Contents

1) Historic perspective and Materials Science
2) Why study properties of materials, Classification of materials
3) Advanced materials, Future materials and Modern materials' needs

Historic perspective

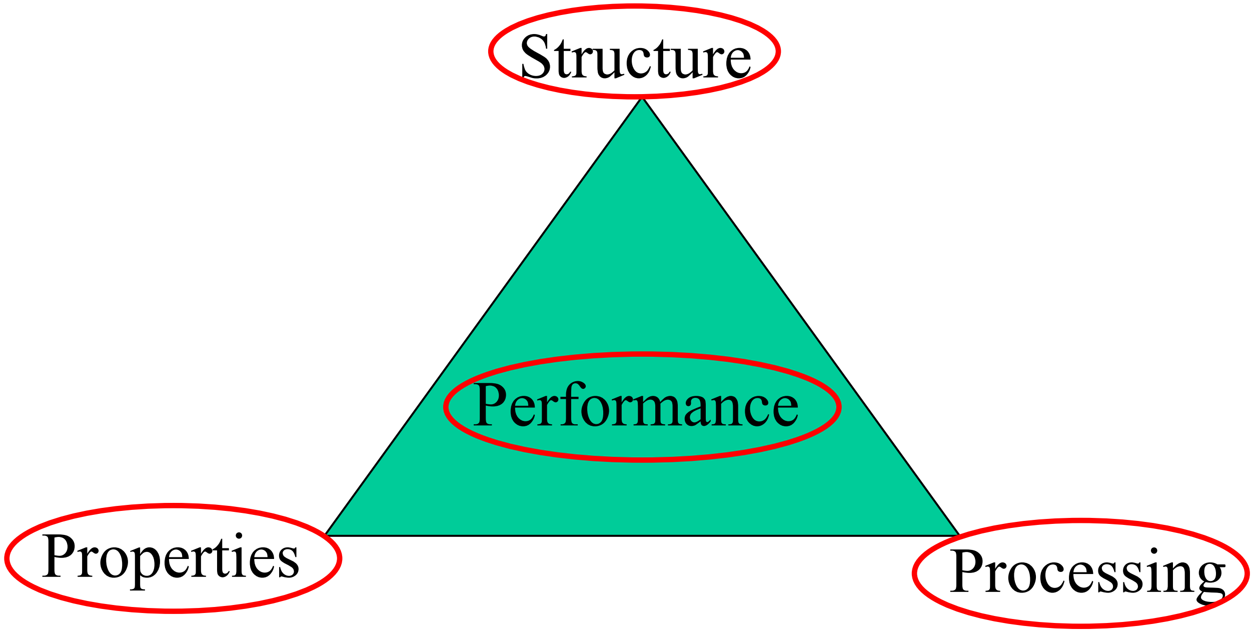
- Materials are very important in development of human civilization. In respect, their names are associated in history, e.g. stone age, Bronze age, Iron age, etc.

- With time humans discovered new materials and also techniques to produce known materials. This is an ongoing process for coming centuries, i.e. no end in sight!

Materials Science

- It can be defined as science dealing the relationships that exist between the structures and properties of materials, which are useful in practice of engineer's profession.

- Basic components and their interrelationship:



Structure

Performance

Properties

Processing

Properties of Materials

- All solid engineering materials are characterized for their properties.

- Engineering use of a material is reflection of its properties under conditions of use.

- All important properties can be grouped into six categories: Mechanical, Electrical, Thermal, Magnetic, Optical, and Deteriorative.

- Each material possess a structure, relevant properties, which dependent on processing and determines the performance.

Why Study Properties of Materials?

- Since there are thousands of materials available it is almost impossible to select a material for a specific task unless otherwise its properties are known.

- There are several criteria on which the final decision is based on.

- There are less chances of material possessing optimal or ideal combination of properties.

- A need to trade off between number of factors!

- The classic example involves strength and ductility:

- Normally material possessing strength have limited ductility.In such cases a reasonable compromise between two or more properties are important.

- A second selection consideration is any deterioration of material properties during service operations.

- Finally the overriding consideration is economics.

Classification of Materials

- Three basic groups of solid engineering materials based on atomic bonds and structures:

  Metals

  Ceramics

  Polymers

- Classification can also be done based on either properties (*mechanical, electrical, optical*), areas of applications (*structures, machines, devices*). Further we can subdivide these groups.

- According to the present engineering needs:

  Composites, Semiconductors, Biomaterials

Metals

- Characteristics are owed to non-localized electrons (metallic bond between atoms) i.e. electrons are not bound to a particular atom.
- They are characterized by their high thermal and electrical conductivities.
- They are opaque, can be polished to high lustre. The opacity and reflectivity of a metal arise from the response of the unbound electrons to electromagnetic vibrations at light frequencies.
- Relatively heavier, strong, yet deformable.

E.g.: Steel, Aluminium, Brass, Bronze, Lead, Titanium, etc.

Ceramics

- They contain both metallic and nonmetallic elements.
- Characterized by their higher resistance to high temperatures and harsh environments than metals and polymers.
- Typically good insulators to passage of both heat and electricity.
- Less dense than most metals and alloys.
- They are harder and stiffer, but brittle in nature.
- They are mostly oxides, nitrides, and carbides of metals.
- Wide range: traditional (*clay, silicate glass, cement*) to advanced (*carbides, pure oxides, non-silicate glasses*).

E.g.: Glass, Porcelain, Minerals, etc.

Polymers

- Commercially called *plastics*; noted for their low density, flexibility and use as insulators.
- Mostly are of organic compounds i.e. based on carbon, oxygen and other nonmetallic elements.
- Consists large molecular structures bonded by covalent and van der Waals forces.
- They decompose at relatively moderate temperatures (100-400 C).
- Application: packaging, textiles, biomedical devices, optical devices, household items, toys, etc.

E.g.: Nylon, Teflon, Rubber, Polyester, etc.

Composites

- Consist more than one kind of material; tailor made to benefit from combination of best characteristics of each constituent.
- Available over a very wide range: natural (*wood*) to synthetic (*fiberglass*).
- Many are composed of two phases; one is matrix – which is continuous and surrounds the other, dispersed phase.
- Classified into many groups: (1) depending on orientation of phases; such as particle reinforced, fiber reinforced, etc. (2) depending on matrix; metal matrix, polymer matrix, ceramic matrix.

E.g.: Cement concrete, Fiberglass, special purpose refractory bricks, plywood, etc.

Semiconductors

- Their electrical properties are intermediate when compared with electrical conductors and electrical insulators.
- These electrical characteristics are extremely sensitive to the presence of minute amounts of foreign atoms.
- Found very many applications in electronic devices over decades through integrated circuits. In can be said that semiconductors revolutionized the electronic industry for last few decades.

Biomaterials

- Those used for replacement of damaged or diseased body parts.
- Primary requirements: must be biocompatible with body tissues, must not produce toxic substances.
- Important materials factors: ability to support the forces, low friction and wear, density, reproducibility and cost.
- All the above materials can be used depending on the application.
- A classic example: hip joint.

E.g.: Stainless steel, Co-28Cr-6Mo, Ti-6Al-4V, ultra high molecular weight polyethelene, high purity dense Al-oxide, etc.

Advanced materials

- Can be defined as materials used in high-tech devices i.e. which operates based on relatively intricate and sophisticated principles (e.g. computers, air/space-crafts, electronic gadgets, etc.).
- These are either traditional materials with enhanced properties or newly developed materials with high-performance capabilities. Thus, these are relatively expensive.
- Typical applications: integrated circuits, lasers, LCDs, fiber optics, thermal protection for space shuttle, etc.

E.g.: Metallic foams, inter-metallic compounds, multi-component alloys, magnetic alloys, special ceramics and high temperature materials, etc.

Future materials

- Group of new and state-of-the-art materials now being developed, and expected to have significant influence on present-day technologies, especially in the fields of medicine, manufacturing and defense.
- Smart/Intelligent material system consists some type of sensor (*detects an input*) and an actuator (*performs responsive and adaptive function*).
- Actuators may be called upon to change shape, position, natural frequency, mechanical characteristics in response to changes in temperature, electric/magnetic fields, moisture, pH, etc.

Future materials (contd…)

- Four types of materials used as actuators:
  - Shape memory alloys
  - Piezoelectric ceramics
  - Magnetostrictive materials
  - Electro-/Magneto-rheological fluids

- Materials / Devices used as sensors:
  - Optical fibers
  - Piezoelectric materials
  - Micro-electro-mechanical systems (MEMS)
  - etc.

Future materials (contd…)

- Typical applications:

  - By incorporating sensors, actuators and chip processors into system, researchers are able to stimulate biological human-like behavior.

  - Fibers for bridges, buildings, and wood utility poles.

  - They also help in fast moving and accurate robot parts, high speed helicopter rotor blades.

  - Actuators that control chatter in precision machine tools.

  - Small microelectronic circuits in machines ranging from computers to photolithography prints.

  - Health monitoring detecting the success or failure of a product.

Modern materials' needs

- Engine efficiency increases at high temperatures; requires high temperature structural materials.
- Use of nuclear energy requires solving problems with residue, *or* advance in nuclear waste processing.
- Hypersonic flight requires materials that are light, strong and resist high temperatures.
- Optical communications require optical fibers that absorb light negligibly.
- Civil construction – materials for unbreakable windows.
- Structures: materials that are strong like metals and resist corrosion like plastics.

Contents

Atomic structure

- Every atom consists of a small nucleus composed of protons and neutrons, which is encircled by moving electrons in their *orbitals*, specific energy levels.
- In an atom, there will be always equal number of protons and electrons
- The top most orbital electrons, *valence electrons*, affect most material properties that are of interest to engineer. E.g.: chemical properties, nature of bonding, size of atom, optical/magnetic/electrical properties.
- Electrons and protons are negative and positive charges of the same magnitude being 1.60×10^{-19} coulombs.
- Neutrons are electrically neutral.
- Protons and neutrons have approximately the mass, 1.67×10^{-27} kg, which is larger than that of an electron, 9.11×10^{-31} kg.

Atomic structure (contd…)

- Atomic number (Z) - is the number of protons per atoms.
- Atomic mass (A) - is the sum of the masses of protons and neutrons within the nucleus.
- Atomic mass is measured in atomic mass unit (*amu*) where 1amu=(1\12) the mass of most common isotope of carbon atom, measured in grams.
- $A \simeq Z+N$, where N is number of neutrons.
- **Isotopes** - atoms with same atomic number but different atomic masses.
- A mole is the amount of matter that has a mass in grams equal to the atomic mass in *amu* of the atoms. Thus a mole of carbon has a mass of 12 grams.

Atomic structure (contd…)

- The number of atoms or molecules in a mole of substance is called the Avogadro's number, N_{ay}. N_{ay}=1gram/1amu = 6.023×10^{23}.

  E.g.: Calculating the number of atoms per cm^3, n, in a piece of material of density δ (g/cm^3)

  $n = N_{av} \times \delta / M$, where M is the atomic mass in *amu*.

  Thus, for graphite (carbon) with a density $\delta = 1.8$ g/cm^3 and $M = 12$, $n = 6.023 \times 10^{23}$ atoms/mol × 1.8 g/cm^3 / 12 g/mol) = 9×10^{22} atoms/cm^3.

- Most solid materials will have atomic density in the order of 6×10^{22}, that's about 39 million atoms per centimeter.
- Mean distance between atoms is in the range of 0.25 nm. It gives an idea about scale of atomic structures in solids.

Atomic Bonding in Solids

- Two questions need to be answered: why the atoms are clustered together?, and how they are arranged?

- Bonds are two kinds – Primary, and Secondary

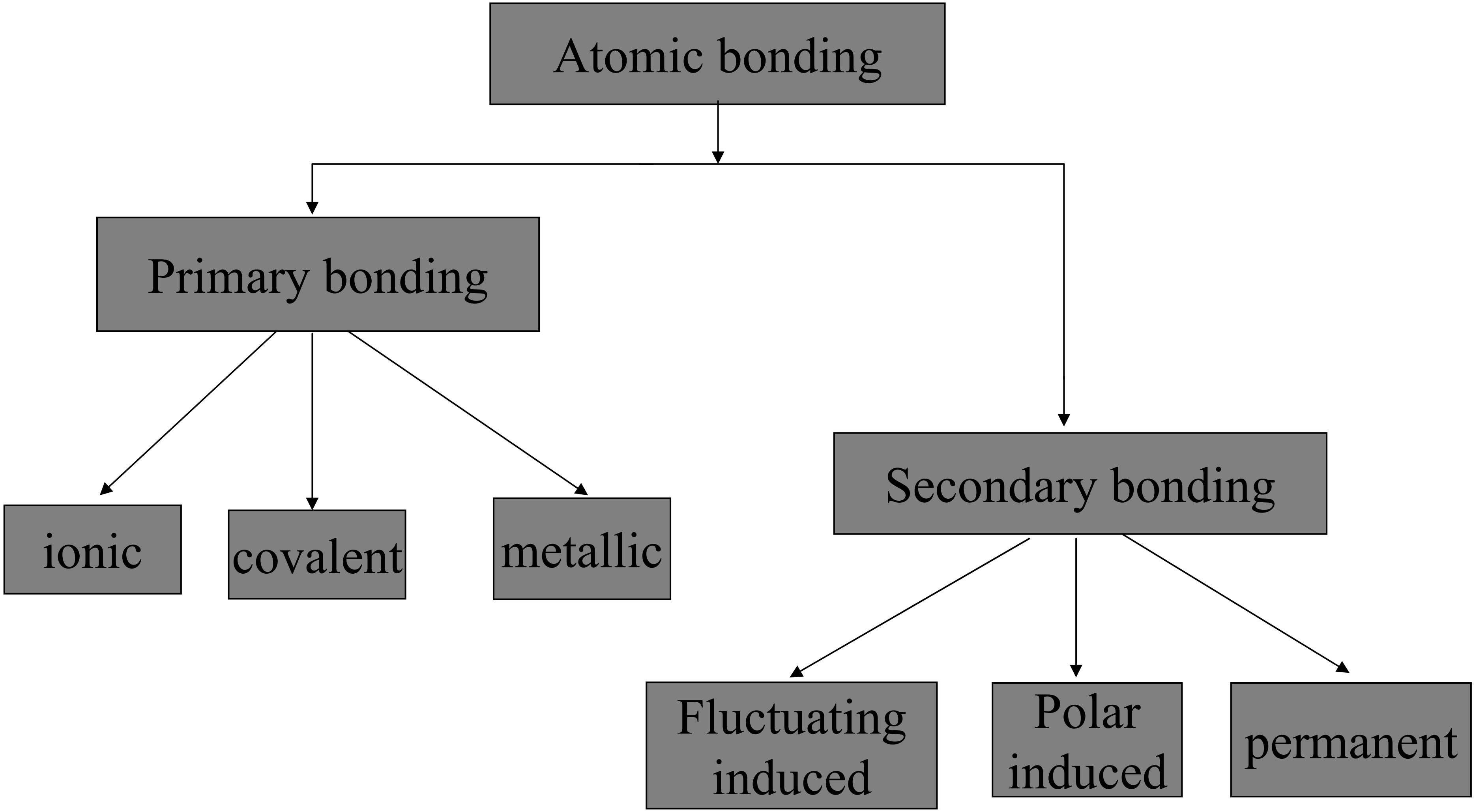
- Primary bonds – relatively stronger. Exists in almost all solid materials.

  E.g.: Ionic, Covalent, and Metallic bonds.

- Secondary bonds – relatively weaker bonds. Exists in many substances like water along with primary bonds.

  E.g.: Hydrogen, and van der Waals forces.

Atomic Bond in Solids



Atomic bonding

Primary bonding

ionic

covalent

metallic

Secondary bonding

Fluctuating induced

Polar induced

permanent

Primary inter-atomic bonds

- These bonds invariably involves valence electrons.
- Nature of bond depends on electron arrangement in respective atoms.
- Atoms tend to acquire stable electron arrangement in their valence orbitals by transferring (ionic), sharing (covalent, and metallic) valence electrons. This leads to formation of bonds.
- Bond energies are in order of 1000 kJ/mol.

Ionic bond

- This primary bond exists between two atoms when transfer of electron(s) results in one of the atoms to become negative (has an extra electron) and another positive (has lost an electron).
- This bond is a direct consequence of strong Coulomb attraction between charged atoms.
- Basically ionic bonds are non-directional in nature.
- In real solids, ionic bonding is usually exists along with covalent bonding.

E.g.: NaCl. In the molecule, there are more electrons around Cl, forming Cl^- and fewer electrons around Na, forming Na^+.

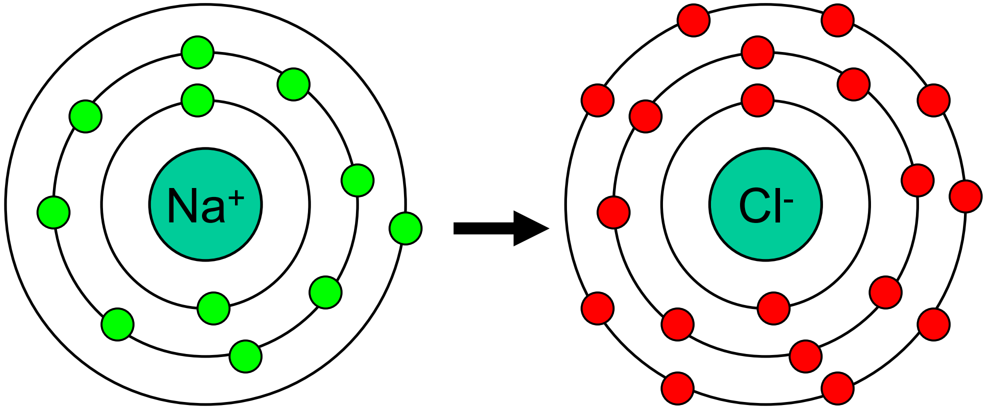


Fig.1 Schematic representation of ioning bonding.
Here, Na is giving an electron to Cl to have stable structure

Covalent bond

- This bond comes into existence if valence electrons are shared between a pair of atoms, thus acquire stability by saturating the valence configuration.
- Covalent bonds are stereospecific i.e. each bond is between a specific pair of atoms, which share a pair of electrons (of opposite magnetic spins).
- Typically, covalent bonds are very strong, and directional in nature.

E.g.: H_2 molecule, where an electron from each of the atom shared by the other atom, thus producing the covalent bond.

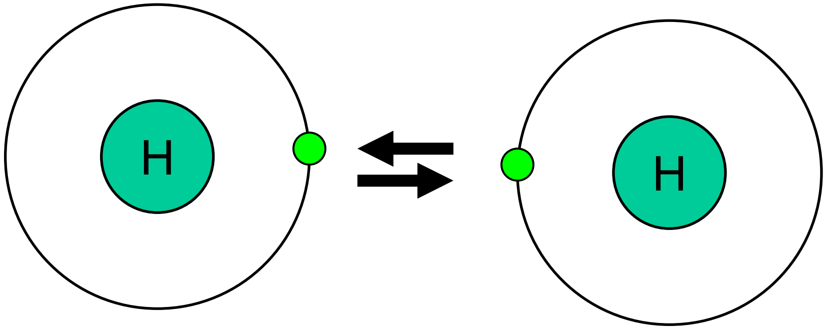
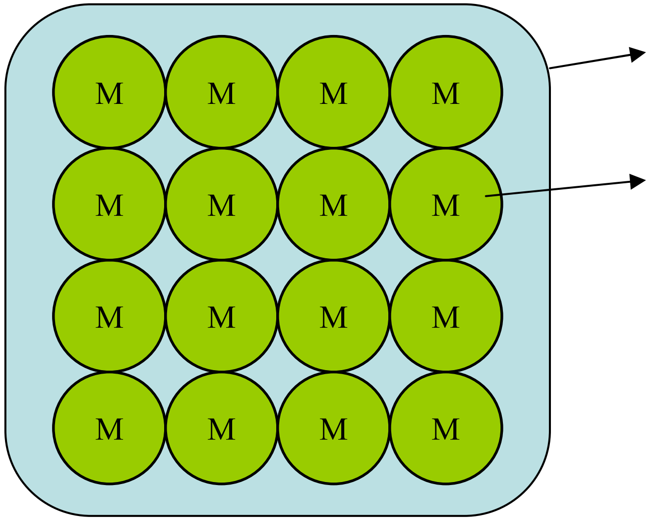


Figure 2. Schematic representation of covalent bond in Hydrogen molecule (sharing of electrons)

Metallic bond

- This bond comes into existence if valence electrons are shared between number of atoms, i.e. arranged positive nucleuses are surrounded by electron pool.
- Shared electrons are not specific to a pair of atoms, in contrast to Covalent bond, i.e. electrons are delocalized.
- As shared electrons are delocalized, metallic bonds are non-directional.
- Very characteristic properties of metals like high thermal and electrical conductivities are result of presence of delocalized electron pool.



Electron cloud from the valence electrons

Core

Figure 3. Metallic bonding

Secondary inter-atomic bonds

- These bonds involves atomic *or* molecular dipoles.

- Bonds can exists between induced and permanent dipoles (polar molecules).

- Bond comes into existence because of Columbic attraction between positive end of one dipole and negative end of another dipole.

- Bond energies are in order of 10 kJ/mol

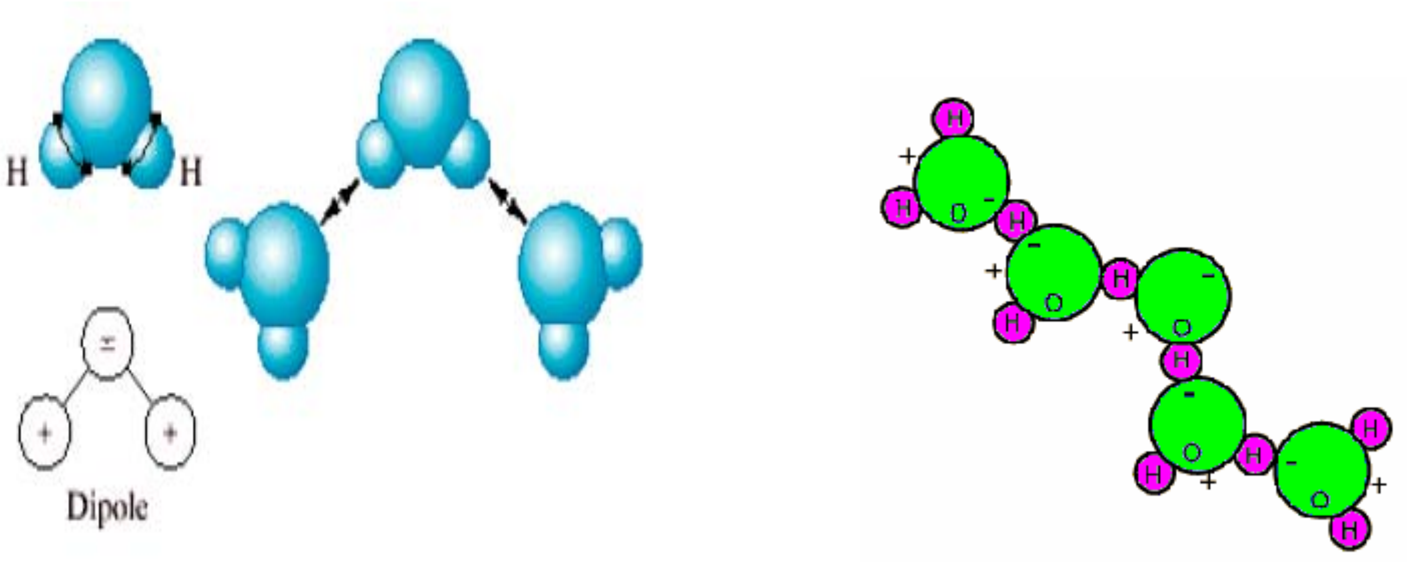


Figure 4. Dipole bonds in water

Secondary inter-atomic bonds (contd...)

- Existence of these depends on three kinds of dipoles – fluctuating dipoles, Polar-molecule dipoles and Permanent dipoles.

- Permanent dipole bonds are also called Hydrogen bonds as covalently bonded hydrogen atoms – for example C-H, O-H, F-H – share single electron becomes positively charged proton that is capable of strong attractive force with the negative end of an adjacent molecule.

- Hydrogen bonds is responsible for water to exist in liquid state at room temperature.

Crystal Structures

- All solid materials are made of atoms/molecules, which are arranged in specific order in some materials, called *crystalline solids*. Otherwise *non-crystalline* or *amorphous solids*.

- Groups of atoms/molecules specifically arranged – crystal.

- *Lattice* is used to represent a three-dimensional periodic array of points coinciding with atom positions.

- *Unit cell* is smallest repeatable entity that can be used to completely represent a crystal structure. It is the building block of crystal structure.

Unit cell

It is characterized by:

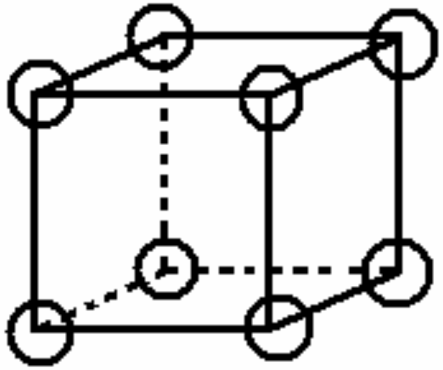
- Type of atom and their radii, *R*
- Cell dimensions (Lattice spacing a, b and c) in terms of *R* and
- Angle between the axis α, β, γ
- a*, b*, c* - lattice distances in reciprocal lattice , α*, β*, γ* - angles in reciprocal lattice
- Number of atoms per unit cell, *n*
- Coordination number (*CN*)– closest neighbors to an atom
- Atomic packing factor, *APF*

Most common unit cells – Face-centered cubic, Body-centered cubic and Hexagonal.

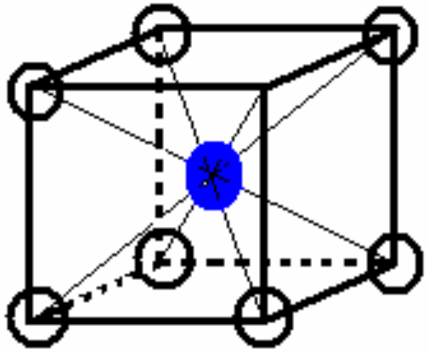
Common Crystal Structures

Unit Cell	n	CN	a/R	APF
Simple Cubic	1	6	$4/\sqrt{4}$	0.52
Body-Centered Cubic	2	8	$4/\sqrt{3}$	0.68
Face-Centered Cubic	4	12	$4/\sqrt{2}$	0.74
Hexagonal Close Packed	6	12		0.74

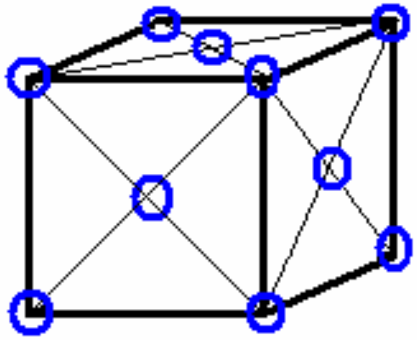
Schematic Unit Cells



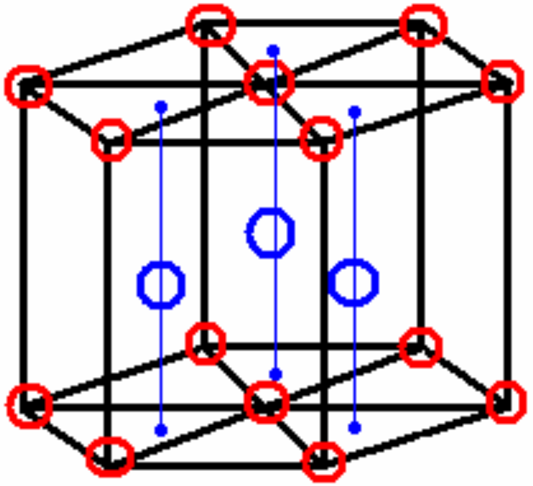
Simple Cubic



Body Centered Cubic



Face Centered Cubic



Hexagonal Close Packed

Miller indices

- A system of notation is required to identify particular direction(s) or plane(s) to characterize the arrangement of atoms in a unit cell
- Formulas involving Miller indices are very similar to related formulas from analytical geometry – simple to use
- Use of reciprocals avoids the complication of infinite intercepts
- Specifying dimensions in unit cell terms means that the same label can be applied to any plane with a similar stacking pattern, regardless of the crystal class of the crystal. Plane (111) always steps the same way regardless of crystal system

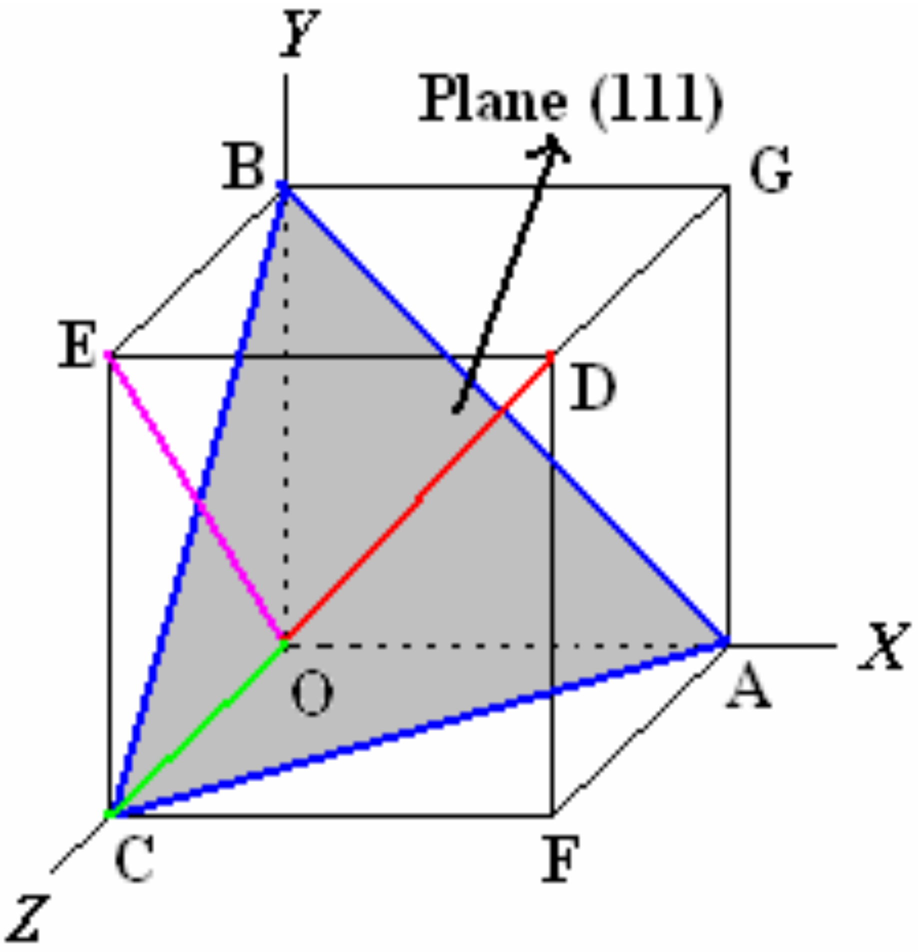
Miller indices - Direction

- A vector of convenient length is placed parallel to the required direction
- The length of the vector projection on each of three axes are measured *in terms of unit cell dimensions*
- These three numbers are made to smallest integer values, known as indices, by multiplying or dividing by a common factor
- The three indices are enclosed in square brackets, *[uvw]*.
- A family of directions is represented by <*uvw*>

Miller indices - Plane

- Determine the intercepts of the plane along the crystallographic axes, *in terms of unit cell dimensions*. If plane is passing through origin, there is a need to construct a plane parallel to original plane
- Take the reciprocals of these intercept numbers
- Clear fractions
- Reduce to set of smallest integers
- The three indices are enclosed in parenthesis, (hkl).
- A family of planes is represented by {hkl}

Miller indices - Examples



🟩 Direction [001]

🟪 Direction [011]

🟥 Direction [111]

Plane ACEG (101)

Plane OAGB (001)

Miller indices – Useful Conventions

- If a plane is parallel to an axis, its intercept is at infinity and its Miller index will be zero
- *Never alter negative numbers.* This implies symmetry that the crystal may not have! Use bar over the number to represent negative numbers.
- A plane or direction of family is not necessarily parallel to other planes or directions in the same family
- The smaller the Miller index, more nearly parallel the plane to that axis, and vice versa
- Multiplying or dividing a Miller index by constant has no effect on the orientation of the plane
- When the integers used in the Miller indices contain more than one digit, the indices must be separated by commas. E.g.: (3,10,13)

Useful Conventions for cubic crystals

- [*uvw*] is normal to (*hkl*) if *u* = *h*, *v* = *k*, and *w* = *l*. E.g.: (111) ┴ [111]
- [*uvw*] is parallel to (*hkl*) if *hu* + *kv* + *lw* = 0
- Two planes (*h1k1l1*) and (*h2k2l2*) are normal if *h1h2* + *k1k2* + *l1l2*=0
- Two directions (*u1v1w1*) and (*u2v2w2*) are normal if *u1u2* + *v1v2* + *w1w2*=0
- Inter-planar distance between family of planes {*hkl*} is given by:

$$d_{\{hkl\}} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

- Angle between two planes is given by:

$$\cos\theta = \frac{h_1h_2 + k_1k_2 + l_1l_2}{\sqrt{h_1^2 + k_1^2 + l_1^2}\sqrt{h_2^2 + k_2^2 + l_2^2}}$$

Miller-Bravis indices

- Miller indices can describe all possible planes/directions in any crystal.
- However, Miller-Bravis indices are used in hexagonal systems as they can reveal hexagonal symmetry more clearly
- Indices are based on four axes – three are coplanar on basal plane at 120° apart, fourth axis is perpendicular to basal plane
- Both for planes/directions, extra index is given by

$$t = -(u+v),\ i = -(h+k)$$

where plane is represented as $[uvtw]$, and a direction is represented by $(hkil)$

E.g.: Basal plane – (0001), Prismatic plane – $(10\bar{1}0)$

Polymers - definition

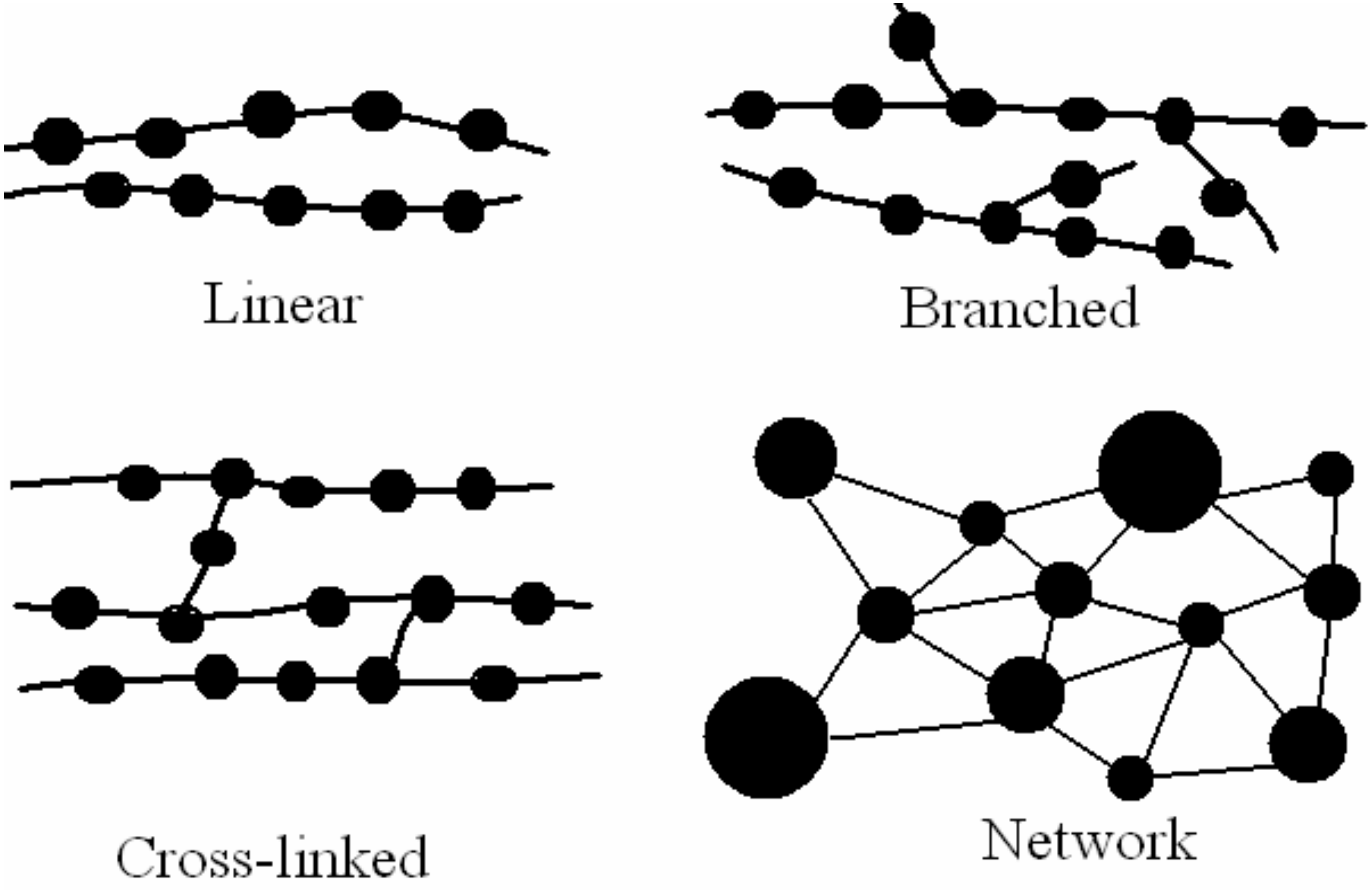
- Polymers are made of basic units called *mers*
- These are usually Hydrocarbons – where major constituent atoms are Hydrogen and Carbon
- When structure consists of only one *mer*, it is monomer. If it contains more than one *mer*, it is called polymer
- *Isomers* are molecules those contain same number of similar *mers* but arrangement will be different

  E.g.: Butene and Isobutene
- When a polumer has ONE kind of *mers* in its structure, it is called *homopolymer*
- Polymer made with more than one kind of *mers* is called *copolymer*

Polymer structures

- *Linear*, where mer units are joined together end to end in single chains. E.g.: PVC, nylon.
- *Branched*, where side-branch chains are connected to main ones. Branching of polymers lowers polymer density because of lower packing efficiency E.g.: Bakelite
- *Cross-linked*, where chains are joined one to another at various positions by covalent bonds. This cross-linking is usually achieved at elevated temperatures by additive atoms. E.g.: vulcanization of rubber
- *Network*, trifunctional mer units with 3-D networks comes under this category. E.g.: epoxies, phenol-formaldehyde.

Polymer structures



Schematic presentation of polymer structures.

Individual *mers* are represented by solid circles.

Thermo-sets – Thermo-plasts

- Polymers mechanical response at elevated temperatures strongly depends on their chain configuration
- Based on this response polymers are grouped in to two - thermo-sets and thermo-plasts
- *Thermo-sets*: become permanently hard when heated, and do not soften during next heat cycle. During first heating covalent bonds forms thus extensive cross-linking takes place. Stronger and harder than thermo-plasts.

  E.g.: Vulcanized rubber, epoxies, some polyester resins
- *Thermo-plasts*: softens at high temperatures, and becomes hard at ambient temperatures. The process is reversible. Usually made of linear and branched structures.

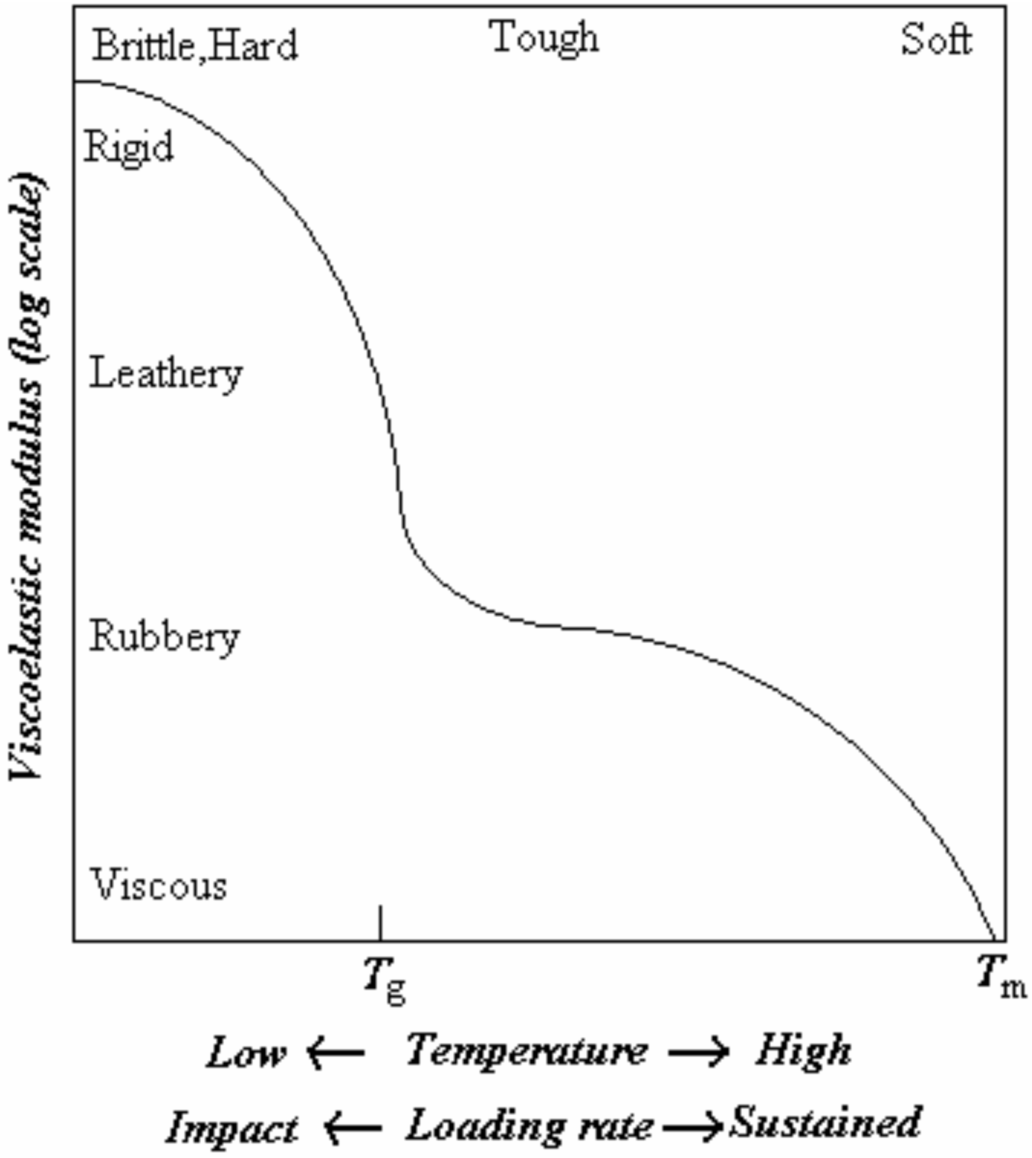
  E.g.: Polystyrene, Acrylics, Cellulosics, Vinyls

Polymer crystallinity

- Crystallinity in polymers is more complex than in metals
- Polymer crystallinity range from almost crystalline to amorphous in nature
- It depends on cooling path and on chain configuration
- Crystalline polymers are more denser than amorphous polymers
- Many semicrystalline polymers form *spherulites*. Each spherulite consists of collection of ribbon like chain folded lamellar crystallites.

E.g.: PVC (Poly Vinyl Chloride)

Polymer properties



Ceramics

- Ceramics are inorganic and non-metallic materials
- Atomic bonds in ceramics are mixed – covalent + ionic
- Proportion of bonds is specific for a ceramic
- Ionic bonds exists between alkalis/alkaline-earth metals and oxygen/halogens.
- Mostly oxides, carbides, nitrides of metals are ceramics

E.g.: Sand, Glass, Bricks, Marbles

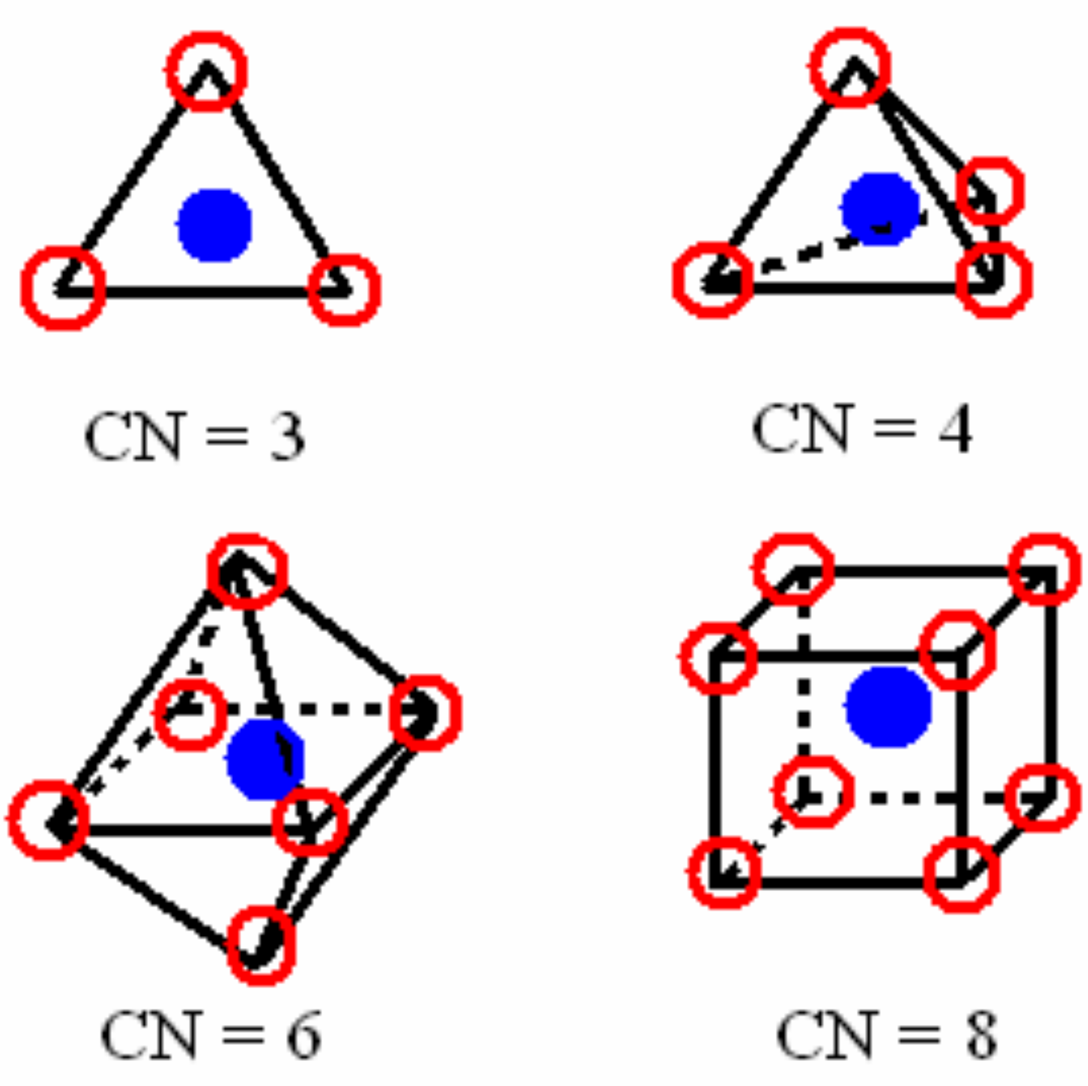
Ceramic structures

- Building criteria for ceramic structures:
  - - maintain neutrality
  - - closest packing

- Packing efficiency can be characterized by coordination number which depends on cation-anion radius ratio (r_c/r_a)

Cation-anion radius ratio (r_c/r_a)	$<$ 0.155	0.155 – 0.225	0.225 – 0.414	0.414 – 0.732	0.732 – 1.000	$>$ 1.000
Coordination number	2	3	4	6	8	12

Ion arrangement – Coordination numbers



Ceramic crystal structures

- AX-type: most common in ceramics. They assume different structures of varying coordination number (CN).

Rock salt structure – CN=6.	E.g.: NaCl, FeO
Cesium Chloride structure – CN=8	E.g.: CsCl
Zinc Blende structure – CN=4	E.g.: ZnS, SiC

- A_mX_p-type: number of anions and cations are different ($m \neq p$). One unit cell is made of eight cubes.

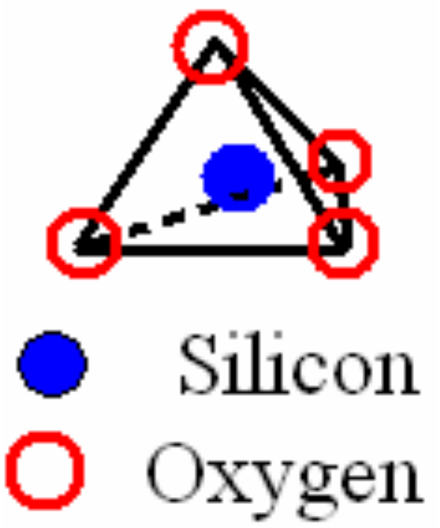
E.g.: CaF_2, ThO_2

- $A_mB_nX_p$-type: when ceramic contains more then one kind of cations. Also called *perovskite crystal structure*.

E.g.: $BaTiO_3$

Silicates

- Most common ceramic in nature – Silicates, as constituent elements – silicon and oxygen – are most abundant in earth's crust.
- Bond between Si^{4+} and O^{2-} is weak ionic and very strong covalent in nature. Thus, basic unit of silicates is SiO_4^{4-} tetrahedron.



Silicates (contd…)

- In Silica (SiO2), every oxygen atom the corner of the tetrahedron is shared by the adjacent tetrahedron.
- Silica can be both crystalline (quartz) and amorphous (glass)
- Crystalline forms of silica are complicated, and comparatively open…thus low in density compared with amorphous glasses
- Addition of network modifiers (Na2O) and intermediates (Al_2O_3, TiO_2)lowers the melting point…thus it is easy to form. E.g.: Bottles.
- In complicated silicates, corner oxygen is shared by other tetrahedra….thus consists SiO_4^{4-}, $Si_2O_7^{6-}$, $Si_3O_9^{6-}$ groups
- Clays comprises 2-D sheet layered structures made of $Si_2O_5^{2-}$

Carbon

- Carbon is not a ceramic, but its allotropic form - Diamond - is
- *Diamond*:

  C-C covalent bonds, highest known hardness, Semiconductor, high thermal conductivity, meta-stable
- *Graphite* - another allotropic form of carbon

  layered structure - hexagonal bonding within planar leyers, good electrical conductor, solid lubricant
- Another allotropic form - C_{60} - also called *Fullerene* / Bucky ball. Structure resembles hallow ball made of 20 hexagons and 12 pentagons where no two pentagons share a common edge.
- Fullerenes and related nanotubes are very strong, ductile - could be one of the important future engineering materials

Imperfections in ceramics

- Imperfections in ceramics – point defects, and impurities. Their formation is strongly affected by charge neutrality

- *Frenkel-defect* is a vacancy-interstitial pair of cations

- *Schottky-defect* is a pair of nearby cation and anion vacancies

- Impurities:

  Introduction of impurity atoms in the lattice is likely in conditions where the charge is maintained.

  E.g.: electronegative impurities that substitute lattice anions or electropositive substitutional impurities

Mechanical response of ceramics

- Engineering applications of ceramics are limited because of presence of microscopic flaws – generated during cooling stage of processing.
- However, as ceramics are high with hardness, ceramics are good structural materials under compressive loads.
- Plastic deformation of crystalline ceramics is limited by strong inter-atomic forces. Little plastic strain is accomplished by process of slip.
- Non-crystalline ceramics deform by viscous flow.
- Characteristic parameter of viscous flow – viscosity. Viscosity decreases with increasing temperature. However, at room temperature, viscosity of non-crystalline ceramics is very high.

Mechanical response of ceramics (contd…)

- *Hardness* – one best mechanical property of ceramics which is utilized in many application such as abrasives, grinding media
- Hardest materials known are ceramics
- Ceramics having Knoop hardness about 1000 or greater are used for their abrasive characteristics
- *Creep* – Ceramics experience creep deformation as a result of exposure to stresses at elevated temperatures.
- Modulus of elasticity, E, as a function of volume fraction of porosity, P: $E = E0\ (1-1.9\ P + 0.9\ P^2)$
- Porosity is deleterious to the flexural strength for two reasons:

  - reduces the cross-sectional area across where load is applied

  - act as stress concentrations

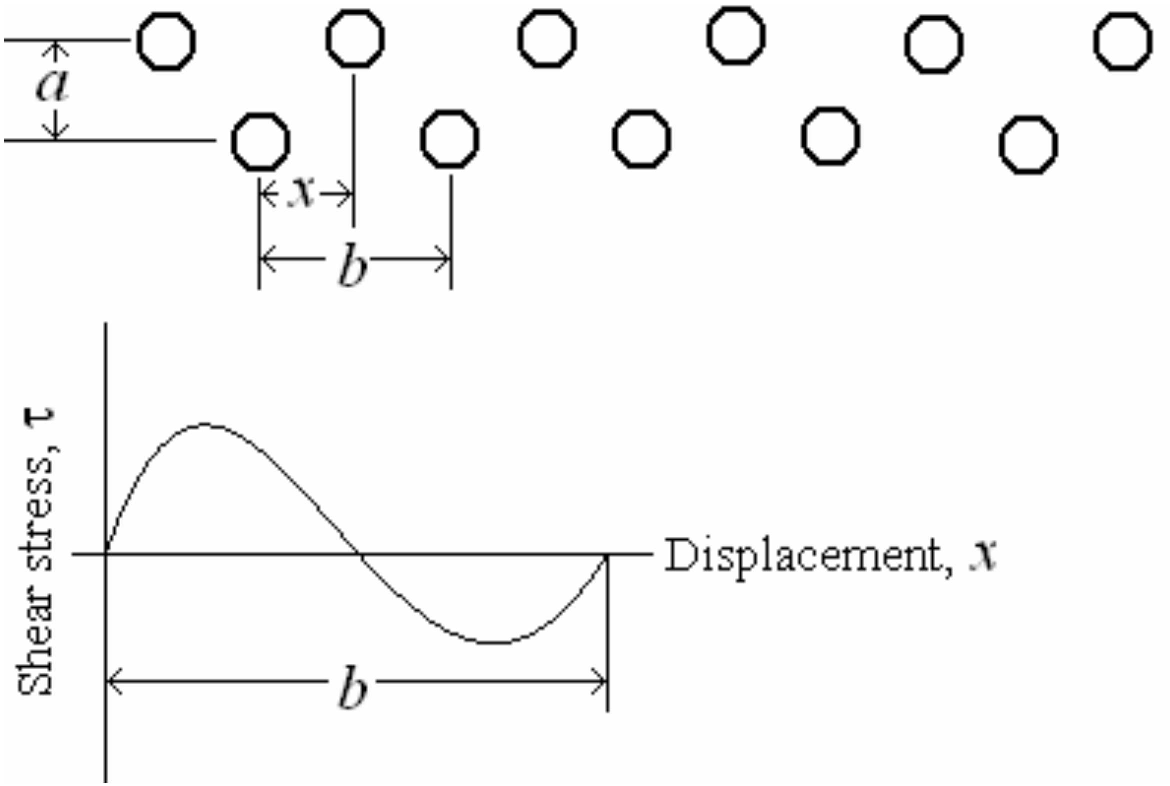
Contents

1) Theoretical yield strength, Point defects and Line defects or Dislocations

2) Interfacial defects, Bulk or Volume defects and Atomic vibrations

Theoretical yield strength

- Ideal solids are made of atoms arranged in orderly way.



Theoretical yield strength (contd…)

- Using a *sin* function to represent the variation in shear stress

$$\tau = \tau_m \sin \frac{2\Pi x}{b} \qquad \tau \approx \tau_m \frac{2\Pi x}{b} \qquad + \qquad \tau = G\gamma = \frac{Gx}{a}$$

(Hooke's law)

⇓

$$\tau_m = \frac{G}{2\Pi}\frac{b}{a}$$

If b≈a

$$\tau_m = \frac{G}{2\Pi}$$

G ≈ 20-150 GPa

⇒ Shear strength ≈ 3-30 GPa

(ideal)

Real strength values ≈ 0.5-10 MPa

Theoretical yield strength (contd…)

- Theoretical strength of solids shall possess an ideal value in the range of 3-30 GPa.

- Real values observed in practice are 0.5-10 MPa.

- The assumption of perfectly arranged atoms in a solid may not valid…..i.e. atomic order must have been disturbed.

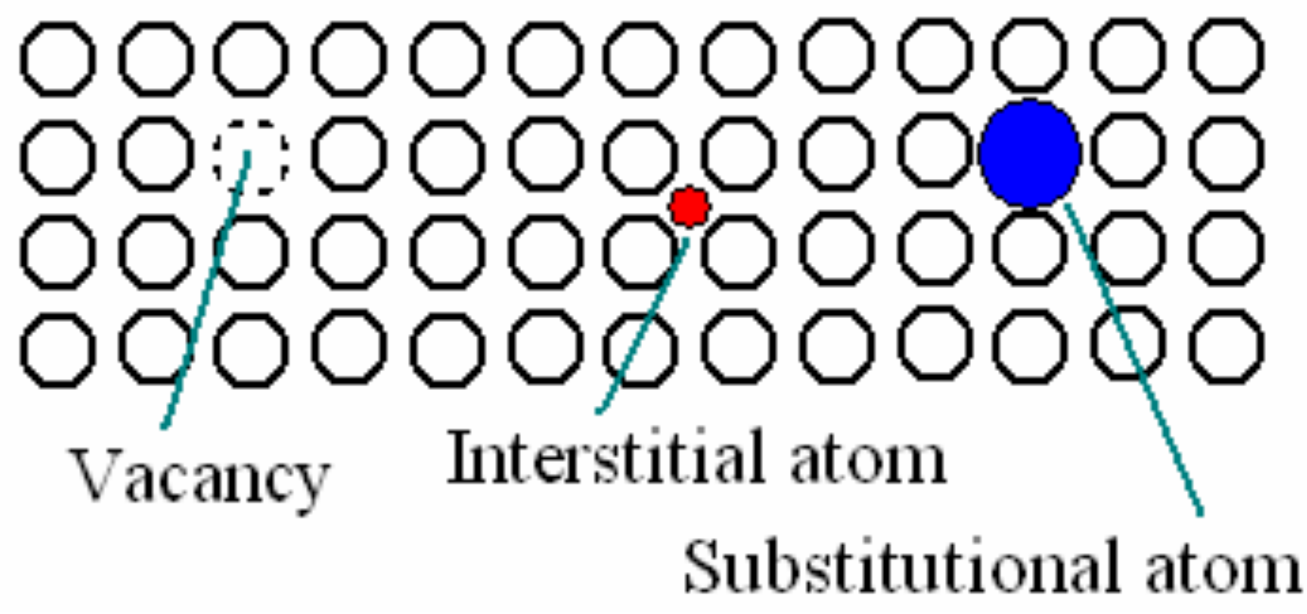
- Disordered atomic region is called *defect* or *imperfection*.

- Based on geometry, defects are: Point defects (zero-D), Line defects (1-D) *or* Dislocations, Interfacial defects (2-D) and Bulk *or* Volume defects (3-D).

Point defects

- Point defects are of zero-dimensional i.e. atomic disorder is restricted to point-like regions.

- Thermodynamically stable compared with other kind of defects.

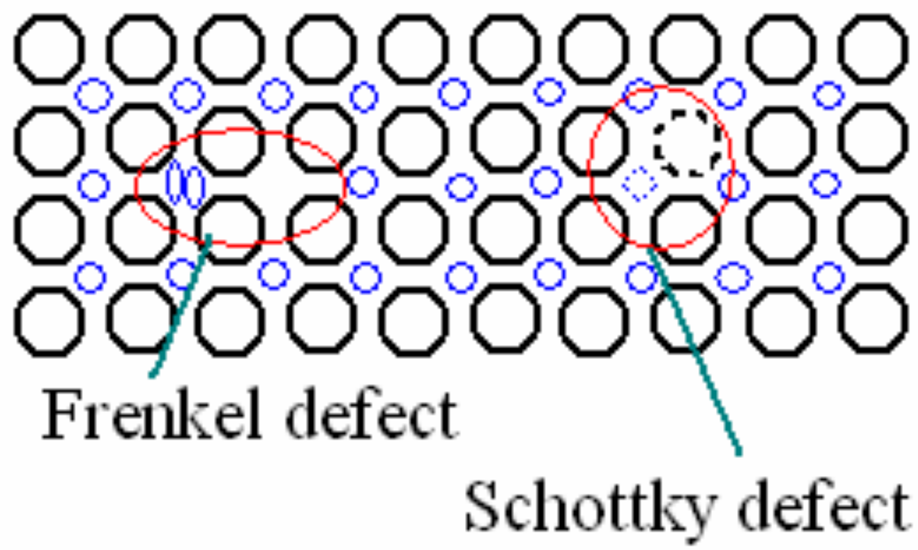


Point defects (contd…)

- Fraction of vacancy sites can be given as follows:

$$\frac{n}{N} = e^{-Q/kT}$$

- In ionic crystals, defects can form on the condition of charge neutrality. Two possibilities are:



Line defects

- *Line defects* or *Dislocations* are abrupt change in atomic order along a line.

- They occur if an incomplete plane inserted between perfect planes of atoms *or* when vacancies are aligned in a line.

- *A dislocation is the defect responsible for the phenomenon of slip, by which most metals deform plastically*.

- Dislocations occur in high densities (10^8-10^{10} m^{-2}), and are intimately connected to almost all mechanical properties which are in fact structure-sensitive.

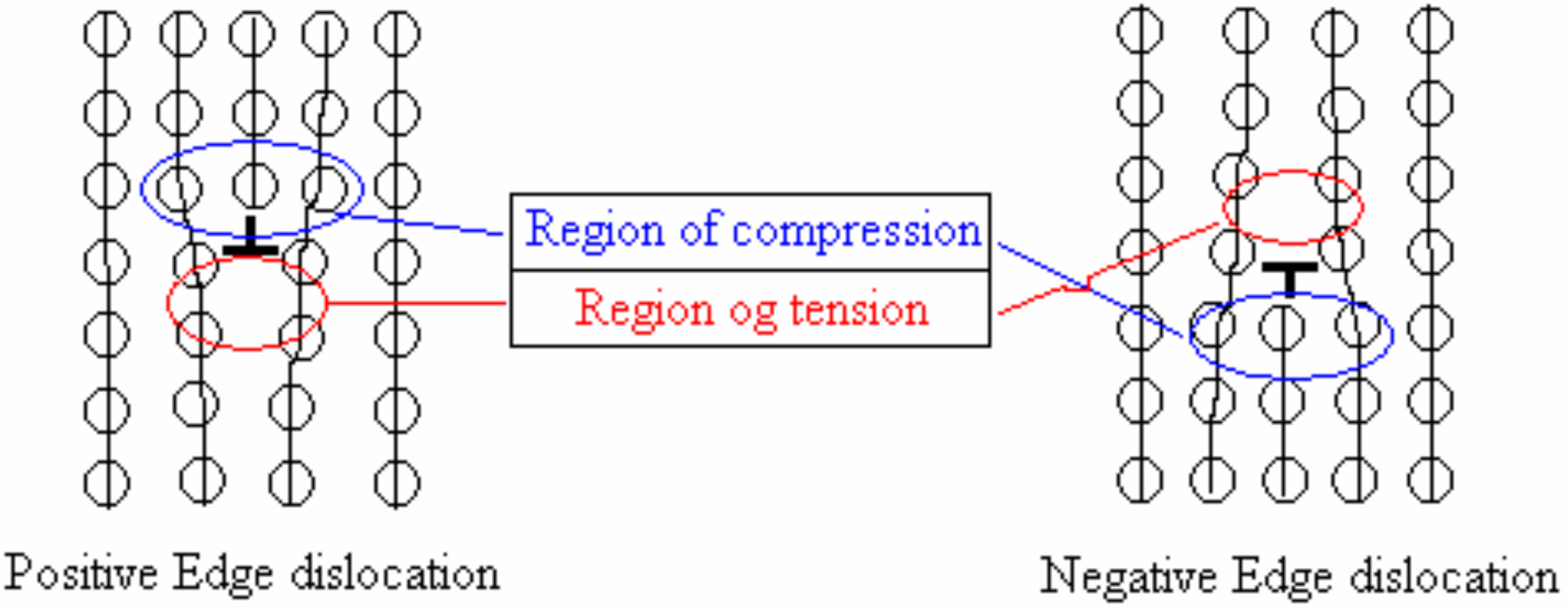
- Dislocation form during plastic deformation, solidification or due to thermal stresses arising from rapid cooling.

Line defects – Burger’s vector

- A dislocation in characterized by Burger’s vector, ***b***.
- It is unique to a dislocation, and usually have the direction of close packed lattice direction. It is also the slip direction of a dislocation.
- *It represents the magnitude and direction of distortion associated with that particular dislocation.*
- Two limiting cases of dislocations, edge and screw, are characterized by Burger’s vector perpendicular to the dislocation line (***t***) and Burger’s vector parallel to the dislocation line respectively. Ordinary dislocation is of mixed character of edge and screw type.

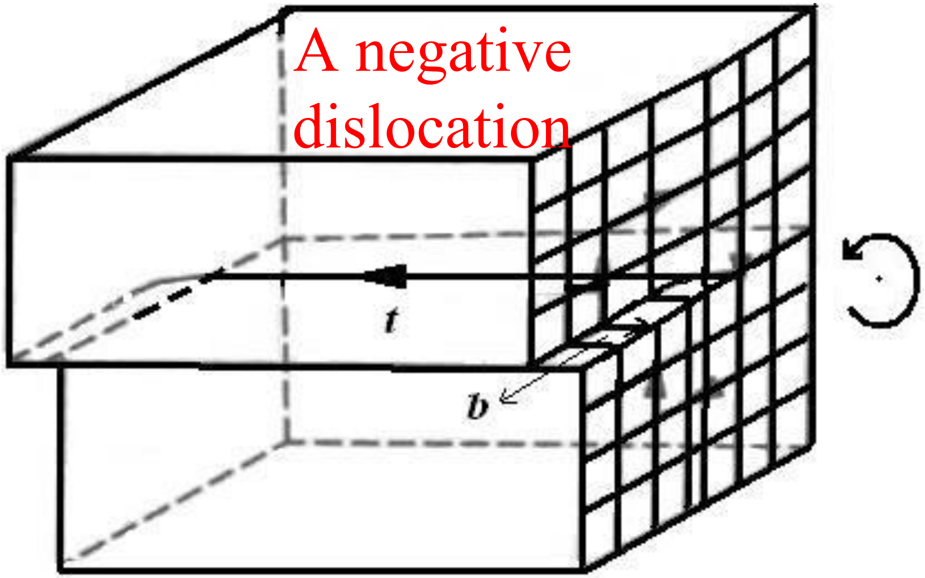
Line defects – Edge dislocation

- It is also called as *Taylor-Orowan dislocation*.
- It will have regions of compressive and tensile stresses on either side of the plane containing dislocation.



Line defects – Screw dislocation

- It is also called as *Burger's dislocation*.
- It will have regions of shear stress around the dislocation line
- For positive screw dislocation, dislocation line direction is parallel to Burger's vector, and vice versa.



Line defects – Dislocation motion

- Dislocations move under applied stresses, and thus causes plastic deformation in solids.
- Dislocations can move in three ways – glide/slip, cross-slip and climb – depending on their character. Slip is conservative in nature, while the climb is non-conservative, and is diffusion-controlled.
- *Any dislocation can slip, but in the direction of its burger's vector.*
- *Edge dislocation moves by slip and climb.*
- *Screw dislocation moves by slip / cross-slip*. Possibility for cross-slip arises as screw dislocation does not have a preferred slip plane as edge dislocation have.

Line defects – Dislocation characteristics

- A dislocation line cannot end at abruptly inside a crystal. It can close-on itself as a loop, either end at a node or surface.
- *Burger's vector for a dislocation line is invariant* i.e. it will have same magnitude and direction all along the dislocation line.
- Energy associated with a dislocation because of presence of stresses is proportional to square of Burger's vector length. Thus dislocations, at least of same nature, tend to stay away from each other.
- Dislocations are, thus, two types – full and partial dislocations. For *full dislocation*, Burger's vector is integral multiple of inter-atomic distance while for *partial dislocation*, it is fraction of lattice translation.

Interfacial defects

- An interfacial defect is a 2-D imperfection in crystalline solids, and have different crystallographic orientations on either side of it.

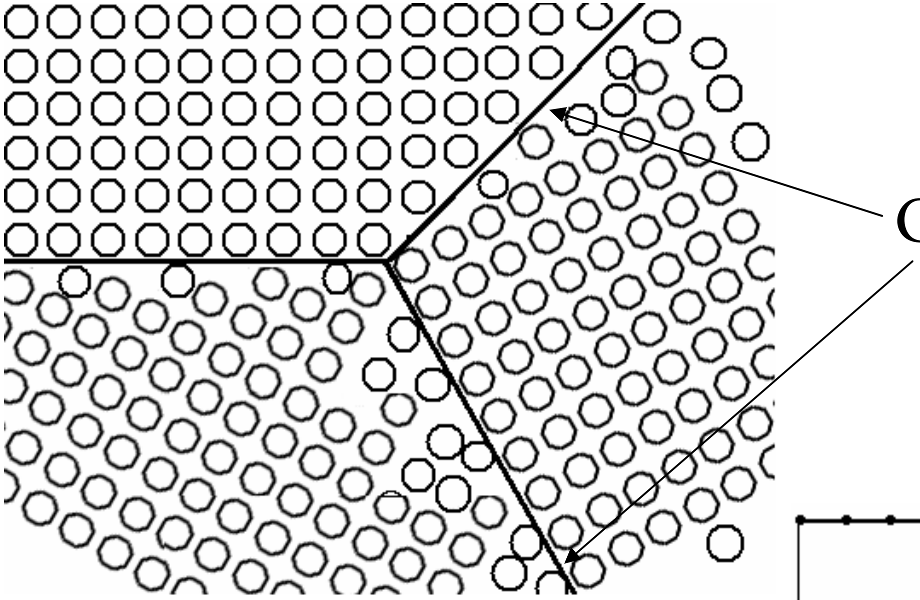
- Region of distortion is about few atomic distances.

- They usually arise from clustering of line defects into a plane.

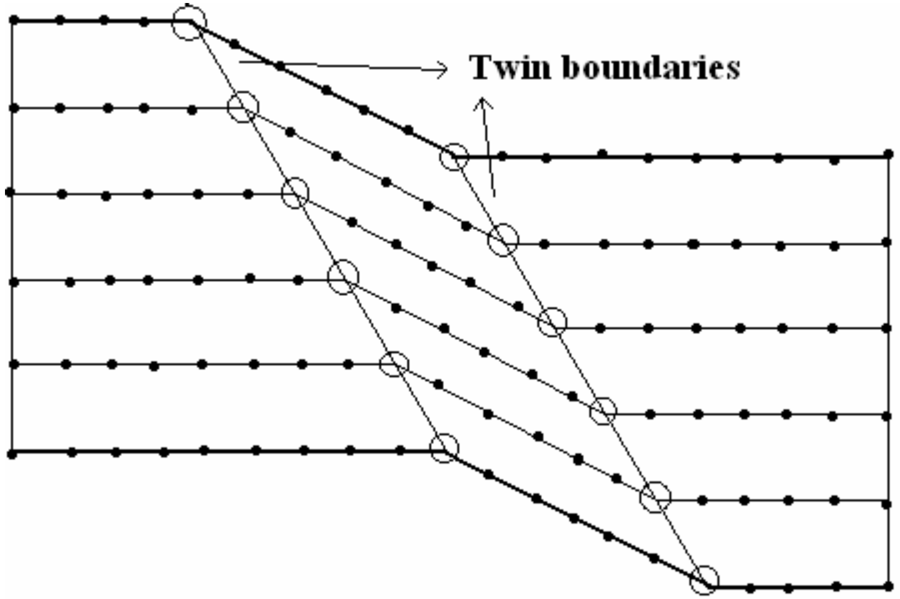
- These imperfections are not thermodynamically stable, but meta-stable in nature.

E.g.: External surface, Grain boundaries, Stacking faults, Twin boundaries, Dislocations and Phase boundaries.

Interfacial defects (contd…)



Grain boundaries



Bulk *or* Volume defects

- Volume defects are three-dimensional in nature.

- These defects are introduced, usually, during processing and fabrication operations like casting, forming etc.

  E.g.: Pores, Cracks, Foreign particles

- These defects act like stress raisers, thus deleterious to mechanical properties of parent solids.

- In some instances, foreign particles are added to strengthen the solid – dispersion hardening. Particles added are hindrances to movement of dislocations which have to cut through or bypass the particles thus increasing the strength.

Atomic vibrations

- Atoms are orderly arranged, but they are expected to vibrate about their positions where the amplitude of vibration increases with the temperature.

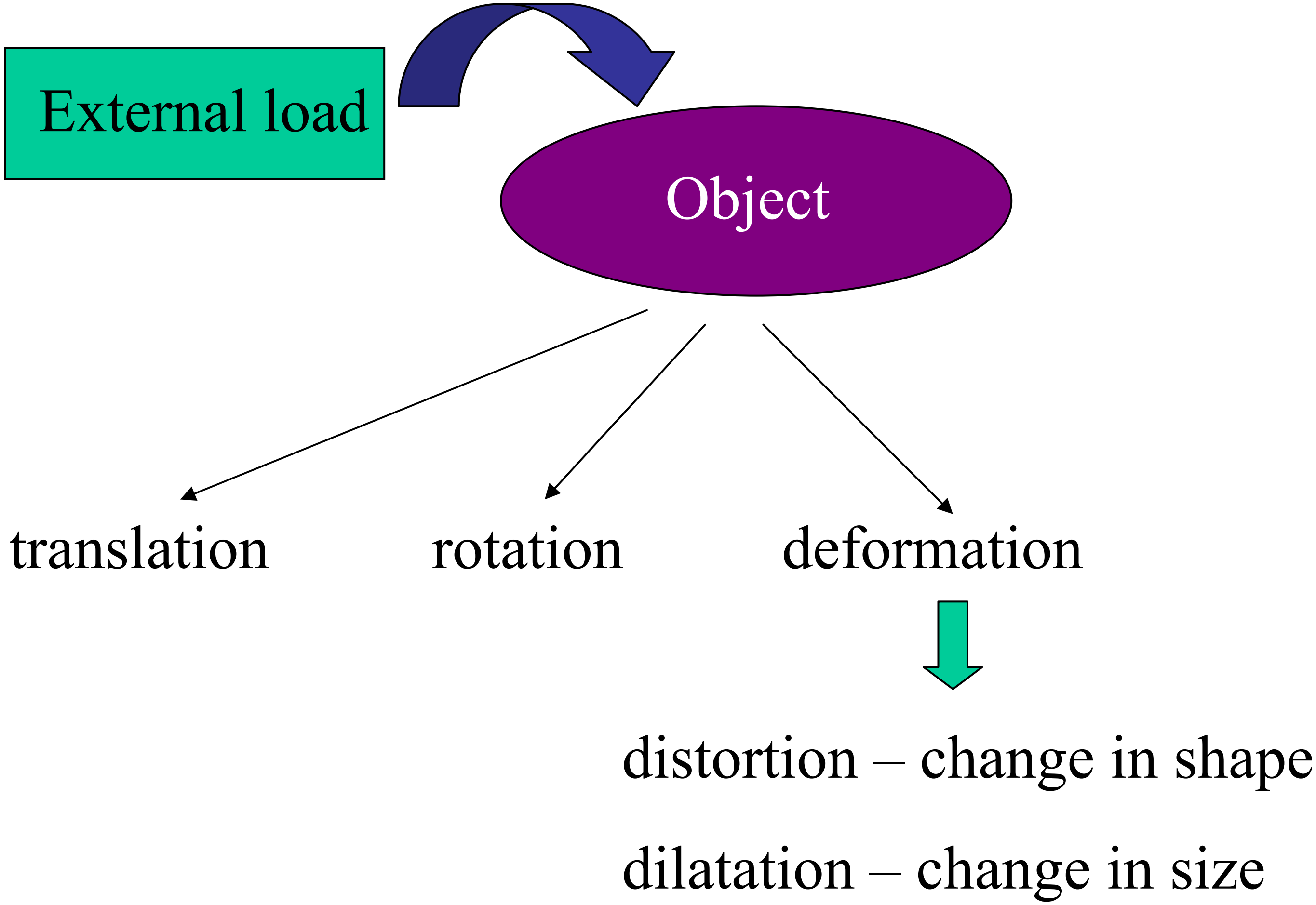
- After reaching certain temperature, vibrations are vigorous enough to rupture the inter-atomic forces casing melting of solids.

- Average amplitude of vibration at room temperature is about 10^{-12}m i.e. thousandth of a nanometer.

- Frequency of vibrations is the range of 10^{13} Hz.

- Temperature of a solid body is actually a measure of vibrational activity of atoms and/or molecules.

Mechanical loads - Deformation



External load

Object

translation

rotation

deformation

distortion – change in shape

dilatation – change in size

Deformation – function of time?

Temporary / recoverable	**Permanent**
time independent –	time independent –
elastic	plastic
time dependent –	time dependent –
anelastic (under load),	creep (under load),
elastic aftereffect (after removal of load)	

combination of recoverable and permanent, but time dependent – visco-elastic

Engineering Stress – Engineering Strain

- Load applied acts over an area.
- Parameter that characterizes the load effect is given as load divided by original area over which the load acts. It is called *conventional stress* or *engineering stress* or simply *stress*. It is denoted by *s*.
- Corresponding change in length of the object is characterized using parameter – given as per cent change in the length – known as *strain*. It is denoted by *e*.

$$s = \frac{P}{A_0}, e = \frac{L - L_0}{L_0}$$

- As object changes its dimensions under applied load, engineering stress and strain are not be the true representatives.

True Stress – True Strain

- *True* or *Natural* stress and strain are defined to give true picture of the instantaneous conditions.

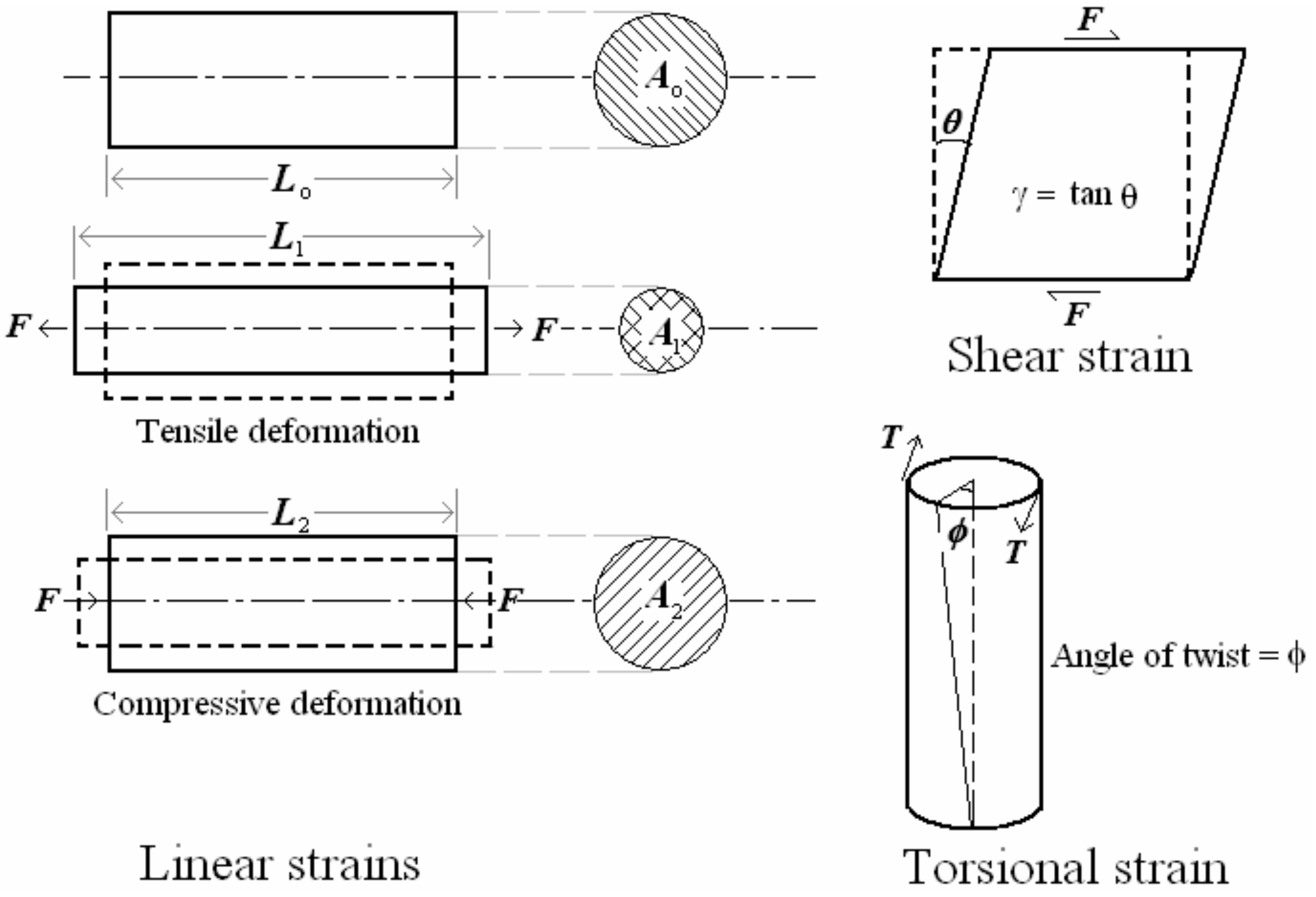
- True strain:

$$\varepsilon = \sum \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} + \ldots \qquad \varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

- True stress:

$$\sigma = \frac{P}{A} = \frac{P}{A_0} \frac{A_0}{A} = s(e+1)$$

Different loads – Strains



Elastic deformation

- A material under goes elastic deformation first followed by plastic deformation. The transition is not sharp in many instances.

- For most of the engineering materials, complete elastic deformation is characterized by strain proportional to stress. Proportionality constant is called *elastic modulus* or *Young's modulus*, *E*.

$$\sigma \propto \varepsilon \qquad \sigma = E\varepsilon$$

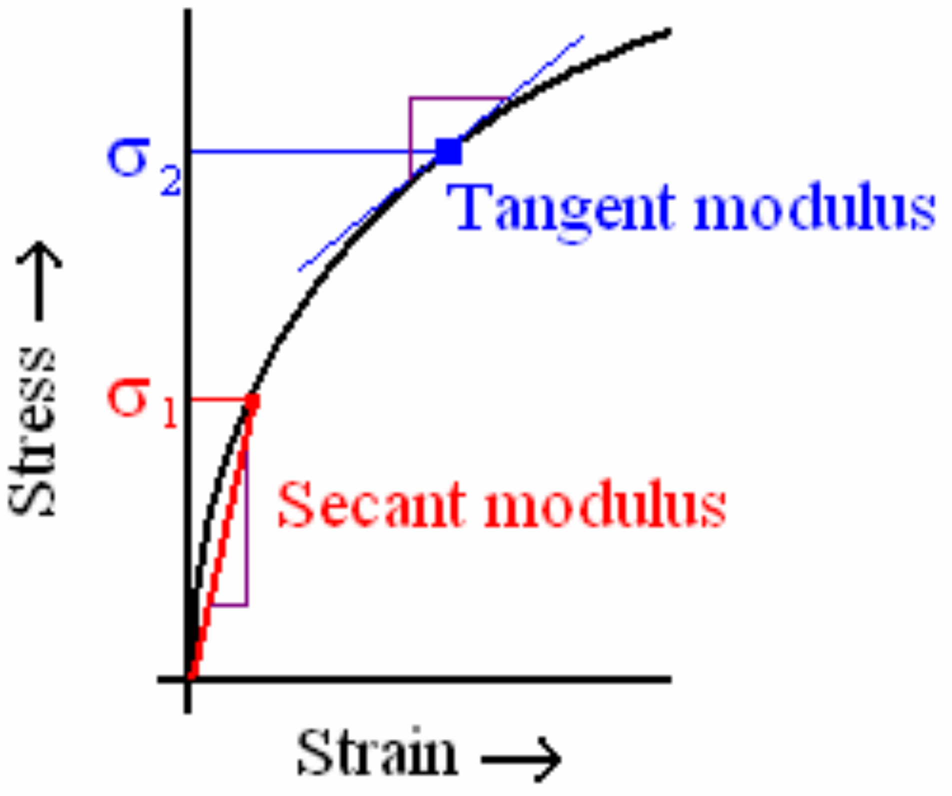
- Non-linear stress-strain relation is applicable for materials. E.g.: rubber.

Elastic deformation (contd…)

- For materials without linear stress-strain portion, either tangent or secant modulus is used in design calculations.

The tangent modulus is taken as the slope of stress-strain curve at some specified level.

Secant module represents the slope of secant drawn from the origin to some given point of the σ-ε curve.



Elastic deformation (contd…)

- Theoretical basis for elastic deformation – reversible displacements of atoms from their equilibrium positions – stretching of atomic bonds.
- Elastic moduli measures *stiffness* of material. It can also be a measure of resistance to separation of adjacent atoms.
- Elastic modulus = *fn* (inter-atomic forces)

  = *fn* (inter-atomic distance)

  = *fn* (crystal structure, orientation)

  => For single crystal elastic moduli are not isotropic.
- For a polycrystalline material, it is considered as isotropic.
- Elastic moduli slightly changes with temperature (decreases with increase in temperature).

Elastic deformation (contd…)

- Linear strain is always accompanied by lateral strain, to maintain volume constant.
- The ratio of lateral to linear strain is called Poisson's ratio (ν).
- Shear stresses and strains are related as $\tau = G\gamma$, where G is shear modulus or elastic modulus in shear.
- Bulk modulus or volumetric modulus of elasticity is defined as ratio between mean stress to volumetric strain. $K = \sigma_m/\Delta$
- All moduli are related through Poisson's ratio.

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{\sigma_m}{\Delta} = \frac{E}{3(1-2\nu)}$$

Plastic deformation

- Following the elastic deformation, material undergoes plastic deformation.
- Also characterized by relation between stress and strain at constant strain rate and temperature.
- Microscopically…it involves breaking atomic bonds, moving atoms, then restoration of bonds.
- Stress-Strain relation here is complex because of atomic plane movement, dislocation movement, and the obstacles they encounter.
- Crystalline solids deform by processes – slip and twinning in particular directions.
- Amorphous solids deform by viscous flow mechanism without any directionality.

Plastic deformation (contd…)

- Because of the complexity involved, theory of plasticity neglects the following effects:

  \- Anelastic strain, which is time dependent recoverable strain.

  \- Hysteresis behavior resulting from loading and un-loading of material.

  \- Bauschinger effect – dependence of yield stress on loading path and direction.
- Equations relating stress and strain are called *constitutive equations*.
- A true stress-strain curve is called *flow curve* as it gives the stress required to cause the material to flow plastically to certain strain.

Plastic deformation (contd…)

- Because of the complexity involved, there have been many stress-strain relations proposed.

$$\sigma = fn(\varepsilon, \dot{\varepsilon}, T, microstructure)$$

$$\sigma = K\varepsilon^n$$

Strain hardening exponent, n = 0.1-0.5

$$\sigma = K\dot{\varepsilon}^m$$

Strain-rate sensitivity, m = 0.4-0.9

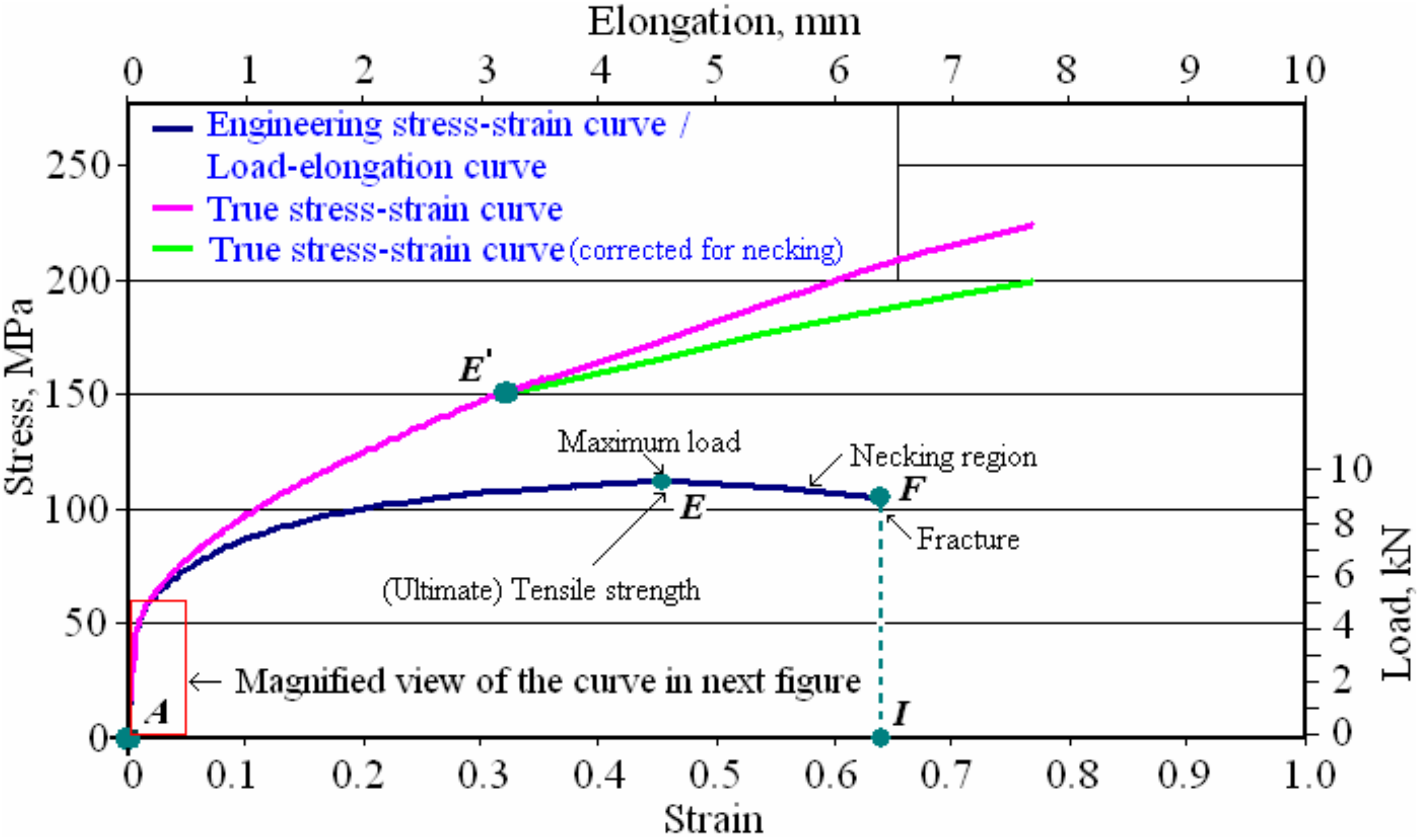
$$\sigma = K(\varepsilon_0 + \varepsilon)^n$$

Strain from previous work – ε_0

$$\sigma = \sigma_o + K\varepsilon^n$$

Yield strength – σ_0

Tensile stress-strain curve



A – Starting point

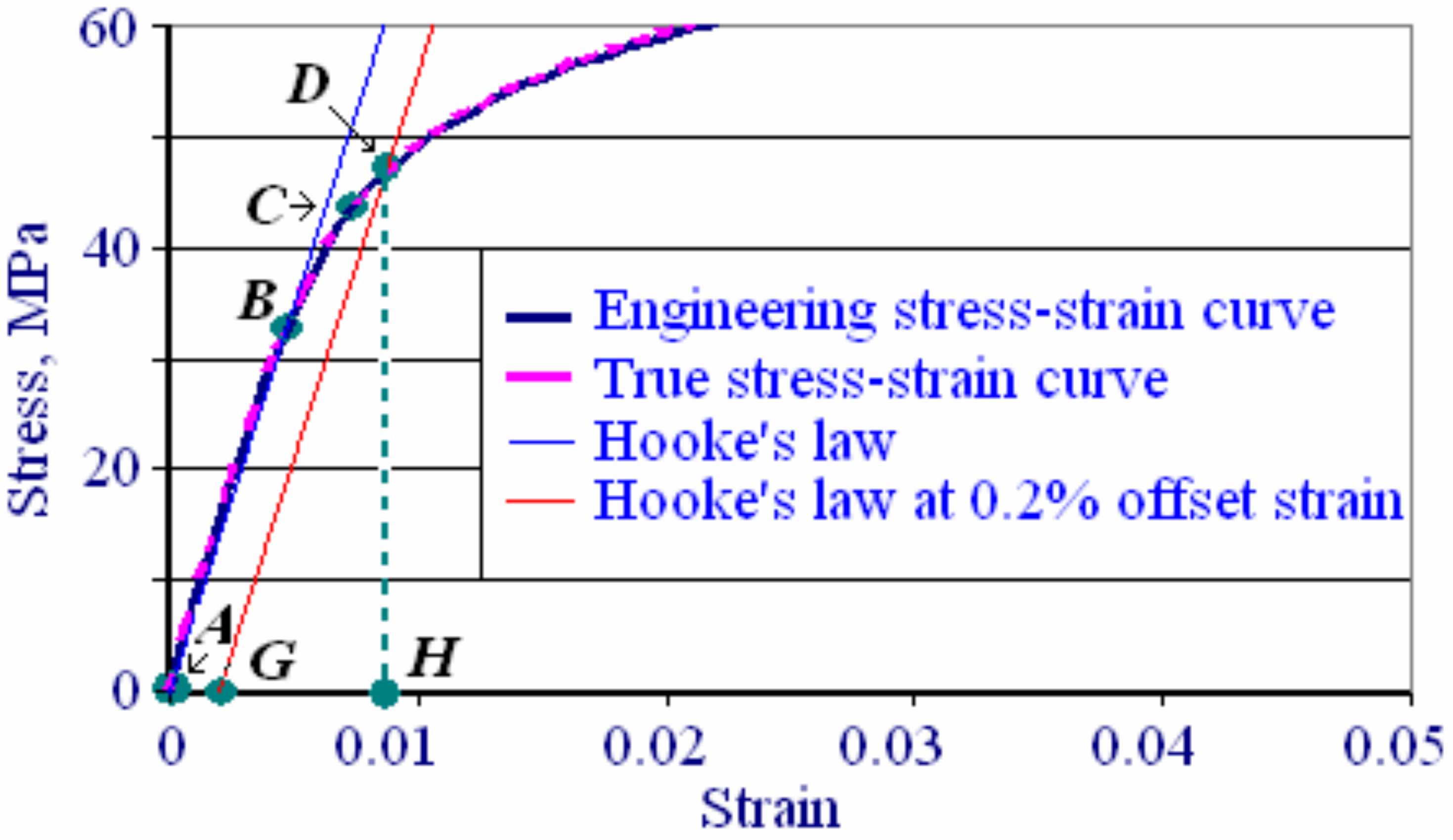
E– Tensile strength

E’ – Corresponding to E on flow curve

F – Fracture point

I – Fracture strain

Tensile stress-strain curve (contd…)



A – Starting point

B – Proportional limit

C – Elastic limit

D – Yield limit

G – 0.2% offset strain

H – Yield strain

Tensile stress-strain curve (contd…)

- Apart from different strains and strength points, two other important parameters can be deduced from the curve are – resilience and toughness.
- Resilience (U_r) – ability to absorb energy under elastic deformation
- Toughness (U_t) – ability to absorb energy under loading involving plastic deformation. Represents combination of both strength and ductility.

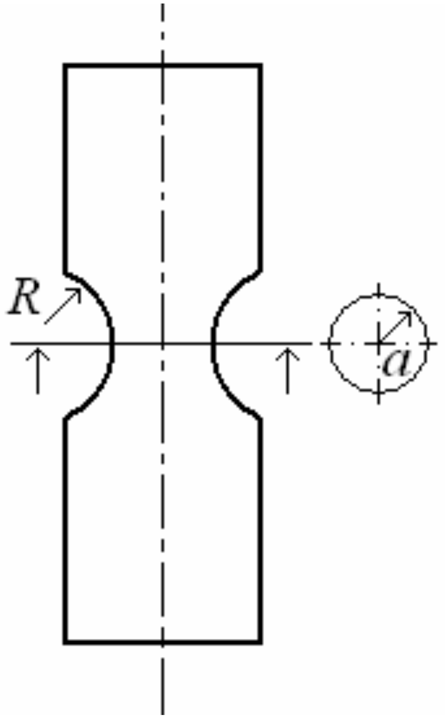
$$U_r = \frac{1}{2} s_0 e_0 = \frac{1}{2} s_0 \frac{s_0}{E} = \frac{s_0^2}{2E} \qquad \textit{area}\ \text{ADH}$$

$$U_t \approx s_u e_f \approx \frac{s_0 + s_u}{2} e_f \qquad \textit{area}\ \text{AEFI} \qquad U_t \approx \frac{2}{3} s_u e_f \qquad \textit{(for brittle materials)}$$

Yielding under multi-axial stress

- With on-set of necking, uni-axial stress condition turns into tri-axial stress as geometry changes tales place. Thus flow curve need to be corrected from a point corresponding to tensile strength. Correction has been proposed by Bridgman.

$$\sigma = \frac{(\sigma_x)_{avg}}{(1+2R/a)\left[\ln(1+a/2R)\right]}$$



where

$(\sigma_x)_{avg}$ measured stress in the axial direction,

a – smallest radius in the neck region,

R – radius of the curvature of neck

Yield criteria

- von Mises or Distortion energy criterion:

  yielding occurs once second invariant of stress deviator (J_2) reaches a critical value. In other terms, yield starts once the distortion energy reaches a critical value.

$$J_2 = k^2 \qquad J_2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]$$

Under uni-axial tension, $\sigma_1 = \sigma_0$, *and* $\sigma_2 = \sigma_3 = 0$

$$\frac{1}{6}(\sigma_0^2+\sigma_0^2) = k^2 \Rightarrow \sigma_0 = \sqrt{3}k$$

$$\Rightarrow \sigma_0 = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$$

$$k = \frac{1}{\sqrt{3}}\sigma_0 = 0.577\sigma_0$$

where k – yield stress under shear

Yield criteria (contd…)

- Tresca or Maximum shear stress criterion

  yielding occurs once the maximum shear stress of the stress system equals shear stress under uni-axial stress.

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2}$$

Under uni-axial tension, $\sigma_1 = \sigma_0$, *and* $\sigma_2 = \sigma_3 = 0$

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2} = \tau_0 = \frac{\sigma_0}{2} \Rightarrow \sigma_1 - \sigma_3 = \sigma_0$$

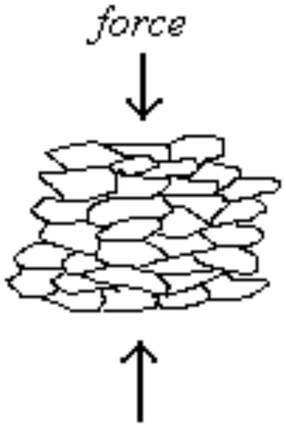
Under pure shear stress conditions ($\sigma_1 =- \sigma_3 = k$, $\sigma_2 = 0$)

$$k = \frac{\sigma_1 - \sigma_3}{2} = \frac{1}{2}\sigma_0$$

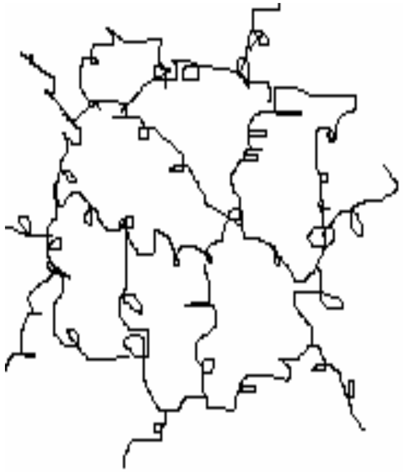
Macroscopic aspects – Plastic deformation

- As a result of plastic deformation (Dislocation generation, movement and (re-)arrangement), following observations can be made at macroscopic level:
  dimensional changes
  change in grain shape
  formation of cell structure in a grain

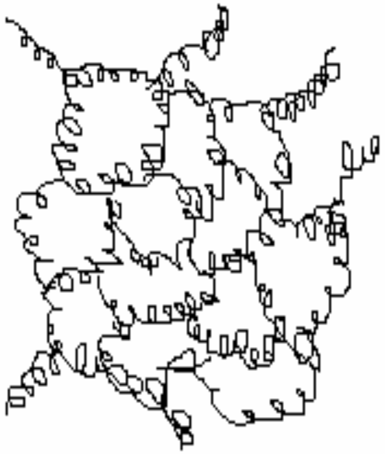
equi-axed grains



deformed grains

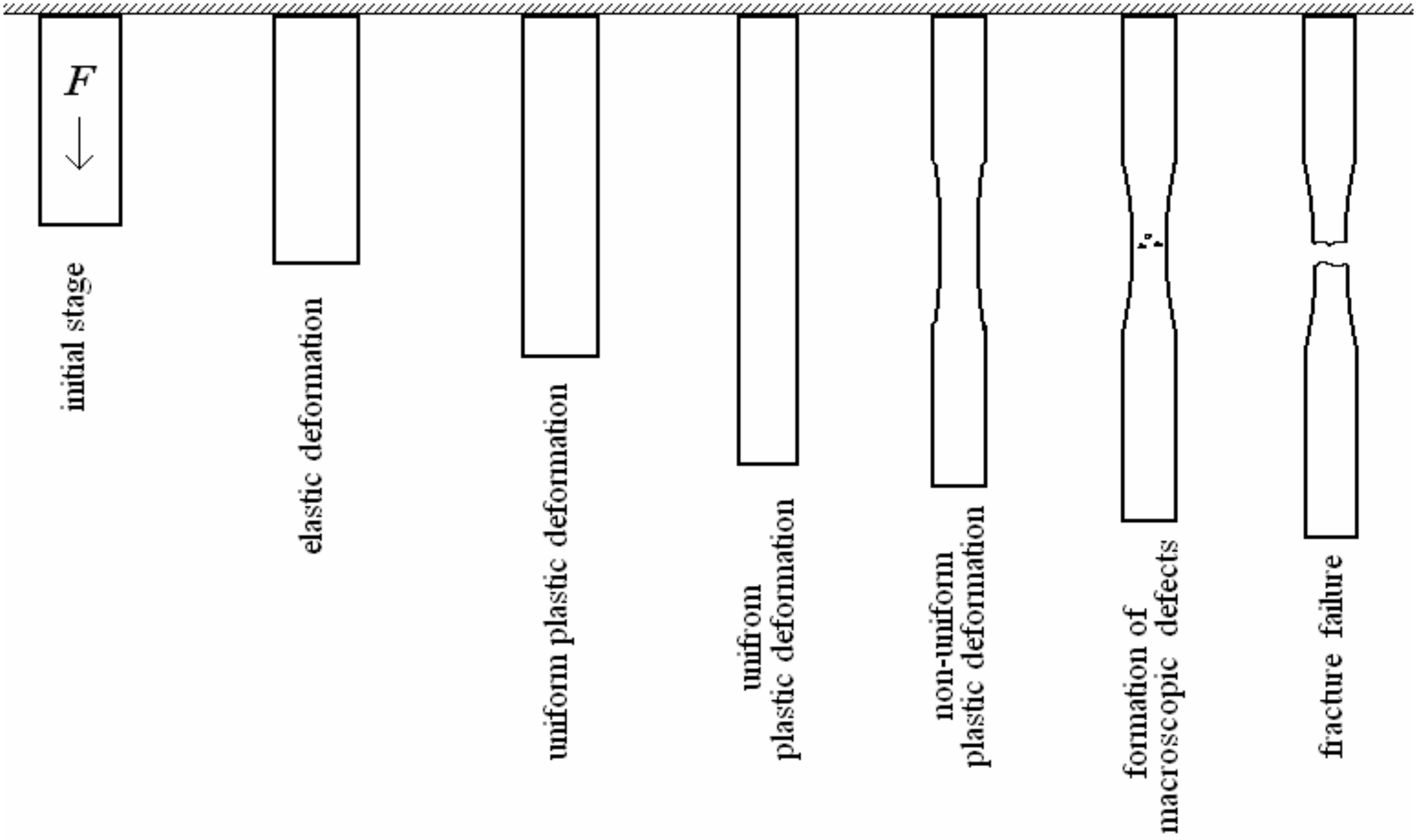


initial cell structure



denser cell structure

Macroscopic aspects – Plastic deformation (contd…)



Property variability

- Scatter in measured properties of engineering materials is inevitable because of number of factors such as:
  - test method
  - specimen fabrication procedure
  - operator bias
  - apparatus calibration, etc.

Average value of x over n samples.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Property variability measure – Standard deviation

$$s = \left[\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1} \right]^{1/2}$$

Scatter limits:

$$\bar{x} - s, \quad \bar{x} + s$$

Design consideration

- To account for property variability and unexpected failure, designers need to consider tailored property values. Parameters for tailoring: safety factor (*N*) *and* design factor (*N'*). Both parameters take values greater than unity only.

E.g.: Yield strength

$$\sigma_w = \sigma_y / N \qquad \sigma_d = N'\sigma_c$$

where σ_w – working stress

σ_y – yield strength

σ_d – design stress

σ_c – calculated stress

Design consideration (contd…)

- Values for *N* ranges around: 1.2 *to* 4.0.

- Higher the value of N, lesser will the design efficiency i.e. either too much material *or* a material having a higher than necessary strength will be used.

- Selection of *N* will depend on a number of factors:
  economics
  previous experience
  the accuracy with which mechanical forces
  material properties
  the consequences of failure in terms of loss of life or property damage.

Contents

Materials – Classification

- Materials are classified into three basic groups based on their mechanical and physical nature as – metals, ceramics and polymers.
- For an engineer, especially, metals are more important owing to ability to carry loads and ease of manufacturing.
- Metallic materials are again classified for ease of selection and/or based on their tonnage of usage broadly into two classes – ferrous and non-ferrous.
- Ferrous materials – chief constituent is iron (*Fe*). E.g.: steel, cast iron.
- Metallic materials those are not ferrous are termed as non-ferrous materials. E.g.: Brass, Silver, Aluminium, Titanium.

Ferrous materials - Introduction

- In engineering applications, lion share is served by ferrous materials.

- Factors account for it are:
  - availability of abundant raw materials combined with economical extraction
  - ease of forming
  - their versatile mechanical and physical properties.

- There are some drawbacks about ferrous materials:
  - poor corrosion resistance
  - high density i.e. low specific strength
  - low thermal and electrical conductivities

Ferrous materials - Classification

- There are two classes – *steels* and *cast irons* – categorized based on carbon content.
- Steels: %C is up to 2.14%
  Cast irons: %C is above 2.14%
- Cast irons are called so because they are usually manufactured through casting technique owing to their brittle nature due to presence of iron carbide.
- Steels are serving major part of present engineering applications.
- However, cast irons mostly serve as structural components. E.g.: automobile motor casings, lathe bed, sliding guides in machinery.

Steels

- In steels, C atoms occupies interstitial sites of Fe.
- Steels are classified based on their C content/alloying additions which in turn dictates their applications: plain carbon steels and alloying steels.
- **Plain carbon steels**
  - *Low-carbon steels*: % wt of C < 0.3
  - *Medium carbon steels*: 0.3 <% wt of C < 0.6
  - *High-carbon steels*: % wt of C > 0.6
- **Alloy Steel:**
  - High Strength Structural Steel
  - Tool Steels
  - Stainless steel

Low carbon steels:

- Carbon present is not enough to strengthen them by heat treatment, hence are strengthened by cold work.
- They are easily weldable and machinable.
- Typical applications: tin cans, automotive body components, structural shapes, etc.

Steels (contd….)

- Medium carbon steels:
  - They are less ductile and stronger than low carbon steels.
  - Heat treatable (austenitizing, quenching and tempering).
  - Hardenability is increased by adding Ni, Cr, Mo.
  - Used in various tempered conditions.
  - Typical applications: gears, railway tracks, machine parts.

- High carbon steels:
  - They are strongest and hardest of carbon steels.
  - Heat treatable. Used in tempered or hardened conditions.
  - Alloying additions – Cr, V, W, Mo
  - Typical applications: Knives, razors, hacksaw blades, etc where high wear resistance is the prime requirement.

HSLA and Stainless Steels

- High Strength Structural Steel

  E.g.. HSLA (high strength low alloy) steels:

  - They can be strengthened by heat treatment.
  - Ductile and formable.
  - Alloying addition – Cu, V, W, Ni, Cr, Mo, etc.
  - Typical applications: support columns, pressure vessels, bridge beams.

- Tool Steels

  General properties are : Wear and abrasion resistance, toughness, red hardness, non-deforming property and minimum cost.

- Stainless steels:

  - They typical consists min.12% Cr along with other alloying elements, thus highly corrosion resistant owing to presence of chromium oxide.
  - Three kinds - ferritic & hardenable Cr steels, austenitic and precipitation hardenable (martensitic, semi-austenitic) – based on presence of prominent microstructural constituent.

Stainless Steels (contd….)

- Stainless steels:

  - Typical applications – cutlery, surgical knives, storage tanks, domestic items

  - *Ferritic steels* are principally Fe-Cr-C alloys with 12-14% Cr. And small additions of Mo, V, Nb, Ni.

  - *Austenitic steels* contain 18% Cr and 8% Ni plus minor alloying elements. Ni stabilizes the austenitic phase assisted by C and N.

  - For, *martensitic steels* ***Ms*** is made to be above the room temperature. These alloys are heat treatable. Major alloying elements are: Cr, Mn and Mo.

  - Ferritic and austenitic steels are hardened and strengthened by cold work because they are not heat treatable.

  - Austenitic steels are non-magnetic as against ferritic and martensitic steels, which are magnetic.

Cast irons

- Grey cast iron

  - Cementite decomposes during solidification to form carbon flakes. Thus they are brittle.

  - Fractured surface looks grey because of presence of graphite, hence the name.

  - Possess good damping properties.

  - Typical applications – base structures, machine beds

- White cast iron

  - Cooled fast so that cementite does not decompose.

  - Fractures surface looks whitish because of cementite, hence the name.

  - They are brittle and extremely difficult to machine.

  - Used as source materials for producing malleable iron.

Cast irons (contd….)

- Nodular cast iron

  - Alloying addition of Mg/Ce to grey cast iron melt results in graphite to form as modules.

  - They are stronger and ductile than grey cast iron.

  - Typical applications – pump bodies, crank shafts, automotive components, etc.

- Malleable cast iron

  - Formed by heat treating white cast iron. Heat treatment involves heating to 800-900C, keep it there for long hours, then cooling to room temperature.

  - Cementite decomposes to form graphite and ferrite.

  - Typical applications – railroad, connecting rods, marine and other heavy-duty services.

Non-Ferrous materials

- Typical advantages of non-ferrous materials over ferrous materials:
  - high specific strength.
  - low density.
  - high electrical and thermal conductivities.
  - distinct properties thus used for specific purposes.
  - can be formed with ease.

E.g.: Al-alloys

Cu-alloys (brass, bronze)

Mg-alloys

Ti-alloys

Noble metals (E.g.: Ag, Au, Pt, Pa)

Refractory metals (E.g.: Nb, Mo, W and Ta)

Fabrication of metals and alloys

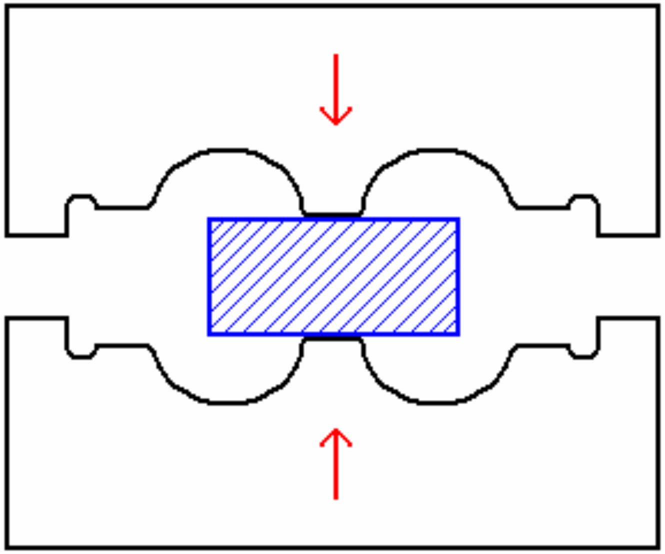
- Four basic manufacturing processes:
- Casting – to give a shape by pouring in liquid metal into a mold that holds the required shape, and letting harden the metal without external pressure.
- Forming – to give shape in solid state by applying pressure.
- Machining – in which material is removed in order to give it the required shape.
- Joining – where different parts are joined by various means.
- Other important technique is powder metallurgy.

Metal Casting – Metal Forming

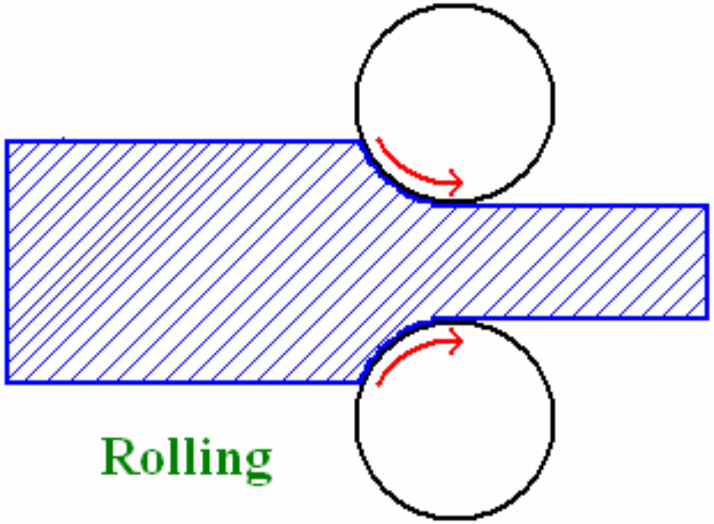
- Four important casting techniques are:
- Sand casting
- Die casting
- Investment casting
- Continuous casting

- Four important forming techniques are:
- Forging
- Rolling
- Extrusion
- Drawing

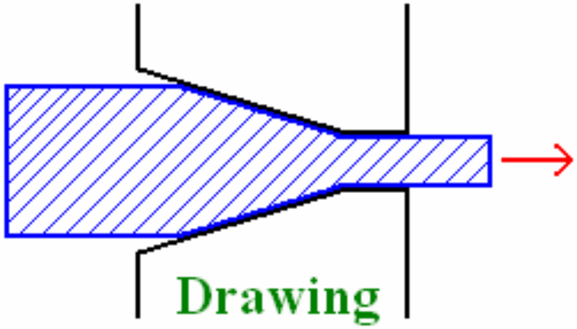
Metal Forming techniques



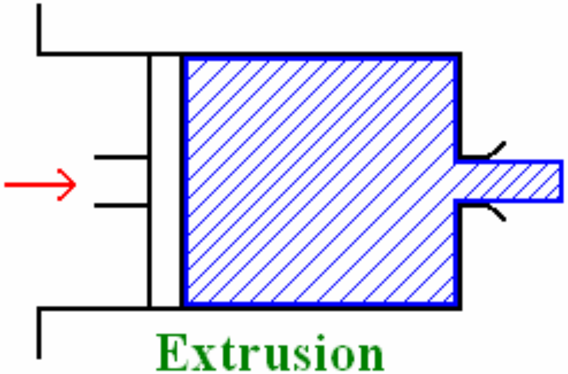
Forging



Rolling



Drawing



Extrusion

Thermal processing

- Two main kinds of metal processing methods – mechanical and thermal.
- Thermal processing is also known as heat treatment.
- Purpose of heat treatment:
  - improvement in ductility
  - relieving internal stresses
  - grain size refinement
  - increase of strength
  - improvement in machinability and toughness
- Thermal processing factors – temperature up to which material is heated, length of time that the material is held at the elevated temperature, rate of cooling, and the surrounding atmosphere under the thermal treatment.

Thermal processing methods

- Two kinds heat treating methods are – *annealing* and *quenching & tempering*.
- These differ in the way material is cooled from an elevated temperature.
- Annealing involves cooling the material slowly, allowing phase changes.
- Quenching (also known as *hardening*) means cooling the material at a rapid rate to arrest the equilibrium phase transformations.
- During annealing, material is cooled in air and/or heating furnace itself.
- For quenching, material is immersed in water / oil quench bath.

Annealing techniques

- Process annealing – applied to cold worked materials to negate effects of cold work. Commonly sandwiched between two cold work operations. Improves ductility.
- Stress relief – purpose of it is to remove stresses. Temperatures are low such that cold work effects are not affected.
- Full annealing – used for products that are to be machined later-on. Cooling is done in furnace itself. Hardness and strength are restored by additional heat treatments after machining.
- Normalizing – used to refine the grains and produce a more uniform and desirable size distribution. It involves heating the component to attain single phase (e.g.: austenite in steels), then cooling in open air atmosphere.

Quenching & Tempering

- Quenching operation is usually followed by tempering.
- Tempering involves heating martensitic steel at a temperature below the eutectoid transformation temperature to make it softer and more ductile. Here Martensite transforms to ferrite embedded with carbide particles.

- *Martempering* is used to minimize distortion and cracking. It involves cooling the austenized steel to temperature just above *Ms* temperature, holding it there until temperature is uniform, followed by cooling at a moderate rate to room temperature before austenite-to-bainite transformation begins. The final structure of martempered steel is tempered Martensite.
- *Austempering* involves austenite-to-bainite transformation. Thus, the final structure of austempered steel is bainite.

Case Hardening

- In case hardening, the surface of the steel is made hard and wear resistant, but the core remains soft and tough.

Induction hardening

- Here, an alternating current of high frequency passes through an induction coil enclosing the steel part to be heat treated.
- The induced ***e m f*** heats the steel.
- Immediately after heating, water jets are activated to quench the surface.
- Martensite is produced at the surface, making it hard and wear resistant.
- The microstructure of the core remains unaltered.

Flame hardening

- Flame hardening is done by means of an oxyacetylene torch.
- Heating should be done rapidly by the torch and the surface quenched, before appreciable heat transfer to the core occurs

Case Hardening

Laser hardening

- A laser beam can be used for surface hardening.
- As laser beams are of high intensity, a lens is used to reduce the intensity by producing a defocused spot of size ranging from 0.5 to 25 mm.
- Proper control of energy input is necessary to avoid melting.
- Laser hardening has the advantage of precise control over the area to be hardened, an ability to harden reentrant surfaces, very high speed of hardening and no separate quenching step.

Carburizing

- The surface layers of low carbon steel are enriched with carbon up to 0.8-1.0%.
- The source of carbon may be a solid medium, a liquid or a gas.
- In all cases, the carbon enters the steel at the surface and diffuses into the steel as a function of time at an elevated temperature.
- Carburizing is done at 920-950° C. This fully austenitic state is essential.
- If carburizing is done in the ferritic region, the carbon, with very limited solubility in ferrite, tends to form massive cementite particles near the surface, making the subsequent heat treatment difficult.

Case Hardening

Cyaniding

- Cyaniding is done in a liquid bath of NaCN, with the concentration varying between 30 and 97%.
- The temperature used for cyaniding is lower than that for carburizing and is in the range of 800-870° C.
- The time of cyaniding is 1-3 hr to produce a case depth of 0.25 mm or less

Nitriding

- Nitriding is carried out in the ferritic region.
- No phase change occurs after nitriding.
- During nitriding, pure ammonia decomposes to yield nitrogen which enters the steel.
- The solubility of nitrogen in ferrite is small. Most of the nitrogen, that enters the steel, forms hard nitrides (e.g., Fe_3N).
- The temperature of nitriding is 500-590° C.
- The time for a case depth of 0.02 mm is about 2 hr.
- In addition to providing outstanding wear resistance, the nitride layer increases the resistance of carbon steel to corrosion in moist atmospheres.