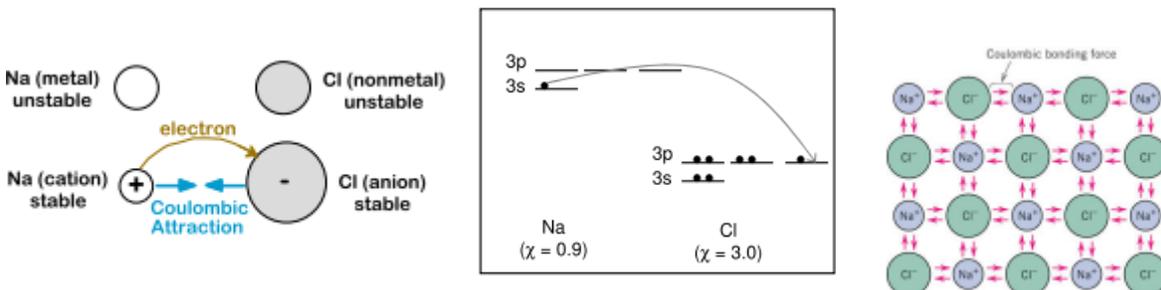
- ✚ Ionic (transfer of valence electrons)
- ✚ Covalent (sharing of valence electrons, directional)
- ✚ Metallic (delocalization of valence electrons)

2- Secondary or van der Waals Bonding: (Common, but weaker than primary bonding).

- ✚ Dipole-dipole
- ✚ H-bonds
- ✚ Polar molecule-induced dipole.

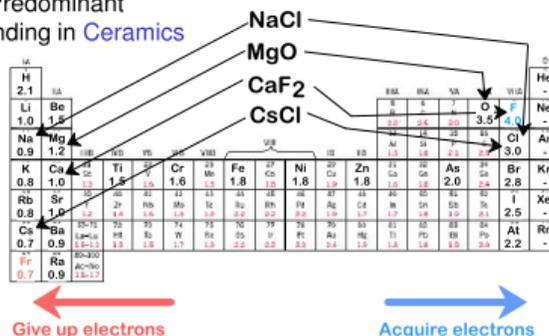
Ionic Bonding

- Occurs between (+) and (-) ions.
- Requires electron transfer.
- Large difference in electronegativity required.
- Example: NaCl



Ionic Bonding: examples

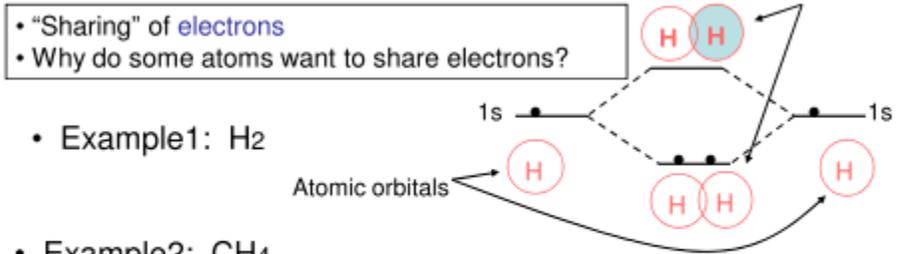
- Predominant bonding in **Ceramics**



Covalent Bonding

A **covalent bond**, also called a **molecular bond**, is a chemical bond that involves the sharing of electron pairs between atoms. These electron pairs are known as shared pairs or bonding pairs, and the stable balance of attractive and repulsive forces between atoms, when they share electrons.

Covalent Bonding



- “Sharing” of electrons
- Why do some atoms want to share electrons?

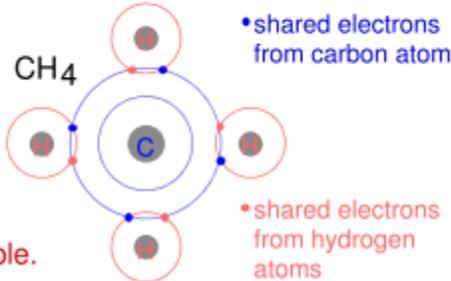
• Example1: H₂

• Example2: CH₄

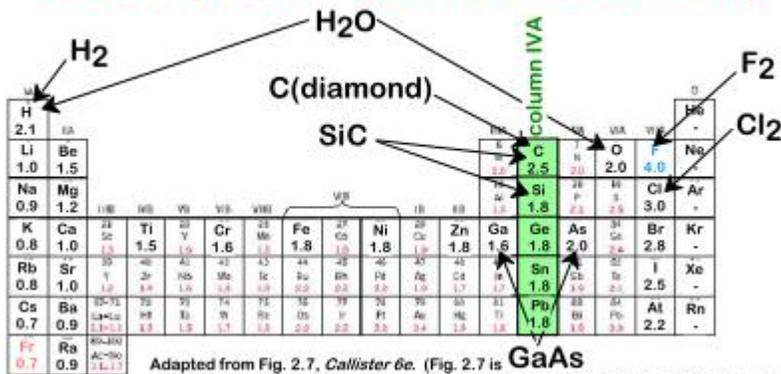
C: has 4 valence e, needs 4 more

H: has 1 valence e, needs 1 more

Electronegativities are same or comparable.



Examples: Covalent Bonding



Adapted from Fig. 2.7, Callister 6e. (Fig. 2.7 is adapted from Linus Pauling, *The Nature of the Chemical Bond*, 3rd edition, Copyright 1939 and 1940, 3rd edition. Copyright 1960 by Cornell University. From Callister 6e resource CD.

Metallic Bonding

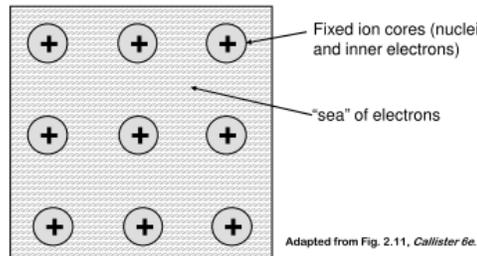
- Valence electrons are completely delocalized to form an electron cloud, in which positive ionic cores are embedded.
- The remaining nonvalence electrons and atomic nuclei form “ion cores”, which

posses a net positive charge equal in magnitude to the total valence electron charge per atom.

- The metallic bond is nondirectional.
- Metallic bonding is found in the periodic table for Group IA and IIA elements.
- Electron delocalization is the origin of good electrical and thermal conductivities in metals. (Ionically and covalently bonded materials are typically electrical and thermal insulators, due to the absence of large numbers of free electrons).

Metallic Bonding

- Arises from a sea of **donated valence electrons**



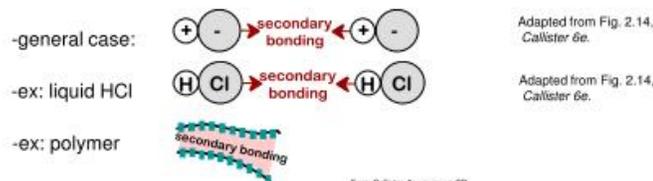
- Primary bond for **metals** and their **alloys**.
- Large atomic radius and small IP will more likely lead to metallic bonding.

Secondary Bonds: Intermolecular Forces

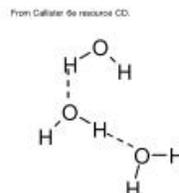
- Secondary, Van der Waals, or physical bonds are weak in comparison to the primary bonds.
- Secondary bonding exists between virtually all atoms or molecules, but its presence may be obscured if any of the three primary bonding types is present.
- Secondary bonding forces arise from atomic or molecular dipoles. An electric dipole exists whenever there is some separation of positive and negative portions of an atom or molecule.
- Dipole interactions occur between induced dipoles and polar molecules (which have permanent dipoles), and between polar molecules.
- Hydrogen bonding, a special type of secondary bonding, is found to exist between some molecules that have hydrogen as one of the constituents.

Secondary Bonds: Intermolecular Forces

- **Dipole-dipole interaction:** secondary bond between molecules with permanent dipole moments



- **Hydrogen bonding**

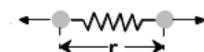


Bonding and materials properties

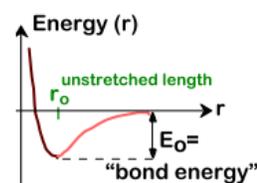
1. Materials with large bonding energies usually have high melting temperatures.
2. There is a correlation between the magnitude of the bonding energy and the state of materials:
 - Solids have large bonding energies
 - Liquids tend to have relatively lower energies
3. The expansion/contraction during heating/cooling of materials is related to the shape of its $E(r)$ curve.
4. A deep and narrow ‘trough,’ which typically occurs for materials having large bonding energies, usually imply a low coefficient of thermal expansion.

PROPERTIES FROM BONDING: T_M

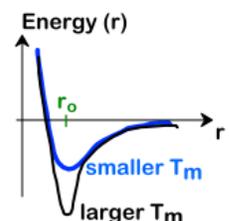
- Bond length, r



- Bond energy, E_0



- Melting Temperature, T_m



T_m is larger if E_0 is larger.

I-6 Alloys: are metallic materials prepared by mixing two or more molten metals. They are used for many purposes, such as construction, and are central to the transportation and electric industries. Some common alloys are present in the following table.

Alloy	Mass percentage composition
brass	up to 40% zinc in copper
bronze	a metal other than zinc or nickel in copper (casting bronze: 10%Sn and 5% Pb)
cupronickel	nickel in copper (coinage cupronickel: 25% Ni)
pewter	6% antimony and 1,5% copper in tin
solder	tin and lead
stainless steel	more than 12% chromium in iron

The structures of alloys are more complicated than those of pure metals because they are built from atoms of two or more elements with different atomic radii.

Because the metallic radii of the d-block elements are all similar, they can form an extensive range of alloys with one another with little distortion of the original crystal structure.

Because the metallic radii of the d-block elements are all similar, they can form an extensive range of alloys with one another with little distortion of the original crystal structure.

An example is the copper-zinc alloy used for some “copper” coins. Because zinc atoms are nearly the same size as copper atoms and have similar electronic properties (they belong to neighboring groups), they can take the place of some of the copper atoms in the crystal. An alloy in which atoms of one metal are substituted for atoms of another metal is called a **substitutional** alloys.

Elements that can form substitutional alloys have atoms with atomic radii that differ by no more than about 15%. Because there are slight differences in size and electronic structure, the less abundant atoms in substitutional alloy distort the shape of the lattice of the more abundant atoms of the host metal and hinder the flow of electrons. Because the lattice is distorted, it is harder for one plane of atoms to slip past another. Therefore, although a substitutional alloy has lower electrical and thermal conductivity than pure element, it is harder and stronger.

Stell is an alloy of about 2% or less carbon in iron. Carbon atoms are much smaller than iron atoms, and so they cannot substitute for iron in the crystal lattice. Indeed, they are so small that they can fit into the interstices (the holes) in the iron lattice. The resulting material is called an interstitial alloy. For two elements to form

an ***interstitial*** alloy, the atomic radius of the solute element must be less than about 60% of the atomic radius of the host metal. The interstitial atoms interfere with the electrical conductivity and with the movement of the atoms forming the lattice. This restricted motion makes the alloy harder and stronger than the pure host metal would be.

Alloys of metals tend to be stronger and have lower electrical conductivity than pure metals. In substitutional alloys, atoms of the solute metal take the place of some atoms of a metal of similar atomic radius. In interstitial alloys, atoms of the solute element fit into the interstices in a lattice formed by atoms of a metal with a larger atomic radius.

Aluminum Alloys

Aluminum has a density of only 2.7 g/cm³, approximately one-third as much as steel (7.83 g/cm³). Such light weight, coupled with the high strength of some aluminum alloys (exceeding that of structural steel), permits design and construction of strong, lightweight structures that are particularly advantageous for anything that moves-space vehicles and aircraft as well as all types of land- and water-borne vehicles. Aluminum resists the kind of progressive oxidization that causes steel to rust away. The exposed surface of aluminum combines with oxygen to form an inert aluminum oxide Al₂O₃ film only a few ten-millionths of an inch thick, which blocks further oxidation. And, unlike iron rust, the aluminum oxide film does not flake off to expose a fresh surface to further oxidation. If the protective layer of aluminum is scratched, it will instantly reseal itself. The thin oxide layer itself clings tightly to the metal and is colorless and transparent-invisible to the naked eye. The discoloration and flaking of iron and steel rust do not occur on aluminum. Appropriately alloyed and treated, aluminum can resist corrosion by water, salt, and other environmental factors, and by a wide range of other chemical and physical agents.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also non-toxic and is routinely used in containers for food and beverages.

Aluminum Alloy: It is convenient to divide aluminum alloys into two major categories: wrought compositions and cast compositions.

ALLOY SERIES	ALLOY	PROPERTIES	APPLICATIONS
1XXX	Pure	Low strength, excellent thermal/ electrical conduction and corrosion resistance, highly reflective	Fuel filters, electrical conductors, radiator tubing, lighting reflectors, decorative components
2XXX	Cu	High strength, relatively low corrosion resistance, good elevated temperature strength	Aircraft skin, aircraft fittings and wheels, ballistic armor, forged and machined components
3XXX	Mn	Medium strength, good formability, good corrosion resistance	Storage tanks, beverage cans, home appliances, heat exchangers, pressure vessels, siding, gutters
4XXX	Si	High castability, high machinability, high fluidity, low ductility	Variety of castings, including large castings, filler metal (2xxx, 3xxx, 5xxx and 7xxx used for castings)
5XXX	Mg	Medium strength, good formability, excellent corrosion resistance	Interior automotive, appliance trim, pressure vessels, aircraft fittings

Applications for aluminium alloys



Construction & Equipment



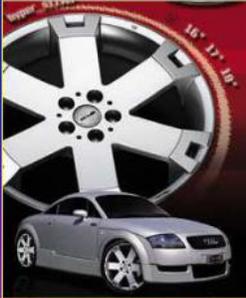


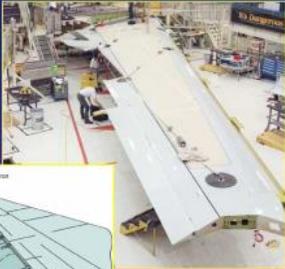
Containers & Packaging



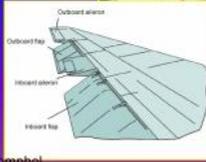


Automotives





Aerospace

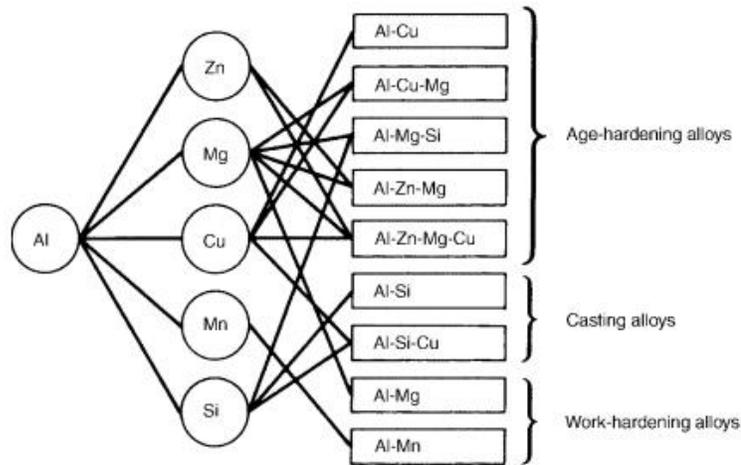


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Alloying and Second-Phase Constituents

The predominant reason for alloying is to increase strength, hardness, and resistance to wear, creep, stress relaxation or fatigue. Effects on these properties are specific to the different alloying elements and combinations of them, and are related to their alloy phase diagrams and to the Aluminum and Aluminum Alloys / 367 microstructures and substructures that they form as a result of solidification, thermomechanical history, heat treatment and/or cold working.

The principal aluminum alloys



Copper alloys

Copper alloys are metal [alloys](#) that have [copper](#) as their principal component. They have high resistance against [corrosion](#). The best known traditional types are [bronze](#), where [tin](#) is a significant addition, and [brass](#), using [zinc](#) instead.

1- Brass

A brass is an alloy of copper with zinc. Brasses are usually yellow in color. The zinc content can vary between few % to about 40%; as long as it is kept under 15%, it does not markedly decrease corrosion resistance of copper.

Brasses can be sensitive to selective leaching corrosion under certain conditions, when zinc is leached from the alloy (dezincification), leaving behind a spongy copper structure.

Alloy Metals

Brass (Copper and Zinc)

Uses:

- Hinges
- Pins
- Screws
- Ammunition cartridges
- Lamps
- Electrical socket
- Horns and bells

Properties:

- Malleable depending on content of Zinc (under 45%)
- Good conductor of electricity
- Soft - Doesn't spark easily
- acoustic properties appropriate for use in musical instruments
- relatively low melting point
- low friction



board works

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2- Bronze

A bronze is an alloy of copper and other metals, most often tin, but also aluminum and silicon, bronze is used in Musical instruments, Coins and medals.

Aluminum bronzes are alloys of copper and aluminum. The content of aluminum ranges mostly between 5-11%. Iron, nickel, manganese and silicon are sometimes added. They have higher strength and corrosion resistance than other bronzes, especially in marine environment, and have low reactivity to sulfur compounds.

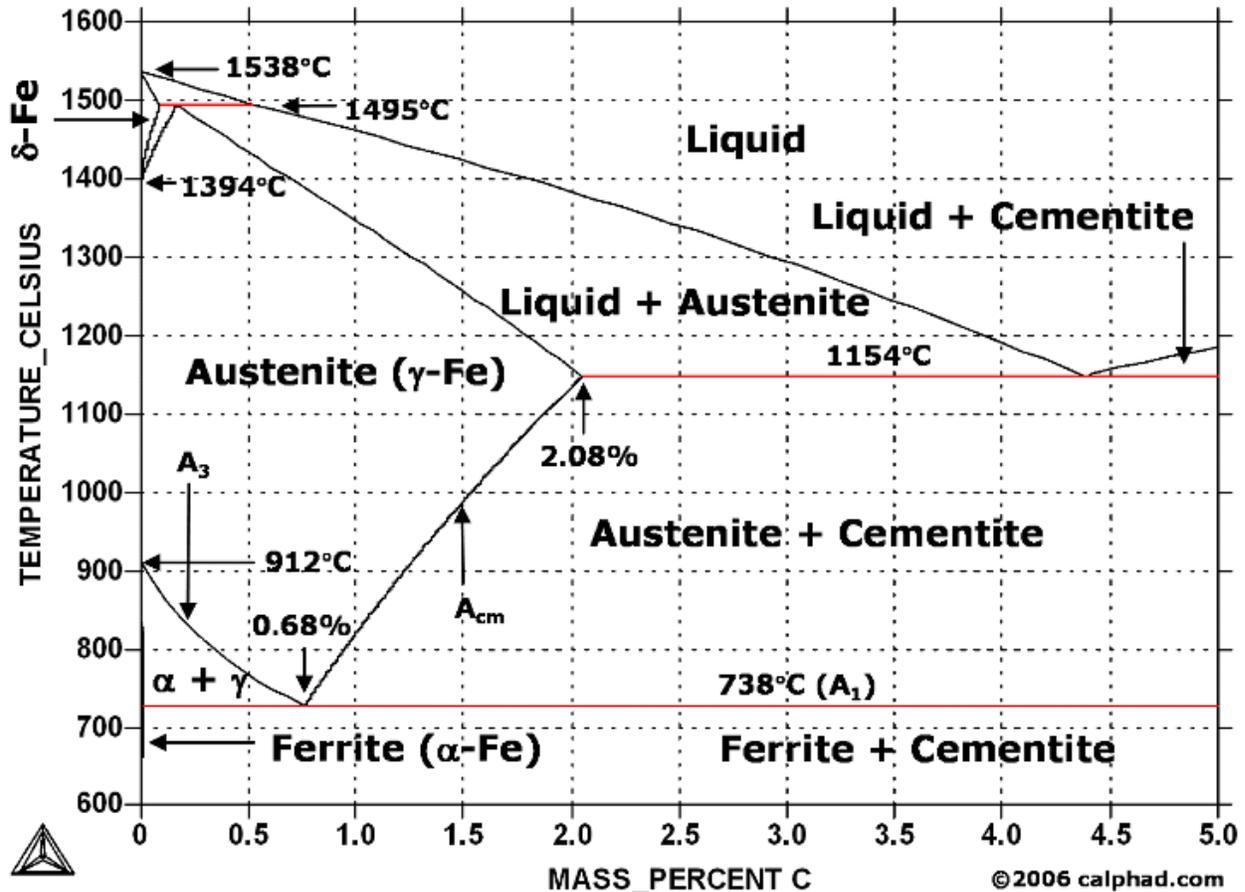
Iron Alloys

Iron castings are produced by a variety of molding methods and are available with a wide range of properties.

The main classes of Iron alloys is: Steels ($Fe + C < 1.7\%$) and Cast iron

1- Carbon Steel is an alloy of iron and other elements, primarily carbon. Because of its high tensile strength and low cost, it is a major component in buildings, infrastructure, tools, ships, automobiles, machines, and weapons. The carbon in typical steel alloys may contribute up to 2.1% of its weight. Varying the amount of carbon and many other alloying elements, as well as controlling their chemical and physical makeup in the final steel (either

as solute elements, or as precipitated phases), slows the movement of those dislocations that make pure iron ductile, and thus controls and enhances its qualities.



Type of Carbon steel

1- Low-carbon steel

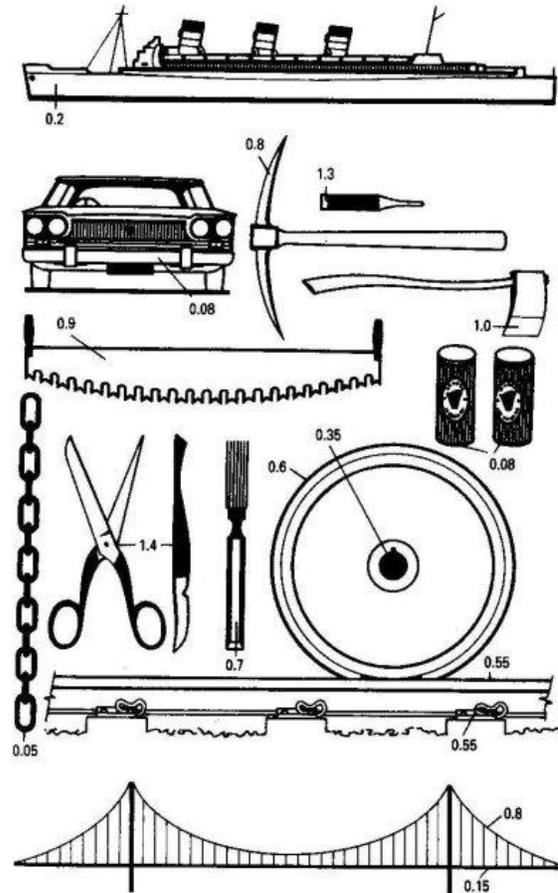
0.05 to 0.30% carbon content.

2- Medium-carbon steel

Approximately 0.3–0.6% carbon content. Balances ductility and strength and has good wear resistance; used for large parts, forging and automotive components.

3- High-carbon steel

Approximately 0.6–1.0% carbon content. Very strong, used for springs, swords, and high-strength wires.



2- Cast iron

Cast iron is a group of [iron-carbon alloys](#) with a carbon content greater than 2% Its usefulness derives from its relatively low melting temperature.

✓ *Grey cast iron*

Grey cast iron is characterised by its graphitic microstructure, which causes fractures of the material to have a grey appearance. Most cast irons have a chemical composition of 2.5 – 4.0% carbon, 1–3% silicon, and the remainder iron. Grey cast iron has less tensile strength and shock resistance than steel, but its compressive strength is comparable to low- and medium-carbon steel. These mechanical properties are controlled by the size and shape of the graphite flakes present in the microstructure

✓ **White cast iron**

White cast iron displays white fractured surfaces due to the presence of an iron carbide precipitate called cementite. With a lower silicon content (graphitizing agent) and faster cooling rate.

✓ **Malleable cast iron**

Malleable iron starts as a white iron casting that is then heat treated for a day or two at about 950 °C and then cooled over a day or two. As a result, the carbon in iron carbide transforms into graphite and ferrite plus carbon (austenite). The slow process allows the surface tension to form the graphite into spheroidal particles rather than flakes.

✓ **Ductile cast iron**

The properties of ductile cast iron are that of a spongy steel without the stress concentration effects that flakes of graphite would produce. Tiny amounts of 0.02 to 0.1% magnesium, and only 0.02 to 0.04% cerium added to these alloys slow the growth of graphite precipitates by bonding to the edges of the graphite planes. The properties are similar to malleable iron, but parts can be cast with larger sections.



I-7 Phase Diagrams

phase can be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics i.e. it is a physically distinct from other phases, chemically homogeneous and mechanically separable portion of a system.

A solution (liquid or solid) is phase with more than one component; a mixture is a material with more than one phase.

In mixtures, there are different phases, each with its own atomic arrangement. It is possible to have a mixture of two different solutions!

In a system under a set of conditions, number of phases (P) exist can be related to the number of components (C) and degrees of freedom (F) by Gibbs phase rule.

Degrees of freedom refers to the number of independent variables (e.g.: pressure, temperature) that can be varied individually to effect changes in a system.

Thermodynamically derived Gibbs phase rule:

In practical conditions for metallurgical and materials systems, pressure can be treated as a constant (1 atm.). Thus Condensed Gibbs phase rule is written as:

$$P + F = C + 1$$

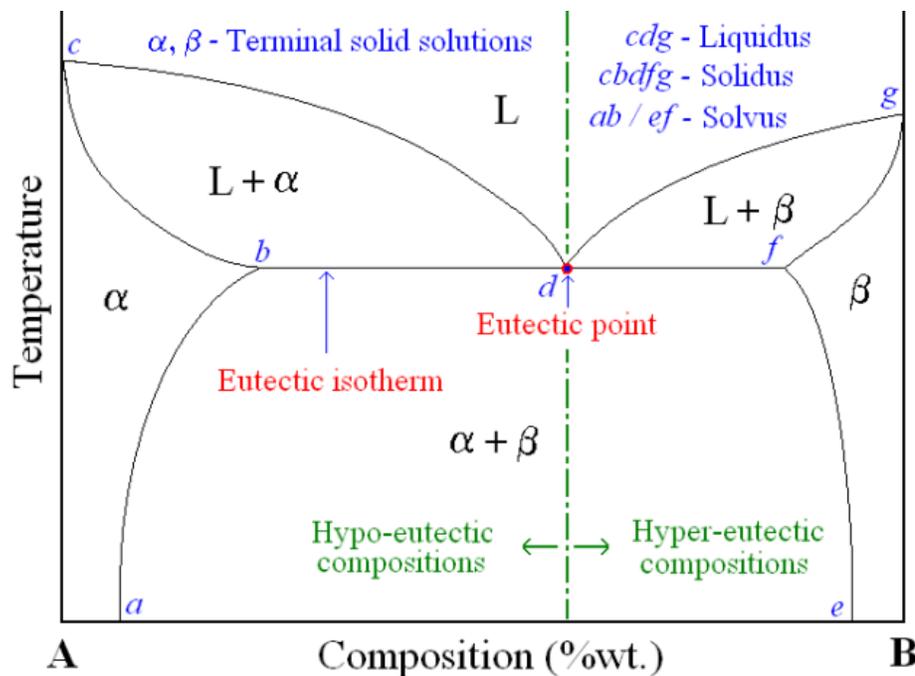
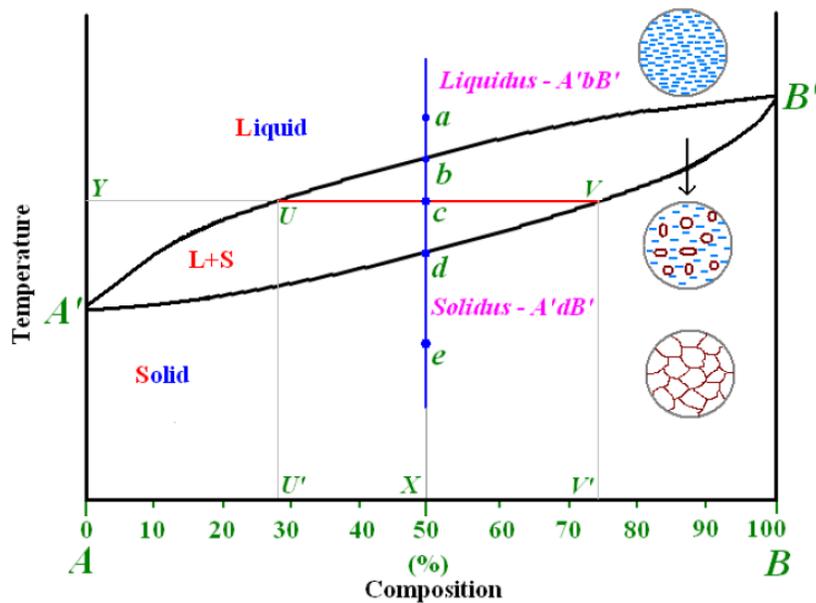
Equilibrium phase diagram

- ✓ A diagram that depicts existence of different phases of a system under equilibrium is termed as phase diagram.
- ✓ It is actually a collection of solubility limit curves. It is also known as equilibrium or constitutional diagram.
- ✓ Equilibrium phase diagrams represent the relationships between temperature, compositions and the quantities of phases at equilibrium.
- ✓ These diagrams do not indicate the dynamics when one phase transforms into another.
- ✓ Phase diagrams are classified according to the number of component present in a particular system.

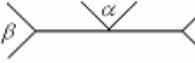
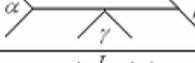
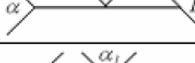
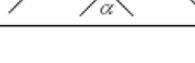
Binary phase diagram

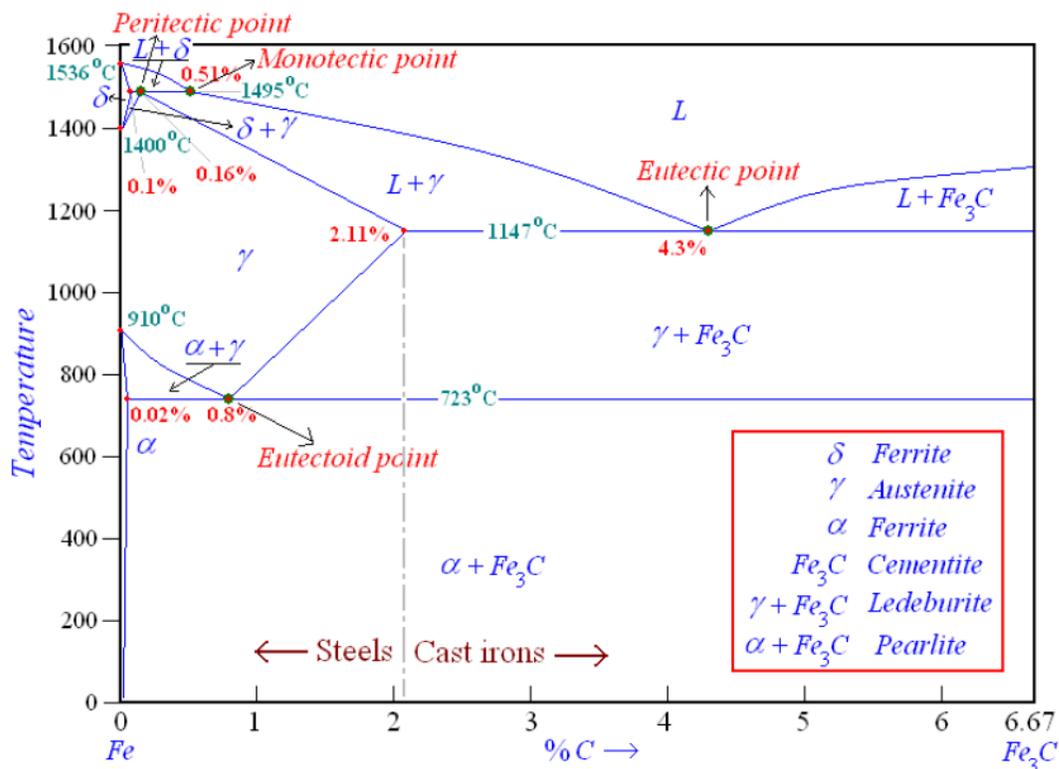
- ✓ If a system consists of two components, equilibrium of phases exist is depicted by binary phase diagram. For most systems, pressure is constant, thus independently variable parameters are – temperature and composition.

- ✓ Two components can be either two metals (Cu and Ni), or a metal and a compound (Fe and Fe₃C), or two compounds (Al₂O₃ and Si₂O₃), etc.
- ✓ Two component systems are classified based on extent of mutual solid solubility – (a) completely soluble in both liquid and solid phases (isomorphous system) and (b) completely soluble in liquid phase whereas solubility is limited in solid state.



Invariant reactions (contd....)

Reaction	Symbolic equation	Schematic presentation	Example
Eutectic	$L \rightarrow \alpha + \beta$		Fe-C, 4.27% C, 1147 C
Eutectoid	$\alpha \rightarrow \beta + \gamma$		Fe-C, 0.80% C, 723 C
Peritectic	$L + \alpha \rightarrow \beta$		Fe-C, 0.16% C, 1495 C
Peritectoid	$\alpha + \beta \rightarrow \gamma$		
Monotectic	$L_1 \rightarrow L_2 + \alpha$		Fe-C, 0.51% C, 1495 C
Monotectoid	$\alpha_1 \rightarrow \alpha_2 + \beta$		
Syntectic	$L_1 + L_2 \rightarrow \alpha$		



Ceramics

The word ceramic is derived from the greek term keramos, which means “potter’s clay” and keramikos means “clay products”. Till 1950s, the most important types of ceramics were the traditional clays, made into pottery, bricks, tiles etc. Ceramic art effects play an important role in historical understanding of the technology and culture of the people who lived many years ago.

A ceramic material is an inorganic, non-metallic material and is often crystalline. Traditional ceramics are basically clays. The earliest application was in pottery. Most recently, different types of ceramics used are alumina, silicon carbide etc. Latest advancements are in the bio-ceramics with examples being dental implants and synthetic bones.

A comparative analysis of ceramics with other engineering materials is shown in table 1. The purpose of presenting this comparative analysis is to show importance of ceramics among different engineering metals and polymers. This comparison would enable to justify application areas of ceramics.

Table 1 Comparison of ceramics with metals and polymers

Property	Ceramic	Metal	Polymer
Density	Low	High	Lowest
Hardness	Highest	Low	Lowest
Ductility	Low	High	High
Wear resistance	High	Low	Low
Corrosion resistance	High	Low	Low
Thermal conductivity	Mostly low	High	Low
Electrical conductivity	Mostly low	High	Low

Applications

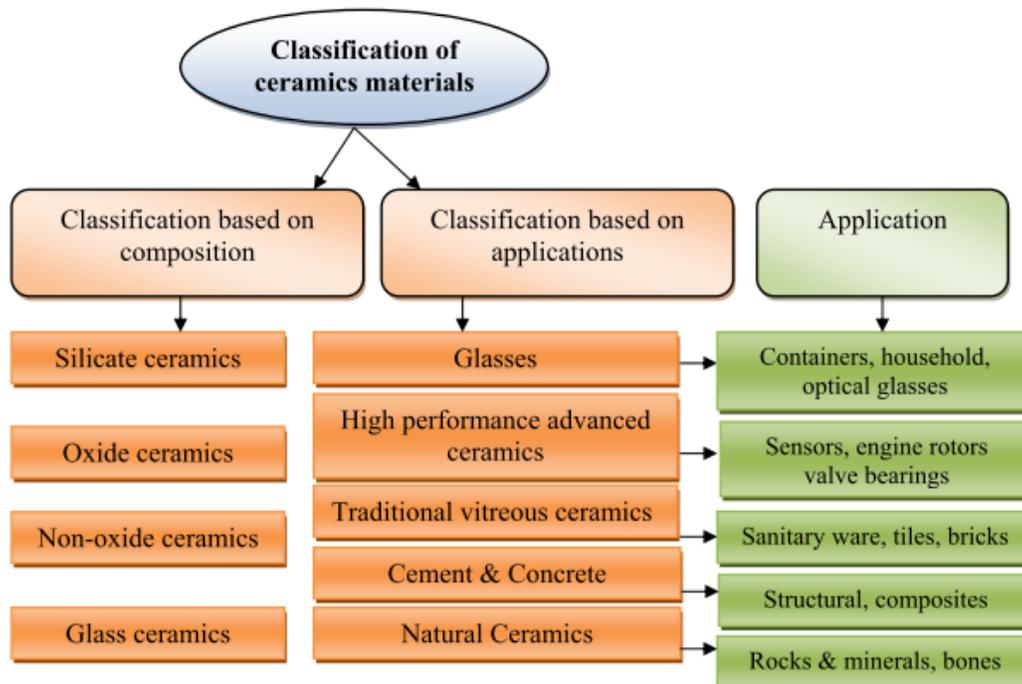
- ✚ Pottery products, sanitary ware, floor and roof tiles.
- ✚ Crucibles, kiln linings, other Refractories.
- ✚ High end applications such as in ceramic matrix composites, tiles in space shuttle, bullet proof jackets, disk brakes, ball bearing applications, bio-ceramics

Classification of ceramics materials

Ceramics can be classified in diverse ways i.e. there are number of ways to classify the ceramic materials. Most commonly, the ceramics can be classified on the following basis :

- Classification based on composition
- Classification based on applications

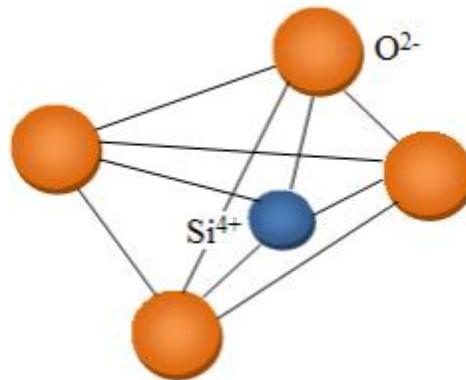
The detailed classification is shown in figure:



(i) Silicate ceramics

Silicates are materials generally having composition of silicon and oxygen four large oxygen (O) atoms surround each smaller silicon (Si) atom.

The main types of silicate ceramics are based either on alumosilicates or on magnesium silicates. Out of these two, the former include clay-based ceramics such as porcelain, earthenware, stoneware, bricks etc. while the latter consists of talc-based technical ceramics such as steatite, cordierite and forsterite ceramics. Silicate ceramics are traditionally categorized into coarse or fine and, according to water absorption, into dense (< 2 % for fine and < 6 % for coarse) or porous ceramics (> 2% and > 6 %, respectively).



(ii) Oxide ceramics

Oxide ceramics include alumina, zirconia, silica, magnesia and other metal oxide based materials. These are non-metallic and inorganic compounds by nature that include oxygen, carbon, or nitrogen. Oxide ceramics possess the following properties:

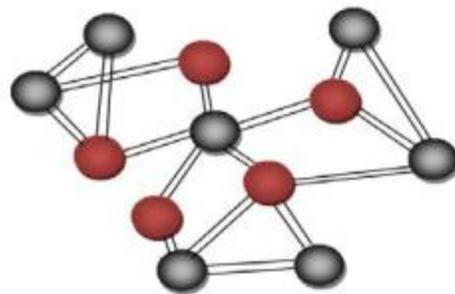
(a) High melting points

(b) Low wear resistance

(c) An extensive collection of electrical properties. These types of ceramics are available with a variety of special features. For example, **glazes** and protective coatings seal porosity, improved water or chemical resistance, and enhanced joining to metals or other materials.

Oxide ceramics are used in a wide range of applications, which include materials and chemical processing, radio frequency and microwave applications, electrical and high voltage power applications and foundry and metal processing.

Aluminum oxide (Al_2O_3) is the most important technical oxide ceramic material. This synthetically manufactured material consists of aluminum oxide ranging from 80 % to more than 99 %.



Structure of Al_2O_3

(iii) Glass ceramics

These are basically polycrystalline material manufactured through the controlled crystallization of base glass. Glass-ceramic materials share many common characteristics with both glasses and ceramics. Glass-ceramics possess an amorphous phase and more than one crystalline phases. These are produced by a controlled crystallization procedure. Glass-ceramics holds the processing advantage of glass and has special characteristics of ceramics.

Glass-ceramics yield an array of materials with interesting properties like zero porosity, fluorescence, high strength, toughness, low or even negative thermal expansion, opacity, pigmentation, high temperature stability, low dielectric constant, machinability, high chemical durability, biocompatibility, superconductivity, isolation capabilities and high resistivity. These properties can be altered by controlling composition and by controlled heat treatment of the base glass.

POLYMERS

Polymers form a very important class of materials without which the life seems very difficult. They are all around us in everyday use; in rubber, in plastic, in resins, and in adhesives and adhesives tapes. The word polymer is derived from greek words, poly= many and mers= parts or units of high molecular mass each molecule of which consist of a very large number of single structural units joined together in a regular manner. In other words polymers are giant molecules of high molecular weight, called macromolecules, which are build up by linking together of a large number of small molecules, called monomers. The reaction by which the monomers combine to form polymer is known as polymerization . The polymerization is a chemical reaction in which two or more substances combine together with or without evolution of anything like water, heat or any other solvents to form a molecule of high molecular weight. The product is called polymer and the starting material is called monomer.

CLASSIFICATION OF POLYMERS

Polymer can have different chemical structure, physical properties, mechanical behavior, thermal characteristics, etc., and on the basis of these properties polymer can be classified in different ways,

Basis of Classification	Polymer Type
Origin	- Natural, Semi synthetic, Synthetic
Thermal Response	- Thermoplastic, Thermosetting
Mode of formation	- Addition, Condensation
Line structure	- Linear, Branched, Cross-linked
Application and Physical Properties	- Rubber, Plastic, Fibers
Tacticity	- Isotactic, Syndiotactic, Atactic
Crystallinity	- Non crystalline(amorphous), Semi-crystalline, Crystalline
Polarity	- Polar, Non polar
Chain	- Hetro, Homo-chain

Natural polymer The polymers, which occur in nature are called natural polymer also known as biopolymers. Examples of such polymers are natural rubber, natural silk, cellulose, starch, proteins, etc..

Semi synthetic polymer They are the chemically modified natural polymers such as hydrogenated, natural rubber, cellulosic, cellulose nitrate, methyl cellulose, etc.

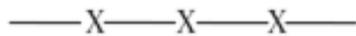
Synthetic polymer The polymer which has been synthesized in the laboratory is

known as synthetic polymer. These are also known as manmade polymers. Examples of such polymers are polyvinyl alcohol, polyethylene, polystyrene, polysulfone, etc.

Thermoplastic polymers They can be softened or plasticized repeatedly on application of thermal energy, without much change in properties if treated with certain precautions. Example of such polymers are Polyolefins, nylons, linear polyesters and polyethers, PVC, sealing wax etc..

Thermosetting polymers Some polymers undergo certain chemical changes on heating and convert themselves into an infusible mass. The curing or setting process involves chemical reaction leading to further growth and cross linking of the polymer chain molecules and producing giant molecules. For example, Phenolic, resins, urea, epoxy resins, diene rubbers, etc.

A. Linear polymer:- If the monomer units are joined in a linear fashion, polymer is said to be linear polymer.

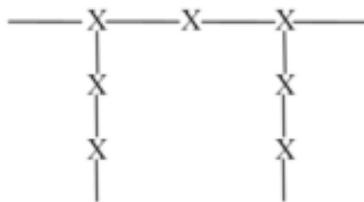


Linear Homopolymer

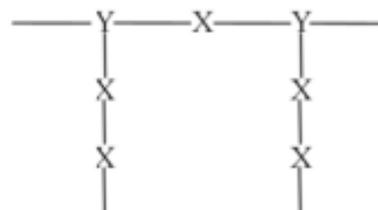


Linear Copolymer

B. Branched polymer:- When monomer units are joined in branched manner, it is called branched polymer.

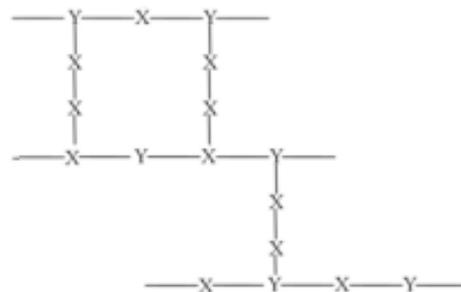
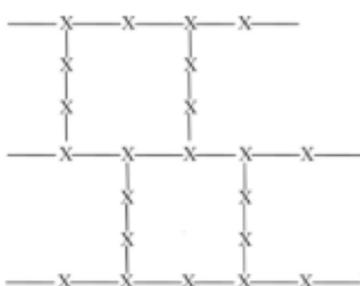


Branched Homopolymer



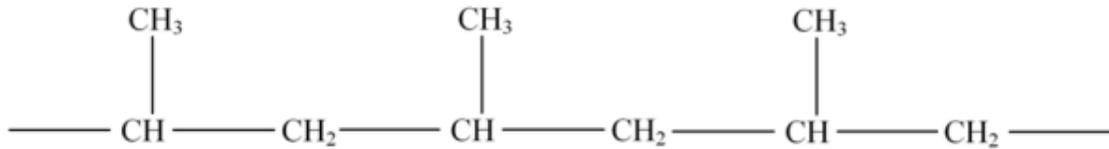
Branched Copolymer

C. Cross linked polymer:- A polymer is said to be a cross linked polymer, if the monomer units are joined together in a chain fashion.



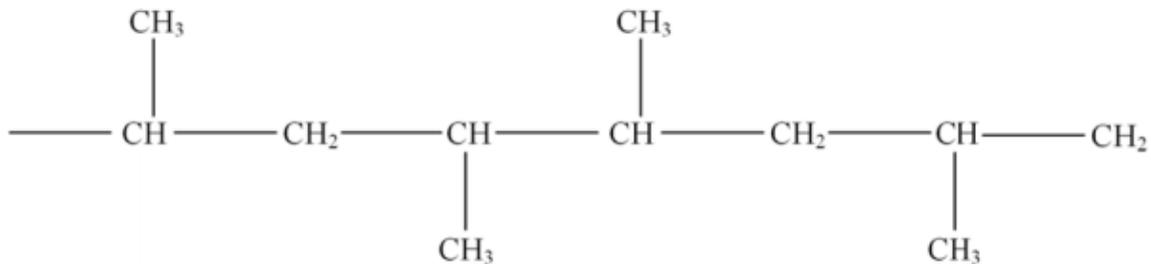
Tacticity

A. Isotactic polymer:- It is the type of polymer in which the characteristic group are arranged on the same side of the main chain.



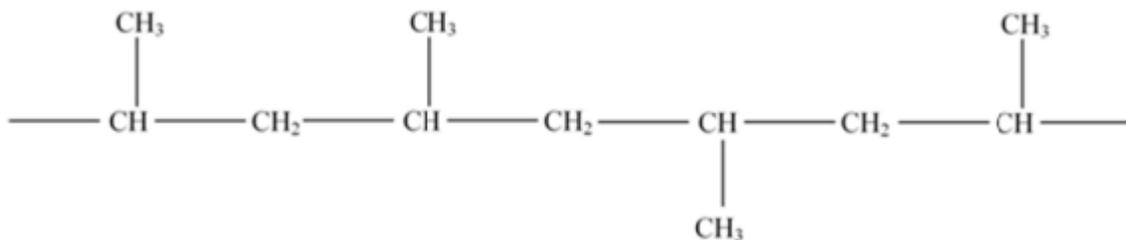
Isotactic Polypropene

B. Syndiotactic polymer:- A polymer is said to be syndiotactic if the side group (characteristic group) are arranged in an alternate fashion.



Syndiotactic Polypropene

C. Atactic polymer:- A polymer is said to be atactic, if the characteristic groups (side group) are arranged in irregular fashion (randomness) around the main chain. It has proper strength and more elasticity.

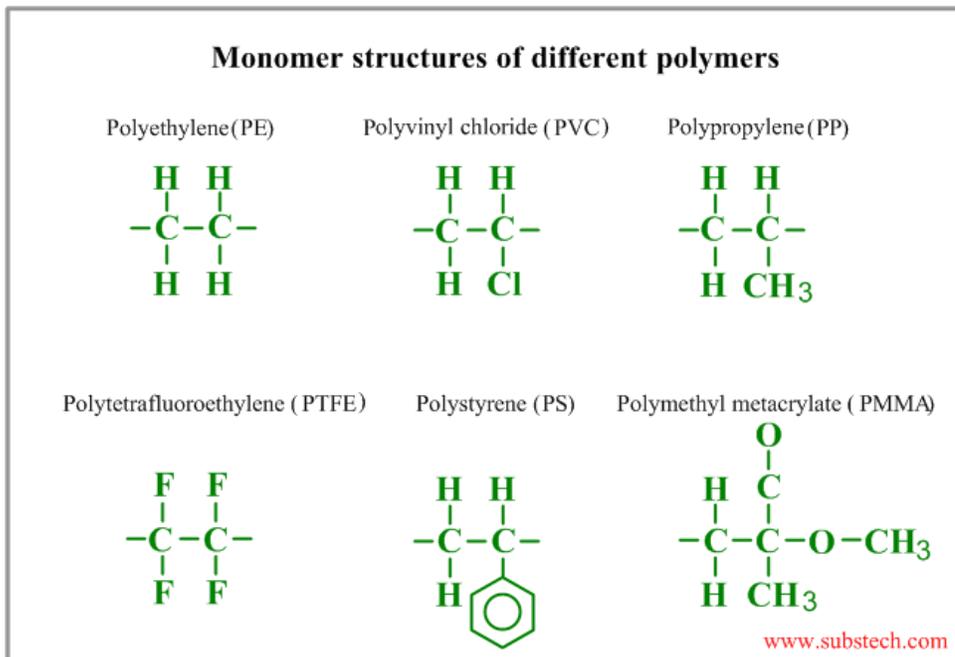


Condensation Polymerization or Step-growth Polymerization

Condensation Polymerization is a chemical reaction in which polymer is formed and a small molecule of by-product with a lower molecular weight is released. The by-product eliminated is called as condensate. The reaction can take place between two similar or different monomers. It is also called as step-growth polymerization.

Addition Polymerization or Chain Polymerization

In addition polymerization, two or more molecules of monomers attach together to form a polymer. In this polymerization, there is no elimination of any molecule. It is a chain reaction and no by product is released. It is obtained by linking together the monomer molecules by a chain reaction to give a polymer whose molecular weight is exactly an integral multiple of that of the monomer as in the case of polyethylene obtained by polymerization of ethylene. Only a single monomer is involved in addition polymerization and hence the polymer is homopolymer and contains the same monomer units. Addition polymerization reaction is usually induced by light, heat or a catalyst for opening the double bond of the monomer and creating the reactive sites.

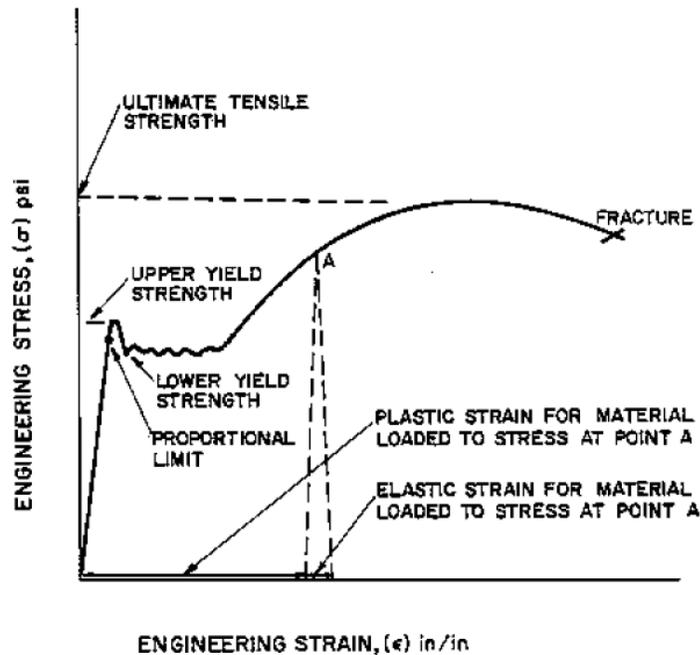


MECHANICAL PROPERTIES OF MATERIALS

Mechanical tests often involves the deformation or breakage of samples of material (called test specimens or test pieces).

1. Tension Test

The tension test is the commonly used test for determining "static" (actually quasi-static) properties of materials. The typical stress-strain curve normally observed in textbooks with some of the common nomenclature is shown in figure



$$\sigma = \frac{\text{Load}}{\text{Original Area}} = \frac{P}{A_0}$$

$$\epsilon = \frac{\text{Deformed length} - \text{Original length}}{\text{Original length}} = \frac{L - L_0}{L_0}$$

2- Hardness

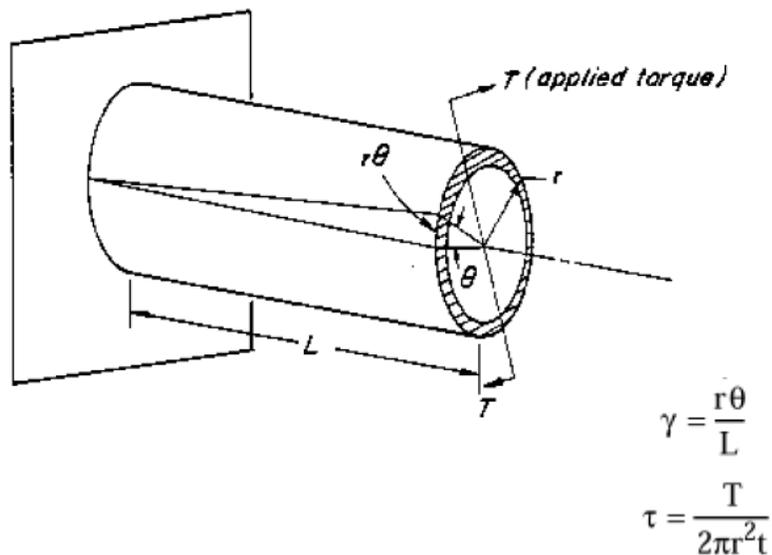
In the field of engineering, hardness is often defined as the resistance of a material to penetration.

Scratch tests commonly involve comparatively scratching progressively harder materials. In mineralogy, a Mohs hardness scale is used as shown in Fig. Diamond, the hardest material, is assigned a value of 10. Decreasing values are assigned to other minerals, down to 1 for the soft mineral, talc. Decimal fractions, such as 9.7 for tungsten carbide, are used for materials intermediate between the standard ones. Where a material lies on the Mohs scale is determined by a simple manual scratch test. If two materials are compared, the harder one is capable of scratching the softer one, but not vice versa. This allows materials to be ranked as to hardness, and decimal values between the standard ones are assigned as a matter of judgment.

Hardness		
	Vickers or Brinell	Mohs
	3000	10
Tantalum carbide	2000	Diamond
Alumina ceramics		9
Zircon ceramics	1000	Corundum
Polycrystalline glass		8
Manganese steels	500	Topaz
		7
Titanium	300	Quartz
		6
Carbon steels	200	Feldspar
		5
Aluminum	100	Apatite
		4
Magnesium	50	Fluorite
		3
	30	Calcite
	20	Gypsum
		2
		1
Hard lead alloys	10	Talc
Soft lead	5	
	3	
	2	

3- Torsion

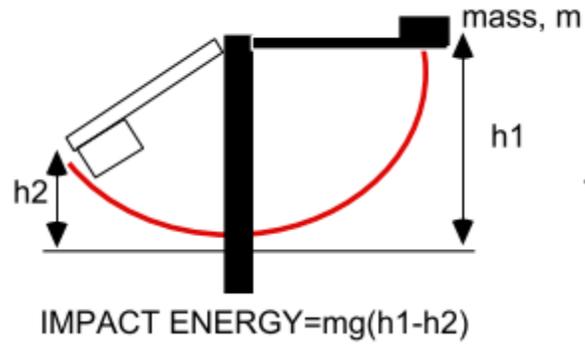
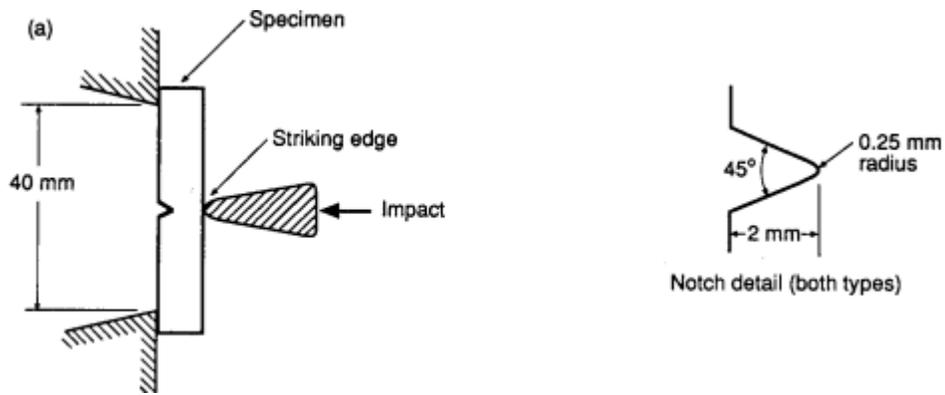
The torsion test is another fundamental technique for obtaining the stress-strain relationship for a metal. Because the shear stress and shear strain are obtained directly in the torsion test, rather than tensile stress and tensile strain as in the tension test, many investigators actually prefer this test to the tension test. Since all deformation of ductile materials is by shear, the torsion test would seem to be the more fundamental of the two.



4- Impact

The static properties of materials and their attendant mechanical behavior are very much functions of factors such as the heat treatment the material may have received as well as design factors such as stress concentrations.

The behavior of a material is also dependent on the rate at which the load is applied.



Part II

Corrosion

Corrosion: is the destruction of a material due to electrochemical attack from the environment.

4 to 5% of the Gross National Product (GNP)

In USA, this amount is about \$400 billion/yr

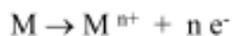
Corrosion depends on:

- chemicals present
- type of material (metal, ceramic, polymer)
- temperature
- exposure time
- stress etc

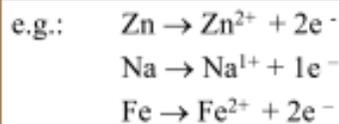
Corrosion of metals takes place through oxidation - reduction process where: oxidation - reduction processes take place and metal atoms lose electrons (become ions) and go into solution.

OXIDATION REACTION (occurs at the anode) - Corrosion (dissolving)

Metals → Ions



i.e. Metal anode dissolves.



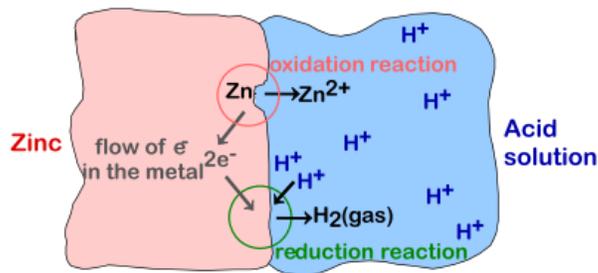
REDUCTION reactions (occur at the cathode - Cathodic Reaction), these depend on what is available:

- ✓ If H^+ ions are available then: $2H^+ + 2e^- \rightarrow H_2$
- ✓ If acid solution with dissolved oxygen: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
- ✓ If basic/neutral with dissolved oxygen: $O_2 + 2H_2O + 4e^- \rightarrow 4(OH^-)$

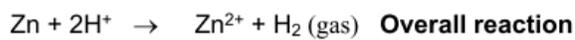
CORROSION OF ZINC IN ACID

• Two reactions are necessary:

- ✓ **oxidation** reaction: $Zn \rightarrow Zn^{2+} + 2e^-$ Reaction
- ✓ **reduction** reaction: $2H^+ + 2e^- \rightarrow H_2 \uparrow (gas)$ Reaction



Added together:



Electrochemical cell

- The anode gives up electrons to the circuit and corrodes.
- The cathode receives electrons from the circuit by means of a chemical or cathode reaction.
- The anode and cathode must be electrically connected (usually by physical contact).
- A liquid electrolyte must be in contact with the anode and cathode to complete the circuit and allow movement of ions.

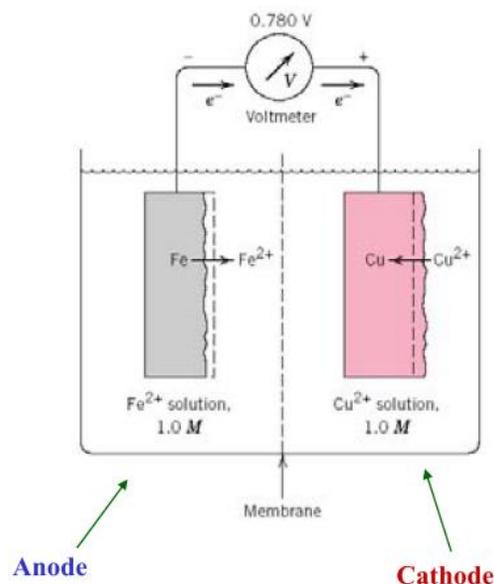


Table 18.1 The Standard emf Series

	Electrode Reaction	Standard Electrode Potential, V° (V)
	$Au^{3+} + 3e^{-} \rightleftharpoons Au$	+1.420
	$O_2 + 4H^{+} + 4e^{-} \rightleftharpoons 2H_2O$	+1.229
	$Pt^{2+} + 2e^{-} \rightleftharpoons Pt$	+1.2
	$Ag^{+} + e^{-} \rightleftharpoons Ag$	+0.800
	$Fe^{3+} + e^{-} \rightleftharpoons Fe^{2+}$	+0.771
	$O_2 + 2H_2O + 4e^{-} \rightleftharpoons 4(OH^{-})$	+0.401
	$Cu^{2+} + 2e^{-} \rightleftharpoons Cu$	+0.340
	$2H^{+} + 2e^{-} \rightleftharpoons H_2$	0.000
	$Pb^{2+} + 2e^{-} \rightleftharpoons Pb$	-0.126
	$Sn^{2+} + 2e^{-} \rightleftharpoons Sn$	-0.136
	$Ni^{2+} + 2e^{-} \rightleftharpoons Ni$	-0.250
	$Co^{2+} + 2e^{-} \rightleftharpoons Co$	-0.277
	$Cd^{2+} + 2e^{-} \rightleftharpoons Cd$	-0.403
	$Fe^{2+} + 2e^{-} \rightleftharpoons Fe$	-0.440
	$Cr^{3+} + 3e^{-} \rightleftharpoons Cr$	-0.744
	$Zn^{2+} + 2e^{-} \rightleftharpoons Zn$	-0.763
	$Al^{3+} + 3e^{-} \rightleftharpoons Al$	-1.662
	$Mg^{2+} + 2e^{-} \rightleftharpoons Mg$	-2.363
	$Na^{+} + e^{-} \rightleftharpoons Na$	-2.714
	$K^{+} + e^{-} \rightleftharpoons K$	-2.924

↑
Increasingly inert
(cathodic)

↓
Increasingly active
(anodic)

Corrosion can be classified in different ways, such as

- Chemical and electrochemical
- High temperature and low temperature
- Wet corrosion and dry corrosion.

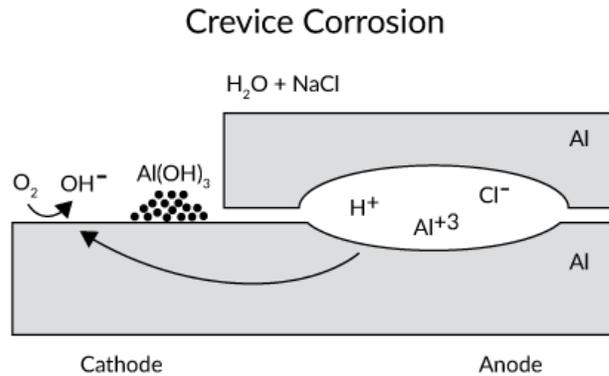
The most important types are

- Uniform corrosion .
- Galvanic corrosion, concentration cells, water line attack
- Pitting .
- Dezincification, Dealloying (selective leaching (
- Atmospheric corrosion .
- Erosion corrosion
- Fretting
- Crevice corrosion; cavitation
- Stress corrosion, intergranular and transgranular corrosion, hydrogen cracking and embrittlement
- Corrosion fatigue.

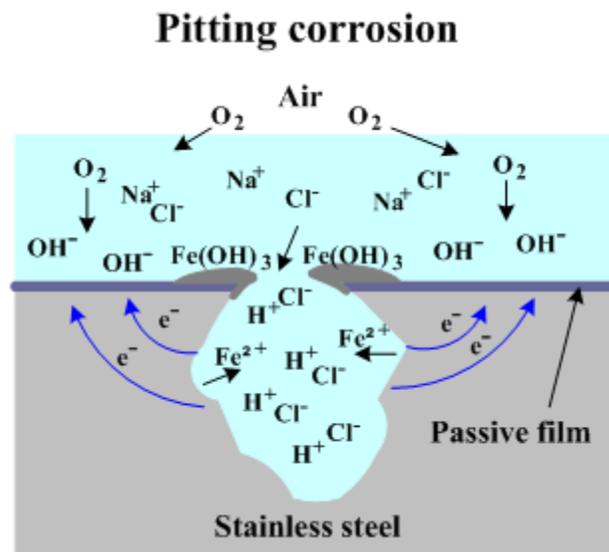
Crevice corrosion is a localized attack on a metal adjacent to the crevice between two joining surfaces (two metals or metal-nonmetal crevices). The corrosion is generally confined to one localized area to one metal. This type of corrosion can be initiated by concentration gradients (due to ions or oxygen). Accumulation of chlorides inside crevice will aggravate damage.

Various factors influence crevice corrosion, such as .

- Materials: alloy composition, metallographic structure .
- Environmental conditions such as pH, oxygen concentration, halide
- concentrations, temperature .
- Geometrical features of crevices, surface roughness .
- Metal to metal or metal to nonmetal type.



Pitting corrosion is a localized phenomenon confined to smaller areas. Formation of micro-pits can be very damaging. Pitting factor (ratio of deepest pit to average penetration) can be used to evaluate severity of pitting corrosion which is usually observed in passive metals and alloys. Concentration cells involving oxygen gradients or ion gradients can initiate pitting through generation of anodic and cathodic areas. Chloride ions are damaging to the passive films and can make pit formation auto-catalytic. Pitting tendency can be predicted through measurement of pitting potentials. Similarly critical pitting temperature is also a useful parameter.



Uniform corrosion is a very common form found in ferrous metals and alloys that are not protected by surface coating or inhibitors. A uniform layer of "rust" on the surface is formed when exposed to corrosive environments Atmospheric corrosion is a typical example of this type.

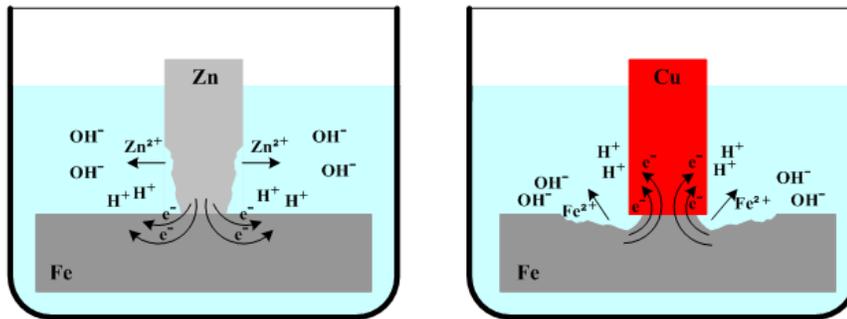
Thickness is reduced uniformly



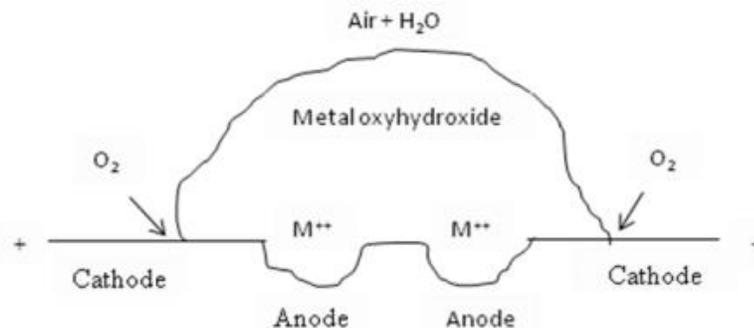
Uniform Corrosion

Galvanic corrosion often referred to as dissimilar metal corrosion occurs in galvanic couples where the active one corrodes. EMF series (thermodynamic) and galvanic series (kinetic) could be used for prediction of this type of corrosion. Galvanic corrosion can occur in multiphase alloys.

Galvanic corrosion



Differential aeration (oxygen concentration cell) and ion concentration (salt concentration) cells create dissimilar polarities (anodic and cathodic areas)

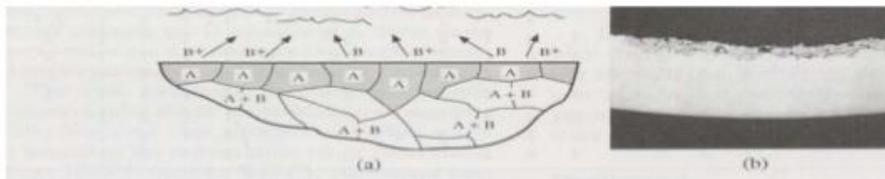


Selective leaching (Dealloying) refers to selective dissolution of active metal phase from an alloy in a corrosive environment.



Dealloying:

- When one element in an alloy is anodic to the other element.
- Example: Removal of zinc from brass (called dezincification) leaves spongy, weak brass.
- Brass alloy of zinc and copper and zinc is anodic to copper (see galvanic series).



Applications of ceramic

1. **Knife blades:** blade of a [ceramic knife](#) will stay sharp for much longer than that of a steel knife, although it is more brittle and susceptible to breaking.
2. **[Carbon-ceramic brake disks:](#)** for vehicles are resistant to [brake fade](#) at high temperatures.
3. "**[Advanced composite ceramic and metal matrices](#)**" have been designed for most modern [armoured fighting vehicles](#) because they offer superior penetrating resistance against [shaped charges](#) ([HEAT](#) rounds) and [kinetic energy penetrators](#).
4. "**Ceramics such as [alumina](#) and [boron carbide](#)**" have been used in [ballistic armored vests](#) to repel high-velocity [rifle](#) fire. Such plates are known commonly as [small arms protective inserts](#), or SAPIs. Similar material is used to protect the [cockpits](#) of some military airplanes, because of the low weight of the material.
5. Ceramics can be used in place of steel for **[ball bearings](#)**. Their higher hardness means they are much less susceptible to wear and typically last for triple the lifetime of a steel part. They also deform less under load, meaning they have less contact with the bearing retainer walls and can roll faster. In very high-speed applications, heat from [friction](#) during rolling can cause problems for metal bearings, which are reduced by the use of ceramics. Ceramics are

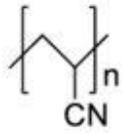
also more chemically resistant and can be used in wet environments where steel bearings would rust. In some cases, their electricity-insulating properties may also be valuable in bearings. Two drawbacks to ceramic bearings are a significantly higher cost and susceptibility to damage under shock loads.

6. In the early 1980s, [Toyota](#) researched production of an [adiabatic engine](#) using ceramic components in the hot gas area. The ceramics would have allowed temperatures of over 1650°C. The expected advantages would have been lighter materials and a smaller cooling system (or no need for one at all), leading to a major weight reduction. The expected increase of [fuel efficiency](#) of the engine (caused by the higher temperature, as shown by [Carnot's](#) theorem) could not be verified experimentally; it was found that the heat transfer on the hot ceramic cylinder walls was higher than the transfer to a cooler metal wall as the cooler gas film on the metal surface works as a [thermal insulator](#). Thus, despite all of these desirable properties, such engines have not succeeded in production because of costs for the ceramic components and the limited advantages. (Small imperfections in the ceramic material with its low [fracture toughness](#) lead to cracks, which can lead to potentially dangerous equipment failure.) Such engines are possible in laboratory settings, but mass production is not feasible with current technology.

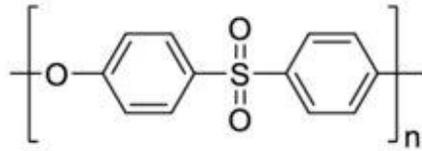
7. Work is being done in developing ceramic parts for [gas turbine engines](#). Currently, even blades made of [advanced metal alloys](#) used in the engines' hot section require cooling and careful limiting of operating temperatures. Turbine engines made with ceramics could operate more efficiently, giving aircraft greater range and payload for a set amount of fuel.
8. Recent advances have been made in ceramics which include [bioceramics](#), such as dental implants and synthetic bones. [Hydroxyapatite](#), the natural mineral component of bone, has been made synthetically from several biological and chemical sources and can be formed into ceramic materials. Orthopedic implants coated with these materials bond readily to bone and other tissues in the body without rejection or inflammatory reactions so are of great interest for gene delivery and [tissue engineering](#) scaffolds. Most hydroxyapatite ceramics are very porous and lack mechanical strength, and are used to coat metal orthopedic devices to aid in forming a bond to bone or as bone fillers. They are also used as fillers for orthopedic plastic screws to aid in reducing inflammation and increase the absorption of these plastic materials. Work is being done to make strong, fully dense nano crystalline hydroxyapatite ceramic materials for orthopedic weight bearing devices, replacing foreign metal and plastic orthopedic materials with a synthetic, but naturally occurring bone

mineral. Ultimately, these ceramic materials may be used as bone replacements or with the incorporation of protein [collagens](#), synthetic bones.

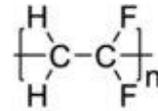
9. Durable actinide-containing ceramic materials have many applications such as in nuclear fuels for burning excess Pu and in chemically-inert sources of alpha irradiation for power supply of unmanned space vehicles or to produce electricity for microelectronic devices. Both use and disposal of radioactive actinides require their immobilization in a durable host material. Nuclear waste long-lived radionuclides such as actinides are immobilized using chemically-durable crystalline materials based on polycrystalline ceramics and large single crystals.
10. High-tech ceramic is used in watchmaking for producing watch cases. The material is valued by watchmakers for its lightweight, scratch resistance, durability, and smooth touch. [IWC](#) is one of the brands that initiated the use of ceramic in watchmaking.



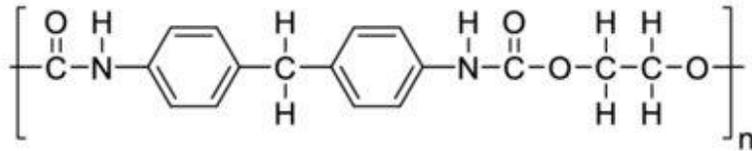
Polyacrylonitrile



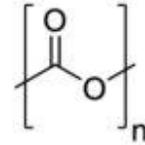
Polyethersulfone



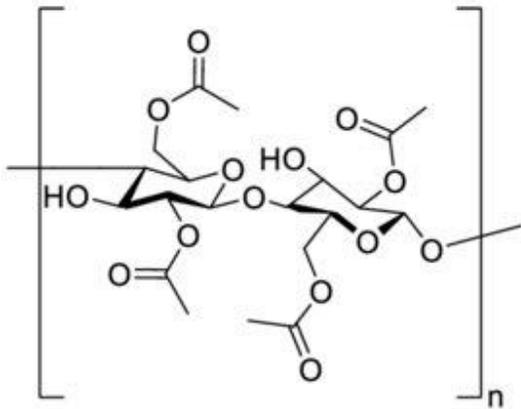
Polyvinylidene fluoride



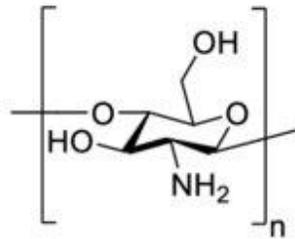
Polyurethane



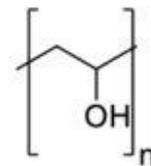
Polyester



Cellulose Acetate



Chitosan

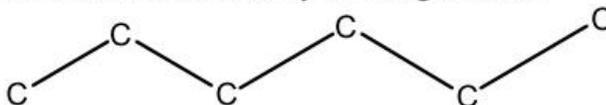


Polyvinyl alcohol

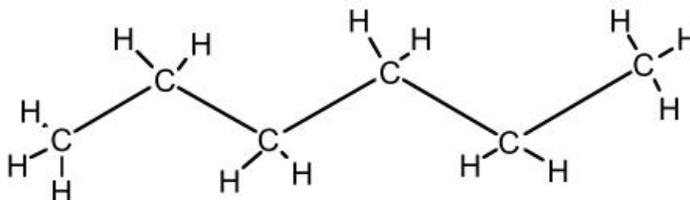
polyethylene



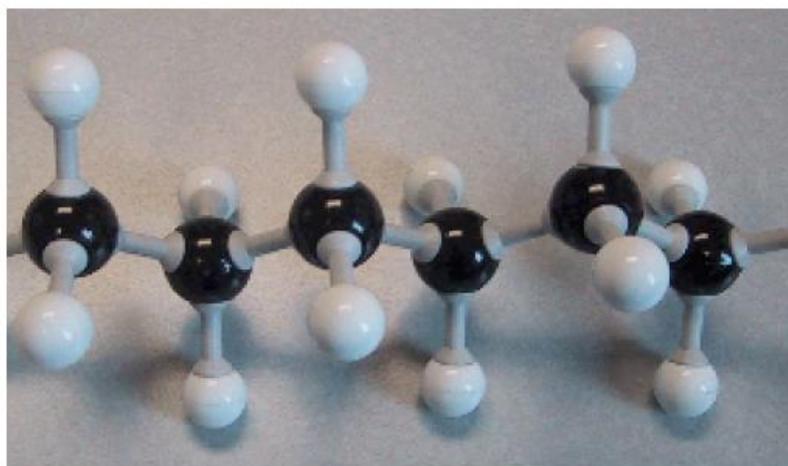
It is possible to figure out the missing information. There should be a carbon atom at the end of each line segment; six are needed, connected by five single bonds.



Since each carbon atom must have four bonds in a molecule, there must be missing bonds to hydrogen atoms. For the carbon atoms on the ends of the molecule, adding three C-H bonds to each will achieve octets. Two C-H bonds should be added to each of the inner carbons.



complete Lewis structure for polyethylene fragment



three dimensional model of polyethylene

Degree of Polymerization and Molecular Weight:

The degree of polymerization (DP)_n in a polymer molecule is defined as the number of repeating units in the polymer chain. For example,



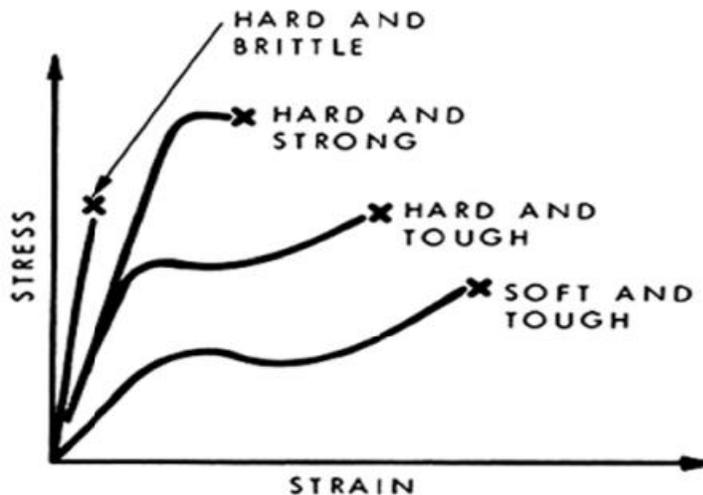
Glass Transition Temperature

In the study of polymers and their applications, it is important to understand the concept of the glass transition temperature T_g. The glass transition is a phenomenon observed in linear amorphous polymer. It occurs at fairly well defined temperature when the bulk material ceases to be brittle and glassy in character and become less rigid and more rubbery. The knowledge of T_g is essential in the selection of materials for various applications. Many Physical properties change profoundly at the glass transition temperature, including mechanical properties and electrical properties. All of these are dependent on the relative degree of freedom for molecular motion within a given polymeric material and each can be used to monitor the point at which the glass transition occurs.

MECHANICAL PROPERTIES OF POLYMERS

Polymers can exhibit the features of glassy, brittle solid or an elastic rubber, or that of a viscous liquid, depending on the temperature and time scale of measurement. The studies on mechanical properties of polymer can, therefore, be carried out by subjecting them to some form of mechanical stress either continuous or in a periodic manner at different rate. Some of the important properties of polymers with regard to their use as engineering material are tensile strength, compressive and flexural strength, hardness, creep, fatigue resistance and impact resistance.

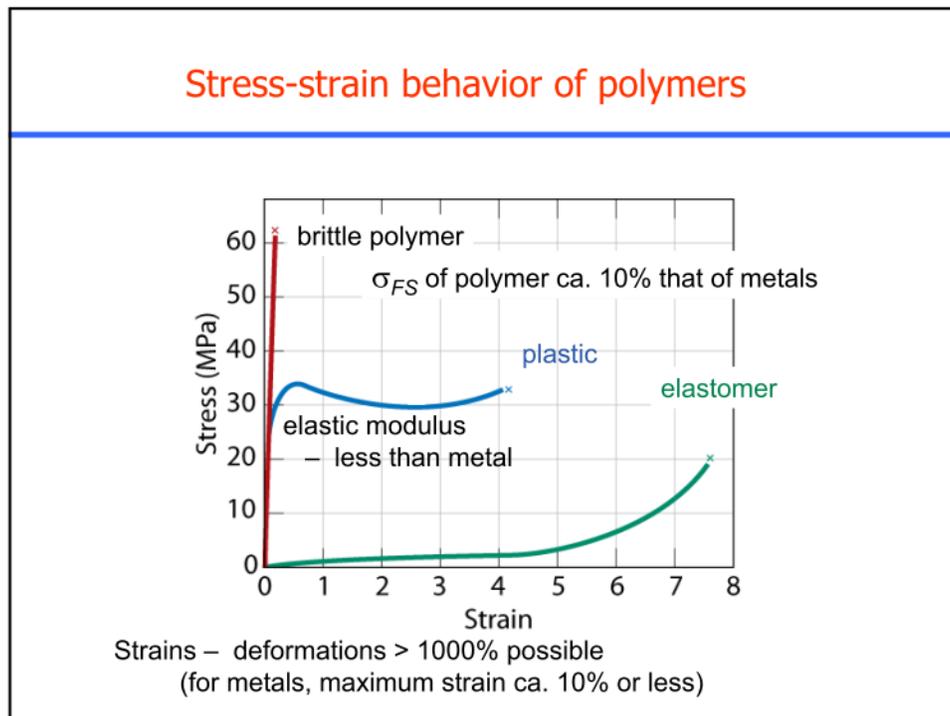
A hard, brittle material such as an amorphous polymer far below its T_g , usually has an initial slope indicative of very high modulus, moderate strength, a low elongation at break, and a low area under the stress-strain curve



Tensile stress-strain curves for four types of polymeric material.

Polymeric materials showing hard brittle behavior at room temperature or below are polystyrene, poly (methyl methacrylate) and many phenol-formaldehyde resins.

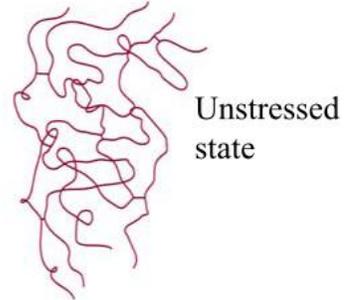
Impact strength is a measure of toughness or resistance to breakage under highvelocity impact conditions. From this point of view, polymeric materials under normal conditions of use are thought to be either brittle or tough. For example, polystyrene, poly(methyl methacrylate) and unmodified, non plasticized PVC are usually rated as brittle, breaking with a sharp fracture; plasticized PVC's are considered to be tough. In general, polymeric materials are either brittle or tough, depending on the temperature and rate of impact, i.e. rate of deformation. Impact strength of polymers and derived plastics depends on the position of the glass transition temperature (T_g) with respect to room temperature and ease of crystallization. Far below the glass-transition, amorphous polymers break with a brittle fracture, but they become tougher as the service temperature approaches T_g .. Above T_g , amorphous polymers are in a rubbery state .



Deformation of elastomers (cont.)

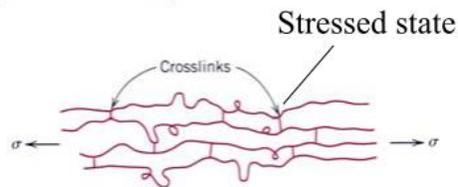
□ Polymeric structures

- amorphous, highly twisted, kinked and coiled
- free rotation of chain bonds



□ Deformation of elastomers

- rubberlike elasticity
- driving force for elastic deformation: entropy



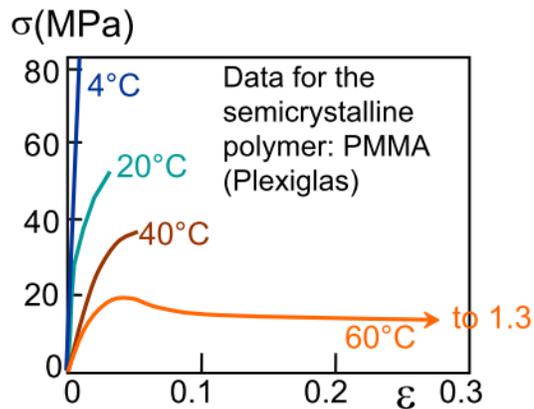
Effect of T and strain rate

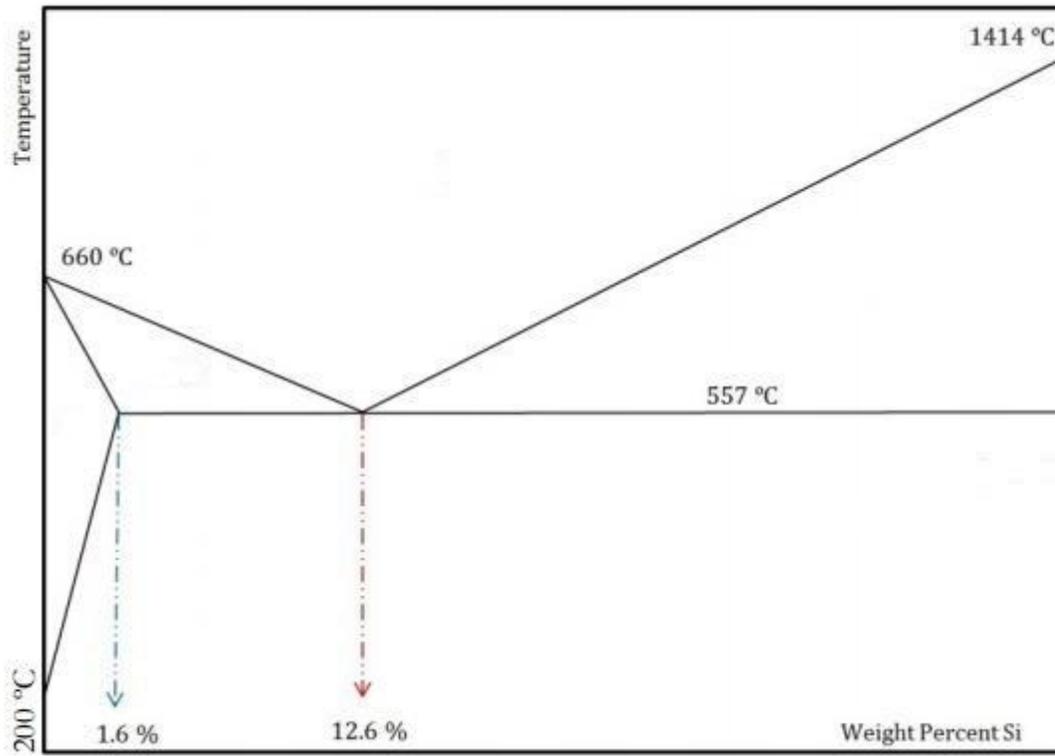
□ Decrease T

- increase E
- increase TS
- decrease ductility

□ Increase strain rate

- same effect as decreasing T





phase diagram of Al-Si.

