

# **Introduction to physical metallurgy**

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# Module-II

**Constitution of alloy-** An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which at least one is metal. If the system is made of two elements, it is called a binary alloy system. Similarly, three elements are known as a ternary alloy system.

- Alloy may be classified according to their structure and completely alloy system may be classified according to the type of their equilibrium or phase diagram.
- In the solid state there are three possible phases: (1) Pure metal (2) Intermediate alloy phase or compound (3) Solid solution.
- Three most common intermediate alloy phases are: **Intermetallic compound or valence compound**-These are generally formed between chemically dissimilar metals and are combined by following the rule of chemical valence. Since they generally have strong bonding (ionic or covalent) their properties are essentially nonmetallic. They usually show poor ductility and poor electrical conductivity and may have a complex crystal structure. Ex-  $Mg_2Pb$ ,  $Mg_2Sn$  and  $Cu_2Se$ .

**Interstitial compounds-** These compounds are formed between transition metals such as scandium (Sc), titanium (Ti), tantalum (Ta), tungsten (W) and iron (Fe), with hydrogen, oxygen, carbon, boron and nitrogen.

**Electronic compound-** A study of the equilibrium diagram of the alloy of copper, gold, silver, iron, and nickel with the metal cadmium, magnesium, tin, zinc, and aluminum.

## Continue

- Example- Compound  $\text{AgZn}$  , the atom of silver has one valence electron while that Zinc has two valence electron so that two atom of the compound will have three valence electron ,or electron to atom ratio 3:2 in the compound  $\text{Cu}_9\text{Al}_4$  each atom of copper has one valence electron.

There are two type of solid solution

(1)Substitutional

(2)Interstitial

Substitutional solid solution:

In this type of solution the atom of solute substitute atom of the solvent. Example- Silver atom substitute for gold atom without losing the F.C.C structure of gold and gold atom may substitute for silver atoms in F.C.C lattice with silver and gold atoms distributed at random through lattice structure . This entire system consist of a continuous series of solid solution

Several factor are now known , largely through the work of Humrothery , that control the range of solubility in alloy system.

- **Crystal –structure factor-** Complete solid solubility of two element is never attained unless the element have the same type of crystal lattice structure.
- **Relative size factor-** Size factor is favorable for solid solution formation when the difference in atomic radii's less than 8% but less than 15% the alloy system usually show minimum. If the relative –size factor is greater than 15% solid solution formation is very limited.
- Example- Silver and lead are both F.C.C and relative size factor is about 20%. The solubility of lead in solid silver is about 1.5%, and the solubility of silver in lead is about 0.1%.

## Continue

Antimony and Bismuth are completely soluble in each other in all proportion, they have same type of crystal structure (rombohedral) and differ in atomic radii by about 7% . However the solubility of antimony in F.C.C aluminum is less than 0.1 % , although the relative size factor is about 2 %.

**Chemical –affinity** factor-Greater the chemical affinity of two metals the more restricted is their solid solubility and greater is the tendency towards compound formation . Generally the farther apart the elements are in in the periodic table, the greater is their chemical affinity.

**Relative Valence factor**-If the solute metals has different valence from that of the solvent metal , the number of valence electron per atom , called the electron ratio , will be changed. Crystal structure are more sensitive to a decrease in electron ratio than to an increase .In other word a metal of lower valence tends to dissolve more of metal of higher valence than vice versa. Example in aluminum –Nickel alloy system both metal are F.C.C . The relative size factor is approximately 14%. However nickel is lower in valence than aluminum , and in according with the relative –valence factor solid nickel dissolve 5 % aluminum, but then higher valence aluminium dissolve only 0.04% nickel.

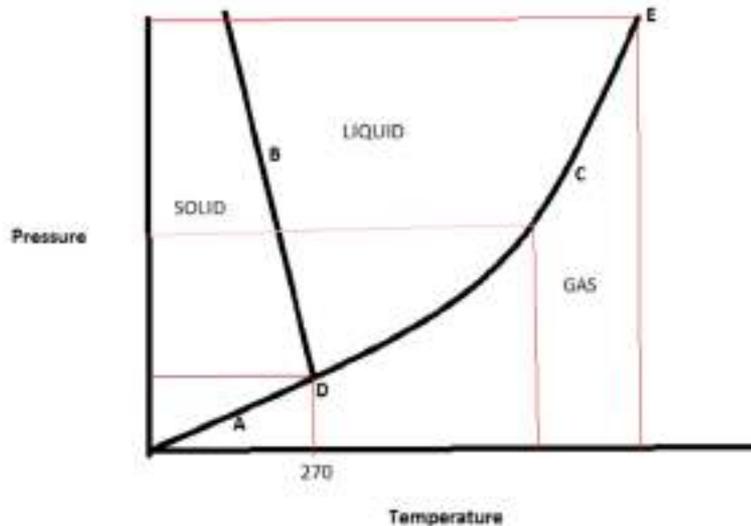
# Content

- (1) Equilibrium phase diagrams, Particle strengthening by precipitation and precipitation reactions .
- (2) Kinetics of nucleation and growth
- (3) The iron-carbon system, phase transformations
- ( 4) Transformation rate effects and TTT diagrams, Microstructure and property changes in iron carbon system

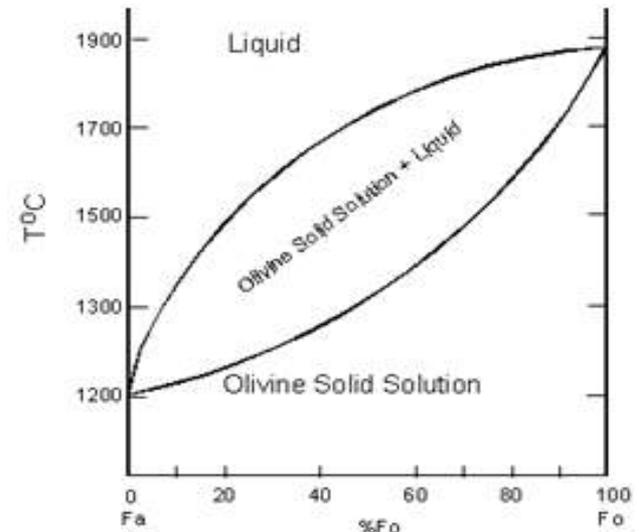
## Module –III(PHASE DIAGRAM)

The understanding of phase diagram for alloy system is extremely important because there is a strong correlation between microstructure and mechanical properties and development of microstructure of an alloy is related to the characteristic of the phase diagram. In addition, phase diagram provide valuable information about melting, casting, crystallization and other phenomena.

- Phase diagram also called equilibrium diagram, now there are three externally controlled parameters that will affect phase diagram –viz. temperature, pressure and composition phase diagram constructed when various combination of three parameters.
- One component phase diagram (unary phase diagram) or (P-T) diagram



Unary phase diagram of water



Unary phase diagram of metal

## Gibbs phase rule :

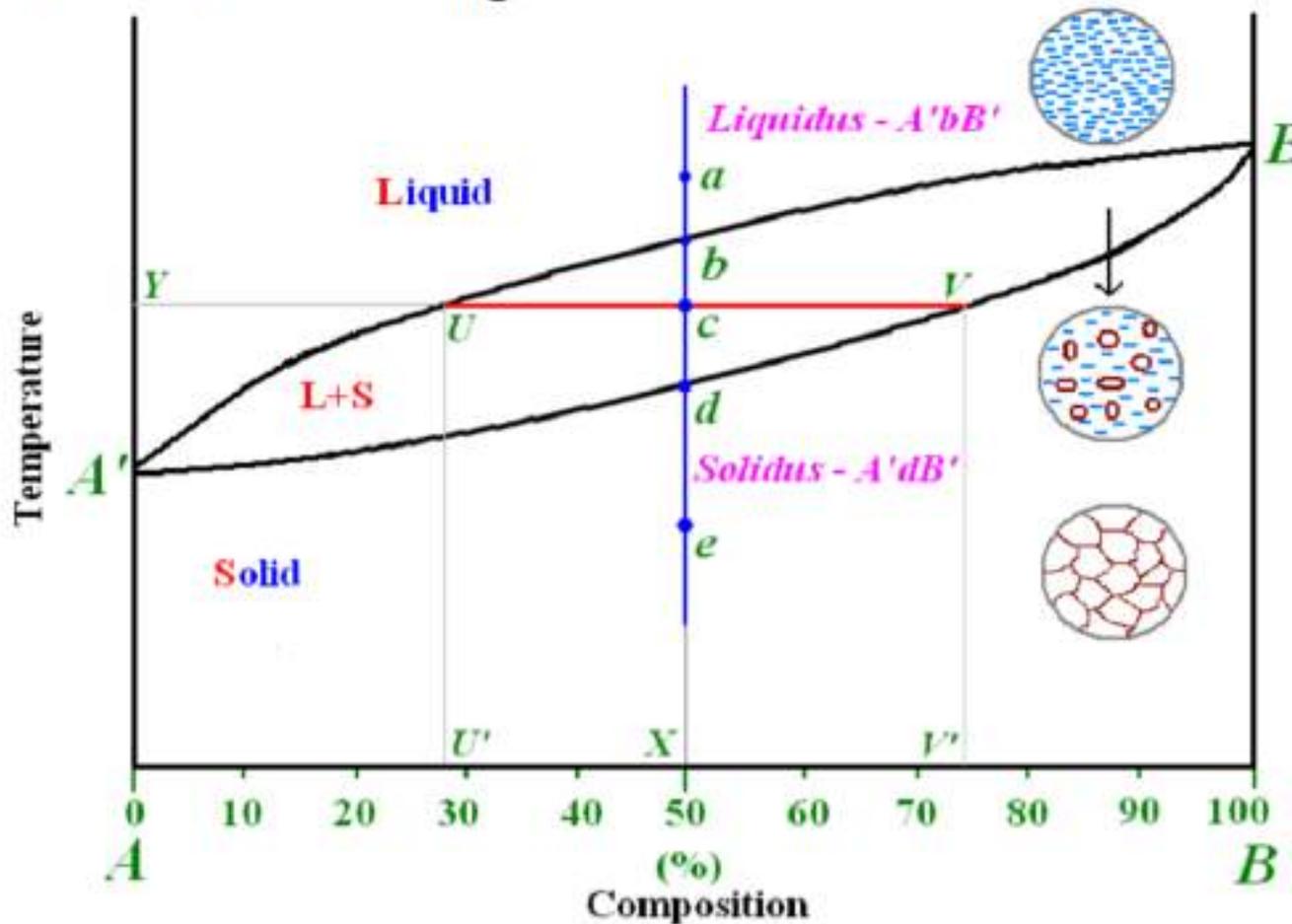
- In a system under a set of conditions, number of phases (P) exist can be related to the number of components (C) and degrees of freedom (F) by Gibbs phase rule.
- Degrees of freedom refers to the number of independent variables (e.g.: pressure, temperature) that can be varied individually to effect changes in a system.
- Thermodynamically derived Gibbs phase rule :  $P + F = C + 2$
- 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:  $P + F = C + 1$

## Binary phase diagram

- In this phase diagram temperature and composition are variable and pressure held constant. Binary phase diagram are map that represent relationship between temperature and composition and quantity of phase equilibrium , which is influence the microstructure of an alloy.
- 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  $Fe_3C$ ), or two compounds ( $Al_2O_3$  and  $Si_2O_3$ ), 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.
- For isomorphous system - E.g.: Cu-Ni, Ag-Au, Ge-Si,  $Al_2O_3$  - $Cr_2O_3$  .

## Isomorphous binary system

- An isomorphous system – phase diagram and corresponding microstructural changes.



## Tie line – Lever rule

- At a point in a phase diagram, phases present and their composition (tie-line method) along with relative fraction of phases (lever rule) can be computed.
- Procedure to find equilibrium concentrations of phases (refer to the figure in previous slide): - A tie-line or isotherm (UV) is drawn across two-phase region to intersect the boundaries of the region.
- - Perpendiculars are dropped from these intersections to the composition axis, represented by  $U'$  and  $V'$ , from which each of each phase is read.  $U'$  represents composition of liquid phase and  $V'$  represents composition of solid phase as intersection U meets liquidus line and V meets solidus line.

## Tie line – Lever rule (cont.....)

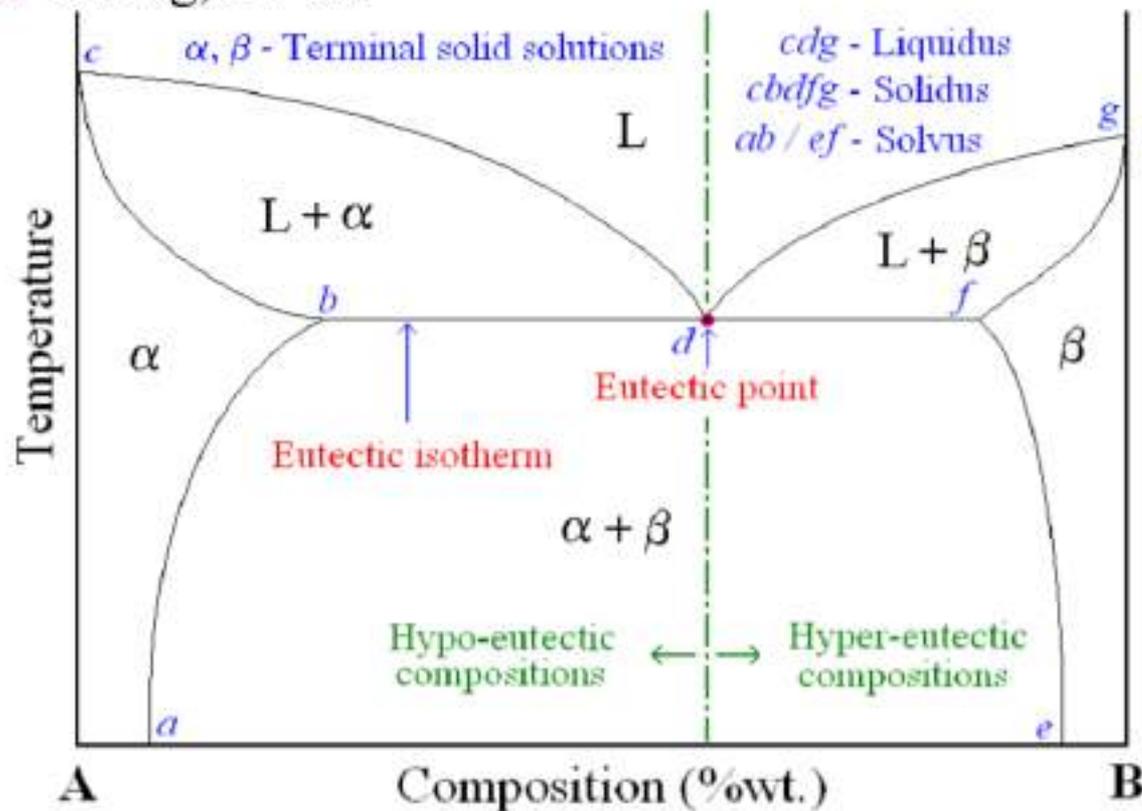
- Procedure to find equilibrium relative amounts of phases (lever rule): - A tie-line is constructed across the two phase region at the temperature of the alloy to intersect the region boundaries.
- The relative amount of a phase is computed by taking the length of tie line from overall composition to the phase boundary for the other phase, and dividing by the total tie-line length. In previous figure, relative amount of liquid and solid phases is given respectively by:

$$C_L = cV/UV \quad C_S = Uc/UV \quad C_L + C_S = 1$$

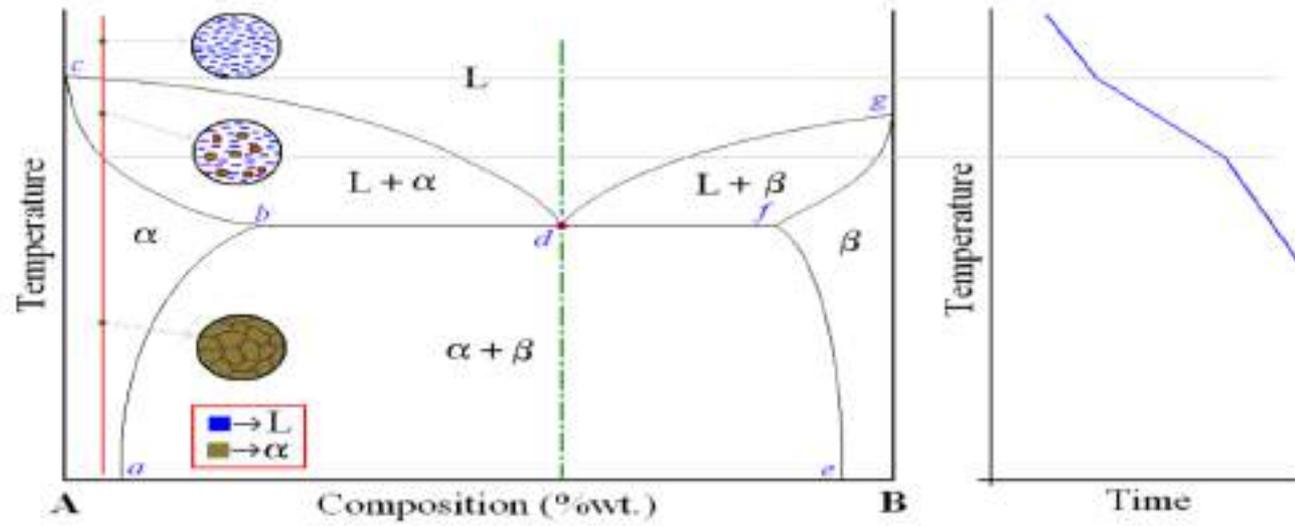
## Eutectic binary system

- Many of the binary systems with limited solubility are of eutectic type – eutectic alloy of eutectic composition solidifies at the end of solidification at eutectic temperature.

E.g.: Cu-Ag, Pb-Sn

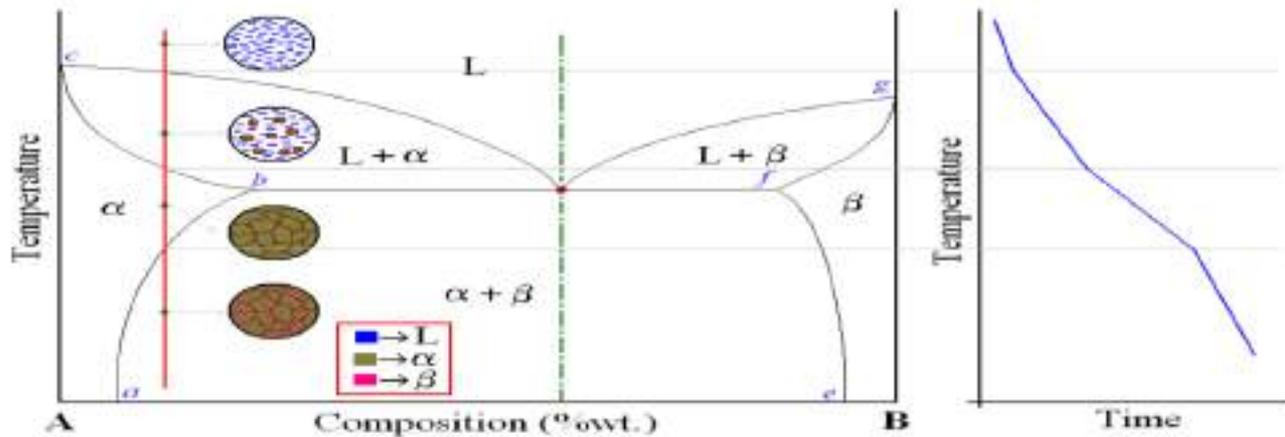


## Eutectic system – Cooling curve – Microstructure



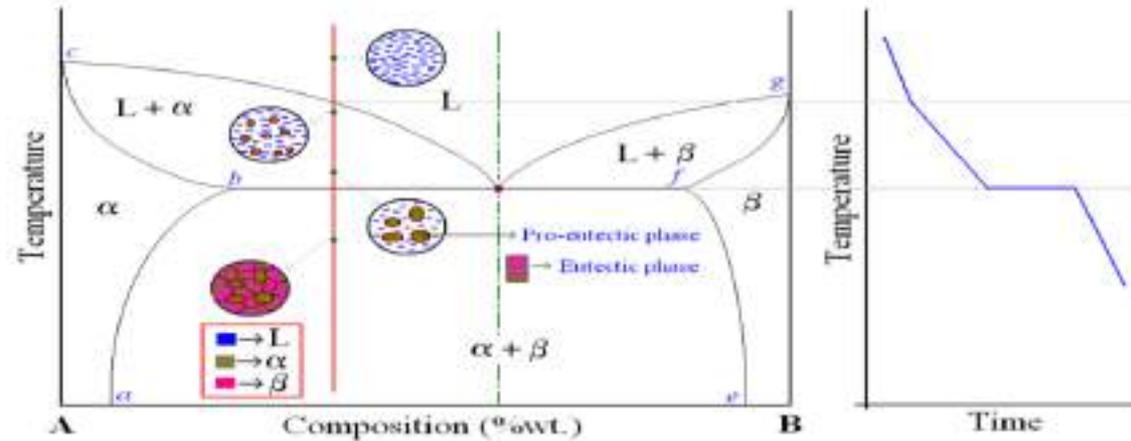
Stage-1

## Eutectic system – Cooling curve – Microstructure (contd....)

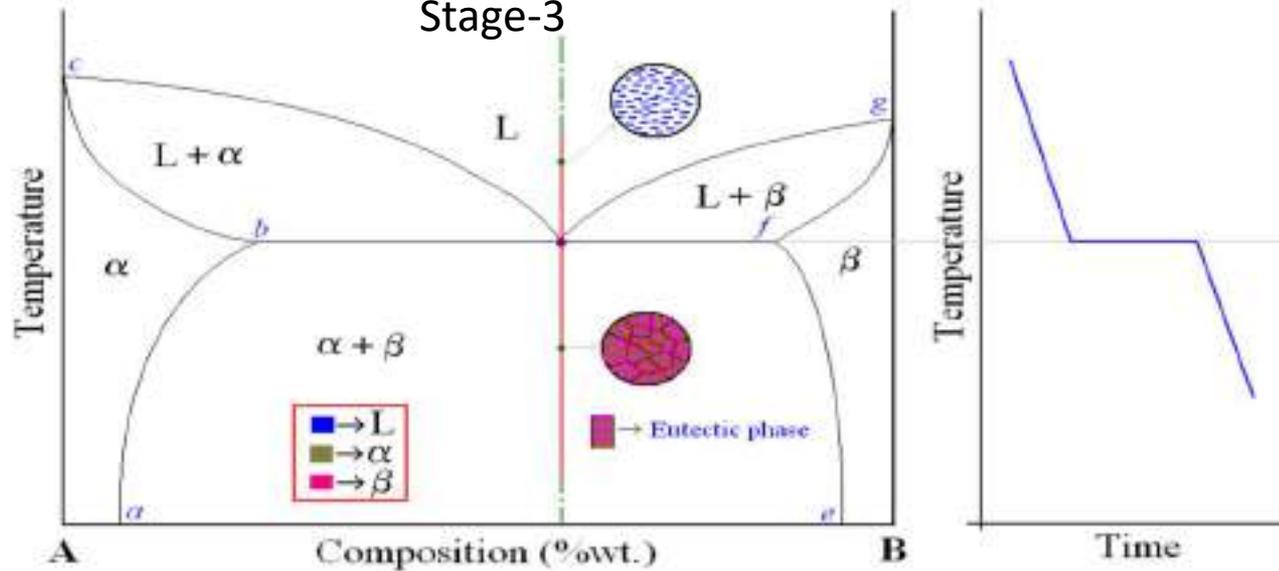


Stage-2

## Eutectic system – Cooling curve – Microstructure (contd....)



Stage-3



Stage-4

## Various reactions in phase diagram

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	$L_1 + L_2 \rightarrow \alpha$		

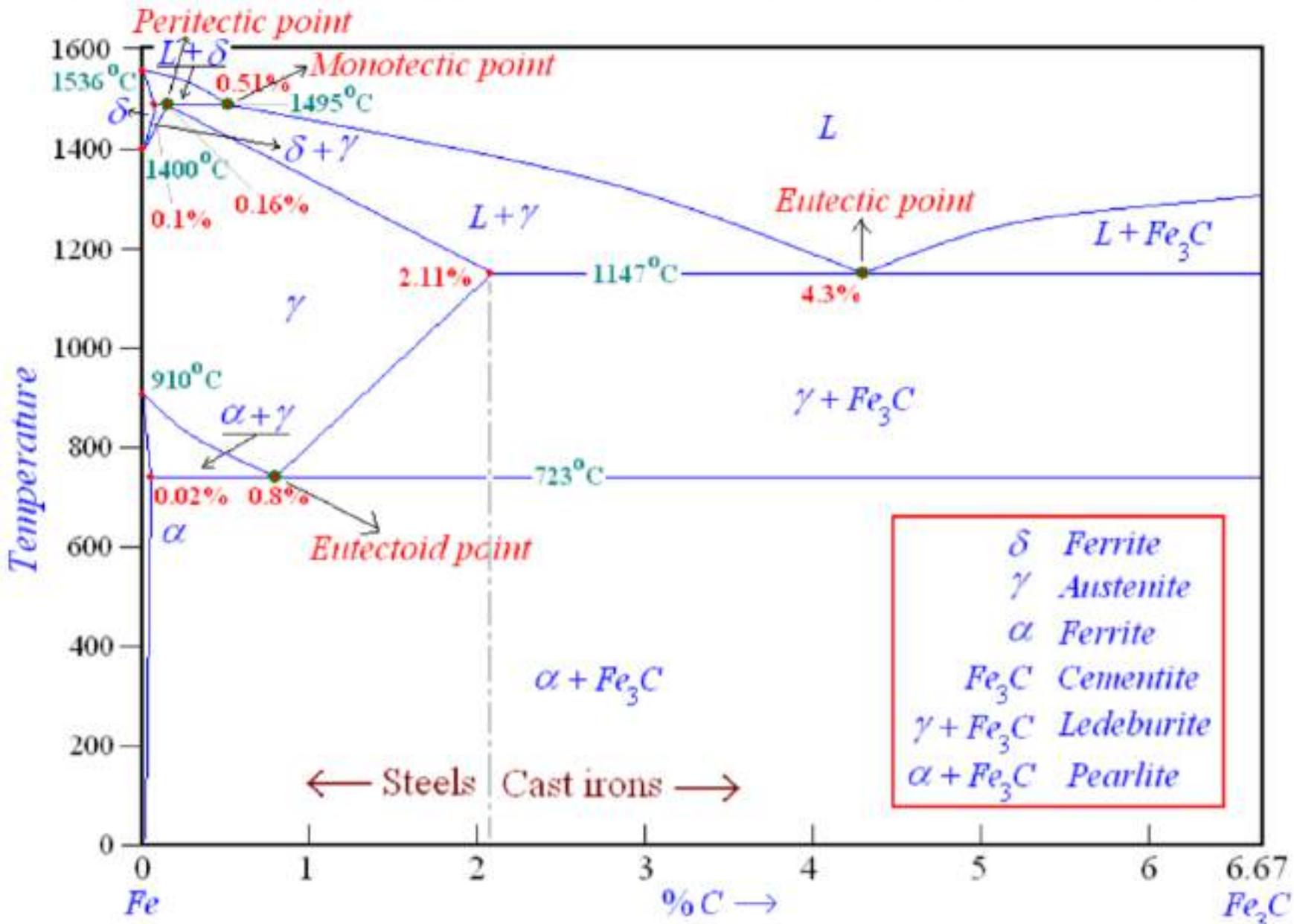
## Precipitation – Strengthening – Reactions

*Solutionizing (solution heat treatment)*, where the alloy is heated to a temperature between solvus and solidus temperatures and kept there till a uniform solid-solution structure is produced.

*Quenching*, where the sample is rapidly cooled to a lower temperature (room temperature). Resultant product – supersaturated solid solution.

*Aging* is the last but critical step. During this heat treatment step finely dispersed precipitate particle will form. Aging the alloy at room temperature is called natural aging, whereas at elevated temperatures is called artificial aging. Most alloys require artificial aging, and aging temperature is usually between 15-25% of temperature difference between room temperature and solution heat treatment temperature.

# Fe-C binary system – Phase transformations



## Fe-C binary system – Phase transformations (contd....)

- Fe-Fe<sub>3</sub>C phase diagram is characterized by *five individual phases*,:  $\alpha$ -ferrite (BCC) Fe-C solid solution,  $\gamma$ -austenite (FCC) Fe-C solid solution,  $\delta$ -ferrite (BCC) Fe-C solid solution, Fe<sub>3</sub>C (iron carbide) *or* cementite - an inter-metallic compound and liquid Fe-C solution **and** *four invariant reactions*:
- peritectic reaction at 1495 C and 0.16%C,  $\delta$ -ferrite +  $L \leftrightarrow \gamma$ -iron (austenite)
  - monotectic reaction 1495 C and 0.51%C,  $L \leftrightarrow L + \gamma$ -iron (austenite)
  - eutectic reaction at 1147 C and 4.3 %C,  $L \leftrightarrow \gamma$ -iron + Fe<sub>3</sub>C (cementite) [ledeburite]
  - eutectoid reaction at 723 C and 0.8%C,  $\gamma$ -iron  $\leftrightarrow \alpha$ -ferrite + Fe<sub>3</sub>C (cementite) [pearlite]

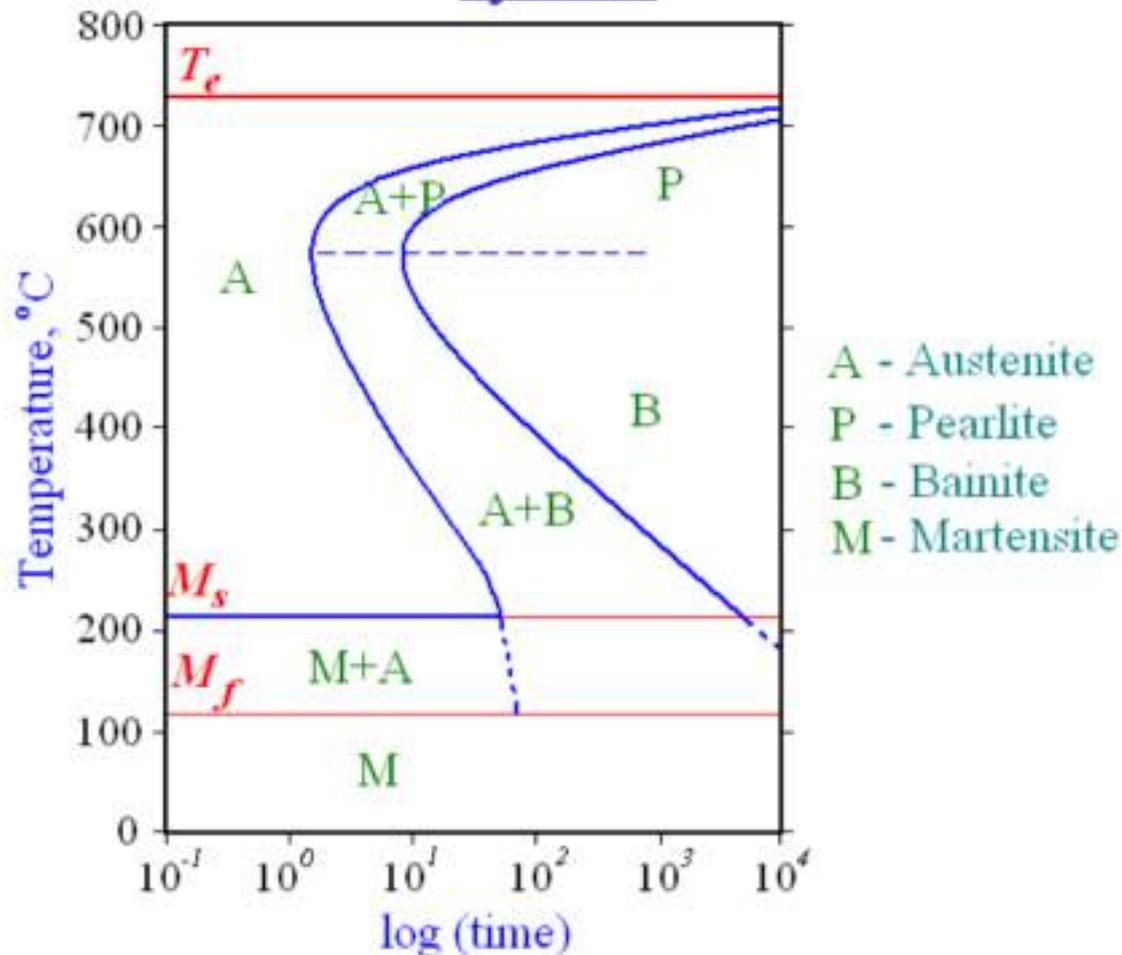
## Fe-C alloy classification

- Fe-C alloys are classified according to wt.% C present in the alloy for technological convenience as follows:

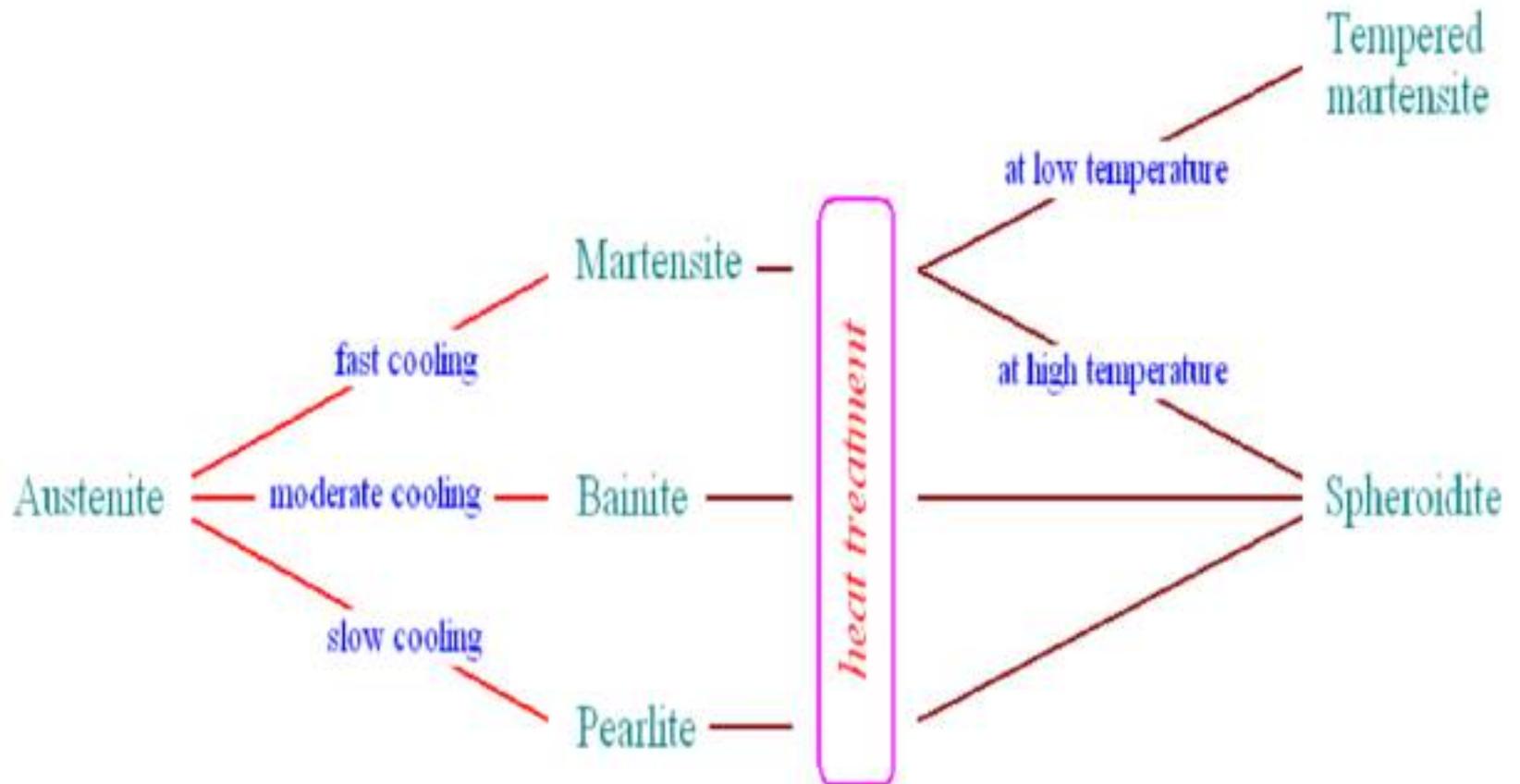
Commercial pure irons	$\% C < 0.008$
Low-carbon/mild steels	$0.008 - \%C - 0.3$
Medium carbon steels	$0.3 - \%C - 0.8$
High-carbon steels	$0.8 - \%C - 2.11$
Cast irons	$2.11 < \%C$

- Cast irons that were slowly cooled to room temperature consists of cementite, look whitish – *white cast iron*. If it contains graphite, look grayish – *gray cast iron*. It is heat treated to have graphite in form of nodules – *malleable cast iron*. If inoculants are used in liquid state to have graphite nodules – *spheroidal graphite (SG) cast iron*.

## TTT diagram for eutectoid transformation in Fe-C system



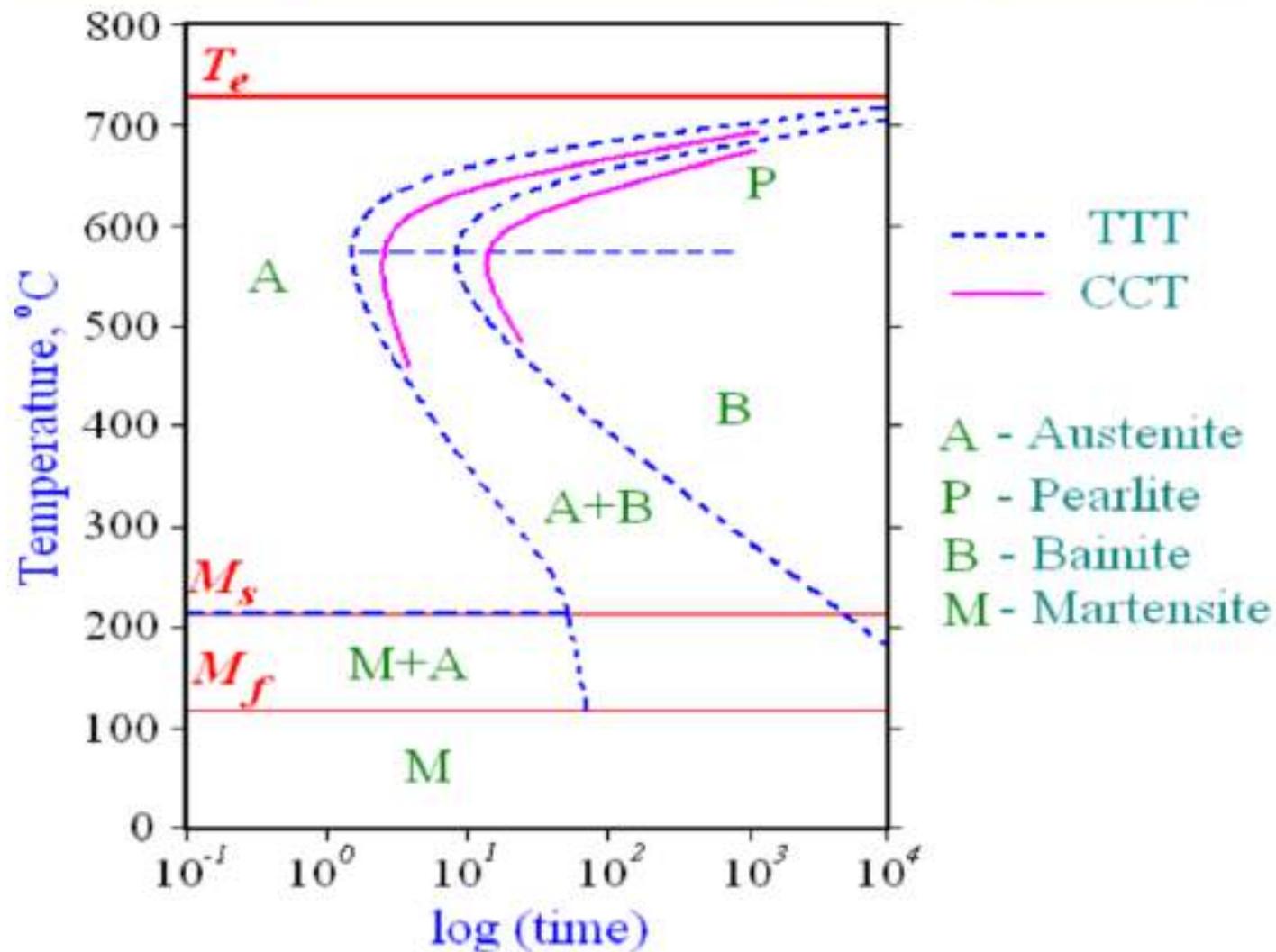
# Transformations involving austenite for Fe-C system



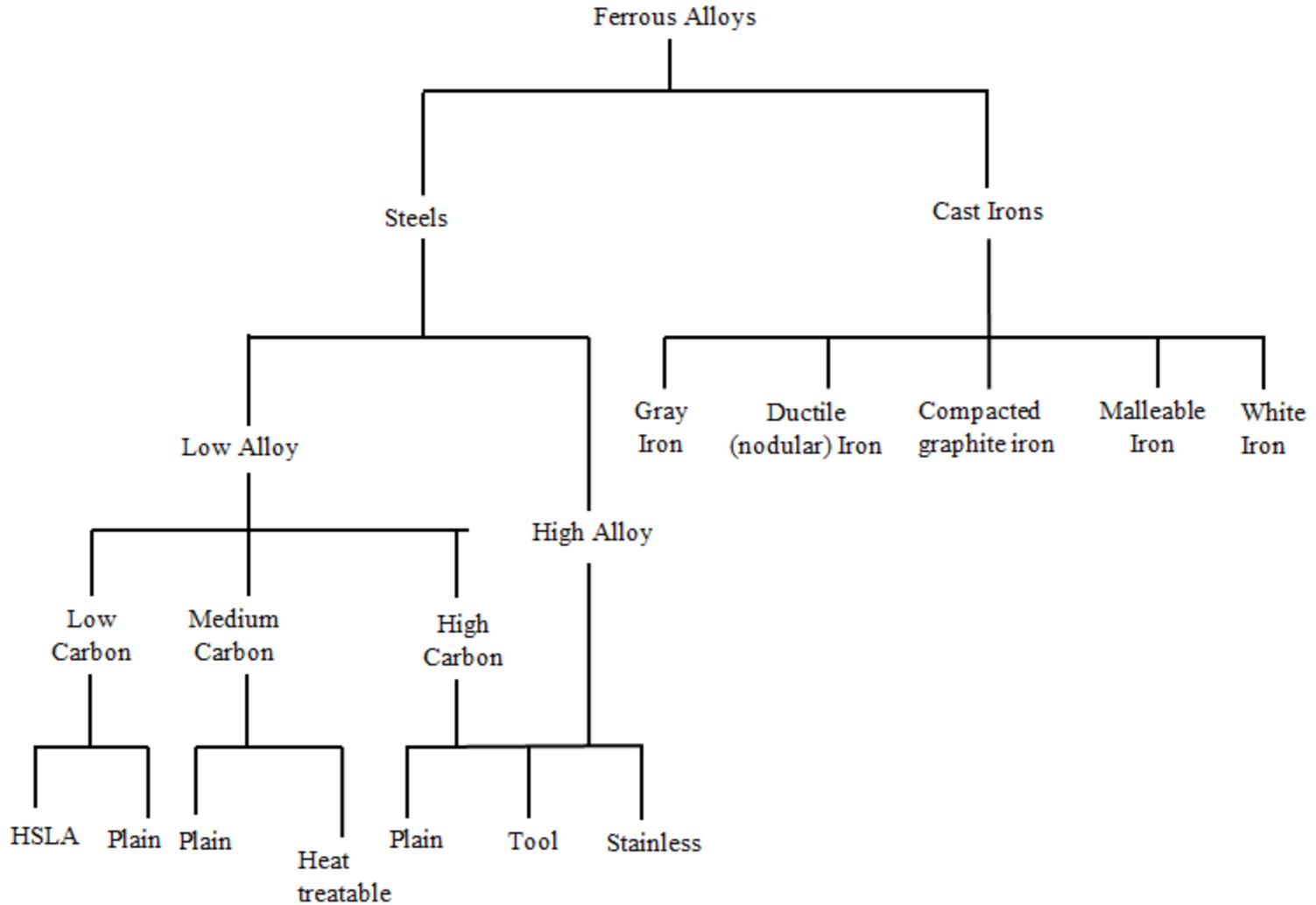
## CCT diagram for Fe-C system

- TTT diagram though gives very useful information, they are of less practical importance since an alloy has to be cooled rapidly and then kept at a temperature to allow for respective transformation to take place.
- Usually materials are cooled continuously, thus Continuous Cooling Transformation diagrams are appropriate.
- For continuous cooling, the time required for a reaction to begin and end is delayed, thus the isothermal curves are shifted to longer times and lower temperatures.
- Main difference between TTT and CCT diagrams: no space for bainite in CCT diagram as continuous cooling always results in formation of pearlite.

## CCT diagram for Fe-C system (contd....)



# Classification of various ferrous alloys



## Low carbon steel

This type of steel generally contain less than about 0.25wt% C and are unresponsive to heat treatment.

- Microstructure consist of ferrite and pearlite constituent
- These alloy are relatively soft and weak but have good ductility and toughness , in addition they are machinable, weldable, and all steel are least expensive to produce.
- Application- pipeline , buildings , bridges, tin cane etc

**Medium carbon steel** have carbon concentration between about 0.25 and 0.60wt %C

These steel are heat treated by austenitizing quenching and tempering to improve there mechanical properties.

Addition of cromium nickel and molybdenum improve capacity of these alloys to be heattreated.

Application –Railway wheel, track, gear, crankshaft and other machine part etc.

**High carbonsteel-** High carbon steel , normally carbon content between 0.60 and 1.4wt%C are hardest , strongest and least ductile carbon steels.

Tool and die steel are highcarbon alloy usually containg cromium ,vanadium , tungsten and molybdenum

Application- Cutting tool , dies, knives,razor, spring etc

- **Stainless steel**

Stainless steels generally contain between 10-20% chromium as the main alloying element and are valued for high corrosion resistance. With over 11% chromium, steel is about 200 times more resistant to corrosion than mild steel. These steels can be divided into three groups based on their crystalline structure:

**Austenitic:** Austenitic steels are non-magnetic and non-heat-treatable, and generally contain 18% chromium, 8% nickel and less than 0.8% carbon.

[Austenitic steels](#) form the largest portion of the global stainless steel market and are often used in food processing equipment, kitchen utensils, and piping.

**Ferritic:**[Ferritic steels](#) contain trace amounts of nickel, 12-17% chromium, less than 0.1% carbon, along with other alloying elements, such as molybdenum, aluminum or titanium. These magnetic steels cannot be hardened by [heat treatment](#) but can be strengthened by cold working.

**Martensitic:** Martensitic steels contain 11-17% chromium, less than 0.4% nickel, and up to 1.2% carbon. These magnetic and heat-treatable steels are used in knives, cutting tools, as well as dental and surgical equipment.

# Tool Steels

- Tool steels contain [tungsten](#), molybdenum, [cobalt](#) and vanadium in varying quantities to increase heat resistance and durability, making them ideal for cutting and drilling equipment.
- [Steel products](#) can also be divided by their shapes and related applications:
- Long/Tubular Products include bars and rods, rails, wires, angles, pipes, and shapes and sections. These products are commonly used in the automotive and construction sectors.
- Flat Products include plates, sheets, coils, and strips. These materials are mainly used in automotive parts, appliances, packaging, shipbuilding, and construction.
- Other Products include valves, fittings, and flanges and are mainly used as piping materials.

**Cast Iron-** Cast iron are a class of ferrous alloy with carbon content above 2.14wt% .

- Most of the cast iron contain 3.0-4.5wt% C
- Its melting point approximately 1150 & 1300 °C which is lower than the steel , so it is easily melted amenable to casting.
- Cast iron are very brittle , therefore casting is most convenient fabrication technique.
- Most common cast iron type are gray ,nodular ,white malleable compacted graphite.

**Gray cast iron** – Iron consist of carbon 2.5-4.0wt%C & silicon 1.0 & 3.0 wt%C form a gray cast iron.

- Mechanically ,gray iron is comparatively weak and brittle in tension
- It is very useful , in damping vibration energy
- Gray iron exhibit high resistance to wear.
- Furthermore , in molten state they have high fluidity at casting temperature, which permits casting piece having intricate shape

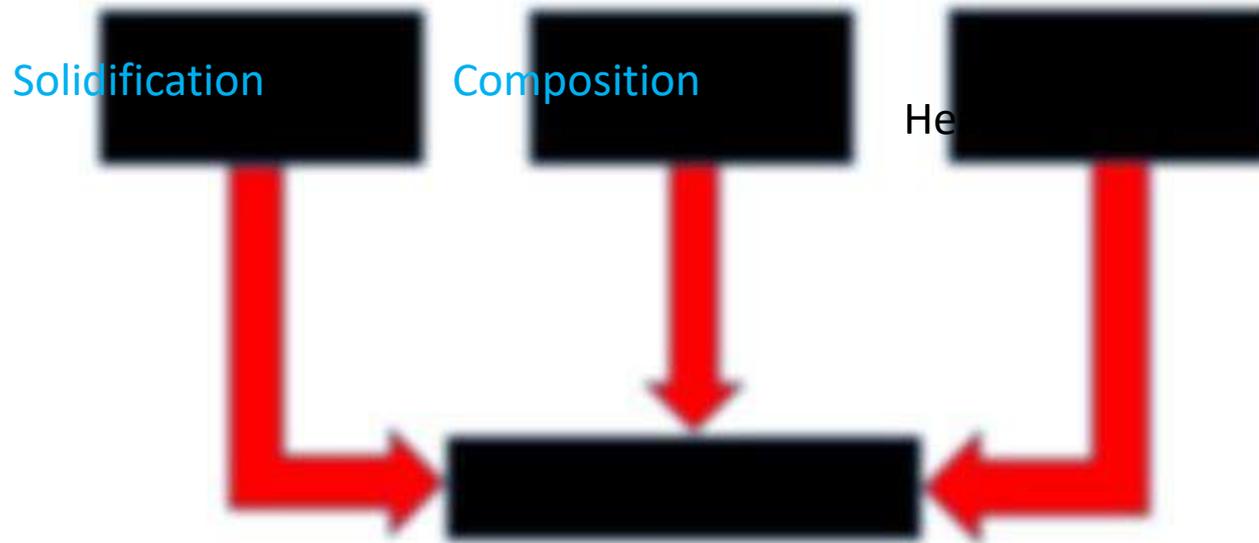
**Ductile Iron-** Adding small amount of magnesium and cerium to gray iron before casting produces a distinctly different microstructure & set of mechanical properties.

- Graphite form in nodular or sphere like particle instead of flakes.
- Casting are stronger and much more ductile than gray iron
- Application- valve, pump bodies, crank shaft, gears etc.

**White iron and malleable Iron-** For low –silicon cast iron (containing less than 1.0wt%Si) and rapid cooling rate ,most of the carbon exist as cementite instead of graphite.

- An optical photomicrograph showing the micro structure of white iron is presented
- As a consequence of large amount of cementite phase white iron is extremely hard but also very brittle , to the point of being virtually un-machinable.
- Its use is limited to application that necessitate a very hard and wear resistance surface, without a high degree of ductility
- Ex- Rollers in rolling mills.

# Heat treatment process :



**Heat treatment process** -Definition:Heat Treatment can be defined as a combination of Heating and Cooling Operations carried out on a metal or alloy in the solid state so as to produce a Particular Microstructure and hence the Desired Properties.

- Generally the Composition is fixed and the Solidification is also completed the only way to change the properties is by Heat treatment.
- Heat Treatment effectively alters the Size and Shape of the Grains and also type (SCC, BCC, FCC, HCP etc) and Distribution of grains hence the PROPERTIES

## Objectives Heat Treatment

- To improve the Mechanical Properties.
- To improve Machinability.
- To increase Wear Resistance.
- To modify Electrical & Magnetic Properties.
- To Refine the Grains.
- To produce Hard Surfaces & Soft Inner Core.
- To Relieve Internal (Residual) Stress due to Mechanical Working.
- To Over come effects of Strain Hardening & Restore Ductile Property.

## Various Stages of Heat Treatment Process

- Stage1: Heating the metal or the alloy to the prescribed temperature.
- Stage2: Holding the specimen at that temperature for a known time period (holding time or Soaking time-depends upon the thickness of the specimen).
- Stage3: Cooling at a rate (Slow or Rapid rate) necessary to obtain a specific microstructure for the desired properties (Furnace Cooling, Air cooling, Water Cooling, Oil cooling, & Ice cooling).

# Types of Heat Treatment

- 1. Annealing Process
  - a. Full Annealing process.
  - b. Partial Annealing Process
  - c. Spheroidising Annealing Process
- 2. Normalizing
- 3. Hardening
- 4. Tempering
  - e. Austemperingg.
  - f. Martempering

## Type of surface heat treatment process

1. Case hardening (involves an intentional built up or addition of a new layer with increase in part dimensions)

(i) Carburizing

(a) Pack Carburizing

(b) Gas Carburizing.

(c) Liquid Carburizing

(ii) Cyaniding

(iii) Nitriding

2. Surface hardening-(surface or sub-surface modification without any intentional built up or increase in part dimensions)

(i) Flame hardening

(ii) Induction hardening

**Annealing process-** Objective of annealing process is to soften the metal, to refine its grain structure, to relieve stress and remove gases trapped in metal. This process consists of heating the steel  $30^{\circ}\text{C}$ -  $50^{\circ}\text{C}$  above the upper critical temperature. The steel is held at this temperature for sometime to enable internal changes to take place. The time allowed is approximately 3 to 4 minutes, and then slowly cooled in furnace.

**Normalizing process-** The process in which steel heat up  $30^{\circ}\text{C}$ -  $50^{\circ}\text{C}$  above upper critical temperature, then it is held at this temp. for 15 minutes and then allow cool down in steel air.

This process provide a homogeneous structure consisting of ferrite and pearlite, homogeneous structure provide higher yield point, ultimate tensile strength.

**Spherodising process-** it is a particular type of annealing in which cementite in granular form is produced in the structure of steel, this is usually applied to high carbon tool steel, which are difficult to machine. The operation consists of heating steel up to a temperature slightly above the lower critical temp. ( $730^{\circ}\text{C} - 770^{\circ}\text{C}$ ). It is held at this temp. for sometime and then cooled slowly to temp.  $600^{\circ}\text{C}$ .

The spherodising improves the machinability of steel, but lowers the hardness and tensile strength. The steel have better elongation properties than normally annealed steel.

**Hardening process-** the main objective of are to increase the hardness of the metal ,so that it can resist wear. The metal up to a temp of  $30^{\circ}\text{c}$ - $50^{\circ}\text{c}$  above upper critical temp. A rapid cooling form the hardening temp. Cause the austenite to be transformed into another constituent called martensite, which is very hard and brittle.

**Tempering-** the main objective of tempering is to reduce brittleness of hardened steel and thus to increase in ductility.

Steel is heated to low tempering temp( $200^{\circ}\text{c}$ - $250^{\circ}\text{c}$ ), the internal stress are reduced and ductility increases.

**Carburising**- The process of introducing carbon to low carbon steel , in order to give hard surface is called carburising.

In this process , the article to be placed in a carburising box which is filled with carbon dust, and the process is kept at elevated temperature for specified period , during heating carbon monoxide gas is formed which reacts with article to form carbon and carbon dioxide gas. The article absorbs carbon into the body of article.

**Nitriding process**- this is also surface hardening process , in this process nitrogen gas is employed in order to obtain hard surface of the steel . This process is commonly used for those steel , which is alloyed with chromium , molybdenum,aluminium etc. the nitriding process is generally carried out in electric furnace with the temp. of  $450^{\circ}\text{c}$ - $550^{\circ}\text{c}$  .the container with the article is placed in the furnace and ammonia gas is passed through it. The ammonia gas when come in contact with steel article get dissociated in the form of nitrogen , which react with surface of article and formed nitride which is very hard

**Cyaniding-** (also called liquid carburising) in process surface hardening is done with both carbon and nitrogen are absorbed by the metal surface to get harden . A piece of low carbon steel is immersed in a bath of cyanide salt maintained temp. of 850°c-950°c.

**Flame hardening-** sometime , a particular portion of an article is required to be hardened . This is generally done in case of portion subject to wear , abrasion or shock. This type of local hardening is done by a process , known as flame hardening .in this process the portion , to be hardened ,is heated with the help of flame or oxyacetylene torch above its critical temp.

**Induction hardening** - it is the process of surface hardening in which surface to be hardened , is surrounded by an inductor block which act as a primary coil of transformer. The inductor blok should not touch the surface to be hardened ,A high frequency current is passed through this block .the heating effect is due to induced eddy current and hysteresis losses in the surface material.

# Optical property of material

## Content

- 1) Basic concepts
- 2) Optical properties of metals
- 3) Optical properties of non-metals
- 4) Applications of optical phenomena C

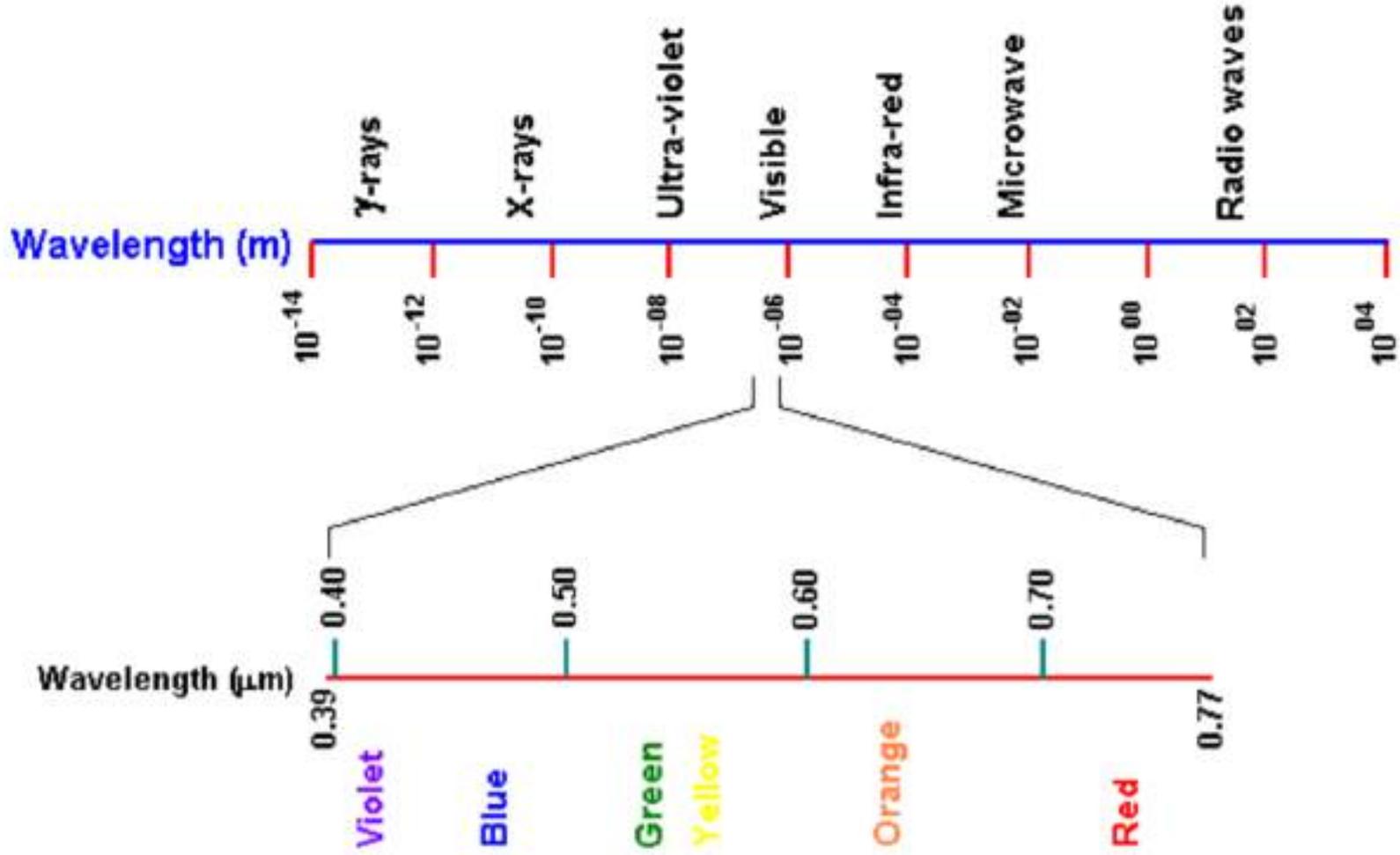
# Introduction

- Engineering materials are important in everyday life because of their versatile structural properties.
- Other than these properties, they do play an important role because of their physical properties.
- Prime physical properties of materials include: electrical properties; thermal properties; magnetic properties; and optical properties.
- The optical properties of engineering materials are useful in different applications.
- Ex.: domestic, medicine, astronomy, manufacturing

## Cont.

- Optical property of a material is defined as its interaction with electro-magnetic radiation in the visible.
- Electromagnetic spectrum of radiation spans the wide range from  $\gamma$ -rays with wavelength as 10-12 m, through x-rays, ultraviolet, visible, infrared, and finally radio waves with wavelengths as long as 105 m.
- Visible light is one form of electromagnetic radiation with wavelengths ranging from 0.39 to 0.77  $\mu\text{m}$ .
- Light can be considered as having waves and consisting of particles called photons.

# Electro-magnetic radiation



## Material – Light interaction

- Interaction of photons with the electronic or crystal structure of a material leads to a number of phenomena.
- The photons may give their energy to the material (absorption); photons give their energy, but photons of identical energy are immediately emitted by the material (reflection); photons may not interact with the material structure (transmission); *or* during transmission photons are changes in velocity (refraction).
- At any instance of light interaction with a material, the total intensity of the incident light striking a surface is equal to sum of the absorbed, reflected, and transmitted intensities i.e.

$$I_0 = I_A + I_R + I_T$$

## Optical materials

- Materials are classified on the basis of their interaction with visible light into three categories.
- Materials that are capable of transmitting light with relatively little absorption and reflection are called *transparent materials* i.e. we can see through them.
- *Translucent materials* are those through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.
- Those materials that are impervious to the transmission of visible light are termed as *opaque materials*. These materials absorb all the energy from the light photons.

## Optical properties - Metals

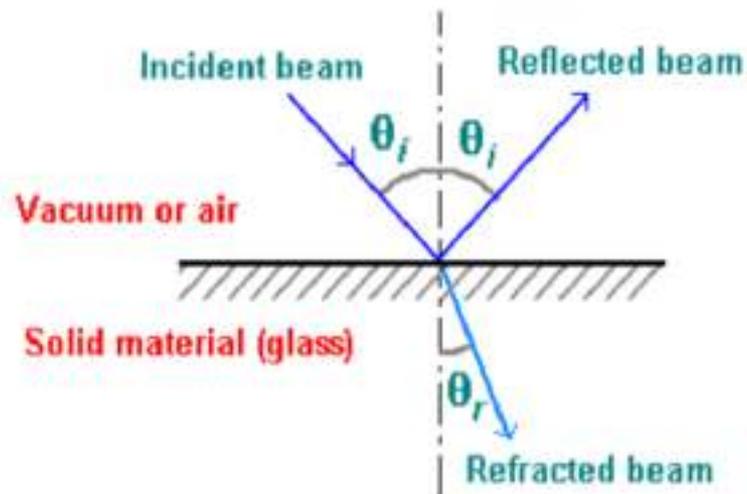
- Metals consist partially filled high-energy conduction bands.
- When photons are directed at metals, their energy is used to excite electrons into unoccupied states. Thus metals are opaque to the visible light.
- Metals are, however, transparent to high end frequencies i.e. x-rays and  $\gamma$ -rays.
- Absorption of takes place in very thin outer layer. Thus, metallic films thinner than  $0.1 \mu\text{m}$  can transmit the light.
- The absorbed radiation is emitted from the metallic surface in the form of visible light of the same wavelength as reflected light. The reflectivity of metals is about 0.95.

## Optical properties – Non-metals

- Non-metallic materials consist of various energy band structures. Thus, all four optical phenomena are important.
- Refraction: when light photons are transmitted through a material, they cause polarization of the electrons and in turn the speed of light is reduced and the beam of light changes direction.

$$n = \frac{c_0}{c}$$

$$n = \frac{\sin \theta_i}{\sin \theta_r}$$



## Reflection

- Reflectivity is defined as fraction of light reflected at an interface.

$$R = \frac{I_R}{I_0}$$

- If the material is in other material with refractive index  $n_i$

$$R = \left( \frac{n - n_i}{n + n_i} \right)^2$$

- Materials with a high index of refraction have a higher reflectivity than materials with a low index. Because the index of refraction varies with the wavelength of the photons, so does the reflectivity.
- In metals, the reflectivity is typically on the order of 0.90-0.95, whereas for glasses it is close to 0.05. The high reflectivity of metals is one reason that they are opaque. High reflectivity is desired in many applications including mirrors, coatings on glasses, etc.

## Absorption

- When a light beam is impinged on a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material.
- Bouguer's law: The fraction of beam that is absorbed is related to the thickness of the materials and the manner in which the photons interact with the material's structure.

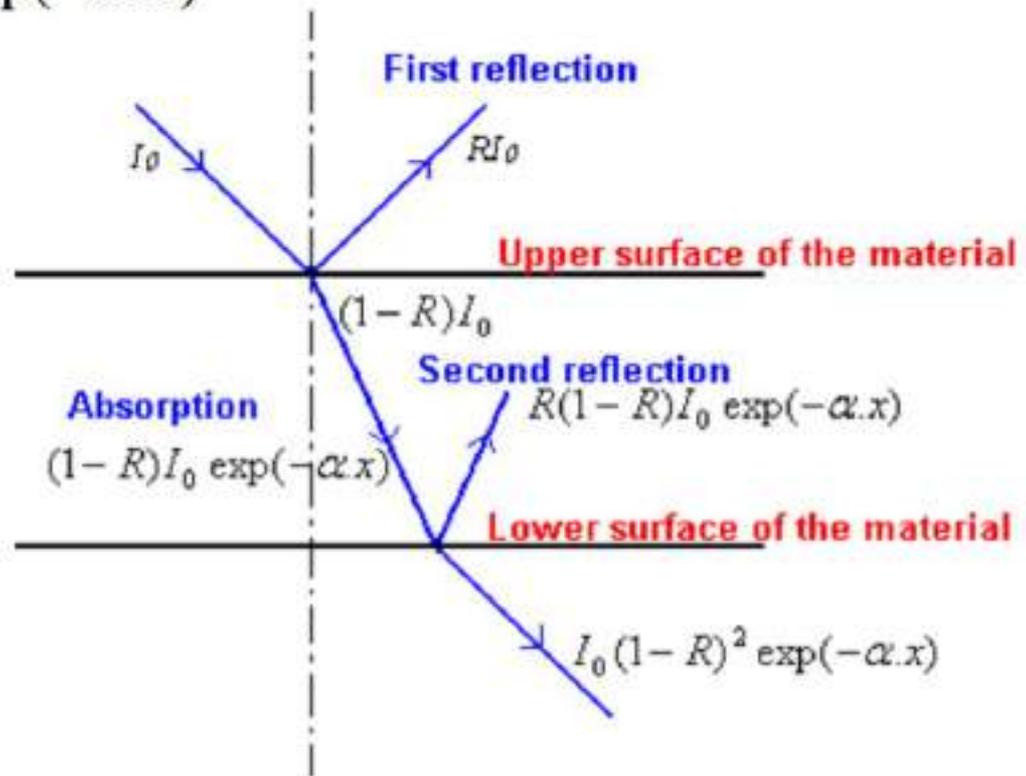
$$I = I_0 \exp(-\alpha \cdot x)$$

- Absorption occurs by two mechanisms: Rayleigh scattering and Compton scattering.

## Transmission

- Fraction of light beam that is not reflected or absorbed is transmitted through the material.

$$I_t = I_0(1 - R)^2 \exp(-\alpha \cdot x)$$



## Thermal emission

- When a material is heated, electrons are excited to higher energy levels, particularly in the outer energy levels where the electrons are less strongly bound to the nucleus.
- These excited electrons, upon dropping back to the ground state, release photons in process what is called thermal emission.
- During thermal emission a continuous spectrum of radiation is emitted with a minimum wavelength and the intensity distribution is dependent on the temperature.
- Higher the temperature, wider will be the range of wavelengths emitted. By measuring the intensity of a narrow band of the emitted wavelengths with a pyrometer, material's temperature can be estimated.

## Optical applications

- Light interacts with a material in many ways.
- Depending on the material, its crystal-/micro-structure, and also on the characteristics of incident light, there are many peculiar phenomena occurs, which are known as *optical phenomena*. These include:
  - luminescence
  - lasers
  - thermal emission
  - photo-conductivity
  - optical fibers
- All these find quite many applications in technology for every day life

## Lasers

- Laser is an acronym for *light amplification by stimulated emission of radiation*. It is in fact special application of luminescence.
- Unlike most radiation processes, such as luminescence, which produce incoherent light, the light produced by laser emission is coherent.
- This is based on the fact that in certain materials, electrons excited by a stimulus produce photons which in turn excite additional photons of identical wavelength.
- Lasers are useful in many applications such as welding, metal cutting, heat treatment, surgery, mapping, reading compact disks, etc. **Ex.:** Ruby, single crystal of  $\text{Al}_2\text{O}_3$  doped with little amount of  $\text{Cr}_2\text{O}_3$ ; yttrium aluminium garnet ( $\text{Y}_3\text{Al}_5\text{O}_{12}$  – YAG) doped with neodymium, Nd;  $\text{CO}_2$  gas; He-Ne gas; some semi-conductors like GaAs and InGaAsP.

## Photo-conductivity

- Bombardment of semiconductors by photons, with energy equal to greater than the band gap, may result in creation of electron-hole pairs that can be used to generate current. This process is called photo-conductivity.
- It is different from photo-electric effect in the sense that an electron-hole pair is generated whose energy is related to the band gap energy instead of free electron alone whose energy is related to the Fermi level.
- The current produced in photo-conductivity is directly related to the incident light intensity.
- This phenomenon is utilized in photographic light meters. Cadmium sulfide (CdS) is commonly used for the detection of visible light, as in light meters.
- Photo-conductivity is also the underlying principle of the photo-voltaic cell, known to common man as solar cell, used for conversion of solar energy into electricity.

## Optical fibers

- Optical fibers have revolutionized the communication industry.
- It primarily consists of core, cladding and coating. The core transmits the signals, while the cladding constrains the light beam to the core; outer coating protects the core and cladding from the external environment.
- Typically both the core and cladding are made of special types of glass with carefully controlled indices of refraction.
- The indices of refraction are selected such that

$$n_{cladding} < n_{core}$$

- Once the light enters the core from the source, it is reflected internally and propagates along the length of the fiber.
- Internal reflection is accomplished by varying the index of refraction of the core and cladding glass materials. Usually two designs are employed in this regard.

## Types of optical fibers

- In step-index optical fiber, there is a sharp change in refractive index between the core and cladding. In this design output pulse will be broader than the input one. It is because light rays traveling in different trajectories have a variety of path lengths.
- It is possible to avoid pulse broadening by using graded-index fiber. This results in a helical path for the light rays, as opposed to zig-zag path in a step-index fiber.
- Here impurities such as boron oxide ( $B_2O_3$ ) or germanium dioxide ( $GeO_2$ ) are added to the silica glass such that the index of refraction varied gradually in parabolic manner across the cross section. This enables light to travel faster while close to the periphery than at the center. This avoids pulse broadening.
- Both step- and graded- index fibers are termed as multi-mode fibers. Third type optical fiber is called single-mode fiber in which light travels largely parallel to the fiber axis with little distortion of the digital light pulse. These are used for long transmission lines.

## Optical fiber properties

- Core and cladding materials are selected not only on the basis of their refractive indices, but also on basis of ease of manufacturability, light loss, mechanical strength properties and dispersion properties.
- However, density ( $\rho$ ) and refractive index ( $n$ ) are critical. These two parameters are related approximately as

$$n = \frac{\rho + 10.4}{8.6}$$

- High-purity silica-based glasses are used as fiber material, with fiber diameter ranging from 5 to 100  $\mu\text{m}$ .
- The fibers are carefully fabricated to be virtually free from flaws.