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New Scheme Based On AICTE Flexible Curricula
Mechanical Engineering, III-Semester
ME-302 Materials Technology

1. Solidification of metals , Crystallisation, Crystal and amorphous , different types of bonds in different metals, Crystallography. Stability and metastability of metals. Different mechanical properties of metals and other engineering materials like strength, hardness, elasticity, plasticity, Malleability, Ductility, Creep, Fatigue etc. Introduction to industrial metals, steels and prevailing manufacturing methods by manufacturers.
2. Cooling curves, Isomorphous, Utectic, Eutectoid , Eutectoid solid solution, Peritectic and other phase diagrams, Alloying , Characteristics of alloying elements, Iron – Carbon phase diagram, T-T-T diagrams, Types of Cast Iron. Types of Stainless Steels, Elastic, anelastic and Viscoelastic behaviour.
3. Heat treatment of metals, Based on phase diagram and T-T-T-Diagram the heat treatment of various metals, Bulk heat treatments, surface heat treatments, Case carburising, Types of Annealing, Normalising, Spherodising, Phase Transformations like Parlite, Cementite, Austenite, Troostite, Bainite, Hard and soft Martensite etc. Laser hardening, Cyniding, Boriding, Nitriding, Flame hardening, Ion implantation, Etc. Heat treatment cycles. Metallographic studies, Optical Microscope, Electron Microscope.
4. Destructive and non-destructive testing methods, Tensile test, Compression test, shear test, bend test, Different types of Hardness tests, Impact tests, Fatigue tests, Hardenability test. Fracture analysis, NDT Methods. Different properties of Steels, Aluminium and it's alloys, Copper and it's alloys, Manganese and it's alloys, Chromium and it's alloys, Nickel and it's alloys.
5. Chemical Analysis of different alloying elements in commercial metals, C, Fe, Cr, Ni, Mn, Mg, S, P, Co, Mo, Etc. Different chemical reagents, Equipments , Volumetric and Gravimetric analysis, Spot test, Colorimetric methods, Optical and spectrophotometric analysis.

References :

1. V. Raghwan, Material Science
2. G.E.Dieter, Mechanical Metallurgy
3. P Chalmers, Physical Metallurgy
4. R. C.Rollason, Metallurgy for mechanical engineers

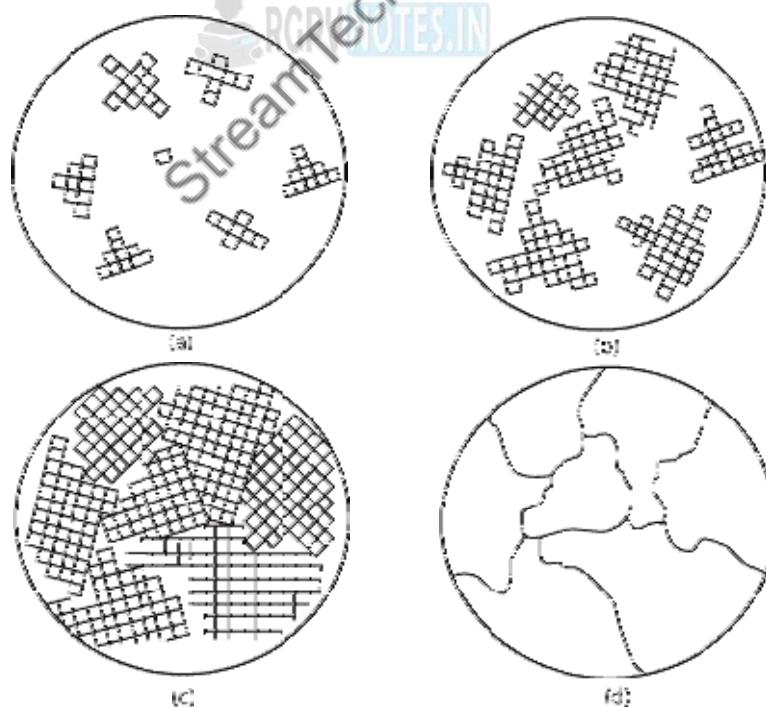
Unit I: Crystal Atoms of Solid

- Solidification of metals, Crystallization, Crystal and amorphous, different types of bonds in different metals, Crystallography. Stability and metastability of metals.
- Different mechanical properties of metals and other engineering materials like strength, hardness, elasticity, plasticity, Malleability, Ductility, Creep, Fatigue etc.
- Introduction to industrial metals, steels and prevailing manufacturing methods by manufacturers.

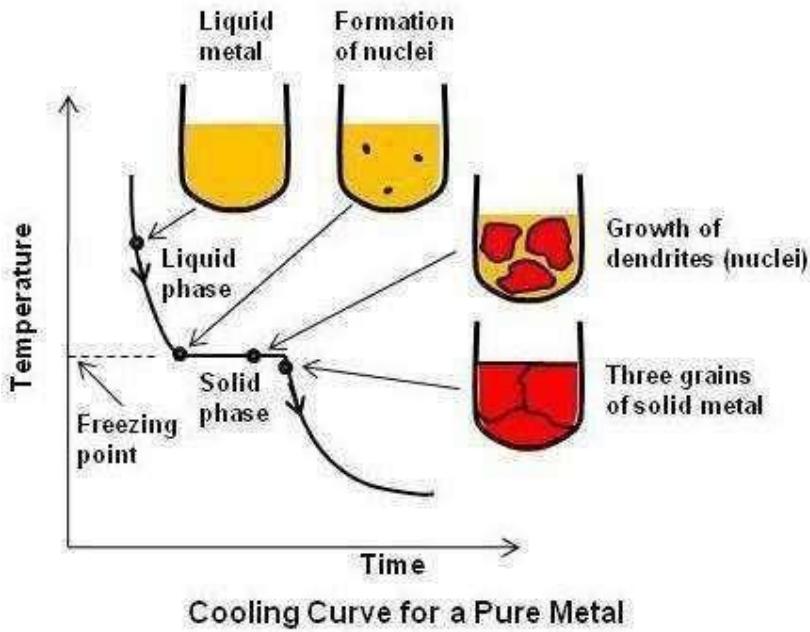
Solidification

The crystallization of a large amount of material from a single point of nucleation results in a single crystal. In engineering materials, single crystals are produced only under carefully controlled conditions. The expense of producing single crystal materials is only justified for special applications, such as turbine engine blades, solar cells, and piezoelectric materials. Normally when a material begins to solidify, multiple crystals begin to grow in the liquid and a polycrystalline (more than one crystal) solid forms.

The moment a crystal begins to grow is known as nucleation and the point where it occurs is the nucleation point. At the solidification temperature, atoms of a liquid, such as melted metal, begin to bond together at the nucleation points and start to form crystals. The final sizes of the individual crystals depend on the number of nucleation points. The crystals increase in size by the progressive addition of atoms and grow until they impinge upon adjacent growing crystal.



a) Nucleation of crystals, b) crystal growth, c) irregular grains form as crystals grow together, d) grain boundaries as seen in a microscope.

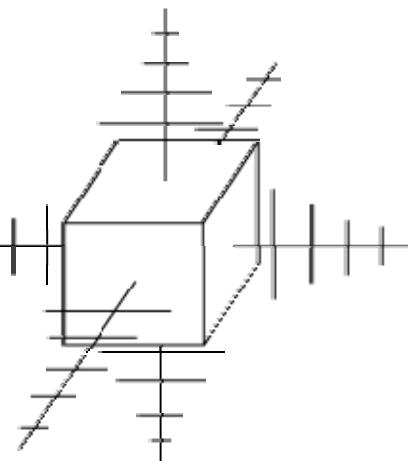


In engineering materials, a crystal is usually referred to as a grain. A grain is merely a crystal without smooth faces because its growth was impeded by contact with another grain or a boundary surface. The interface formed between grains is called a grain boundary. The atoms between the grains (at the grain boundaries) have no crystalline structure and are said to be disordered.

Grains are sometimes large enough to be visible under an ordinary light microscope or even to the unaided eye. The spangles that are seen on newly galvanized metals are grains. Rapid cooling generally results in more nucleation points and smaller grains (a fine grain structure). Slow cooling generally results in larger grains which will have lower strength, hardness and ductility.

Dendrites

In metals, the crystals that form in the liquid during freezing generally follow a pattern consisting of a main branch with many appendages. A crystal with this morphology slightly resembles a pine tree and is called a dendrite, which means branching. The formation of dendrites occurs because crystals grow in defined planes due to the crystal lattice they create. The figure to the right shows how a cubic crystal can grow in a melt in three dimensions, which correspond to the six faces of the cube. For clarity of illustration, the adding of unit cells with continued solidification from the six faces is shown simply as lines. Secondary dendrite arms branch off the primary arm, and tertiary arms off the secondary arms and etcetera.



During freezing of a polycrystalline material, many dendritic crystals form and grow until they eventually become large enough to impinge upon each other. Eventually, the interdendritic spaces between the dendrite arms crystallize to yield a more regular crystal. The original dendritic pattern may not be apparent when examining the microstructure of a material. However, dendrites can often be seen in solidification voids that sometimes occur in castings or welds, as shown to the right..



Shrinkage

Most materials contract or shrink during solidification and cooling. Shrinkage is the result of:

- Contraction of the liquid as it cools prior to its solidification
- Contraction during phase change from a liquid to solid
- Contraction of the solid as it continues to cool to ambient temperature.

Shrinkage can sometimes cause cracking to occur in component as it solidifies. Since the coolest area of a volume of liquid is where it contacts a mold or die, solidification usually begins first at this surface. As the crystals grow inward, the material continues to shrink. If the solid surface is too rigid and will not deform to accommodate the internal shrinkage, the stresses can become high enough to exceed the tensile strength of the material and cause a crack to form. Shrinkage cavitation sometimes occurs because as a material solidifies inward, shrinkage occurred to such an extent that there is not enough atoms present to fill the available space and a void is left.

What do you understand by chemical bonding? Explain the two main types of bonds.

Chemical compounds are formed by the joining of two or more atoms. A stable compound occurs when the total energy of the combination has lower energy than the separated atoms.

The bound state implies a net attractive force between the atoms-a chemical bond.

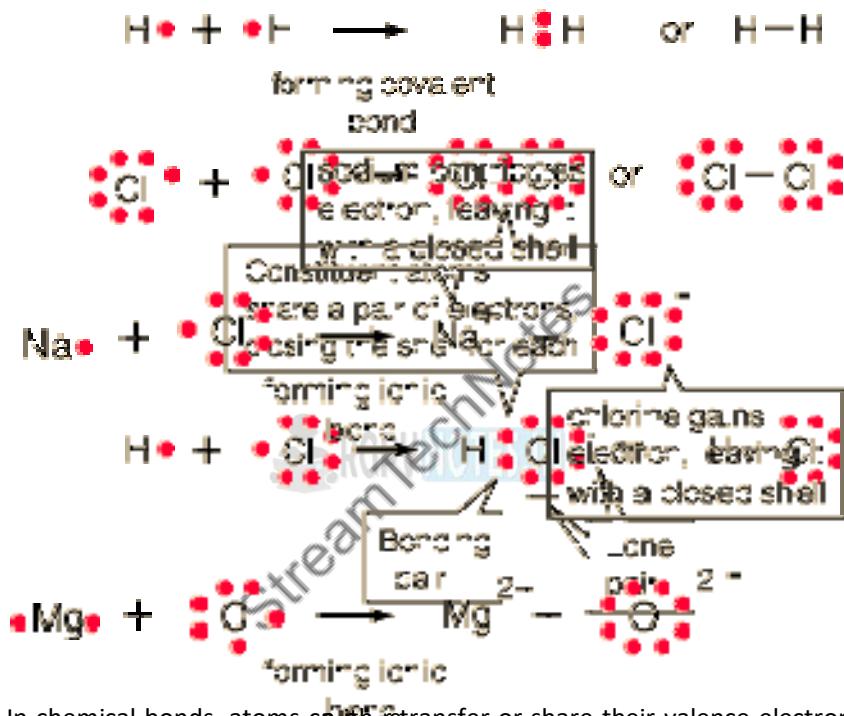
The two extreme cases of chemical bonds are:

Covalent bond: bond in which one or more pairs of electrons are shared by two atoms.

Ionic bond: bond in which one or more electrons from one atom are removed and attached to another atom, resulting in positive and negative ions which attract each other.

Covalent chemical bonds involve the sharing of a pair of valence electrons by two atoms, in contrast to the transfer of electrons in ionic bonds. Such bonds lead to stable molecules if they share electrons in such a way as to create a noble gas configuration for each atom.

Hydrogen gas forms the simplest covalent bond in the diatomic hydrogen molecule. The halogens such as chlorine also exist as diatomic gases by forming covalent bonds. The nitrogen and oxygen which makes up the bulk of the atmosphere also exhibits covalent bonding in forming diatomic molecules.



Ionic bond: In chemical bonds, atoms can either transfer or share their valence electrons. In the extreme case where one or more atoms lose electrons and other atoms gain them in order to produce a noble gas electron configuration, the bond is called an ionic bond.



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Intermolecular forces They differ from covalent and ionic bonding in that they are caused by correlations in the fluctuating polarizations of nearby particles.

The much weaker *intermolecular bonds* between these molecules result from the relatively weak van der Waals forces.

The van der Waals forces holding CO₂ molecules together in dry ice, for example, are so weak that dry ice sublimes and it passes directly from the solid to the gas phase at -78 degree C.

Q. Explain the Lattice and Crystal system arrangement. What is the difference between the two?

Lattice and crystal are two words that go hand in hand. These two words are interchangeably used, but there is a small difference between the two.

Lattice

Lattice is a mathematical phenomenon. In chemistry, we can see different types of ionic and covalent lattices. It can be defined as a solid, which has a three-dimensional ordered arrangement of basic units. The basic unit can be an atom, molecule or an ion. Lattices are crystalline structures with these repeated basic units. When ions joined with ionic bonds, they form ionic crystals. For example, sodium chloride can be taken. Sodium is a group 1 metal, thus forms a +1 charged cation. Chlorine is a nonmetal and has the ability to form a -1 charged anion. In the lattice, each sodium ion is surrounded by six chloride ions, and each chloride ion is surrounded by six sodium ions. Due to all the attractions between ions, the lattice structure is more stable. The number of ions present in the lattice varies with the size of it. Lattice energy or enthalpy of lattice is the measure of the strength of the ionic bonds in the lattice. Normally lattice enthalpy is exothermic.

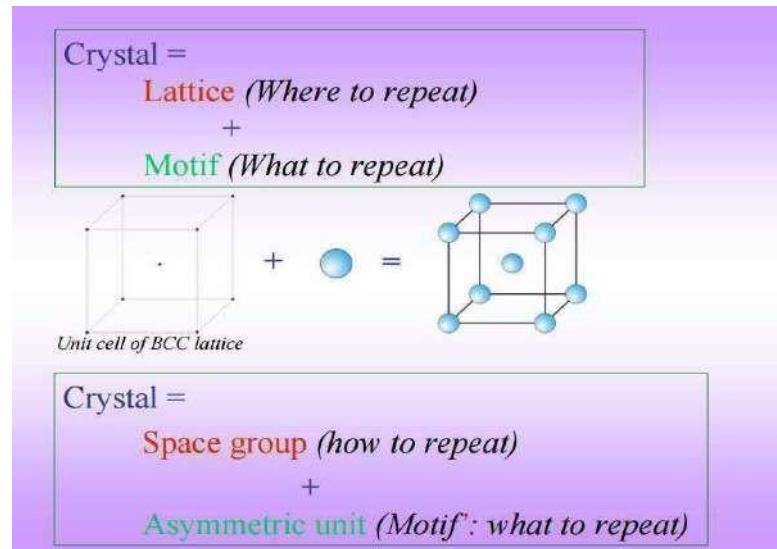
Diamond and quartz are two examples for three-dimensional covalent lattices. Diamond is composed of only carbon atoms, and each carbon atom is covalently bonded to four other carbon atoms to form the lattice structure. Therefore, each carbon atom has the tetrahedral arrangement. Diamond, by forming a structure like this, has gained a high stability. (Diamond is known to be one of the strongest minerals.) Quartz or silicon dioxide also has covalent bonds, but they are between silicon and oxygen atoms (lattice of different atoms). Both of these covalent lattices have a very high melting point, and they cannot conduct electricity.

Crystal

Crystals are solids, which have ordered structures and symmetry. The atoms, molecules, or ions in crystals are arranged in a particular manner, thus have a long-range order. Crystals are naturally occurring on earth as large crystalline rocks, such as quartz, granite. Crystals are formed by living organisms too. For example, calcite is produced by mollusks. There are water-based crystals in the form of snow, ice or glaciers. Crystals can be categorized according to their physical and chemical properties. They are covalent crystals (e.g. diamond), metallic crystals (e.g. pyrite), ionic crystals (e.g. sodium chloride) and molecular crystals (e.g. sugar). Crystals can have different shapes and colors. Crystals have an aesthetic value, and it is believed to have healing properties; thus, people use them to make jewelry.

What is the difference between Lattice and Crystal?

- Lattice describes the structure of crystals. When a group of molecules tends to arrange each unit repeatedly at a lattice point, a crystal is made.
- In a crystal structure, there is a pattern of arranging the atoms or units. These patterns are located upon the points of a lattice. These lattice points are arranged in a three dimensionally ordered manner



Lattice and Crystal

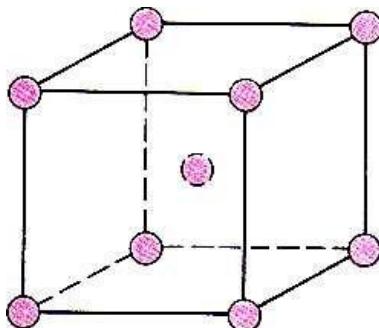
An ideal crystal is a repetition of identical structural units in three dimensional space. The periodicity is described by a mathematical lattice (which are mathematical points at specific coordinates in space), the identical structural units (or base of the crystal) are the atoms in some specific arrangement which are unambiguously placed at every lattice point. Note that **a lattice is not a crystal**, even so the two words are often used synonymously in colloquial language, especially in the case of elemental crystals where the base consists of one atom only.

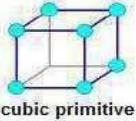
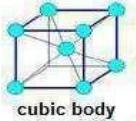
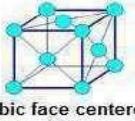
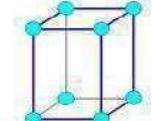
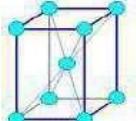
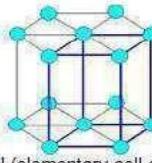
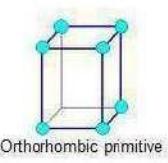
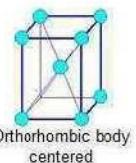
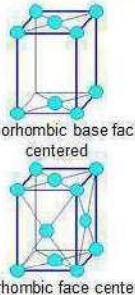
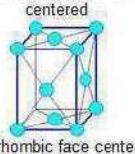
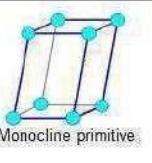
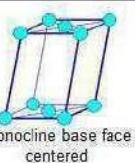
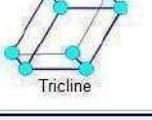
- All possible lattices can be described by a set of three linearly independent vectors \underline{a}_1 , \underline{a}_2 and \underline{a}_3 , the unit vectors of the lattice. Each lattice point than can be reached by a translation vector T of the lattice given by

$$\underline{T} = (u \cdot \underline{a}_1, v \cdot \underline{a}_2, w \cdot \underline{a}_3)$$

with $u, v, w = \text{integers}$.

- It is convenient, to classify lattices according to some basic symmetry groups. This yields the 14 Bravais lattices, which are commonly used to describe lattice types. Their basic features are shown below (For sake of clarity, the lattice points are shown as little spheres and occasionally only visible lattice points are shown. These are **not atoms**, however!)



Name of crystal system Length of Base vectors	Angles between axes	Bravais Lattices		
Cubic $a_1 = a_2 = a_3$	$a = b = g = 90^\circ$	 cubic primitive	 cubic body centered (bcc)	 cubic face centered (fcc)
Tetragonal $a_1 = a_2 \neq a_3$	$a = b = g = 90^\circ$	 Tetragonal primitive	 Tetragonal body centered	
Hexagonal $a_1 = a_2 \neq a_3$	$a = b = 90^\circ, g = 120^\circ$	 Hexagonal (elementary cell continued to show hex. symmetry)		
Rhombohedral $a_1 = a_2 = a_3$	$a = b = g \neq 90^\circ$	 Rhombohedral		
Orthorhombic $a_1 \neq a_2 \neq a_3$	$a = b = g \neq 90^\circ$	 Orthorhombic primitive	 Orthorhombic body centered	 Orthorhombic base face centered  Orthorhombic face centered
Monoclinic $a_1 \neq a_2 \neq a_3$	$a = b = 90^\circ, g \neq 90^\circ$	 Monoclinic primitive		 Monocline base face centered
Tricline $a \neq b \neq g \neq 90^\circ$		 Tricline		

Q. Distinguish between ionic and Covalent bonds in solids.

2

Ionic	Covalent
Metal–metal, non-metal–metal	Non-metal
Total transfer of electrons	Shared electrons
High melting and boiling points	Low melting and room temperature boiling points
Solids at room temperature	Liquids and gases at room temperature
Hard/brittle (inorganic compounds)	Relatively soft (organic compounds)
Strong bonds	Weak bonds
Electrically reactive	Does not normally conduct electricity
Soluble in water	Insoluble in water
Electron orbitals are separate	Electron orbitals overlap

Q. What do you understand by the term 'crystal lattice' and how many types of this are found in metal? 2

The crystal lattice can be thought of as an array of 'small boxes' infinitely repeating in all three spatial directions. Such a unit cell is the smallest unit of volume that contains all of the structural and symmetry information to build-up the macroscopic structure of the lattice by translation.

Types: Simple Cubic, Body Centered Cubic, Face Centered Cubic and Hexagonal Closed Pack.

3

Q. Show that the atomic packing factor (volume of atoms/volume of unit cell) for FCC and BCC structure are 0.74 and 0.68 respectively.

For BCC :

Close-packed directions: length = $4R = 3a$

Unit cell contains: $1 + 8 \times 1/8 = 2$ atoms/unit cell

$$\text{APF} = \frac{2 \cdot \frac{4}{3} \pi \left(\frac{\sqrt{3}a}{4} \right)^3}{a^3} = 0.68$$

For FCC:

$$\text{length} = 4R = \sqrt{2}a$$

cell volume Unit cell contains: $6 \times 1/2 + 8 \times 1/8 = 4$ atoms/unit cell

$$\frac{4 \cdot \frac{4}{3} \pi \left(\frac{\sqrt{2}a}{4} \right)^3}{a^3} = 0.74$$

Metallic Bond in metals

Metallic bond is the bonding between molecules within metals called alkali reactive force. It is the sharing of a sea of delocalized electrons amongst a lattice of positive ions, where the electrons act as a "glue" giving the substance a definite structure.

Crystallography

Crystallography is the experimental science of determining the arrangement of atoms in crystalline solids.

Crystallography is used by materials scientists to characterize different materials. In single crystals, the effects of the crystalline arrangement of atoms is often easy to see macroscopically, because the natural shapes of crystals reflect the atomic structure. In addition, physical properties are often controlled by crystalline defects. The understanding of crystal structures is an important prerequisite for understanding crystallographic defects. Mostly, materials do not occur as a single crystal, but in poly-crystalline form (i.e., as an aggregate of small crystals with different orientations). Because of this, the powder diffraction method, which takes diffraction patterns of polycrystalline samples with a large number of crystals, plays an important role in structural determination.

Crystallographic methods depend on analysis of the diffraction patterns of a sample targeted by a beam of some type. X-rays are most commonly used; other beams used include electrons or neutrons. This is facilitated by the wave properties of the particles. Crystallographers often explicitly state the type of beam used, as in the terms *X-ray crystallography*, *neutron diffraction* and *electron diffraction*.

Laws of Crystallography

Crystallography is based on three fundamental laws.

- (i) Law of constancy of interfacial angles: This law states that angle between adjacent corresponding faces is interfacial angles of the crystal of a particular substance is always constant inspite of different shapes and sizes and mode of growth of crystal. The size and shape of crystal depend upon the conditions of crystallisation. This law is also known as Steno's Law.
- (ii) Law of rational indices: This law states that the ratio of intercepts of different faces of a crystal with the three axes are constant and can be expressed by rational numbers that the intercepts of any face of a crystal along the crystallographic axes are either equal to unit intercepts (i.e., intercepts made by unit cell) a, b, c or some simple whole number multiples of them e.g., na, n' $b, n''c$, where n, n' and n'' are simple whole numbers. The whole numbers n, n' and n'' are called Weiss indices. This law was given by Hauy.
- (iii) Law of constancy of symmetry: According to this law, all crystals of a substance have the same elements of symmetry is plane of symmetry, axis of symmetry and centre of symmetry.

Metastable state- A particular excited state of an atom, nucleus, or other system that has a longer lifetime than the ordinary excited states and that generally has a shorter lifetime than the lowest, often stable, energy state, called the ground state. A metastable state may thus be considered a kind of temporary energy trap or a somewhat stable intermediate stage of a system

the energy of which may be lost in discrete amounts.

In quantum mechanical terms, transitions from metastable states are “forbidden” and are much less probable than the “allowed” transitions from other excited states.

Theoretically every element has a metastable state. These are produced by giving energy to electrons to jump to lowest unoccupied orbital.

Every element has metastable states because they possess unoccupied orbitals.

Some have low excitation energies so are commonly used in visible wavelength applications. Some have very high excitation energy like Helium which is used in LASERs.

In Metastable state, an atom remains excited for 10^{-6} to 10^{-3} seconds enough time to emit photons by returning to ground state. When a number of atoms usually in the order of 10^{25} repeat the same process we obtain a beam of light.

Mechanical properties of metals & other engineering materials

Materials are subject to an external force when they are used. Mechanical Engineers calculate those forces and material scientists how materials deform or break as a function of force, time, temperature, and other conditions. Materials scientists learn about these mechanical properties by testing materials.

Some of the important mechanical properties of the metals are Brittleness, Creep, Ductility, Elasticity, Fatigue, Hardness, Malleability, Plasticity, Resilience, Stiffness, Toughness, Yield strength. Above mechanical properties of metals are explained below in brief.

Brittleness:

The tendency of material to fracture or fail upon the application of a relatively small amount of force, impact or shock.

Creep:

When a metal is subjected to a constant force at a high temperature below its yield point, for a prolonged period of time, it undergoes a permanent deformation.

Ductility:

Ductility is the property by which a metal can be drawn into thin wires. It is determined by percentage elongation and percentage reduction in the area of metal.

Elasticity:

Elasticity is the tendency of solid materials to return to their original shape after being deformed.

Fatigue:

Fatigue is the of material weakening or breakdown of equipment subjected to stress, especially a repeated series of stresses.

Hardness:

Hardness is the ability of material to resist permanent change of shape caused by an external force.

Malleability:

Malleability is the property by which a metal can be rolled into thin sheets.

Plasticity:

Plasticity is the property by which a metal retains its deformation permanently, when the external force applied on it is released.

Resilience:

Resilience is the ability of metal to absorb energy and resist soft and impact load.

Stiffness:

When an external force is applied on metal, it develops an internal resistance. The internal resistance developed per unit area is called stress. Stiffness is the ability of metal to resist deformation under stress.

Toughness:

When a huge external force is applied on metal, the metal will experience a fracture. Toughness is the ability of metal to resist fracture.

Yield strength:

The ability of metal to bear gradual progressive force without permanent deformation.

Creep Properties

Creep is a time-dependent deformation of a material while under an applied load that is below its yield strength. It is most often occurs at elevated temperature, but some materials creep at room temperature. Creep terminates in rupture if steps are not taken to bring to a halt.

Creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature. Results of tests are usually plotted as strain versus time up to rupture. As indicated in the image, creep often takes place in three stages. In the initial stage, strain occurs at a relatively rapid rate but the rate gradually decreases until it becomes approximately constant during the second stage. This constant creep rate is called the minimum creep rate or steady-state creep rate since it is the slowest creep rate during the test. In the third stage, the strain rate increases until failure occurs.

Creep in service is usually affected by changing conditions of loading and temperature and the number of possible stress-temperature-time combinations is infinite. While most materials are subject to creep, the creep mechanisms is often different between metals, plastics, rubber, and concrete.

Introduction to industrial metals

Chosen for their durability, strength and resistance to weather, metals used in the construction industry serve a wide range of functions. The most common of them are carbon steel, aluminum, copper tubing and stainless steel, which each have their particular qualities and ideal uses.

Carbon steel is one alloy that is prized in the construction industry for its hardness and strength. It is typically used to make beams for structural framework, plates for highway construction, and rectangular tubing for welded frames trailer beds, and bridges.

Aluminum is also commonly used in the industry because it is resistant to corrosion, highly conductive and ductile.

Aluminum

Aluminum is one of the most versatile elements available to today's engineers; however its properties can be further improved by the addition of other elements such as copper manganese and zinc. These improve the aluminium's strength, hardness, cast-ability and resistance to corrosion.

The main application is in the transport sector, particularly in the construction of aircraft and railway rolling stock. Aluminum alloys are also used extensively in the car industry in the production of engines and gearboxes.

Zinc

Zinc is used along with copper to form brass, and was used exclusively for valves when I was serving my time in Harland & Wolff shipyard in the sixties, where within the engine-works department there was a large dedicated brass valve turning shop.

However, brass is not as popular in engineering nowadays apart from manufacture of brass fittings on fire hoses, screwed rod and screws, the main application being in the domestic sector and in the production of musical instruments.

Zinc is also alloyed along with lead and tin to make solder, a low melting point alloy used in soldering.

Tin

Used to produce bronze and solder as previously discussed but also to form the alloy Babbitt, used to line white metal bearings.

Lead

As previously noted, lead is used with tin in the formation of solder alloy. It is also used in the formation of typesets in the printing industry and again in Babbitt white metal alloy production

Vanadium

The main application of vanadium alloys are high speed tool steels (HSTS). Its properties give a reduction in weight, an increase in tensile strength, and resistance to corrosion. It is also used along with chrome in the formation of hand tools such as spanners and socket sets.

Chromium

Chromium is used to produce stainless steel and is known for its resistance to corrosion and hardness properties. Stainless steel has many industrial uses – the main ones being tools, surgical equipment, specialist valves and piping, liquid storage tanks, and structural sections.

Manganese

Manganese gives an alloy the properties of hardness without causing brittleness. Applications are the production of railroad tracks, switching points which require the above properties. Manganese is also used to produce a very hard alloy known as Spartan steel being used in the steel construction industry.

Tungsten

When small quantities of tungsten are added to steel, a very hard-wearing, tough alloy is formed. It has many applications in the military sector both as armor and armor piercing components. It is also used in engineering where high temperatures are prevalent such as gas turbine components and where the properties of toughness without brittleness are a requirement.

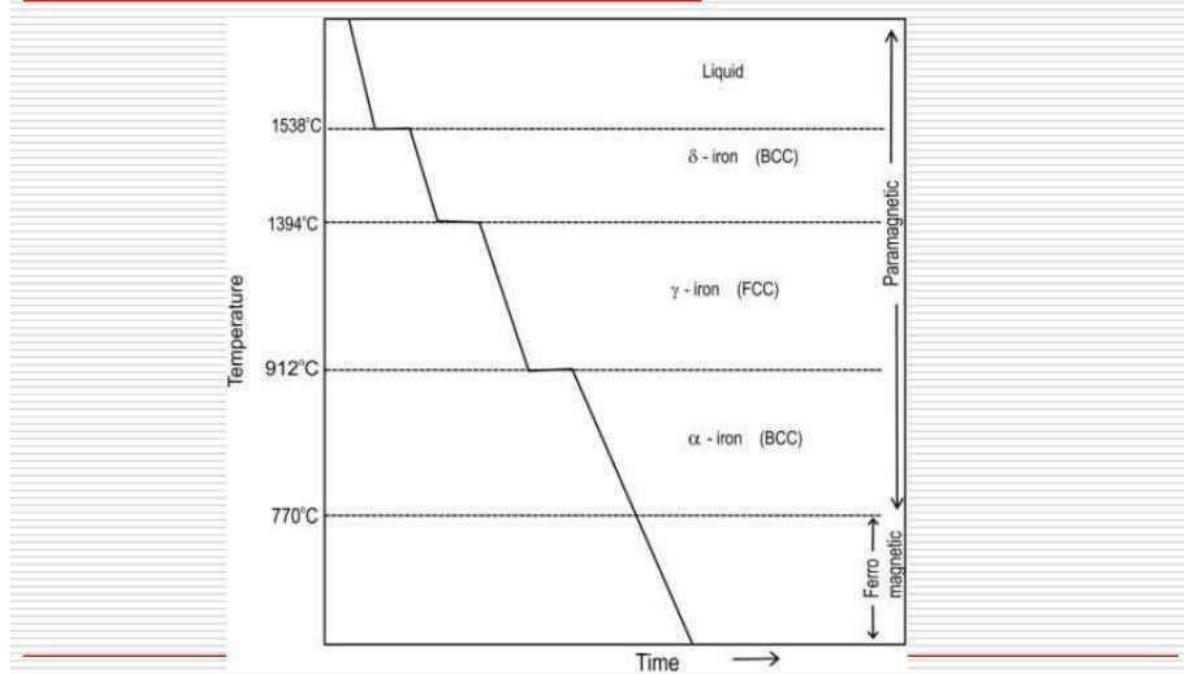
Tungsten alloys are also used in x-ray tubes and incandescent light fittings as well tungsten inert gas welding components, due to its high melting property.

Nickel

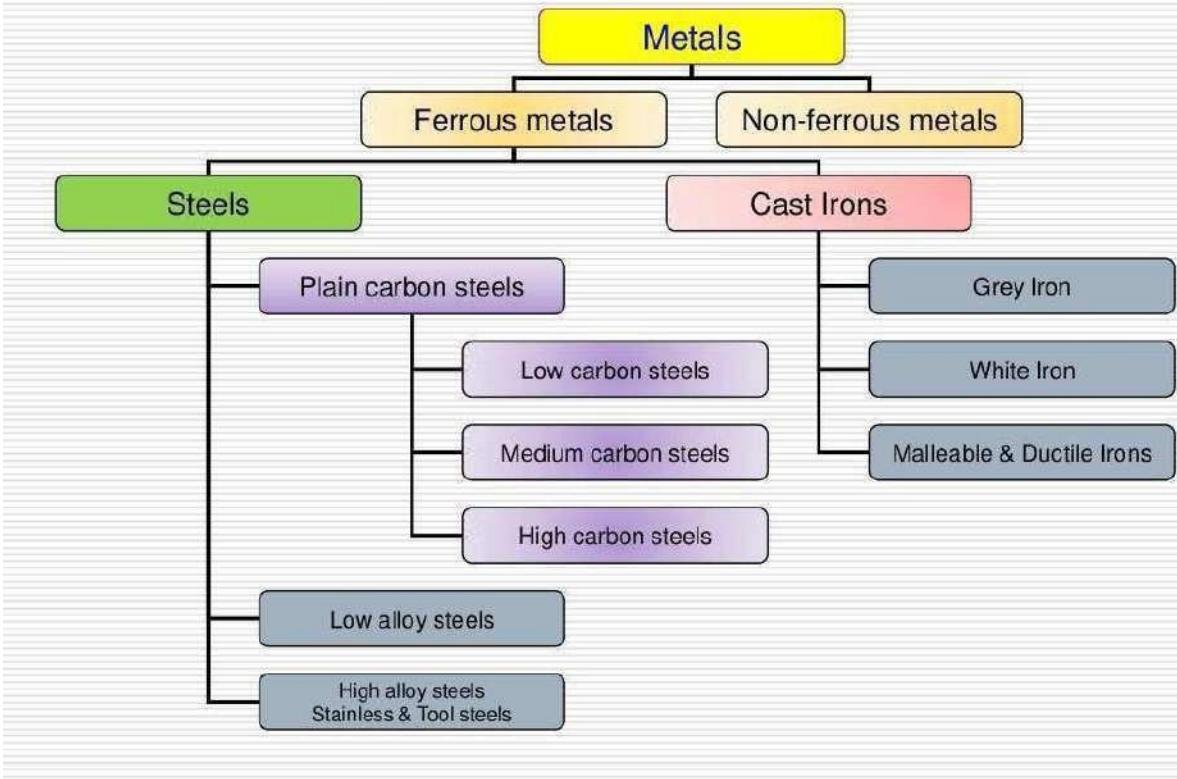
Nickel is corrosion resistant and it is used along with other elements to form stainless steel, brass and bronze with their attendant properties. Its applications are in power station rotary components which require the alloys properties of resistance to cracking, deformation, corrosion under sustained high temperatures are numerous.

Nickel alloys are also used in the aerospace and chemical industries.

Allotropes of Iron



Fe-C alloy classification



Classification of Steels

Steels are generally classified by method of manufacture, use and chemical composition.

If steel is classified by method of manufacture, it gives rise to crucible steel, bessemer steel, open-hearth steel, basic oxygen steel and electric-furnace steel.

When steel is classified by use, it is generally classified by the final use for the steel such as machine steel, spring steel, boiler steel, structural steel or tool steel.

The easiest and the most popular way to classify steels are by their chemical composition. Various alloying elements are added to iron for the purpose of attaining certain specific properties and characteristics. These elements include, but are not limited to, carbon, manganese, silicon, nickel, chromium, molybdenum, vanadium, columbium (niobium), copper, aluminum, titanium, tungsten, and cobalt. A numbering system is used in classification by chemical composition method, giving information on the approximate content of the important alloying elements in the steel.

The carbon content in steel can range from 0.1-1.5%, but the most widely used grades of steel contain only 0.1-0.25% carbon. Elements such as manganese, phosphorus and sulphur are found in all grades of steel, but, whereas manganese provides beneficial effects, phosphorus and sulphur are deleterious to steel's strength and durability.

Different types of steel are produced according to the properties required for their application, and various grading systems are used to distinguish steels based on these properties. According to the American Iron and Steel Institute (AISI), steels can be broadly categorized into four groups based on their chemical compositions:

1. Carbon Steels

2. Alloy Steels
3. Stainless Steels
4. Tool Steels

1) Carbon Steels:

Carbon steels contain trace amounts of alloying elements and account for 90% of total steel production. Carbon steels can be further categorized into three groups depending on their carbon content:

Low Carbon Steels/Mild Steels contain up to 0.3% carbon

Medium Carbon Steels contain 0.3 – 0.6% carbon

High Carbon Steels contain more than 0.6% carbon

2) Alloy Steels:

Alloy steels contain alloying elements (e.g. manganese, silicon, nickel, titanium, copper, chromium and aluminum) in varying proportions in order to manipulate the steel's properties, such as its hardenability, corrosion resistance, strength, formability, weldability or ductility.

Applications for alloys steel include pipelines, auto parts, transformers, power generators and electric motors.

3) Stainless Steels:

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:

1. *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.
2. *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 with heat treatment, but can be strengthened by cold works.
3. *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.

4) 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.

High-Speed Tool Steels: High-speed alloys include all molybdenum (M1 to M52) and tungsten (T1 to T15) class alloys. High-speed tools steels can be hardened to 62-67 HRC and can maintain this hardness in service temperatures as high as 540°C (1004°F), making them very useful in high-speed machinery. Typical applications are end mills, drills, lathe tools, planar tools, punches, **reamers**, routers, taps, saws, broaches, **chasers**, and **hobs**.



(A reamer is a type of rotary cutting tool used in metalworking. Precision reamers are designed to enlarge the size of a previously formed hole by a small amount but with a high degree of accuracy to leave smooth sides.)

Bosch - Wall Chasers



Wall Chasers

Bosch wall chasers cut grooves up to 65 mm deep and 40 mm wide in concrete, masonry and stone, and are ideal for cutting cable ducts and laying water, gas and heating pipes.

A Gear Hob



Hobbing is a machining process for making gears, splines, and sprockets on a hobbing machine, which is a special type of milling machine. The teeth or splines are progressively cut into the workpiece by a series of cuts made by a cutting tool called a hob.

Hot-work Tool Steels: Hot-work tool steels include all chromium, tungsten, and molybdenum class H alloys. They are typically used for forging, die casting, heading, piercing, trim, extrusion, and hot-shear and punching blades.

Cold-work Tool Steels: Cold-work tool steels include all high-chromium class D, medium-alloy air-hardening class A alloys, water hardening W alloys, and oil hardening O alloys. Typical applications include cold working operations such as stamping dies, draw dies, burnishing tools, coining tools, and shear blades.

Shock-Resistant Tool Steels: Cold-work tool steels include all class S alloys. They are among the toughest of the tool steels, and are typically used for screw driver blades, shear blades, chisels, knockout pins, punches, and riveting tools.

Mechanical properties of metals & other engineering materials

Materials are subject to an external force when they are used. Mechanical Engineers calculate those forces and material scientists how materials deform or break as a function of force, time, temperature, and other conditions. Materials scientists learn about these mechanical properties by testing materials.

Some of the important mechanical properties of the metals are Brittleness, Creep, Ductility, Elasticity, Fatigue, Hardness, Malleability, Plasticity, Resilience, Stiffness, Toughness, Yield strength. Above mechanical properties of metals are explained below in brief.

Brittleness:

The tendency of material to fracture or fail upon the application of a relatively small amount of force, impact or shock.

Creep:

When a metal is subjected to a constant force at a high temperature below its yield point, for a prolonged period of time, it undergoes a permanent deformation.

Ductility:

Ductility is the property by which a metal can be drawn into thin wires. It is determined by percentage elongation and percentage reduction in the area of metal.

Elasticity:

Elasticity is the tendency of solid materials to return to their original shape after being deformed.

Fatigue:

Fatigue is the material weakening or breakdown of equipment subjected to stress, especially a repeated series of stresses.

Hardness:

Hardness is the ability of material to resist permanent change of shape caused by an external force.

Malleability:

Malleability is the property by which a metal can be rolled into thin sheets.

Plasticity:

Plasticity is the property by which a metal retains its deformation permanently, when the external force applied on it is released.

Resilience:

Resilience is the ability of metal to absorb energy and resist soft and impact load.

Stiffness:

When an external force is applied on metal, it develops an internal resistance. The internal resistance developed per unit area is called stress. Stiffness is the ability of metal to resist deformation under stress.

Toughness:

When a huge external force is applied on metal, the metal will experience a fracture.

Toughness is the ability of metal to resist fracture.

Yield strength:

The ability of metal to bear gradual progressive force without permanent deformation.

Properties, types, uses and brief description of the manufacturing processes for Iron and steel making.

Iron is a chemical element with the symbol Fe (from Latin: ferrum) and atomic number 26.

It is a metal in the first transition series.

It by mass is the most common element on Earth, forming much of Earth's outer and inner core.

It is the fourth most common element in the Earth's crust.

Extraction

1 Much of the world's iron ore is extracted through open pit mining in which the Pure iron is a soft, grayish white metal.

Although iron is a common element, pure iron is almost never found in nature. Minerals near the surface of the earth that have the highest iron content are known as iron ores and are mined commercially.

Surface of the ground is removed by heavy machines, often over a very large area, to expose the ore beneath. In cases where it is not economical to remove the surface, shafts are dug into the earth, with side tunnels to follow the layer of ore.

Refining

2 The mined ore is crushed and sorted. The best grades of ore contain over 60% iron. Lesser grades are treated, or refined, to remove various contaminants before the ore is shipped to the blast furnace.

Collectively, these refining methods are called beneficiation and include further crushing, washing with water to float sand and clay away, magnetic separation, pelletizing, and sintering. As more of the world's known supply of high iron content ore is depleted, these refining techniques have become increasingly important.

3 The refined ore is then loaded on trains or ships and transported to the blast furnace site.

Charging the blast furnace

4 After processing, the ore is blended with other ore and goes to the blast furnace.

A blast furnace is a tower-shaped structure, made of steel, and lined with refractory, or heat-resistant bricks.

1. The mixture of raw material, or charge, enters at the top of the blast furnace.
2. At the bottom of the furnace, very hot air is blown, or blasted, in through nozzles called tuyeres.
3. The coke burns in the presence of the hot air.
4. The oxygen in the air reacts with the carbon in the coke to form carbon monoxide.
5. The carbon monoxide then reacts with the iron ore to form carbon dioxide and pure iron.

Separating the iron from the slag

5 The melted iron sinks to the bottom of the furnace.

1. The limestone combines with the rock and other impurities in the ore to form a slag which is lighter than the iron and floats on top.
2. As the volume of the charge is reduced, more is continually added at the top of the furnace.
3. The iron and slag are drawn off separately from the bottom of the furnace.
4. The melted iron might go to a further alloying process, or might be cast into ingots called pigs.
5. The slag is carried away for disposal.

(For Long answer type questions)

6 A blast furnace is a type of metallurgical furnace used for smelting to produce industrial metals, generally iron, but also others such as lead or copper.

7 In a blast furnace, fuel, ore, and flux (limestone) are continuously supplied through the top of the furnace, while a hot blast of air (sometimes with oxygen enrichment) is blown into the lower section of the furnace through a series of pipes called tuyeres, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace. The downward flow of the ore and flux in contact with an upflow of hot, carbon monoxide rich combustion gases is a countercurrent exchange process.

8 In contrast, air furnaces (such as reverberatory furnaces) are naturally aspirated, usually by the convection of hot gases in a chimney flue. According to this broad definition, bloomeries for iron, blowing houses for tin, and smelt mills for lead would be classified as blast furnaces.

However, the term has usually been limited to those used for smelting iron ore to produce pig iron, an intermediate material used in the production of commercial iron and steel, and the shaft furnaces used in combination with sinter plants in base metals smelting.

- 9 The hot gases produced in the chemical reactions are drawn off at the top and routed to a gas cleaning plant where they are cleaned, or scrubbed, and sent back into the furnace; the remaining carbon monoxide, in particular, is useful to the chemical reactions going on within the furnace.
- 10 A blast furnace normally runs day and night for several years. Eventually the brick lining begins to crumble, and the furnace is then shut down for maintenance.

DEFINITION: STEEL (as per IS:7598-1990)

For the purpose of classification, steel is an iron base alloy generally suitable for working to the required shape in the solid state having a carbon content generally less than 1.5 percent and containing varying amounts of other elements.

A limited number of high alloyed steels may have more than 2 percent carbon but 2 percent is the usual dividing line between steel and cast iron.

Steelmaking is the process for producing steel from iron and ferrous scrap.

In steelmaking, impurities such as nitrogen, silicon, phosphorus, and excess carbon are removed from the raw iron, and alloying elements such as manganese, nickel, chromium and vanadium are added to produce different grades of steel.

Limiting dissolved gases such as nitrogen and oxygen, and entrained impurities (termed "inclusions") in the steel is also important to ensure the quality of the products cast from the liquid steel.

There are two major processes for making steel, namely basic oxygen steelmaking which has liquid pig-iron from the blast furnace and scrap steel as the main feed materials, and electric arc furnace (EAF) steelmaking which uses scrap steel or direct reduced iron (DRI) as the main feed materials. Oxygen steelmaking is fuelled predominantly by the exothermic nature of the reactions inside the vessel whereas in EAF steelmaking, electrical energy is used to melt the solid scrap and/or DRI materials.

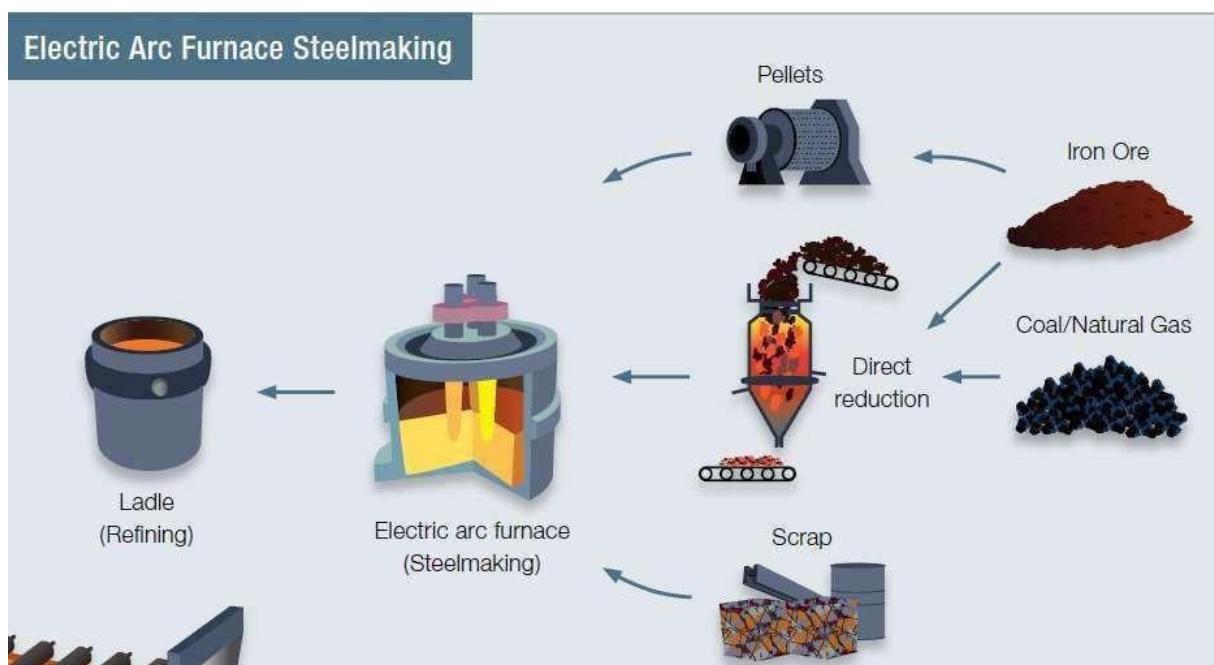
In recent times, EAF steelmaking technology has evolved closer to oxygen steelmaking as more chemical energy is introduced into the process.

Modern steelmaking processes can be broken into two categories:

Primary and Secondary steelmaking.

Primary steelmaking involves converting liquid iron from a blast furnace and steel scrap into steel via basic oxygen steelmaking or melting scrap steel and/or direct reduced iron (DRI) in an electric arc furnace.

Secondary steelmaking involves refining of the crude steel before casting and the various operations are normally carried out in ladles. In secondary metallurgy, alloying agents are added, dissolved gases in the steel are lowered, inclusions are removed or altered chemically to ensure that high-quality steel is produced after casting.



Best Wishes for an excellent performance in MST.

-Arvind Shrimali

Unit II: Alloy Formation and Binary Diagram

Syllabus

- Cooling Curves, Isomorphous, Eutectic, Eutectoid solid Solution, Peritectic and other phase diagrams,
- Alloying elements, Iron carbon phase diagram, T-T-T diagrams,
- Types of Cast Irons, Types of Stainless Steels,
- Elastic, anelastic and Viscoelastic behaviour.

An alloy is a metal (parent metal) combined with other substances (alloying agents), resulting in superior properties such as; strength, hardness, durability, ductility, tensile strength and toughness.

The parent metal is the majority of the alloy.

For example, mild steel is 0.1 - 0.3% Carbon and 99.9 - 99.7% Iron.

Alloys are sometimes described as a mixture of two or more metals. However, this is misleading, as often alloys are composed of just one metal, as well as other non-metal elements.

Cast iron is an example, as it is a combination of iron (metal) and carbon (non-metal).

Metal alloys have specific enhanced properties compared to their 'parent' metals.
For example, steel.

Steel is itself an alloy of iron and carbon. Iron is a very brittle metal, likely to break or snap if it receives a sudden blow/shock. Adding the alloying agent carbon, gives the new alloy the property of toughness and tensile strength.

Steel can be used in the construction industry for bridges and large buildings.

A bridge manufactured only from the parent metal, iron, would eventually collapse due to its inability to absorb shocks/blows. The table below gives three alloying elements that can be added to the alloy steel, to further improve its physical properties.

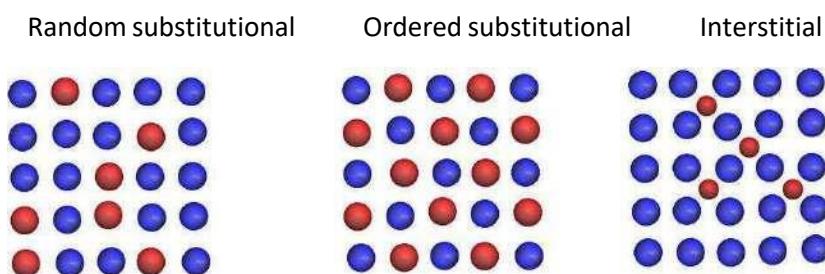
Solid Solution

When two metals are mixed together they form an alloy if one metal is soluble in the other one in solid state. Therefore, an alloy is a solid solution of two or more metals.

Primarily there are two types of solid solutions –

§ Substitutional – Solute atoms occupy the regular lattice sites of the parent metal (solvent). Substitutional solid solutions can be random (Cu-Ni) or ordered (Cu-Au).

§ Interstitial – Solute atoms occupy the interstitial positions (Steel-C solute atoms in Fe).



Hume-'othery's rules

For Interstitial Solid Solution Rules

For interstitial solid solutions, the Hume-Rothery rules are:

1. Solute atoms must be smaller than the interstitial sites in the solvent lattice.
2. The solute and solvent should have similar electro-negativity.

Hume-'othery's rule for substitutional solid solution.

For Substitutional solid solutions, the Hume-Rothery rules are:

1. The atomic diameter of the solute and solvent atoms must differ by no more than 15%:

$$\% \text{ difference} = \left(\frac{r_{\text{solute}} - r_{\text{solvent}}}{r_{\text{solvent}}} \right) \times 100 \leq 15\%.$$

2. The crystal structures of solute and solvent must match.
3. Complete solubility occurs when the solvent and solute have the same [valency](#). A metal will dissolve a metal of higher valency to a greater extent than one of lower valency. e.g. Zn is much more soluble in Cu than Cu in Zn.
4. The solute and solvent should have similar electro-negativity. If the electro-negativity difference is too great, the metals will tend to form intermetallic compounds instead of solid solutions. (minimum chemical affinity to each other).

Phase Diagrams

A phase diagram is a type of graph used to show the equilibrium conditions between the thermodynamically-distinct phases; or to show what phases are present in the material system at various T, p, and compositions “equilibrium” is important: phase diagrams are determined by using slow cooling conditions ⇒ no information about kinetics.

Phase diagrams provide valuable information about melting, casting, crystallization, and other phenomenon. Phase equilibrium diagrams are plots of the relationship between temperature, pressure and composition.

Phase diagrams and phase transformation are used in the understanding of how microstructure evolves and their properties in relation to manufacturing and engineering processes. The details of the thermal history controls the way phase transformation takes place. The processing of most materials involves a thermal history such as the thermal history of solidification which is cooling from a high temperature process.

Degree of freedom (or variance) F is the number of variables (T, p, and composition) that can be changed independently without changing the phases of the system

Using Cooling Curves to Construct Phase Diagrams

The *cooling curve method* is one of the oldest and simplest methods to determine phase diagrams and phase transition temperatures. This is achieved by recording temperature (T) of a material versus time as it cools from its molten state through solidification (at constant pressure).

Whenever a phase change takes place in a metal or alloy, the total energy content changes because cooling or heating is the process of evolution or absorption of heat.

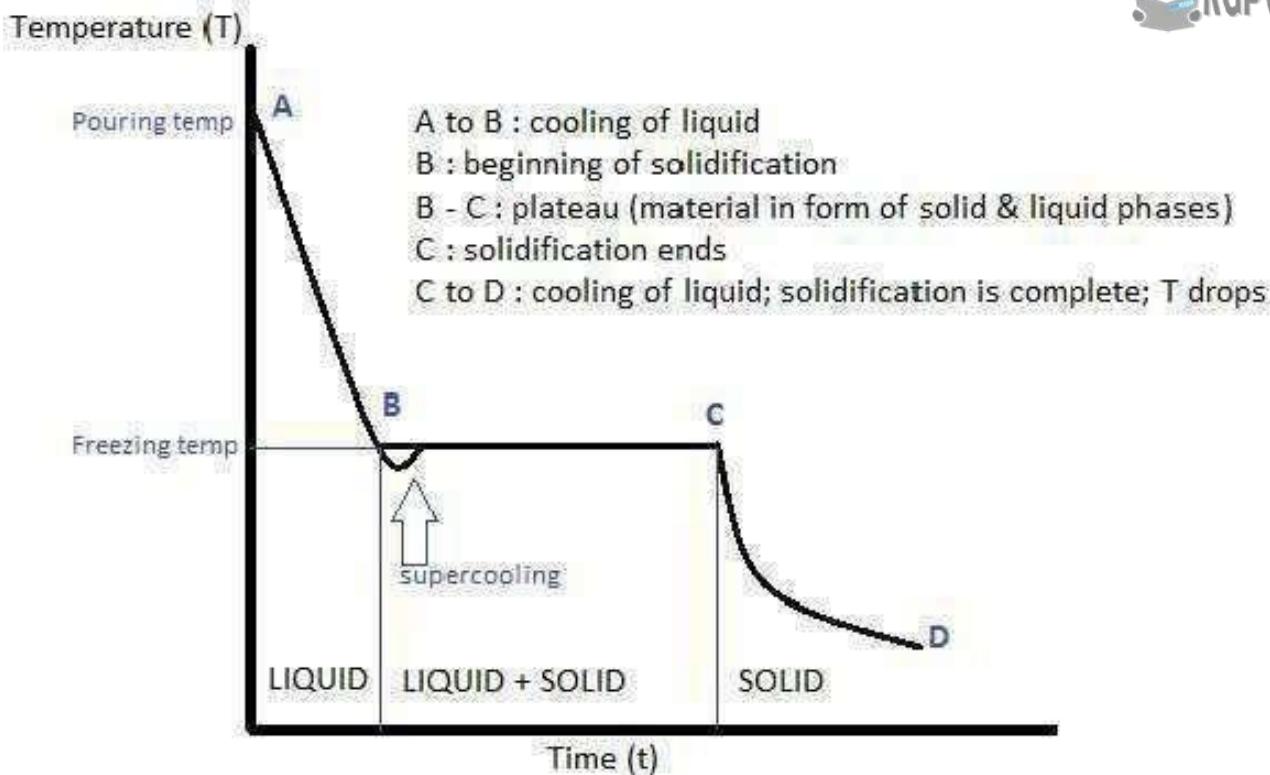


Diagram showing cooling curve of a pure metal

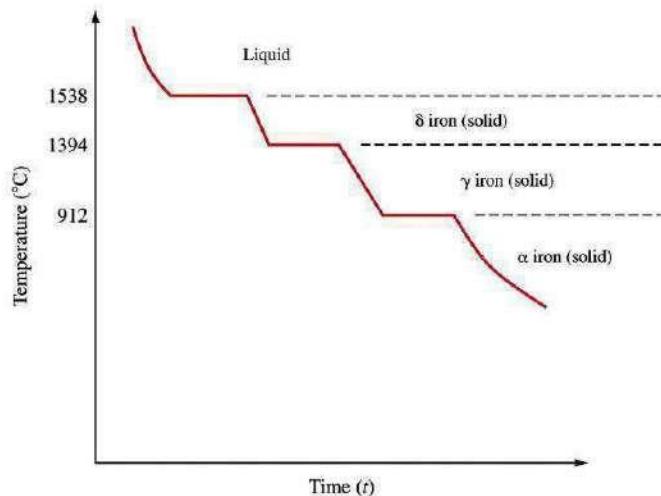
Suppose you allow a pure metal to cool down until it has all solidified (i.e. cooled under near equilibrium conditions from the liquid state), plotting its temperature as a function of time, the resulting cooling curve will show a plateau (B-C); this is also known as thermal arrest. The plateau corresponds to the beginning (at point B) and end of solidification (at point C).

Sometimes the liquid may cool to a temperature below its freezing point before crystallization occurs and this is called supercooling (this is explained in the Physical Chemistry).

While the process of solidification begins, the temperature drops and remains there until solidification is complete (C to D).

Cooling curve for pure iron @ 1atm

As $T \downarrow$: melted iron (liquid) \Rightarrow bcc Fe, δ (solid) \Rightarrow fcc Fe, γ (solid) \Rightarrow bcc Fe, α (RT)



Gibbs' phase rule describes the possible # of **degrees of freedom (F)** in a **closed system** at **equilibrium**, in terms of the number of separate **phases (P)** and the number of **chemical components (C)** in the system (derived from thermodynamic principles by Josiah W. Gibbs in the 1870s)

$$F + P = C + 2$$

F is # of degrees of freedom or variance

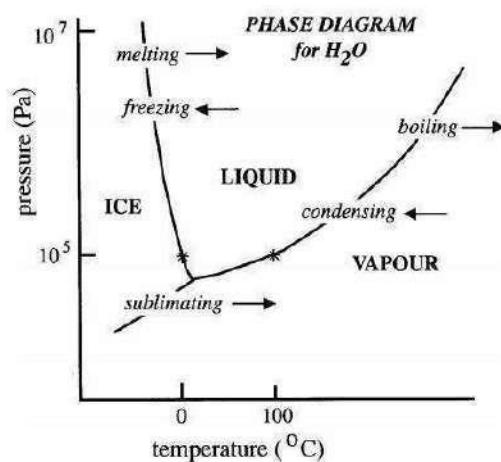
P is # of phases

C is # of components

Component is the minimum # of species necessary to define the composition of the system

H₂O C=1

- (i) P=1, F=2;
- (ii) P=2, F=1;
- (iii) P=3, F=0



By cooling alloys from the liquid state and recording their cooling rates, the temperature at which they start to solidify can be determined and then plotted on the phase diagram. If enough experiments are performed over a range of compositions, a start of solidification curve can be plotted onto the phase diagram.

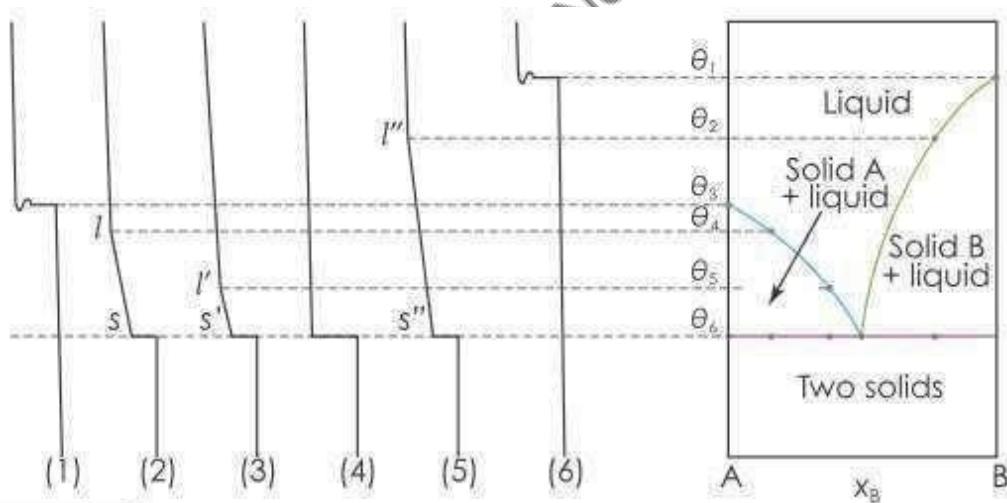
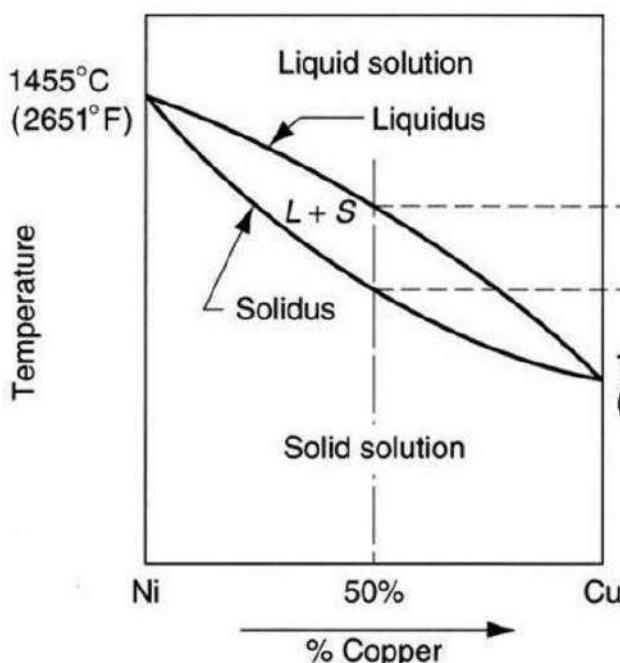
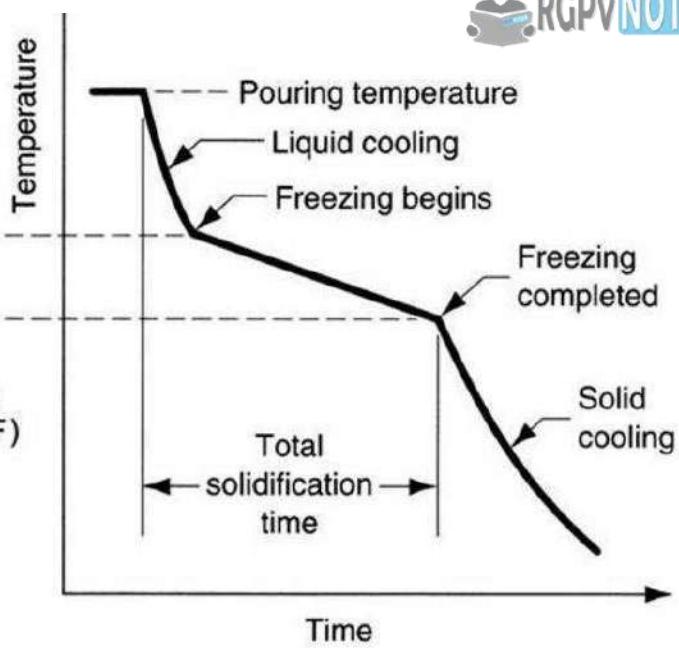


Figure 6.17

Use of thermal analysis. Demonstration of how thermal analysis can be used to determine a phase diagram. Cooling curves (1) and (6) represent behavior for pure A and B, respectively.



(a)



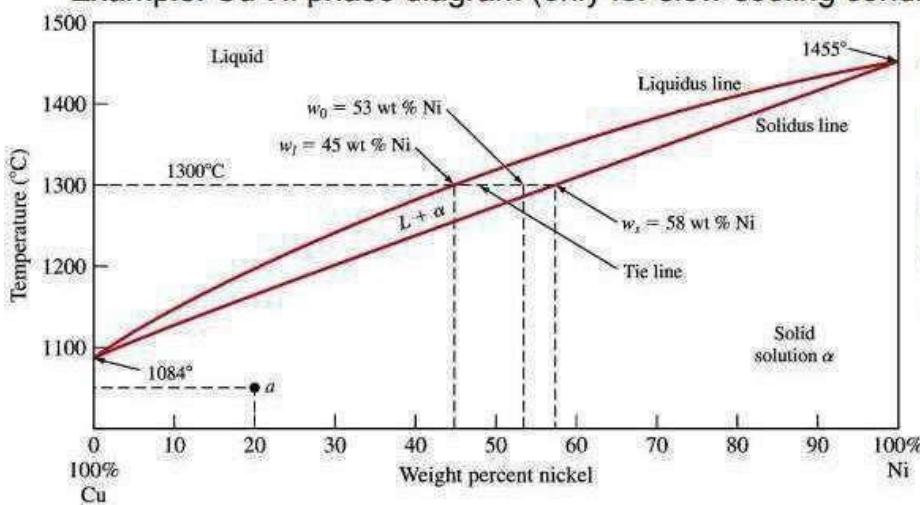
(b)

Binary Isomorphous Alloy System (C=2)

Isomorphous: Two elements are completely soluble in each other in solid and liquid state; substitutional solid state solution can be formed; single type of crystal str. exist

Reminder: Hume-Rothery rules: (1) atoms have similar radii; (2) both pure materials have same crystal structure; (3) similar electronegativity (otherwise may form a compound instead); (4) solute should have higher valence

Example: Cu-Ni phase diagram (only for slow cooling conditions)



Liquidus line: the line connecting Ts at which liquid starts to solidify under equilibrium conditions

Solidus: the temperature at which the last of the liquid phase solidifies

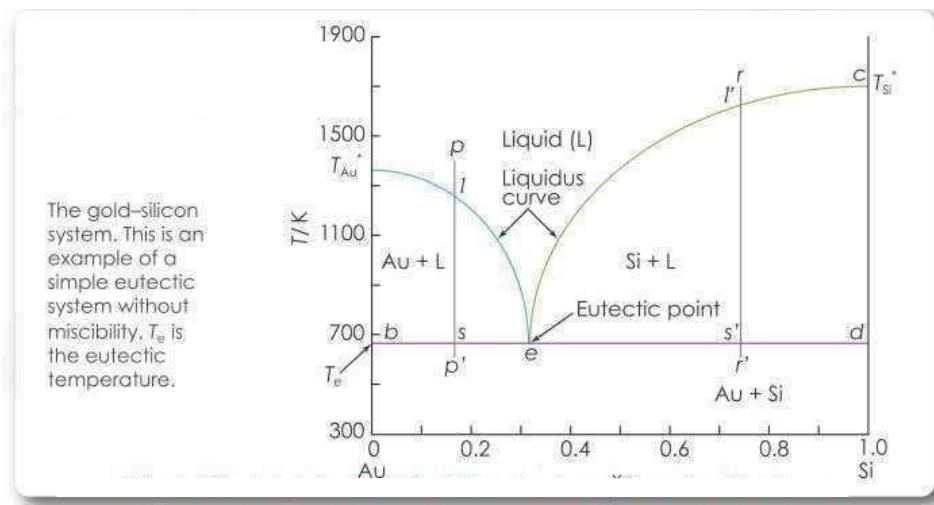
Between liquidus and solidus: P = 2

Eutectic Alloys

Pb-Sn alloy is a good example of a eutectic alloy system.

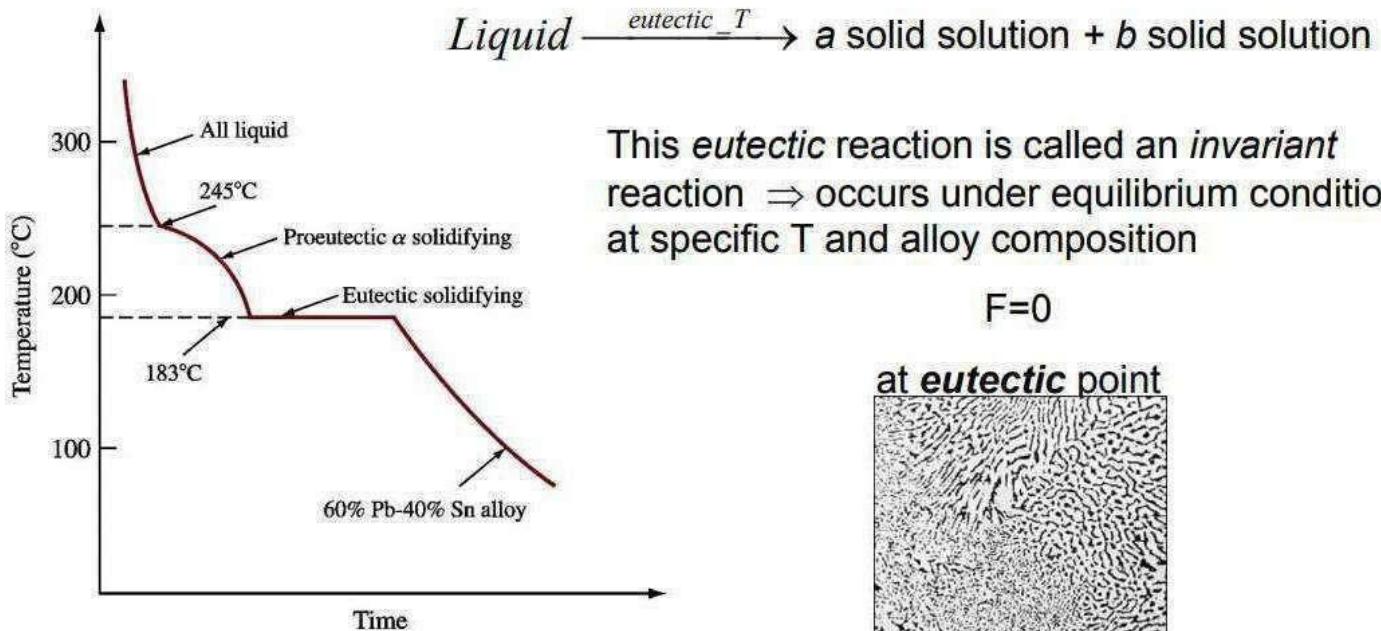
Eutectic is a ‘term’ used to describe two components which are completely soluble in each other in the liquid state, but only partially soluble in the solid state.

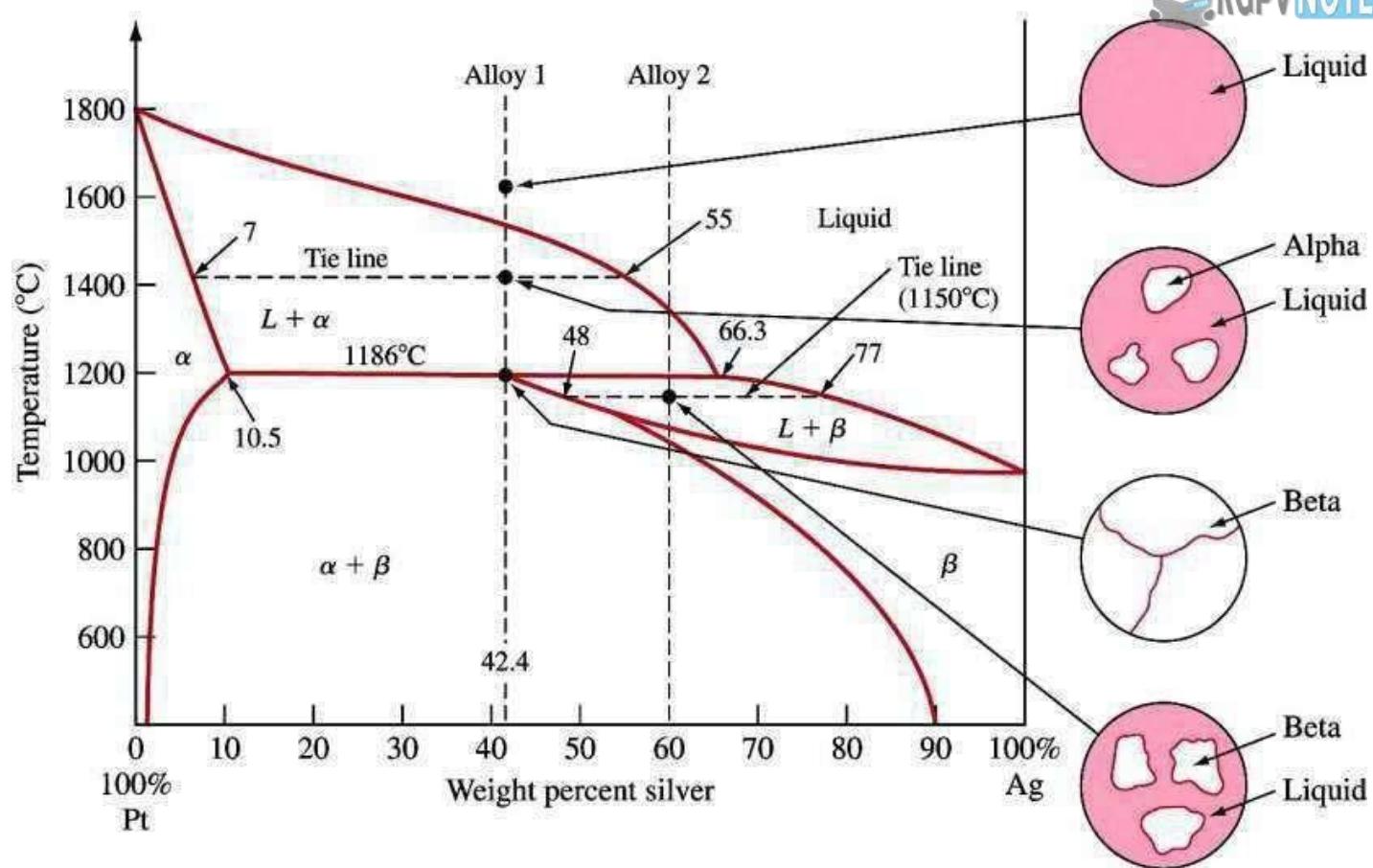
In a eutectic system, the “eutectic alloy” composition has the lowest melting point in the system. It is lower than the melting points of either of the pure components.



Many eutectic alloy systems have been found to be useful as solders. A typical old-fashioned solder is Pb-Sn comprising 40% lead and 60% tin. This ‘combination’ is close to the idealized eutectic composition having a low melting point (comprising 38% lead and 62% tin). Because this alloy system melts and freezes cleanly over a very limited temperature range, they have been found to be useful for electrical work.

- Components has **limited** solid solubility in each other
- Example: cooling 60%Pb – 40%Sn system



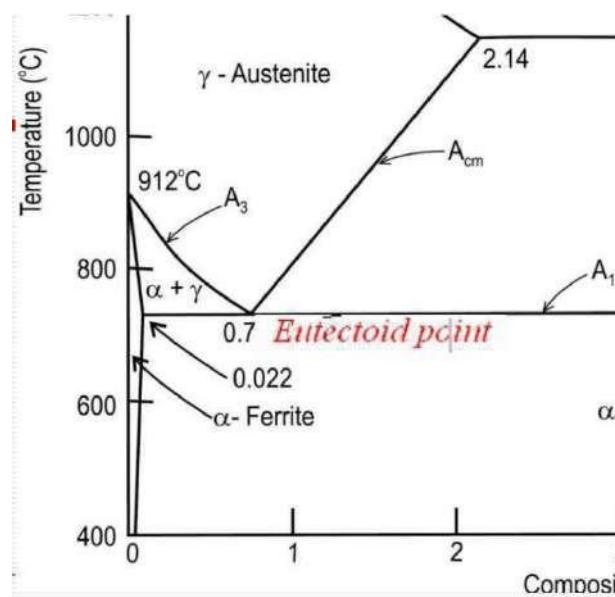


Invariant Reactions

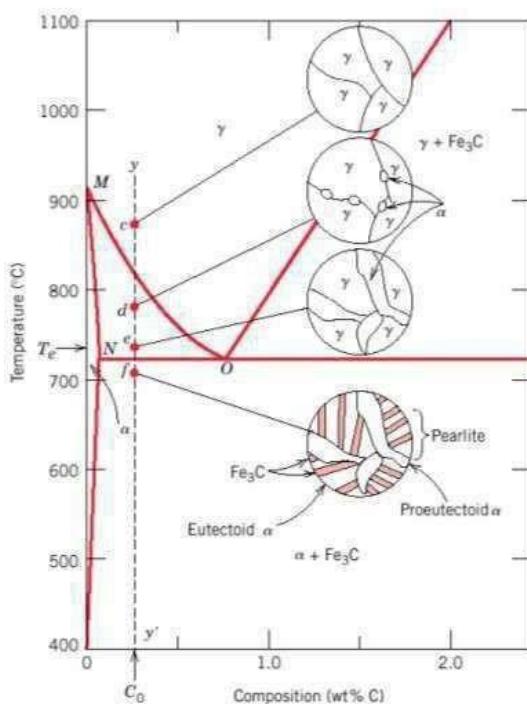
To summarize: 5 invariant reactions ($F = 0$)

- | | | |
|----------------|-------------------|------------------------------|
| 1. Eutectic | Liquid | $\rightarrow \alpha + \beta$ |
| 2. Eutectoid | α | $\rightarrow \beta + \gamma$ |
| 3. Peritectic | Liquid + α | $\rightarrow \beta$ |
| 4. Peritectoid | $\alpha + \beta$ | $\rightarrow \gamma$ |
| 5. Monotectic | L1 | $\rightarrow \alpha + L2$ |

The eutectic and eutectoid reactions are similar in that they both involve the decomposition of a single phase into two solid phases. The –oid suffix indicates that a solid, rather than liquid, phase is decomposing.

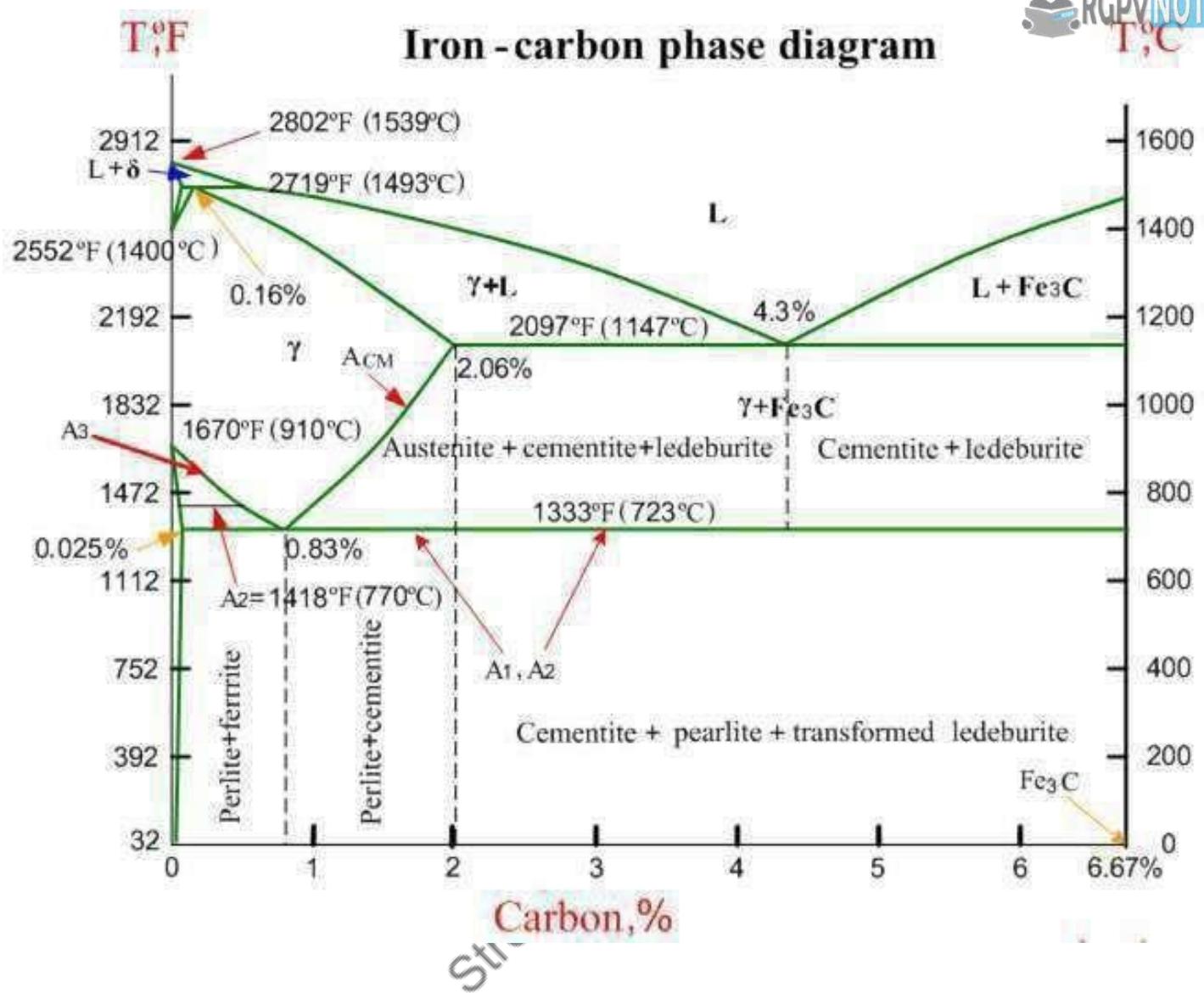


Microstructure of Hypoeutectoid Steel



Compositions to the left of eutectoid (0.022 - 0.76 wt % C) is **hypoeutectoid (less than eutectoid) alloys**. Microstructure change is $y \rightarrow \alpha + \gamma \rightarrow \alpha + P$

1. First ferrite is formed when temperature comes down below Ae_3 temperature.
 $y \rightarrow \alpha + \gamma$
2. The amount of ferrite increases with decrease in temperature till eutectoid temperature.
3. Remaining austenite changes to pearlite at eutectoid temperature.
 $\alpha + \gamma \rightarrow \alpha + P$



Phases Observed in Fe-C Diagram

1. Ferrite

Ferrite is the interstitial solid solution of carbon in alpha iron. It has B.C.C. Structure. It has very limited solubility for carbon (maximum 0.022% at 727°C and 0.008% at room temperature). Ferrite is soft and ductile.

2. Austenite

Austenite is the interstitial solid solution of carbon in gamma (γ) iron. It has FCC structure. Austenite can have maximum 2.14% carbon at 1143°C. Austenite is normally not stable at room temperature. Austenite is non-magnetic and soft.

3. Cementite

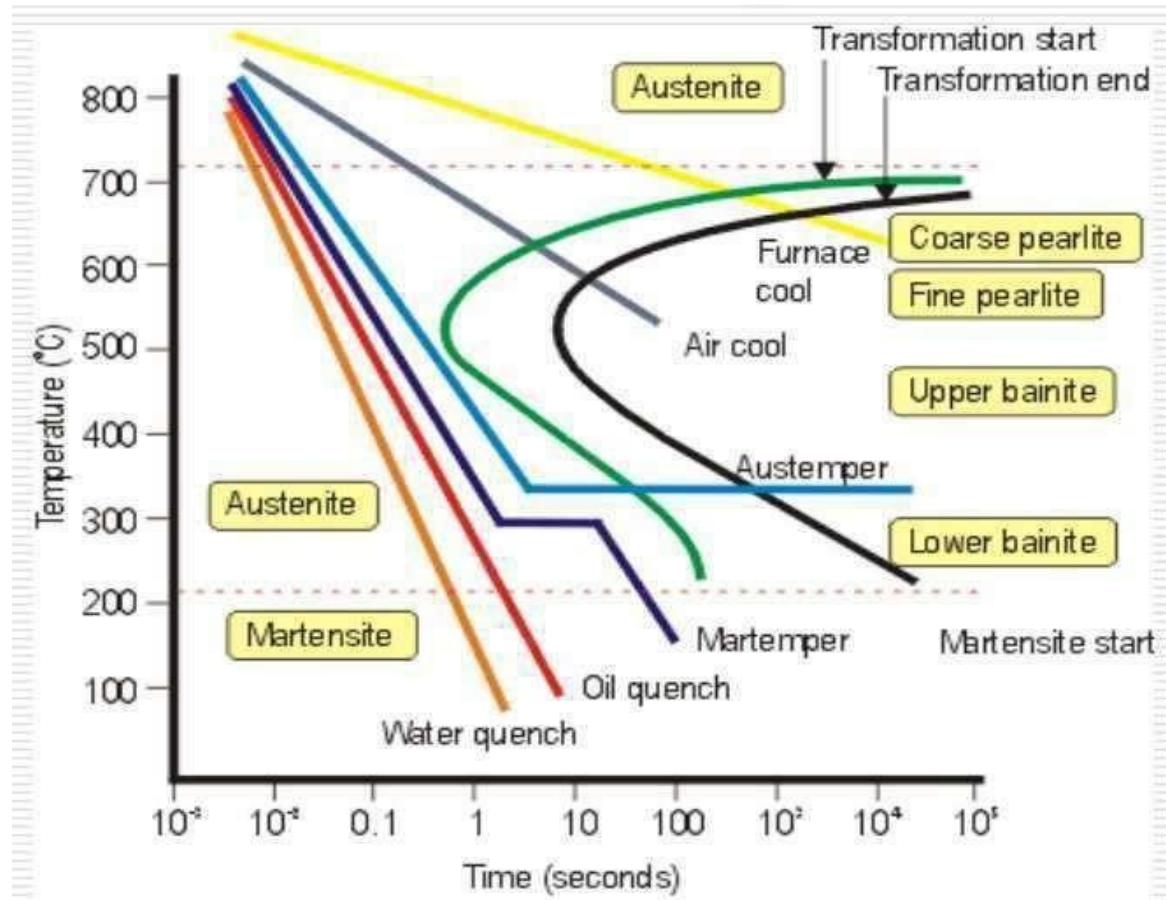
Cementite or iron carbide (Fe_3C) is an intermetallic compound of iron and carbon. It contains 6.67% carbon. It is very hard and brittle. This intermetallic compound is a metastable phase and it remains as a compound indefinitely at room temperature.

4. δ -ferrite

It is a solid solution of carbon in δ -iron. It is stable at high temperatures. It has BCC structure.

Time-temperature Transformation Diagram

An isothermal transformation diagram is only valid for one specific composition of material, and only if the temperature is held constant during the transformation, and strictly with rapid cooling to that temperature. Though usually used to represent transformation kinetics for steels, they also can be used to describe the kinetics of crystallization in ceramic or other materials. Time-temperature-precipitation diagrams and time-temperature-embrittlement diagrams have also been used to represent kinetic changes in steels.



Types of iron

There are two major types of iron produced: wrought iron and cast iron. Within those, cast iron includes its own family of metals.

Wrought iron

The first type of iron produced and worked by blacksmiths was wrought iron. It is virtually pure elemental iron (Fe) that is heated in a furnace before being wrought (worked) with hammers on an anvil. Hammering iron expels most of the slag from the material and welds the iron particles together.



A typical cast iron bearing housing casting in its rough, un-machined condition

During the industrial revolution and the associated acceleration of construction activities, a new use for wrought iron was discovered. Its high tensile strength (resistance to breaking when under tension) made it ideal to use for beams in large construction projects such as bridges and high-rise buildings. However, the use of wrought iron for this purpose was largely abandoned in the early 20th century when steel products were developed with superior performance to iron for construction applications.

Wrought iron has become famous for decorative pieces. Churches of the 15th and 16th century contain fine wrought iron pieces produced by skilled artisans. In the modern world, railings, doors, and benches are still made from wrought iron as custom pieces.

Cast iron

Cast iron is a family of metals produced by smelting metal, and then pouring it into a mold. The primary difference in production between wrought iron and cast iron is that cast iron is not worked with hammers and tools. There are also differences in composition—cast iron contains 2–4% carbon and other alloys, and 1–3% of silicon, which improves the casting performance of the molten metal. Small amounts of manganese and some impurities like sulfur and phosphorous may also be present. Differences between wrought iron and cast iron can also be found in the details of chemical structure and physical properties.

Cast iron products such as barbell weights can be found at local sports gyms

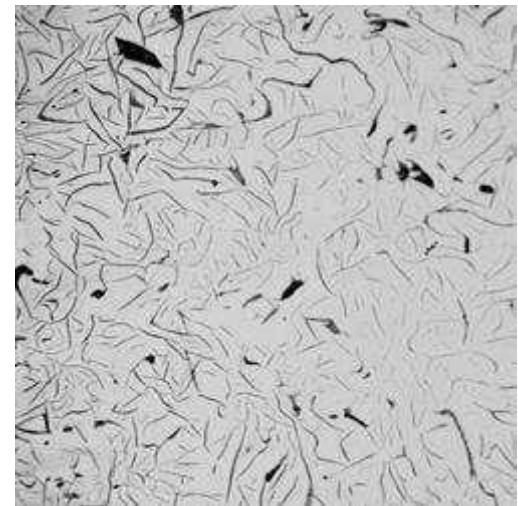
Due to the presence of carbon in cast iron, it may sometimes be confused with steel. However, there are significant differences. Steel contains less than 2% carbon, which enables the final product to solidify in a single microcrystalline structure. The higher carbon content of cast iron means that it solidifies as a heterogeneous alloy, and therefore has more than one microcrystalline structure present in the material.

It is the combination of high carbon content, and the presence of silicon, that gives cast iron its excellent castability.



Gray iron

Gray iron is characterized by the flake shape of the graphite molecules in the metal. When the metal is fractured, the break occurs along the graphite flakes, which gives it the gray color on the fractured metal's surface. The name gray iron comes from this characteristic.



It is possible to control the size and matrix structure of the graphite flakes during production by adjusting the cooling rate and composition. Gray iron is not as ductile as other forms of cast iron and its tensile strength is also lower. However, it is a better thermal conductor and has a higher level of vibration damping. It has a damping capacity that is 20–25 times higher than steel and superior to all other cast irons. Gray iron is also easier to machine than other cast irons, and its wear resistance properties make it one of the highest volume cast iron products.

White iron

With the right carbon content and a high cooling rate, carbon atoms combine with iron to form iron carbide. This means that there are little to no free graphite molecules in the solidified material. When white iron is sheared, the fractured face appears white due to the absence of graphite. The cementite microcrystalline structure is hard and brittle with a high compressive strength and good wear resistance. In certain specialized applications, it is desirable to have white iron on the surface of the product. This can be achieved by using a good conductor of heat to make part of the mold. This will draw heat out of the molten metal quickly from that specific area, while the rest of the casting cools at a slower rate.



One of the most popular grades of white iron is Ni-Hard Iron. The addition of chromium and nickel alloys gives this product excellent properties for low impact, sliding abrasion applications.

White irons and ni-hard irons fall under a classification of alloys referred to as ASTM A532; the "Standard Specification for Abrasion-'esistant Cast Irons".

Malleable iron

White iron can be further processed into malleable iron through a process of heat treatment. An extended program of heating and cooling, results in the breakdown of the iron carbide molecules, releasing free graphite molecules into the iron. Different cooling rates, and the addition of alloys, produces a malleable iron with a microcrystalline structure.

Ductile iron (Nodular iron)

Ductile iron, or nodular iron, obtains its special properties through the addition of magnesium into the alloy. The presence of magnesium causes the graphite to form in a spheroid shape as opposed to the flakes of gray iron. Composition control is very important in the manufacturing process. Small amounts of impurities such as sulfur and oxygen react with the magnesium, affecting the shape of the graphite molecules. Different grades of ductile iron are formed by manipulating the microcrystalline structure around the graphite spheroid. This is achieved through the casting process, or through heat treatment, as a downstream processing step.

Compacted graphite iron

Compacted graphite iron has a graphite structure and associated properties that are a blend of gray and white iron. The microcrystalline structure is formed around blunt flakes of graphite which are interconnected. An alloy, such as titanium, is used to suppress the formation of spheroidal graphite. Compacted graphite iron has a higher tensile strength and improved ductility compared to gray iron. The microcrystalline structure and properties can be adjusted through heat treatment or the addition of other alloys.

Summary of cast iron compositions

Following table shows the different composition ranges for the various types of cast iron:

Range of compositions for typical unalloyed cast irons

Values in percent (%)

Type of Iron	Carbon	Silicon	Manganese	Sulfur	Phosphorus
Gray	2.5 - 4.0	1.0 - 3.0	0.2 - 1.0	0.02 - 0.25	0.02 - 1.0
Ductile	3.0 - 4.0	1.8 - 2.8	0.1 - 1.0	0.01 - 0.03	0.01 - 0.1
Compacted Graphite	2.5 - 4.0	1.0 - 3.0	0.2 - 1.0	0.01 - 0.03	0.01 - 0.1
Malleable (Cast White)	2.0 - 2.9	0.9 - 1.9	0.15 - 1.2	0.02 - 0.2	0.02 - 0.2
White	1.8 - 3.6	0.5 - 1.9	0.25 - 0.8	0.06 - 0.2	0.06 - 0.2

Mechanical properties of cast iron

The mechanical properties of a material indicate how it responds under specific stresses, which helps to determine its suitability for different applications. Specifications are set by organizations such as the American Society for Testing and Materials (ASTM) so that users can purchase materials with confidence that they meet the requirements for their application. The most commonly used cast gray iron specification is ASTM A48.

In order to qualify cast products according to their specifications, a standard practice is to cast a test bar along with the engineered castings. The ASTM tests are then applied to this test bar and the results are used to qualify the entire batch of castings.

Specifications are also important when welding cast iron parts together. The weld must meet or exceed the mechanical properties of the material being welded together—otherwise, fractures and failures can occur.

A few common mechanical properties for cast iron include:

- Hardness – material's resistance to abrasion and indentation
- Toughness – material's ability to absorb energy
- Ductility – material's ability to deform without fracture
- Elasticity – material's ability to return to its original dimensions after it has been deformed
- Malleability – material's ability to deform under compression without rupturing
- Tensile strength – the greatest longitudinal stress a material can bear without tearing apart
- Fatigue strength – the highest stress that a material can withstand for a given number of cycles without breaking

What Is Stainless Steel?

Stainless steel is an alloy of Iron with a minimum of 10.5% Chromium. Chromium produces a thin layer of oxide on the surface of the steel known as the 'passive layer'. This prevents any further corrosion of the surface. Increasing the amount of Chromium gives an increased resistance to corrosion.

Stainless steel also contains varying amounts of Carbon, Silicon and Manganese. Other elements such as Nickel and Molybdenum may be added to impart other useful properties such as enhanced formability and increased corrosion resistance.

When was stainless steel discovered?

There is a widely held view that stainless steel was discovered in 1913 by Sheffield metallurgist Harry Brearley. He was experimenting with different types of steel for weapons and noticed that a 13% Chromium steel had not corroded after several months.

How many types of stainless steel are there?

Stainless steel is usually divided into 5 types:

- a. Ferritic – These steels are based on Chromium with small amounts of Carbon usually less than 0.10%. These steels have a similar microstructure to carbon and low alloy steels. They are usually limited in use to relatively thin sections due to lack of toughness in welds. However, where welding is not required they offer a wide range of applications. They cannot be hardened by heat treatment. High Chromium steels with additions of Molybdenum can be used in quite aggressive conditions such as sea water. Ferritic steels are also chosen for their resistance to stress corrosion cracking. They are not as formable as austenitic stainless steels. They are magnetic.
- b. Austenitic - These steels are the most common. Their microstructure is derived from the addition of Nickel, Manganese and Nitrogen. It is the same structure as occurs in ordinary steels at much higher temperatures. This structure gives these steels their characteristic combination of weldability and formability. Corrosion resistance can be enhanced by adding Chromium, Molybdenum and Nitrogen. They cannot be hardened by heat treatment but have the useful property of being able to be work hardened to high strength levels whilst retaining a useful level of ductility and toughness. Standard austenitic steels are vulnerable to stress corrosion cracking. Higher nickel austenitic steels have increased resistance to stress corrosion cracking. They are nominally non-magnetic but usually exhibit some magnetic response depending on the composition and the work hardening of the steel.
- c. Martensitic - These steels are similar to ferritic steels in being based on Chromium but have higher Carbon levels up as high as 1%. This allows them to be hardened and tempered much like carbon and low-alloy steels. They are used where high strength and moderate corrosion resistance is required. They are more common in long products than in sheet and plate form. They have generally low weldability and formability. They are magnetic.
- d. Duplex - These steels have a microstructure which is approximately 50% ferritic and 50% austenitic. This gives them a higher strength than either ferritic or austenitic steels. They are resistant to stress corrosion cracking. So called "lean duplex" steels are formulated to have comparable corrosion resistance to standard austenitic steels but with enhanced strength and resistance to stress corrosion cracking. "Superduplex" steels have enhanced strength and resistance to all forms of corrosion compared to standard austenitic steels. They are weldable but need care in selection of welding consumables and heat input. They have moderate formability. They are magnetic but not so much as the ferritic, martensitic and PH grades due to the 50% austenitic phase.
- e. Precipitation hardening (PH) - These steels can develop very high strength by adding elements such as Copper, Niobium and Aluminium to the steel. With a suitable "aging" heat treatment, very fine particles form in the matrix of the steel which imparts strength. These steels can be machined to quite intricate

shapes requiring good tolerances before the final aging treatment as there is minimal distortion from the final treatment. This is in contrast to conventional hardening and tempering in martensitic steels where distortion is more of a problem. Corrosion resistance is comparable to standard austenitic steels like 1.4301 (304).

Elastic, anelastic and Viscoelastic behaviour

What are elastic materials?

Elasticity is the tendency of solid materials to return to their original shape after forces are applied on them.

When the forces are removed, the object will return to its initial shape and size if the material is elastic.

What are viscous materials?

Viscosity is a measure of a fluid's resistance to flow. A fluid with large viscosity resists motion. A fluid with low viscosity flows. For example, water flows more easily than syrup because it has a lower viscosity. High viscosity materials might include honey, syrups, or gels – generally things that resist flow. Water is a low viscosity material, as it flows readily. Viscous materials are thick or sticky or adhesive. Since heating reduces viscosity, these materials don't flow easily. For example, warm syrup flows more easily than cold.

What is viscoelastic?

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Synthetic polymers, wood, and human tissue, as well as metals at high temperature, display significant viscoelastic effects. In some applications, even a small viscoelastic response can be significant.

Elastic behavior versus viscoelastic behavior

The difference between elastic materials and viscoelastic materials is that viscoelastic materials have a viscosity factor and the elastic ones don't. Because viscoelastic materials have the viscosity factor, they have a strain rate dependent on time. Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed; however, a viscoelastic substance does.

What are uses of a viscoelastic material?

Viscoelastic materials are used for isolating vibration, dampening noise, and absorbing shock. They give off the energy absorbed as heat.

Anelasticity

Anelastic solids represent a subset of viscoelastic materials: they have a unique equilibrium configuration and ultimately recover fully after removal of a transient load. After being squeezed, they return to their original shape, given enough time. Transient strain is recoverable after the load or deformation is removed. The time scale for recovery may be very short, or it may be so long as to exceed the observer's patience or even lifetime.

Elastic deformation is usually time independent. Upon release of the load, the elastic strain is completely recovered (i.e., the strain returns to zero immediately). However, in some materials, there also exists a time-dependent elastic-strain component and some finite time is required for complete recovery after the load has been released. This time-dependent elastic behavior is known as anelasticity, and it is due to time-dependent microscopic and atomistic processes that are attendant to the deformation.

Anelasticity has been observed in polymers, metallic alloys, polycrystalline ceramics, and bulk metallic glasses. The underlying mechanisms of the anelasticity in different materials are different. For example, phase transformations, reversible motion of twins, grain reorientation, and cooperative motion of many atoms at grain boundaries are the dominant mechanisms for the anelasticity in Cu–Al–Ni alloys, In–Ti alloys, yttria-stabilized zirconia, and nanocrystalline Au, respectively. Note that none of these materials is a single crystal, and the polycrystalline feature of these materials is a key factor for anelasticity.

- Heat treatment of metals, Based on phase diagram and T-T-T-Diagram the heat treatment of various metals, Bulk heat treatments, surface heat treatments, Case carburising, Types of Annealing, Normalising, Spherodising,
- Phase Transformations like Pearlite, Cementite, Austenite, Troostite, Bainite, Hard and soft Martensite etc.
- Laser hardening, Cyniding, Boriding, Nitriding, Flame hardening, Ion implantation, Etc.
- Heat treatment cycles.
- Metallographic studies, Optical Microscope, Electron Microscope.

Heat treating, as the name implies, is a series of treatments in which heat is used to alter the properties of a metal or alloy.

Because time at temperature is also important, heat treatment can be further defined as a series of time-temperature treatments.

Heat treatments are used for a variety of purposes, the most important being to control the mechanical properties, especially hardness, ductility, strength, toughness, and internal stresses.

There are many types of heat treatment processes, some of which are applied only to steels and others that are applied only to other alloys.

Heat treatment processes can be classified into four general categories:

- Annealing(softening)
- Hardening
- Surface hardening
- Miscellaneous

The purpose of heat treating carbon steel is to change the mechanical properties of steel, usually ductility, hardness, yield strength, or impact resistance.

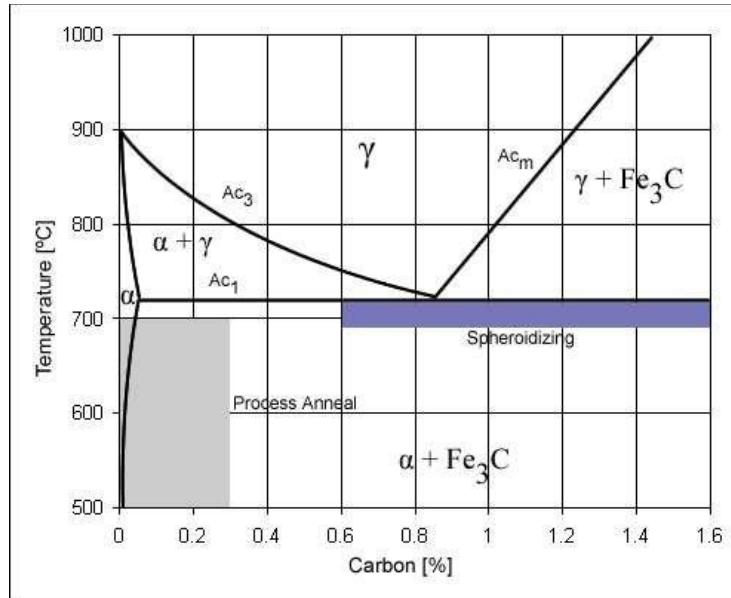
Note that the electrical and thermal conductivity are slightly altered.

As with most strengthening techniques for steel, Young's modulus is unaffected.

Steel has a higher solid solubility for carbon in the austenite phase; therefore all heat treatments, except spheroidizing and process annealing, start by heating to an austenitic phase. The rate at which the steel is cooled through the eutectoid reaction affects the rate at which carbon diffuses out of austenite. Generally speaking, cooling swiftly will give a finer pearlite (until the martensite critical temperature is reached) and cooling slowly will give a coarser pearlite. Cooling a hypoeutectoid (less than 0.77 wt% C) steel results in a pearlitic structure with α - ferrite at the grainboundaries.

If it is hypereutectoid (more than 0.77 wt% C) steel then the structure is full pearlite with small grains of cementite scattered throughout. The relative amounts of constituents are found using the lever rule.

Iron-carbon phase diagram, showing the temperature and carbon ranges for certain types of heat treatments.



Phase Diagrams

A phase diagram is a type of graph used to show the equilibrium conditions between the thermodynamically-distinct phases; or to show what phases are present in the material system at various T, p, and compositions
 “equilibrium” is important: phase diagrams are determined by using slow cooling conditions \Rightarrow no information about kinetics.

Phase diagrams provide valuable information about melting, casting, crystallization, and other phenomenon.
 Phase equilibrium diagrams are plots of the relationship between temperature, pressure and composition.

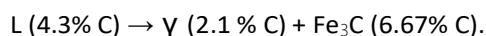
Phase diagrams and phase transformation are used in the understanding of how microstructure evolves and their properties in relation to manufacturing and engineering processes. The details of the thermal history controls the way phase transformation takes place. The processing of most materials involves a thermal history such as the thermal history of solidification which is cooling from a high temperature process.

Phase transformation in Fe-C system

- Peritectic reaction at 1495°C

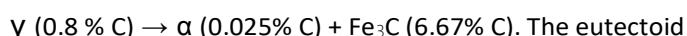


- Eutectic reaction at 1146°C



The eutectic mixture of austenite (γ) and cementite (Fe_3C) is called Ledeburite. Compositions right and left of 4.3% are called hyper and hypoeutectic steels (Cast iron) respectively.

- Eutectoid reaction at 727°C

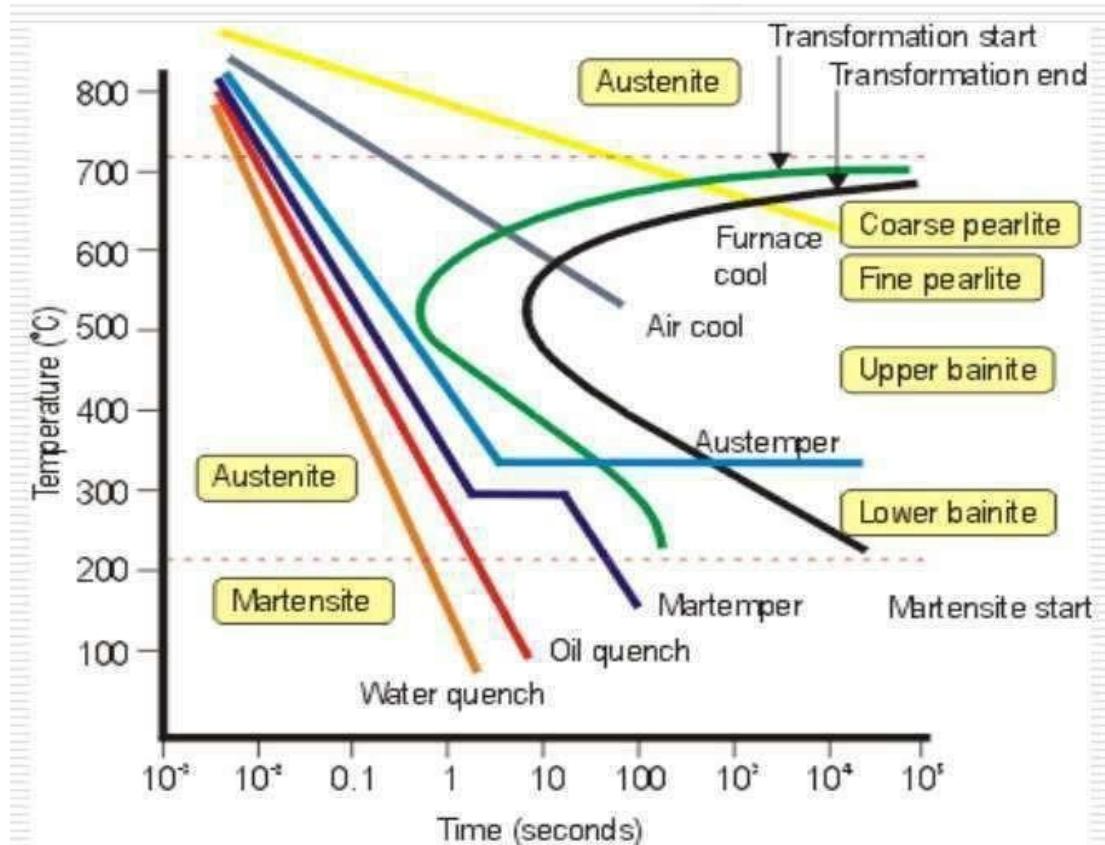


The eutectoid mixture of ferrite (α) and cementite (Fe_3C) is called Pearlite.

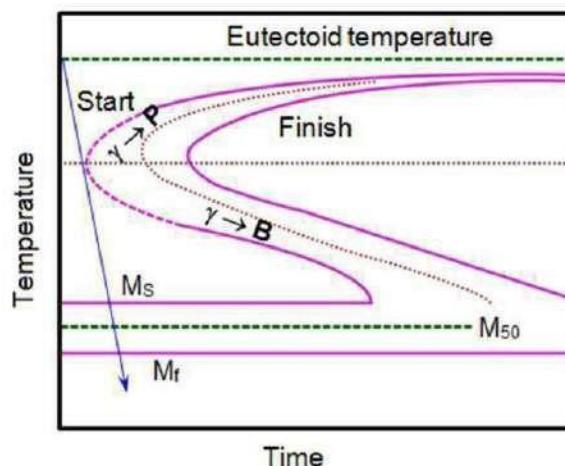
- Compositions right and left of 0.8% are called hyper and hypoeutectoid steels respectively.
- Compositions up to 2.1% C are steels and beyond this it is considered as cast iron.

Time-temperature Transformation Diagram (T-T-T)

An isothermal transformation diagram is only valid for one specific composition of material, and only if the temperature is held constant during the transformation, and strictly with rapid cooling to that temperature. Though usually used to represent transformation kinetics for steels, they also can be used to describe the kinetics of crystallization in ceramic or other materials. Time-temperature-precipitation diagrams and time-temperature-embrittlement diagrams have also been used to represent kinetic changes in steels.



A typical T-T-T diagram is shown below. The phases formed on isothermal holding at a given temp for a certain period of time are indicated.



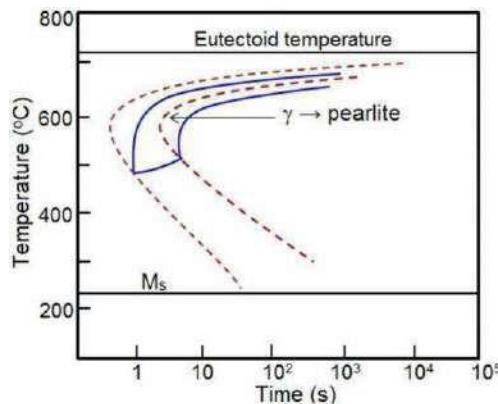
At normal cooling rates pearlite (P) forms, higher cooling rates generates bainite (B). The size of pearlite or Bainite depends on the transformation temp.

Martensite (M) forms when the steel is cooled below the maternsite start (M_s) temp at much higher cooling rate so that the nose of the T-T-T curve (shown dotted) is avoided (the long blue arrow).

Diffusion rates below M_s is so low that γ to M transformation is a diffusionless process (the C content remains same). However, the crystal structure changes from FCC (γ) to body centered tetragonal (BCT).

In actual practice a steel is generally cooled continuously. Continuous-cooling-transformation (C-C-T) diagrams depict this situation.

The C-C-T curve (Blue) is shifted to the right of the T-T-T (dashed) curve as continuous cooling transformation occurs at lower temperature and longer time compared isothermal holding.



Bainite generally does not form in steels during continuous cooling and hence the C-C-T curve ceases just below the nose.

The microstructure (fine or coarse) depends on the cooling rate. Higher the cooling rate finer the microstructure is.

Finer size pearlite is called sorbite and very fine size pearlite is called troostite.

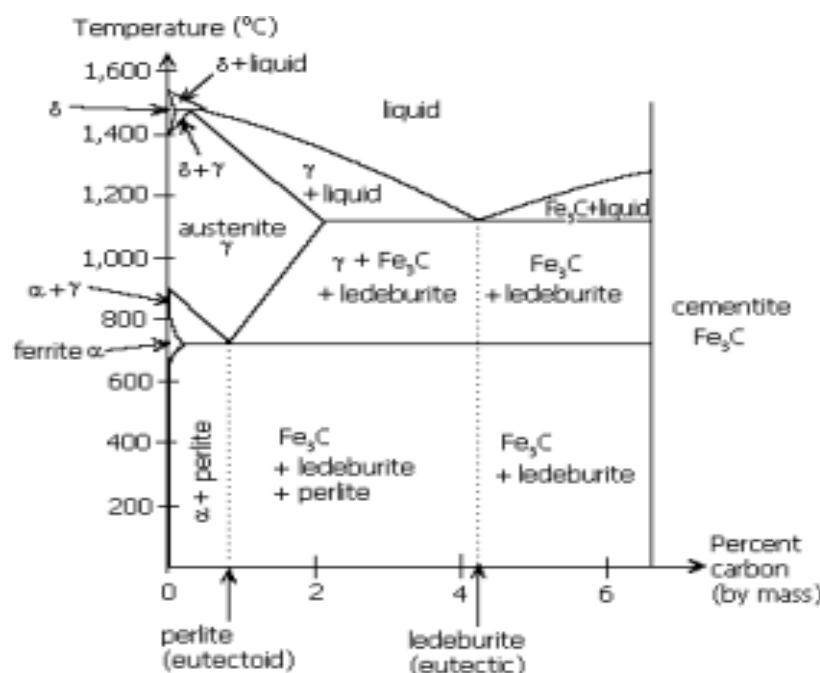
The critical cooling rate is the one at which the cooling curve just touches the nose of the C-C-T curve.

A cooling rate higher than the critical rate is needed to form martensite.

AUSTENITE

Austenite (or gamma phase iron) is a metallic non-magnetic solid solution of iron and an alloying element. In plain-carbon steel, austenite exists above the critical eutectoid temperature of 1000 K (about 727 °C); other alloys of steel have different eutectoid temperatures. It is named after Sir William Chandler Roberts-Austen (1843-1902).

Phase diagram of iron carbon



BAINITE

Bainite is a mostly metallic substance that exists in steelheat

treatments. First described by Davenport E. S. and Edgar Bain, it forms when austenite (a solution of carbon in iron) is rapidly cooled past a critical temperature of 723°C (about 1333°F). after certain

A fine non-lamellar structure, bainite commonly consists of ferrite and cementite. It is similar in constitution to pearlite, but with the ferrite forming by a displacive mechanism similar to martensite formation, usually followed by precipitation of carbides from the supersaturated ferrite or austenite.

When formed during continuous cooling, the cooling rate to form bainite is higher than that required to form pearlite, but lower than that to form martensite, in steel of the same composition.

Bainite is generally stronger but less ductile than pearlite.

Spheroidizing

Spheroidite forms when carbon steel is heated to approximately 700°C for over 30 hours.

Spheroidite can form at lower temperatures but the time needed drastically increases, as this is a diffusion-controlled process. The result is a structure of rods or spheres of cementite within primary structure (ferrite or pearlite, depending on which side of the eutectoid you are on).

The purpose is to soften higher carbon steels and allow more formability. This is the softest and most ductile form of steel. The image shows where spheroidizing usually occurs.

Full annealing

Carbon steel is heated to approximately 40°C above Ac_3 or Ac_1 for 1 hour; this assures all the ferrite transforms into austenite (although cementite might still exist if the carbon content is greater than the eutectoid).

The steel must then be cooled slowly, in the realm of 38°C (68.4°F) per hour. Usually it is just furnace cooled, where the furnace is turned off with the steel still inside. This results in a coarse pearlitic structure, which means the "bands" of pearlite are thick.

Fully annealed steel is soft and ductile, with no internal stresses, which is often necessary for cost-effective forming.

Only spheroidized steel is softer and more ductile.

Annealing

Process annealing: A process used to relieve stress in a cold-worked carbon steel with less than 0.3 wt% C. The steel is usually heated up to $550\text{--}650^{\circ}\text{C}$ for 1 hour, but sometimes temperatures as high as 700°C . The image shows the area where process annealing occurs.

Isothermal annealing: It is a process in which hypoeutectoid steel is heated above the upper critical temperature and this temperature is maintained for a time and then the temperature is brought down below lower critical temperature and is again maintained. Then finally it is cooled at room temperature.

Normalizing

Carbon steel is heated to approximately 55°C above Ac_3 or Acm for 1 hour; this assures the steel completely transforms to austenite. The steel is then air-cooled, which is a cooling rate of approximately 38°C (68°F) per minute.

This results in a fine pearlitic structure, and a more-uniform structure.

Normalized steel has a higher strength than annealed steel; it has a relatively high strength and ductility.

Quenching

Carbon steel with at least 0.4 wt% C is heated to normalizing temperatures and then rapidly cooled (quenched) in water, brine, or oil to the critical temperature.

The critical temperature is dependent on the carbon content, but as a general rule is lower as the carbon content increases. This results in a martensitic structure; a form of steel that possesses a super-saturated carbon content in a deformed body-centered cubic (BCC) crystalline structure, properly termed body-centered tetragonal (BCT), with much internal stress. Thus quenched steel is extremely hard but brittle, usually too brittle for practical purposes. These internal stresses cause stress cracks on the surface.

Quenched steel is approximately three to four (with more carbon) fold harder than normalized steel.

Martempering

Martempering (Marquenching): Martempering is not actually a tempering procedure, hence the term "marquenching".

It is a form of isothermal heat treatment applied after an initial quench of typically in a molten salt bath at a temperature right above the "martensite start temperature". At this temperature, residual stresses within the material are relieved and some bainite may be formed from the retained austenite which did not have time to transform into anything else.

In industry, this is a process used to control the ductility and hardness of a material.

With longer marquenching, the ductility increases with a minimal loss in strength; the steel is held in this solution until the inner and outer temperatures equalize. Then the steel is cooled at a moderate speed to keep the temperature gradient minimal.

Not only does this process reduce internal stresses and stress cracks, but it also increases the impact resistance.

Quench and tempering

This is the most common heat treatment encountered, because the final properties can be precisely determined by the temperature and time of the tempering.

Tempering involves reheating quenched steel to a temperature below the eutectoid temperature then cooling. The elevated temperature allows very small amounts of spheroidite to form, which restores ductility, but reduces hardness.

Actual temperatures and times are carefully chosen for each composition.

Austempering

The austempering process is the same as martempering, except the steel is held in the molten salt bath through the bainite transformation temperatures, and then moderately cooled.

The resulting bainite steel has a greater ductility, higher impact resistance, and less distortion.

The disadvantage of austempering is it can only be used on a few steels, and it requires a special salt bath.

Figure demonstrates the effect of chill rate upon final structure, and is called a time- temperature-transformation or TTT diagram.

Essentially, when cooling from the melt or high temperature phases, there is an incubation period below the equilibrium melting point or transformation temperature (723°C in the case of the steel shown) before the transformation occurs. This undercooling provides the driving force for the transformation.

During a furnace cool (i.e. slow cooling rate) the austenite will start to transform to ferrite and cementite after sufficient undercooling, resulting in a microstructure of coarse pearlite.

With a high cooling rate such as that experienced with a water quench, it is possible to miss the 'nose' of the TTT curve altogether. Martensite is produced starting at about 220°C for the composition shown. The finish temperature of the martensite reaction for certain alloys can be below room temperature, so that at room temperature some unstable austenite is present.

Case hardening

Case hardening or surface hardening is the process of hardening the surface of a metal, often a low carbon steel, by infusing elements into the material's surface, forming a thin layer of a harder alloy. Case hardening is usually done after the part in question has been formed into its final shape, but can also be done to increase the hardening element content of bars to be used in a pattern welding or similar process.

The term face hardening is also used to describe this technique, when discussing modern armour.

Laser Hardening

Laser hardening is a heat treatment process or surface hardening process in which a laser beam is used to heat the surface of a metal part and then let it quickly cool down in surrounding air. This process is used exclusively on ferrous materials suitable for hardening, including steels and cast iron with a carbon content of more than 0.2 percent.

Laser hardening requires less refinishing work and has the ability to process irregular, three-dimensional workpieces. Laser hardening increases hardness and wear resistance, which leads to reduction of abrasive wear.

To harden the workpiece, the laser beam usually warms the outer layer to just under the melting temperature (about 900 to 1400 degrees Celsius). Once the desired temperature is reached, the laser beam starts moving. As the laser beam moves, it continuously warms the surface in the processing direction. The high temperature causes the iron atoms to change their position within the metal lattice (austenization). As soon as the laser beam moves away, the hot layer is cooled very rapidly by the surrounding material in a process known as self-quenching. Rapid cooling prevents the metal lattice from returning to its original structure, producing martensite. Martensite is a very hard metal structure. The transformation into martensite yields greater hardness.

Carburizing

- o Carburizing is a process used to case harden steel with a carbon content between and 0.3 wt% C. In this process steel is introduced to a carbon rich environment

- and elevated temperatures for a certain amount of time, and then quenched so that the carbon is locked in the structure; one of the simpler procedures is repeatedly to heat a part with an acetylene torch set with a fuel-rich flame and quench it in a carbon-rich fluid such as oil.
- Carburization is a diffusion-controlled process, so the longer the steel is held in the carbon-rich environment the greater the carbon penetration will be and the higher the carbon content. The carburized section will have a carbon content high enough that it can be hardened again through flame or induction hardening.
- It's possible to carburize only a portion of a part, either by protecting the rest by a process such as copper plating, or by applying a carburizing medium to only a section of the part.
- The carbon can come from a solid, liquid or gaseous source; if it comes from a solid source the process is called pack carburizing. Packing low carbon steel parts with a carbonaceous material and heating for some time diffuses carbon into the outer layers. A heating period of a few hours might form a high-carbon layer about one millimeter thick.
- Liquid carburizing involves placing parts in a bath of a molten carbon-containing material, often a metal cyanide; gas carburizing involves placing the parts in a furnace maintained with a methane-rich interior.

Nitriding

Nitriding heats the steel part to 482–621 °C (900–1150 °F) in an atmosphere of ammonia gas and dissociated ammonia.

The time the part spends in this environment dictates the depth of the case. The hardness is achieved by the formation of nitrides. Nitride forming elements must be present for this method to work; these elements include chromium, molybdenum, and aluminium.

The advantage of this process is it causes little distortion, so the part can be case hardened after being quenched, tempered and machined.

Cyaniding

Cyaniding is a case hardening process that is fast and efficient; it is mainly used on low carbon steels. The part is heated to 871–954 °C (1600–1750 °F) in a bath of sodium cyanide and then is quenched and rinsed, in water or oil, to remove any residual cyanide.



This process produces a thin, hard shell (between 0.25 - 0.75 mm,

0.01 and 0.03 inches) that is harder than the one produced by carburizing, and can be completed in 20 to 30 minutes compared to several hours so the parts have less opportunity to become distorted. It is typically used on small parts such as bolts, nuts, screws and small gears. The major drawback of cyaniding is that cyanide salts are poisonous.

Destructive and non-destructive testing methods

- Tensile test, Compression test, shear test, bend test,
- Different types of Hardness tests, Impact tests, Fatigue tests, Hardenability test.
- Fracture analysis,
- NDT Methods.
- Different properties of Steels, Aluminum and it's alloys,
- Copper and it's alloys, Manganese and it's alloys, Chromium and it's alloys, Nickel and it's alloys.

Why are metals tested?

- Ensure quality
- Test properties
- Prevent failure in use
- Make informed choices in using materials

Factor of Safety is the ratio comparing the actual stress on a material and the safe useable stress.

Two forms of testing

- Mechanical tests – the material may be physically tested to destruction. Will normally specify a value for properties such as strength, hardness, toughness, etc.
- Non-destructive tests (NDT) – samples or finished articles are tested before being used.

Destructive and non-destructive testing methods

Destructive Testing (DT)

As the name suggests, destructive testing (DT) includes methods where your material is broken down in order to determine mechanical properties, such as strength, toughness and hardness. In practice it means, for example, finding out if the quality of a weld is good enough to withstand extreme pressure or to verify the properties of a material.

These properties can't be examined with non-destructive methods, as specimens of the material must be extracted. Destructive testing is generally most suitable and economic for mass produced objects, as the cost of destroying a small number of pieces is negligible. The samples are put under different loads and stress. That way we can analyze in which point your material eventually gives up and cracks. The results gained are then compared to regulations and/or quality guidelines.

Benefits of Destructive Testing (DT)

- Verifies properties of a material
- Determines quality of welds
- Helps to reduce failures, accidents and costs
- Ensures compliance with regulations

Destructive tests

- Bend test
- Break test
- Tensile test
- Hardness test
- Impact test
- Macro examination
- Micro examination

Nondestructive testing or non-destructive testing (NDT) is a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage. The terms nondestructive examination (NDE), nondestructive inspection (NDI), and nondestructive evaluation (NDE) are also commonly used to describe this technology. Because NDT does not permanently alter the article being inspected, it is a highly valuable technique that can save both money and time in product evaluation, troubleshooting, and research. The six most frequently used NDT methods are eddy-current, magnetic-particle, liquid penetrant, radiographic, ultrasonic, and visual testing.

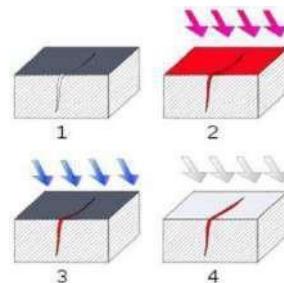
Non-destructive tests

- Visual testing
- Radiographic testing
- Ultrasonic testing
- Penetrant testing
- Magnetic particle testing
- Eddy current testing
- Physical testing of soil
- Physical testing of buildings and building constructions

Application- Weld verification

In manufacturing, welds are commonly used to join two or more metal parts. Because these connections may encounter loads and fatigue during product lifetime, there is a chance that they may fail if not created to proper specification. For example, the base metal must reach a certain temperature during the welding process, must cool at a specific rate, and must be welded with compatible materials or the joint may not be strong enough to hold the parts together, or cracks may form in the weld causing it to fail. The typical welding defects (lack of fusion of the weld to the base metal, cracks or porosity inside the weld, and variations in weld density) could cause a structure to break or a pipeline to rupture.

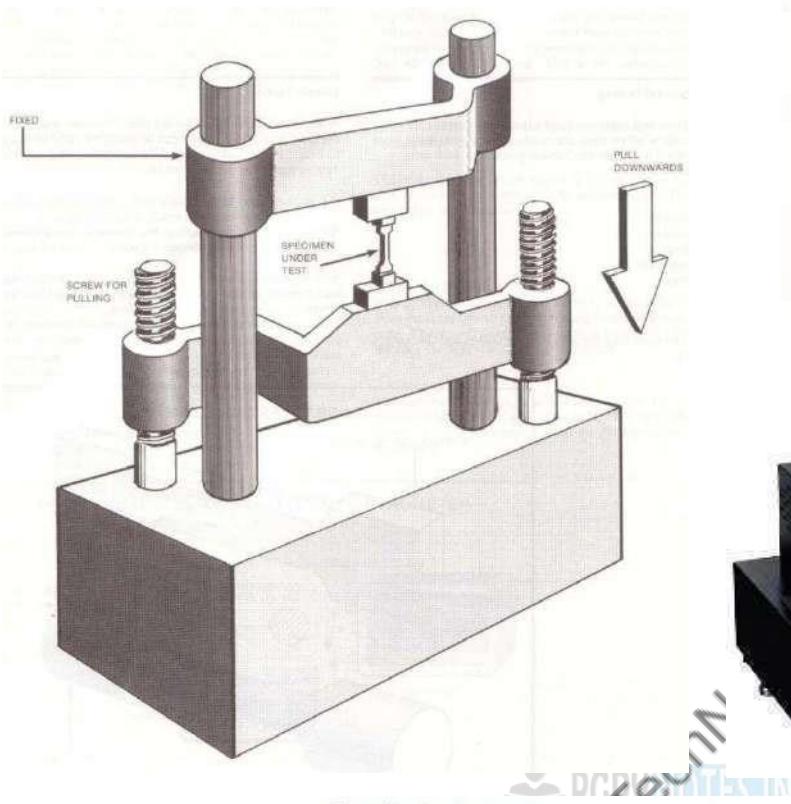
1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface.
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.



Welds may be tested using NDT techniques such as industrial radiography or industrial CT scanning using X-rays or gamma rays, ultrasonic testing, liquid penetrant testing, magnetic particle inspection or via eddy current. In a proper weld, these tests would indicate a lack of cracks in the radiograph, show clear passage of sound through the weld and back, or indicate a clear surface without penetrant captured in cracks.

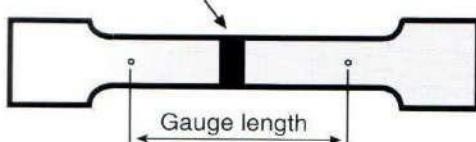
Tensile Testing

- Uses an extensometer to apply measured force to a test specimen. The amount of extension can be measured and graphed.
- Variables such as strain, stress, elasticity, tensile strength, ductility and shear strength can be gauged.
- Test specimens can be round or flat.



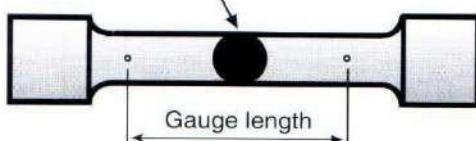
Tensile test specimens

Cross-sectional area

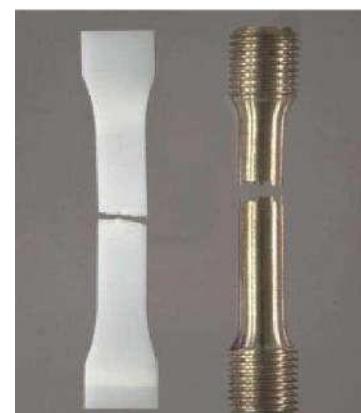


Flat
test
piece

Cross-sectional area

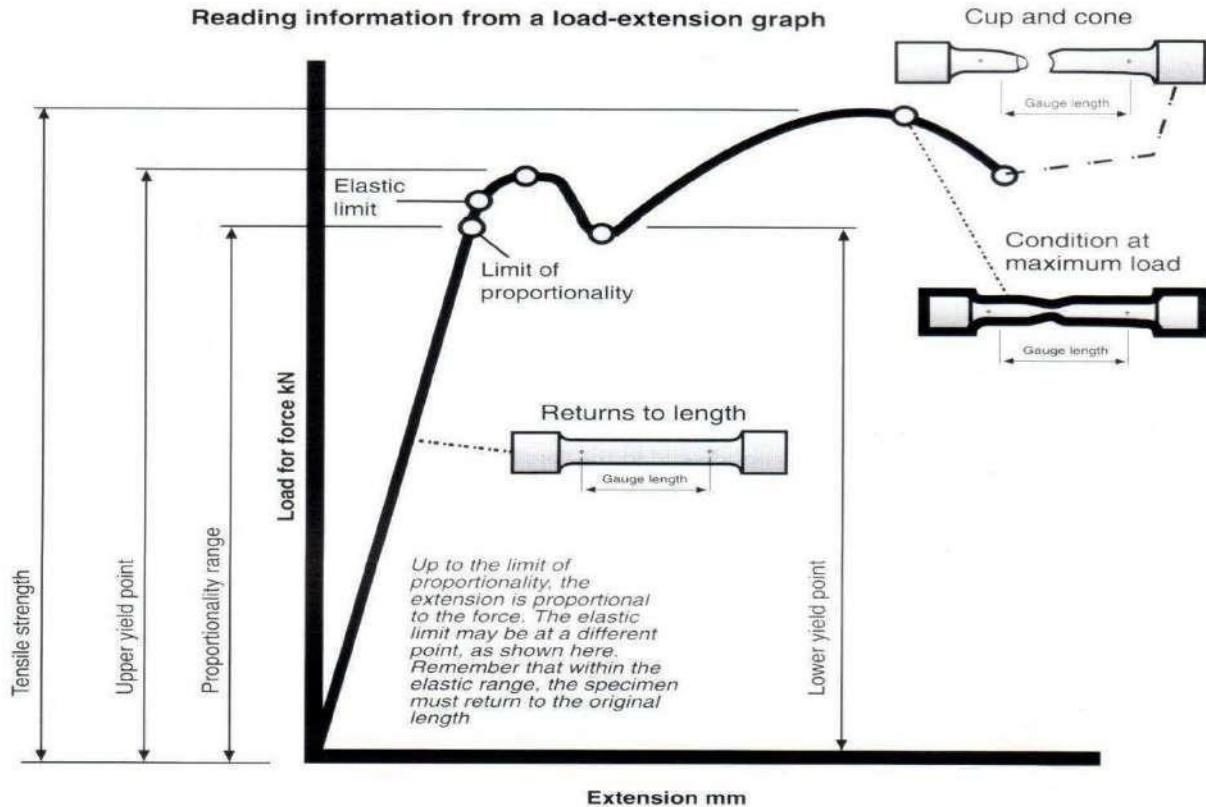


Round
test
piece



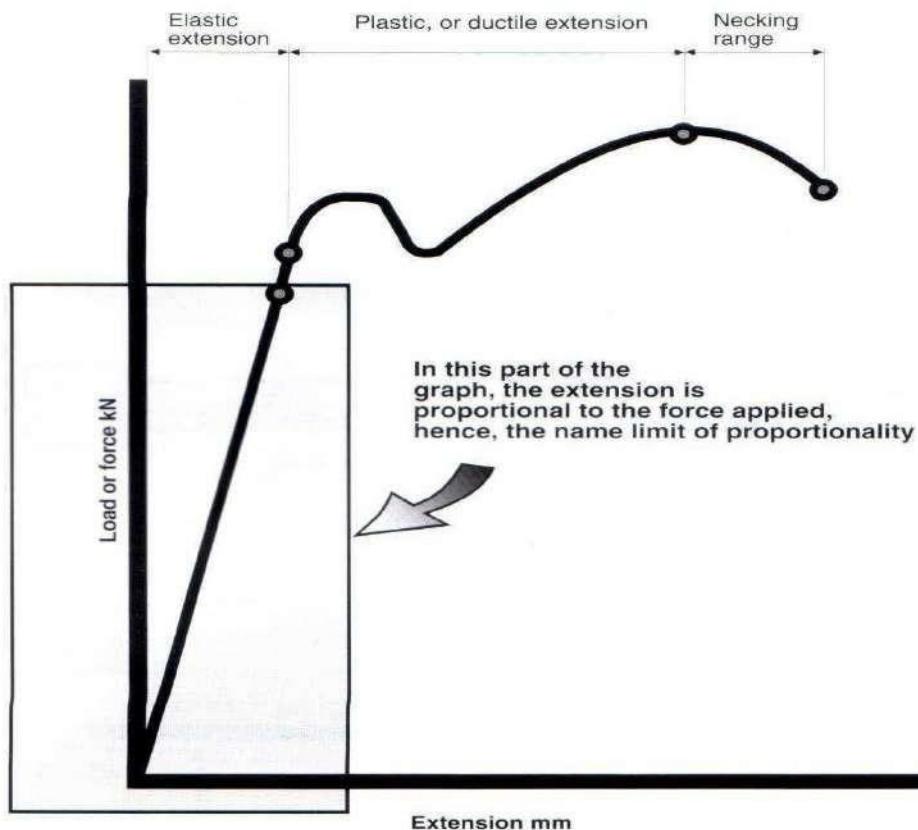
Standard lengths are given below. As well as gauge length, minimum parallel, and total lengths, radii, width, and for round pieces, diameter, are also specified

- Cup and cone fracture signifies a ductile material
- A shear fracture would indicate a brittle material



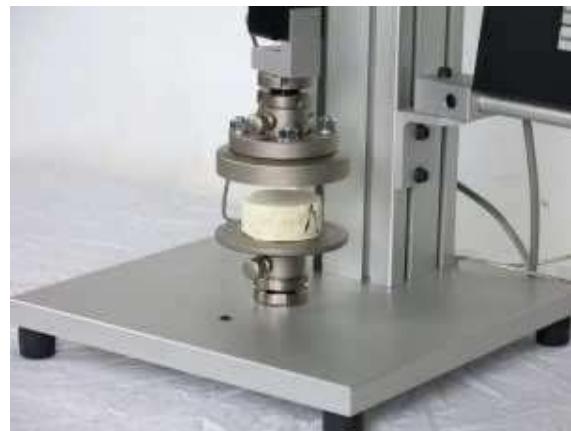
Graph similar to that for a low carbon steel, that has a definite yield point

Types of extension



Compression Test

A compression test is any test in which a material experiences opposing forces that push inward upon the specimen from opposite sides or is otherwise compressed, "squashed", crushed, or flattened. The test sample is generally placed in between two plates that distribute the applied load across the entire surface area of two opposite faces of the test sample and then the plates are pushed together by a universal test machine causing the sample to flatten. A compressed sample is usually shortened in the direction of the applied forces and expands in the direction perpendicular to the force. A compression test is essentially the opposite of the more common tension test.



Purpose of Compression Tests:

The goal of a compression test is to determine the behavior or response of a material while it experiences a compressive load by measuring fundamental variables, such as, strain, stress, and deformation. By testing a material in compression the compressive strength, yield strength, ultimate strength, elastic limit, and the elastic modulus among other parameters may all be determined. With the understanding of these different parameters and the values associated with a specific material it may be determined whether or not the material is suited for specific applications or if it will fail under the specified stresses.

Types of Compression Tests:

In general a compression test for a material involves at least two opposing forces directed towards each other applied to opposite face of the test sample so that the sample is compressed. However, there are many different variations to this basic test setup that involve any combination of different variables. The more common compression tests involve forces applied to more than one axis of the specimen as well as the testing of the sample at elevated and lowered temperatures. Uniaxial, biaxial, triaxial, cold temperature, elevated temperature, fatigue and creep are all examples of different compression tests that may be performed upon a material.

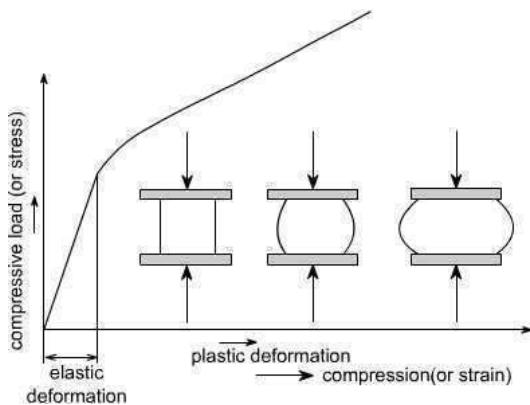
Almost all materials can experience compressive forces in one way or another depending upon their application, but the most common materials are composites, concretes, wood, stone, brick, mortars, grouts, polymers, plastics, foam and metals among many others.

Shape of the specimen: The shape of the machine to be used for the different materials are as follows:

- (i) For metals and certain plastics: The specimen may be in the form of a cylinder
- (ii) For building materials: Such as concrete or stone the shape of the specimen may be in the form of a cube.

Shape of stress stain diagram

(a) Ductile materials: For ductile material such as mild steel, the load Vs compression diagram would be as follows



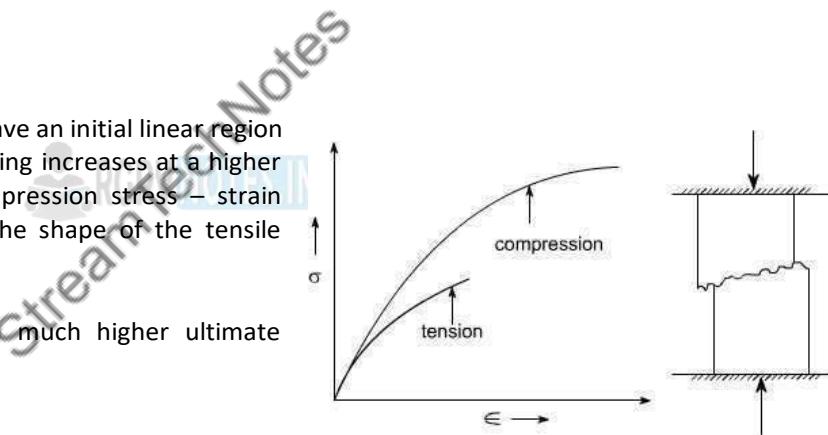
- (1) The ductile materials such as steel, Aluminum, and copper have stress – strain diagrams similar to ones which we have for tensile test, there would be an elastic range which is then followed by a plastic region.
- (2) The ductile materials (steel, Aluminum, copper) proportional limits in compression test are very much close to those in tension.
- (3) In tension test, a specimen is being stretched, necking may occur, and ultimately fracture takes place. On the other hand when a small specimen of the ductile material is compressed, it begins to bulge on sides and becomes barrel shaped as shown in the figure above. With increasing load, the specimen is flattened out, thus offering increased resistance to further shortening (which means that the stress – strains curve goes upward) this effect is indicated in the diagram.

Brittle materials (in compression test)

Brittle materials in compression typically have an initial linear region followed by a region in which the shortening increases at a higher rate than does the load. Thus, the compression stress – strain diagram has a shape that is similar to the shape of the tensile diagram.

However, brittle materials usually reach much higher ultimate stresses in compression than in tension.

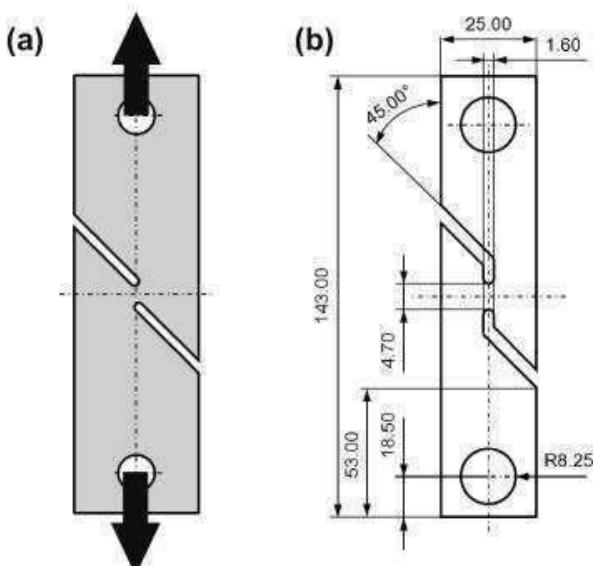
For cast iron, the shape may be like this-



Shear test

Simple shear tests are widely used for material characterization especially for sheet metals to achieve large deformations without plastic instability. This work describes three different shear tests for sheet metals in order to enhance the knowledge of the material behavior under shear conditions. The test setups are different in terms of the specimen geometry and the fixtures.

Fig.- Simple shear test specimen according to (a) ASTM B831–05 standard and (b) a modified ASTM specimen proposed by Merklein and Biasutti (2011). The arrows indicate the direction of force.



What does *Bend Test* mean?

A bend test is a method for measuring stiffness and yield properties of certain materials. Bend tests for ductility provide a simple way to evaluate the quality of materials by their ability to resist cracking or other surface irregularities during one continuous bend. In certain cases the bend test can determine tensile strength.

Bend tests are common in springs and brittle materials with linear failure behaviors like:



- Concrete/stone
- Wood/plastic
- Glass/ceramics
- Powder metallurgy-processed metals and materials

Bend tests are also known as bending tests.

As per IS:1599-1985

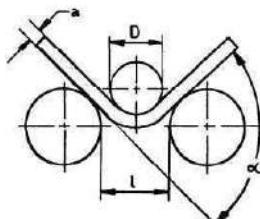
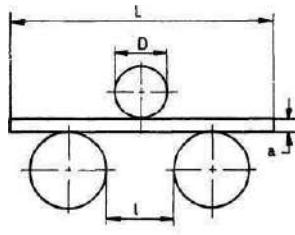


FIG. 1 SIMPLE BEND TEST

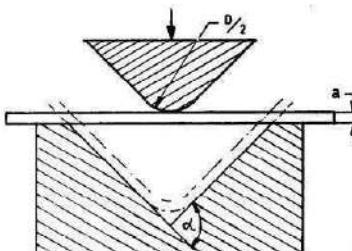


FIG. 2 BEND TEST BY THE USE OF V-BLOCK

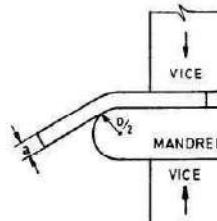


FIG. 3 BEND TEST THROUGH AN ANGLE OVER A SPECIFIED RADIUS'

Hardness testing

Hardness is the ability to withstand indentation or scratches.

The term 'hardness' is one having a variety of meanings; a hard material is thought of as one whose surface resists indentation or scratching, and which has the ability to indent or cut other materials.

Hardness test: The hardness test is a comparative test and has been evolved mainly from the need to have some convenient method of measuring the resistance of materials to scratching, wear or indentation this is also used to give a guide to overall strength of a materials, after as an inspection procedure, and has the advantage of being a non – destructive test, in that only small indentations are left permanently on the surface of the specimen.

Four hardness tests are customarily used in industry namely

- (i) Brinell
- (ii) Vickers
- (iii) Rockwell
- (iv) Shore Scleroscopy

The most widely used are the first two.

In the Brinell test the indenter is a hardened steel ball which is pressed into the surface using a known standard load. The diameter of resulting indentation is than measured using a microscope & scale.

Units:

The units of Brinell Hardness number in S.I Unit would have been N/mm² or Mpa

To avoid the confusion which would have been caused of her wise Hardness numbers are quotes as kgf / mm²

Brinell Hardness test:

In the Brinell hardness test, a hardened steel ball is pressed into the flat surface of a test piece using a specified force. The ball is then removed and the diameter of the resulting indentation is measured using a microscope.

The Brinell Hardness no. (BHN) is defined as

$$BHN = P / A$$

Where P = Force applied to the ball.

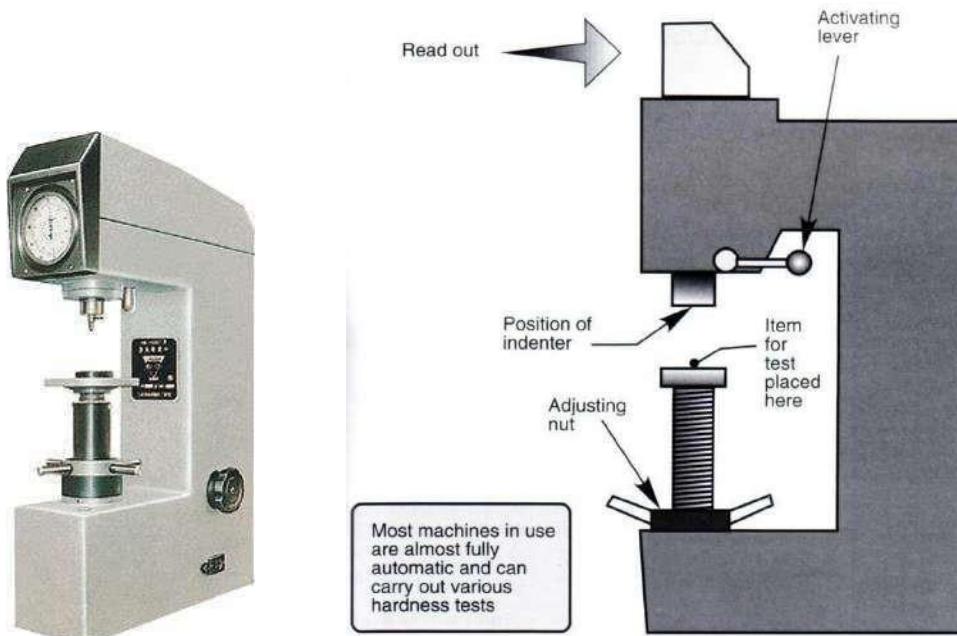
A = curved area of the indentation

It may be shown that

$$A = \frac{1}{2} \pi D [D - \sqrt{D^2 - d^2}]$$

- D = diameter of the ball,
- d = the diameter of the indentation.

In the Brinell Test, the ball diameter and applied load are constant and are selected to suit the composition of the metal, its hardness, and selected to suit the composition of the metal, its hardness, the thickness etc. Further, the hardness of the ball should be at least 1.7 times than the test specimen to prevent permanent set in the ball.



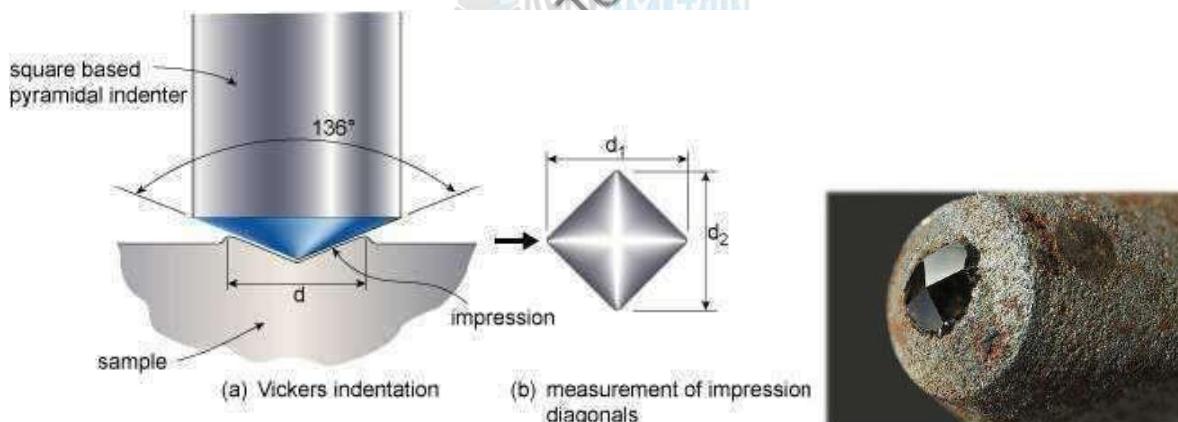
Brinell hardness test

- Uses ball shaped indentor.
- Cannot be used for thin materials.
- Ball may deform on very hard materials
- Surface area of indentation is measured.



Vickers hardness test

- Uses square shaped pyramid indentor.
- Accurate results.
- Measures length of diagonal on indentation.
- Usually used on very hard materials



Rockwell hardness tests

- Gives direct reading.
- Rockwell B (ball) used for soft materials.
- Rockwell C (cone) uses diamond cone for hard materials.
- Flexible, quick and easy to use.

Two most common
indenters are
Ball – B and
Cone – C



Comparison of HT Methods

Test	Indenter	Shape of Indentation		Load	Formula for Hardness Number ^a
		Side View	Top View		
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres			60 kg 100 kg 150 kg 15 kg 30 kg 45 kg	Rockwell Superficial Rockwell

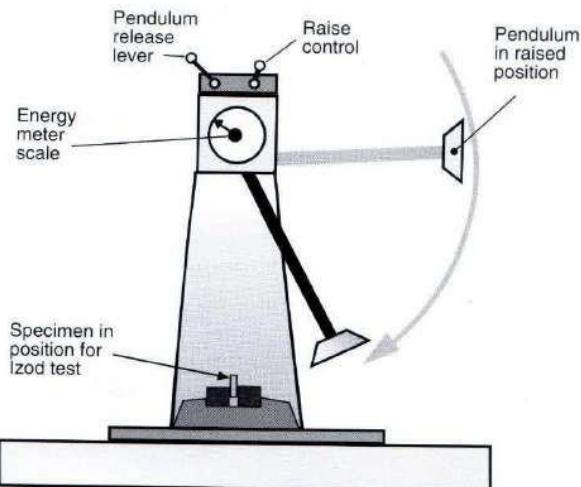
Impact Tests

Toughness of metals is the ability to withstand impact.

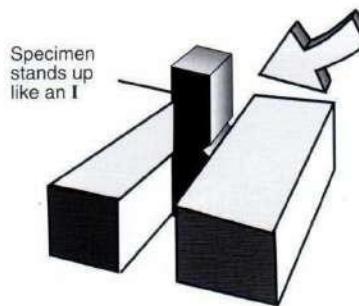
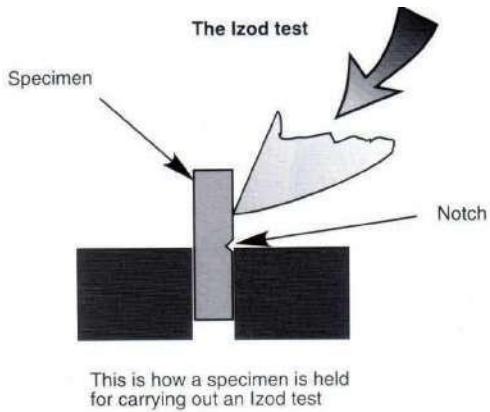
- Strikes at 167 Joules.
- Test specimen is held vertically.
- Notch faces striker.



Impact or notched bar testing machine set-up



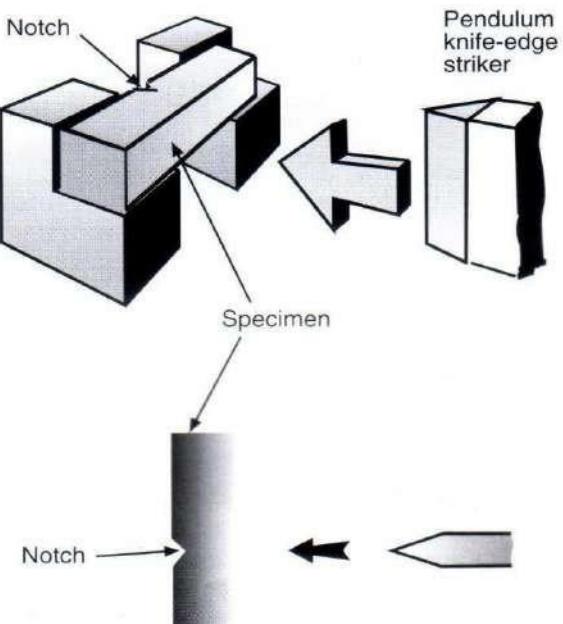
A different striker is fitted for Charpy testing and the specimen is held in a horizontal position with the notch facing away from the pendulum



Charpy impact test

- Strikes from higher position with 300Joules.
- Test specimen is held horizontally.
- Notch faces away from striker.

The Charpy test



Fatigue

- Fatigue is due to the repeated loading and unloading.
- When a material is subjected to a force acting in different directions at different times it can cause cracking. In time this causes the material to fail at a load that is much less than its tensile strength, this is fatigue failure. Vibration for example is a serious cause of fatigue failure.

Fatigue can be prevented with good design practice.

1. A smooth surface finish reduces the chance of surface cracking.
2. Sharp corners should be avoided.
3. Corrosion should be avoided as this can cause fatigue cracks.

Fatigue Test

It is a method for determining the behavior of materials under fluctuating loads. A specified mean load (which may be zero) and an alternating load are applied to a specimen and the number of cycles required to produce failure (fatigue life) is recorded.

Generally, the test is repeated with identical specimens and various fluctuating loads. Loads may be applied axially, in torsion, or in flexure. Depending on amplitude of the mean and cyclic load, net stress in the specimen may be in one direction through the loading cycle, or may reverse direction. Data from fatigue testing often are presented in an S-N diagram which is a plot of the number of cycles required to cause failure in a specimen against the amplitude of the cyclical stress developed. The cyclical stress represented may be stress amplitude, maximum stress or minimum stress. Each curve in the diagram represents a constant mean stress.

Most fatigue tests are conducted in flexure, rotating beam, or vibratory type machines.

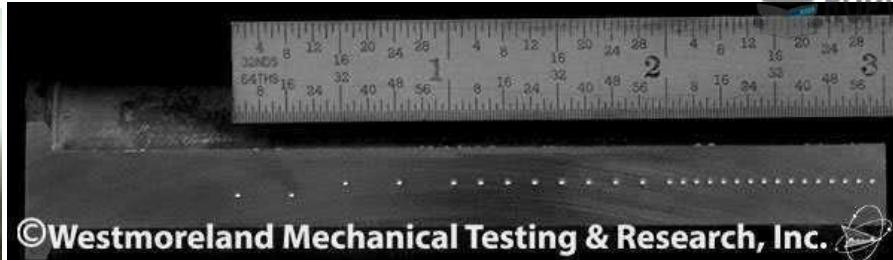


Hardenability Test

The Jominy End Quench Test ASTM A 255 measures Hardenability of steels. Hardenability is a measure of the capacity of a steel to be hardened in depth when quenched from its austenitizing temperature. Hardenability of a steel should not be confused with the hardness of a steel. The Hardness of a steel refers to its ability to resist deformation when a load is applied, whereas hardenability refers to its ability to be hardened to a particular depth under a particular set of conditions. Information gained from this test is necessary in selecting the proper combination of alloy steel and heat treatment to minimize thermal stresses and distortion when manufacturing components of various sizes.



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To perform the Jominy Test: First, a sample specimen cylinder either 100mm in length and 25mm in diameter, or alternatively, 102mm by 25.4mm is obtained. Second, the steel sample is normalized to eliminate differences in microstructure due to previous forging, and then it is austenitised. This is usually at a temperature of 800 to 900°C. Next, the specimen is rapidly transferred to the test machine, where it is held vertically and sprayed with a controlled flow of water onto one end of the sample. This cools the specimen from one end, simulating the effect of quenching a larger steel component in water. Because the cooling rate decreases as one moves further from the quenched end, you can measure the effects of a wide range of cooling rates from very rapid at the quenched end to air cooled at the far end.

Next, the specimen is ground flat along its length to a depth of .38mm (15 thousandths of an inch) to remove decarburized material. The hardness is measured at intervals along its length beginning at the quenched end. For alloyed steels an interval of 1.5mm is commonly used whereas with carbon steels an interval of .75mm is typically employed.

And finally the Rockwell or Vickers hardness values are plotted versus distance from the quenched end.

The Jominy Test data illustrates the effect of alloying and microstructure on the hardenability of steels. Commonly used elements that affect the hardenability of steel are carbon, boron, Chromium, Manganese, Molybdenum, Silicon, and Nickel.

Carbon is primarily a hardening agent in steel, although to a small degree it also increases hardenability by slowing the formation of pearlite and ferrite. But this effect is too small to be used as a control factor for hardenability.

Boron can be an effective alloy for improving hardenability at levels as low as .0005%. Boron is most effective in steels of 0.25% Carbon or less. Boron combines readily with both Nitrogen and Oxygen and in so doing its effect on hardenability is sacrificed. Therefore Boron must remain in solution in order to be effective. Aluminum and Titanium are commonly added as "gettering" agents to react with the Oxygen and Nitrogen in preference to the Boron.

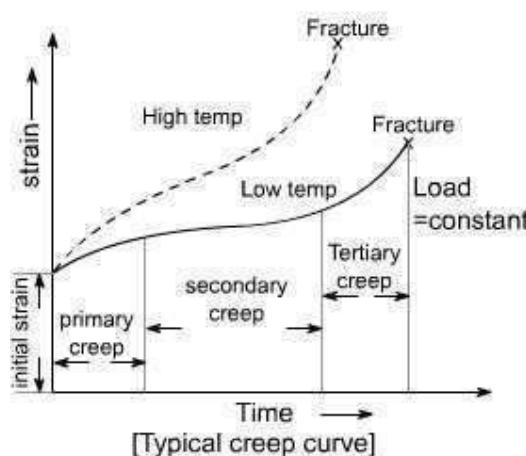
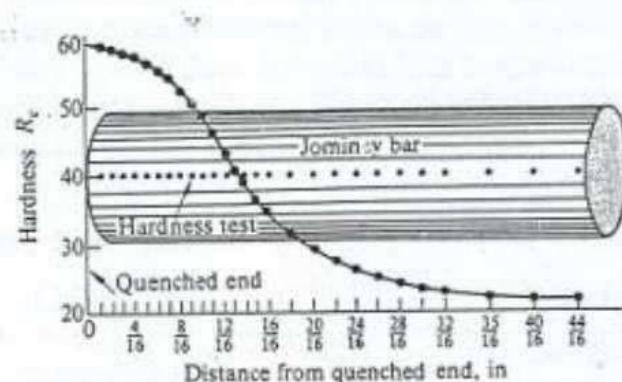
Slowing the phase transformation of austenite to ferrite and pearlite increases the hardenability of steels. Chromium, Molybdenum, Manganese, Silicon, Nickel and Vanadium all effect the hardenability of steels in this manner. Chromium, Molybdenum and Manganese being used most often.

Creep

Creep is the gradual increase of plastic strain in a material with time at constant load. Particularly at elevated temperatures some materials are susceptible to this phenomena and even under the constant load, mentioned strains can increase continually until fractures. This form of fracture is particularly relevant to the turbines blades, nuclear reactors, furnaces rocket motors etc.

The general form of strain versus time graph or creep curve is shown below.

The general form of $\dot{\epsilon}$ Vs t graph or creep curve is shown below for two typical operation conditions, In each case the curve can be considered to exhibit four principal features-



- (a) An initial strain, due to the initial application of load. In most cases this would be an elastic strain.
- (b) A primary creep region, during which the creep rate (slope of the graph) dimensions.
- (c) A secondary creep region, when the creep rate is sensibly constant.
- (d) A tertiary creep region, during which the creep rate accelerates to final fracture.

It is obvious that a material which is susceptible to creep effects should only be subjected to stresses which keep it in secondary (st.line) region throughout its service life. This enables the amount of creep extension to be estimated and allowed for in design.

Fracture Analysis

Flaws and defects in structures and components sometimes lead to disastrous results even though the stress level in a "perfect" structure may indicate a satisfactory design. The study of crack initiations and growth is a complicated topic which involves physics, chemistry, mechanics etc. The engineering field of fracture mechanics was established to develop a basic understanding of such crack propagation problems.

For example, engineers usually want to know the conditions under which an existing crack will continue to grow.

The energy-balance approach

Griffith employed an energy-balance approach that has become one of the most famous developments in materials science. When a crack has grown into a solid to a depth a , a region of material adjacent to the free surfaces is unloaded, and its strain energy released. Using the Inglis solution, Griffith was able to compute just how much energy this is.

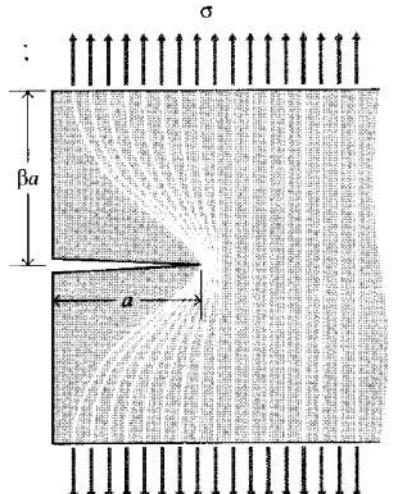
Figure: Idealization of unloaded region near crack flanks.

A simple way of visualizing this energy release, illustrated in Fig. 1, is to regard two triangular regions near the crack flanks, of width a and height βa , as being completely unloaded, while the remaining material continues to feel the full stress σ . The parameter β can be selected so as to agree with the Inglis solution, and it turns out that for plane stress loading $\beta = \pi$. The total strain energy U released is then the strain energy per unit volume times the volume in both triangular regions:

$$U = -\sigma^2 2E \cdot \pi a^2$$

Here the dimension normal to the x-y plane is taken to be unity, so U is the strain energy released per unit thickness of specimen. This strain energy is liberated by crack growth. But in forming the crack, bonds must be broken, and the requisite bond energy is in effect absorbed by the material. The surface energy S associated with a crack of length a (and unit depth) is:

$$S = 2\gamma a$$



where γ is the surface energy (e.g., Joules/meter²) and the factor 2 is needed since two free surfaces have been formed. The total energy associated with the crack is then the sum of the (positive) energy absorbed to create the new surfaces, plus the (negative) strain energy liberated by allowing the regions near the crack flanks to become unloaded.

The stress intensity approach While the energy-balance approach provides a great deal of insight to the fracture process, an alternative method that examines the stress state near the tip of a sharp crack directly has proven more useful in engineering practice. The literature treats three types of cracks, termed mode I, II, and III as illustrated in Fig. Mode I is a normal-opening mode and is the one we shall emphasize here, while modes II and III are shear sliding modes.

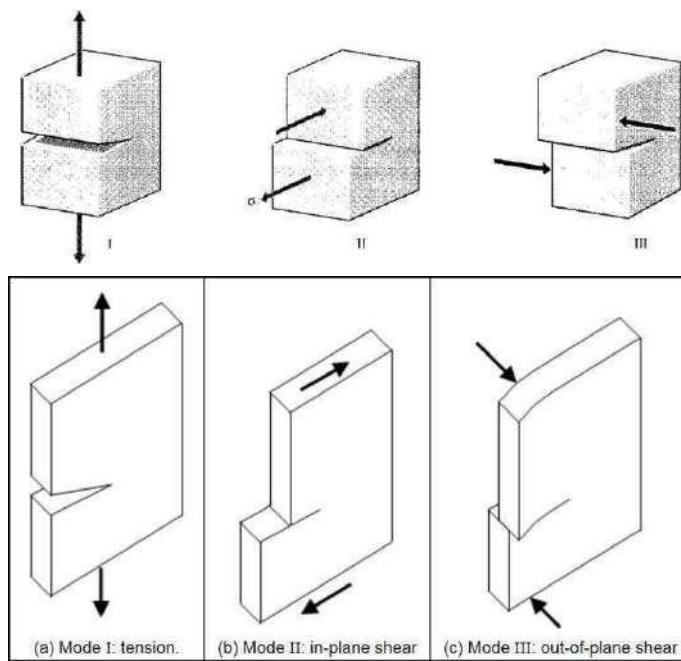


Figure: Fracture modes.

Non Destructive Testing (NDT)

Why use NDT?

- Components are not destroyed
- Can test for internal flaws
- Useful for valuable components
- Can test components that are in use

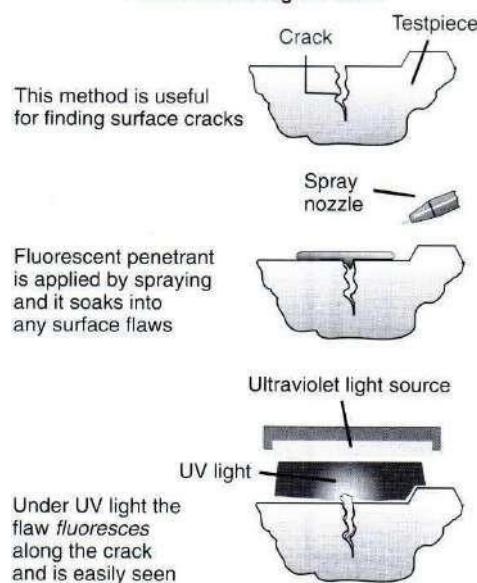
Penetrant testing

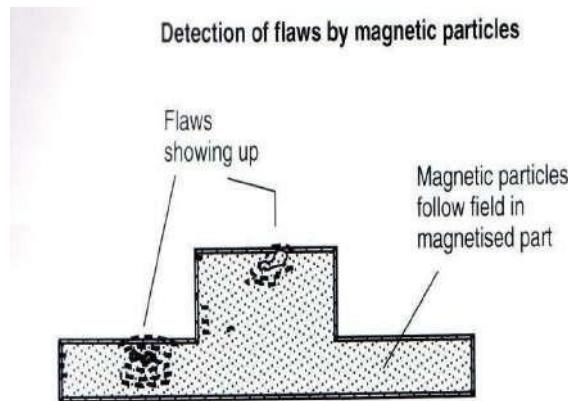
- Used for surface flaws.
- The oil and chalk test is a traditional version of this type of testing. Colored dyes are now used.

Magnetic particle testing

- Used for ferrous metals.
- Detects flaws close to the surface of the material.
- The component to be tested must first be magnetized.
- Magnetic particles which can be dry or in solution are sprinkled onto the test piece.
- The particles stick to the magnetic field and flaws can be inspected visually by examining the pattern to see if it has been distorted.
- The component must be demagnetized after testing.

Penetrant testing for flaws



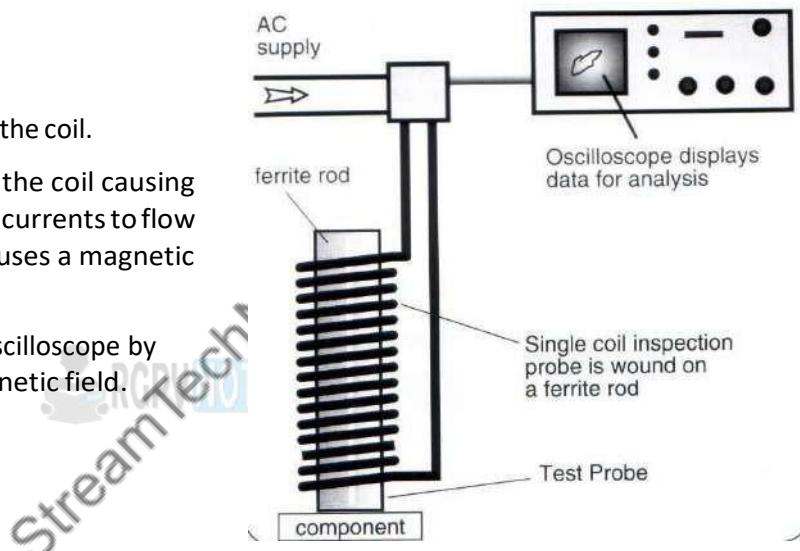


Flaws which are near the surface are more likely to be detected because the distorted magnetic field shows up in the magnetic particle pattern.

Eddy current testing

Eddy current testing

- Used for non-ferrous metals
- A.C. current is passed through the coil.
- The test piece is passed under the coil causing secondary currents called eddy currents to flow through the test piece. This causes a magnetic field to flow in the testpiece.
- The flaws are detected on an oscilloscope by measuring a change in the magnetic field.



Ultrasonic testing

Ultrasonic Sound waves are bounced off the component and back to a receiver. If there is a change in the time taken for the wave to return this will show a flaw. This is similar to the operation of a sonar on a ship.

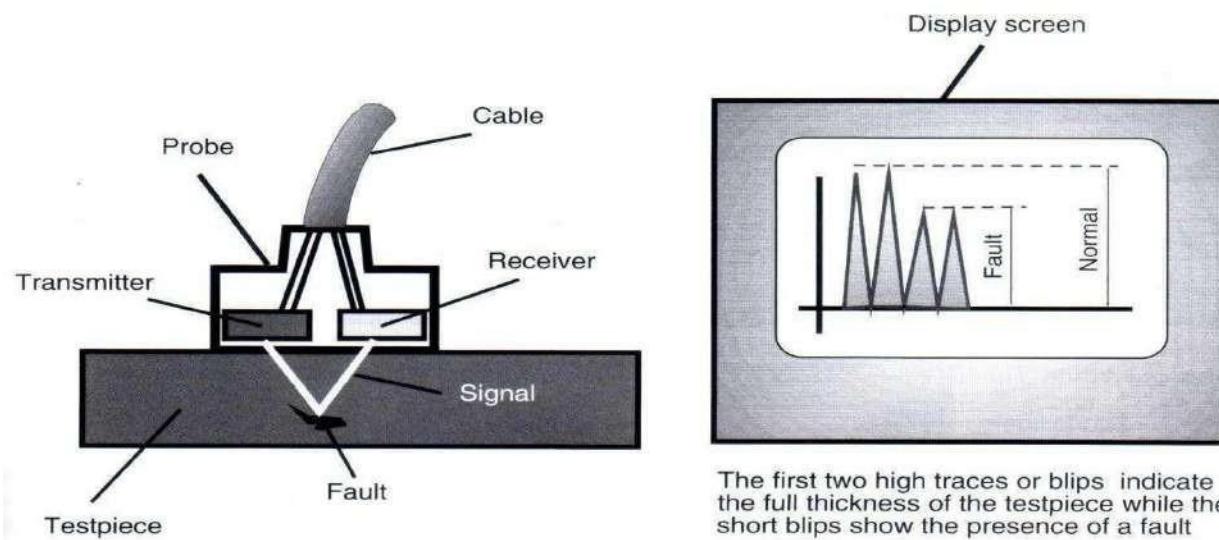
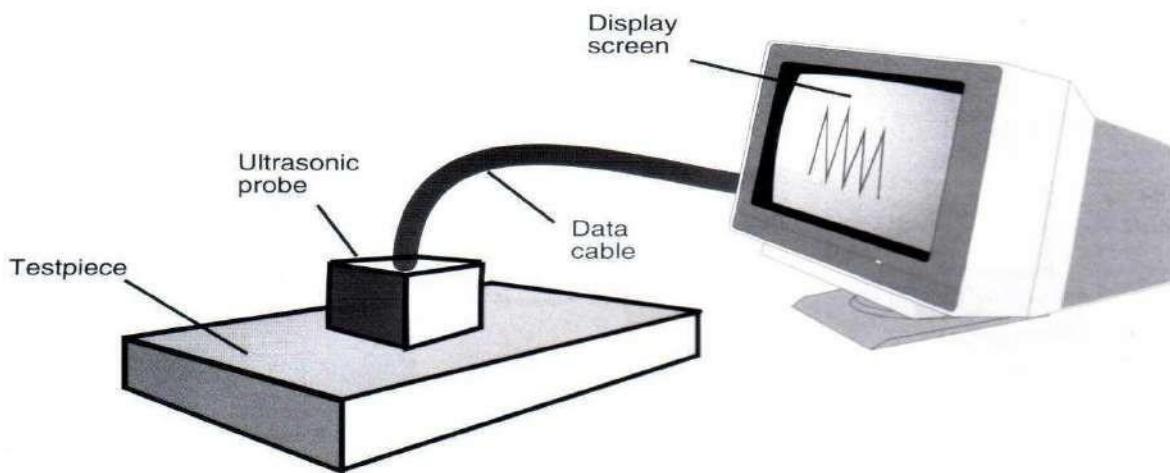
Operation.

1. The ultrasonic probe sends the sound wave through the piece.
2. The sound wave bounces off the piece and returns.
3. The results are then placed on the display screen in the form of peaks.
4. Where the peaks fluctuate this will show a fault in the piece.

Uses.

This is generally used to find internal flaws in large forgings, castings and in weld inspections.

Ultrasonic testing



The first two high traces or blips indicate the full thickness of the testpiece while the two short blips show the presence of a fault

The probe may be of the split type where the transmitter is held on one side of the component under test and the receiver is held on the opposite side

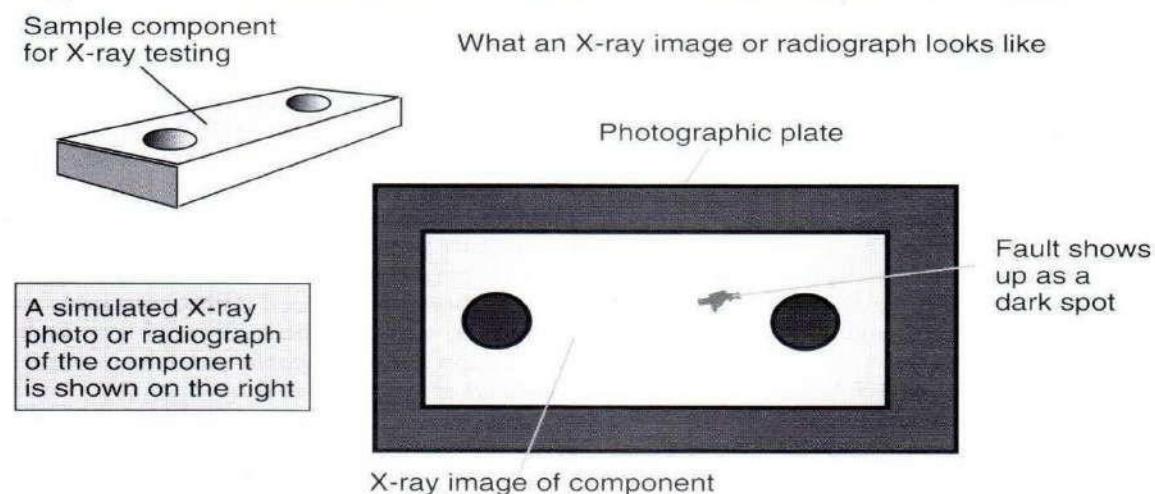
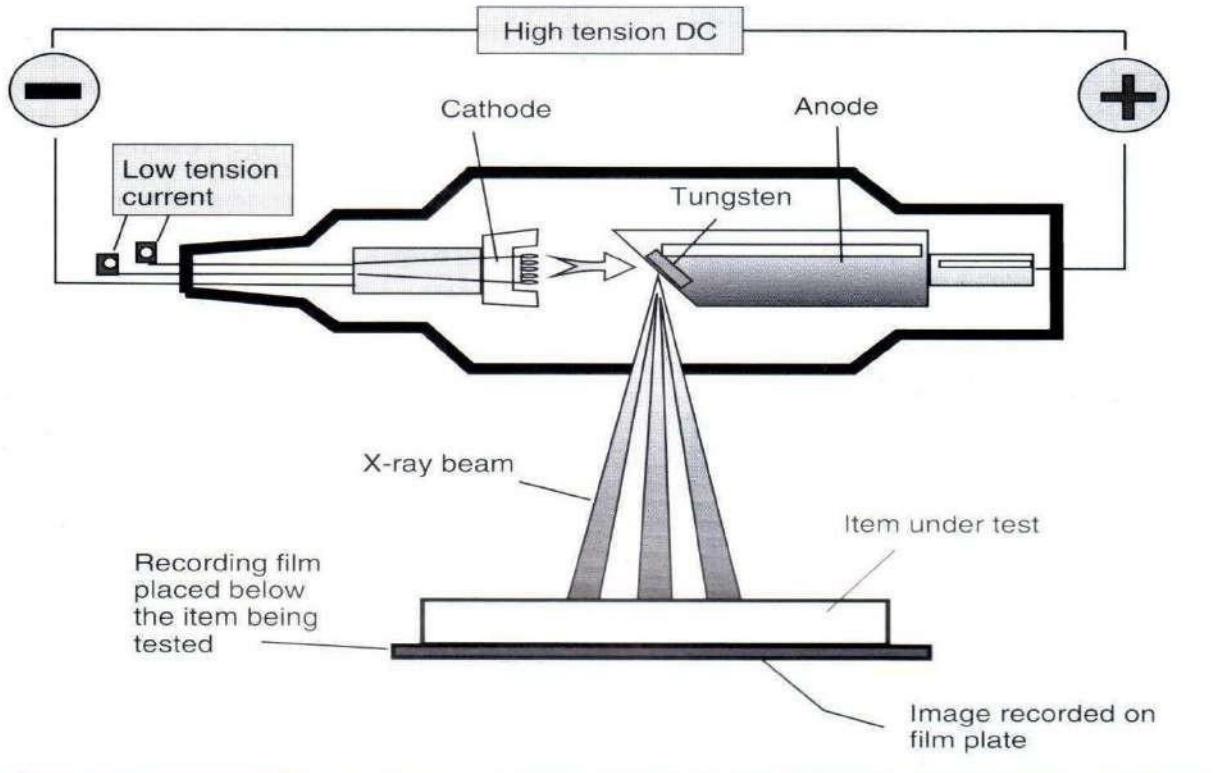
Radiography (X-ray) Testing

1. The x-ray are released by heating the cathode.
2. They are then accelerated by the D.C. current and directed onto the piece by the tungsten anode.
3. The x-rays then pass through the test piece onto an x-ray film which displays the results.
4. The x-rays cannot pass through the faults as easily making them visible on the x-ray film.

Uses.

5. This is a test generally used to find internal flaws in materials. It is used to check the quality of welds, for example, to find voids or cracks.

Radiography or X-ray testing



Aluminum

- Aluminum is a light metal ($\rho = 2.7 \text{ g/cc}$); is easily machinable; has wide variety of surface finishes; good electrical and thermal conductivities; highly reflective to heat and light.
- Versatile metal - can be cast, rolled, stamped, drawn, spun, roll-formed, hammered, extruded and forged into many shapes.
- Aluminum can be riveted, welded, brazed, or resin bonded.
- Corrosion resistant - no protective coating needed, however it is often anodized to improve surface finish, appearance.
- Al and its alloys - high strength-to-weight ratio (high specific strength) owing to low density.
- Such materials are widely used in aerospace and automotive applications where weight savings are needed for better fuel efficiency and performance.
- Al-Li alloys are lightest among all Al alloys and find wide applications in the aerospace industry.

- Aluminum alloys are classified into two categories – Cast and Wrought alloys.
- Wrought alloys can be either heat-treatable or non-heat-treatable.
- Alloys are designated by a 4 digit number. Wrought – the 1st digit indicates the major alloying element. Cast – The last digit after the decimal indicates product from(casting - 0 or ingot -1)

Wrought

Alloy Series	Principal Alloying Element
1xxx	Minimum 99.00% Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

As Cast

Alloy Series	Principal Alloying Element
1xx.x	Aluminum, 99.00% or greater
2xx.x	Copper
3xx.x	Silicon with Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

Compositions, Properties and Application of some Al Alloys

Al Ass. No	Composition (wt.%)	Condition	YS (MPa)	UTS (MPa)	%El	Applications
1100	0.12 Cu	Annealed (O)	35	90	45	Food/chemical handling equipment, heat exchangers light reflectors
3003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed	40	110	30	Utensils, pressure vessels and piping
5052	2.5 Mg, 0.25 Cr	Strain-hardn. (H32)	195	230	14	Bellows, clutch disk, diaphragm, fuse clips, springs
2024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat treated (T4)	325	470	20	Aircraft structure, rivets, truck wheels, screw
6061	1 Mg, 0.6 Si, 0.3 Cu, 0.2 Cr	T4	145	240	22	Trucks, canoes, railroad cars, furniture, pipelines
7075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Peak-aged (T6)	505	570	11	Aircraft structures and other highly loaded applications
359.0	7 Si, 0.3 Mg	T6	164	228	4	Aircraft pump parts, automotive transmission cases, cylinder blocks
8090	2.0 Li, 1.3 Cu, 0.95 Mg, 0.12 Zr	Heat treated cold-worked (T651)	360	465	-	Damage tolerant aircraft structures

Copper

- Copper is one of the earliest metals discovered by man.
- The boilers on early steamboats were made from copper.
- The copper tubing used in water plumbing in Pyramids was found in serviceable condition after more than 5,000 years.
- Cu is a ductile metal. Pure Cu is soft and malleable, difficult to machine.
- Very high electrical conductivity – second only to silver.
- Copper is refined to high purity for many electrical applications.
- Excellent thermal conductivity – Copper cookware most highly regarded – fast and uniform heating.

- Electrical and construction industries are the largest users of Cu.
- The second largest use of Cu is probably in coins.

Copper Alloys

- Brasses and Bronzes are most commonly used alloys of Cu. Brass is an alloy with Zn. Bronzes contain tin, aluminum, silicon or beryllium.
- Other copper alloy families include copper-nickels and nickel silvers. More than 400 copper-base alloys are recognized.

Alloy	Alloying element
Brass	Zinc (Zn)
Phosphor bronze	Tin (Sn)
Aluminium bronzes	Aluminium (Al)
Silicon bronzes	Silicon (Si)
Copper nickel, nickel silvers	Nickel (Ni)

Copper Alloys

Brass

- Brass is the most common alloy of Cu – It's an alloy with Zn
- Brass has higher ductility than copper or zinc.
- Easy to cast - Relatively low melting point and high fluidity
- Properties can be tailored by varying Zn content.
- Some of the common brasses are yellow, naval and cartridge.
- Brass is frequently used to make musical instruments (good ductility and acoustic properties).

Bronze

- Copper alloys containing tin, lead, aluminum, silicon and nickel are classified as bronzes.
- Cu-Sn Bronze is one of the earliest alloy to be discovered as Cu ores invariably contain Sn.
- Stronger than brasses with good corrosion and tensile properties; can be cast, hot worked and cold worked.
- Wide range of applications: ancient Chinese cast artifacts, skateboard ball bearings, surgical and dental instruments.

Nickel

- Nickel is a high-density, high-strength metal with good ductility and excellent corrosion resistance and high temperature properties.
- Ni has many unique properties including its excellent catalytic property. Nickel Catalyst for Fuel Cells: Nickel-cobalt is seen as a low-cost substitute for platinum catalysts.
- Two-thirds of all nickel produced goes into stainless steel production. Also used extensively in electroplating various parts in variety of applications.
- Ni-base super alloys are a unique class of materials having exceptionally good high temperature strength, creep and oxidation resistance. Used in many high temperature applications like turbine engines.
- Shape Memory Alloys: Ni base (Ni-Ti) and Ni containing (Cu-Al-Ni) shape memory alloys that can go back to original form, are an important class of engineering materials finding widespread use in many applications.
- Nickel-containing materials are used in buildings and infrastructure, chemical production, communications, energy (batteries: Ni-Cd, Ni-metal hydrides), environmental protection, food preparation, water treatment and transportation.

Manganese

Manganese is a silvery-gray metal that resembles iron. It is hard and very brittle, difficult to fuse, but easy to oxidize. Manganese is reactive when pure, and as a powder it will burn in oxygen. It reacts with water (rusting like iron) and dissolves in dilute acids. It is an important trace element which is essential for all species and is widely distributed in soil and oceans.

The applications of manganese

At present steel making accounts for 85% to 90% of total manganese consumption. Manganese is often used by the steel industry in deoxidizing and desulfurizing additives and as an alloying constituent.

Chromium

Chromium is a chemical element with symbol Cr and atomic number 24. It is the first element in group 6. It is a steely-grey, lustrous, hard and brittle metal which takes a high polish, resists tarnishing, and has a high melting point.

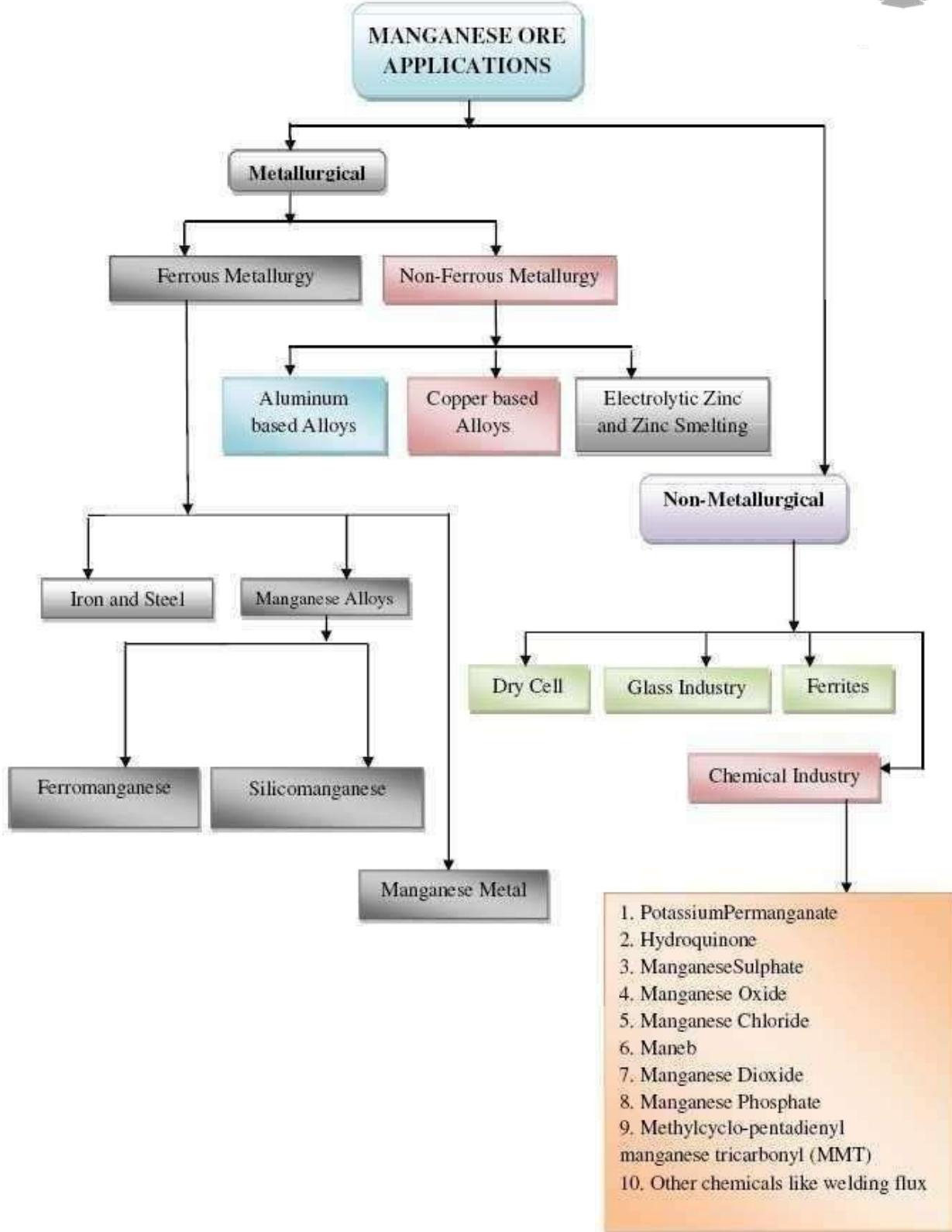
Chromium is remarkable for its magnetic properties: it is the only elemental solid which shows antiferromagnetic ordering at room temperature (and below). Above 38 °C, it changes to paramagnetic.

Chromium metal is most widely recognized for its use in chromium plating (which is often referred to simply as 'chrome'), but its largest use is as an ingredient in stainless steels. Both applications benefit from chromium's hardness, resistance to corrosion, and ability to be polished for a lustrous appearance.

Applications

Out of the total chromite ore extracted, 95.2% was consumed by the metallurgical industry, 3.2% by the refractory and foundry industry, and 1.6% by chemical producers. The major uses for chromium are in stainless steels, alloyed steels, and nonferrous alloys.

Stainless steels refer to a range of steels that contain between 10% to 30% chromium (by weight) and that do not corrode or rust as easily as regular steels. Between 150 and 200 different stainless steel compositions exist, although only about 10% of these are in regular use.



Analysis of different alloying elements in commercial metals

- Chemical Analysis of different alloying elements in commercial metals, C, Fe, Cr, Ni, Mn, Mg, S, P, Co, Mo, etc.
- Different chemical reagents, Equipment
- Volumetric and Gravimetric analysis
- Spot test, Colorimetric methods
- Optical and spectrophotometric analysis.

Chemical analysis of metals is used for a wide variety of purposes and can help companies with their manufacturing quality control, reverse engineering and failure investigations.

Material identification, characterisation and verification are essential for businesses to ensure their materials or products have been manufactured to the correct alloy grade and conform to national or international codes and standards. Metal chemical analysis is also used in reverse engineering to determine the alloys used to produce a component and in failure investigations to establish whether the correct alloy was used.

CLASSIFICATION OF PHYSICAL-CHEMICAL METHODS OF THE ANALYSIS: OPTICAL, ELECTROCHEMICAL, CHROMATOGRAPHIC, KINETIC.

PCMA are divided on:

- § Optical methods are based on measurement of optical properties of substances.
- § Chromatographic methods are based on usage of ability of different substances to selective sorption.
- § Electrochemical methods are based on measurement of electrochemical properties of substances.
- § Radiometric methods are based on measurement of radioactive properties of substances.
- § Thermal methods are based on measurement of heat effects of substances.
- § Mass spectrometric methods are based on studying of the ionized fragments ("splinters") of substances.
- § Kinetic methods are based on measurement of dependence of speed of reaction from concentration of substance

Advantage of PCMA

- § High sensitivity - a low limit of detection (10⁻⁹ mg) and definition
- § High selectivity
- § Rapid analysis methods
- § Automation and computerization is possibility
- § Analysis is possibility on distance
- § Possibility of the analysis without destruction of the sample
- § Possibility of the local analysis

Reagents and Laboratory Chemicals Information

Reagents and laboratory chemicals include substances of sufficient purity for use in chemical analysis, chemical reactions or physical testing.

More technically, IUPAC defines a reagent as a substance or compound that is added to a system in order to bring about a chemical reaction, or added to see if a reaction occurs." Reagents may be either organic or inorganic compounds that are commonly used for analytical purposes such as chemical analysis, physical testing or testing of chemical reactions.



Types

Chemicals reagents are commonly referred to as reagent. It is a large class of pure chemical substances with various standard purities and can be used for education, scientific research, analysis and testing as well as the functional materials and raw materials required by some kinds of novel industrial materials. There is a large variety of chemical reagents and the number has reached hundreds of thousands in the world. There are also tens of thousands of reagents that have been used in daily life in this world.

There is still no uniform international rules in the classification methods for chemicals. It is customary divided by subject and actual application. Take the representative catalog issued by the Germany E • Merck Company as example, there are twelve categories and seventy categories while in most countries, it is divided with the scope of application. We divide the reagents into four categories.



1. General reagents: generally refers to inorganic reagents and organic reagents that can meet standard purity. It is often applied to scientific research, analysis and testing, and synthetic reaction and used as new materials.

2. Analysis Reagents: reagent dedicated to analysis and test and can be divided into two subcategories:

(1) Reagents for chemical analysis: testing items for the chemical reaction analysis.

- 1) Baseline Reagent: pure compound directly used for the standard solution in the formulation and volumetric analysis.
- 2) Indicator: it can be used to indicate the end of the titration reagent and can be classified into pH indicator, redox indicator adsorption indicator, metal indicator, a fluorescent indicator, and so on.

(2) Regents for instrument analysis: high-purity compounds dedicated to instrumental analysis.

- 1) Spectroscopically pure reagents: spectroscopically pure compound, often expressed in the SP for spectral analysis reagents.
 - 2) Chromatography pure reagents: reagents dedicated to analysis of gas chromatography and liquid chromatography analysis.
- 3) Deuterated reagents: reagent decided to the analysis of the nuclear resonance instrument.

3. Reagents of electronics industry: special chemical products dedicated to electronics industry.

4. Biochemical reagents: they are basic chemical substances extracted from living organisms or chemically synthesized and is a large type of reagent as important reagents for biological component research and analysis and identification including clinical immunology reagents, genetic engineering reagent, cell culture reagents, hormone-type substances, reagent for poison carcinogenic research and reagent for anti-mold and insecticide research.

Standards

Purity standards for reagents and laboratory chemicals are set by organizations such as ASTM International or the American Chemical Society.

ASTM D4447 - This guide is intended to provide the chemical laboratory manager with guidelines for the disposal of small quantities of laboratory wastes safely and in an environmentally sound manner.

BS 6376 P2 - Reagents for chemical analysis.

DOD-R-23679 - This specification covers reagents for use in checking the quality of water testing chemicals and equipments used in boiler powered ships.

VOLUMETRIC ANALYSIS

BASIC CONCEPTS OF VOLUMETRIC ANALYSIS

Chemical analysis of the compounds is carried out in two ways

1. Qualitative analysis.
2. Quantitative analysis.

Qualitative analysis shows what element a given contains.

Quantitative analysis determines the quantity of a particular component present in substance.

It is carried out in two ways

1. Gravimetric analysis.
2. Volumetric analysis.

Gravimetric analysis involves the estimation of the amount of a given compound from the results of weighing.

Volumetric analysis is based on the measuring the volume of the solution of a substance.

Terms involved in volumetric analysis

1. Titration: The process of finding out the volume of one of the solution required to react completely with a definite volume of one the other solution of known concentration is called titration.
2. Titrant: The solution of known strength is called titrant.
3. Titrate: The solution whose concentration to be estimated.
4. Indicator: The reagent which indicates the endpoint or equivalent point of the titration. The strength of concentration of a solution is expressed in the following ways.

NORMALITY:

Number of gram equivalents of the substance dissolved per liter of the solution is called Normality.

It is denoted by N

$$\text{Normality} = \frac{W_{\text{solute}}}{E_{\text{solute}}} \times \frac{1}{V_{\text{solvent}}} \text{ (in lit)}$$

Where E is Gram equivalent weight

MOLARITY:

Number of grams moles of a solute dissolved per liter of solution is called Molarity. It is denoted by

$$\text{M Molarity} = \frac{W_{\text{solute}}}{M_{\text{solute}}} \times \frac{1}{V_{\text{solvent}}} \text{ (in lit)}$$

Where M is Gram molecular weight

MOLALITY:

It is the number of mole of the substance dissolved in 1kg of the solvent it is denoted by (m).

$$\text{Molality} = \frac{W_{\text{solute}}}{M_{\text{solute}}} \times \frac{1}{W_{\text{solvent}}} \text{ (in kg)}$$

Gravimetric Analysis

Gravimetric analysis is a process of measuring the amount of an analyte by its mass. Hence, it is a quantitative determination. Here, the desired constituent in a liquid is converted to a solid form that can easily be separated and weighed in order to determine the amount of it and that solid mass can be used for further analysis. The typical gravimetric analysis will have the following steps.

1. Preparation of a solution
2. Separation of the desired constituent from the solution
3. Weighing the amount of constituent

In order to make this analysis a success, the constituent must be completely precipitated as a pure compound and it also must be easy to separate the precipitate via filtration. For the formation of a precipitate, a reagent is added to the solution. This reagent is known as a precipitating agent. Either a filtration method or a volatilization method can be used to separate the precipitate from the solution,

Here, filtration includes filtering of the liquid phase, leaving the solid precipitate on the filter paper. The separation of the precipitate can be done using the following methods;



1. Filtration under gravity
2. Filtration in a Buchner funnel (vacuum filtration)
3. Volatilization of the liquid phase leaving the precipitate

Some applications of gravimetric analysis include precipitation of Ag^+ , Pb^{2+} , and Hg^{2+} as halides, precipitation of Ca^{2+} as calcium oxalate (CaC_2O_4), precipitation of Ba^{2+} as Barium sulfate (BaSO_4), etc.

Volumetric Analysis

Volumetric analysis is a process used to determine the amount of the desired constituent by its volume. Hence it is a quantitative determination. Here, the volume of the constituent is measured via a [titration](#) (titrimetric analysis).

In titrations, a reagent that can react with the analyte is added as proportions until all analyte molecules react with the reagent molecules. When both the sample and the reagent are colorless solutions, an indicator should be used in order to determine the [endpoint](#) of the reaction. The endpoint indicates the end of the analyte molecules.

The indicator is a reagent that can give a color change when the endpoint has been reached. The color change occurs when a change in the reaction mixture has occurred. For example, an acid-base indicator is sensitive to the change of pH in the reaction mixture. It gives the color change when the pH is changed. But some reagents act as self-indicators. Ex: Potassium permanganate.



The reagent used to determine the amount of analyte should completely and quickly react with all analyte molecules. The concentration of this reagent should be known and the portions added should be noted, because these details are required for the calculation of the concentration of the analyte.

Main Difference – Gravimetric vs Volumetric Analysis

The amount of a constituent present in a mixture of constituents can be determined using either gravimetric analysis or volumetric analysis. These methods can be used to determine the purity of a constituent in a given sample. The main difference between gravimetric and volumetric analysis is that in gravimetric analysis, the mass of the analyte is determined whereas, in volumetric analysis, the volume of the analyte is determined.

Gravimetric analysis is a process of measuring the amount of an analyte by its mass	Volumetric analysis is a process used to determine the amount of a desired constituent by its volume
Mass of the analyte is determined	Volume of the analyte is determined
Involves the formation of a solid mass known as a precipitate, which can be separated from the sample solution	Done via a titration, in which the volume of analyte is determined by adding portions of a reagent that can react with the analyte
Generally gives the final result in grams	Gives the final result in milliliters

Spot analysis, spot test analysis, or spot test

is a chemical test, a simple and efficient technique where analytic assays are executed in only one, or a few drops, of a chemical solution, preferably in a great piece of filter paper, without using any sophisticated instrumentation.

Spot tests are simple chemical procedures which uniquely identify a substance. They can be done on small samples, even microscopic samples of matter with no preliminary separation.

In a typical spot test, a drop of chemical reagent is added to a drop of an UNKNOWN mixture.

If the substance in question is present, it produces a chemical reaction characterized by one or more unique observables.

These observables can include- gas bubbling, color change, odor, precipitation.

Occasionally the presence of one substance will interfere with the identification of another. This is referred to as an Interference. Alternative or additional tests must be used to get correct results.

IDENTIFYING an UNKNOWN

1.	CO_3^{2-}	adding H^+ produces effervescence (CO_2)
2.	SO_4^{2-}	acidified Ba^{+2} produces a white precipitate
3.	PO_4^{3-}	$(\text{NH}_4)_2\text{MoO}_4 + \text{HNO}_3$ produces a yellow precipitate
4.	CrO_4^{2-}	acidified H_2O_2 produces a blue solution + O_2
5.	SCN^-	acidic Fe^{+3} produces a blood red solution
6.	Cl^-	acidified Ag^+ gives a white curdy precipitate

7.	CH_3CO_2^-	acidification produces a vinegar odor
8.	NH_4^+	heating with base produces a basic gas (NH_3)

NOTES: (numbers refer to above ions)

1. No heat necessary. To see effervescence may require shaking the tube. This effervescence will also be seen in acidifying UNKNOWN for other tests.
2. Acidify to prevent precipitation of BaCO_3 , $\text{Ba}_3(\text{PO}_4)_2$ or BaCrO_4 .
3. Heat may be necessary. Must form yellow precipitate! Yellow solution indicates only a trace of PO_4^{3-} .
4. Very characteristic test!
5. May require many drops of Fe^{+3} if ions such as PO_4^{3-} are present.
6. If SCN^- is present it must first be destroyed by oxidizing with boiling HNO_3 .
7. Use H_2SO_4 to acidify because it is less volatile than other strong acids. Caution your nose can become less effective at recognizing the vinegar odor after smelling it for a while.
8. Heat solution and test vapors with moist red litmus paper to confirm presence of NH_3 . Caution: placing litmus paper in the test liquid will turn it blue due to the NaOH present.

Colorimetric Methods

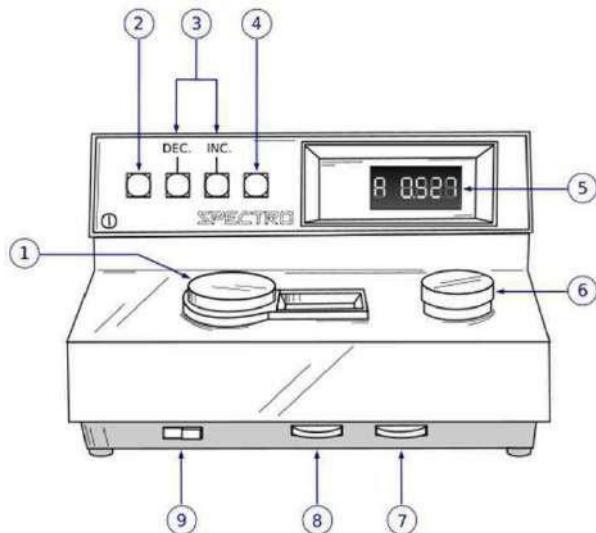
Colorimetric analysis is a method of determining the concentration of a chemical element or chemical compound in a solution with the aid of a color reagent. It is applicable to both organic compounds and inorganic compounds and may be used with or without an enzymatic stage.

Colorimetric methods possess a measurement parameter, where the concentration is directly proportional to color development and intensity after addition of a known volume of reagent(s).

Equipment

The equipment required is a colorimeter, some cuvettes and a suitable color reagent. The process may be automated, e.g. by the use of an AutoAnalyzer or by Flow injection analysis. Recently, colorimetric analyses developed for colorimeters have been adapted for use with plate readers to speed up analysis and reduce the waste stream.

A colorimeter is a device used in colorimetry. In scientific fields the word generally refers to the device that measures the absorbance of particular wavelengths of light by a specific solution. This device is commonly used to determine the concentration of a known solute in a given solution by the application of the Beer-Lambert law, which states that the concentration of a solute is proportional to the absorbance.



- (1) Wavelength selection,
- (2) Printer button,
- (3) Concentration factor adjustment,
- (4) UV mode selector (Deuterium lamp),
- (5) Readout,
- (6) Sample compartment,
- (7) Zero control (100% T),
- (8) Sensitivity switch,
- (9) ON/OFF switch

A cuvette (French: cuvette = "little vessel") is a small tube-like container with straight sides and a circular or square cross section. It is sealed at one end, and made of a clear, transparent material such as plastic, glass, or fused quartz. Cuvettes are designed to hold samples for spectroscopic measurement, where a beam of light is passed through the sample within the cuvette to measure the absorbance, transmittance, fluorescence intensity, fluorescence polarization, or fluorescence lifetime of the sample. This measurement is done with a spectrophotometer.



Output

The output from a colorimeter may be displayed by an analogue or digital meter and may be shown as transmittance (a linear scale from 0-100%) or as absorbance (a logarithmic scale from zero to infinity). The useful range of the absorbance scale is from 0-2 but it is desirable to keep within the range 0-1 because, above 1, the results become unreliable due to scattering of light.

In addition, the output may be sent to a chart recorder, data logger, or computer.

Optical Analysis

Optical analysis is the application of generally non-contact methods, with emphasis on optical principles, i.e. different types of lighting, scene capture and algorithms.

CLASSIFICATION OF OPTICAL METHODS OF THE ANALYSIS:

A major part of modern Instrumental Analytical Chemistry, focuses on the study of the energy exchange between electromagnetic radiation and matter. These interactions are visible to the naked eye, when the radiations concerned fall within the visible spectrum.

A) On investigated objects

- § The nuclear spectral analysis
- § The molecular spectral analysis

B) On the nature of interaction of electromagnetic radiation with substance

1. Absorption analysis

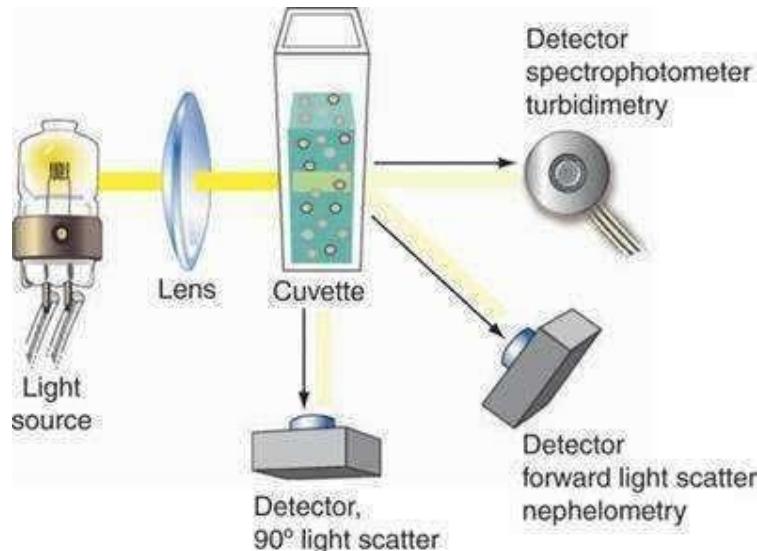
- § Atomic-absorption analysis - Atomic absorption spectroscopy (AAS) is a spectroanalytical procedure for the quantitative determination of chemical elements employing the absorption of optical radiation (light) by free atoms in the gaseous state.
- § Molecular-absorption analysis - Molecular absorption spectroscopy in the ultraviolet (UV) and visible (VIS) is concerned with the measured absorption of radiation in its passage through a gas, a liquid or a solid.
- § Turbidimetric analysis - Turbidimetry (the name being derived from turbidity) is the process of measuring the loss of intensity of transmitted light due to scattering effect particles suspended in it. Light is passed through a filter creating a light of known wavelength which is then passed through a cuvette containing a solution.

2. The emissive spectral analysis

- § Flame photometry - Flame photometry, more properly called flame atomic emission spectrometry, is a fast, simple, and sensitive analytical method for the determination of trace metal ions in solution.
- § Fluorescence analysis - Luminescence is emission of light by a substance not resulting from heat; it is thus a form of cold body radiation.
- § The spectral analysis with usage of effect of combinational dispersion of light

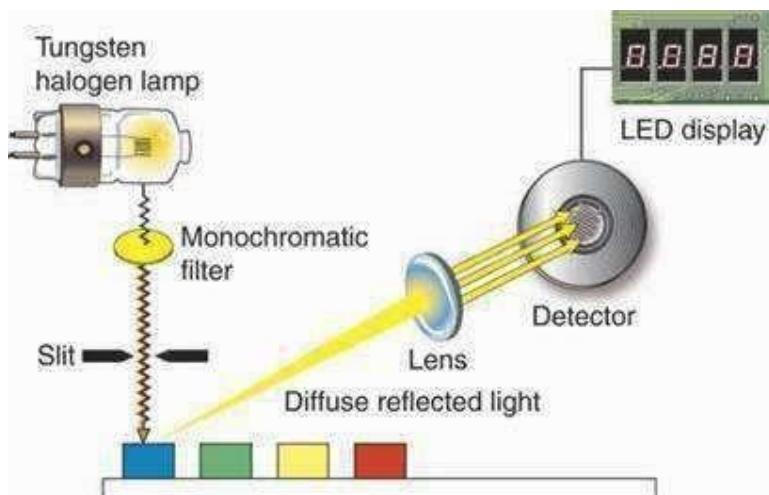
3. Other methods

- § Nephelometric method - Nephelometry is the measurement of scattered light. This technique requires a special measuring instrument, where the detector is set at an angle to the incident light beam.



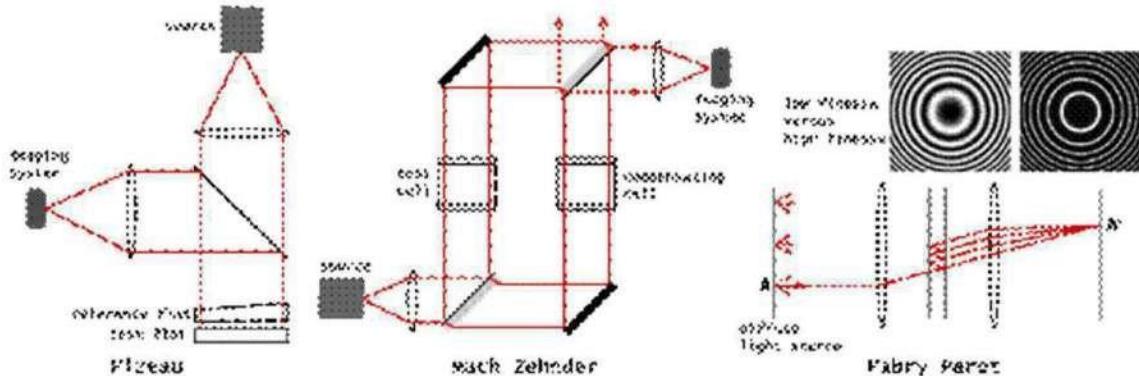
Optical arrangements of nephelometry and turbidimetry

- § Refractometric analysis - Refractometry is the method of measuring substances' refractive index (one of their fundamental physical properties) in order to, for example, assess their composition or purity. A refractometer is the instrument used to measure refractive index ("RI")



Components in a typical reflectometer used to measure analytes on urine dipstick

§ Interferometric analysis - Interferometry is a family of techniques in which waves, usually electromagnetic, are superimposed in order to extract information about the waves.



Three amplitude-splitting interferometers: Fizeau, Mach-Zehnder, and Fabry Perot

C) On electromagnetic spectral range which use in analysis:

- § Spectroscopy (spectrophotometry) in UV and visible spectrum
- § IR - Spectroscopy - Infrared spectroscopy (IR spectroscopy) is the spectroscopy that deals with the infrared region of the electromagnetic spectrum, that is light with a longer wavelength and lower frequency than visible light.
- § X-ray spectroscopy - X-ray spectroscopy is a gathering name for several spectroscopic techniques for characterization of materials by using x-ray excitation.
- § Microwave spectroscopy - The interaction of microwaves with matter can be detected by observing the attenuation or phase shift of a microwave field as it passes through matter.

D) By the nature of energy jump

- § Electronic spectrum
- § Vibrational spectrum
- § Rotational spectrum

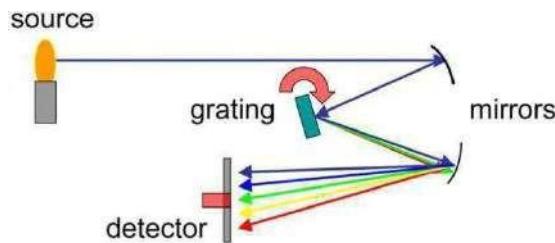
Spectrophotometry

Spectrophotometry is a tool that hinges on the quantitative analysis of molecules depending on how much light is absorbed by colored compounds. Spectrophotometry uses photometers, known as spectrophotometers, that can measure a light beam's intensity as a function of its color (wavelength). Important features of spectrophotometers are spectral bandwidth (the range of colors it can transmit through the test sample), the percentage of sample-transmission, the logarithmic range of sample-absorption, and sometimes a percentage of reflectance measurement.

A spectrophotometer is commonly used for the measurement of transmittance or reflectance of solutions, transparent or opaque solids, such as polished glass, or gases. Although many biochemicals are colored, as in, they absorb visible light and therefore can be measured by colorimetric procedures, even colorless biochemicals can often be converted to colored compounds suitable for chromogenic color-forming reactions to yield compounds suitable for colorimetric analysis. However, they can also be designed to measure the diffusivity on any of the listed light ranges that usually cover around 200 nm - 2500 nm using different controls and calibrations. Within these ranges of light, calibrations are needed on the machine using standards that vary in type depending on the wavelength of the photometric determination

What is an optical spectrometer?

An optical spectrometer (spectrophotometer, spectrograph or spectroscope) is an instrument used to measure properties of light over a specific portion of the electromagnetic spectrum, typically used in spectroscopic analysis to identify materials. The variable measured is most often the light's intensity but could also, for instance, be the polarization state. The independent variable is usually the wavelength of the light or a unit directly proportional to the photon energy, such as reciprocal centimeters or electron volts, which has a reciprocal relationship to wavelength.



A spectrometer is used in spectroscopy for producing spectral lines and measuring their wavelengths and intensities. Spectrometers may also operate over a wide range of non-optical wavelengths, from gamma rays and X-rays into the far infrared. If the instrument is designed to measure the spectrum in absolute units rather than relative units, then it is typically called a spectrophotometer. The majority of spectrophotometers are used in spectral regions near the visible spectrum.

In general, any particular instrument will operate over a small portion of this total range because of the different techniques used to measure different portions of the spectrum. Below optical frequencies (that is, at microwave and radio frequencies), the spectrum analyzer is a closely related electronic device.