

METALLURGY

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(COURSE MATERIAL FOR DEPARTMENTAL PROMOTION EXAMINATION (DPE))

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1. MATERIALS – AN OVERVIEW

1.1 HISTORICAL BACKGROUND: -

History of material is as old as the human civilization. Materials are probably more deeply seated in our culture & society than most of us realize. Transportation, housing, clothing, food, communication—virtually every segment of our every day life is influenced & dependent to one degree or another by materials. Early civilizations were designated by the level of their material development. (I.e. Stone Age, Bronze Age, Iron Age)

Human beings of earlier civilizations had access to only a limited number of materials. Most of them were those which occur naturally: stone, wood, clay, skin & so on. With time they discovered techniques for producing material that had superior properties to those occurring naturally. Furthermore, it was learned by doing experimentation that the properties of a material could be changed by addition of other substances & heating. At that point, material utilization was totally a selection process that is to decide, from a limited number of materials available at that time, the one best suited for an application by virtue of its properties.

It was not until recent times that scientists & engineers came to understand the relationship between the structure of materials & their properties. The advancement in science & technology to make air level comfortable & luxurious, had led to a whole new class of materials including the metals, alloys, plastics, glass, ceramics, fibers, composite.

1.2 CLASSIFICATION OF MATERIALS:-

Now a day materials are grouped into three basic classes: metals, ceramics & polymers. The classification is based primarily on chemical composition & atomic structure. In addition, there are two other groups of materials which are being used increasingly in our everyday life: composites & semiconductors. A brief introduction of each class and their characteristics are given below. However, the main emphasis in this book will be on metals & alloys.

METALS: -

Metallic materials both (metals & alloys) are either composed of single metallic element or combination of metallic elements. Metals are defined as substances which possess luster & are hard, malleable, heavy, ductile, tenacious, good conductor of heat & electricity & have fixed melting & boiling points. These properties make them the most widely used material in our life. Examples are iron, silver, aluminum, gold, copper, brass, bronze, steel, cast iron.

CERAMICS: -

The term "Ceramics" comes from the Greek word "Keramikos" which means "burnt stuff", indicating that desirable properties of these materials are normally achieved through a high temperature, heat treatment process called Firing. Ceramics are compounds between metallic & non-metallic elements. They are mostly oxides, nitrides and carbides. Interatomic bonding in ceramics is either totally ionic or predominantly ionic but having some covalent characters. Typical examples of ceramics include clay minerals, glass, cement, refractories, abrasives, etc. Ceramics are insulative to the passage of electricity and heat. They are more resistant to high temperature than metals & polymers. With respect to mechanical properties, they are hard but brittle.

POLYMERS: -

There are mainly two types of polymer materials.

Naturally occurring polymer --- normally derived from plants & animals e.g. wood, natural rubber, cotton, wool, leather & silk.

Synthetic polymers --- synthesized from small organic molecules e.g. plastics, synthetic rubber, fiber material, PE, PVC, PTFE, PP. polymers are mostly organic in nature & are chemically composed of "C", "H", and other non-metallic elements. Polymers have very large molecular structure. Intermolecular bonding in polymers is covalent. These materials typically have low densities & may be chemically flexible.

COMPOSITE: -

Composites are artificially produced multiphase material in which the constituent phases must be chemically dissimilar and separated by a distinct interface. Many composite materials are composed of just two phases: matrix and the dispersed phase (also known as reinforcement). Matrix is mostly continuous and surrounds the reinforcement. Properties of composite are a function of the properties of the constituent phases, their relative amounts & the geometry of the dispersed phase.

Glass fiber is a familiar example in which glass fibers are embedded within a polymeric material. Fiber glass acquires strength from the glass and flexibility from the polymer. Other examples include tungsten carbide, fiber reinforced plastics, concrete.

SEMICONDUCTORS: -

They have electrical properties intermediate between the electrical conductors and insulators. Furthermore, the electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms.

1.3 METALS & THEIR PROPERTIES:-

Metals: -

Metal is defined as “an element that is lustrous, hard, malleable, heavy, ductile, and strong and is conductor of heat and electricity”. Metals in their solid state exist in the form of crystals. Furthermore, metals have a definite melting & boiling point. Metals crystallize either in the cubic or hexagonal crystal system. In metals, mostly three types of space lattices are encountered: B.c.c. (body centered cubic) F.c.c (face centered cubic), C.p.h (close packed hexagonal).



FIGURE 1.1 - VARIOUS METALS

Space Lattice: -

The three dimensional network of imaginary lines connecting the atoms in a crystal is called space lattice whereas the smallest unit having the full symmetry of the crystal is called the unit cell.

Polymorphism & allotropy: -

Polymorphism is the property of a material to exist in more than one type of space lattice in solid state. If the change in structure is reversible, then the polymorphic change is known as allotropy well known example is Fe. When it crystallizes at 2800 °F, it is b.c.c (δ iron), at 2554 °F, structure changes to f.c.c (γ iron), at 1670 °F it is again changed to b.c.c (α iron).

Most widely used metals include iron, Al, Cu, Ti, Zn, P, Ni, Sn, etc. some of these are used extensively in the pure state but a large number of metals are used in the form of alloys.

Alloy: -

Alloy is a combination of two or more elements, one of which is at least a metal, which exhibits metallic properties.

The prime importance of metals lies principally in their ability to combine with one another to produce substances having wide range of properties that may not be attained with pure metals alone. But there are some instances in which the characteristics of a pure metal make it superior to an alloy for a particular application. e.g. the use of pure Cu for electrical conductors.

PROPERTIES OF METALS: -

A material is completely described by the specification of its properties. These properties can be divided into three classes: physical, mechanical & chemical.

PHYSICAL PROPERTIES: -

Those characteristics which are employed to describe a material under conditions in which external forces are not concerned are called physical properties. In most cases, these characteristics are structure insensitive or intrinsic properties of the material. It means that any change in structure have either very little or no effect upon the particular property.

Density: -

A metal is said to be dense, when it is compact and does not contain defects such as slag, inclusions, porosity etc.

Density is defined as "mass per unit volume".

Density of carbon steel is 7.85gm /cm^3 , Density of Al steel is 2.7gm /cm^3

Density of depleted uranium is 19 gm /cm^3 (used as shielding for gamma sources).

Porosity: -

it is opposite to density. Materials that are porous have an internal structure that lacks compactness or has other defects that leave voids in the metal.

Melting Point: -

Temperature at which a substance passes from a solid to liquid condition is called melting point.

M.P for water is 0°C (32°F) M.P for steel is around 1482°C (2700°F) depending upon the carbon range.

Fusibility:-

It is the ease with which a metal may be melted. In general, soft metals are easily fusible, whereas harder metals melt at higher temperature e.g. Sn, Pb, and Zn are more easily fused than Fe, Mo, & Cr.

Volatility:-

It is the ease with which a substance may be vaporized. A metal which has a low M.P is more volatile than a metal with a high M.P. Volatility is measured by "the temperature at which a metal boils under atmospheric pressure".

Weldability: -

It is the capacity of a metallic substance to form a strong bond of adherence while under presence or during solidification from a liquid state.

Electrical Conductivity:-

It is the ability of a substance to conduct electric current. S.I unit of electrical conductivity is "siemens / metr". Electrical conductivity of Ag is 63 MS / m , while that of Nichrome (heating element) is 1.

Electrical Resistance:-

Opposition to the flow of current is called as electrical resistance. SI unit of resistance is "ohm". Electrical resistance of Ag is 159 micro ohm-cm while that of Nichrome is more than 100 micro ohm-cm .

Thermal Conductivity:-

It is the ability of a substance to carry heat. Thermal conductivity of Ag is $1 \text{ Cal /cm}^3\cdot\text{sec}^{\circ}\text{C}$ ($15.33\text{KJ/m}^3\cdot\text{sec}^{\circ}\text{K}$), while that of Fe is $0.18 \text{ Cal /cm}^3\cdot\text{sec}^{\circ}\text{C}$ ($2.76\text{KJ/m}^3\cdot\text{sec}^{\circ}\text{K}$).

Co-efficient of Thermal Expansion: -

It is the amount of expansion a metal undergoes when it is heated & the amount of contraction that occurs when it is cooled. It can also be defined as "Change in length per unit original length per $^{\circ}\text{C}$ rise in temperature. Co-efficient of thermal expansion of Ag is $19.68 \mu \text{ m/m}^{\circ}\text{C}$ at 20°C , while that of iridium is $6.8 \mu \text{ m/m}^{\circ}\text{C}$ at 20°C .

Specific Heat: -

Amount of heat that is required to raise the temperature of a gram mole of a substance to 1°K . There are two ways of increasing this property. One is this heat capacity at constant volume of specimen (Cr); other is

the heat capacity at constant external pressure (C_p). Magnitude of C_p is always greater than C_v however for most solid materials this difference is very slight at room temperature & below.

Thermal Shock & Thermal shock Resistance: -

Thermal shock is the fracture of the body resulting from thermal stresses induced by rapid temperature changes. Since ceramics are brittle, they are especially susceptible to this type of failure.

Thermal shock resistance (TSR) is the resistance to the thermal failure for many materials. TSR is directly proportional to fracture strength & thermal conductivity and inversely proportional to both the modulus of elasticity & coefficient of thermal expansion.

Hot Shortness: -

Brittleness in metals in the hot forms range.

Hot Forming Range:-

It is defined as mechanical working of metal above its re-crystallization temperature.

Recrystallization Temperature:-

The approximate minimum temperature at which complete recrystallization of a highly cold worked metal occurs within a specified time, approximately 1hr.

Recrystallization is the formation of new, strain free grains structure in a cold worked metal, usually accomplished by heating.

Cold Shortness: -

Brittleness in some metals at temperature below the recrystallization temperature.

MECHANICAL PROPERTIES: -

Those characteristics of a material that describe its behavior under the action of external forces are called mechanical properties. For example the strength of a material is definitely structure sensitive & is seriously affected by small degree of imperfections.

Hardness: -

Hardness can be defined in many ways;

Resistance to penetration / Resistance to indentation / Resistance to abrasion or cutting. In general terms, "it is the ability of one material to penetrate another material without fracture of either is known as Hardness".

A hard material is also a strong material but is not necessarily a ductile one.

Three not commonly used hardness test methods are:-

Rockwell Hardness Testing (Units HRA, HRB, HRC)

Brinell Hardness Testing (Unit HB)

Vickers Hardness Testing (Unit HV)

Elastic Deformation: -

The degree to which a structure deforms / strains depends on the magnitude of applied stress. Most metals that are deformed in tension and at relatively low stress levels, stress & strain are proportional to each other:

$$\sigma \propto \varepsilon$$

$$\text{or} \quad \sigma = E \varepsilon$$

Where E is the modulus of elasticity or Young's Modulus.

Deformation in which stress & strain are proportional is called Elastic Deformation.

Elastic deformation is non-permanent, which means that upon release of applied load, the metal returns to its original shape.

Elasticity: -

Ability of a material to return to its original shape, after removal of applied load is called elasticity.

Anelasticity: -

Earlier it was assumed that elastic deformations are time independent, that is, the applied stress produces an instantaneous elastic strain which remains constant over the period of time, the stress is maintained. It was also assumed that upon release of load, the strain is totally recovered. But in most engineering materials there exists a time dependent elastic strain component. That is, elastic deformation will continue after stress application and upon release of load, some finite time is required for complete recovery, this time dependent behavior is called Anelasticity. For metals, the anelastic behavior is usually small & is often neglected.

Plastic Deformation: -

For most metals, deformation persists only to strains of about 0.005. As the material is deformed beyond this point, stress is no longer proportional to strain and permanent, non-recoverable plastic deformation occurs.

Plasticity: -

Ability of a material to deform permanently without breaking is called plasticity.

TENSILE PROPERTIES:-

Elastic Limit: -

The greatest load that may be applied after which the material will return to its original shape.

Yield Point: -

When a sample of low or medium carbon, steel is subjected to tensile loading, a point is found at which a definite increase in length occurs without an increase in load. The stress at this point is called yield point of the material.

Yield Strength: -

Non-ferrous metals and steels other than low or medium carbon steels do not have a sharp yield point. There is a gradual elastic-plastic transition. For those materials, the maximum useful strength is the yield strength.

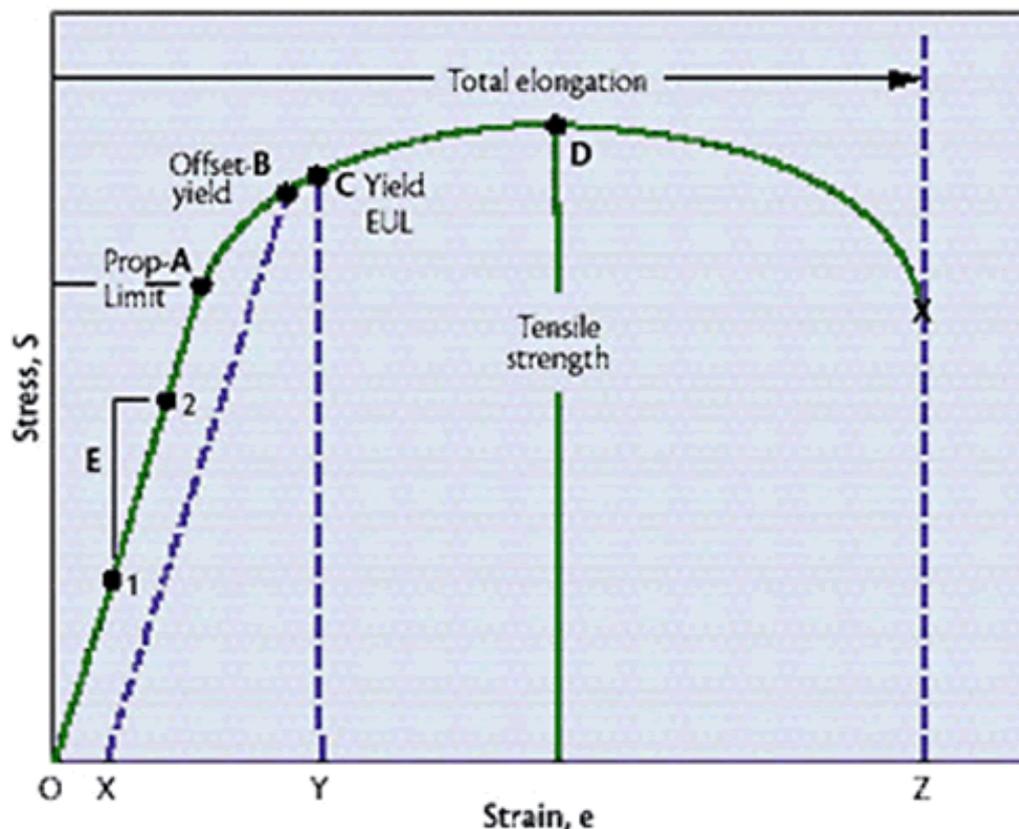


FIGURE 1.2 - A TYPICAL STRESS-STRAIN CURVER FOR NON-FERROUS METALS

Yield strength is the stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. This value is usually determined by the strain offset method. A straight line is constructed

parallel to the elastic portion of the stress strain curve at some specified strain offset usually it is in between 0.10 & 0.20 of the gauge length. The stress corresponding to the intersection of this line and the stress-strain curve as it bends over in the plastic region is called yield strength. Magnitude of yield strength of a metal is measure of its resistance to plastic deformation.

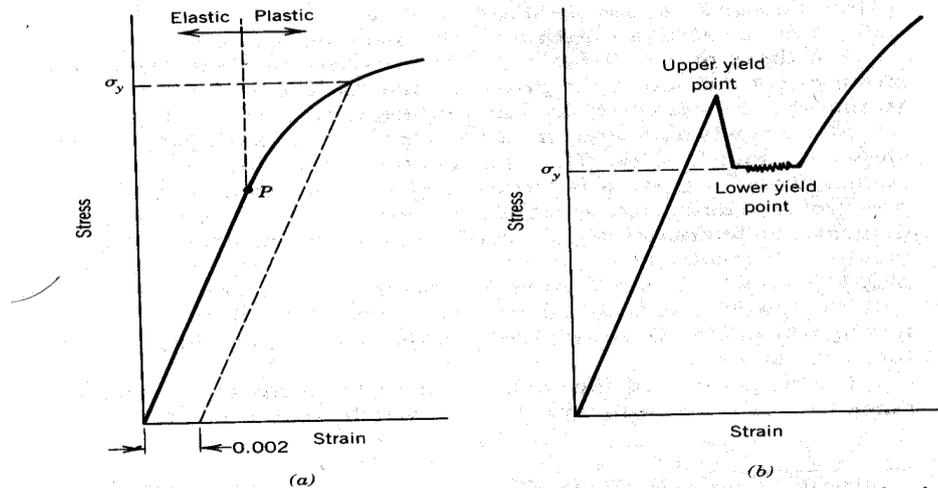


FIGURE 1.3 - STRESS-STRAIN CURVE FOR NON-FERROUS (a) AND FERROUS METALS (b)

Yield strength may range from 35 MPa for a low strength Al to over 1400 MPa for high strength steels.

Tensile Strength: -

After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum and then decreases to the eventual fracture. The Ultimate Tensile Strength (UTS) or Tensile Strength is the maximum strength that can be sustained by a metal in tension. If this strength is applied and maintained, fracture will occur. UTS may vary from 50 Mpa for Al to as high a 3000 Mpa for high strength steels.

It is in practice that when the strength of a metal is cited for design purposes, Yield Strength is quoted. This is because by the time a stress corresponding to UTS has been applied, the material / structure have experienced so much plastic deformation that it is useless.

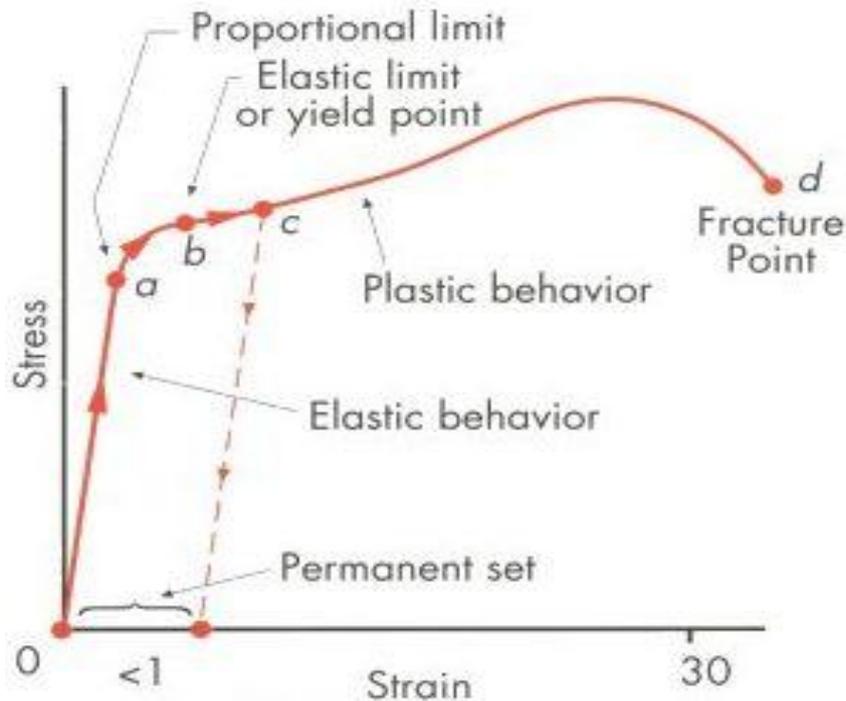


FIGURE 1.4 - TYPICAL PLOT OF STRESS-STRAIN CURVE

Modulus of Elasticity: -

To stretch some materials require higher strength than others. To compare the stiffness of materials, a term called Modulus of Elasticity is defined. It is the ratio of stress to strain and is a measure of relative stiffness. A material that stretches easily has a low modulus.

Resilience: -

Resilience or springiness is the energy stored in a material under strain (within its elastic limit) that causes it to resume / regain its original shape when the load is removed. Mathematically, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the stress-strain curve up to yielding.

Toughness: -

It is a measure of the ability of a material to absorb energy up to fracture. It is the area under stress-strain curve up to the point of fracture. For a material to be tough it must display both strength and ability to deform permanently without breaking.

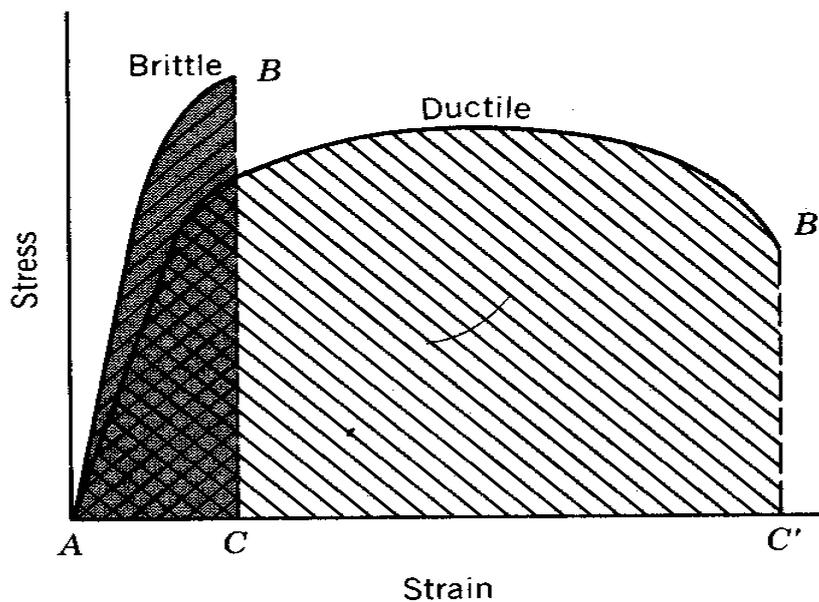


FIGURE 1.5 - STRESS-STRAIN CURVES FOR DUCTILE AND BRITTLE MATERIALS

Ductility: -

It is the ability of materials to be permanently deformed by tensile loading without fracture. When this happens, both elongation and reduction in area takes place in the material. Ductility may be expressed quantitatively as either by % Elongation or by % Area Reduction. Metals with high ductility may be stretched, formed or drawn without tearing or cracking. It must be kept in mind that a ductile metal is not necessarily a soft metal.

Brittleness: -

Brittle materials fail without warning through plastic deformation, elongation or change of shape. They lack plasticity and toughness. Brittle materials have same UTS and Fracture Strength.

Often ductile materials are tougher than brittle ones. It is demonstrated in Fig shown above where stress-strain curves are plotted for both materials. Even though the brittle materials have higher Yield and Tensile strength but by virtue of its lack of ductility, it has lower toughness than ductile ones.

Malleability: -

Ability of a material to deform permanently under compression without breaking is called its malleability (ability to bend). Metals with this property can be rolled or forged into thinner shape.

Impact / Shock Resistance: -

It is the ability of a material to withstand a maximum load applied suddenly. Impact resistance of a material is often taken as an indication of its toughness.

Fatigue Failure: -

Failure of metals under repeated or alternating stresses below UTS is known as Fatigue failure. Fatigue limit is that load which may be applied for an indefinite number of cycles without fatigue failure.

Creep Failure: -

It is time dependent and permanent deformation of materials when subjected to constant stress at elevated temperature.

Correlation between Tensile Strength and Hardness: -

As a rule of thumb, for most steels, Brinell Hardness and Tensile Strength are related according to

$$\text{T.S (Psi)} = 500 \times \text{HB}$$

$$\text{T.S (MPa)} = 3.45 \times \text{HB}$$

Chemical Properties: -

These describe the combining tendencies, corrosion characteristics, reactivity, solubilities & oxidation of substance.

Corrosion: -

Corrosion is the distortion of a material by chemical or electrochemical interaction with its environment. It includes destruction of metals in all types of atmospheres and liquids and at any temperature. Basic cause of corrosion is the instability of metals in their refined forms. The metals tend to revert to their natural states through the process of corrosion.

Oxidation: -

Oxidation is caused by the formation of metal oxides on metal surface. Oxides cause porosity, reduced strength and reduced ductility in the metals.

2. INTRODUCTION TO METALLURGY

2.1 HISTORICAL PERSPECTIVE:-

Metallurgy as an art has been practiced since ancient times. Ancient man knew and used many native metals. Gold, silver and copper was used for ornaments, plates & utensils as early as 3500 B.C. Meteoric iron-nickel alloys was used for making weapons.

Towards the end of the Stone Age, man discovered the art of smelting. It seems likely that the first casting was accidentally produced in the ashes of his campfire. Charcoal served as a reducing agent in the primitive smelting process and the first crude bronzes were probably the result of accidental roasting of mixtures of copper and tin ores. About 2500 B.C with the start of Bronze Age, it is believed that the art of extracting relatively pure tin had advanced to a point where intentional additions to copper were possible. Thus bronze has been identified as the first alloy actually made by man. Brass was introduced about 500 B.C by the smelting of copper and zinc ores, but the widespread use of this alloy did not occur until developments of the eighteenth century made possible the availability of metallic zinc.

The first smelting of iron ore is believed to have taken place about 1500 B.C and thus started the Iron Age. Man-made iron was chiefly used during this period for coinage, cooking utensils and implements of war. Metallurgists of the early Iron Age discovered the cementation process for steel making and the art of quenching steel for use in weapons.

In the Middle Ages knowledge of dealing with metals was generally passed directly from master to apprentice leading to an era of superstition surrounding many of the processes. Very little was written on metallurgical processes until Biringuccio published his "Pirotechnia" in 1540. This book recorded the overall progress in the field of applied metallurgy & ore reduction. "Pirotechnia" was followed by "De Re Metallurgica" by Georgius Agricola in 1556.

Until the beginning of the last quarter of the nineteenth century, most investigations of metal structure had been macroscopic and superficial. The science of the structure of metals was almost non-existent. The individual most responsible for the period of rapid development that followed was "Henry Clifton Sorby". Sorby was an amateur English scientist who started with the study of meteorites and then went on to study metals.

In September 1864, Sorby presented a paper to the British Association for the Advancement of Science in which he exhibited and described a number of microscopical photographs of various kinds of iron and steel. This paper marks the beginning of Metallography, the field associated with the use of microscope to study the structure of metals. It seems that while many people appreciated

the value of Sorby's studies at the time they were done, none of them had sufficient interest to develop the technique independently and Metallography lay dormant for almost twenty years.

Additional work by Martens in Germany (1878) revived Sorby's interest in metallurgical problems and in 1887 he presented a paper to the Iron and Steel Institute which summarized all his work in the field. In the early 1890's Albert Sauveur was actively engaged in trying to introduce metallurgical control into industry. He, with others, proposed theories to explain the change of properties that resulted from the heat treatment of steel. Of course many of these theories were incorrect and with the advancement in physics better theories were developed and tested experimentally.

Around 1922, more knowledge of the structure and properties of metals were added by the application of X-Ray diffraction and wave mechanics.

Later the work of Bain, Davenport, Mehl and many others has contributed to a better understanding of the behavior of metals and alloys and introduced the scientific approach in this field that for centuries had been purely an art. At no time has there been such a close relationship between physics, chemistry and metallurgy as there now exists. This relationship will be closer in the future developments of the Atomic and Space age.

2.2 CLASSIFICATION OF METALLURGY:-

Metallurgy is defined as "The art and science of metals". In broader perspective, it is the branch of engineering dealing with extraction of metals and alloys and shaping them into useful products, followed by alteration of properties by cold working and heat treatment.

Field of metallurgy may be divided into four branches:

Extractive Metallurgy or Chemical Metallurgy

Physical Metallurgy

Mechanical Metallurgy

Powder Metallurgy

i) **Extractive Metallurgy: -**

It involves extraction (reduction) of metals from ores, refining and alloying. This branch is sometime referred to as process metallurgy, main sub-branches of extractive metallurgy include:

Hydrometallurgy: - It includes selective leaching, floatation, etc.

Pyrometallurgy: - It includes roasting, calcination, etc.

Electrometallurgy: - It includes electrolysis etc.

Extractive metallurgy also deals with methods of ore preparation & concentration by application of suitable methods such as cyaniding, calcination, floatation etc.

ii) **Physical Metallurgy:** -

It deals with nature, structure & physical properties of metals & alloys. It also deals with the mechanism of varying such properties by heat treatment & cold working. Physical metallurgy includes metal structure & crystallization, deformation of metals, cold working, annealing & hot working, metals and alloy system, phase diagrams, heat treatment, metallography, mechanical testing, wear & corrosion.

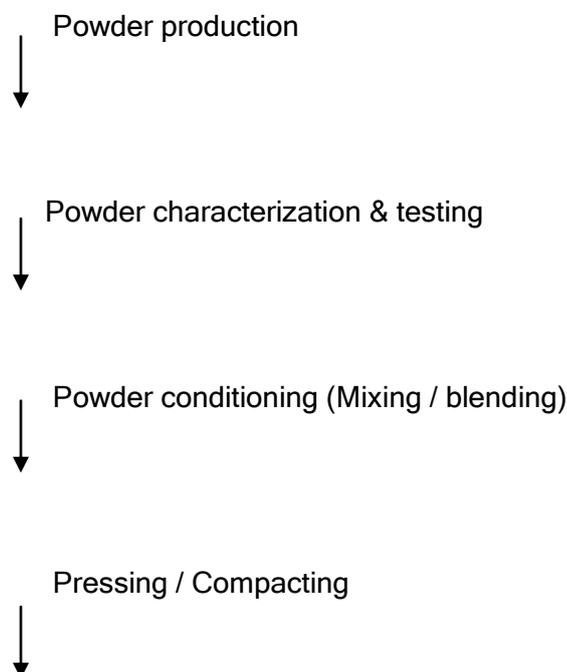
iii) **Mechanical Metallurgy:** -

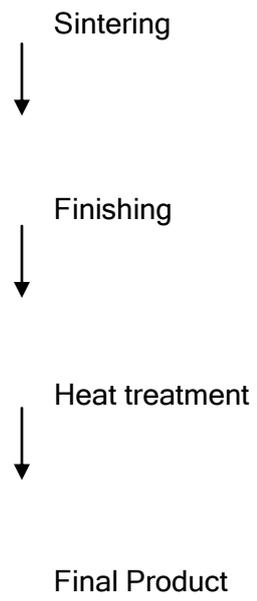
It is the field of metallurgy which is mainly concerned with the response of metals to forces/loads to convert them to useful shapes. It includes metal forming processes such as forging, rolling, extrusion, drawing, casting, welding, soldering, & brazing.

iv) **Powder Metallurgy:** -

It may be defined as the art of producing metal powders and using them to make serviceable objects.

A simplified flow sheet diagram of various operations involved in powder metallurgy is given below:





3. EXTRACTIVE METALLURGY

3.1 INTRODUCTION: -

It deals with extraction of metals from ore refining & alloying. There are mainly three routes by which metals are extracted from ore.

- *Pyrometallurgy*: - It involves application of heat to reduce metal from ore. Most commonly used methods of pyrometallurgy are Roasting, Calcinations,
- *Hydrometallurgy*: - It involves application of methods such as selective leaching, froth floatation to extract metal.
- *Electrometallurgy*: - It involves application of electrolysis process to obtain metal from ore.

Before applying any of the above mentioned routes, the first step is ore dressing in which ore is cleaned from unwanted gangue material and concentrated.

Various steps of ore dressing are as follows:

1. Handpicking
2. Washing
3. Gravity separation
4. Jigging
5. Calcinations
6. Froth flotation
7. Agglomeration
8. Sintering
9. Palletizing

3.2 IRON PRODUCTION FROM ORE: -

Iron is produced from its ore in a furnace called B.F. the ingredients required to make iron (pig iron) are as follows:-

Iron ore, coke, limestone, hot air.

U.S bureau of mines states, "Metallurgy of iron consists of the passage of ore, coke, & limestone through the B.F. As they progress downwards, carbon from

the coke combines with "o" from the ore, freeing the iron, which is tapped from the bottom of the furnace as a liquid.

1) IRON ORE:-

Common ores of iron are as follows:-

Magnetite :- (Fe_3O_4) It is called Black oxide of iron. It is the richest ore of iron containing 72.4% iron.

Hematite:- (Fe_2O_3) It is called Red oxide of iron. It contains 70% of iron & is used mainly to produce pig iron in a B.F.

Siderite:- (FeCO_3) It is called carbonate of iron. It contains 40% of iron.

Limonite:-It is called Grey oxide of iron. It contains 20-55% of iron .Its chemical composition is either $2\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ or $\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

Iron pyrites: - (FeS_2) It is also called Yellow sulphide of iron. It contains 42% of Fe & is rich in sulphur.

2) COKE:-

Coke is a product derived from coal. There are two types of coke.

- a) Hard coke (Anthracite) b) Soft coke (Bituminous)

Bituminous coke contains good percentage of combined carbon & is used in B.F.

Good coke should be free from dust, clay & other earthy materials, contains low percentage of sulphur & moisture less than 4%.

Coke acts in two ways in blast furnace. When it burns under limited supply of air, it produces CO. This is an exothermic reaction and as a result, temperature rises inside B.F. The CO acts as a reducing agent & reduces iron oxide into iron.

3) Limestone:-

It is a mineral which is mined in a manner similar to that of iron ore. It occurs either as CaCO_3 or in another form ($\text{CaCO}_3 \cdot \text{MgCO}_3$) called dolomite. It is found with other impurities such as silica, clay & alumina.

In B.F. it is used as Flux. It reacts with gange material (unwanted material) of iron ore, mostly SiO_2 & Al_2O_3 , lowers their melting points & combines them chemically to form slag. Slag is a low density compound and floats at the top of molten iron & is tapped out separately.

4) HOT AIR:-

Hot blast of air is used to oxidize coke and start the chemical reaction. To produce one ton of pig iron, five to six tons of hot air are required. Air is pre –

heated to 8000C with the help of stoves. Hot blast of air is introduced through tuyeres at a pressure of 15 to 20 psi.

Construction of Blast Furnace: -

In simplified terms, the B.F is a steel tower about 100 ft high with a 25 ft inside diameter which is tapered towards the top & also somewhat tapered towards the bottom. Outside walls are built of 1 inch to 1.13 inch thick steel plates. Inside walls are lined with refractory material (mostly fire brick) to withstand high temperature.

Lower portion of B.F is called Hearth. It contains molten iron and slag floating on top of it. Molten iron is drawn off the furnace through a tap hole called "Iron notch" and slag is tapped out through "Cinder notch".

The portion above "Hearth" is called "Bosh". It is the portion of B.F where maximum heat is generated.

Blast of hot air is force through a pipe surrounding the base of B.F. Smaller pipes, called tuyeres; lead this blast of hot air into the furnace.

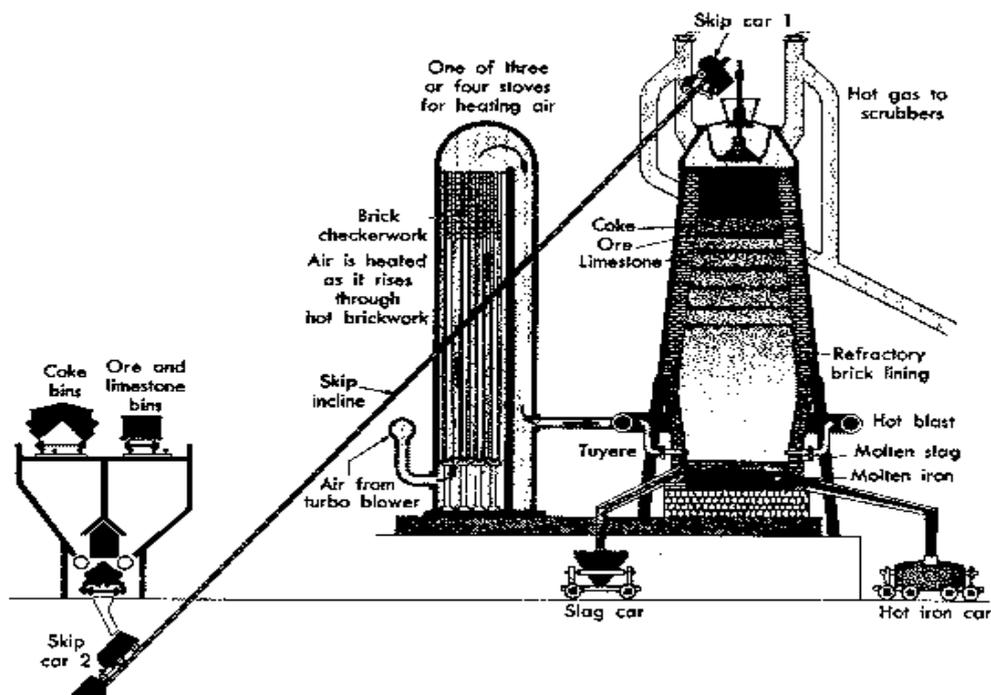


FIGURE 3.1 - BLAST FURNACE

Raw materials are dropped into the furnace through "Bell & charge hopper" located at the top of B.F. conveyor belt carries the charge materials up to the hopper, which is closed after it drops a charge into the furnace. An exit pipe is

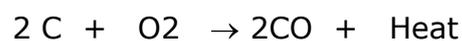
also provided near the top of the furnace for drawing off the gases formed into the furnace by combustion of coke.

3.3 CHARGE OF BLAST FURNACE:-

Blast furnace works 24hrs a day and molten iron is tapped out of furnace after every 6hrs, so furnace is charged with iron ore, coke & limestone, frequently at regular intervals. To produce one ton of iron, two tons of iron ore, one ton coke & 0.5 ton limestone along with four tons of hot iron is required. As a by product, 0.5 ton of slag and six tons of exhaust gases are produced. Slag being lighter in weight is tapped from top of molten iron and may be used to prepare cement, where as hot exhaust gases are used to pre-heat hot blast of air in stoves. Blast furnace is charged with iron ore, coke & limestone in the form of layers in which the lowest layer is of coke.

Operation of Blast Furnace: -

When the B.F is charged from top through hopper and hot blast of air is introduced from bottom through tuyeres. Coke is ignited and reacts with "O" of air to make "CO".



This is a strong exothermic reaction and as a result a lot of heat is generated at Boosch.

"CO" rises upwards and meets with descending iron ore reducing iron oxide to Fe.



CO₂ thus produced again react with "O" of hot air blast to produce CO.

At this temperature, calcinations of limestone occurs.



CaO acts as a flux and combines with the gangue material associated with iron ore to produce slag.



Hot gases produced as a result of chemical reactions are drawn from a pipe at the top of furnace & used to heat the incoming air blast.

Slag floating on the molten iron is tapped out through cinder notch & iron is tapped into ladles. The molten iron is either poured into moulds called pigs (thus named pig iron) or transported directly to a steel mill for conversion into steel. Pig iron as such is hardly a useful material for practical use because of its high impurities & gas contents. Upon solidification most of the gases are desorbed. Pig iron contains 3_4.5% carbon along with appreciable amount of Si, Mn, S, and P, which may add up to 8% by weight of total impurities. The proportion of residual impurities depends upon the purity of charge, control of heat & the purifying action of the flux.

3.3 STEEL MAKING PROCESSES: -

Pig iron is not a useful material for practical use because of its high impurities & gas content .By remelting & minor adjustment; it can be rendered useful as cast iron for founding. The major disadvantage of cast iron is that it is not a malleable & ductile alloy. The malleable & ductile form of iron can only be produced by removing of the impurities present in pig iron, & converting it into steel. Steel making process is reverse of iron making in the sense that here selective oxidation of impurities take place. The oxides are eliminated either as gas or as liquid slag.

CLASSIFICATION OF STEEL MAKING PROCESSES: -

Commonly used steel making processes are listed below:-

1. Bessemer process
2. Open hearth process
3. Electric furnace process
4. LD process
5. Kaldo process
6. Rotor process

Bessemer, open hearth & electric furnace processes are often called conventional methods of steel making.

LD, Kaldo, Rotor & their modifications are called oxygen steel making processes. They are also called Basic oxygen furnace processes because of their basic nature.

RAW MATERIALS FOR STEEL MAKING -

The chief materials for steel making are as follows:-

1. Sources of metallic iron
2. oxidizing agents
3. fluxes
4. sources of heat
5. deoxidizers and alloying additions
6. furnace refractories

1. Sources of Metallic Iron:-

There are two sources of metallic iron, primary and the secondary, for making steel.

The primary source is in the form of molten pig iron, often called as hot metal, from a B.F or solid pigs. Since iron is to be refined in molten state, use of hot metal as a raw material is bound to enhance the production rate as well as thermal efficiency when compared to the use of solid pigs. Steel making furnace is, therefore, invariably located along with the B.F in the form of an integrated steel works.

Composition of pig iron produced in an integrated steel plant is always controlled, as otherwise permissible, to suit the steel making process. In other words, the choice of steel making process is made, besides considering other factors, in relation to the quality of iron that would be produced. If the iron contains less than 0.05% phosphorus acid steel making process could be adopted. This iron is known as acid, or hematite or Swedish iron, this type of iron can be produced only at some exceptional places. By and large, the iron produced all over the world contains phosphorous more than 0.05% , is called basic iron and basic steel making process is needed to refine the iron. A special category of basic iron that contains more than 1.5% P is known as Thomas iron and special basic steel making process have been developed to refine this iron.

The secondary source of metallic iron is steel scrap. Steel plant itself generates scrap in the form of spillage, sheared ends, rejected material, etc. to the tune of about 30-45% of its ingot steel production. This is variously called as new scrap, home scrap, home returns, plant returns, circulating scrap, etc. and which must be recycled into the steel making.

Besides circulating scrap, scrap is also generated at the customer's end while making finished products. Its percentage varies considerably with the nature of

the product and may be around 10 to 20% of the equivalent ingot weight. This is returned to steel works either assorted or in classified forms. The capital scrap arising from obsolete articles is also returned to steel making units. Its percentage share is as high as 15% of the equivalent ingot weight in developed countries.

A certain fraction of the total scrap is used by foundries and for assorted reuses. On the whole it can be said that about 50% of each hot metal and return scrap go in the steel furnaces to produce the total ingot production. Integrated steel plants wherein B.F and steel making furnace are located together, the proportion of hot metal in the charge is generally more than 50% (60 – 70%), whereas the steel furnaces located near the centers of scrap generation use entirely cold charges –mainly scrap and a small fraction as pigs.

2. Oxidizing Agent.-

The oxidizing agents used for steel makings are iron oxide, air and oxygen gas.

Iron oxide is used in the form of lumpy hematite ore and mill scale. Mill scale is the oxide of iron produced during hot fabrication of steel and is readily available in an integrated steel plant. The usual analysis of both is as follows:

	%Fe	%S	%volatiles	Others
Iron ore	60-69	0.03	0.5	Gangue oxides
Mill scale	71	0.10	4.5	(Should be low in silica)minor impurity oxides

Both of these contain nearly 25% of oxygen by weight. The ores are generally low in sulphur and high in gangue oxides whereas the mill scale is nearly pure form of oxide but it may contain a high proportion of sulphur. Both are used in practice in suitable proportions. The use of iron oxide as an oxidizing agent results in improving the yield of the process but it needs thermal energy to dissociate itself and make oxygen available for refining reactions.

Atmospheric oxygen in the form of air is used in the Bessemer process but nitrogen present in the air gets dissolved in the steel and makes it strain brittle.

The purity of oxygen should at least be 99.5%. The nitrogen content of refined steel increases with decreasing purity of oxygen.

3. Fluxes:-

a flux is a substance added during smelting and refining to bring down the softening point of the gangue materials, so reduce the viscosity of slag and to decrease the activity of some component(s) to make it stable in the slag phase. Lime/limestone is generally added during steel making to make the slag basic enough to retain phosphorous & sulphur. Fluorspar and bauxite are added to decrease the viscosity of refining slag. The typical analysis of these is given in the table below.

	%CaO	%S	%MgO	%SiO ₂
Lime	90-95	0.1-0.2	2-3	1.5
Limestone	50	0.01	1	1
Calcined dolomite	55	0.1	34-38	3-4
Ganister	0.5	--	0.1	94

4. Sources of Heat:-

Pneumatic processes like the Bessemer and the BOF's are autogeneous since enough heat is generated during refining by the exothermic oxidation of impurities. These processes need hot metal, preferably of a suitable composition, as a charge to run the process. The amount of heat generated is always more than necessary so that scrap and/or iron ore is required to keep the bath temperature within required limits. These processes can not be run with cold charges alone. As against this, hearth processes like the open hearth and the electric are provided a source of heat to melt the solid charge and to maintain steel making temperatures inside the furnace. These can take up to 100% cold charges.

Chemical:-

Solid --- pulverized fuel

Liquid --- oils, tar, etc.

Gas --- producer, water, coke oven, natural and B.F gases.

For economic reasons the chemical fuels should be burnt with excess air and thus the furnace atmosphere would always be oxidizing.

Electrical:-

introduction heat

resistance heating

arc heating

The electric furnaces have no atmosphere of their own and hence oxidizing as well as reducing conditions can be maintained in the furnace with the help of suitable slags.

5:- Deoxidizers and Alloying Additions:-

Elements like Al, Si, Mn, etc. are added primarily as common deoxidizers. Elements like Zr, B, Ti, etc. are added for deoxidation in special cases and elements like Cr, W, Mo, Ni, V, Nb, etc. are added generally as alloying additions. Carbon is added to recarburise steel or as deoxidizer under vacuum. Excess additions of Al, Si, Mn, Ti, etc. above what is consumed for deoxidation, can also remain in the melt as alloying additions.

Silicon: -

This is a very effective common deoxidizer and is used in the form of Ferro—silicon. Silicon is added as alloying element for better strength, harden ability and electrical properties.

Manganese:-

It is a weaker deoxidizer than silicon. As an alloying element it gives strength and toughness. It is added as Ferro—manganese of various grades. Where silicon and manganese are added together it may be added as a mixture of individual Ferro—alloy or as silico—manganese.

Aluminum:-

It is a very effective deoxidizer and is used in the form of stars, rods, pellets, wires, powder, etc. chemically it is used as Ferro—aluminum or Aluminum—silicon compounds with 90-97% purity. It is an alloying addition in heat resistant steels, e.g. Kanthal.

Nickel:-

It does not act as a deoxidizer. It is added as an alloying addition in stainless steels. It can be added any time during the heat.

Chromium:-

It is used as an alloying addition for stainless and heat resistant steel. It is available in the form of Ferro—chrome of several grades. It can act as a deoxidizer but is costly to be used for this purpose. It increases hardness, strength, yield point and elasticity of steels.

Titanium:-

It is a strong deoxidizer and neutralizes the effect of nitrogen on steel by bonding it into stable insoluble nitride compounds. Titanium steels are useful for aircraft industry for its lightness coupled with strength.

Vanadium:-

It is a strong deoxidizer. It increases the strength, plasticity and resistance to attrition and impact. It is usually added in structural, tool, and spring tools. It is added as Ferro—vanadium.

Tungsten:-

It is a strong deoxidizer. As an alloying addition it increases hardness, strength, and elasticity of steel. It is used in tool steels, high speed steels, cemented carbide alloys, etc. it is added as Ferro—tungsten.

Molybdenum:--

It is only an alloying addition to improve the mechanical properties. Its presence ensures uniform microcrystalline structure, augments hardenability and eliminates post-temper brittleness. It is used for shafts, gears, rolls, etc. like Ni it can also be added at any time during refining.

Zirconium;--

It is used as a deoxidizer. It decreases the deleterious effects of nitrogen & sulphur in steel. It is added in the form of zirconium—ferrosilicon.

Boron:--

This is used as a deoxidizer. As an alloying element it enhances the mechanical properties and hardenability of steel. It is added to steel in almost negligible amounts (0.0025—0.0030%) in the form of ferroboron and ferroborel.

Niobium:--

The addition of niobium to stainless and heat resisting steels enhances their plasticity and corrosion resistance. It improves welding properties of structural steels and has stabilizing influence on stainless steels. It is added in the form of Ferro—niobium—tantalum.

Cobalt:-

It is used as an alloying addition for magnetic steels and like Ni or Mo; it can also be added at any time during the heat. It is added in elemental form.

6. Furnace Refractories:--

Steelmaking furnace is lined by suitable refractory materials. The lining is eroded during steelmaking and hence the material of lining is also required as a recurring consumable raw material. The lining is often repaired to maintain it in proper shape and state. The lining is made either by laying bricks (or blocks) or by shaping the required contour in situ using a refractory mix.

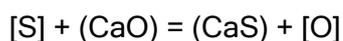
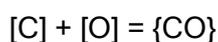
The materials used for lining acid furnace and acid roofs of basic furnaces are essentially silica-sand, ganister, etc. Since the bulk steel production comes from basic processes, dolomite and dolomite enriched with magnesite are extensively used as lining material for basic furnaces, particularly if oxygen lancing of the bath is adopted. Similarly magnesite-chrome is being adopted in place of chrome-magnesite for its better performance.

Fire bricks for insulation and chromite as neutral bricks are also used in steelmaking furnaces.

Principles of Steel Making:-

Steel making is a refining or an oxidation process with the exception of reducing conditions being specifically required to eliminate sulphur. Being an oxidation process steelmaking needs a source of oxidizing agent. The obvious choice being the oxygen in the form of atmospheric air and / or iron oxide in the form of iron ore and mill scale (oxide produced during hot working of steels). The conventional methods of steelmaking use either or both of these reagents. The oxygen steelmaking processes use pure oxygen whereas the modified conventional processes use iron oxide, air and pure oxygen judiciously.

The chemistry of steelmaking refining process can be simply described as



Except the sulphur reaction, all the rest are oxidizing processes and are favored under the oxidizing conditions of steelmaking. In the case of oxidation of carbon the product, being a gas, will pass off into the atmosphere but the rest of the oxide products shall remain in contact with the iron melt in the form of a slag phase. As far as the physical requirement of the oxide product is concerned it should be readily separable from the iron melt. This is achieved by keeping the slag and the metal both as thin liquids so that the metal being heavier settles

down and the slag floats on top in the form of two immiscible liquids which can be separated readily.

The steelmaking processes can be divided into two broad categories:

- i) When silicon is the chief impurity to be eliminated from iron and that phosphorus and sulphur need not be eliminated
- ii) When phosphorus and to some extent sulphur are the chief impurities to be eliminated along with even silicon.

The elimination of manganese will take place under both the categories. In the finished steel phosphorus and sulphur each must be below 0.05%, however there are few exceptions to this. If sulphur is more steel becomes hot short and if phosphorus is above this limit, it becomes cold short. Higher sulphur contents are recommended for free cutting variety of steels and a slightly high phosphorus level is desirable for efficient pack rolling of steel sheets.

If the pig iron composition is such that phosphorus and sulphur both are below 0.05% and need not be eliminated it is possible to remove silicon along with manganese in such a way that slag of the type MnO-FeO-SiO_2 is formed without the necessity of addition of an external flux. Such a process of steel making is called "acid steel making process" which is carried out in an acid brick lined furnace. On the other hand, to eliminate phosphorus and sulphur, the reverse action rate can only be suppressed if the slag contains a good amount of strong base than as is internally available in the form of FeO and MnO . External CaO (and also MgO) is used as a flux and slag of the type $\text{CaO-FeO-P}_2\text{O}_5$ is made. Such a process is called "basic steel making process". The furnace lining in this case has to be basic in nature.

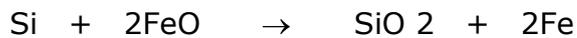
In brief the composition of pig iron is the only factor that determines the acid or the basic character of the process to be adopted for steelmaking. In an acid process slag is acidic and the furnace lining has to be acidic to withstand the atmosphere. Similarly in a basic process the slag contains excess basic oxide and the furnace lining should be basic in nature. If the lining is of opposite chemical character slag will readily react with the lining and cause damage to the furnace.

Bessemer Process: -

This process uses pear shaped iron converter which is supplied with pig iron melted in a cupola. Converter can revolve about the horizontal turnions. The bottom is pierced by a number of tuyeres connecting with wind box underneath and much detachable since the wear on it is very severe. It is usually changed after every 15-20 belows.

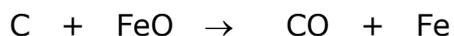
A Bessemer converter is furnished with an acidic lining (ganister) if the pig iron is free from sulphur & phosphorous, otherwise a basic lining of dolomite is employed. For removal of sulphur, Calcined lime is added to the charge and then heated to red heat. A portion of it burns out while a portion combines with lime to form slag. The basic lining is least affected by this slag containing phosphorous.

To receive the charge, the converter is turned down in the horizontal position and again brought to vertical position, i.e. , working position. A strong blast of air is supplied to the charge for about 20 minutes. The metal becomes agitated by the passage of air blast, and a shower of sparks is continuously emitted from the mouth of the converter. Iron oxide is formed which in turn reacts with the impurities present, in the iron. Silicon is first removed as it is most easily oxidized of the elements present.



Due to this reaction an enormous amount of heat is generated, therefore it is important that iron should contain adequate quantity of silicon for the purpose. Iron having less than 1.5% of silicon will blow cold, while more than 2.5% will generate too much heat. As the blow proceeds, a flame gradually appears at the mouth of the vessel and manganese starts oxidizing. Some of silicon, manganese, and iron are ejected in the form of brown fumes but those remaining in the converter combine to form a slag which floats on the metal.

The last element to be eliminated is the carbon which follows the reaction:



This stage of the process is known as "the boil" owing to the violent agitation caused by the evolution of carbon monoxide gas from the metal. As the carbon is eliminated the boil gradually subsides and large white flame finally drops after sometime. The metal in the converter is now virtually pure iron in the liquid form. The blast is shut off and a quantity of Ferro-manganese (an alloy of iron containing manganese up to 80% and carbon up to 5%, used in making additions of Mn to steel or cast iron), spiegeleisen (an alloy of iron containing 15-30% Mn and 4-5% carbon; added to steel a deoxidizing agent and to raise the Mn content of the steel) or some other suitable alloy steel as required is added and the blast resumed for a few minutes more to ensure the alloy thoroughly mixing with iron. The converter is then swung into discharging position, and discharged

into ladles from which the metal is poured into moulds where it solidifies to form ingots. To remove quantity of aluminum or ferrosilicon or nitrogen or oxygen, a small quantity of aluminum or ferrosilicon is also added.

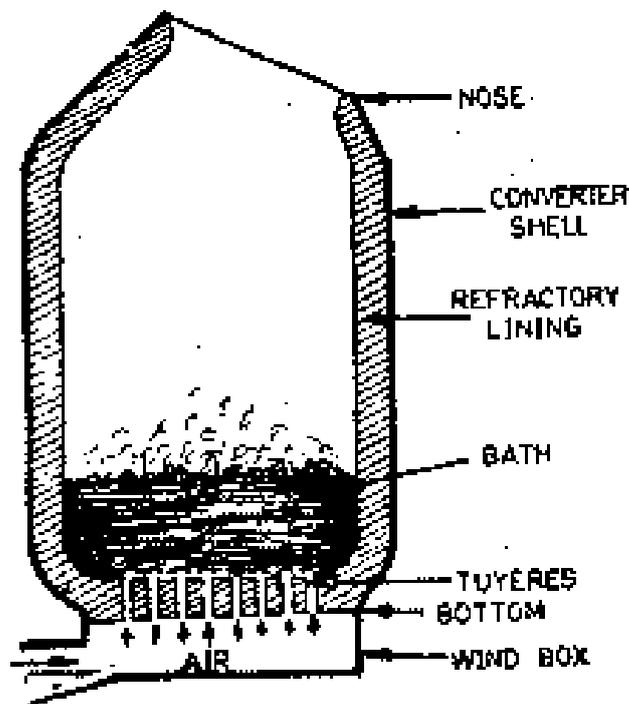


FIGURE 3.2 - BESSEMER CONVERTER

Advantages & Disadvantages of Bessemer Process: -

The cost of building a Bessemer converter plant is comparatively less than that of an open hearth plant of equivalent capacity. Tending to balance this is the greater B.F capacity required because only a small amount of (10 percent of the charge) scrap is used in the process as contrasted to 40 to 100% in the open hearth process. Therefore, the investment in the B.F facilitates for a Bessemer plant would be greater as compare to an open hearth plant and must be considered a part of capital investment. It is now thought that with proper facilities in an integrated plant consisting of Bessemer converter and tilting or stationary open hearth furnace, the cost of producing Bessemer ingots should be less than for open hearth ingots.

A Bessemer converter, with its small size & ease of handling makes it possible to produce small tonnages of many different grades of steel, actually three grades of steel in less than an hour. A contrasted to an open hearth furnace major repairs can also be made in a fraction of time.

Finally probably because of higher ferrous oxide content of the acid grade, it has peculiar properties of machinability, stiffness, Weldability and sensitivity to cold work. High sulphur Bessemer steel possesses a tremendous inherent advantage

by reason of ease of machinability. Bessemer steel, both hot rolled and cold drawn, is generally stiffer than open hearth steel of equivalent tensile properties. In many hot working operations the effect of quenching can be neglected in Bessemer steel because it contains as little as 0.1% of carbon and does not respond to heat treatment.. a very large output for Bessemer steel lies in welded pipes, because Bessemer steel appear to produce joints which are more closely knit and free from blow holes and inclusions, than open hearth steel.

Open Hearth Process: -

The furnace used in this process resembles a reverberatory furnace. Here pig iron is melted in the furnace and large quantity of scrap iron is dissolved in the liquid bath. The source of heat is heated air and coal gas. In open hearth furnace a great economy in fuel is obtained by the utilization of heat of the hot gases of combustion. These gases are made to pass through brick gratings of two regenerators before leaving the chimney. The air and gas on the other hand traverse through two other chambers. After an hour direction of flow is reversed. In this way, when the entering air and gas are being adequately heated in their passage through the heated gratings in the two regenerators, the other two regenerators get heated by the hot gases escaping into chimney.

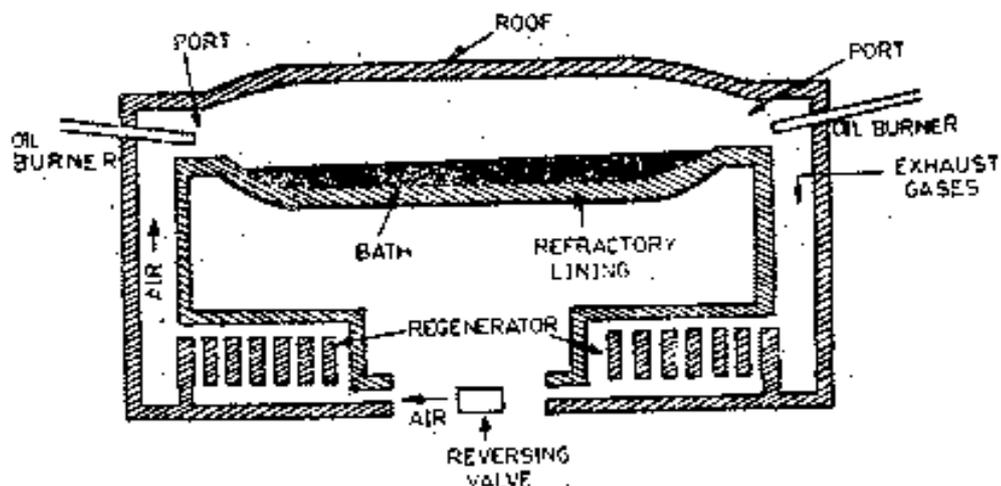


FIGURE 3.3 - OPEN HEARTH FURNACE

The intense heat produced by burning of air and coal gas keeps the charge in the molten condition. Silicon gets converted into silicate and is removed as a slag and carbon burns to carbon dioxide leaving practically pure iron. A measured quantity of ferro-manganese or suitable alloy steel is added to supply the necessary carbon, manganese, chromium, or nickel. The liquid steel finally is poured into the moulds through ladles.

The furnace lining may be basic or acidic depending upon the fact whether phosphorus is present or absent in the pig iron. acidic lining comprises of either silica or ganister (83% quartz, 10% clay, 4% moisture and other impurities). Basic lining is usually magnesite ($MgCO_3$) or dolomite ($CaCO_3 \cdot MgCO_3$).

The basic open hearth process is steadily replacing the acid open hearth due to the following reasons:

The process is not limited to relatively low phosphorus and sulphur materials but, instead makes possible the removal of relatively large amounts of these elements and, by so doing, open up vast tonnages of ores and steel scrap which ordinarily could not be available for acid steel.

It permits the use of all types of steel scraps, lights and bulky, heavy & dense, dirty & clean to produce high grade steel of any chemical analysis.

It is much more flexible process, permitting operator to vary the proportion of steel scrap, solid pig iron and molten metal to meet local and economic conditions.

There is relatively, wide permissible range in the chemical composition and physical characteristics of lining materials, the slag and molten metal.

Steels of wide range of carbon content, from as low as 0.03 to as high as 1.1% can be made. Likewise a wide range of quality (plain carbon and low alloy) may also be obtained by this process varying from the open or rimmed steel; up to especially finished deoxidized, grain controlled and forging steels.

<i>Bessemer Process</i>	<i>Open Hearth Process</i>
1. It can use comparatively higher pigs of wider ranges of composition.	1. It can use lower phosphatic pigs of narrower range of composition.
2. Scrap iron can not be used.	2. Scrap iron can be used.
3. Refining and finishing require 10 to 20 minutes.	3. Refining and finishing are completed within 8 to 10 hours.
4. Operations depend entirely on eye judgment, so it is very difficult to produce a uniform product.	4. Operation is guided by laboratory analysis, so it is comparatively possible to produce a uniform product.
5. It produces inferior quality steel associated with blow holes and inclusions.	5. Open hearth steel is of much superior quality containing lesser blow-holes and inclusions.

adjustment to the arc voltage. As the power supply is a three phase circuit, three electrodes are arranged in an equilateral triangle over the metal. Owing to low voltage required by the arc, the current must be very high to obtain the desired output.

The hearth of an electric furnace may have acid and basic lining depending upon the process adopted. Basic process is used for making steel ingots and some castings while the acid process mostly for making steel casting. The usual capacity of this furnace is between 5 to 10 tonnes, though 50 and 100 tonnes furnaces have been produced. This type of furnace is used for making alloy steels such as stainless, high speed steel, etc.

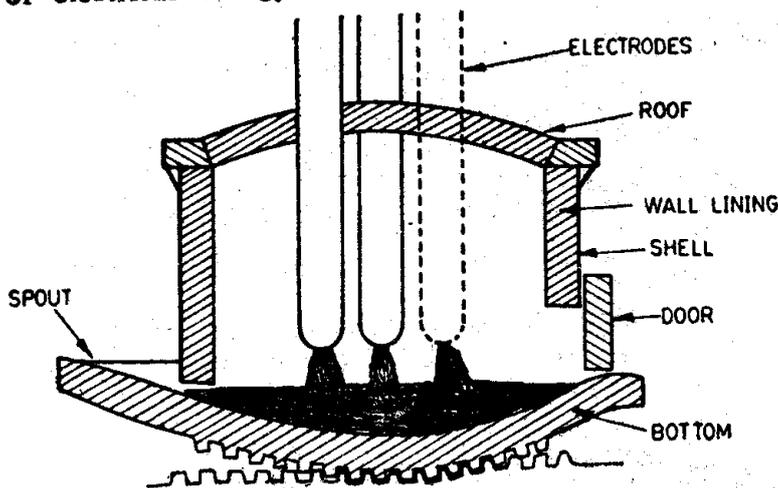


FIGURE 3.4 - ELECTRIC ARC FUNCTION

The advantage of this furnace is that purer product is obtained and composition can be exactly controlled during refining process. This is the reason that direct arc furnace even being costlier in initial as well as operating cost is preferred. Though this furnace is employed for melting and refining but due to higher cost its use is restricted to refining than melting. It operates at a power factor about 0.8 lagging.

b). High Frequency Electric Furnace:-

This type of furnace works on the principle that when a piece of metal is held in a coil of wire carrying alternate current, eddy currents flow in the steel is due to the alternating magnetic field being produced. Due to these currents steel is heated up. When the charge gets melted, the eddy currents flowing through molten metal agitate or stir it and mix the constituent thoroughly. It is a high frequency induction furnace which works up to 10000 cycles per second and is most suitable when the charge is of the same composition as the casting. In this furnace tubular shaped conductors are used to:

Produce inductive effect.

Withstand high temperature at high frequency.

The wire solenoid is not used as it can not stand as high temperature as 1800 °C which may be produced in this furnace.

It is usual practice to operate the high frequency furnace purely as melting furnace, and only rarely are refining operations attempted. For this reason it is possible to avoid oxidizing conditions during melting & steel containing high percentages of easily oxidized elements like chromium, manganese, and vanadium can be melted with practically no loss of these elements. The perfection can not be attained in the arc furnace, so that the high frequency furnace is used for melting such materials as stainless steel, high speed steel, magnet steel, and other high alloy steels.

Even when operated intermittently, the high frequency furnace can prove economical owing to the very small weight refractory material which has to be heated up with steel. A high frequency furnace costs about three times as much to install as does an arc furnace of the same capacity.

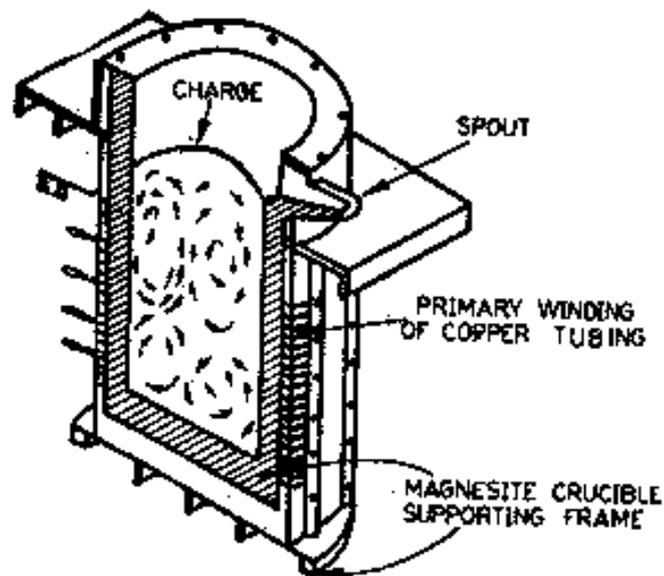


FIGURE 3.5 - ELECTRIC INDUCTION FURNACE

Advantages of the Electric Furnace:-

The generation of heat within an electric furnace is independent of the furnace atmosphere, and this may be maintained oxidizing, neutral, or reducing, as desired.

The temperature is more under control than in an open hearth furnace and very high temperature can be attained by means of the arc. This fact combined with

the ability to maintain a highly reducing atmosphere within the furnace, permits the formation of chemical compounds which are non-existent in other processes, and which promote desulphurizing and deoxidizing conditions unattainable in Bessemer converters and open hearth furnaces.

The close control over steel making conditions possible in the electric furnace permits high grade steel to be made from low grade scrap, often without using pig iron. This is the principal reason why the electric furnace is able to complete at all with the open hearth. Electric steels are mostly of superior qualities not normally made by an open hearth process.

The gas, fumes and impurities which exist in fuel bed furnaces are absent.

L.D Process:-

This process originated in 1953 at Linz steel works in Austria. It combines the high productivity of the acid Bessemer process and the superior quality of the basic open hearth steel. The furnace is a vessel similar to that of the Bessemer converter except that the capacity is 30 to 40 tonnes (double that of Bessemer) and there is no detachable bottom with its row of tuyeres bricks. The vessel has a basic lining.

In this process a jet of pure oxygen (99%) is blown at a pressure of 7.0 to 10.5 kg/cm² and at a speed even greater than the sound to the molten bath of hot metal. The temperature thus produced is about 2550 °C due to which the impurities like carbon, nitrogen, phosphorus, and sulphur, etc. are burnt. For a converter of capacity 50 tonnes, the blow lasts for about half an hour whilst the complete operation consumes about one hour.

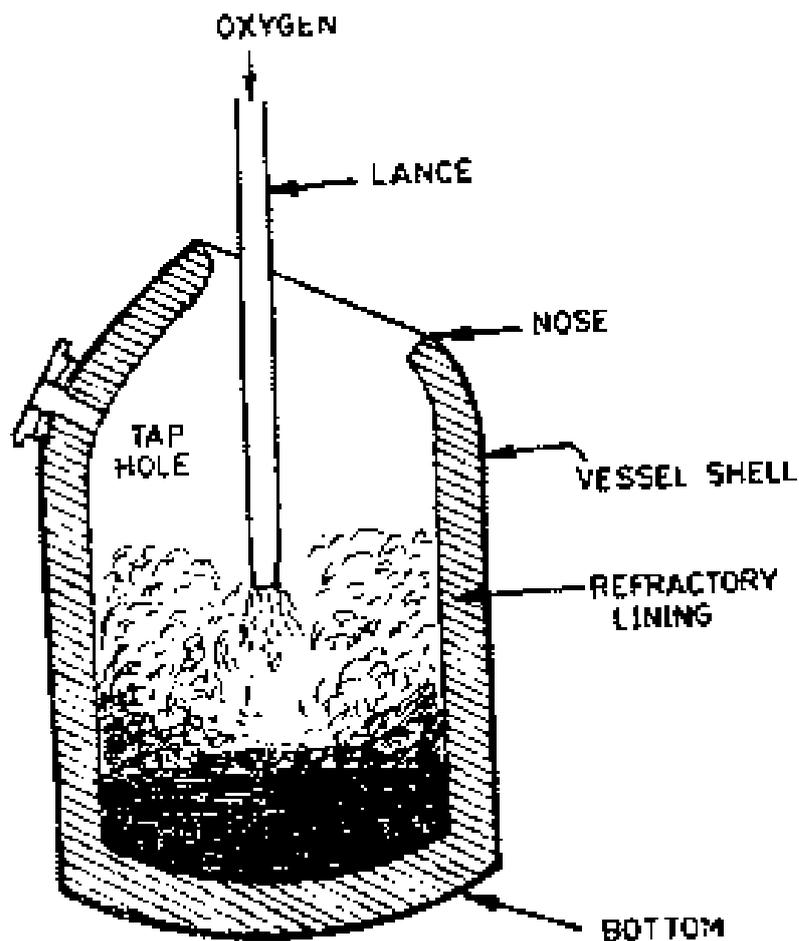


FIGURE 3.6 - LD VESSEL

The different steps involved are:

The converter still hot from previous blow is charged with 15% steel scrap and 85% molten pig iron from the mixer.

Oxygen is blown through water cooled nozzle at a pressure of 7 - 10.5 kg/cm² and lime added.

The blow lasts for about half an hour the dropping of flame indicates that the molten mass has been refined.

The separation of low carbon steel is effected by pouring out steel into a ladle and the liquid slag thickened with burnt lime is left mostly in the converter.

L.D. process is the only process where sulphur can be effectively reduced. The reasons for this are as follows:

Large volume of slag which is highly rich in lime is formed and is kept fluid due to the intense heat. Sulphur is eliminated as gas.

The residual manganese in bath is higher and the MnS gets oxidized giving out SO₂ gas.

Duplex Process: -

This process is designed to combine the advantage of the Bessemer and open hearth process while avoiding their disadvantages. For duplexing two methods are used. In one method, hot metal from the B.F or mixture is partially blown in a basic converter and then transferred to a basic open hearth furnace, where refining is completed in 5-6 hours. In another method, five acid Bessemer converter are used to eliminate silicon, manganese and carbon and the soft steel so made is passed on to a 200 tonnes basic tilting furnace for removal of sulphur and phosphorus. A sixth converter is used to supply partially blown metal for recarburising the steel in the tilting furnace, which is tapped every 4 ½ hours, leaving 50 tonnes of steel in the furnace.

This process has the following characteristics:

The life of open hearth is increased because of the absence of silica oxide which has detrimental effect on the basic lining.

Pig iron associated with silica and phosphorus contents is converted into a good quality of steel. Silica undergoes oxidation in acid Bessemer converter while phosphorus in the basic open hearth process.

Since the time of open hearth is reduced, labour, maintenance and overhead costs are less.

Kaldo Process: -

The difficulties experienced in dealing with high phosphorus pig iron by L.D. process was responsible for the advent of the Kaldo process, which was introduced by Professor Killing. The fundamental departure from the L.D. process is the rotation of the bath during oxygen injection whereby slag metal contact and reactions are affected. In the Kaldo rotary oxygen process conversion of pig iron into steel is carried out into a rotating converter into which oxygen is introduced through a water cooled lance which enters the converter through a central opening at one end, which simultaneously acts as an outlet for the exhaust gases. The speed of the rotation can be varied up to 30 r.m.p., which is most suitable speed for main stage of the process. The furnace of converter is lined with ordinary tarred dolomite.

The usual procedure is to inject oxygen until most of the phosphorous has been removed at which stage the carbon will approximate 1.5%, when the first slag is removed. The first slag contains about 22% P₂O₅ with only 3% Fe. Owing to

heat evolved during oxygen injection, it is necessary to add either iron ore or scrap as a cooler. The usual practice is to employ iron ore for cooling purpose, since this increases the metallic yield and reduce the oxygen. After the first stage has been removed blowing is continued until the carbon has been reduced to about 1% by which time the phosphorus will be less than 0.1%. At this stage second slag is removed. The second slag contains about 17% to 20% P_2O_5 with about 6% iron. These two phosphoric slags which average 16 to 32 % P_2O_5 can therefore be sold for fertilizing purposes.

After removing the second slag, a final slag is collected with lime additions and blowing is continued until the metal has been refined to the desired specification. The final slag remains in the vessel as a base for subsequent heat. The metallic yield is about 92% and the average blowing time is 35 to 40 minutes for a 30 tons heat.

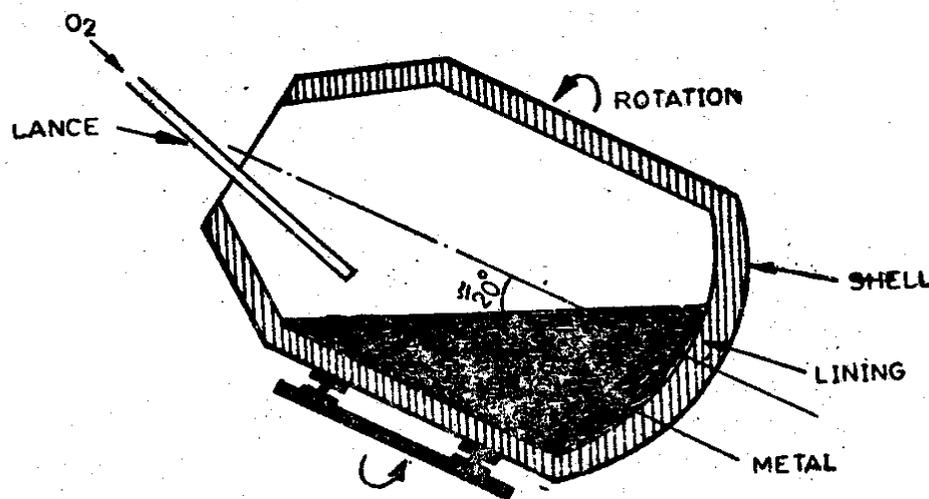


FIGURE 3.7 KALDO VESSEL

This process has following advantages:

It is capable of giving high rates of productivity at a low capital cost.

It is particularly suitable for manufacturing high grade steel from high phosphorus pig iron and the surplus heat produced in the process permits the employment of an appreciable quantity of iron ore as a cooling agent.

The satisfactory by-product value of the high phosphorus acid slag produced is another economic advantage.

The main disadvantage of this process is the number of moving parts and their weight which probably exercise the adverse effect on the maintenance cost.

3.4 SOLIDIFICATION OF STEEL IN INGOT MOULDS: -

Most steel contains dissolved gases, in particular oxygen. During cooling of steel the solubility of dissolved gases decreases and the excess comes out of solution. Of greater significance is the chemical equilibrium between carbon and oxygen dissolved in steel. The equilibrium shifts during cooling in such a way that the two react to form carbon monoxide gas which is expelled from steel. The amount of oxygen in solution and the amount that is expelled as CO is decided by its carbon content, the type and amount of deoxidizer added to steel prior to solidification.

Steel that is fully deoxidized by strong deoxidizer is called "Killed *Steel*", since no activity is observed in this case by gas evolution during solidification. It remains quiet in the mould as if it is dead and hence the term killed. Killed steel solidifies progressively from the side and bottom of the mould till finally a shrinkage cavity, known as pipe, formed in the top central portion of the ingot.

If the steel contains oxygen so that CO evolution is possible during solidification, depending upon the amount of gas evolved, a series of ingot structures are produced. If the evolution of gas is appreciable i.e. deoxidation is not fully carried out, it gives appearance of boiling to liquid steel in the mould. This boiling action is termed as "rimming" and the steel is known as "*Rimming Steel*".

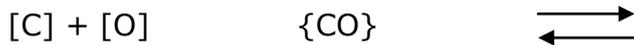
In between violently rimming and killed steels lie the "*Semi Killed Steels*" which are only partially deoxidized such that some gas evolution takes place during later stages of solidification.

The "*Capped Steel*" is only a special variety of rimming steels in which the rimming action is less violent.

Mechanism of Solidification: -

Killed steel solidifies in three zones in an ingot. The metal next to mould walls and bottom is chilled by cold mould surfaces. This is a thin layer and is known as a chill, shell or skin of an ingot and has fine equiaxed grains. The rate of solidification is very high in forming the skin. However, the rate of solidification soon slows down. The mould expands on heating and the skin contracts on solidification resulting in separation of the two and formation of an air gap in between. It reduces the rate of heat flow and thereby slows down the cooling of an ingot. The solidification front moves inwards perpendicular to the mould faces resulting in columnar grains next to the chill. Their lateral growth is restricted due to the adjacent crystals. The columnar crystals rarely extend to the center of the mould. The central portion solidifies as equiaxed grains of bigger sizes than those in the chill due to slow cooling. Although the zone boundaries are not as distinct as one would imagine, rather one zone blends to the other next gradually. The extent of each one varies with composition and temperature of liquid steel, mould design and its temperature at the time of teeming.

The change in solidification mechanism of these zones is due to the mechanism of gas evolution. If the steel is not fully deoxidized the reaction



forms the basis of gas evolution during cooling & solidification. Carbon and oxygen react to form carbon monoxide only if the product of concentrations of carbon and oxygen in steel exceed the equilibrium value, which is a function of temperature and pressure.

If the oxygen content of steel is very low, the necessary super saturation of carbon and oxygen for CO formation is not achieved until towards the end of solidification. It means that the formation of chill layer and the columnar crystals are not much disturbed. Only the central zone of equiaxed crystals is disturbed by the way of formation of blow holes in the top middle portion of the ingot. This is how a semi-killed steel ingot will solidify.

As oxygen content of steel increases CO evolution takes place more and the amount of evolved gas also increases. When oxygen content is appreciable, marked gas evolution is seen immediately after pouring steel in the mould. The gas is evolved at the solid liquid interface and the rising bubbles cause metal to circulate, which brings hot metal to the surface and freezing on the top is delayed. It prevents formation of columnar grains and the interior of an ingot is at a more uniform temperature. This finally gives rise to the capped or rimming ingots in which gas that is evolved is mechanically entrapped as blow holes. In a rimming ingot pipe is very small and irregular.

Ingot Types: -

A series of ingot types are produced depending upon the extent of deoxidation carried out prior to solidification of steel in ingot moulds. These are shown in Fig below. The amount of gas evolved during solidification progressively increases from No.1 to 8 i.e. steels are deoxidized to the lesser degree in the same order. The details of the ingot types thus produced are given below:

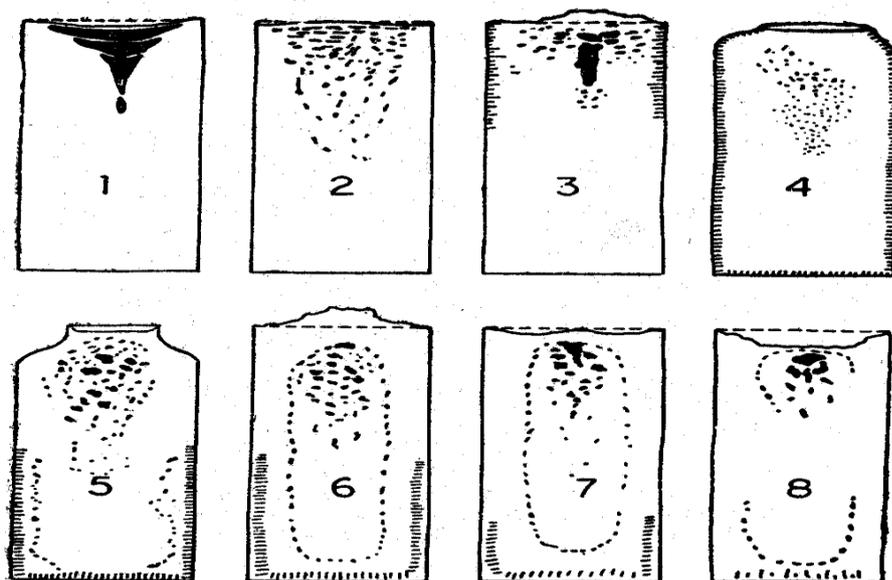


FIGURE 3.8 - VARIOUS TYPES OF INGOTS

No.1

This is a typical killed steel ingot with intermittently bridged pipe. The killed steels are almost invariably cast in wide-end-up moulds with a hot top so that the pipe is confined to the top portion of the ingot.

No.2

This is partially deoxidized steel. The gas is not evolved in the early stages of solidification. The gas is evolved in small amount towards the end of solidification i.e. at the middle portion of the ingot. It is enough in volume to compensate for shrinkage and thereby reduce or nearly eliminate the pipe. This is typical semi-killed steel ingot.

No.3

The gas is still evolved only towards the end of solidification. Since the amount of gas evolved is more than that in No.2 the pressure developed is high enough to burst the solidified top surface. This is called "Bleeding". The blow holes are near the walls and are confined to upper portion of the ingot.

No.4

The gas evolution is appreciable and commences early to cause the liquid steel to rise in the mould. This rimming action does not allow the top to solidify immediately after pouring. The rising level of the metal is stopped by putting a metal cap at the top. The remainder of the evolved gas is thereby entrapped to form a series of honeycomb shaped blow holes all along the walls and bottom.

No.5

The gas evolution is so large and is evolved so early that a lot of its escapes out from the ingot. The ingot slowly rises in the mould and is capped to produce a typical capped ingot. The ingot is capped after the rimming action slows down. The net result is that a thick skin is formed first and then the honeycomb blow holes which are less than those in No.4

No.6

A lot of evolved gas escapes out. The ingot, therefore, does not rise in the mould as much as in No.5. The honeycomb blow holes are formed after thick skin formation and are confined to the lower portion of the ingot.

No.7

The brisk gas evolution finally leads to the formation of a very thick skin and honeycomb blow holes in the bottom quarter of the ingot. The ingot does not

rise in the mould to any appreciable extent. The volume of blow holes just compensates for the shrinkage. This is typical rimming steel ingot.

No.8

This gives a very violent rimming action such that no blowhole formation is possible. The ingot in fact sinks to some extent during solidification.

Control of Ingot Structure: -

The final structure of an ingot is almost entirely determined by the total degree of deoxidation carried out prior to solidification of steel in a mould. The residual oxygen in steel at the end of refining is determined by the steelmaking practice and the type of steel produced. For a given type of steel the steelmaking as well as deoxidation practices have to be properly adjusted to finally obtain the desired ingot structure.

Rimming Steels: -

Rimming steels require a lot of gas evolution during solidification. The steel, therefore, must contain enough dissolved oxygen and which is possible only in low carbon steel. Hence rimming steels are produced only if carbon is less than 0.15%

Rimming ingot has a smooth surface which is relatively clean due to the brisk evolution at the beginning of solidification. Such a structure is desirable for rolling of products wherein surface finish is most important e.g. in flat products. Rimming steels are cast in narrow-end-up moulds.

Capped Steels: -

This is another variety of rimming steels in which the gas evolution is much less brisk than in usual rimming steel i.e. it is less active. Steel is cast in bottle shape narrow-end-up moulds in which the constricted top facilitate mechanical capping of the ingot. Capped ingots are produced from the steels containing around 0.15% carbon. These are used for producing flats, wires and bars.

Semi-Killed Steel: -

These are partially deoxidized steels such that only a small amount of gas is evolved during solidification. The carbon content has to be in the range of 0.15-0.30%. These steels find a very wide use in the manufacture of structural shapes, plates & merchant products.

Killed Steel: -

No gas evolution takes place in killed steels during solidification. All steels containing more than 0.3% Carbon are killed. These steels are almost always cast in wide-end-up moulds with hot tops. Although solidification of killed steel is accompanied by marked segregation, the killed steel structure is quite sound

and dense which is particularly suitable for forgings. Alloy steels are in general fully killed steels because soundness of the ingot is what is essentially required.

3.5 INGOT DEFECTS AND REMEDIES: -

It is always an endeavor to produce both physically and chemically a homogeneous ingot which would have a fine equiaxed crystal structure, free from chemical segregation, non-metallic inclusions, cavities etc. and would have a smooth surface finish. Unfortunately this is not possible in practice because of the natural laws that govern pouring and solidification of steel in an ingot. Within itself an ingot may develop pipe, blow holes, chemical segregation, non-metallic inclusions, columnar crystals and internal fissures. Externally it may exhibit surface cracks, seams, scabs etc. The factors that lead to the formation of these defects and the possible remedies to minimize them are described below.

1) Pipe:-

The volumetric contraction resulting from solidification appears in the form of a cavity known as pipe which amounts to about 2.5 – 3.0% of the total apparent volume of the ingot. Rimming and semi-killed steels show slight tendency for piping which can be eliminated by careful melting and pouring practice. Capped steel is practically free of pipe. The problem of pipe formation is however serious in case of killed steels. The shape and location of pipe in killed steels depend upon the mould type as shown in figure below. In a wide-end-up mould the pipe is short and wide. In a narrow-end-up mould it is narrow and long and a secondary pipe may also be formed.

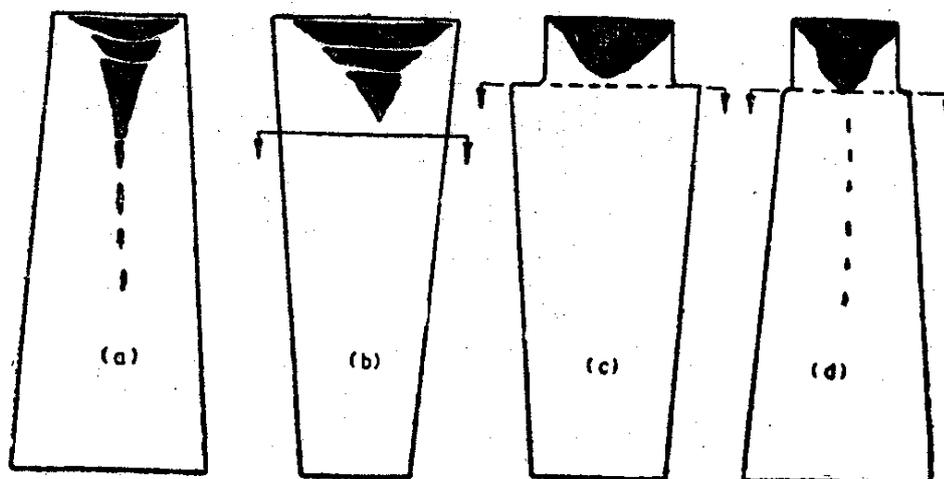


FIGURE 3.9 - VARIOUS TYPES OF PIPING PRODUCED IN INGOTS

Primary pipe get oxidized and does not weld during rolling. As a result much of the ingot portion has to be discarded, which decreases the ingot yield. Being deep seated the secondary pipe does not get oxidized and is welded up during rolling.

The detrimental effect of pipe formation on the yield can be reduced by adopting a hot top feeder so that the pipe is confined to the feeder box of a wide-end-up mould as shown in figure. Use of insulating or exothermic materials on the top of the ingot further ensures, by keeping the metal in the hot top molten for long, that the pipe will be confined to the feeder head without extending into the ingot. Another method of reducing piping in an ingot is to pour little more of the metal after partial solidification of the ingot to compensate for the shrinkage. This is however not a very common practice.

2) Blow Holes: -

The entrapment of gas evolved during solidification of steel produces cavities known as blow holes in all except killed steels. The blow holes are of two types. The primary blow holes are elongated or like honeycomb and are located next to the ingot skin. The secondary blow holes are more spherical and are located further in. Formation of blow holes eliminates partially or fully the piping, thereby increasing the ingot yield during rolling, provided they are located at proper depth from the surface from all sides of the ingot. Deep seated blow holes do not open up and thus do not get oxidized during soaking and rolling of the ingot. Such blow holes are welded up during rolling and do not leave any mark of theirs in the product. Blow holes that are located closer to the surface often get oxidized during soaking or get first punctured and then oxidized during rolling. Oxidized blow holes do not heal up during and leave surface defects (seams) on the product.

Gas evolution during solidification should, therefore, be controlled to obtain these blow holes only after an ingot skin of adequate thickness is formed.

3) Columnar Structure or Ingotism: -

Steel is a crystalline solid. After the formation of initial chill layer further solidification results in the formation of dendrites which grow along their principal axes perpendicular to the mould walls. Their lateral growth is restricted due to the growth of adjoining dendrites giving rise to elongated crystals. If the length of these is appreciable it is known as columnar structure and in an exaggerated form Ingotism. Ingots possessing Ingotism tend to crack during rolling unless in the first few passes the reduction in cross-section is kept low.

In general columnar structure does not extend to the center of the ingot. The middle portion of the ingot solidifies as equiaxed grains. The relative proportion of columnar and equiaxed grains are adjusted to keep the Ingotism to a minimum. The adjustment is carried out with respect to the composition of steel, its temperature while pouring, mould temperature and gas evolution during solidification.

4) Segregation: -

Segregation means departure from the average composition. If the concentration is greater than the average it is called positive and if it is less than the average, it is called negative segregation. Segregation is the result of differential solidification, a characteristic of all liquid solutions. Steel is a liquid solution of S, Si, C, P, Mn etc in iron and hence is prone to segregation during solidification. The initial chill layer of the ingot has practically the same composition as that of the steel poured in the mould, i.e. there is no segregation in the chill layer because of very rapid rate of solidification. The progressive solidification thereafter results in solidification of purer phase (rich in iron) while the remaining liquid gets richer in impurity contents.

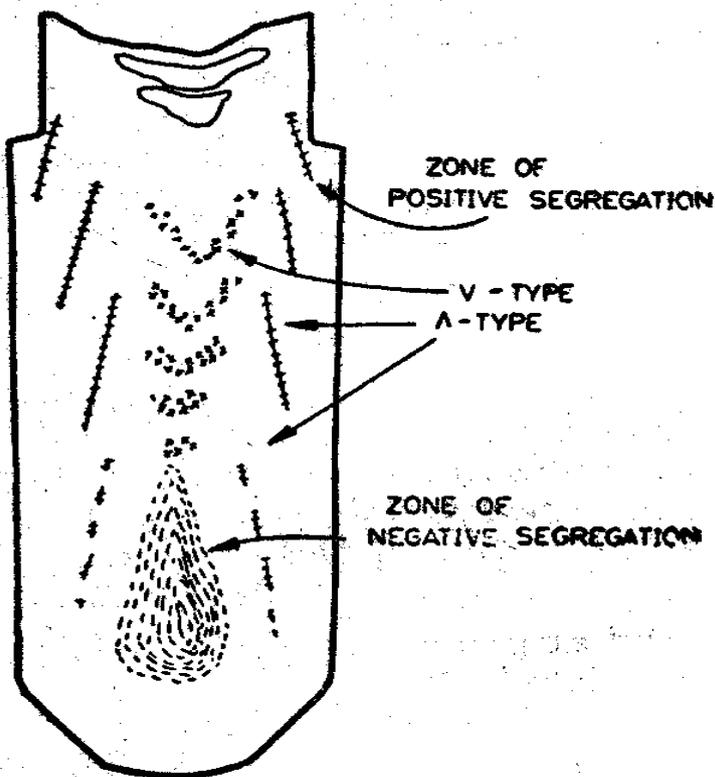


FIGURE 3.10 - AN INGOT SHOWING VARIOUS TYPES OF SEGREGATIONS

A killed ingot cast in wide-end-up mould shows two types of segregation as shown in figure. The impurity segregation at the top follows the shape of the pipe and is known as V Segregation. Side by side inverted V or Λ -shaped segregation is also observed at the top. It may be due to the sinking of purer crystals down and rising up of the impure liquid in the upper part. The impurities get entrapped in impure part at the end of solidification. This is the positive segregation. The negative segregation is confined to the lower central portion of the ingot. In the actual ingot these zones are not sharp rather they are quite diffused.

Segregation increases with the increasing time of solidification required for an ingot, so that large ingots tend to segregate more than small ingots. Segregation

in ingots of same cross-section is increased by turbulence and convection caused by the gas evolution during cooling and solidification of steel. Segregation, therefore increases in the order killed, semi-killed, capped and rimming steels. In the semi-killed steels the V segregate is less sharp and is pushed downwards. The V segregates is also at lower position than in killed steel. The rimmed zone of a rimming ingot exhibits negative segregation. The boundary of these two zones is at time so sharp that they appear as steels of two different compositions.

Besides the above, the micro segregation of sulphur as revealed by sulphur print of the section is quite important. Sulphur segregation values are quite critical in certain areas of the structural shapes.

Segregation can be minimized by prolong soaking of ingots before working.

5) NON-METALLIC INCLUSIONS: -

The term cleanliness is used to refer relative freedom from the entrapped non-metallic particles of solid ingot. In some steels this is the most important criteria in judging their quality. Inclusions are of two types:

Indigenous – those arising in the course of steel making

Exogenous – those arising from mechanical erosion of contacting refractory lining

Indigenous inclusions comprise of deoxidation products like oxides, oxy-sulphides or precipitates like sulphides, carbides, nitrides etc. Almost all sulphur is precipitated as iron or manganese sulphides. The best way is to keep sulphur as low as possible to avoid formation of inclusions. Oxide inclusions can be kept to a minimum level by suitable deoxidation practice. Enough time is allowed for them to rise to the surface in the ladle. Alternatively, if economically permissible, vacuum treatment may be adopted to decrease the oxygen content of steel. Deoxidation carried out in the furnace also helps to minimize them.

Nitrides form only if dissolved nitrogen level is high. Addition of Zirconium, Titanium and Vanadium form stable nitrides. In general proper care during refining and more particularly during deoxidation can minimize the indigenous inclusions.

The exogenous inclusions arise from the mechanical erosion of refractory lining with which metal comes in contact during its processing. In particular the erosion of ladle and more so of the refractories used in the assembly of the mould contribute most to the formation of exogenous inclusions. The best way to keep them down is to use minimum of such refractory channels through which metal has to flow before solidification. Use of strong refractory for such places is beneficial.

Inclusions are not always undesirable. These are purposely introduced to gain certain desirable effect. For example sulphur is added to obtain sulphides inclusions to improve machinability. Exogenous inclusions are used for dispersion strengthening of steels. Stable nitrides are useful since the bad effects of dissolved excess nitrogen are thereby eliminated.

6) INTERNAL FISSURES AND HAIRLINE CRACKING: -

The term cinked ingot is used to denote internally cracked ingot. These cracks or fissures arise due to two reasons:

- i) Too rapid reheating of an ingot such that the outer layers expand more rapidly than the core giving rise to internal rupture. Certain classes of alloy steels are prone to such cracking because of their coarse and weak crystal structure.
- ii) Too rapid cooling of an ingot after stripping the mould cause uneven contraction at the surface and in the core, finally resulting in internal fissures.

Internal fissures may extend to the surface and cause surface cracking or may open up during soaking and working. These can be eliminated by preventing too rapid cooling and reheating of an ingot.

Hairline cracks are formed all through the section and are revealed only after deep etching. These are oriented at random. Desorption of dissolved hydrogen is believed to be the principal cause of formation of hairline cracks in large sections. The solubility of hydrogen is decreased during solidification and further cooling of steel. Hydrogen is desorbed very slowly even after cooling of steel, for days or even weeks, depending upon the type of steel, the cross section, the residual stresses and the hydrogen content of steel when it was molten. Alloy steels are much more susceptible to hairline cracking. Since the hydrogen content of liquid steel is determined by the type of raw materials used and the steelmaking process adopted, these factors do influence hairline cracking appreciably.

Hydrogen content less than 2.0-2.5 cc/100 gm in liquid is safe to avoid hairline cracking. Hydrogen content can be reduced further by vacuum treatment of liquid steel. In the absence of such treatment steel must not be allowed to cool to room temperature unless sufficient time is allowed for hydrogen to diffuse out. In practice the steel is held at 600 – 650 °C to reduce hydrogen content to below the safe limit. The holding time increases with the increasing cross section and may even extend to several days. Many times the ingot is stripped off and transferred to a soaking pit for prolonged soaking to allow hydrogen to diffuse out. This procedure also minimizes the tendency to form internal fissures.

There is also a link between the sulphur content of steel and hydrogen content. If the sulphur content is less the safe hydrogen level also decreases.

7) SURFACE DEFECTS: -

These are the defects apparent on the surface of an ingot after solidification or are visible in some form after mechanical working of an ingot.

Ingot Cracks:

The chilling effect of a mould forms a thin solid layer on the side faces and bottom of the ingot immediately after pouring and is known as ingot skin. The contraction of the ingot on skin formation and the expansion of the mould on heating tend to separate the two and forms an air gap in between. The pressure of the liquid core of the ingot has now to be withstood by the ingot skin alone. If the skin is not thick enough to stand the internal pressure, it ruptures giving rise to cracks in the surface. The factors that tend to decrease the skin thickness tend to help form cracks. A too high teeming temperature, rapid rate of teeming also high mould temperature decreases the skin thickness and thereby increases its tendency to crack. The formation of hot short i.e. the area which cools less rapidly than adjacent areas owing to less close contact with the mould, tends to develop surface cracks. The friction between ingot and mould may also develop sufficient tension to cause surface cracking. If steel is poured more on one side than the other it may decrease skin thickness on the hotter side and thereby help form cracks.

Longitudinal Cracks: -

These are more or less parallel to the vertical axis of the ingot and are caused due to the development of lateral tension in the skin. These are formed more at the bottom position of the ingot. Alloy steels are more prone to form such cracks than mild steels.

Transverse Cracks: -

These are nearly parallel to the base of the ingot and are formed due to longitudinal tension in the skin. This is the most common type of ingot cracks.

Restriction Cracks: -

These may be longitudinal or transverse in direction and are located at the corners of the ingot.

Sub-Cutaneous Cracks: -

These are internal fissures close to the surface and are caused due to thermal shocks. These open up during soaking and/or rolling.

Much of the surface cracks can be eliminated by designing the mould properly. Sufficiently thick mould walls ensure adequate chilling to produce skin strong enough to stand internal ferro-static pressure. The use of corrugated or fluted

mould walls in place of plane walls increases the specific surface area so that chilling is improved. It also minimizes the transverse tensile stresses in the skin, developed due to its solidification.

Smooth corners of the mould and neither too large nor too small radius of curvature of the corner, minimize the restriction cracks.

The mould walls are trapped to 1-2% to help strip the mould smoothly. The friction between the mould and the ingot can be minimized by dressing the mould before pouring.

The operational variables like the teeming temperature of steel, mould temperature, thickness of mould dressing, rate of teeming centering of the stream and so on should be adjusted carefully to minimize not only ingot crack but many other surface defects as well.

8. OTHER SURFACE DEFECTS: -

A number of other surface defects are known to occur mainly due to the faulty teeming practice and the use of faulty mould. These are described below:

Scab:-

A projection on the side surface of an ingot caused by freezing of steel in a cavity in the mould wall or in a mould with uneven wall.

Lappiness: -

Lap is a fold in the ingot skin caused by freezing of a slowly rising top surface of the metal in the mould before the pouring is over.

Splash: -

Metals drops are thrown off due to the impact of metal stream on the mould bottom. If these drops stick to the mould wall they form seams in the rolled products because, being oxidized on the surface, the drops do not weld up to the rest of the ingot during rolling.

Crazing:-

If a large number of cracks are present in the mould wall steel may freeze in these cracks and give rise to a network of fins on the ingot face. This is known as crocodile skin.

Doble Skin: -

The skin is formed in the lower parts of the ingot contracts and steel flows in the gap between the mould and the ingot giving rise to a double skin in the lower part of the ingot. This is due to the slow rate of pouring and/or severe chilling effects of the mould.

Flash: -

It is a plate of solidified steel formed due to steel entering cervices in the mould assembly at the joining of mould with bottom place or hot top.

Boot Leg: -

It is the sinking of an ingot top below the original level in the mould due to decreased evolution of gas. It calls for extra front crop during rolling.

3.6 GASES IN STEELS & THEIR REMEDIES: -

Even at the end of refining when most of the impurities like C, Si, Mn, S, P, etc. are eliminated below the required level gases like oxygen, nitrogen and hydrogen may still remain in solution as deleterious impurities. The solubility of these impurities depends upon the composition of steel and it increases with temperature. On heating the rise in solubility, in solid state, is slow but at the melting point it increases very steeply and thereafter, in liquid state, it continues to increase but at a slow rate. The amount of these gases dissolved in steel at the end of refining depends upon the quality of raw material used and the steelmaking process itself. On solidification the excess dissolved gases are liberated which may form skin or pin holes, blow holes, etc. these cavities are in general detrimental to the mechanical properties of steel except where the gas evolution is successfully controlled to obtain semi-killed and rimming steel ingots.

OXYGEN IN STEEL: -

Oxygen is supplied for refining iron and hence a certain fraction is inevitably left over as dissolved oxygen in liquid steel at the end of refining. The use of deoxidizers, unless, it forms gaseous product of deoxidation reaction, tends to decrease cleanliness of steel. Except where cleanliness is of supreme importance (e.g. ball bearing steels, die steels, tool steels, air and space craft steels, etc.) deoxidation of liquid steel prior to teeming, in the usual manner, is however adequate to eliminate the deleterious effect of excess dissolved oxygen in steel.

Where cleanliness is of supreme importance and where oxygen is to be reduced to a level lower than that attainable by normal deoxidation practice, liquid steel has to be treated under vacuum prior to solidification.

Nitrogen in Steel: -

Since steel making operation is carried out in furnaces open to atmospheric air a certain amount of nitrogen always finds its way in liquid steel. Nitrogen also comes from the raw material charged in the furnace and, from the nitrogen that is directly brought in contact with the bath along with oxygen during melting and/or refining. Nitrogen content of refined steel very much depends on the steel making process adopted.

In oxygen steelmaking processes high nitrogen absorption can take place in the hot zone, where oxygen jet impinges on the metal, if the jet gas contained nitrogen. The purity of oxygen used is thus very important and it should not be below 99.5% to produce steels with less than 0.002% nitrogen, since these processes are meant to produce deep drawing type dead soft steels.

Nitrogen is picked up by liquid steel during tapping as it comes in direct contact with atmospheric air. The amount of nitrogen thus picked up depends directly upon the height of furnace tap hole from the ladle. It also depends upon its own content in steel; the pick up is more if it is already low (e.g. in L.D. process) and is less if it is already high (e.g. in Bessemer process).

Sulphur content of steel has often been found to be related to its nitrogen level. Low sulphur content is accompanied by high nitrogen content in Bessemer process whereas the reverse is true in case of electric arc process. Tapping temperature within the usual range does not indicate any appreciable variation in nitrogen content of steel. The addition of recarburizer, in particular, does increase nitrogen content of steel as nitrogen is always associated with the usual recarburizer.

Nitrogen content is decreased while teeming rimming steels whereas it is increased in semi-killed and killed steels.

Nitrogen is a deleterious impurity in steel. It makes steel strain brittle so that it cannot be cold worked much without intermediate annealing, and hence in general, and more particularly in deep drawing type of steels, it must be less than 0.002%.

Fortunately bulk steels with such low nitrogen content can be readily produced by adopting oxygen or modified processes of steelmaking to meet the vast requirements of sheets, strips, etc. no further treatment, except proper care in steelmaking as such, is therefore, required to obtain low nitrogen steels.

The vacuum treatment that is adopted to reduce oxygen and hydrogen content of steel, side by side, does reduce some nitrogen content as well. However in general vacuum treatment is not specified for the removal of nitrogen alone.

HYDROGEN IN STEEL: -

Hydrogen is formed when water vapour comes in contact with steel or slag. The amount of hydrogen dissolved in steels varies with the partial pressure of hydrogen, composition of steel and its temperature. Hydrogen content is expressed as cc or ml per 100g of steel or parts per million (ppm). 1.2cc hydrogen per 100g equals 1ppm (0.0001%). The solubility of hydrogen in solid iron at its melting point is nearly 10cc/100g. Liquid steel may contain as high as 20cc/100g in high alloy steels made under unfavorable conditions. It constitutes serious problems of hairline cracking in fully killed high alloy steels with large cross sectional area. In rimming steels, it causes no problem because it is

reduced well below the safe limit by the scavenging action of gases evolved during cooling. In semi-killed steels some believe that it causes defects which cannot however be identified with certainty. The ductility of steel is decreased with increasing hydrogen content. High level of hydrogen content leads to the formation of even blow and pin holes. The deep seated holes weld-up but the shallower ones are punctured and oxidized and hence, need increased surface dressing operation.

The sources of hydrogen in steelmaking are:

1. Wet & rusty scrap.
2. Wet solid charge materials (other than scrap).
3. Steam fed into the furnace e.g. atomization of oil in an open hearth.
4. Atmospheric humidity, if air blast is used for refining or burning.
5. Wet refractory channels, runners, containers, etc. with which steel comes in contact prior to its solidification.

In order to decrease the final hydrogen content of steel rusty and wet solid materials should not be charged in the furnace, as far as possible. Alternatively these materials should be dried before charging, to minimize hydrogen pick up. Similarly all refractory linings must be thoroughly dried before metal comes in contact with them prior to solidification. In addition, in every process refining is carried out in such a way that the hydrogen content of bath is reduced during refining, and is not allowed to pick up subsequently.

In general if steel contains hydrogen less than 5cc/100g it picks up hydrogen from the open atmosphere during tapping and teeming whereas it slightly desorbs hydrogen to the atmosphere if it is more than this level. If the moulds are not rusty, proper grade of mould dressing is used and, the refractories in the mould assembly are thoroughly dried no significant pick up of hydrogen takes place in the mould.

In general hydrogen content of less than 2cc/100g is considered to be a safe limit to avoid possible defects that arise due to the presence of hydrogen in steel.

Hydrogen level can be kept at the lower level If the following precautions are taken:

1. Avoid use of rusty scrap.
2. Avoid use of most raw materials.
3. The refractory lining must be thoroughly dried.
4. A vigorous and long carbon boil must take place during refining.

Bath should not be left in the furnace for long in quiet state. i.e. without boil.

Jet degassing or flushing can be adopted to decrease hydrogen content if it is high. An inert gas like argon is bubbled through liquid steel so that hydrogen is desorbed in these bubbles. hydrogen content can be reduced to 3cc/100g by this method. High cost of argon is the prohibitive factor in applying this method commercially.

Prolonged annealing in the range of 600 – 650 °C for sufficiently long time allows hydrogen to diffuse out. Until recently this was the only technique by which hydrogen content was reduced to below 2cc/100g in commercial practice.

It is now possible to reduce the gas content of steel in general and hydrogen content in particular, below the safe limits by vacuum treatment of steel, at any stage after the refining but prior to its solidification in moulds. The most deleterious gas impurity, i.e. hydrogen can be reduced to less than 2cc/100g by vacuum treatment of steel.

4. 4. PHYSICAL METALLURGY

4.1 METAL STRUCTURE & CRYSTALLIZATION: -

4.1.a) ATOMIC STRUCTURE: -

All matter is considered to be composed of unit substances known as chemical elements. These are the smallest units that are distinguishable on the basis of their chemical activity & physical properties. The elements are composed of atoms which have distinct structure characteristics of each atom.

While each chemical element is composed of atoms, it is the difference in atomic structure that gives the element its characteristic properties. Atom is composed of three elementary particles:

1. Electrons, tiny particles of negative electricity.
2. Protons, particles of positive electricity.
3. Neutrons, electrically neutral particles.

Almost the entire mass of the atom is concentrated in the nucleus, which contains the protons & neutrons. The mass of the proton is approximately 1.673×10^{-24} g, and the neutron is just slightly heavier, approximately 1.675×10^{-24} g, therefore, the electron is approximately 1 / 1800 the mass of a proton. The diameter of the nucleus is of the order of 10^{-12} cm and is very small compared with the atomic diameter, which is approximately 10^{-8} cm. The atom consists of a minute positively charged nucleus made up of protons and neutrons surrounded by a sufficient number of electrons to keep the atom as a whole electrically neutral. Since the electrons & protons have equal but opposite electrical charge (proton charge = 4.8×10^{-10} esu, electron charge -4.8×10^{-10} esu), the neutral atom must contain an equal number of electrons & protons.

The atomic number of an element is equal to the number of protons, or since the atom has to be electrically neutral, the atomic number is also equal to the number of electrons.

The atomic mass (A) of a specific atom may be expressed as the sum of the masses of protons and neutrons within the nucleus. Although the number of protons is the same for all atoms of a given element, the number of neutrons may be variable. Thus atoms of same elements have two or more different atomic masses and are called *isotopes*. The atomic weight corresponds to the weight average of the atomic masses of the atoms naturally occurring isotopes. Hydrogen, for example, is a mixture of three isotopes. Most of its atoms contain one proton, but a few contain one proton one neutron, and still fewer contain one proton and two neutrons. The double weight form of hydrogen is known as *deuterium*, the

prime constituent of heavy water. The triple weight form is known as *tritium*. In ordinary hydrogen, these masses of one, two and three are mixed in such proportion as to give an average atomic weight of 1.008. Nickel has isotopes of atomic weights 58, 60, 61, and 62, producing an average atomic weight of 58.71.

4.1.b) CLASSIFICATION OF ELEMENTS: -

The chemical elements may be roughly classified into three groups, metals, metalloids, and non-metals. Elements considered to be metals are distinguished by several characteristic properties:

1. In the solid state, they exist in the form of crystals.
2. They have relatively high thermal and electrical conductivity.
3. They have the ability to be deformed plastically.
4. They have relatively high reflectivity of light (metallic luster).
5. The metals are on the left side of the periodic table and constitute about three-fourths of elements.

Metalloids resemble metals in some respects and non-metals in others. Generally they have some conductivity but little or no plasticity. Examples of metalloids are carbon, boron and silicon.

The remaining elements are known as non-metals, e.g. inert gases, N, O, P, S, etc.

Periodic Table

1																	18																												
H 1																	He 2																												
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10																												
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18																												
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36																												
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54																												
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86																												
Fr 87	Ra 88	Ac 89	Unq 104	Unp 105	Unh 106	Uns 107	Uno 108	Une 109																																					
<table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>Ce 58</td> <td>Pr 59</td> <td>Nd 60</td> <td>Pm 61</td> <td>Sm 62</td> <td>Eu 63</td> <td>Gd 64</td> <td>Tb 65</td> <td>Dy 66</td> <td>Ho 67</td> <td>Er 68</td> <td>Tm 69</td> <td>Yb 70</td> <td>Lu 71</td> </tr> <tr> <td>Th 90</td> <td>Pa 91</td> <td>U 92</td> <td>Np 93</td> <td>Pu 94</td> <td>Am 95</td> <td>Cm 96</td> <td>Bk 97</td> <td>Cf 98</td> <td>Es 99</td> <td>Fm 100</td> <td>Md 101</td> <td>No 102</td> <td>Lr 103</td> </tr> </table>																		Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71																																
Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103																																

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FIGURE 4.1 - PERIODIC TABLE OF ELEMENTS

4.1.c) ATOMIC BONDING: -

There are four possible types of bonds found in solids:

1. Ionic bond
2. Covalent or homopolar bond
3. Metallic bond
4. Van der Waals forces

1). IONIC BOND: -

The electron structure of atoms is relatively stable when the outer shell contains eight electrons (or two in the case of first shell). An element like sodium with one excess electron will readily give it up so that it has a completely filled outer shell. It will have more protons than electrons and become a positive ion (charged atom) with a +1 charge. An atom of chlorine, on the other hand, with seven electrons in its outer shell, would like to accept one electron. When it does so, it will have one more electron than protons and become a negative ion with a -1 charge. When sodium and chlorine atoms are placed together, there is a

transfer of electrons from the sodium to the chlorine atoms, resulting in a strong electrostatic attraction between the positive sodium ions and the negative chlorine ions and forming the compound sodium chloride, which is ordinary table salt. The fact that this compound has its own properties, not necessarily related to sodium or chlorine, demonstrates that the ionic bond is a very strong bond. This is fortunate, since sodium is highly reactive metal and chlorine is a poisonous gas; yet table salt is something we use every day without any harm. This explains the strong attraction between paired ions typical of the gas or liquid state. In the solid state, however, each sodium ion is surrounded by six negative chlorine ions, and vice versa, so that the attraction is equal in all directions.

2). COVALENT BOND: -

Atoms of some elements may attain a stable electron structure by sharing one or more electrons with adjacent atoms. Nitrogen (atomic number 7) has 5 electrons in the outer shell and needs 3 more to complete that shell. Hydrogen has 1 electron in the outer shell. To attain a stable structure, nitrogen & hydrogen behave differently than do sodium & chlorine. A nitrogen atom shares the electrons of three hydrogen atoms and in turn shares three of its electrons with the three hydrogen atoms to form the compound ammonia (NH₃). In this case ions are not formed; instead, the strong bond is due to the attraction of the shared electrons by the positive nuclei. The three hydrogen atoms are united to the nitrogen atom by three pairs of electron, each atom furnishing 1 electron of each pair. This is known as the covalent or homopolar bond. The covalent bond is typical of most gas molecules.

3). METALLIC BOND:-

The lack of oppositely charged ions in the metallic structure and the lack of sufficient valence electrons to form a true covalent bond necessitate the sharing of valence electrons by more than 2 atoms. Each of the atoms of the metal contributes its valence electrons to the formation of the negative electron cloud. These electrons are not associated with a particular ion but are free to move among the positive metallic ions in definite energy levels. The metallic ions are held together by virtue of their mutual attraction for negative electron cloud. The metallic bond may be thought of as an extension of the covalent bond to a large number of atoms.

4). VAN DER WAALS FORCES: -

This type of bond arises in neutral atoms such as the inert gases. When the atoms are brought close together there is a separation of the centers of positive and negative charges, and a weak attractive force results. It is of importance only at low temperatures when the weak attractive forces can overcome the thermal agitation of the atoms.

4.1.d) CRYSTAL STRUCTURE: -

Since atoms tend to assume relatively fixed positions, this gives rise to the formation of crystals in the solid state. The atoms oscillate about fixed locations and are in dynamic equilibrium rather than statically fixed. The three dimensional network of imaginary lines connecting the atoms is called the space lattice while the smallest unit having the full symmetry of crystals is called the unit cell. The specific unit cell for each metal is defined by its parameters, which are the edges of the unit cell a , b , c , and the angles α (between b & c), β (between a & c), and γ (between a & b).

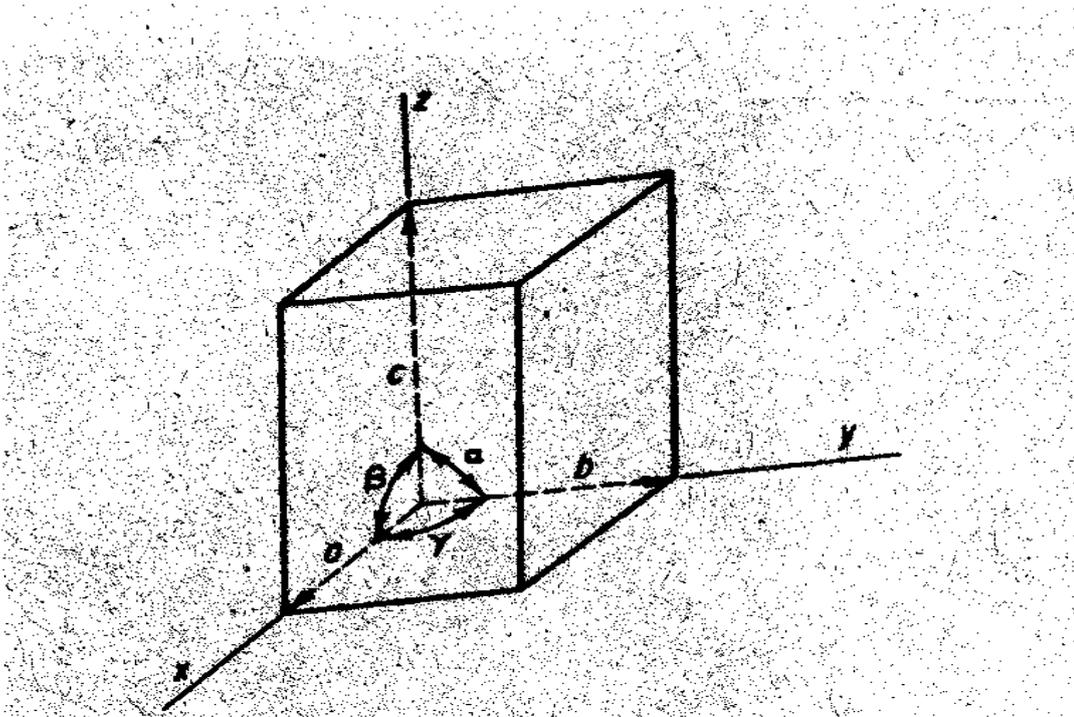


FIGURE 4.2 - SPACE LATTICE

There are only 14 possible types of space lattice, and they fall into 7 crystal systems which are:

Triclinic, Monoclinic, Orthorhombic, Rhombohedral (trigonal), Hexagonal, Tetragonal, and Cubic.

Fortunately, most of the important metals crystallize in either the cubic or hexagonal systems, and only 3 types of space lattices are commonly encountered: the b.c.c. (body centered cubic), the f.c.c. (face centered cubic), and the c.p.h. (close packed hexagonal).

BODY CENTERED CUBIC: -

If the atoms are represented as spheres, the central atom touches each corner atom but these do not touch each other. Since each corner atom is shared by

eight adjoining cubes and the atom in the center can not be shared by any other cube, the unit cell of the b.c.c. structure contains:

$$8 \text{ atoms at the center} \times 1/8 = 1 \text{ atom}$$

$$1 \text{ center atom} = 1 \text{ atom}$$

$$\text{Total} = 2 \text{ atoms}$$

Examples of metals that crystallizes in b.c.c. structure are chromium, tungsten, alpha (α) iron, delta (δ) iron, molybdenum, vanadium, and sodium.

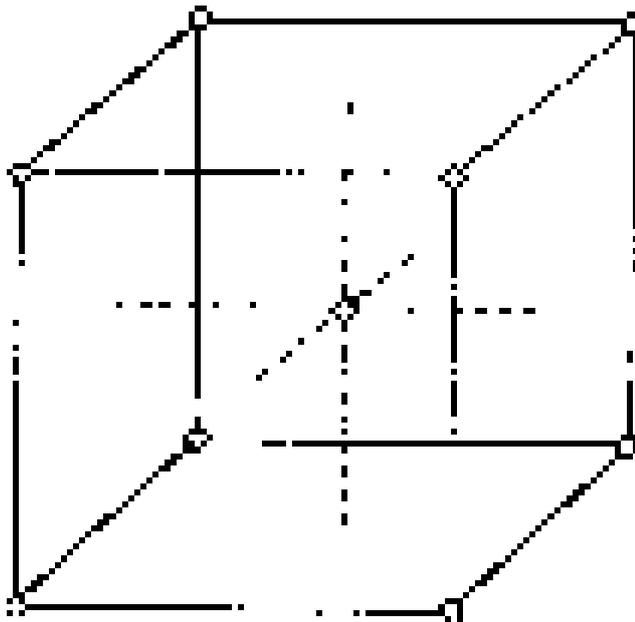


Fig. 4.2

FIGURE 4.2 UNIT CELL OF THE B.C.C

FACE CENTERED CUBIC: -

In addition to an atom on each corner of the cube, there is one in the center of each face, but none in the center of the cube. Since each corner atom is shared by 8 adjoining cubes and each face atom is shared by only one adjacent cube, the unit cell contains:

$$8 \text{ atoms at the corner} \times 1/8 = 1 \text{ atom}$$

$$6 \text{ face centered atoms} \times 1/2 = 3 \text{ atoms}$$

$$\text{Total} = 4 \text{ atoms}$$

This indicates that the f.c.c. structure is more densely packed than the b.c.c. structure. Another way to show the difference in packing is to calculate the fraction of the volume of a f.c.c. cell that is occupied by atoms and compare it to that of a b.c.c. cell. Since there are 4 atoms per unit cell and each atom is a sphere of radius r_a , then;

$$V_{\text{atoms}} = 4 \left(\frac{4}{3} \pi r_a^3 \right) = \frac{16}{3} \pi r_a^3$$

$$V_{\text{cell}} = a^3$$

Where a is the lattice parameter. It is now necessary to find the cell volume in terms of r_a .

$$a\sqrt{2} = 4 r_a, \quad \text{or} \quad a = 2\sqrt{2} r_a$$

$$\text{Packing factor} = \frac{V_{\text{atoms}}}{V_{\text{cell}}} = \frac{16/3 \pi r_a^3}{(2\sqrt{2} r_a)^3} = \frac{\pi}{3\sqrt{2}} = 0.74$$

Examples of metals that crystallize in the f.c.c. lattice are aluminum, nickel, copper, gold, silver, lead, platinum and gamma iron.

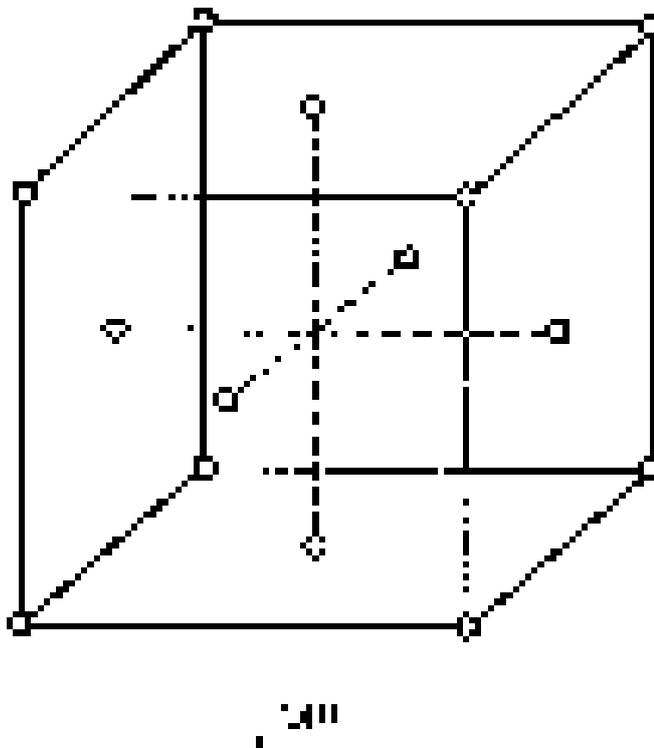


FIGURE 4.3 UNIT CELL OF THE F.C.C

CLOSE- PACKED HEXAGONAL: -

The usual picture of a close packed hexagonal lattice shows two basal planes in the form of regular hexagons with an atom at each corner of the hexagon and one atom at the center. In addition, there are three atoms in the form of a triangle midway between the two basal planes. If the basal plane is divided into six equilateral triangles, the additional three atoms are nestled in the center of alternate equilateral triangles.

The parallel repetition of this hexagonal prism will not built up the entire lattice. The hexagonal prism, therefore, contains two whole unit cells and two halves.

If a number of these unit cells are packed together with axes parallel to one another, as in space lattice, a hexagonal prism may be carved out of them.

Since each atom at the corner of the unit cell is shared by eight adjoining cells and one atom inside the cell can not be shared, the c.p.h. unit cell contains two atoms. Examples of metals that crystallize in this type of structure are magnesium, beryllium, zinc, cadmium, and hafnium.

The unit cell of the cubic system may be specified by a single lattice parameter a , but the hexagonal cells requires the width of the hexagon a , and the distance between basal planes c . these determine the axial ratio c / a , which is sometimes given. It may be shown mathematically that the axial ratio of a c.p.h. structure formed of spheres in contact is 1.633. In reality, metals of this structure have axial ratios that vary from 1.58 for beryllium to 1.88 for cadmium. Therefore, if the atoms are still considered to be in contact, they must be spheroidal in shape rather than spherical.

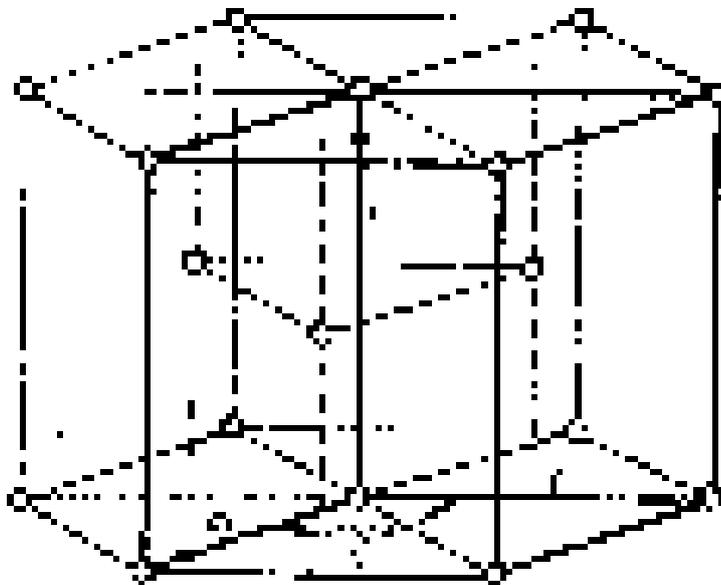


FIGURE 4.4 - UNIT CELL OF THE C.P.H

4.1.e) POLYMORPHISM AND ALLOTROPY: -

Polymorphism is the property of a material to exist in more than one type of space lattice in the solid state. If the changes in the structure are reversible, then the polymorphic change is known as allotropy. At least fifteen metals show this property, and the best known example is iron. When iron crystallizes at 2800 °F it is b.c.c. (δ Fe), at 2554 °F the structure changes to f.c.c. (γ Fe), and at 1670 °F it again becomes b.c.c. (δ Fe).

4.1.f) MECHANISM OF CRYSTALLIZATION: -

Crystallization is the transition form from the liquid to the solid state and occurs in two stages:

Nuclei formation

Crystal growth

Although the atoms in the liquid state do not have any definite arrangement, it is possible that some atoms at any given instant are in positions exactly corresponding to the space lattice they assume when solidified.

These chance aggregates or groups are not permanent but continually break up and reform at other points. How long they last is determined by the temperature & size of the group. The higher the temperature, the greater the kinetic energy of the atoms and the shorter is the life of the group. Small groups are very unstable since they are formed of only a small number of atoms and the loss of only one atom may destroy the group. When the temperature of the liquid is decreased, the atom movement decreases, lengthening the life of the group, and more groups will be present at the same time.

Atoms in a material have both kinetic & potential energy. Kinetic energy is related to the speed at which the atoms move and is strictly a function of temperature. The higher the temperature, the more active are the atoms and the greater is the kinetic energy. Potential energy on the other hand, is related to the distance between the atoms. The greater the average distance between atoms, the greater is their potential energy.

Now consider a pure metal at its freezing point where both the liquid and solid states are at the same temperature. The kinetic energy of the atoms in the liquid and the solid must be the same, but there is a significant difference in potential energy. The atoms in the solid are much closer together, so the solidification occurs with the release of energy. This difference in potential energy between the liquid and solid states is known as the latent heat of fusion. However, energy is required to establish a surface between the solid & a liquid. In pure materials,

at the freezing point, insufficient energy is released by the heat of fusion to create a stable boundary, and some under cooling is always necessary to form stable nuclei. Subsequent release of the heat of fusion will raise the temperature to the freezing point. The amount of under cooling required may be reduced by the presence of solid impurities which reduce the amount of surface energy required.

When the temperature of the liquid metal has dropped sufficiently below its freezing point, stable aggregates or nuclei appear spontaneously at various points in the liquid. These nuclei, which have now solidified, act as centers for further crystallization. As cooling continues, more atoms tend to freeze and they may attach themselves to already existing nuclei, or form new nuclei of their own. Each nucleus grows by the attraction of atoms from the liquid into its space lattice. Crystal growth continues in three dimensions, the atoms attaching themselves in certain preferred directions, usually along the axes of the crystal. This gives rise to a characteristic tree like structure which is called a dendrite. Since each nucleus is formed by chance, the crystal axes are pointed at random and the dendrites growing from them will grow in different directions in each crystal. Finally, as the amount of liquid decreases, the gaps between the arms of the dendrite will be filled and the growth of the dendrite will be mutually obstructed by that of the neighbors. This leads to a very irregular external shape. The crystals found in all commercial metals are commonly called grains because of this variation in external shape. The area along which crystals meet known as the grain boundary, is a region of mismatch. This leads to a non-crystalline (amorphous) structure at the grain boundary with the atoms irregularly spaced. Since the last liquid to solidify is generally along the grain boundaries, there tends to be a higher concentration of impurity atoms in that area.

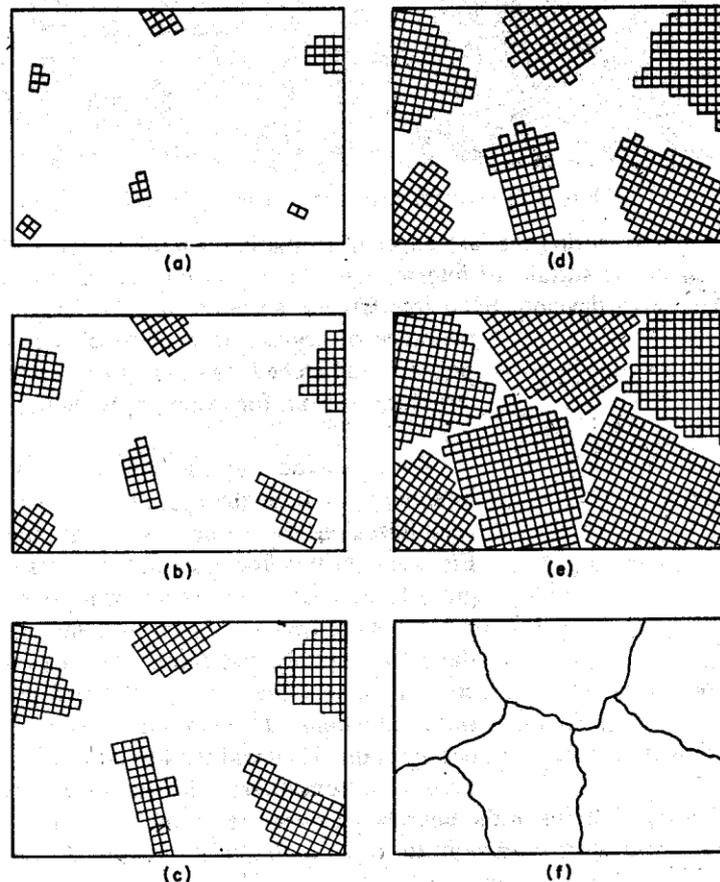


FIGURE 4.5 - SOLIDIFICATION MECHANISM

4.1.g) DIFFERENCE BETWEEN GRAIN & CRYSTAL:-

If, during the growth process, the development of external features, such as regular faces, is prevented by interference from the growth of other nuclei, each unit is called a grain rather than a crystal. The term crystal is usually applied to a group of space lattices of the same orientation which shows symmetry by the development of regular faces. Each grain is essentially a single crystal.

4.1.h) PARAMETERS AFFECTING THE SIZE OF GRAINS:-

The size of grain depends upon temperature from which the metal is cast, the cooling rate, and the nature of metal. Slow removal of heat at solidification temperature will produce a few large grains, whereas the rapid removal of heat will produce many small grains.

Two parameters control the size of grains formed in the solidification of a metal: the rate of nucleation and the rate of growth. The first is the number of nuclei that form per unit of time and is dependent upon temperature. The second is the velocity of growth expressed in length per unit of time and is also dependent

upon temperature. The rate of nucleation and the rate of growth as a function of temperature vary from metal to metal.

4.2 DEFORMATION OF METALS: -

When a material is stressed below its elastic limit, the resulting deformation or strain is temporary. Removal of the stress results in a gradual return of the object to its original dimensions. When a material is stressed beyond its elastic limits, plastic or permanent deformation takes place, and it will not return to its original shape by application of force alone. The ability of a metal to undergo plastic deformation is probably its most outstanding characteristic in comparison with other materials. All shaping operations such as stamping, pressing, spinning, rolling, forging, drawing & extruding involve plastic deformation of metals. Various machining operations such as milling, turning, sawing, and punching also involve plastic deformation. The behavior of a metal under plastic deformation and the mechanism by which it occurs are of essential interest in perfecting the working operation.

Plastic deformation may take place by slip, twinning, or a combination of both methods.

4.2.a) STRAIN HARDENING / COLD WORKING:-

It is a phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called *work hardening*, or, because the temperature at which deformation takes place is cold relative to the absolute melting temperature of the metal, *cold working*. Most metals strain hardens at room temperature.

It is sometimes convenient to express the degree of plastic deformation as percent cold work rather than as strain. Percent cold work (%CW) is defined as:

$$\%CW = (A_0 - A_d / A_0) \times 100$$

Where A_0 is the original area of the cross section that experiences deformation, and A_d is the area after deformation.

A material is considered to be cold worked if its grains are in a distorted condition after plastic deformation is completed. All the properties of a metal that are dependent on the lattice structure are affected by plastic deformation or cold working. Tensile strength, yield strength, and hardness are increased while ductility, as represented by percent elongation, is decreased. Distortion of the lattice structure hinders the passage of electrons and decreases electrical conductivity. This effect is slight in pure metals but is appreciable in alloys.

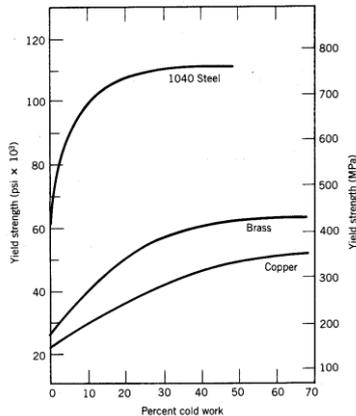


FIGURE 4.6 - STRENGTH VARIATION WITH COLD WORKING

The increase in internal energy, particularly at the grain boundaries, makes the material more susceptible to intergranular corrosion, thereby reducing its corrosion resistance, known as stress corrosion; this is an acceleration of corrosion in certain environments due to residual stresses resulting from cold working. One of the ways to avoid stress corrosion cracking is to relieve the internal stress by suitable heat treatment after cold working and before placing the material in service.

4.2.b) FULL ANNEALING:-

As a result of cold working, the hardness, tensile strength, and electrical resistance increased, while the ductility decreased. There was also a large increase in the number of dislocations, and certain planes in the crystal structure were severely distorted. It was emphasized that while most of the energy used to cold work the metal was dissipated in heat, a finite amount was stored in the crystal structure as internal energy associated with the lattice defects created by the deformation. The stored energy of cold work is that fraction, usually from 1 to approximately 10 percent of the energy put into a material while producing a cold working state, which is retained in the material.

“Full annealing is the process by which the distorted cold worked lattice structure is changed back to one which is strain free through the application of heat”. This process is carried out entirely in the solid state and is usually followed by slow cooling in the furnace from the desired temperature. The annealing process may be divided into three stages: recovery, recrystallization, and grain growth.

Recovery: -

This is primarily a low temperature process, and the property changes produced do not cause appreciable change in the microstructure. The principal effect of recovery seems to be the relief of internal stresses due to cold working. At a given temperature, the rate of decrease in residual strain hardening is fastest at the beginning and drops off at longer times. Also, the amount of reduction in residual stress that occurs in a practical time increases with increasing

temperature. When the load which has caused plastic deformation in a polycrystalline material is released, all the elastic deformation does not disappear. This is due to the different orientation of the crystal, which will not allow some of them to move back when the load is released. As the temperature is increased, there is some spring back of these elastically displaced atoms which relieves most of the internal stress. In some cases there may be a slight amount of plastic flow, which may result in a slight increase in hardness and strength. Electrical conductivity is also increased appreciably during the recovery stage.

Since the mechanical properties of the metal are essentially unchanged, the principal application of heating in the recovery range is in stress relieving cold-worked alloys to prevent stress-corrosion cracking or to minimize the distortion produced by residual stresses. Commercially, this low temperature treatment in the recovery range is known as stress relief annealing.

RECRYSTALLIZATION: -

Even after recovery is complete, the grains are still in a state of high strain energy. Recrystallization is the formation of strain free equiaxed grains / crystals.

As the upper temperature of the recovery range is reached, minute new crystals appear in the microstructure. These new crystals have the same composition and lattice structure as the original underformed grains and are not elongated but are approximately uniform in dimensions (equiaxed). The new crystals generally appear at the most drastically deformed portions of the grain, usually the grain boundaries. The cluster of atoms from which the new grains are formed is called a nucleus. Recrystallization takes place by a combination of nucleation of strain free grains and the growth of these nuclei to absorb the entire cold worked material.

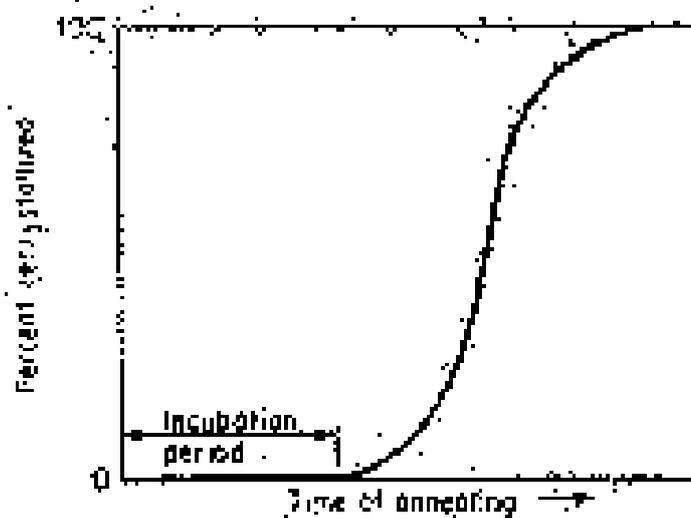


Fig 4.7 Recrystallization curve at constant temperature

Fig shows a typical recrystallization curve. This is a plot of the percent of the material recrystallized versus the time of annealing at constant temperature for affixed composition and degree of cold working. This curve is typical of any process that occurs by nucleation and growth. Initially, there is an incubation period in which enough energy is developed in order to start the process going. In this case, the incubation period is to allow the strain-free nuclei to reach a visible microscopic size. It is important to realize that the growth of recrystallized embryo is irreversible. Embryos, that is, clusters of less than critical size would redissolve or disappear. However, since there is no simple way to recreate the distorted, dislocation-filled structure, the recrystallization embryo cannot redissolve. Therefore, these embryos merely wait for additional energy to attract more atoms into their lattice structure. Eventually the critical size is exceeded, and visible recrystallization begins. The incubation period corresponds to the irreversible growth of the embryo.

RECRYSTALLIZATION TEMPERATURE: -

The term recrystallization temperature does not refer to a definite temperature below which recrystallization will not occur but refers to the approximate temperature at which a highly cold-worked material completely recrystallizes in 1hr. the recrystallization temperature of several metals and alloys is listed in table.

MATERIAL	RECRYSTALLIZATION TEMP. (°F)
Copper (99.999%)	250
Copper, 5% zinc	600
Copper, 5% aluminum	550
Copper, 2% beryllium	700
Aluminum (99.999%)	175
Aluminum (99.0%+)	550
Aluminum alloys	600
Nickel (99.99%)	700
Monel metal	1100
Iron (electrolytic)	750
Low-carbon steel	1000
Magnesium (99.99%)	150

Magnesium alloys	450
Zinc	50
Tin	25
Lead	25

Notice that very pure metals seem to have low recrystallization temperatures as compared with impure metals and alloys. Zinc, tin and lead have recrystallization temperature below room temperature. This means that these metals cannot be cold-worked at room temperature since they recrystallize spontaneously, reforming a strain-free lattice structure.

The greater the amount of prior deformation, the lower the temperature for the start of recrystallization, since there will be greater distortion and more internal energy left.

Increasing the annealing time decreases the recrystallization temperature. The recrystallization process is far more sensitive to changes in temperature than to variations in time at constant temperature.

For equal amounts of cold-working, more strain hardening is introduced into initially fine-grained metal than into initially coarse-grained metal. Therefore, the finer the initial grains size the lower the recrystallization temperature. By the same reasoning, the lower the temperature of cold working, the greater the amount of strain introduced, effectively decreasing the recrystallization temperature for a given annealing time.

A certain minimum amount of cold working (usually 2 to 8%) is necessary for recrystallization. It is seen that a deformation of approximately 7% is required before any change in grain size occurs. This is known as the critical deformation. At degrees of deformation smaller than this, the number of recrystallization nuclei becomes very small.

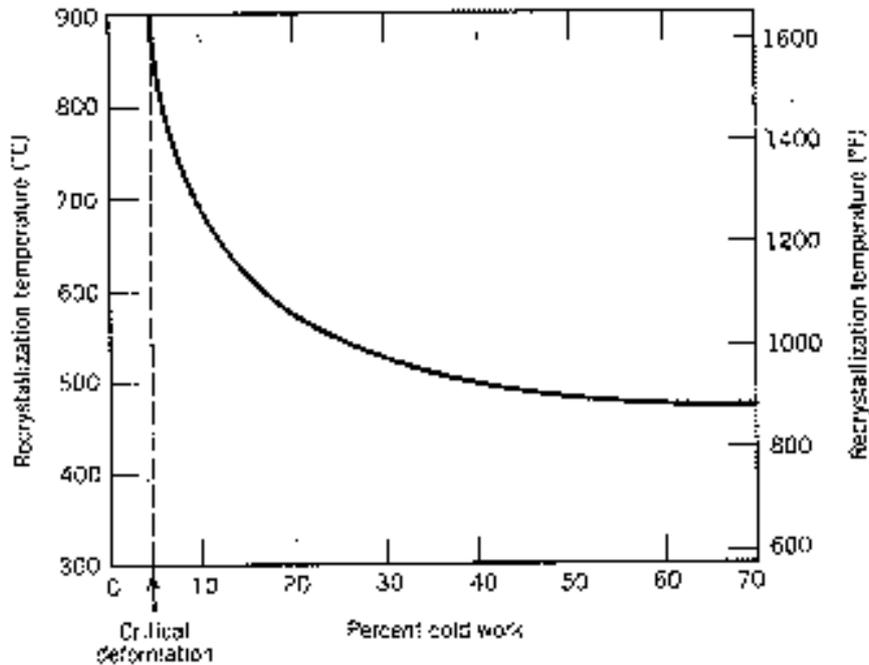


FIGURE 4.8 - RECRYSTALLIZATION TEMPERATURE VS % COLD WORK

Grain Growth: -

Large grains have lower free energy than small grains. This is associated with the reduction of amount of grain boundary. Therefore, under ideal conditions, the lowest energy state for a metal would be as a single crystal. This is the driving force for grain growth. Opposing this force is the rigidity of the lattice. As the temperature increases, the rigidity of the lattice decreases and the rate of grain growth is more rapid. At any given temperature, there is a maximum grain size at which these two effects are in equilibrium.

It is therefore theoretically possible to grow very large grains by holding a specimen for long time high in the grain growth region, i.e. at elevated temperature, under the melting point of specimen.

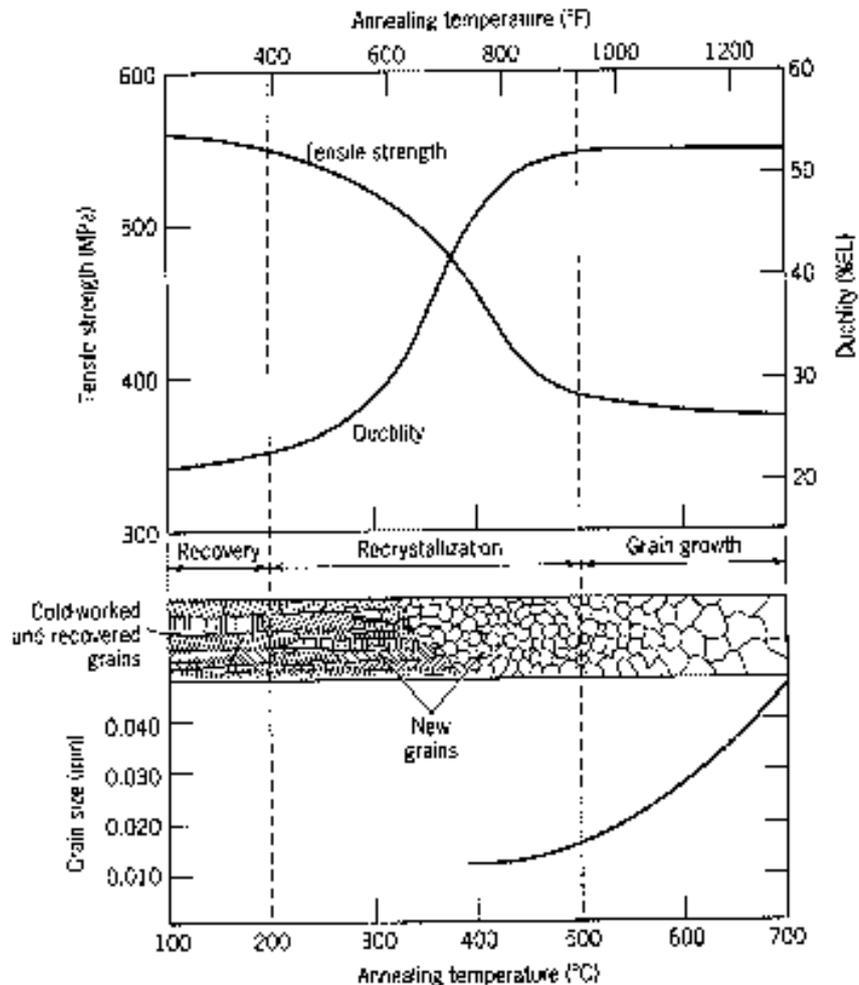


FIGURE 4.9 - GRAIN STRUCTURE DURING VARIOUS STAGES OF ANNEALING

Grain Size: -

Since annealing involves nucleation and grain growth, factors that favor rapid nucleation and slow growth will result in the fine-grained material and those which favor slow nucleation and rapid growth will result in coarse-grained material. The factors that govern the final recrystallized grain size are:

Degree of Prior Deformation: -

This is the most important factor. Increasing the amount of prior deformation favors nucleation and decreases the final grain size. With increasing degrees of deformation, an increasing number of points of high stress or high energy are present, leading to recrystallization from a greater number of nuclei, and finally a greater number of grains, and thus to a continually smaller grain size.

Time at Temperature:-

Increasing the time at any temperature above the recrystallization temperature favors the grain growth and increases the final grain size.

Annealing Temperature:-

The lower the temperature above the recrystallization temperature, the finer the final grain size.

Heating Time:-

The shorter the heating time for the annealing temperature, the finer the final grain size. Slow heating will form few nuclei, favoring grain growth and resulting in coarse grain.

Insoluble Impurities:-

The greater the amount and the finer the distribution of insoluble impurities the finer the final grain size. They not only increase nucleation but act as barriers to the growth of grains.

Since full annealing restores the material to a strain-free lattice structure, it is essentially a softening process. Property changes produced by plastic deformation are removed, and the material returns very nearly to its original properties. Therefore, during annealing, the hardness and strength decreases and ductility increases.

4.2.c) HOT WORKING:-

Hot working is usually described as working a material above its recrystallization temperature. When a material is plastically deformed, it tends to become harder, but the rate of work hardening decreases as the temperature is increased. When a material is plastically deformed at an elevated temperature, two opposing effects take place at the same time- a hardening effect due to plastic deformation and a softening effect due to recrystallization. For a given rate of working, there must be some temperature at which these two effect will just balance. If the material is worked above this temperature, it is known as hot working; below this temperature it is known as cold working.

The terms hot and cold as applied to the working do not have the same significance as they ordinarily have. For example, lead and tin, whose recrystallization is below room temperature, may be hot worked at room temperature; but steel with a high recrystallization temperature may be cold worked at 1000 °F.

4.2.d) HOT WORKING VS COLD WORKING: -

Most of the metal shapes are produced from cast ingots. To manufacture sheets, plate, rod, wire etc from this ingot, the most economical method is by hot

working. However in the case of steel, the hot worked material reacts with oxygen as it cools down to room temperature and forms a characteristic dark oxide coating called scale. Occasionally, this scale may give difficulty during machining or forming operations.

It is not possible to manufacture hot worked material to exact size because of dimensional changes that takes place during cooling. Cold worked material, on the other hand, may be held to close tolerances. It is free of surface scale but require more power for deformation and is therefore more expensive to produce. Commercially the initial reductions are carried out with the material at an elevated temperature, and the final reductions are done cold to take advantage of both processes.

The finishing temperature in hot working will determine the grain size that is available for further cold working. Higher temperatures are used initially to promote uniformity in the material, and the resulting large grains allow more economical reduction during the early working operation. As the material cools and working continues the grain size will decrease, becoming very fine just above the recrystallization temperature.

4.3 CONSTITUTION OF ALLOYS:-

4.3 a) INTRODUCTION: -

An alloy is a substance that has metallic properties and is composed of two or more chemical elements of which atleast one is metal. An alloy system contains all the alloys that can be formed by several elements combined in all possible proportions. If the system is made up of two elements it is called a binary alloys system; three elements, a ternary alloys system: etc. Taking only 45 of the most common metals, any combination of two gives 990 binary systems. Combinations of three give over 14000 ternary systems.

Alloys may be classified according to their structure, and complete alloy systems may be classified according to the type of their equilibrium or phase diagram.

4.3 b) CLASSIFICATION OF ALLOYS: -

Alloys may be homogeneous (uniform) or mixtures. If the alloy is homogeneous it will consist of a single phase and if it is a mixture it will be a combination of several phases. A phase is anything which is homogeneous and physically distinct. Any structure which is visible as physically distinct microscopically may be considered a phase. For most pure elements the term phase is synonymous

with state. There is, therefore, for pure elements, a gaseous, liquid and solid phase. Some metals are allotropic in the solid state and will have different solid phases. When the metal undergoes a change in crystal structure, it undergoes a phase change since each type of crystal structure is physically distinct. In the solid state there are three possible phases: 1) pure metals 2) Intermediate alloys phase or compound 3) solid solution

If any alloy is homogeneous (composed of a single phase) in the solid state, it can be only a solid solution or a compound. If the alloy is a mixture, it is then composed of any combination of the phases possible in the solid state. It may be a mixture of two pure metals or two solid solutions or two compounds or a pure metal and a solid solution and so on. The mixture may also vary in degree of fineness.

4.3 c) PURE METALS: -

The characteristics of a pure metal have already been discussed in detail in earlier chapters. However one property is worth repeating. Under equilibrium conditions, all metals exhibit a definite melting or freezing point. The term "under equilibrium conditions" implies conditions of extremely slow heating and cooling. In other words, if any change is to occur, sufficient time must be allowed for it to take place. If a cooling curve is plotted for a pure metal, it will show a horizontal line at the melting or freezing point.

4.3 d) INTERMEDIATE ALLOY PHASE OR COMPOUND: -

Most ordinary chemical compounds are combinations of positive and negative valence elements. The various kinds of atoms are combined in a definite proportion, which is expressed by a chemical formula. Some typical examples are water: H_2O (two atoms of hydrogen combined with one atom of oxygen) and table salt: $NaCl$ (one atom of sodium combined with one atom of chlorine). The atoms that are combined to form the molecule, which is the smallest unit that has the properties of the compound, are held together in a definite bond. Various types of atomic bonding have already been discussed in detail.

When a compound is formed, the elements lose their individual identity and characteristic properties to a large extent. The resultant compound thus formed has its own characteristic physical, mechanical and chemical properties. A good example is table salt ($NaCl$). Sodium is a very active metal that oxidizes rapidly and is usually stored under kerosene. Chlorine is a poisonous gas. Yet one atom of each combines to give the harmless and important compound, table salt.

Most compounds like pure metals also exhibit a definite melting point within a narrow limit of temperature. Therefore, the cooling curve for a compound is similar to that for a pure metal. In reference to equilibrium diagram, the intermediate alloys phases are phases whose chemical compositions are intermediate between the two pure metals and generally have crystal structure different from those of the pure metals.

The three most common intermediate alloy phases are:

Inter metallic Compounds or Valency Compounds: -

These are generally formed between chemically dissimilar metals and are combined by following the rules of chemical valence. Since they generally have strong bonding (ionic or covalent), their properties are essentially non metallic. They usually show poor ductility and poor electrical conductivity and may have a complex crystal structure. Examples are CaSe, Mg₂Sn, Mg₂Pb and Cu₂Se.

Interstitial Compounds: -

These compounds formed between the transition metals such as scandium, titanium, tantalum, tungsten and iron with hydrogen, oxygen, carbon, boron and nitrogen. The word interstitial means "between the spaces" and latter five elements have relatively small atoms that fit into the spaces of the lattice structure of the metal. These same five elements also form interstitial solid solutions, which will be described later. The interstitial compounds are metallic, may have a narrow range of composition, high melting points and are extremely hard. Examples are TiC, TaC, Fe₄N, Fe₃C, W₂C, CrN and TiH.

Electron Compounds: -

A study of the equilibrium diagrams of the alloys of copper, gold, silver, iron and nickel with the metals cadmium, magnesium, tin, zinc and aluminum shows that a number of intermediate phases are formed in these systems with similar lattice structures. Hume-Rothery first pointed out that these intermediate phases are found to exist at or near compositions in each system that have a definite ratio of valence electrons to atoms and are therefore called "electron compounds". For example in the compound AgZn, the atom of silver has one valence electron while that of zinc has two valence electrons so that the two atoms of the compound will have three valence electrons or an electron-to-atom ratio of 3:2. Many electron compounds have properties resembling those of solid solutions, including a wide range of composition, high ductility and low hardness.

4.3 e) SOLID SOLUTIONS: -

Any solution is composed of two parts: a solute and a solvent. The solute is the minor part of the solution or the material which is dissolved, while the solvent constitutes the major portion of the solution. It is possible to have solutions involving gases, liquids or solids as either the solute or the solvent. The most common solutions involve water as the solvent, such as sugar or salt dissolved in water.

The amount of solute that may be dissolved by the solvent is generally a function of temperature (with pressure constant) and usually increases with increasing temperature. There are three possible conditions for a solution: Unsaturated, Saturated and Super saturated.

A solid solution is simply a solution in the solid state and consists of two kinds of atoms combined in one type of space lattice. There is usually a considerable difference in the solubility of the solute in the liquid and solid states of the solution. The solute is generally more soluble in the liquid state than in the solid state. Moreover, when solidification of the solution starts, the temperature may be higher or lower than the freezing point of the pure solvent. Most solid solutions solidify over a range in temperature.

There are two types of solid solutions, Substitutional solid solution and interstitial solid solution.

Substitutional Solid Solution: -

In this type of solution, the atoms of the solute substitute for atoms of the solvent in the lattice structure of the solvent. For example, silver atoms may substitute for gold atoms without losing the f.c.c structure of gold, and gold atoms may substitute for silver atoms in the f.c.c lattice structure of silver. All alloys in the silver-gold system consist of an f.c.c lattice with silver and gold atoms distributed at random through the lattice structure. This entire system consists of a continuous series of solid solutions.

Several factors are now known which control the range of solubility in alloy systems. These are summarized below:

a) Crystal Structure Factor: -

Complete solid solubility of two elements is never attained unless the elements have the same type of crystal lattice structure.

b) Relative Size Factor: -

The size factor is favorable for solid solution formation when the difference in atomic radii is less than about 15%. For example, silver and lead are both f.c.c and the relative size factor is about 20%. The solubility of lead in solid silver is about 1.5% and the solubility of silver in solid lead is about 0.1%. Antimony and bismuth are completely soluble in each other in all proportions. They have the same type of crystal structure (rhombohedral) and differ in atomic radii by about 7%.

c) Chemical Affinity Factor: -

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

d) Relative Valence Factor:-

If the solute metal has a different valence from that of the solvent metal, the number of valence electrons per atom, called the electron ratio, will be changed. Crystal structures are more sensitive to a decrease in the electron ratio than to an increase. In other words, a metal of lower valence tends to dissolve more of a metal of higher valence than vice versa. For example in the aluminum-nickel alloys system, both metals are f.c.c. The relative size factor is approx. 14%. However nickel is lower in valence than aluminum and in accord with the relative valence factor solid nickel dissolves 5% aluminum but the higher valence aluminum dissolves only 0.04% nickel.

It is important to note that an unfavorable relative size factor alone is sufficient to limit solubility to a low value. If the relative size factor is favorable then the other three factors should be considered in deciding on the probable degree of solid solubility. The lattice structure of a solid solution is basically that of the solvent with slight changes in lattice parameters. An expansion occurs if the solute atom is larger than the solvent atom and a contraction if the solute atom is smaller.

Interstitial Solid Solution: -

These are formed when atoms of small atomic radii fit into the spaces or interstices of the lattice structure of the large solvent atoms. Since the spaces of the lattice structure are restricted in size, only atoms with atomic radii less than

1 angstrom are likely to form such solid solutions. These are hydrogen (0.46), boron (0.97), carbon (0.77), nitrogen (0.71) and oxygen (0.60).

This type of solution differs from interstitial compounds in that the amount of smaller atoms required to form the compound is always greater than the amount that may be dissolved interstitially. When a small amount of solute is added to the solvent and the difference in atomic radii is great enough, an interstitial solid solution is formed. In this condition, the solute atoms have considerable mobility and may move in the interstitial spaces of the lattice structure. More solute atoms may be dissolved interstitially until the solution becomes saturated at that temperature. Increasing the amount of solute atoms beyond this limit severely restricts the mobility of these atoms in a particular area and the interstitial compound of fixed composition starts to form. The interstitial compound showing a narrow range of composition is expressed by a chemical formula, but the interstitial solution being of variable composition cannot be represented by chemical formula. The lattice structure always shows an expansion when this type of solution is formed.

Interstitial solid solutions normally have a very limited solubility and generally are of little importance. Carbon in iron is a notable exception and forms the basis for hardening steel. Carbon dissolves in iron interstitially. The maximum solubility of carbon in γ iron (f.c.c) is 2% at 2065°F, while the maximum solubility of carbon in α iron (b.c.c) is only 0.025% at 1333°F.

Both types of solid solutions are illustrated in figure below.

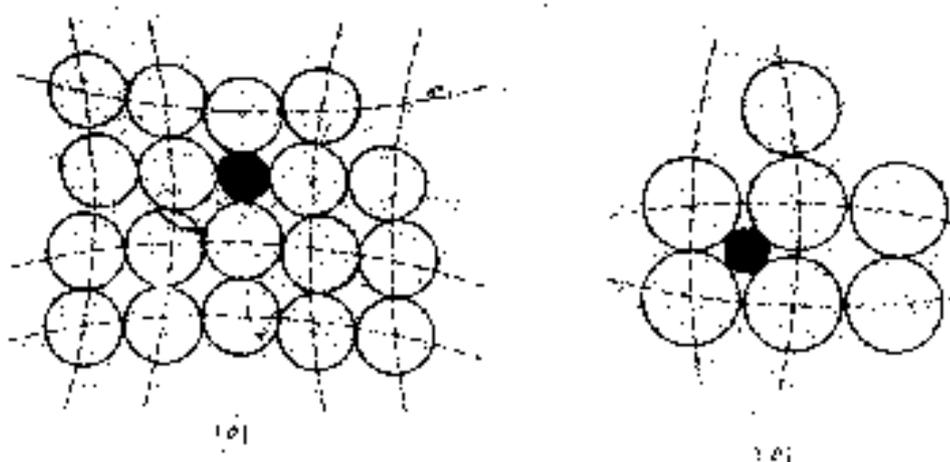


FIGURE 4.10 SCHEMATIC REPRESENTATION OF SOLID SOLUTIONS

In contrast to intermetallic and interstitial compounds, solid solutions in general are easier to separate, melt over a range in temperature, have properties that are influenced by those of the solvent and solute and usually show a wide range of composition so that they are not expressed by a chemical formula.

4.4 PHASE DIAGRAMS / EQUILIBRIUM DIAGRAMS:-

4.4 a) INTRODUCTION: -

The study of the interrelation of phases in an alloy system at different temperatures and for different alloys compositions is of great importance in understanding the characteristics of alloys. Since the properties of an alloy depends to a great extent upon the type, number, amount and form of phases present and can be changed by altering these quantities.

A great deal of information concerning the phase changes in many alloy system has been accumulated and the best method of recording the data is in the form of Phase Diagram, also known as Equilibrium Diagrams or Constitutional Diagrams. In order to specify completely the state of a system in equilibrium, it is necessary to specify three independent variables i.e. temperature, pressure and composition. Since pressure remains virtually constant in most applications, the equilibrium diagram indicates the structural changes due to variation of temperature and composition.

An equilibrium diagram may be defined as **“a plot of the composition of phases as a function of temperature in any ally system under equilibrium conditions”**.

If there are two components in a phase diagram, it is called binary phase diagram; for three components, ternary and so on. Equilibrium diagrams may be classified according to the relation of the components in the liquid and solid states as follows:

1) Components completely soluble in liquid state

- a) Components completely soluble in solid state
- b) Components partly soluble in solid state
- c) Components insoluble in solid state

2) Components partially soluble in liquid state

- a) Components completely soluble in solid state
- b) Components partly soluble in solid state

3) Components completely insoluble in liquid state

- a) Components completely insoluble in solid state

The first type of equilibrium diagram in which the components are completely soluble in both liquid as well as solid states is most common in engineering alloys and will be discussed in detail.

4.4 b) TWO METALS COMPLETELY SOLUBLE IN THE LIQUID AND SOLID STATES:

-

The easiest type of binary phase diagram to understand and interpret is probably that which is characterized by the copper-nickel system, shown in figure below.

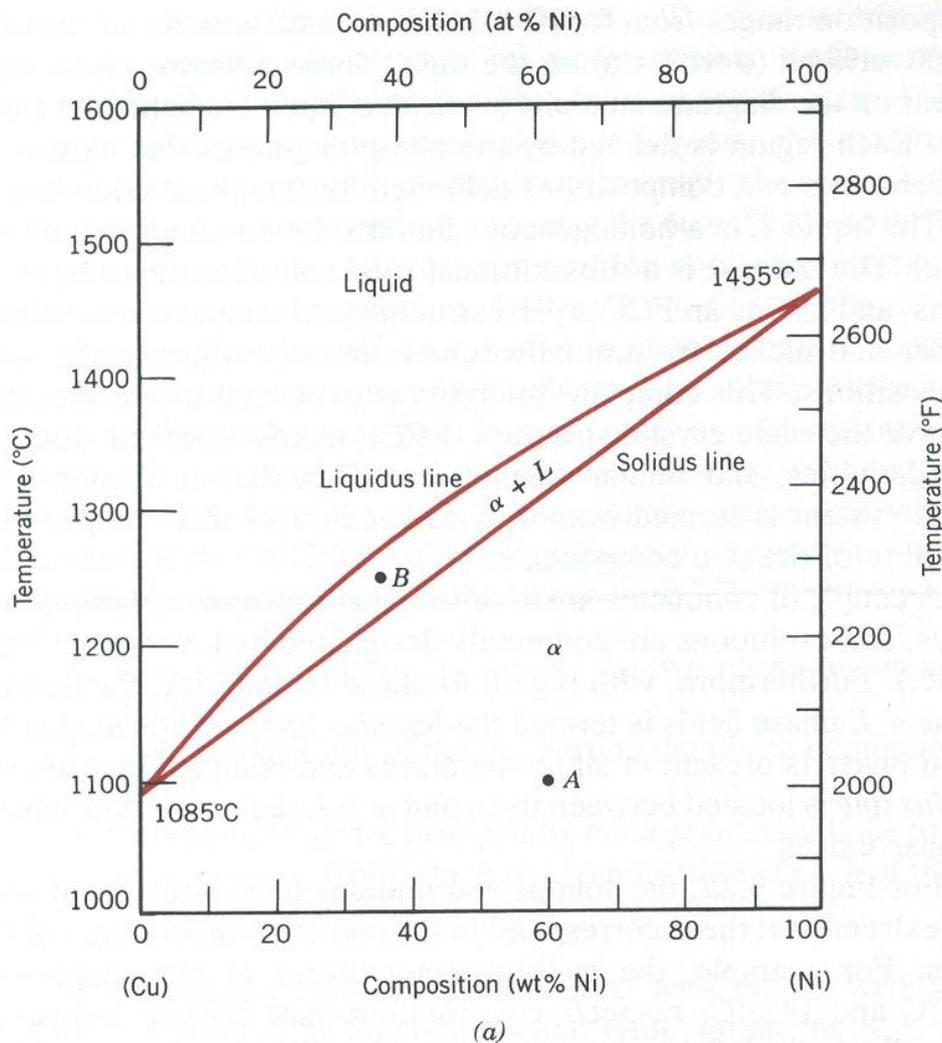


FIGURE 4.11 (A) COPPER-NICKEL PHASE DIAGRAM

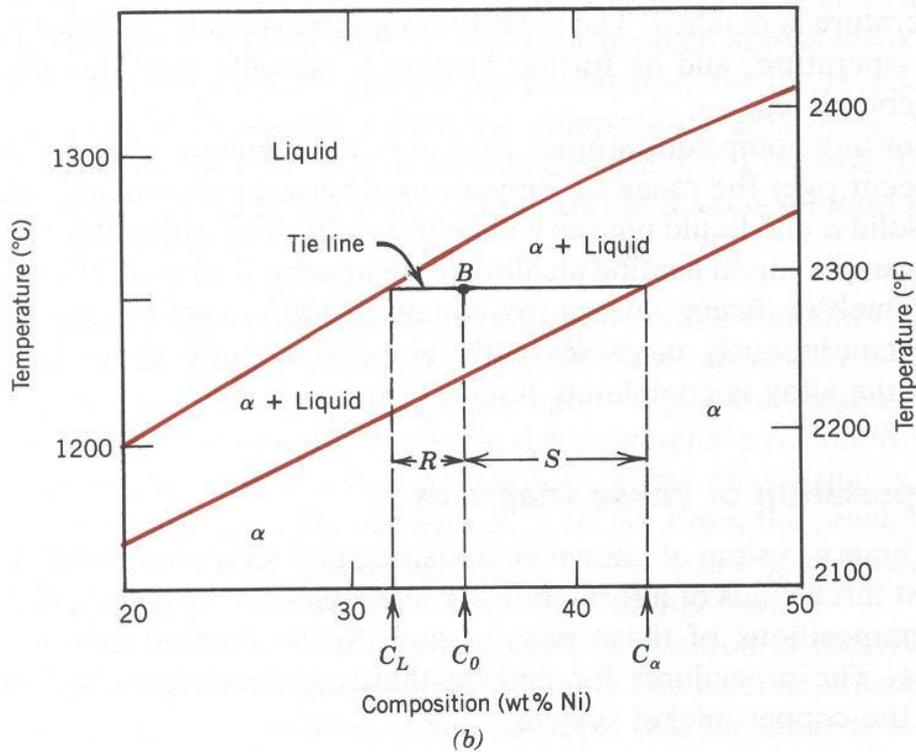


FIGURE 4.11 (B) COPPER-NICKEL PHASE DIAGRAM

Temperature is plotted along the ordinate and the abscissa represents the composition of alloy in weight or atomic % of Ni. The composition ranges from 0 Wt % Ni (100 Wt % Cu) on the left horizontal line to 100 Wt % Ni (0 Wt % Cu) on the right. Three different phase regions appear on the diagram, an alpha (α) region, a liquid (L) region and a two-phase ($\alpha + L$) region. Each region is defined by the phase or phases that exist over the range of temperature and composition delimited by the phase boundary lines.

The liquid L is a homogeneous liquid solution composed of both Cu and Ni. The α phase is a substitutional solid solution consisting of both Cu and Ni atoms and having an f.c.c structure. At temperatures below about 1080 °C, Cu and Ni are mutually soluble in each other in the solid state for all compositions. This complete solubility is explained by the fact that both Cu and Ni have the same crystal structure (f.c.c), nearly identical atomic radii and electronegativities and similar valences. The Cu-Ni system is called *isomorphous* because of this complete liquid and solid solubility of the two components.

4.4 c) EXPLANATION OF PHASE DIAGRAM: -

For metallic alloys, solid solutions are commonly designated by lowercase Greek letters (α , β , γ etc). Further more with regard to phase boundaries, the line separating the L and $\alpha + L$ phase fields is termed the *Liquidus line*, as indicated in figure shown above; the liquid phase is present at all temperatures and compositions above this line. The *Solidus line* is located between the α and $\alpha + L$ regions, below which only the solid α phase exists

The solidus and liquidus lines intersect at the two composition extremities; these correspond to the melting temperatures of the pure components. For example, the melting temperatures of pure Cu and Ni are 1085 °C and 1455 °C, respectively. Heating pure copper corresponds to moving vertically up the left-hand temperature axis. Copper remains solid until its melting temperature is reached. The solid-to-liquid transformation takes place at the melting temperature and no further heating is possible until this transformation has been completed. This phenomenon is called *Isothermal Transformation*.

For any composition other than pure components, this melting phenomenon will occur over the range of temperatures between the solidus and liquidus lines; both solid α and liquid phases will be in equilibrium within this temperature range. For example, upon heating an alloy of composition 50 Wt % Ni – 50 Wt % Cu, melting begins at approximately 1280 °C; the amount of liquid phase continuously increases with temperature until about 1320 °C, at which the alloys is completely liquid.

4.4 d) INTERPRETATION OF PHASE DIAGRAM: -

For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available.

- 1) The phases which are present
- 2) The composition of these phases
- 3) The percentage or fractions of the phases.

Phases Present: -

The establishment of what phases are present is relatively simple. One just locates the temperature-composition point on the diagram and notes the phase(s) with which the corresponding phase field is labeled. For example, an alloys of composition 60 Wt % Ni – 40 Wt % Cu at 1100 °C would be located at point A in fig (a); since this is within the α region, only the single α phase will be present. On the other hand, a 35 Wt % Ni – 65 Wt % Cu alloy at 1250 °C (point B) will consist of both α and liquid phases at equilibrium.

Determination of Phase Compositions: -

The first step in the determination of phase compositions (in terms of concentrations of the components) is to locate the temperature-composition point on the phase diagram. Different methods are used for single and two phase regions. If only one phase is present, the composition of this phase is simply the same as the overall composition of the alloy. For example, consider the 60 Wt % Ni – 40 Wt % Cu alloy at 1100 ° C (point A in Fig a). At this composition and temperature, only the α phase is present, having a composition of 60 Wt % Ni – 40 Wt % Cu.

For an alloy having composition and temperature located in a two-phase region, the situation is bit complicated. In all two-phase regions, one may imagine a series of horizontal lines, one at every temperature; each of these is known as a *tie line*, or sometimes as an *isotherm*. These tie lines extend across the two-phase region and terminate at the phase boundary lines on either side. To compute the equilibrium concentrations of the two phases, the following procedure is used:

1. A tie line is constructed across the two-phase region at the temperature of the alloy
2. The intersections of the tie line and the phase boundaries on either side are noted
3. Perpendiculars are dropped from these intersections to the horizontal composition axis, from which the composition of each of the respective phases is read.

For example, consider the 35 Wt % Ni – 65 Wt % Cu alloy at 1250 ° C, located at point B in Fig b and lying within the $\alpha + L$ region. Now we want to determine the composition (in Wt % Ni and Cu) for both the α and liquid phases. The tie line has been constructed across the $\alpha + L$ phase region, as shown in Fig b. The perpendicular from the intersection of the tie line with the liquidus boundary meets the composition axis at 32 Wt % Ni – 68 Wt % Cu, which is the composition of the liquid phase, C_L . Likewise for the solidus-tie line intersection, we find a composition for the α solid solution phase, C_α of 43 Wt % Ni – 57 Wt % Cu.

Determination of Phase Amounts: -

The relative amounts (as fraction or as %) of the phases present at equilibrium may also be computed with the aid of phase diagrams. Again, the single and two phase situations must be treated separately. The solution is obvious in the single phase region: since only one phase is present, the alloy is composed entirely of

that phase; that is, the phase fraction is 1.0 or alternately, the percentage is 100 %. From the previous example of 60 Wt % Ni – 40 Wt % Cu at 1100 ° C (point A in Fig a), only the α phase is present; hence, the alloy is completely or 100 % α .

If the composition and temperature position is located within a two-phase region, things are more complex. The tie line must be utilized along with a procedure often called *Lever Rule*, which is applied as follows.

1. The tie line is constructed across the two-phase region at the temperature of the alloy.
2. The overall alloy composition is located on the tie line.
3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the *other* phase, and dividing by the total tie line length.
4. The fraction of the other phase is determined in the same manner.
5. If phase % is desired, each phase fraction is multiplied by 100.

In the employment of lever rule, tie line segment lengths may be determined either by direct measurement from the phase diagram using a linear scale, or by subtracting compositions as taken from the composition axis.

Consider again the example shown in Fig b, in which at 1250 ° C both α and liquid phases are present for a 35 Wt% Ni- 65 Wt % Cu alloy. We want to compute the fraction of each of the α and liquid phases. The tie line has been constructed that was used for the determination of α and L phase compositions. Let the overall alloy composition be located along the tie line and denoted as C_0 , and mass fractions be represented by W_L and W_α for the respective phases. From the lever rule, W_L may be computed as

$$W_L = S / (R + S)$$

Or, by subtracting compositions,

$$W_L = (C_\alpha - C_0) / (C_\alpha - C_L)$$

Composition need be specified only in terms of one of the constituents for a binary alloy; for the computation above, weight % Ni will be used (i.e. $C_0 = 35$ Wt % Ni, $C_\alpha = 43$ Wt % Ni and $C_L = 32$ Wt % Ni), and

$$W_L = (43 - 35) / (43 - 32) = 0.73$$

Similarly, for the α phase,

$$W_\alpha = R / (R + S)$$

$$W_\alpha = (C_0 - C_L) / (C_\alpha - C_L)$$

$$W_\alpha = (35 - 32) / (43 - 32) = 0.27$$

Of course, identical answers are obtained if compositions are expressed in Wt % Cu instead of Ni.

Thus the lever rule may be employed to determine the relative amounts or fractions of phases in any two-phase region for a binary alloy if the temperature and composition are known and if equilibrium has been established.

4.4 e) CHEMICAL REACTION IN EQUILIBRIUM DIAGRAMS:-

A number of reactions take place in equilibrium diagrams. Most common ones are listed below.

1) Monotectic Reaction:-

When one liquid forms another liquid plus a solid on cooling, it is known as a monotectic reaction. General equation for such reaction may be written as



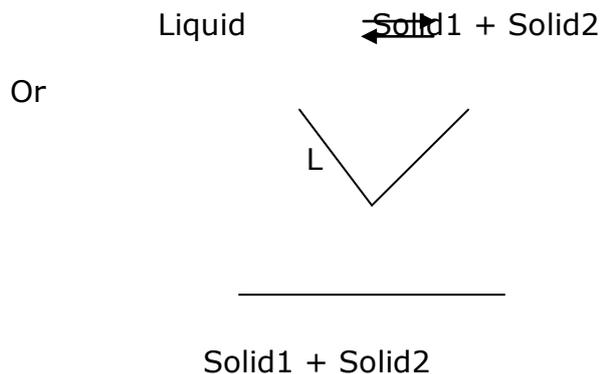
Or



L2 + Solid

2) Eutectic Reaction:-

When one liquid transforms into two solids on cooling, it is known as a eutectic reaction. General equation for such reaction may be written as

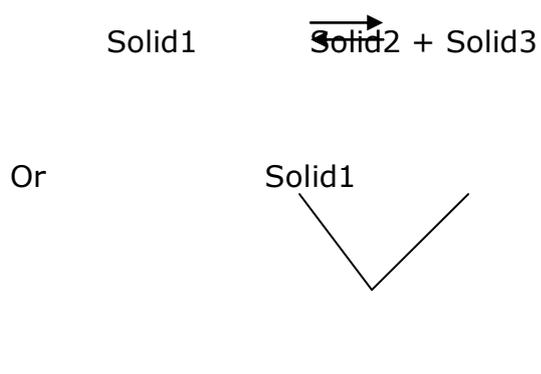


The extremely fine mixture of two solids which is visible only under microscope is called Eutectic Mixture. This mixture consists of two different solid phases. It may be two pure metals, two solid solutions, two intermediate phases or any combination of the above.

3) Eutectoid Reaction:-

It is a common reaction in the solid state. It is very much similar to the eutectic reaction but does not involve any liquid. In this case a solid phase transforms into two new solid phases upon cooling.

General equation for such reaction may be written as

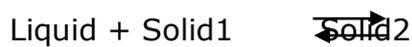


Solid2 + Solid3

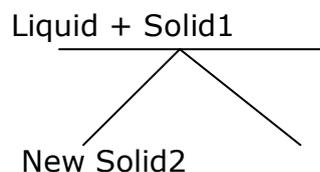
The resultant eutectoid mixture is extremely fine, just like the eutectic mixture.

4) Peritectic Reaction:-

In this reaction, a liquid and a solid react to form a new solid upon cooling. The general equation for such reaction may be written as



Or

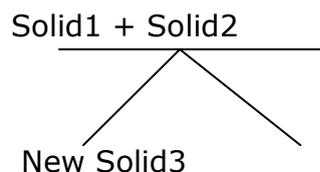


5) Peritectoid Reaction:-

This is very common reaction in the solid state and appears in many alloy systems. In this reaction, two solids upon cooling transforms into a new solid phase. The general equation for such reaction may be written as



Or



It is important to note that all the above reactions take place at constant temperature i.e. the reactions are isothermal reactions. In phase diagrams, they

are indicated by a horizontal line also known as isotherms. The points on phase diagram where these reactions take place are named according to the nature of reaction going on i.e. Eutectic point, Eutectoid point and so on. The composition of a particular alloy system at these points is then named as Eutectic Composition or Eutectic Alloy and so on. It is common practice to call all alloys to the left of Eutectic composition as Hypo Eutectic (less than eutectic) Alloys & those to the right as Hyper Eutectic (more than eutectic) alloys. The same rule follows for Eutectoid compositions.

4.5- IRON- IRON CARBIDE EQUILIBRIUM DIAGRAM: -

4.5 a) INTRODUCTION: -

Iron is an allotropic metal, which means that it can exist in more than one type of lattice structure depending upon temperature. A cooling curve for pure iron is shown in Fig below.

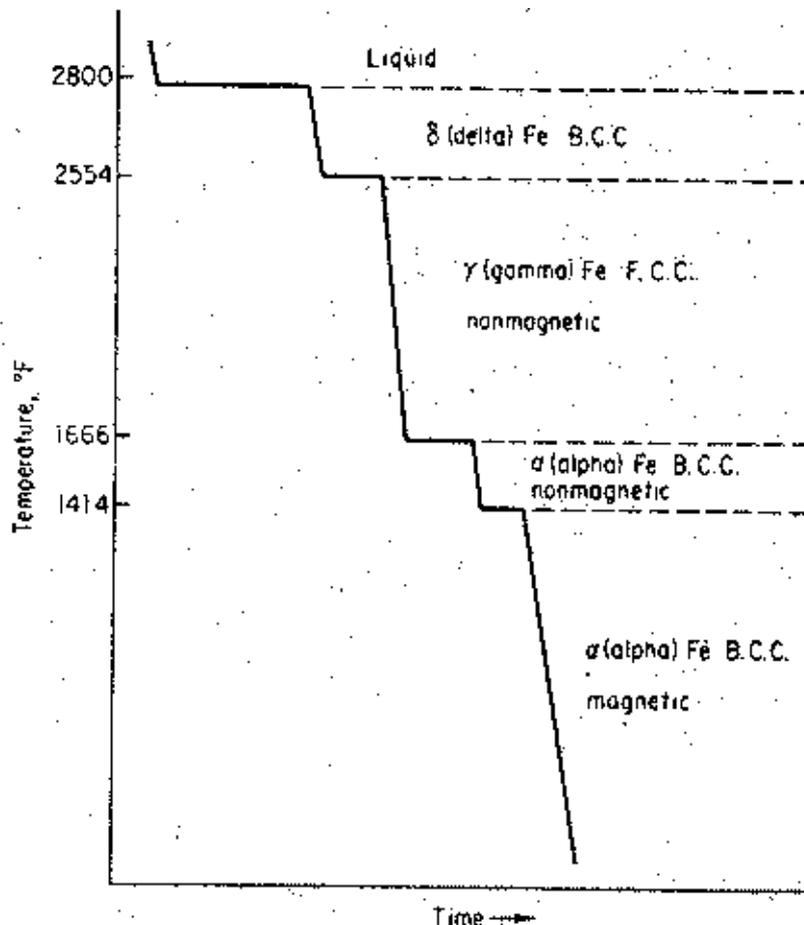


FIGURE 4.12 COOLING CURVE FOR PURE IRON

When iron first solidifies at 2800 ° F, it is in the b.c.c δ (delta) form. Upon further cooling, at 2554 ° F, a phase change occurs and the atoms rearrange themselves into the γ (gamma) form, which is f.c.c and non-

magnetic. When the temperature reaches 1666 ° F, another phase change occurs from f.c.c non-magnetic γ iron to b.c.c non-magnetic α iron. Finally at 1414 ° F, the α iron becomes magnetic without a change in lattice structure.

All the allotropic changes give off heat when iron is cooled and absorb heat when iron is heated.

4.5 b) IRON-IRON CARBIDE DIAGRAM:-

The temperature at which the allotropic changes take place in iron is influenced by alloying elements, the most important of which is carbon. The portion of the iron-carbon alloy system which is of interest is shown in the Fig below. This is the part between pure iron and an interstitial compound, iron carbide, Fe_3C , containing 6.67 % C by weight. Therefore we call this portion the iron-iron carbide equilibrium diagram. Before going into the study of this diagram, it is important to understand that this is not a true equilibrium diagram, since equilibrium implies no change of phase with time. It is a fact, however, that the compound iron carbide will decompose into iron and carbon (graphite). This decomposition will take a very long time at room temperature and even at 1300 ° F it takes several years to form graphite. So iron carbide is called a metastable phase. Therefore the iron-iron carbide diagram, even though it technically represents metastable condition can be considered as representing equilibrium changes, under conditions of relatively slow heating and cooling.

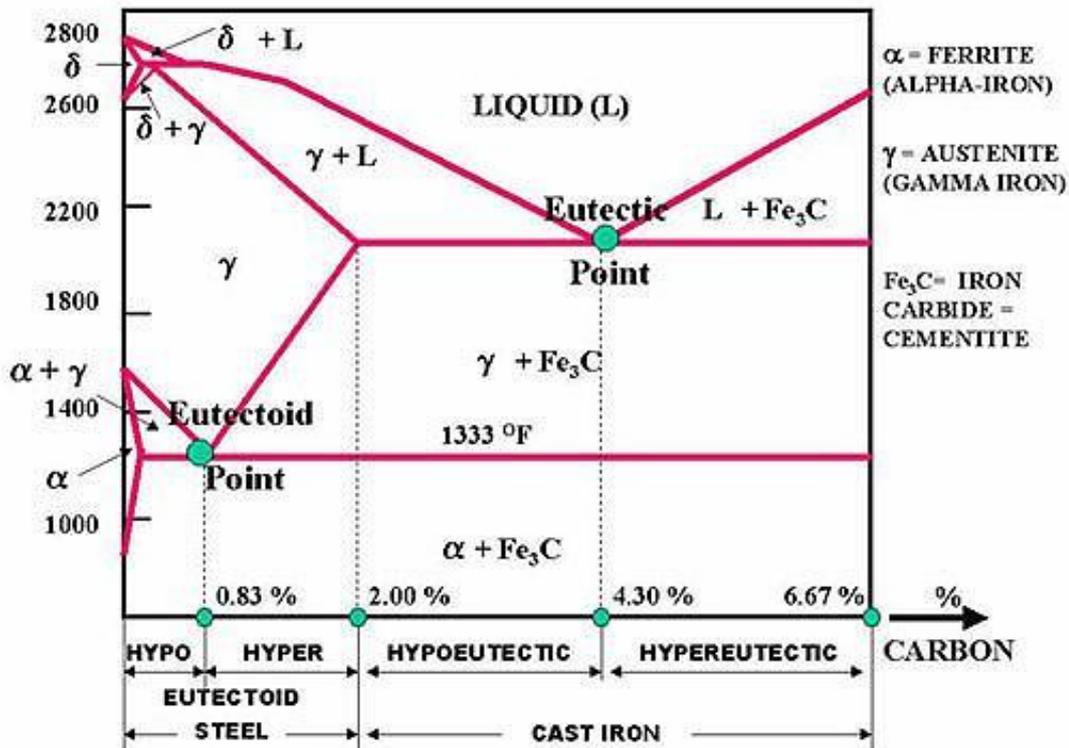
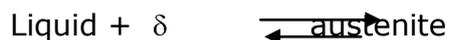


FIGURE 4.13 IRON-IRON CARBIDE EQUILIBRIUM DIAGRAM

The diagram shows three horizontal lines which indicate isothermal reactions. The figure has been labeled in general terms with Greek letters to represent the solid solutions. However, it is common practice to give special names to most of the structures that appear on the diagram. The γ solid solution is called *Austenite*. The portion of the diagram in the upper left hand corner is expanded in the figure shown below. This is known as Delta region because of the δ solid solution. The horizontal line at 2720 ° F represents a peritectic reaction. The equation of the reaction may be written as



The maximum solubility of carbon in b.c.c δ iron is 0.10 % (Point M), while in f.c.c γ iron, the solubility is much greater. The presence of carbon influences the δ to γ allotropic change. As carbon is added to iron, the temperature of allotropic change increases from 2554 ° F to 2720 ° F at 0.10 % Carbon.

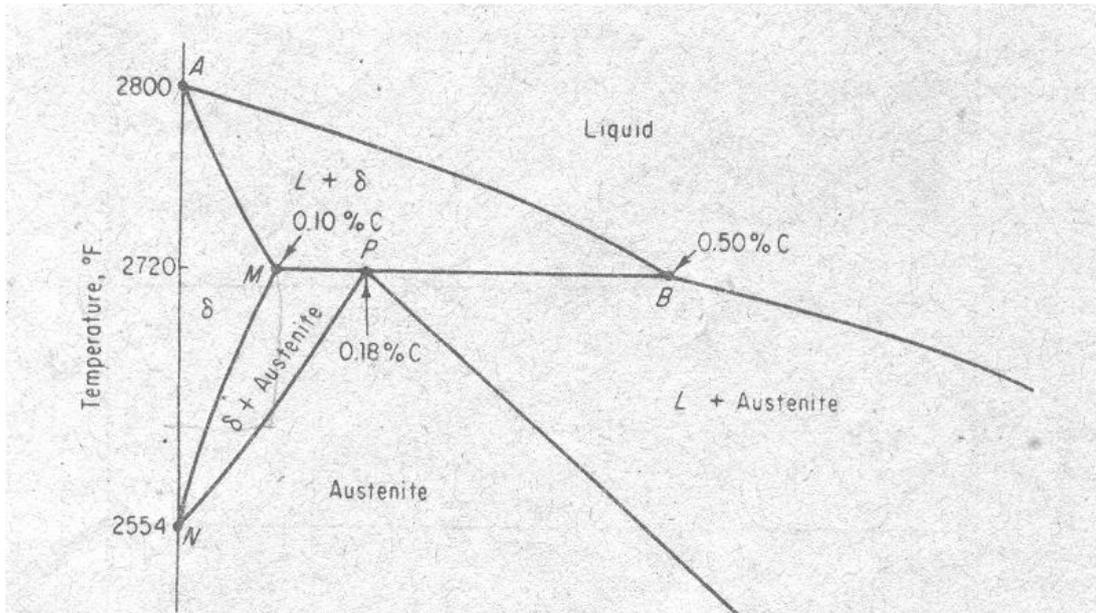


FIGURE 4.14 DELTA REGION OF IRON-IRON CARBIDE DIAGRAM

Consider the significance of the line NMPB. On cooling, the portion NM represents the beginning of the crystal structure change from b.c.c δ iron to f.c.c γ iron for alloying containing less than 0.10% C. The portion MP represents the beginning of this crystal structure change by means of a peritectic reaction for alloys between 0.10 and 0.18 % Carbon. For alloys containing less than 0.18 % C, on cooling, the end of the crystal structure change is given by the line NP. The portion PB represents the beginning and the end of the crystal structure change by means of a peritectic reaction. In other words, for alloys between 0.18 and 0.50 % C, the allotropic change begins and ends at a constant temperature. Notice that any alloy containing more than 0.50 % C will cut the diagram to the right of point B and will solidify austenite directly. The delta solid solution and the allotropic change will be completely by passed.

The diagram below, which has the common names inserted, shows a eutectic reaction at 2065 ° F. The Eutectic point, E is at 4.3 % C and 2065 ° F. Since the horizontal line CED represents the eutectic reaction, whenever an alloy crosses this line the reaction must take place. Any liquid that is present when this line is reached must now solidify into the very fine intimate mixture of the two phases that are at either end of the horizontal line, namely austenite and iron carbide (called *cementite*). This eutectic mixture has been given the name *ledeburite* and the equation may be written as



The eutectic mixture is not usually seen in the microstructure, since austenite is not stable at room temperature and must undergo another reaction during cooling.

There is a small solid solution area to the left of line GH. This area is a solid solution of a small amount of carbon dissolved in b.c.c α Fe and is called *Ferrite*. The diagram shows a third horizontal line HJK, which represents a Eutectoid reaction.

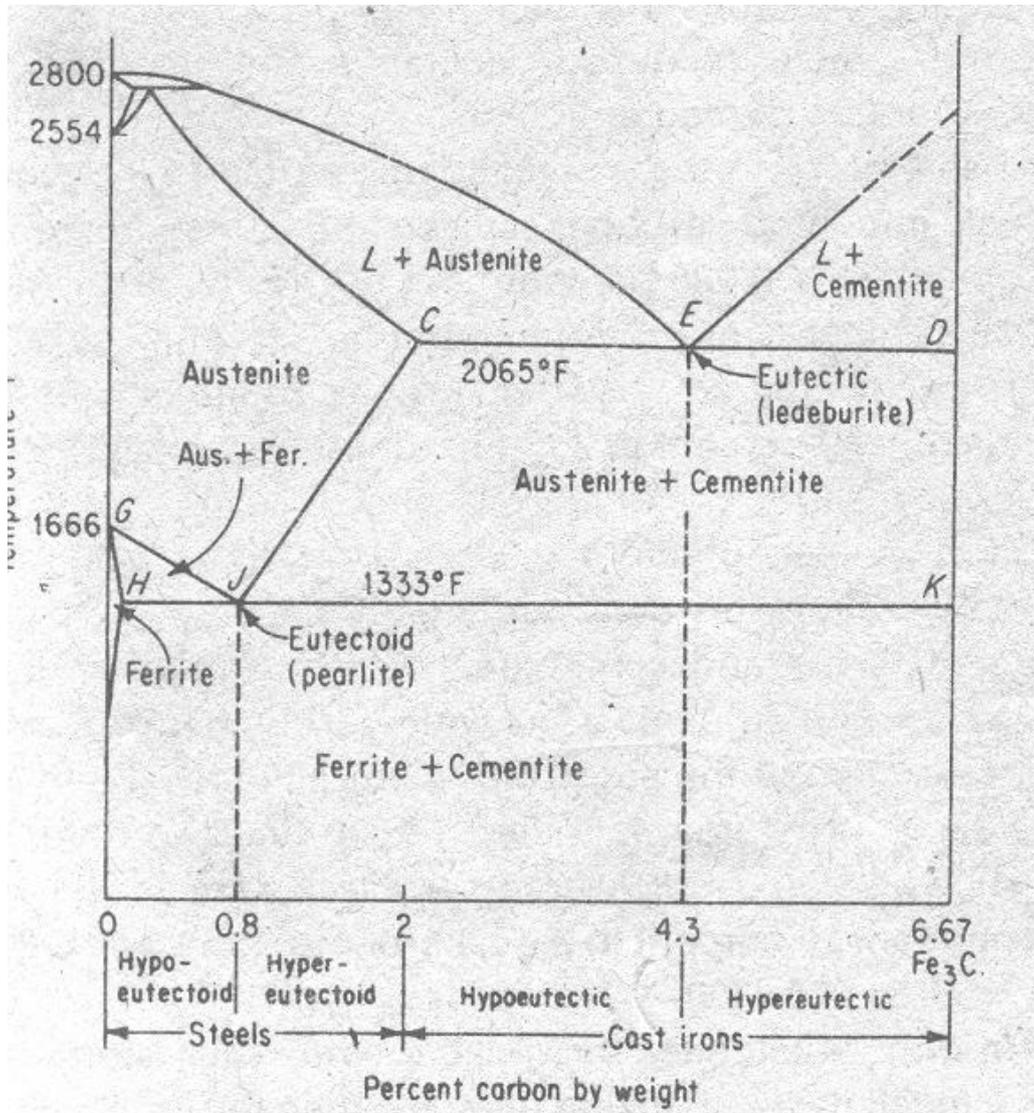


FIGURE 4.15 IRON-IRON CARBIDE DIAGRAM LABELED WITH COMMON NAMES FOR STRUCTURES

The eutectoid point, J, is at 0.80 % C and 1333 ° F. Any austenite present must now transform into the very fine eutectoid mixture of ferrite and cementite called *Pearlite*. The equation may be written as

Liquid \rightleftharpoons Ferrite + cementite (Eutectoid mixture- Pearlite)

Below the eutectoid temperature line every alloy will consist of a mixture of ferrite and cementite as indicated.

On the basis of carbon content it is common practice to divide the iron-iron carbide diagram into two parts. Those alloys containing less than 2 % carbon are known as steels, and those containing more than 2% are known as cast iron. The steel range is further subdivided by the eutectoid carbon content (0.8% C). Steels containing less than 0.8% C are called hypoeutectic steels, while those containing between 0.8 and 2% C are called hypereutectic steels. The cast iron range may also be subdivided by eutectic carbon content (4.3% C). Cast iron that contains less than 4.3% C are known as hypoeutectic cast irons, whereas those that contain more than 4.3% C are called hypereutectic cast iron.

4.5 c) DEFINITION OF STRUCTURES: - the names which, for descriptive or commemorative reasons, have been assigned to the structures appearing on this diagram will now be defined.

Cementite, or iron carbide, chemical formula Fe_3C contains 6.67% C by weight. It is a typical hard and brittle interstitial compound of low tensile strength (approx. 5000 psi) but high compressive strength. It is the hardest structure that appears on the diagram. Its crystal structure is orthorhombic.

Austenite is the name given to the γ solid solution. It is an interstitial solid solution of carbon dissolved in γ (f.c.c.) iron. Maximum solubility is 2% C at 2065 °F (point C). Average properties are tensile strength, 150,000psi; elongation, 10% in 2 in.; hardness, Rockwell C40, approx.; and toughness, high. It is normally not stable at room temperature. Under certain conditions it is possible to obtain austenite at room temperature, and its microstructure is shown in Fig (a).



FIGURE 4.16 (A) MICROSTRUCTURES OF AUSTENITE

Ledeburite is the eutectic mixture of austenite and cementite. It contains 4.3% C and is formed at 2065 °F.

Ferrite is the name given to a solid solution. It is an interstitial solution of a small amount of carbon dissolved in α (b.c.c.) iron. The maximum solubility is 0.025% C at 1333 °F (point H), and it dissolves only 0.008% C at room temperatures. It is the softest structure that appears on the diagram. Average properties are: tensile strength, 40,000psi; elongation, 40% in 2 in; hardness, less than Rockwell C 0 or less than Rockwell B90. Microstructure of ferrite is shown in Fig (b).

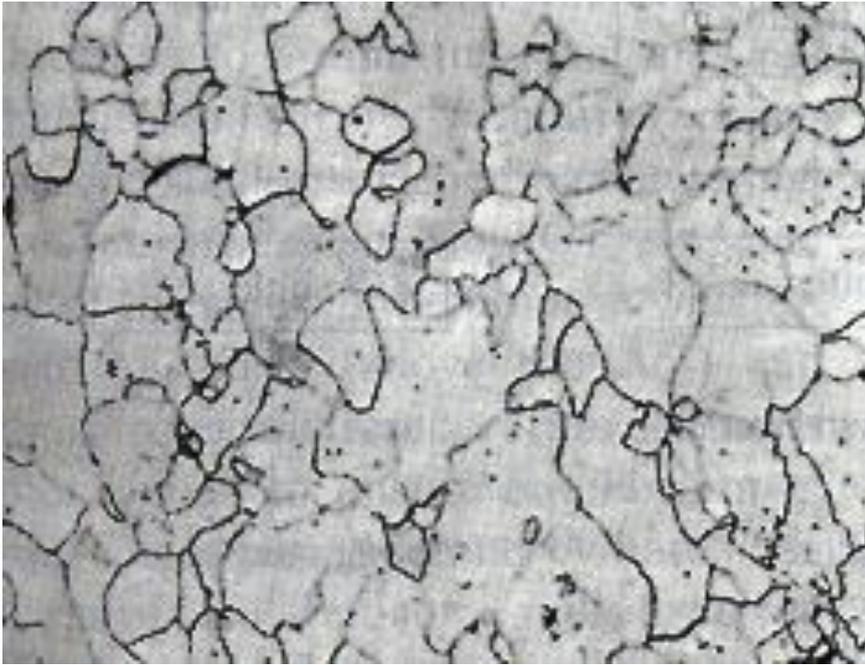


FIGURE 4.16 (B) MICROSTRUCTURES OF FERRITE

Pearlite (point j) is the eutectoid mixture containing 0.8% C and is formed at 1333 °F on very slow cooling. It is a very fine plate like or lamellar mixture of ferrite and cementite. The fine fingerprint mixture called Pearlite is shown in Fig (c). The white ferritic background or matrix which makes up most of the eutectoid mixture contains thin plates of cementite. Average properties are: tensile strength, 120,000psi; elongation, 20% in 2 in.; hardness, Rockwell C 20, Rockwell B 95-100, or BHN 250-300.

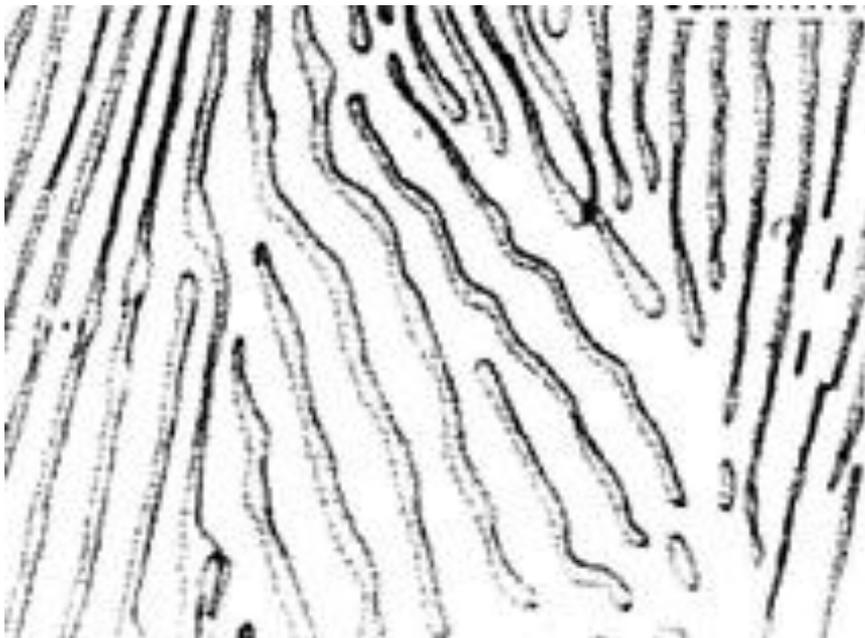


FIGURE 4.16 (C) MICROSTRUCTURES OF PEARLITE

4.5 d) SLOW COOLING OF STEEL:-

The steel portion of the iron-iron carbide diagram is of greatest interest, and the various changes that take place during the very slow cooling, from the austenite range, of several steels will be discussed.

Hypoeutectoid steel: -

Alloy 1 shown in figure below is a hypoeutectoid steel containing 0.20% carbon. in the austenite range, this alloy consists of a uniform interstitial solid solution. Each grain contains 0.20% carbon dissolved in the spaces of the f.c.c. iron lattice structure Fig (a).

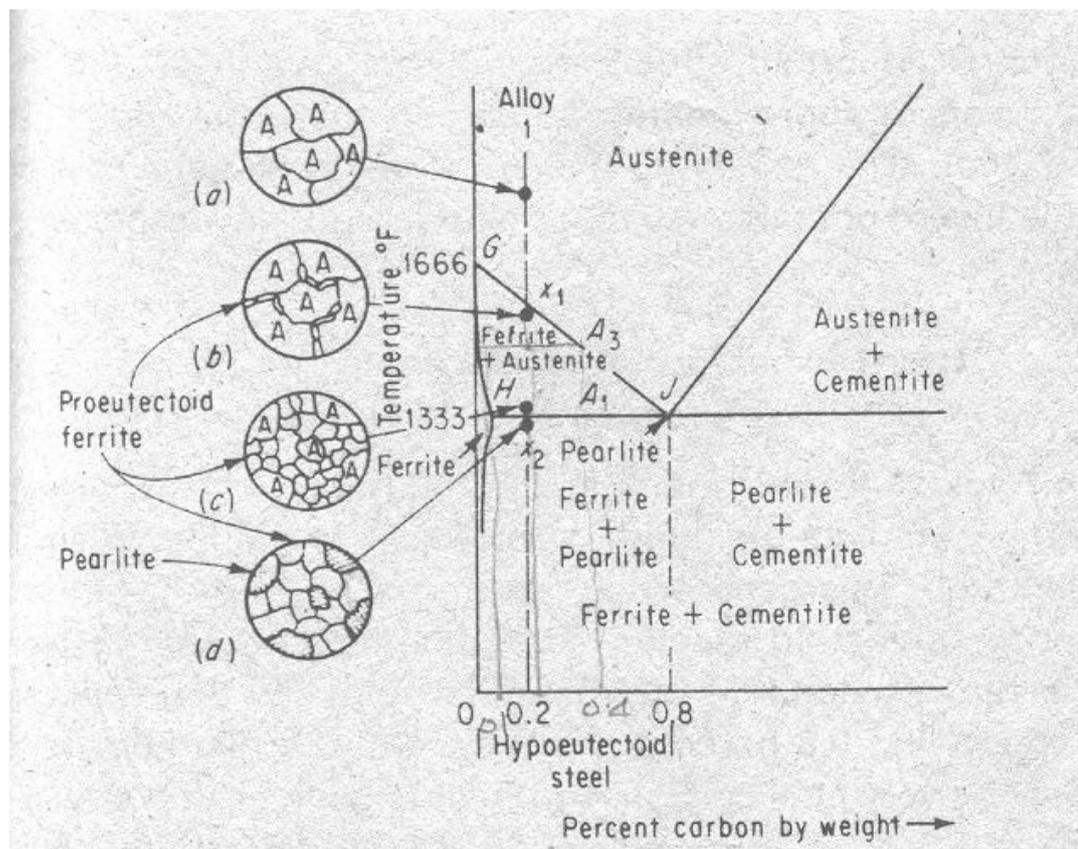


FIGURE 4.17 SLOW COOLING OF 0.2 % CARBON STEEL

Upon slow cooling, nothing happens until the line GJ is crossed at point x_1 . This line is known as the upper-critical-temperature line on the hypoeutectoid side and is labeled A_3 . The allotropic change from f.c.c. to b.c.c. iron takes place at 1666 °F for pure iron and decrease in temperature with increasing carbon content, as shown by the line A_3 . Therefore at x_1 , ferrite must begin to form at the austenite grain boundaries Fig (b). Since ferrite can dissolve very little carbon, in those

areas that are changing to ferrite the carbon must come out of solution before the atoms rearrange themselves to b.c.c. The carbon which comes out of solution is dissolved in remaining austenite, so that, as cooling progresses and the amount of ferrite increases, the remaining austenite becomes richer in carbon. Its carbon content is gradually moving down and to the right along the A_3 line. Finally the line HJ is reached at point x_2 . This line is known as the lower-critical-temperature line on the hypoeutectoid side and is labeled A_1 . The A_1 line is the eutectoid-temperature line and is the lowest temperature at which f.c.c. iron can exist under equilibrium conditions. Just above the A_1 line, the microstructure consists of approximately 25% austenite & 75% ferrite Fig (c). The remaining austenite, about 25% of the total material and containing 0.8% carbon, now experiences the eutectoid reaction.



Note that it is only austenite which is changing at the A_1 line. Therefore, when the reaction is complete the microstructure will show approximately 25% Pearlite and 75% ferrite Fig (d).

Since ferrite & Pearlite are stable structures, the microstructure remains substantially the same down to room temperature and consists of approximately 75% proeutectoid ferrite (formed between the A_3 and A_1 lines) and 25% Pearlite (formed from austenite at the A_1 line).

Hypereutectoid steel: -

Alloy 2 shown in Fig below is a hypereutectoid steel containing 1% carbon. In the austenite range, this alloy consists of a uniform f.c.c. solid solution with each grain containing 1% carbon dissolved interstitially Fig (a).

Upon slow cooling nothing happens until the line CJ is crossed at point x_3 . This line is known as the upper-critical-temperature line on the hypereutectoid side and is labeled A_{cm} . The A_{cm} line shows the maximum amount of carbon that can be dissolved in austenite as a function of temperature. Above the A_{cm} line, austenite is an unsaturated solid solution. At the A_{cm} line, point x_3 , the austenite is saturated in carbon.

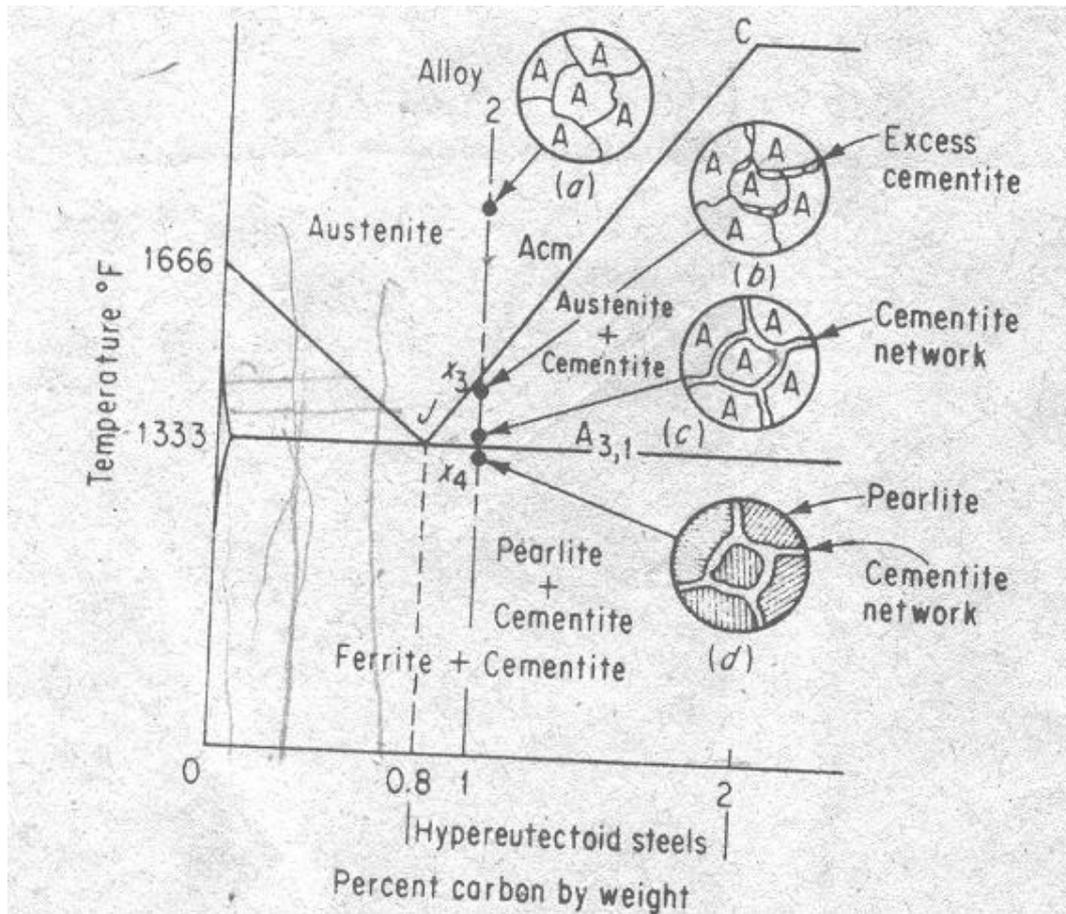


FIGURE 4.18 SLOW COOLING OF 1.0 % CARBON STEEL

As the temperature is decreased, the carbon content of the austenite, that is, the maximum amount of carbon that can be dissolved in austenite, moves down along the A_{cm} line towards point J. therefore, as the temperature decreases from x_3 to x_4 , the excess carbon above the amount required to saturate austenite is precipitated as cementite primarily along the grain boundaries Fig (b & c). Finally, the eutectoid-temperature line is reached at x_4 . This line is called lower-critical-temperature line on the hypereutectoid side and is labeled $A_{3,1}$. Just above the $A_{3,1}$ line the microstructure consists largely of austenite, with the excess proeutectoid cementite as a network surrounding the austenite grains Fig (c). The amount of cementite would be:

$$\% \text{ cementite} = (1.0 - 0.8) / (6.67 - 0.8) \times 100 = 3.4\%$$

and the amount of austenite would be:

$$\% \text{ austenite} = (6.67 - 1.0) / (6.67 - 0.8) \times 100 = 96.6\%$$

The $A_{3,1}$ line for hypereutectoid steels represents the beginning and the end of the allotropic change from f.c.c. austenite to b.c.c. ferrite. By the same process described earlier, the remaining austenite (containing 0.8% carbon) transforms to the eutectoid mixture, Pearlite. At room temperature the microstructure consists of 96.6% Pearlite (formed from austenite at the $A_{3,1}$ line) and a network of 3.4% proeutectoid cementite (formed between the A_{cm} and $A_{3,1}$ lines).

4.5 e) EFFECT OF SMALL QUANTITIES OF OTHER ELEMENTS: -

The previous discussion of the iron-iron carbide equilibrium diagram assumed that only iron and iron carbide were present. However, commercial plain carbon steels contains small quantities of other elements besides iron and carbon as part of the normal composition.

Sulfur: -

Sulfur in commercial steels is generally kept below 0.05%. Sulfur combines with iron to form iron sulfide (FeS). Iron sulfide forms a low melting point eutectic alloy with iron which tends to concentrate at the grain boundaries. When the steel is forged or rolled at elevated temperatures, the steel becomes brittle, or hot-short, due to the melting of the iron sulfide eutectic which destroys the cohesion between grains, allowing cracks to develop. In the presence of manganese, sulfur tends to form manganese-sulfide (MnS) rather than iron sulfide, the manganese sulfide may pass out in the slag or remains as well distributed inclusions through out the structure. It is recommended that the amount of manganese be 2 to 8 times the amount of sulfur. In the free-machining steels, the sulfur content is increased to between 0.08 and 0.35%. The improvement in machinability is due to the presence of more numerous sulfide inclusions which break up the chips, thus reducing tool wear.

Manganese: -

It is present in all commercial plain carbon steels, in the range of 0.03 to 1.00%. The function of manganese in counteracting the ill effects of sulfur was just pointed out. When there is more manganese present than required to form MnS , the excess combines with some of the carbon to form the compound Mn_3C which is found associated with the iron carbide, Fe_3C , in cementite. Manganese also promotes the surrounding of steel casting through its deoxidizing action on liquid steel.

Phosphorus: -

The phosphorus content is generally kept below 0.04%. This small quantity tends to dissolve in ferrite, increasing the strength and hardness slightly. In some steels 0.07 to 0.12% phosphorus seems to improve cutting properties. In larger quantities, phosphorus reduces ductility, thereby increasing the tendency of steel to crack when cold worked, making it cold short.

Silicon: -

Most commercial steel contains between 0.05 and 0.3% silicon. Silicon dissolves in ferrite, increasing the strength of the steel without greatly decreasing the ductility. It promotes the deoxidation of molten steel through the formation of silicon dioxide, SiO_2 , thus tending to make for greater soundness in casting.

4.6 HEAT TREATMENT OF STEEL AND CASE HARDENING: -**4.6 a) INTRODUCTION TO HEAT TREATMENT: -**

The definition of heat treatment as given in the *Metals handbook* is "A combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties."

All basic heat treatment processes for steel involve the transformation or decomposition of austenite. The nature and appearance of these transformation products determine the physical and mechanical properties of any given steel.

The first step in the heat treatment of steel is to heat the material to some temperature in or above the critical range in order to form austenite. In most cases, the rate of heating to the desired temperature is less important than other factors in the heat-treating cycle. Highly stressed materials produced by cold working should be heated more slowly than stress-free materials to avoid distortion. Usually less overall damage will be done to the steel by utilizing as slow a heating rate as is practical.

4.6 b) FULL ANNEALING: -

This process consists in heating the steel to the proper temperature and then cooling slowly through the transformation range, preferably in the furnace or in any good heat-insulating material. The slow cooling is generally continued to low temperatures.

The purpose of annealing may be to refine the grain, induce softness, improve electrical and magnetic properties and in some cases to improve machinability. Since the entire mass of the furnace must be cooled down along with the material, annealing is a very slow cooling process and therefore comes closest to following the iron-iron carbide equilibrium diagram.

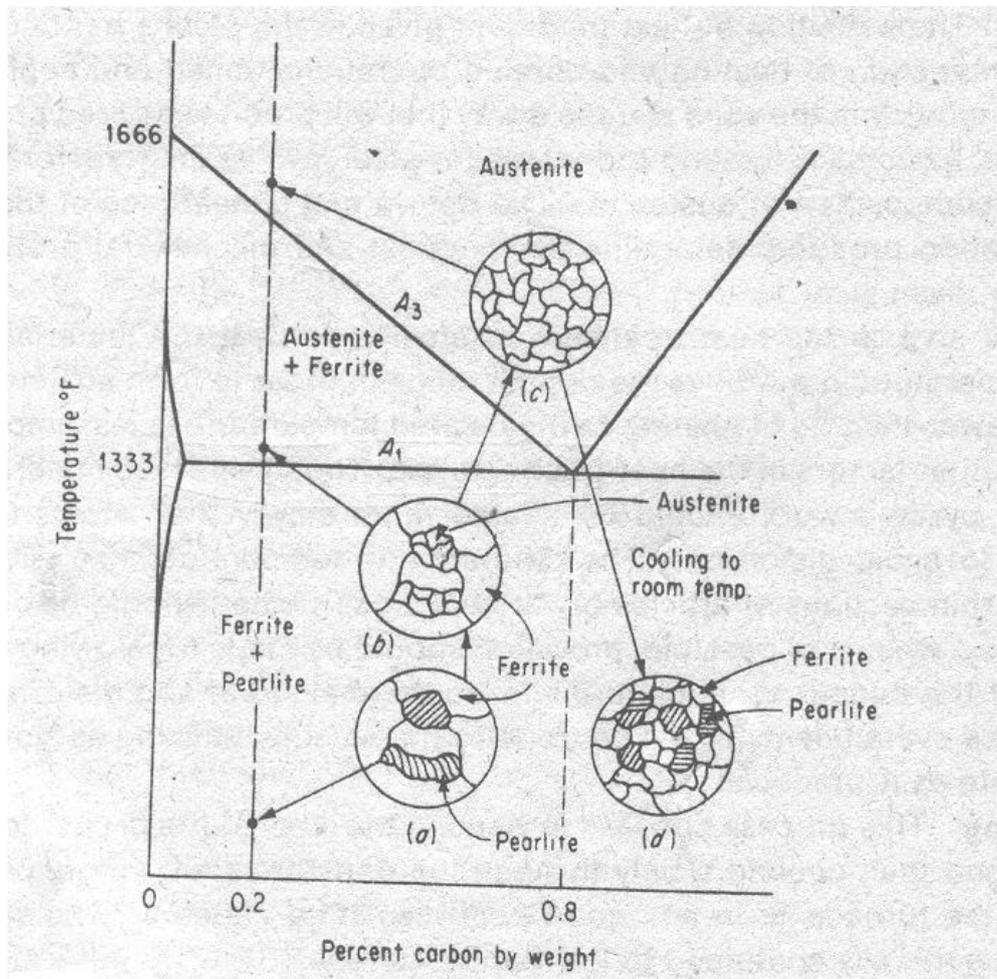


FIGURE 4.19 CHANGES IN MICROSTRUCTURE DURING ANNEALING OF 0.2 % CARBON STEEL

Assume that we have a coarse-grained 0.20 % C (hypoeutectoid) steel and that it is desired to refine the grain size by annealing. The microstructure is shown below in Fig (a). When this steel is heated, no change will occur until the A₁ (lower-critical) line is crossed. At that temperature the pearlite areas will transform to small grains of austenite by means of the eutectoid reaction, but the original large ferrite grains will remain unchanged Fig (b). Cooling from this temperature will not refine the grain. Continued heating between the A₁ and A₃ lines will allow the large ferrite grains to transform to small grains of austenite, so that above the A₃ (upper critical) line, the entire microstructure will show only small grains of austenite (Fig c). Subsequent furnace cooling will result in small grains of proeutectoid ferrite and small areas of coarse lamellar pearlite

(Fig d). Therefore the proper annealing temperature for hypoeutectoid steels is approximately 50 ° F above the A_3 line. Refinement of the grain size of hypereutectoid steel will occur about 50 ° F above the lower critical temperature ($A_{3,1}$) line. Heating above this temperature will coarsen the austenitic grains, which, on cooling, will transform to large pearlitic areas. The microstructure of annealed hypereutectoid steel will consist of coarse lamellar pearlite areas surrounded by a network of proeutectoid cementite.

Because this excess cementite network is brittle and tends to be a plane of weakness, annealing should never be a final heat treatment for hypereutectoid steels. The presence of a thick, hard, grain boundary will also result in poor machinability.

4.6 c) SPHEROIDIZING: -

Annealed hypereutectoid steel with a microstructure of pearlite and a cementite network will generally give poor machinability. Since cementite is hard and brittle, the cutting tool cannot cut through these plates. Instead, the plates have to be broken. Therefore, the tool is subjected to continual shock load by the cementite plates and a ragged surface finish results. A heat treatment which improves the machinability of such alloy of steel is known as *Spheroidize Annealing*. The process produces a spheroidal or globular form of carbide in a ferritic matrix. One of the following methods may be used.

1. Prolonged holding at a temperature just below the lower critical line.
2. Heating and cooling alternately between temperatures that is just above and just below the lower critical line.
3. Heating to a temperature above the lower critical line and then either cooling very slowly in the furnace or holding at a temperature just below the lower critical line.

Prolonged time at the elevated temperature will completely break up the pearlitic structure and cementite network. The cementite will become spheres, which is the geometric shape in greatest equilibrium with its surroundings. The cementite particles and the entire structure may be called *Spheroidite*. The spheroidized structure is desirable when minimum hardness, maximum ductility or maximum machinability is important. Low carbon steels are seldom spheroidized for machining, because in the spheroidized condition they are excessively soft and gummy. The cutting tool will tend to push the material rather than cut it, causing excessive heat and wear on the cutting tip. Medium carbon steels are sometimes spheroidize-annealed to obtain maximum ductility for certain working

operations. If the steel is kept too long at the spheroidize-annealing temperature, the cementite particles will coalesce (join) and become elongated thus reducing machinability.

4.6 d) STRESS-RELIEF ANNEALING: -

This process, sometimes called *subcritical annealing*, is useful in removing residual stresses due to heavy machining or other cold working processes. It is usually carried out at temperatures below lower critical line (1000 to 1200 ° F)

4.6 e) PROCESS ANNEALING: -

This heat treatment is used in the sheet and wire industries and is carried out by heating the steel to a temperature below the lower critical line. It is applied after cold working and softens the steel, by crystallization, for further working. It is very much similar to stress-relief annealing.

4.6 f) NORMALIZING: -

The normalizing of steel is carried out by heating approximately 100 ° F above the upper critical temperature (A_3 or A_{cm}) line followed by cooling in still air to room temperature. The temperature range for normalizing is shown below.

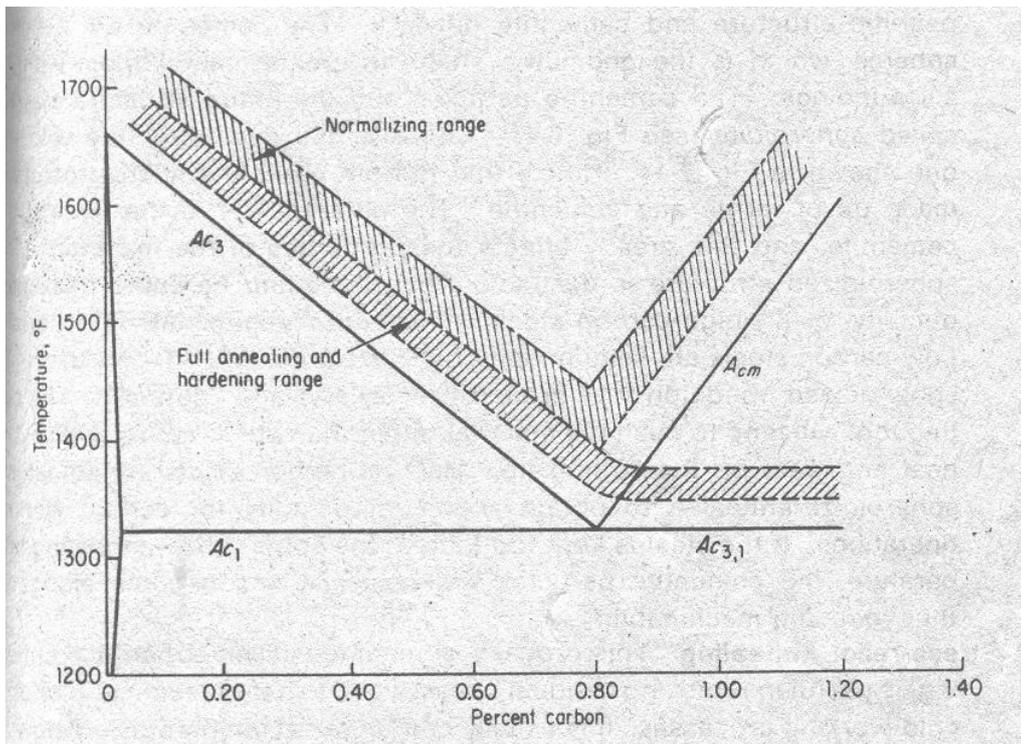


FIGURE 4.20 ANNEALING, NORMALIZING AND HARDENING RANGE FOR PLAIN CARBON STEELS

The purpose of normalizing is to produce harder and stronger steel than full annealing so that for some applications normalizing may be the final treatment. Normalizing may also be used to improve machinability, modify and refine cast dendritic structures and refine the grains and homogenize the microstructure in order to improve the response in hardening operations. The increase in cooling rate due to air cooling as compared with furnace cooling affects the transformation of austenite and the resultant microstructure in several ways. Since we are no longer cooling under equilibrium conditions, the iron-iron carbide diagram cannot be used to predict the proportions of proeutectoid ferrite and pearlite or proeutectoid cementite and pearlite that will exist at room temperature. There is less time for the production of proeutectoid constituent; consequently there will be less proeutectoid ferrite in normalized hypoeutectoid steels and less proeutectoid cementite in hypereutectoid steels as compared with annealed ones. Since it was the presence of cementite network which reduced the strength of annealed hypereutectoid steels, normalized steels should show an increase in strength.

In general, the faster cooling rate, the lower the temperature of austenite transformation and the finer the pearlite. The difference in spacing of the cementite plates in the pearlite between annealing and normalizing is shown in Fig below.

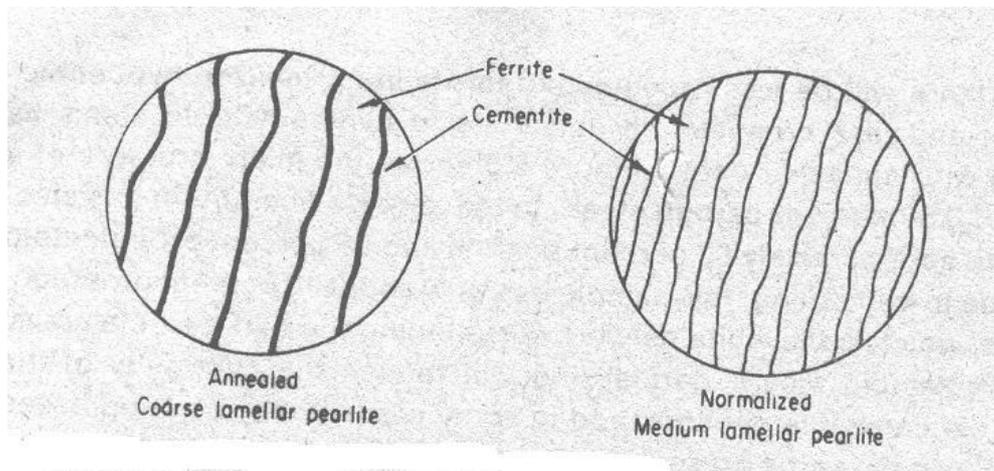


FIGURE 4.21 DIFFERENCE IN PEARLITIC STRUCTURE DUE TO ANNEALING AND NORMALIZING

Ferrite is very soft, while cementite is very hard. With the cementite plates closer together in the case of normalized medium pearlite, they tend to stiffen the ferrite so it will not yield as easily, thus increasing hardness.

4.6 g) HARDENING / QUENCHING: -

Under slow or moderate cooling rates, the carbon atoms are able to diffuse out of the austenite structure. The iron atoms then move slightly to become b.c.c. This gamma to alpha transformation takes place by a process of nucleation and growth and is time-dependent. With a still further increase in cooling rate, insufficient time is allowed for the carbon to diffuse out of solution, and although some movement of the iron takes place, the structure can not become b.c.c. while the carbon is trapped in solution. The resultant structure, called martensite, is a supersaturated solid solution of carbon trapped in a body-centered tetragonal structure. This highly distorted lattice structure is the prime reason for the high hardness of martensite. Since the atoms of martensite are less densely packed than in austenite, an expansion occurs during the transformation. This expansion during the formation of martensite produces high localized stresses which result in plastic deformation of the matrix. After drastic cooling (quenching), martensite appears microscopically as a white needle like or articular structure sometimes described as a pile of straw.

There are several important characteristics of the martensite transformation:

The transformation is diffusionless, and there is no change in chemical composition.

The transformation proceeds only during cooling and ceases if cooling is interrupted. Therefore, the transformation depends only upon the decrease in temperature and is independent of time.

The martensite transformation of a given alloy cannot be suppressed. The transformation range of the formation of martensite is characteristic of a given alloy and cannot be lowered by increasing the cooling rate.

Martensite is probably never in a condition of real equilibrium, although it may persist indefinitely at or near room temperature.

The most significant property of the martensite is its potential of very great hardness. Although martensite is always harder than the austenite from which it forms, extreme hardness is achieved only in steels that contain sufficient carbon. The high hardness of martensite is believed to be a result of the severe lattice distortions produced by its formation, since the amount of carbon present is many times more than can be held in solid solution. The maximum hardness obtainable from a steel in the martensitic condition seems to be a function of carbon content only.

Quenching Medium: -

The following industrial quenching media are listed in order of decreasing quenching severity.

Water solution of 10% NaCl (Brine)

Tap water

Fused or liquid salts

Soluble oil and water solutions

Oil

Air

4.6 h) TEMPERING: -

In the as-quenched martensitic condition, the steel is too brittle for most applications. The formation of martensite also leaves higher residual stresses in the steel. Therefore, hardening is almost always followed by tempering, which consists in heating the steel to some temperature below the lower critical temperature. The purpose of tempering is to relieve residual stresses and to improve the ductility and toughness of the steel. This increase in ductility is usually attained at the sacrifice of the hardness or strength.

In general, over the broad range of tempering temperatures, hardness decreases and toughness increases as the tempering temperature is increased.

The tempering range of 400-800 ° F is a dividing line between applications that require high hardness and those requiring high toughness. If the principal desired property is hardness or wear resistance, the part is tempered below 400 ° F; if the primary requirement is toughness, the part is tempered above 800 ° F. If the part does not have any "stress raisers" or notches, the change in ductility may be a better indication of toughness than the notched-bar test, and tempering in the range of 400-800 ° F may not be detrimental.

Residual stresses are relieved to a large extent when the tempering temperature reaches 400 ° F, and by 900 ° F they are almost completely gone.

Certain alloy steels exhibit a phenomenon known as temper brittleness, which is a loss of notched-bar toughness when tempered in the range of 1000-1250 ° F followed by relatively slow cooling. Toughness is maintained, however, if the part is quenched in water from the tempering temperature. The precise mechanism which causes temper brittleness has not been established, although the behavior suggests some phase which precipitates along the grain boundaries during slow cooling. High manganese, phosphorus and chromium appear to promote susceptibility, while molybdenum seems to have a definite retarding effect.

4.6 i) SURFACE HEAT TREATMENT OR CASE HARDENING: -

Numerous industrial applications require a hard wear-resistant surface called the case, and a relatively soft, tough inside called the core. The method by which this change in hardness at case and core is achieved is called Surface Heat Treatment or Case Hardening.

There are five principal methods of case hardening.

Carburizing

Nitriding

Cyaniding or Carbonitriding

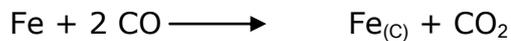
Flame Hardening

Induction Hardening

The first three methods change the chemical composition, carburizing by the addition of carbon, Nitriding by the addition of nitrogen and cyaniding by the addition of both carbon and nitrogen. The last two methods do not change the chemical composition of the steel and are essentially shallow-hardening methods. In flame and induction hardening, the steel must be capable of being hardened; therefore, the carbon content must be about 0.30 % or higher.

4.6 j) CARBURIZING: -

This is the oldest and one of the cheapest methods of case hardening. A low carbon steel usually about 0.20 % carbon or lower is placed in an atmosphere that contains substantial amount of carbon monoxide. The usual carburizing temperature is 1700 ° F. At this temperature the following reaction takes place.



Where $\text{Fe}_{(\text{C})}$ represents carbon dissolved in austenite. As a result a surface layer of high carbon (about 1.2 %) is built up very quickly. Since the core is of low carbon content, the carbon atoms trying to reach equilibrium will begin to diffuse inwards. After diffusion has taken place for the required amount of time depending upon the case depth desired, the part is removed from the furnace and cooled. If the part is furnace-cooled and examined microscopically, the carbon gradient will be visible in the gradual change in the structure. The case depth may be measure microscopically with a micrometer eyepiece. The carburizing equation given previously,



is reversible and may proceed to the left, removing carbon from the surface layer if the steel is heated in an atmosphere containing carbon dioxide. This is called *decarburization*.

Decarburization is a problem primarily with high carbon steels and tool steels. The surface, depleted of carbon, will not transform to martensite on subsequent hardening, and the steel will be left with a soft skin. Decarburization may be prevented by using an endothermic gas atmosphere in the furnace to protect the surface of the steel from oxygen, carbon dioxide and water vapours.

Commercial carburizing may be accomplished by means of *packed carburizing*, *gas carburizing* and *liquid carburizing*.

In **packed carburizing**; the work is surrounded by a carburizing compound in a closed container. The container is heated to the proper temperature for the required amount of time and then slow cooled. This is essentially a batch method and does not lend itself to high production. Commercial carburizing compounds usually consists of hard wood charcoal, coke and about 20 % of

barium carbonate as an energizer. The carburizing compound is in the form of coarse particles or lumps so that, when the cover is sealed on the container, sufficient air will be trapped inside to form carbon monoxide. The principal advantages of packed carburizing are that it does not the use of prepared atmosphere and that is efficient and economical for individual processing of small lots of parts or of large, massive parts. The disadvantages are that it is not well suited to the production of thin carburized cases that must be controlled to close tolerances; it cannot provide the close control of surface carbon that can be obtained by gas carburizing; parts cannot be direct-quenched from the carburizing temperature; an excessive time is consumed in heating and cooling the charge.

Gas carburizing

may be either batch or continuous and lends itself better to production heat treatment. The steel is heated in contact with carbon monoxide and / or a hydrocarbon which is readily decomposed at the carburizing temperature. The hydrocarbon may be methane, propane, natural gas or vaporized fluid hydrocarbon.

By using a diffusion period, during which the gas is turned off but the temperature maintained, gas carburizing allows the surface carbon to be reduced to any desired value. Use of diffusion period also produces much cleaner work by dissipation of carbon deposit (soot) during the time when no gas is flowing. Gas carburizing allows quicker handling by direct quenching, lower cost, cleaner surroundings, closer quality control and greater flexibility of operation in comparison with packed carburizing.

Liquid carburizing

is a method of case-hardening steel by placing it in a bath of molten cyanide so that carbon will diffuse from the bath into the metal and produce a case comparable to one resulting from pack or gas carburizing. Liquid carburizing may be distinguished from cyaniding by the character and composition of the case produced. The cyanide case is higher in nitrogen and lower in carbon; the reverse is true of liquid carburized cases.

In general, liquid carburizing is best suited to small and medium sized parts, since large parts are difficult to process in salt baths.

The advantages of liquid carburizing are:

Freedom from oxidation and sooting problems

Uniform case depth and carbon content

A rapid rate of penetration

The fact that the bath provides high thermal conductivity thereby reducing the time required for the steel to reach the carburizing temperature.

The disadvantages are:

Parts must be thoroughly washed after treatment to prevent rusting

Regular checking and adjustment of the bath composition is necessary to obtain uniform case depth

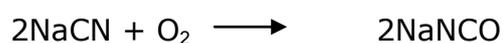
Some shapes cannot be handled because they either float or will cause excessive drag out of salt.

Cyanide salts are poisonous and require careful attention to safety.

4.6 k) CYANIDING & CARBONITRIDING: -

Cases that contain both carbon and nitrogen are produced in liquid salt baths (cyaniding) or by use of gas atmospheres (Carbonitriding). The temperatures used are generally lower than those used in carburizing, being between 1400 - 1600 ° F. Exposure is for a shorter time and thinner cases are produced, up to 0.010 inches for cyaniding and up to 0.030 inches for Carbonitriding.

In cyaniding, the proportion of nitrogen and carbon in the case produced by a cyanide bath depends on both composition and temperature of the bath, the latter being the most important. Several mixtures of cyanide are available for the bath. Although the baths of higher sodium cyanide concentrations are employed, the most commonly used mixture is made up of 30 % sodium cyanide, 40 % sodium carbonate and 30 % sodium chloride. This mixture has a melting point of 1140 ° F and remains quite stable under continuous operating conditions. The active hardening agents of cyaniding baths, carbon and nitrogen, are not produced directly from sodium cyanide (NaCN). Molten cyanide decomposes in the presence of air at the surface of the bath to produce sodium cyanate (NaNCO), which in turns decomposes as follows:





The carbon content of the case developed in the cyanide bath increases with an increase in the cyanide concentration of the bath, thus providing considerable flexibility.

Carbonitriding is a case-hardening process in which a steel is heated in a gaseous atmosphere of such composition that carbon and nitrogen are absorbed simultaneously. The process is also known as *dry cyaniding*, *gas cyaniding* and *nicarbing*. The atmospheres used in carbonitriding generally comprise a mixture of carrier gas, enriching gas and ammonia. The carrier gas is usually a mixture of nitrogen, hydrogen and carbon monoxide. The enriching gas is usually propane or natural gas and is the primary source for the carbon added to the surface. At the furnace temperature the added ammonia breaks up or dissociates to provide the nitrogen to the surface of the steel.

4.6 I) NITRIDING: -

This is a process for case hardening of alloy steel in an atmosphere consisting of a mixture in suitable proportions of ammonia gas and dissociated ammonia. The effectiveness of the process depends on the formation of nitrides in the steel by reaction of nitrogen with certain alloying elements. Although at suitable temperatures and with the proper atmospheres all steels are capable of forming iron nitrides, the best results are obtained in those steels that contain one or more of the major nitride-forming alloying elements. These are aluminum, chromium and molybdenum. The nitrogen must be supplied in the atomic or nascent form; molecular nitrogen will not react.

The parts to be nitrided are placed in an air tight container through which the Nitriding atmosphere is supplied continuously while the temperature is raised and held between 925 – 1050 ° F. The Nitriding cycle is quite long, depending upon the case depth desired. A 60-h cycle will give a case depth of approximately 0.024 inches at 975 ° F.

Since Nitriding is performed at relatively low temperatures and no quenching is required, distortion is reduced to a minimum, although some growth does occur due to the increase in volume of the case. However, this growth is constant and predictable for a given part and cycle, so that in most cases parts may be machined very close to final dimensions before Nitriding. This is an advantage of Nitriding over carburizing. Some complex parts which can not be case-hardened satisfactorily by carburizing have been nitrided without difficulty. Water

resistance is an outstanding characteristic of the nitrided cases and is responsible for its selection in most applications. The hardness of a nitrided case is unaffected by heating to temperatures below the original Nitriding temperature. Substantial hardness is retained to at least 1150 ° F, in marked contrast with a carburized case, which begins to lose its hardness at relatively low temperatures. Fatigue resistance is also an important advantage. Tool marks and surface scratches have little effect on the fatigue properties of nitrided steels. Disadvantages of nitriding include the long cycles usually required, the brittle case, use of special alloy steels if maximum hardness is to be obtained, cost of ammonia atmosphere, and the technical control required. Nitriding is used extensively for air craft engine parts such as cams, cylinder liners, valve stems, shafts, and piston rods.

4.6 n) FLAME HARDENING:-

Flame hardening does not change the chemical composition of the steel. It is essentially a shallow hardening method. Selected areas of the surface of a steel are heated into the austenite range and then quenched to form martensite. Therefore, it is necessary to start with a steel which is capable of being hardened. Generally this is in the range of 0.30 – 0.60 % Carbon.

In flame hardening, heat may be applied by a single oxyacetylene torch. Depth of the hardened zone may be controlled by an adjustment of the flame intensity, heating time or speed of travel. Skill is required in adjusting and handling manually operated equipment to avoid over heating the work because of high flame temperature. Over heating can result in cracking after quenching and excessive grain growth in the region just below the hardened zone.

Four methods are in general use for flame hardening:

Stationary

Progressive

Spinning

Progressive-Spinning

In the first, both torch and work are stationary. This method is used for the spot hardening of small parts such as valve stems and open end wrenches.

In the progressive method, the torch moves over a stationary work piece; this is used for hardening of large parts, such as the way of a lathe, but is also adoptable to the treatment of teeth of large gears.

In the spinning method, the torch is stationary while the work rotates. This method is used to harden parts of circular cross section, such as precision gears, pulleys and similar components.

The progressive-spinning method, in which the torch moves over a rotated work piece, is used to surface-harden long circular parts such as shafts and rolls.

In all procedures, provision must be made for rapid quenching after the surface has been heated to the required temperature. This may be accomplished by the use of water sprays, by quenching the entire piece in water or oil, or even by air-cooling for some steels. After quenching the part should be stressed-relieved by heating in the range of 350 -400 ° F and air cooled. Such a treatment does not appreciably reduced surface hardness. The hardened zone is generally much deeper than that obtained by carburizing, ranging from 1/8 to 1/4 inches in depth. Thinner cases of the order of 1/16 inches can be obtained by increasing the speed of heating and quenching.

Among the advantages of flame hardening are adoptability and portability. The equipment can be taken to the job and adjusted to treat only the area which requires hardening. Parts too large to be placed in a furnace can be handled easily and quickly with the torch. Another advantage is the ability to treat components after surface finishing, since there is little scaling, decarburization or distortion. Disadvantages include the possibility of over heating and thus damaging the part and difficulty in producing hardened zones less than 1/16 inches in depth.

4.6 o) INDUCTION HARDENING: -

Induction hardening depends for its operation on localized heating produced by currents induced in a metal placed in a rapidly changing magnetic field. The operation resembles a transformer in which the primary or work coil is composed of several turns of copper tubing that are water cooled and the part to be hardened is made the secondary of a high-frequency induction apparatus. When high-frequency alternating current passes through the work coil, a high frequency magnetic field is set up. This magnetic field induces high frequency eddy currents and hysteresis currents in the metal. Heating results from the resistance of the metal to the flow of these currents. The high frequency induced currents tend to travel at the surface of the metal. This is known as *skin effect*. Therefore it is possible to heat a shallow layer of the steel without heating the interior. However, heat applied to the surface tends to flow towards the center by conduction, so time of heating is an important factor in controlling the depth of the hardened zone. The surface layer is heated instantaneously to a depth which is inversely proportional to the square

root of the frequency. The range of frequencies commonly used is between 10,000 and 500,000 Hz. Greater case depths may be obtained at each frequency by increasing the time of heating.

As in flame hardening, provision must be made for rapid quenching of the part after it has reached the desired temperature. The case obtained by induction heating is similar to that obtained by flame hardening and thinner cases are possible. The steels used are similar to those used for flame hardening. Plain-carbon steels of medium carbon content are used for most applications, particularly for the production of thin cases. The carbon dissolves completely even in the short time required to heat the steel to the quenching temperature. Alloy steels can also be induction-hardened and are needed particularly for deep cases. Low alloy steels are more readily surface-hardened by this method, but highly alloyed steels are more sluggish and may require an increase in temperature to achieve the desired structure for satisfactory hardening.

Steel parts that have been surface-hardened by induction generally exhibit less total distortion than the same parts quenched from a furnace. Another advantage of induction hardening is the ability to fit the equipment directly into the production line and use relatively less skilled labor since the operation is practically automatic. Typical parts that have been induction-hardened are piston rods, pump shafts, spur gears and cams.

Among disadvantages are the cost of the equipment, the fact that small quantities or irregular-shaped parts cannot be handled economically and high maintenance cost.

4.7 CLASSIFICATION OF STEELS: -

A wide variety of steels are in common use today and many of them are sold under trade names. As a result, their identification becomes difficult. All steels may be classified according to:

- 1) Kind
- 2) Class
- 3) Grade

4.7 a) CLASSIFICATION W.R.T. KIND: -

The method by which the steel is produced determines its kind. The five distinctly different kinds of steel most commonly produced are listed below:

- Basic open-hearth
- Electric furnace

- Basic oxygen process
- Acid Bessemer
- Acid open hearth

Basic open-hearth steels are further classified as *Killed* or *Rimmed*, depending upon the degree of degasification at the time of solidification.

Killed steels are those which have been completely deoxidized in the refining process and in which there is no gas evolution upon solidification.

Rimmed steels are those in which deoxidation is only partially completed upon pouring in to the ingot mould.

4.7 b) CLASSIFICATION W.R.T CLASS: -

Steel may be classified according to form and use. In the broad sense, the form may be either cast or wrought. Steel products may originate in semi finished form either as a steel casting or as a wrought shape, such as a bar, billet, rod, plate, sheet, forging etc produced by any hot-working process. Several typical commercial classes of steel are available. Most important ones are listed below:

- Boiler Steel: - Steels that are particularly suited for the construction of boilers and accessories.
- Corrosion and Heat Resistant Steel: - Steels that are particularly suitable for applications under corrosive or high temperature conditions
- Deep-Drawing Steel: - Steels that are principally used for forming into automobile bodies and fenders, refrigerators, stoves etc.
- Forging Steel: - Any steel that is particularly well adapted for hot-working operations such as in forging, pressing etc.
- Free-Cutting Steel: - Steels that are readily machinable and used for high-rate production.
- Machinery Steel: -Steels used for manufacture of automotive and machinery parts.
- Pipe and Welding Steel: - Very soft steels which are particularly suited for the production of welded pipe, usually of a low carbon content.
- Spring Steel: - Steels employed in the manufacture of springs of all types.
- Structural Steel: - Steels used in the construction of ships, car, buildings, bridges etc
- Tool Steel: - Steels employed principally for the machining of metals.

4.7 c) CLASSIFICATION W.R.T GRADE: -

A more specific classification of steels is found under the term grade, which refers to the composition of the steel. These classifications are as follows:

- Plain Carbon Steels
- Alloy Steels
- Stainless Steels
- Tool Steels

4.7 d) PLAIN CARBON STEEL: -

It includes those steels in which the properties are primarily derived from the presence of carbon. Other elements, such as manganese, silicon, phosphorus and sulphur may be present in relatively small amounts, but their purpose is not principally that of modifying the mechanical properties of the steel. The carbon content of this grade may vary in composition from traces to 1.7 %, although rarely over 1.3 %. The plain carbon steels may be further sub divided according to carbon content as follows:

- Low Carbon Steels: containing up to 0.30 % carbon
- Medium Carbon Steel: - containing from 0.30 to 0.60 % carbon
- High Carbon Steel: - containing from 0.60 to 1.3 % carbon

Plain carbon steels containing more than 1.3% carbon are seldom produced or used.

Alloy steel includes those steels that contain other elements added for the purpose of modifying the mechanical properties of the plain carbon steels..

Low Carbon Steels: -

Of all the different steels, those produced in the greatest quantities fall within the low-carbon classification. These generally contain less than about 0.30 wt% C and are unresponsive to heat treatments. Strengthening is accomplished by cold work. Microstructure consists of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak, but have outstanding ductility and toughness: in addition, they are machinable, weldable and of all steels, are the least expensive to produce. Typical applications include automobile body components, structural shapes (I-beams, channels and angle iron) and sheets that are used in pipe lines, buildings, bridges and tin cans.

Medium Carbon Steels: -

The medium carbon steels have carbon concentrations between about 0.30 and 0.60 wt %. These alloys may be heat treated by austenitizing, quenching and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructure of tempered martensite. The plain medium carbon steels have low hardenabilities and can be successfully heat treated only in very thin sections and with very rapid quenching rates. These heat treated alloys are stronger than low carbon steels but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshaft and other machine parts and high strength structural components calling for a combination of high strength, wear resistance and toughness.

High Carbon Steels: -

The high carbon steels, normally having carbon contents between 0.60 and 1.3 wt %, are the hardest, strongest and yet least ductile of the carbon steels. They are almost always used in a hardened and tempered condition and are specially wear resistant and capable of holding a sharp cutting edge. The tool and die steels are high-carbon alloys, usually containing chromium, vanadium, tungsten and molybdenum. These steels are utilized as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs and high strength wires.

4.7 e) ALLOY STEELS: -Introduction: -

Plain carbon steels are very satisfactory where strength and other requirements are not too severe. They are also used successfully at ordinary temperatures and in atmospheres that are not highly corrosive, but their relatively low hardenability limits the strength that can be obtained except in fairly thin sections. Almost all hardened steels are tempered to reduce internal stresses. Plain carbon steels show a marked softening with increasing tempering temperature. This behavior will lessen their applicability for parts that require hardness above room temperature. The low corrosion and oxidation resistance, loss of strength at elevated temperature and low hardenability limits their broad usefulness. Most of the limitations of plain carbon steels may be overcome by the use of alloying elements.

Alloy steel may be defined as one whose characteristics properties are due to some element other than carbon. Although all plain carbon steels contain moderate amounts of manganese (up to about 0.90 %) and silicon (up to about 0.30 %), they are not considered alloy steels because the principal function of the manganese and silicon is to act as deoxidizers. They combine with oxygen and sulphur to reduce the harmful effect of those elements.

Purpose of Alloying. -

Alloying elements are added to steel for many purposes. Some of the most important are:

1. Increase hardenability
2. Improve strength at ordinary temperature
3. Improve mechanical properties at either high or low temperatures
4. Improve toughness at any minimum hardness or strength
5. Increase wear resistance
6. Increase corrosion resistance and oxidation resistance
7. Improve magnetic properties

Classification of Alloy Steels:-

Alloy steels may be classified on the basis of total alloy content in the following manner:

Low alloy ----- less than 10% alloy

High alloy -----more than 10% alloy

The low alloy steels are often referred to as pearlite steels since their microstructures are similar to the plain carbon grades. The high alloy group includes the alloy tool steels together with the corrosion-, scale-, and wear resistant steels, the structures of which may consists largely of austenite or ferrite rendered stable at room temperature by the high alloy content.

Types of Alloy Steels: -

Since a large number of alloy steels are manufactured, it is not feasible to discuss the individual alloy steels; however, a brief consideration of the specific effects of the common alloy elements and their application will be given.

NICKEL STEELS (2XXX SERIES):-

Nickel is one of the oldest, most fundamental steel-alloying elements. It has unlimited solubility in gamma (γ) iron and is highly soluble in ferrite, contributing to the strength

and toughness of this phase. Ni permits the attainment of given strength levels at lower carbon contents, thus increasing toughness, plasticity, and fatigue resistance. Ni steels are highly suited for high strength structural steels which are used in the as-rolled condition or for large forgings which are not adapted to quenching. The 3.5% nickel steels (23xx series) with low carbon are used extensively for carburizing of drive gears, connecting-rod bolts, studs, and kingpins. The 5% nickel steels (25xx series) provide increased toughness and are used for heavy-duty applications such as bus and truck gears, cams, and crankshafts. Nickel has only a mild effect on hardenability but is outstanding in its ability to improve toughness, particularly at low temperatures.

CHROMIUM STEELS (5XXX SERIES): -

Chromium is less expensive alloying element than nickel and forms simple carbides (Cr_7C_3 , Cr_4C) or complex carbides [$(\text{FeCr})_3\text{C}$]. These carbides have high hardness and good wear resistance. Chromium is soluble up to about 13% in iron and has unlimited solubility in ferrite. In low carbon steels, chromium tends to go into solution, thus increasing the strength and toughness of the ferrite. When chromium is present in amounts in excess of 5%, the high temperature properties and corrosion resistance of the steel are greatly improved.

The low carbon alloy steels in this series are usually carburized. The presence of chromium increases the wear resistance of the case, but the toughness in the core is not as high as the nickel steels. With medium carbon, these steels are oil-hardening and are used for springs, engine bolts, studs, axles, etc. A high carbon (1%), high chromium (1.5%) alloy steel (52100) is characterized by high hardness and wear resistance. The steel is used extensively for ball and roller bearings and for crushing machinery. A special type of chromium steel containing 1 % C and 2 to 4 % Cr has excellent magnetic properties and is used for permanent magnets.

NICKEL - CHROMIUM STEELS (3XXX SERIES): -

In these steels the ratio of nickel to chromium is approximately 2.5 parts nickel to 1 part chromium. A combination of alloying elements usually imparts some of the characteristic properties of each one. The effect of nickel in increasing toughness and ductility is combined with the effect of chromium in improving hardenability and wear resistance. It is important to remember that the combined effect of two or more alloying elements on hardenability is usually greater than the sum of the effects of the same alloying elements used separately. The low carbon-nickel-chromium alloy steels are carburized. With 1.5 % Ni and 0.60 % Cr (31xx series) they are used for worm gears, piston pins etc. For heavy duty applications, such as aircraft gears, shafts and cams, the nickel content is increased to 3.5 % and the chromium content to 1.5 % (33xx series). The medium-carbon nickel-chromium steels are used in the manufacture of automotive connecting rods and drive shafts.

MANGANESE STEELS (31XX SERIES): -

Manganese is one of the least expensive alloying elements and is present in all steels as a deoxidizer. It also reduces the tendency towards hot-shortness (red shortness) resulting from the presence of sulphur, thereby enabling the metal to be hot-worked. When manganese is absent or very low, the predominant sulphides is FeS, which forms a eutectic with iron and has a tendency to form thin continuous films around the primary crystals during solidification of the steel. These films are liquid at the rolling temperature of steel and produce a condition of hot-shortness which is a tendency to crack through the grain boundaries during working. Manganese is outstanding in its power to combine with sulphur, and MnS has a much higher melting point than the FeS eutectic. The manganese sulphide remains solid at the rolling temperature and has a less adverse effect on the hot-working properties of the steel.

It is only when the manganese content exceeds about 0.8. % that the steel may be classed as an alloy steel. Manganese contributes markedly to strength and hardness, but to a lesser degree than carbon, and is most effective in the higher-Carbon steels.

Fine-grained manganese steels attain unusual toughness and strength. These steels are often used for gears, spline shafts, axel and rifle barrels. With a moderate amount of vanadium added, manganese steels are used for large forgings that must be air-cooled. After normalizing, this steel will yield properties equivalent to those obtained in a plain carbon steel after a full hardening and tempering operations.

MOLYBDENUM STEELS (4XXX SERIES): -

Molybdenum is a relatively expensive alloying element, has a limited solubility in γ & α irons, and is a strong carbide former. Molybdenum has a strong effect on hardenability and like chromium, increases the high temperature hardness and strength of steels. Steels containing molybdenum are less susceptible to temper brittleness than other alloy steels. This element is most often used in combination with nickel or chromium or both. For carburizing applications it improves the wear resistance of the case and the toughness of the core. The amount of molybdenum added in any of molybdenum steel varies between 0.15 and 0.60 %.

The plain molybdenum steels (40xx & 44xx series) with low carbon content are generally carburized and are used for spline shafts, transmission gears and similar applications where service conditions are not too severe. With higher carbon they have been used for automotive coil and leaf springs. The triple-alloy nickel-chromium-molybdenum steels (43xx and 47xx series) have the advantages of the nickel-chromium steels along with the high hardenability imparted by molybdenum. They are used extensively in the aircraft industry for the structural parts of the wing assembly, fuselage and landing gears.

TUNGSTEN STEELS (5XXX SERIES): -

Tungsten has a marked effect on hardenability. It is a strong carbide former and it retards the softening of martensite on tempering. In general, the effect of tungsten in steel is similar to that of molybdenum, although large quantities are required. Approximately 2-3 % tungsten is equivalent to 1 % molybdenum. Since tungsten is relatively expensive and large quantities are necessary to obtain an appreciable effect, it is not used in general engineering steels. Tungsten is used primarily in tool steel.

VANADIUM STEELS: -

Vanadium is the most expensive of all the common alloying elements. It is a powerful deoxidizer and a strong carbide former which inhibits grain growth. Vanadium additions of about 0.05 % produce a sound, uniform and fine grain casting. When dissolved, vanadium has a marked effect on hardenability, yielding high mechanical properties on air cooling. Therefore, carbon-vanadium steels are used for heavy locomotive and machinery forging that are normalized.

The principal alloying element that is used with vanadium is chromium. The low-carbon chromium-vanadium steels (61xx series) are used in the case-hardened condition in the manufacture of crankshafts. The medium-carbon chromium-vanadium steels have high toughness and strength and are used for axles and springs. The high-carbon grade with high hardness and wear resistance is used for bearing and tools.

SILICON STEELS (92XX SERIES): -

Silicon, like manganese, is present in all steels as a cheap deoxidizer. When a steel contains more than 0.60 % silicon, it is classified as silicon steel. Like nickel, silicon is not a carbide former but rather dissolves in ferrite, increasing strength and toughness. A steel containing 1-2 % Si known as *navy steel* is used for structural applications requiring a high yield point. *Hadfield silicon steel* with less than 0.01 % C and about 3 % Si has excellent magnetic properties for use in the cores and poles of electrical machinery.

A properly balanced combination of manganese and silicon produces a steel with unusually high strength and with good ductility and toughness. This silicon-manganese steel (9260) is widely used for coil and leaf springs and also for chisels and punches.

4.7 f) Stainless Steels: -

Stainless steels are used for both corrosion and heat resisting applications. A three-numeral numbering system is used to identify stainless steels. The last two digits have no particular significance, but the first numeral indicates the group as follows:

Series Designation	Groups
2xx	Chromium-nickel-manganese: non-hardenable, austenitic, non-magnetic
3xx	Chromium-nickel: non-hardenable, austenitic, non-magnetic
4xx	Chromium: hardenable, martensitic, magnetic
4xx	Chromium: non-hardenable, ferritic, magnetic
5xx	low chromium: heat resisting, martensitic, hardenable, magnetic

The corrosion-resisting property is due to a thin, adherent, stable chromium oxide or nickel oxide film that effectively protects the steel against many corroding media. This property is not evident in the low-chromium structural steels and is apparent only when the chromium content exceeds about 10 %.

The response of stainless steels to heat treatment depends upon their composition. They are divided into three general groups.

- Martensitic Stainless Steels
- Ferritic Stainless Steels
- Austenitic Stainless Steels

Martensitic Stainless Steels: -

These steels are primarily straight chromium steels containing between 11.5 and 18 % Cr. Some examples of this group are types 403, 410, 416, 420, 440, 501 and 502. Type 410 and 416 are the most popular alloys in this group and are used for turbine blades and corrosion-resistant castings.

The martensitic type of stainless steels are magnetic, can be cold-worked without difficulty, specially with low carbon content, can be machined satisfactorily, have good toughness, show good corrosion resistance to weather and to some chemicals and are easily hot-worked. They attain the best corrosion resistance when hardened from the recommended temperature but are not as good as the austenitic or ferritic stainless steels. These steels are usually hardened by heating them above the

transformation range to temperatures near 1850 °F, then cooling in air or oil. Tempering is usually done above 1100 °F. The higher tempering temperature will cause some precipitation of carbides with a subsequent reduction in corrosion resistance. However with lower carbon content, the lowering of corrosion resistance is not too severe.

Stainless steel of type 440 has high corrosion resistance, strength and wear resistance and is used for cutlery, valve parts and bearings. Type 431 has been used for aircraft fittings, paper machinery parts, pumps and bolts. The relatively low-chromium alloy steels containing 4-6 %Cr (types 501 & 502) have excellent resistance to oxidation and much better corrosion resistance than ordinary steel.

Ferritic Stainless Steels: -

This group of straight-chromium stainless steels contains approximately 14 to 27 % chromium and includes types 405, 430 and 446. Low in carbon content but generally high in chromium than the martensitic grades, these steels are not hardened by heat treatment and are only moderately hardened by cold working. They are magnetic and can be cold-worked or hot-worked, but they develop their maximum softness, ductility and corrosion resistance in the annealed condition. In the annealed condition, the strength of these steels is approximately 50% higher than that of carbon steels and they are superior to the martensitic stainless steels in corrosion resistance and machinability. Since the ferritic steels may be cold-formed easily, they are used extensively for deep-drawn parts such as vessels for chemical and food industries and for architectural purposes.

The only heat treatment applied to truly ferritic steels is annealing. This treatment serves primarily to relieve welding or cold-working stresses.

Austenitic Stainless Steels: -

These are the chromium-nickel (type 3xx) and chromium-nickel-manganese stainless steels (type 2xx). These types are austenitic, essentially non-magnetic in the annealed condition and do not harden by heat treatment. The total content of nickel and chromium is at least 23 %. They can be hot-worked easily and can be cold-worked when proper allowance is made for their rapid work hardening. Cold working develops a wide range of mechanical properties and the steel in this condition may become slightly magnetic. They are extremely shock-resistant and difficult to machine unless they contain sulphur and selenium (types 303 and 303Se). These steels have the best high-temperature strength and resistance to scaling of the stainless steels. The corrosion resistance of the austenitic steels is usually better than that of martensitic or ferritic stainless steels.

Precipitation Hardening Stainless Steels: -

As a result of research during World War II, a new group of stainless steels with precipitation-hardening characteristics were developed. The first of these nonstandard grades of stainless steels, 17-7 was made available in 1948. These steels are usually solution-annealed at the mill and supplied in that condition. After forming they are aged to attain the increase in hardness and strength. Aside from the increase in strength and ductility, aging also improves both toughness and resistance to stress-corrosion. In general, they have lower nickel content, thus reducing the stability of the austenite. These steels may also have elements such as copper and aluminum and tend to form coherent alloy precipitates.

Maraging Steels: -

A series of iron-base alloys capable of attaining yield strength up to 300,000 psi in combination with excellent fracture toughness was made available early in 1960. These steels are low-carbon, containing 18 to 25% Ni together with other hardening elements and are called *Maraging* (Martensitic plus Aging). They are also considered to be martensitic as annealed and attain ultrahigh strength on being aged in the annealed or martensitic condition. The martensite formed is soft and tough rather than the hard, brittle martensite of conventional low-alloy steels. This ductile martensite has a low work-hardening rate and can be cold-worked to a high degree.

4.7 g) TOOL STEELS: -

Any steel used as tool may be technically classified as tool steel. However, the term is restricted to high quality special steels used for cutting, shearing or forming purposes.

There are several methods of classifying tool steels. One method is according to the quenching media used, such as water-hardening steel, oil-hardening steels and air-hardening steels. Alloy content is another means of classification such as carbon tool steel, low-alloy steels and medium-alloy tool steels. A final method of grouping is based on the application of the tool steel, such as hot-work steels, shock-resisting steels, high-speed steels and cold-work steels.

The method of identification and type classification of tool steels adopted by the AISI (American Iron and Steel Institute) includes the method of quenching, applications, special characteristics and steels for special industries. The commonly used tool steels have been grouped into seven major headings and each group or sub grouping has been assigned an alphabetical letter as follows:

Group	Symbol and Type
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Water-hardening	W	
Shock-resisting	S	
Cold-work	O	Oil-hardening
	A	Medium-alloy air-hardening
	D	High-carbon high-chromium
Hot-work	H	(H1-H19, including Chromium-base)
		(H20-H39, including Tungsten-base)
		(H40-H59, including Molybdenum-base)
High-speed	T	Tungsten-base
	M	Molybdenum-base
Mold	P	Mold steels (P1-P19, including Low-carbon)
		(P20-P39, including other types)
Special-purpose	L	Low-alloy
	F	Carbon-tungsten

The most commonly used tool steel is high speed tool steel and will only be discussed here.

High Speed Tool Steels:-

These steels are among the most highly alloyed of the tool steels and usually contain a large amount of tungsten or molybdenum along with chromium, vanadium, and sometimes cobalt. The carbon content varies between 0.70 and 1% , although some types contain as much as 1.5% carbon.

The major application of high-speed steels is low for cutting tools, but they are also used for making extrusion dies, burnishing tools, and blanking punches and dies.

Compositions of the high-speed steels are designed to provide excellent red-hardness and reasonably good shock resistance. They have good non-deforming properties and may be quenched in oil, air, or molten salts. They are rated as deep-hardening, have good wear resistance, fair machinability and fair to poor resistance to decarburization.

4.8 CAST IRONS: -

4.8 a) INTRODUCTION: -

Cast irons like steels are basically alloys of iron and carbon. In relation to the iron-iron carbide diagram, cast irons contain a greater amount of carbon than that necessary to saturate austenite at the eutectic temperature. Therefore cast irons contain between 2.0 to 6.67 % C. since high carbon content tends to make the cast iron very brittle, most commercially manufactured types are in the range of 2.5 to 4 % C.

The ductility of the cast iron is very low and it cannot be rolled, drawn or work at room temperature. Most of the cast irons are not malleable at room temperature. However they melt readily and can be cast into complicated shapes which are usually machine to final dimensions. Since casting is the only suitable process applied to these alloys, they are known as cast irons.

Although the common cast irons are brittle and have lower strength properties than most steels, they are cheap, can be cast more readily than steel and have other useful properties. In addition, by proper alloying, good foundry control and appropriate heat treatment the properties of any type of cast iron may be varied over a wide range.

4.8 b) TYPES OF CAST IRONS: -

The best method of classifying cast iron is according to metallographic structure. There are four variables to be considered which lead to the different type of cast irons, namely the carbon content, the alloy and impurity content, the cooling rate during and after freezing and the heat treatment after casting. These variables control the condition of the carbon and also its physical form. The carbon may be combined as iron carbide in cementite, or it may exist as free carbon in graphite. The shape and distribution of the free carbon particles will greatly influence the physical properties of the cast iron. They types of the cast irons are as follow:

- *White Cast Irons* in which all the carbon is in the combined form as cementite
- *Malleable Cast Iron* in which most or all of the carbon is un-combined in the form of irregular round particles known as temper carbon. This is obtained by heat treatment of white cast iron.
- *Gray Cast Iron* in which most or all of the carbon is un-combined in the form of graphite flakes.

- *Chilled Cast Iron* in which a wide cast iron layer at the surface is combined with a gray iron interior.
- *Nodular Cast Iron* in which by special alloy addition, the carbon is largely un-combined in the form of compact spheroids. This structure differs from malleable iron in that it is obtained directly from solidification and the round carbon particles are more regular in shape.
- *Alloy Cast Iron* in which the properties or the structure of any of the above type are modified by the addition of the alloying elements.

4.8 c) WHITE CAST IRON:-

The changes that take place in white cast iron during solidification and subsequent cooling are determined by the iron-iron carbide diagram. All white cast irons are hypoeutectic alloys and the cooling of 2.50 % C will be described.

The alloy at X_1 in Fig below exists as a uniform liquid solution of carbon dissolved in liquid iron. It remains in this condition as cooling takes place until the liquidus line is crossed at X_2 . Solidification now begins by the formation of austenite crystals containing about 1 % C. As the temperature falls, primary austenite continues to solidify, its composition moving down and to the right along the solidus line towards point C. The liquid in the mean time is becoming richer in carbon, its composition also moving down and to the right along the liquidus line towards point E. At the eutectic temperature, 2065 °F, the alloy consists of austenite dendrites containing 2 % C and liquid solution, containing 4.3 % C. The liquid accounts for $(2.5 - 2.0) / (4.3 - 2.0)$, or 22 % of the alloy by weight. This liquid now undergoes the eutectic reaction isothermally to form the eutectic mixture of austenite and cementite known as Ledeburite. Since the reaction takes place at relatively high temperature, ledeburite tends to appear as a coarse mixture rather than a fine mixture typical of many eutectics. It is not unusual for ledeburite to be separated completely, with the eutectic austenite added to the primary austenite dendrites, leaving behind layers of massive free cementite.

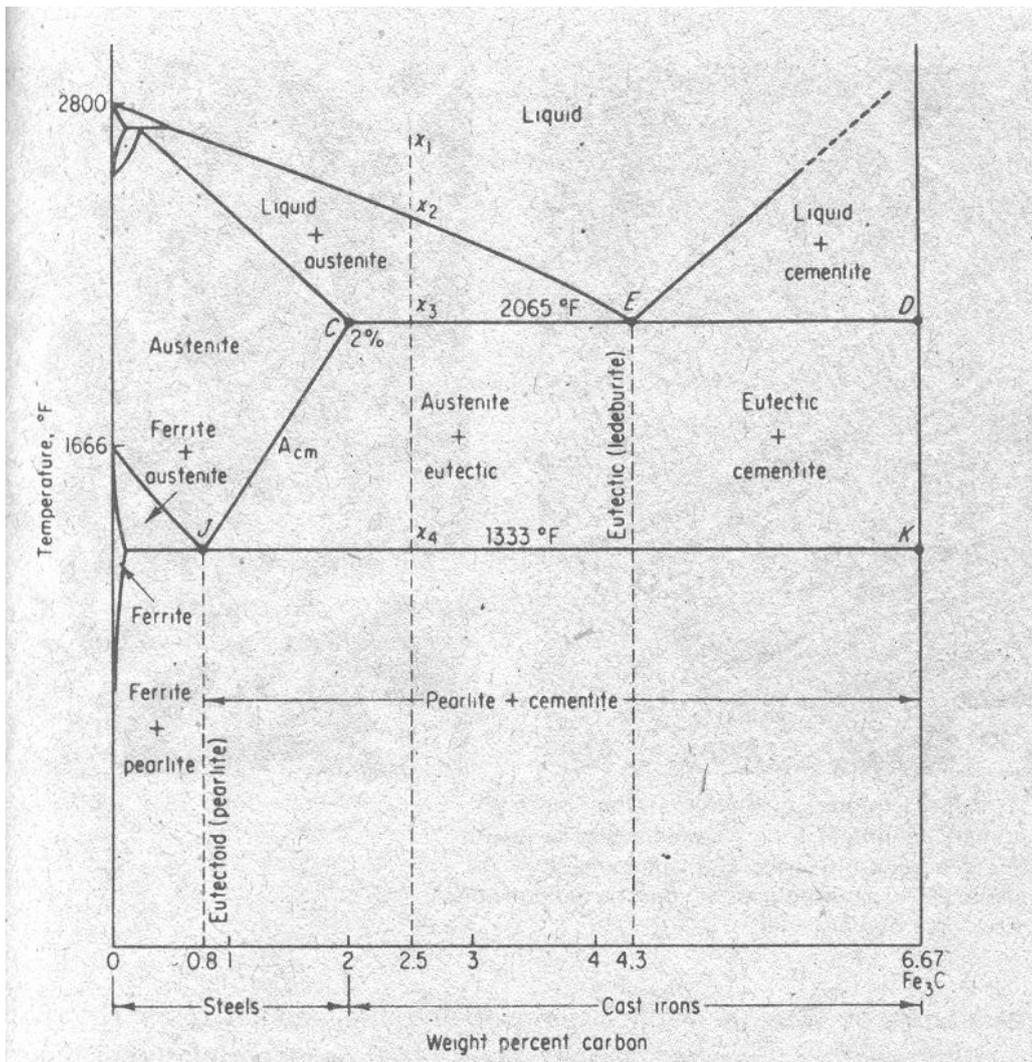


FIGURE 4.22 METASTABLE IRON-IRON CARBIDE PHASE DIAGRAM

As the temperature falls between X_3 and X_4 , the solubility of carbon in austenite decreases, as indicated by the A_{cm} line CJ . This causes precipitation of proeutectoid cementite, most of which is deposited upon the cementite already present. At the eutectoid temperature, 1333°F , the remaining austenite containing 0.8% carbon and constituting $(6.67-2.5) / (6.67-0.8)$, or 70% of the alloy, undergoes the eutectoid reaction isothermally to form pearlite. During subsequent cooling to room temperature, the structure remains essentially unchanged.

The typical microstructure of white cast iron consists of dendrites of transformed austenite (pearlite) in a white interdendritic network of cementite as shown in the Fig below.

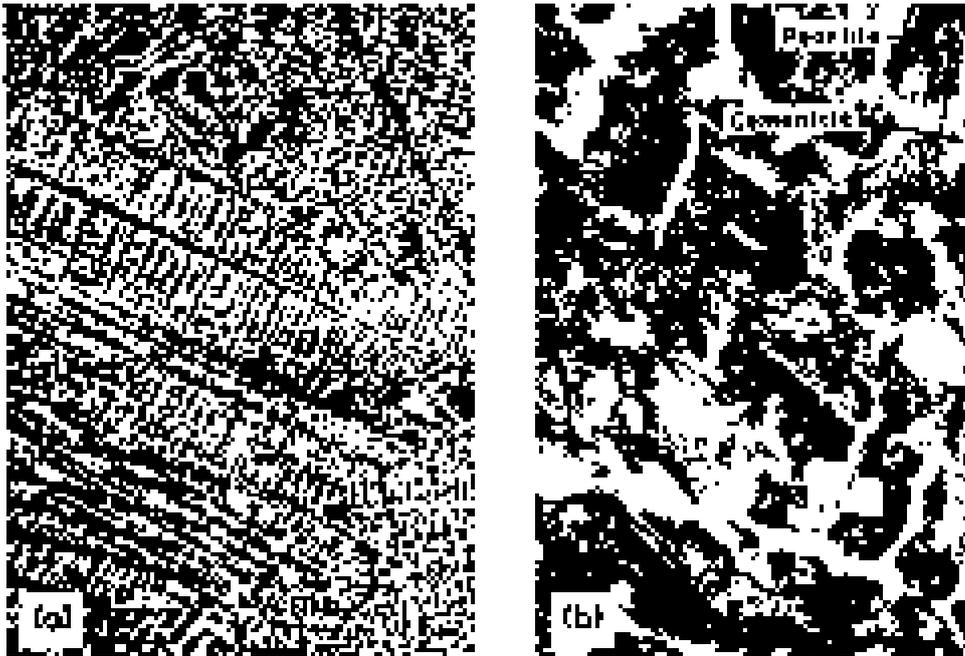


FIGURE 4.23 MICROSTRUCTURE OF WHITE CAST IRON AT TWO DIFFERENT MAGNIFICATIONS

Since white cast irons contain relatively large amount of cementite as a continuous interdendritic network, it makes the cast iron hard and wear resistant but extremely brittle and difficult to machine. Completely white cast irons are limited in engineering applications because of this brittleness and lack of machinability. They are used where resistance to wear is most important and the service does not require ductility such as liners for cement mixers, ball mills, certain types of drawing dies and extrusion nozzles. A large tonnage of white cast iron is used as a starting material for the manufacture of malleable cast iron.

4.8 d) MALLEABLE CAST IRON:-

Cementite (iron carbide) is actually a metastable phase. There is a tendency for cementite to decompose into iron and carbon, but under normal conditions it tends to persist indefinitely in its original form. Up to this point, cementite has been treated as a stable phase; however this tendency to form free carbon is the basis for the manufacture of malleable cast iron.

The reaction



is favored by elevated temperatures, the existence of solid non-metallic impurities, higher carbon contents and the presence of elements that aid the decomposition of Fe_3C .

On the iron-iron carbide equilibrium diagram for the metastable system, shown in figure below are superimposed the phase boundaries of the stable iron-carbon (graphite) system as dotted lines.

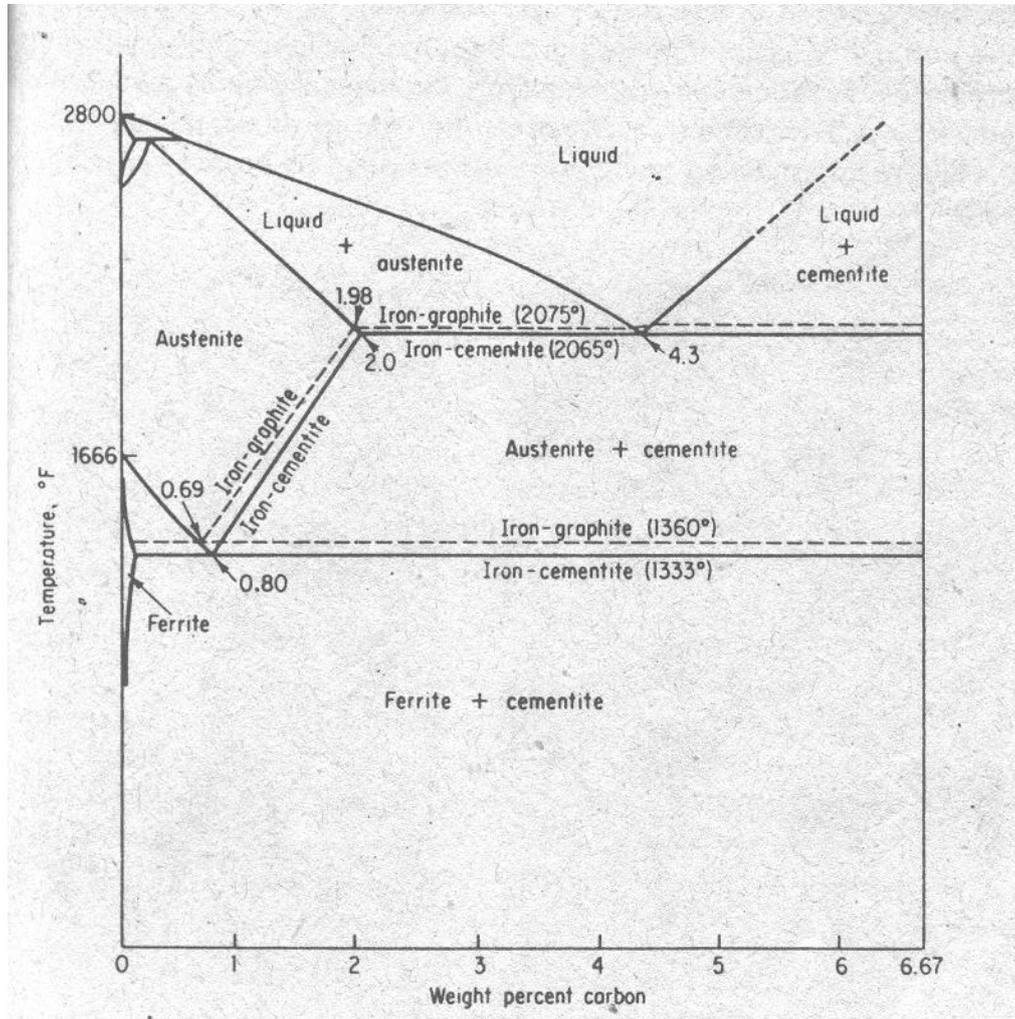


FIGURE 4.24 STABLE IRON GRAPHITE SYSTEM

The purpose of malleabilization is to convert all the combined carbon in white iron in to irregular nodules of temper carbon (graphite) and ferrite. Commercially this process is carried in two steps known as the first and second stages of the anneal.

White irons suitable for conversion to malleable iron are of the following range of composition:

Carbon	2.00 – 2.65 %
Silicon	0.90 – 1.40 %
Manganese	0.25 – 0.55 %
Phosphorus	< 0.18 %
Sulphur	0.05 %

In the first-stage annealing the white-iron casting is slowly reheated to a temperature between 1650 – 1750 °F. During heating, the pearlite is converted to austenite at the lower critical line. The austenite thus formed dissolves some additional cementite as it is heated to the annealing temperature.

The white-iron casting is held at the first-stage annealing temperature until all massive carbides have been decomposed. Since graphitization is a relatively slow process, the casting must be soaked at temperature for at least 20 hr, and large loads may require as much as 72 hr. The structure at completion of first-stage graphitization consists of temper-carbon nodules distributed throughout the matrix of saturated austenite.

After first-stage annealing, the castings are cooled as rapidly as practical to about 1400 °F in preparation for the second stage of the annealing treatment. The fast cooling cycle usually requires 2-6 hr, depending upon the equipment used.

In the second-stage annealing, the castings are cooled slowly at a rate of 5-15 °F/hr through the critical range at which the eutectoid reaction would take place. During the slow cooling, the carbon dissolved in the austenite is converted to graphite on the existing temper-carbon particles, and the remaining austenite transforms into ferrite. Once graphitization is complete, no further structural changes take place during cooling to room temperature and the structure consists of temper-carbon nodules in a ferrite mixture as shown below. This type is known as standard or ferrite malleable iron. In the form of compact nodules, the temper carbon does not break up the continuity of the tough ferritic mixture. This results in a higher strength and ductility than exhibited by gray cast iron. The graphite nodules also serve to lubricate cutting tools which accounts for the very high machinability of malleable iron.

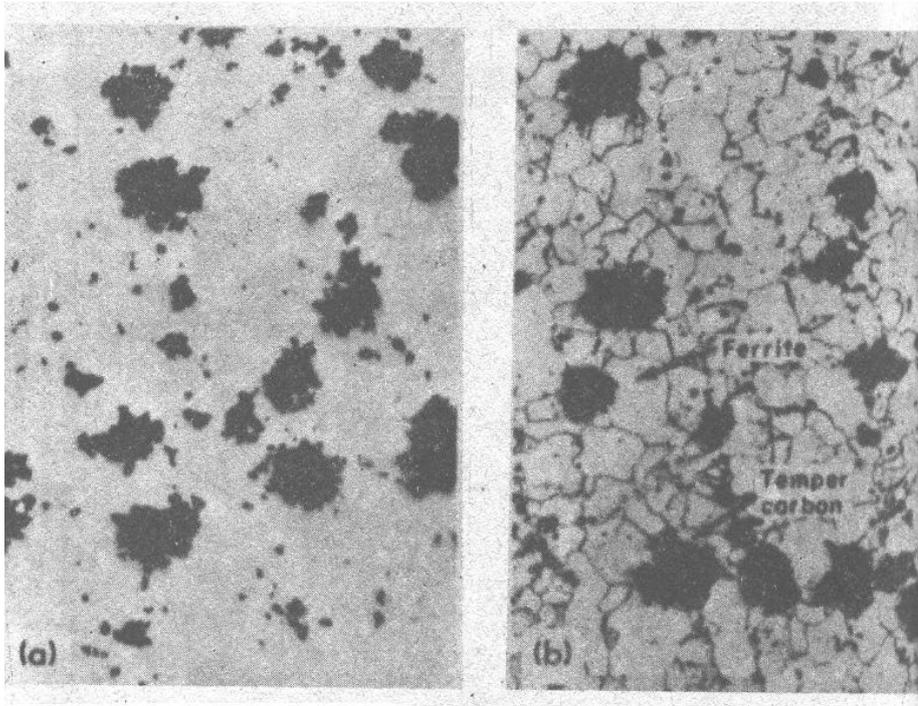


FIGURE 4.25 MICROSTRUCTURE OF FERRITIC MALLEABLE IRON

Ferritic malleable iron has been widely used for automotive, agricultural and rail road equipments; expansion joints and railing casting on bridges; chain-hoist assemblies, industrial casters; pipe fittings and many applications in general hardware.

4.8 e) GRAY CAST IRON: -

This group is one of the most widely used alloys of iron. In the manufacture of gray cast irons, the tendency of cementite to separate into graphite and austenite or ferrite is favored by controlling alloy composition and cooling rates. Most gray cast irons are hypoeutectic alloys containing between 2.5 and 4 %.

These alloys solidify by first forming primary austenite. The initial appearance of combined carbon is in the cementite resulting from the eutectic reaction at 2065 °F. The graphitization process is aided by high carbon content, high temperature and the proper amount of graphitizing elements, notably silicon.

There is experimental evidence that with proper control of the above factor, the alloy will follow the stable iron-graphite equilibrium diagram forming austenite and graphite at the eutectic temperature of 2075 °F. At any rate, any cementite which is formed will graphitize rapidly. The graphite appears as many irregular generally elongated and curved plates which gives gray cast iron its characteristic grayish or blackish fracture. It should be emphasized that while

the microstructure represents their appearance on a plane surface, the flakes are three dimensional particles.

During continued cooling, there is additional precipitation of carbon because of the decrease in solubility of carbon in austenite. This carbon is precipitated as graphite or as proeutectoid cementite which promptly graphitizes.

The strength of gray cast iron depends almost entirely on the matrix in which the graphite is embedded. This matrix is largely determined by the condition of the eutectoid cementite.



FIGURE 4.26 MICROSTRUCTURE OF GRAY CAST IRON

If the composition and cooling rate are such that the eutectoid cementite also graphitizes, then the matrix will be entirely ferritic. On the other hand, if graphitization of the eutectoid cementite is prevented, the matrix will be entirely pearlitic. The constitution of the matrix may be varied from pearlite, through mixtures of pearlite and ferrite in different proportions, down to practically pure ferrite. The graphite-ferrite mixture is the softest and weakest gray iron; the strength and hardness increases with the increase in combined carbon, reaching a maximum with the pearlitic gray iron.

Gray iron is widely used also for guards and frames around hazardous machinery. Many types of gear housings, enclosures for electrical equipments, pump housings and steam turbine housings are cast in gray iron because of its low cost. Other similar gray-iron castings are used for motor frames, fire hydrants and sewer covers.

4.8 f) CHILLED CAST IRON:-

Chilled-cast iron castings are made by casting the molten metal against a metal chiller, resulting in a surface of white cast iron. This hard, abrasion-resistant white-iron surface or case is backed up by the softer gray-iron core. The case-core structure is obtained by careful control of the overall alloy composition and adjustment of the cooling rate.

Freezing starts first, and the cooling rate is more rapid where the molten metal is in contact with the mold walls. The cooling rate decreases as the center of the casting is approached. A chilled-iron casting is produced by adjusting the composition of the iron so that the normal cooling rate at the surface is just fast enough to produce white-iron while the slower cooling rate below the surface will produce mottled or gray iron.

If only selected surfaces are to be white iron, it is common practice to use a composition which would normally solidify as gray iron and employ metal liners (chills) to accelerate the cooling rate of the selected areas. The depth of the white iron layer is controlled by using thin metal plates whenever a thin white-iron layer is desired and heavier metal plates where a deeper chill is necessary.

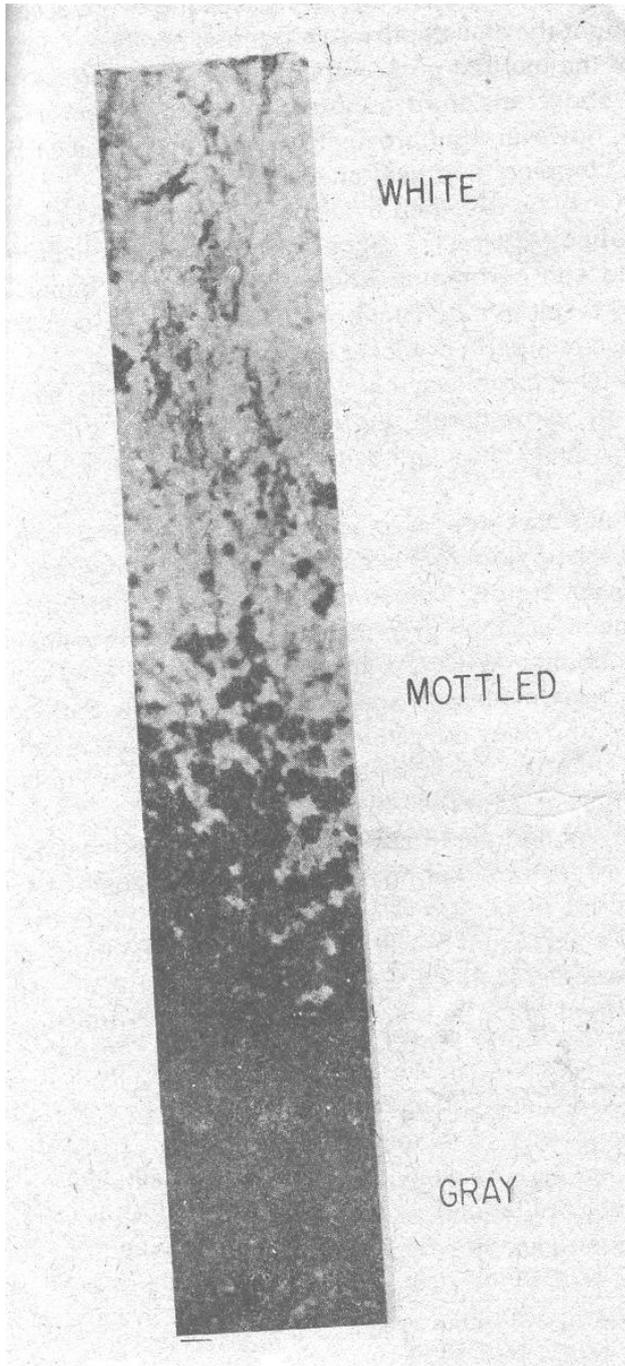


FIG 4.27 DIFFERENT PORTIONS IN CHILLED CAST IRON

The depth of chill is decreased and the hardness of the chilled zone increases with increasing carbon content. Since silicon is a graphitizer, the depth of chill is decreased with increasing silicon content.

Chilled-iron casting is used for railway-car wheels, crushing rolls, stamp shoes and dies, sprockets, plowshares, and many other heavy-duty machinery parts.

4.8 g) NODULAR CAST IRON:-

Nodular cast iron, also known as *ductile iron*, *spheroidal graphite iron* and *spherulitic iron*, is cast iron in which the graphite is present as tiny balls or spheroids. The compact spheroids interrupt the continuity of the matrix much less than graphite flakes; this results in higher strength and toughness compared with a similar structure of gray iron. Nodular cast iron differs from malleable iron in that it is usually obtained as a result of solidification and does not require heat treatment. The spheroids are more rounded than the irregular aggregates of temper carbon found in malleable iron.

The total carbon content of nodular iron is the same as in gray cast iron. Spheroidal graphite particles are formed during solidification because of the presence of a small amount of certain alloying elements. The nodule forming addition, usually magnesium or cerium is made to the ladle just before casting. Since these elements have a strong affinity for sulphur, the base iron-alloy sulphur content must be below 0.01 % for the treatment to be effective and the alloys are described as desulphurized.

The amount of ferrite in the as-cast matrix depends on composition and rate of cooling. Nodular irons with a matrix having a maximum of 10% pearlite are known as ferritic irons. This structure gives maximum ductility, toughness and machinability.

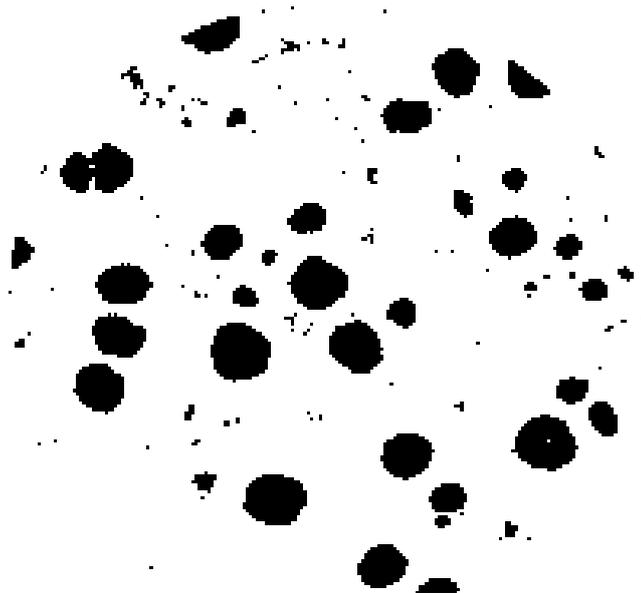


FIG 4.28 MICROSTRUCTURE OF FERRITIC NODULAR IRON

A matrix structure which is largely pearlite can be produced as cast or by normalizing. Normalizing is carried out by air cooling from a temperature of 1600 – 1650 °F. Pearlitic ductile irons (microstructure shown below) are stronger but less ductile than ferritic irons.

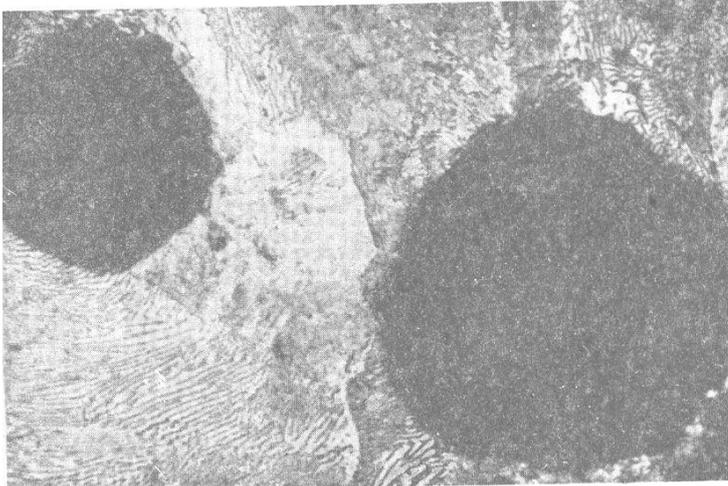


FIG 4.29 MICROSTRUCTURE OF PEARLITIC NODULAR IRON

A martensitic matrix may be obtained by quenching in oil or water from 1600 - 1700 °F. The quenched structures are usually tempered, after hardening, to the desired strength and hardness levels.

Austenitic ductile irons are highly alloyed types which retain their austenitic structures down to at least - 75 °F. These irons are of interest because of their relatively high corrosion resistance and good creep properties at elevated temperatures.

Some typical applications of nodular irons are agricultural- tractor and implement parts; automotive and diesel- crankshafts, pistons and cylinder heads; electrical fittings, switch boxes, motor frames and circuit breaker parts; mining- hoist drums, drive pulleys, flywheels and elevator buckets; steel mill- work rolls, furnace doors, table rolls and bearings; tool and die- wrenches, levers, handles, clamp frames, chuck bodies and miscellaneous dies for shaping steels, aluminum, brass, bronze and titanium.

4.8 h) ALLOY CAST IRONS: -

An alloy cast iron is one which contains a specially added element or elements in sufficient amounts to produce a measurable modification in the physical or mechanical properties. Elements normally obtained from raw materials such as silicon, manganese; sulphur and phosphorus are not considered alloy additions.

Alloying elements are added to cast iron for special properties such as resistance to corrosion, heat or wear and to improve mechanical properties. Most alloying elements in cast iron will accelerate or retard graphitization and this is one of the most important reasons for alloying. The most common alloying elements are chromium, molybdenum, nickel and vanadium.

Chromium increases combined carbon by forming complex iron-chromium carbides that are more stable than iron carbides. Small amounts of chromium increase strength, hardness, depth of chill and resistance to wear and heat but decrease machinability. For resistance to corrosion or for use at high temperature, as much as 35 % Cr is used in combination with other alloying elements.

Copper is a graphitizer but is only about one fifth as potent as silicon in this respect. For general engineering applications the copper content is between 0.25 – 2.5 %. Copper tends to break up massive cementite and strengthen the matrix.

Molybdenum improves mechanical properties and is a mild stabilizer of carbides. It is added in quantities from 0.25 -1.25 % and its effect is similar to that in steel. Fatigue strength, tensile strength, transverse strength, heat resistance and hardness of the cast iron are all improved. Molybdenum also retards the transformation of austenite, thus increasing hardenability and freedom from cracking and distortion. It is always used in combination with other alloying elements.

Vanadium is a very powerful carbide former, stabilizes cementite and reduces graphitization. Vanadium additions, between 0.10 – 0.25% increase tensile and transverse strength and hardness.

Nickel is a graphitizer but only about one half as effective as silicon in this respect. The purpose of nickel (0.5 – 6.0 %) in the engineering gray irons is to control the structure by retarding austenite transformation, stabilizing pearlite and maintaining combined carbon at the eutectoid quantity. For excellent abrasion resistance, about 4 % Ni in combination with about 1.5 % Cr is added to white cast iron. The addition of 14- 38 % Ni to gray irons result in high heat resistance, high corrosion resistance and low expansively.

4.9 NON-FERROUS METALS & ALLOYS: -

Metallic materials may be divided into two large groups, ferrous & non-ferrous. The ferrous materials are iron based and the non-ferrous materials have some element other than iron as the principal constituent. The bulk of the non-ferrous materials is made up of the alloys of Cu, Al, Mg, Ni, Sn, Pb, Zn. Other non-ferrous metals that are used to a lesser extent include Mo, Co, Ti, Zr, Be, and the precious metals, gold, silver and platinum.

We will discuss the most important of non-ferrous metals & alloys i.e. copper and aluminum.

4.9 a) COPPER & COPPER ALLOYS: -

4.9 b) COPPER: -

The properties of copper that are most important are high electrical and thermal conductivity, good corrosion resistance, machinability, strength and ease of fabrication. In addition, copper is non-magnetic has a pleasing colour, can be welded, brazed and soldered, and is easily finished by plating or lacquering. Many of these basic properties may be improved by suitable alloying. Most of the copper that is used for electrical conductors contains over 99.9 % Cu and is identified as electrolytic tough-pitch copper (ETP) or Oxygen-free high-conductivity copper (OFHC). ETP copper is also used for roofing, gutters, down spouts, automobile radiators and gaskets, kettles, vats, pressure vessels and distillery and other process equipments.

OFHC is used in electronic tubes or in similar applications because it makes a perfect seal to glass.

Arsenical Copper containing about 0.3 % arsenic has improved resistance to special corrosive conditions and is used for certain condenser and heat exchanger applications.

Free-cutting copper with about 0.6 % tellurium has excellent machining properties and is used for bolts, studs, welding tips and electrical parts such as contact pins, switch gears, relays and precision electrical equipments.

Silver-bearing copper has a silver content of 7-30 oz/ton. Silver raises the recrystallization temperature of copper, thus preventing softening during soldering of commutators. It is preferred in the manufacture of electric motor for railroad and aircraft use.

Since copper and most copper alloys are homogeneous single phases, they are not susceptible to heat treatment, and their strength may be altered only by cold working.

4.9 c) COPPER ALLOYS: -

The most important commercial copper alloys may be classified as follows.

Brasses- alloys of copper and zinc

A. Alpha Brasses- alloys containing up to 36% Zn

- Yellow alpha brasses (20-36% Zn)

- Red brasses (5-20% Zn)

B. Alpha + Beta Brasses (54-62% Cu)

- 2) Bronzes- up to 12% of alloying elements
 - A. Tin Bronzes
 - B. Silicon Bronzes
 - C. Aluminum Bronzes
 - D. Beryllium Bronzes
- 3) Cupronickels- alloys of copper and nickel
- 4) Nickel silvers- alloys of copper, nickel and zinc

4.9 d) Brasses: -

Brasses are essentially alloys of copper and zinc. Some of these alloys have small amounts of other elements such as lead, tin or aluminum. Variations in composition will result in desired colour, strength, ductility, machinability, corrosion resistance or a combination of such properties.

Alpha Brasses:-

Alpha brasses containing up to 36% Zn possess relatively good corrosion resistance and good working properties. The colour of alpha brasses varies according to copper content from red for high copper alloys to yellow at about 62% Cu. The alpha brasses may be divided into two groups, yellow alpha brasses and red brasses.

Yellow Alpha Brasses:-

These contain 20-36% Zn, combine good strength with high ductility and are therefore suited for drastic cold working operations. It is common practice to stress relief anneal these brasses after severe cold working to prevent season cracking. Season cracking or stress corrosion cracking is due to the high residual stresses left in the brass as a result of cold working. These stresses make the brass more susceptible to intergranular corrosion particularly in ammonia atmospheres.

Yellow alpha brasses are also subject to pitting corrosion called dezincification. This type of corrosion usually occurs when brass is in contact with sea water or with fresh waters that have a high content of oxygen and carbon dioxide. Dezincification involves dissolution of the alloy and a subsequent deposition of porous non-adherent copper. Action of this kind unless stopped will eventually penetrate the cross section of the metal and lead to leakage through the porous

copper layer. If it occurs in a localized area, it is known as plug type dezincification. Small amounts of tin or antimony minimize dezincification in yellow brasses.

The most widely used yellow alpha brasses are cartridge brass (70Cu-30Zn) and yellow brass (65Cu-35Zn). Typical applications include automotive radiator cores, tanks, head light reflectors; electrical- flash light shells, lamp fixtures, socket shells, screw shells; hardware- eyelets, fasteners, grommets, rivets, springs; plumbing accessories and ammunition components.

The addition of 0.5-3.0 % lead improves machinability so that leaded brasses are used for screw-machine parts, engraving plates, keys, lock parts, tumblers, gears and watch parts.

Red Brasses: -

These contain 5-20% zinc. They generally have better corrosion resistance than yellow brasses and are not susceptible to season cracking or dezincification. The most common low zinc brasses are gliding metals (95 Cu-5Zn), commercial bronze (90Cu-10Zn), red brass (85Cu-15Zn), and low brass (80Cu-20Zn).

Gliding metal (95Cu-5Zn) has higher strength than copper and is used for coins, medals, tokens, fuse caps, primers, emblems, plaques, and as a base for articles to be gold-plated or highly polished.

Commercial bronze (90Cu-10Zn) has excellent cold-working and hot-working properties and is used for costume jewelry, compacts, lipstick cases, marine hardware, forgings, rivets, and screws. Leaded commercial bronze (1.75% Pb) is used for screws and other parts for automatic screw-machine work.

Red brass (85Cu-15Zn) is used for electrical conduit, screw shells, sockets, hardware, condenser and heat exchanger tubes, plumbing pipe, lipstick cases, compacts, nameplates, tags, and radiator cores.

Low brass (80Cu-20Zn) is used for ornamental metal work, medallions, thermostat bellows, musical instruments, flexible hose, and other deep-drawn articles.

Alpha Plus Beta Brasses:-

These brasses contain 54-62% copper. These alloys consist of two phases, α & β . The β phase is harder and more brittle at room temperature than α , therefore, these alloys are more difficult to cold-work than α brasses. At elevated temperatures the β phase becomes very plastic, and since most of these alloys may be heated into the single-phase region, they have excellent hot-working properties

The most widely used $\alpha + \beta$ brass is *munz metal* (60Cu-40Zn), which has high strength and excellent hot-working properties. Munz metal is used in sheet form for ship-sheathing, condenser heads, perforated metal, and architectural work. It is also used for valve stems, brazing rods, and condenser tubes. Leaded munz metal containing 0.40-0.80% lead has proved machinability.

Free-cutting brass (61.5Cu-35.5Zn-3Pb) has the best machinability of any brass combined with good mechanical and corrosion-resistant properties. It is used for hardware, gears, and automatic high-speed screw machine parts.

Forging brass (60Cu-38Zn-2Pb) has the best hot-working properties of any brass and is used for hot forgings, hardware and plumbing parts.

Architectural bronze (57Cu-40Zn-3Pb) has excellent forging and free matching properties. Typical applications are handrails, decorative moldings, grilles, storefronts, hinges, lock bodies, and industrial forgings.

Naval brass (60Cu-39.25Zn-0.75Sn), also known as tobin bronze, has increased resistance to salt water corrosion and is used for condenser plates, welding rods, propeller shafts, piston rods, and valve stems.

Manganese bronze (58.5Cu-39Zn-1.4Fe-1Sn-0.1Mn), has high strength combined with excellent wear resistance and is used for clutch disks, extruded disks, extruded shapes, forgings, pump rods, shafting rods, valve stems, and welding rod.

4.9 e) BRONZES:-

The term bronze was originally applied to the copper-tin alloys; however, the term is now used for any copper alloy, with the exception of copper-zinc alloys, that contains up to approximately 12% of the principal alloying element. Commercial bronzes are primarily alloys of copper and tin, aluminum, silicon, or beryllium. In addition, they may contain phosphorus, lead, zinc, or nickel.

TIN BRONZES:-

These are generally referred to as phosphor bronzes since phosphorus is always present as a deoxidizer in casting. The usual range of phosphorus content is between 0.01 and 0.5%, and of tin between 1 and 11%.

Zinc is sometimes used to replace part of the tin. The result is an improvement in the casting properties and toughness with little effect on wear resistance. Lead is often added to tin bronze to improve machinability and wear resistance. High-lead tin bronze may contain as much as 25% lead. The leaded alloys are for bushing and bearings under moderate or light loads.

PHOSPHOR BRONZES: -

These are characterized by high strength, toughness, high corrosion resistance, low coefficient of friction, and freedom from season cracking. They are used extensively for diaphragms, bellows, lock washers, cotter pins, bushings, clutch disks, and springs.

SILICON BRONZES:-

Commercial silicon bronzes generally contain less than 5 % silicon and are single-phase alloys. They are the strongest of the work-hardenable copper alloys. They have mechanical properties comparable to those of mild steel and corrosion resistance comparable to that of copper. They are used for tanks, pressure vessels, marine construction and hydraulic pressure lines.

Aluminum Bronze: -

Most commercial aluminum bronzes contain between 4 and 11 % aluminum. Those alloys containing up to 7.5 % aluminum are generally single-phase alloys, while those containing between 7.5 % and 11 % aluminum are two-phase alloys. Other elements such as iron, nickel, manganese and silicon are frequently added to aluminum bronze. Iron (0.5-5.0%) increases strength and hardness and

refines the grain; nickel (up to 5.0%) has the same effect as iron but is not as effective; silicon (up to 2.0%) improves machinability; manganese promotes soundness in castings by combining with gases and also improves strength.

The single phase aluminum bronzes show good cold-working properties and good strength combined with corrosion resistance to atmospheric and water attack. They are used for condenser tubes, cold-work forms, corrosion-resistant vessels, nuts and bolts and protective sheathing in marine applications.

The $\alpha + \beta$ aluminum bronzes are interesting because they can be heat treated to obtain structures similar to those in steel. Heat-treated aluminum bronzes are used for gears, propeller hubs, blades, pump parts, bearings, bushings, nonsparking tools and drawing & forming dies.

Beryllium Bronze: -

These bronzes can be aged hardened. They are used for parts requiring a combination of excellent formability in the soft condition with high yield strength, light fatigue strength and creep resistance in the hardened condition; parts requiring corrosion resistance, high strength and relatively high electrical conductivity (diaphragms, contact bridges, surgical instruments, bolts and screws)

4.9 f) CUPRONICKELS: -

These are copper-nickel alloys that contain up to 30 % nickel. All cupronickels are single-phase alloys. They are not susceptible to heat treatment and may have their properties altered only by cold working.

The cupronickel alloys have high resistance to corrosion fatigue and also high resistance to the corrosive and erosive action of rapidly moving sea water. They are widely used for condenser, distiller, evaporator and heat exchanger tubes for naval vessels and coastal power plants.

4.9 g) NICKEL SILVERS: -

These are essentially ternary alloys of copper, nickel and zinc. Commercial alloys are produced with the following range of composition:

Copper 50% - 70%, Nickel 5% - 30%, Zinc 5% - 40%

The nickel silvers containing over 60% Cu are single-phase alloys that show only fair hot-working properties but are ductile and easily worked at room temperature. The addition of nickel to the copper-zinc alloy gives it a pleasing

silver-blue white colour and good corrosion resistance to food chemicals, water and atmosphere. These alloys make excellent base metals for plating with chromium, nickel or silver. They are used for rivets, screws, table flatware, zippers, costume jewelry, name-plates and radio dials.

The nickel silvers containing between 50 and 60% copper are two phase $\alpha + \beta$ alloys. They have a relatively high modulus of elasticity and are readily hot-worked. Nickel silvers are less susceptible to stress corrosion than binary copper-zinc alloys of the same zinc content. Typical applications of the $\alpha + \beta$ nickel silvers include springs and contacts in telephone equipment, resistance wire, hardware and surgical and dental equipments.

4.9 h) ALUMINUM & ALUMINUM ALLOYS: -

4.9 i) ALUMINUM:-

The best-known characteristic of aluminum is its light weight, the density being about one-third that of steel or copper alloys. Certain aluminum alloys have a better strength-to-weight ratio than that of high strength steels. Aluminum has good malleability and formability, high corrosion resistance and high electrical & thermal conductivity. An ultra-pure form of aluminum is used for photographic reflectors to take advantage of its high light reflectivity and non-tarnishing characteristics.

Aluminum is non-toxic, non-magnetic and non-sparking. The non-magnetic characteristic makes aluminum useful for electrical shielding purposes such as bus-bar housings or enclosures for other electrical equipments. Although electrical conductivity of electric-conductor (EC) grade aluminum is about 62% that of copper, its light weight makes it more suitable as an electrical conductor for many industrial applications.

Pure aluminum has a tensile strength of about 13000 psi. However, substantial increase in strength is obtained by cold working or alloying. Some alloys properly heat-treated, approach tensile strengths of 100,000 psi.

One of the most important characteristics of aluminum is its machinability and workability. It can be cast by any known method, rolled to any desired thickness, stamped, drawn, spun, hammered, forged and extruded to almost any conceivable shape.

Commercially pure aluminum, 1100 (99.0 + % Al), is suitable for applications where good formability or very good resistance to corrosion (or both) are required and where high strength is not necessary. It has been used extensively

for cooking utensils, various architectural components, food and chemical handling and storage equipment and welded assemblies.

4.9 j) ALLOY DESIGNATION SYSTEM: -

The designation of wrought aluminum and wrought aluminum alloys was standardized by The Aluminum Association (AA) in 1954. It follows a four-digit numbering system. The first digit indicates the alloy group. The second digit indicates modification of the original alloy or impurity limits; zero is used for the original alloy and integers 1 through 9 indicate alloy modifications. In the 1xxx group for minimum aluminum purities of 99.00 % and greater, the last two digits are the same as the two digits to the right of the decimal point in the minimum Al % when it is expressed to the nearest 0.01 %. Thus 1060 indicates a material of 99.60 minimum % Al purity and no special control on individual impurities.

In the 2xxx through 8xxx alloy groups, the last two digits serve only to identify the different aluminum alloys in the group.

Major Constituents	Aluminum Association Number
Aluminum, 99.00 % and greater	1xxx
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and Silicon	6xxx
Zinc	7xxx
Other Elements	8xxx
Unused Series	9xxx

4.9 k) TEMPER DESIGNATION:-

The temper designation follows the alloy designation and is separated from it by a dash. The Aluminum Association Temper Designation System is used for wrought and cast aluminum and aluminum alloys.

There are four basic tempers: F as fabricated, O annealed, H Strain Hardened and T Heat-Treated

-F: As Fabricated applied to products which acquire some temper as the result of normal manufacturing operations. There is no guarantee of mechanical properties.

-O: Annealed, Recrystallized this is the softest temper of wrought alloy products

-H: Strain-Hardened applies to products which have their mechanical properties increased by cold working only.

-T: Thermally Treated applies to products thermally treated, with or without supplementary strain hardening, to produce stable tempers.

4.9 l) ALUMINUM-COPPER ALLOYS (2xxx series): -

These alloys respond to heat treatment by age hardening. The three most widely used wrought aluminum-copper alloys are 2014, 2017 and 2024. The oldest of the heat-treatable aluminum alloys is duralumin (2017) containing 4% Cu. This alloy is widely used for rivets in aircraft construction. Since this is a natural-aging alloy, after solution treatment it is refrigerated to prevent aging.

Alloy 2014 has higher copper and manganese content than 2017 and is susceptible to artificial aging. In the artificially aged temper, 2014 has a higher tensile strength, much higher yield strength and lower elongation than 2017. This alloy is used for heavy-duty forgings, aircraft fittings and truck frames.

Alloy 2024, containing 4.5% Cu and 1.5% Mg, develops the highest strengths of any naturally aged aluminum-copper type of alloy. The higher Mg content, compared with 2017, makes it more difficult to fabricate. A combination of strain hardening and aging will develop the maximum yield strength attainable in high-strength alloy sheet. Typical uses of 2024 alloy are aircraft structures, rivets, hardware, truck wheels and screw-machine products.

4.9 m) ALUMINUM-MANGANESE ALLOYS (3xxx series): -

Alloys in this group are generally not age-hardenable. One of the alloys in this group is the popular 3003 alloy, which has good formability, very good resistance to corrosion and good weldability. Typical applications are utensils, food & chemical handling and storage equipments, gasoline and oil tanks, pressure vessels and piping.

4.9 n) ALUMINUM-SILICON ALLOYS (4 xxx series): -

These alloys are generally not heat-treatable. Wrought alloy 4032, containing 12.5% silicon has good forgeability and low coefficient of thermal expansion. It is used for forged automotive pistons.

Aluminum silicon casting alloys have excellent castability and resistance to corrosion. Alloy 13 (12% Si) and alloy 43 (5% Si) are used for intricate castings, food-handling equipments and marine fittings.

4.9 o) ALUMINUM-MAGNESIUM ALLOYS (5 xxx series): -

Most commercial wrought alloys in this group contain less than 5 % Mg, and, with low silicon content, they are not heat-treatable.

The wrought alloys are characterized by good weldability, good corrosion resistance and moderate strength. Alloy 5005 (0.8% Mg) is used for architectural extrusions; alloy 5050 (1.2% Mg) for tubing and automotive gas and oil lines; alloy 5052 (2.5% Mg) for aircraft fuel and oil lines; alloy 5083 (4.5% Mg) for marine and welded structural applications and alloy 5056 (5.2% Mg) for insect screens, cable sheathing and rivets for use with magnesium alloys.

Aluminum-magnesium casting alloys include 214 (3.8% Mg), alloy 218 (8% Mg) and alloy 220 (10% Mg). The first two are used for dairy and food handling equipment, fittings for chemical and sewage use, fittings for marine use and aircraft brake shoes. Alloy 220 is the only one in this group which is age-hardenable, resulting in the highest mechanical properties of any of the aluminum casting alloys.

4.9 p) ALUMINUM-SILICON-MAGNESIUM ALLOYS (6 xxx series): -

These alloys are characterized by excellent corrosion resistance and are more workable than other heat-treatable alloys. The popular wrought alloys in this

group include 6053, 6061 and 6063. Typical applications include aircraft landing mats, canoes, furniture, vacuum-cleaner tubing, bridge railings and architectural applications.

The aluminum-silicon-magnesium casting alloys 355, 356 and 360 provide a desirable combination of castability, pressure-tightness, and strength & corrosion resistance. They are widely used in aircraft applications, machine-tool parts and general-purpose castings.

4.9 q) ALUMINUM-ZINC ALLOYS (7 xxx series): -

Commercial wrought alloys contain zinc, magnesium and copper with smaller additions of manganese and chromium. Alloy 7075 (5.5% Zn, 2.5% Mg, 1.5%Cu), alloy 7079 (4.3% Zn, 3.3% Mg, 0.6% Cu) and alloy 7178 (6.8% Zn, 2.7% Mg, 2.0% Cu) develop the highest tensile strengths obtainable in aluminum alloys.

The susceptibility of these alloys to stress corrosion has been minimized by the addition of chromium and by proper heat treatment. They are used in applications requiring high strength and good corrosion resistance, such as aircraft structural parts.

The aluminum-zinc casting alloy known as 40E, containing 5.5% Zn, 0.6% Mg, 0.5% Cr and 0.2% Ti provides high mechanical properties without solution treatment. This alloy also has fair casting characteristics and good corrosion resistance. It is used for aircraft fittings, turret housings and radio equipments.

4.9 r) CORROSION RESISTANCE OF ALUMINUM AND ALUMINUM ALLOYS: -

The high corrosion resistance of aluminum is due to the self-protecting, thin, invisible oxide film that forms immediately on exposing surfaces to the atmosphere. This film protects the metal from further corrosion. If the oxide film is removed, in many environments, a new film will form immediately and the metal remains fully protected.

In certain strongly acid or alkaline solutions, or in contact with moist corrosive materials that prevent access of oxygen to the aluminum surface, the protective film does not form readily. Therefore, the aluminum should be adequately protected or not used at all.

A relatively thick oxide coating on aluminum and aluminum alloys may be produced by placing the metal in to an aqueous solution containing 15 to 25% Sulphuric acid. This process, known as, anodizing, produces a clear, transparent coating containing submicroscopic pores that are usually sealed before use to

prevent absorption and staining. Sealing may be accomplished by suitable heating in hot water.

4.10 DEGRADATION OF METALS: -

There are two broad classes by which metal products degrade during service.

Corrosion

Wear

4.10 a) CORROSION: -

Corrosion may be defined as "the destruction of a material by chemical, electrochemical or metallurgical interaction between the environment and the material". Generally it is slow but persistent in character. In some instances the corrosion products exist as a thin adherent film which merely stains or tarnishes the metal and may act as a retardant to further corrosive action. In other cases, the products of corrosion are bulky and porous in character, offering no protection.

Corrosion causes damage in the billions of dollars each year. It is a complex problem. In some cases, such as direct chemical attack, corrosion is highly obvious, but in other cases, such as intergranular corrosion, it is less obvious but just as damaging.

The basic cause of corrosion is the instability of metals in their refined forms. The metals tend to revert to their natural states through the processes of corrosion.

4.10 b) ELECTROCHEMICAL PRINCIPLES: -

Corrosion is essentially an electrochemical process resulting in part or all of the metal being transformed from the metallic to the ionic state. Corrosion requires a flow of electricity between certain areas of a metal surface through an electrolyte. The electrolyte may be plain water, salt water or acid or alkaline solutions of any concentration. To complete the electric circuit, there must be two electrodes, an anode and a cathode, and they must be connected. The electrodes may be two different kinds of metals, or they may be different areas on the same piece of metal. The connection between the anode and the cathode may be a metallic bridge, but in corrosion, it is usually achieved simply by contact. In order for the electricity to flow there must be a potential difference between the electrodes.

4.10 c) TYPES OF CORROSION: -

There are many types of corrosion. Only the most important types will be discussed here.

Uniform Corrosion: -

When the entire surface of the metal is attacked to the same degree, it is known as uniform corrosion. This type is unusual in metals, since they are rarely so homogeneous that the surface will be evenly corroded. Familiar examples are general rusting of iron and tarnishing of silverware.

Pitting Corrosion: -

This is an example of non-uniform corrosion resulting from in-homogeneities in metal due to inclusions, coring and distorted zones. These in-homogeneities set up differences of potential at localized spots to cause deep isolated holes.

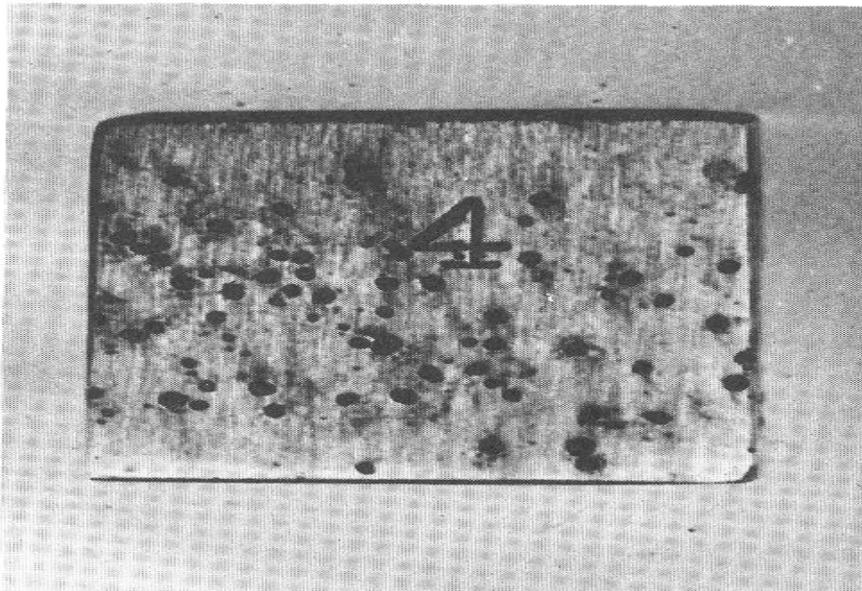


FIGURE 4.30 - PITTING OF 304 SS PLATE BY ACID CHLORIDE SOLUTION

Cavitation Corrosion: -

It is caused by the collapse of bubbles and cavities within a liquid. Vibrating motion between a surface and a liquid is such that repeated loads are applied to the surface, causing very high stresses when these bubbles form and collapse regularly. These collapses produce high stress impacts which gradually remove

particles of the surface, eventually forming deep pits, depressions and pockmarks.

Crevice Corrosion: -

It is a general term including accelerated attack at the junction of two metals exposed to a corrosive environment. Corrosion is more likely to occur in crevices which retain solutions and take longer to dry out. It is also possible for corrosion to occur at crevices even when they are completely immersed. Accelerated attack can occur because of a differential in oxygen concentration. Oxygen has relatively easy access to the outside of the joint, which is cathodic. The metal in the joint is relatively anodic. The deposit of insoluble corrosion product around the anodic center tends to more completely exclude oxygen, resulting in a low oxygen concentration area and increased electrical potential. If the action continues, a pit forms in the center. Corrosion always occurs in the region of oxygen deficiency. Crevices can also lead to differences in metal-ion concentrations at different locations. For example, it is possible for an area in a crevice to have a higher metallic-ion concentration than the area outside. Thus, corrosion can take place in the region of metal-ion deficiency at the edge of a mechanical joint.

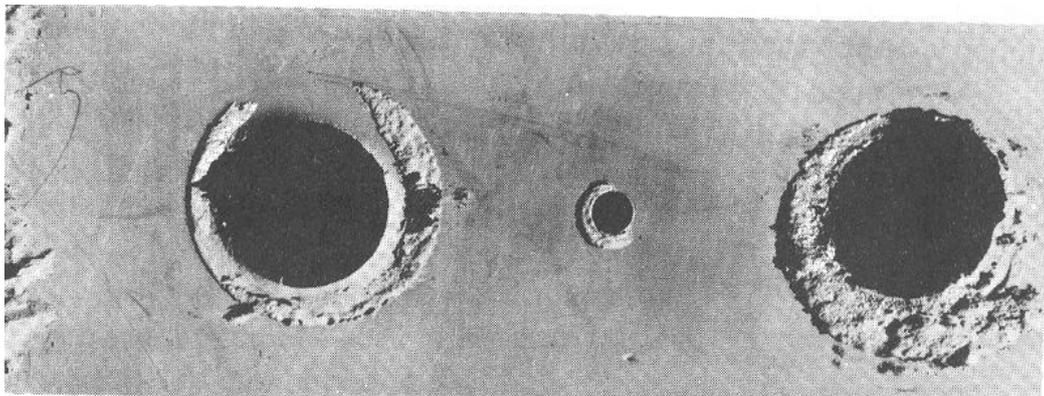


FIGURE 4.31 - CREVICE CORROSION OF A PLATE IMMERSSED IN SEA WATER

The best way to eliminate this type of corrosion is to eliminate crevices entirely by changing the design or by filling in joints that are liable to cause trouble.

Fretting Corrosion: -

It is a common type of surface damage produced by vibration, which results in striking or rubbing at the interface of close-fitting, highly loaded surfaces. Such corrosion is common at surfaces of clamped or press fits, splines, keyways and other close-fitting parts subject to minute relative movement. This type of corrosion is a mechanical-chemical phenomenon. When two components rub together, adhesive forces cause small particles of the surface to weld. With

continued slight motion, the welded particles tear away from the opposing surfaces and react chemically with the atmosphere, forming debris or powder in the joint.

Intergranular Corrosion: -

It is another type of non-uniform corrosion when a potential difference exists between the grain boundaries and the rest of the alloy. This type of corrosion usually takes place when precipitation of a phase from a solid solution occurs. Since precipitation usually takes place faster at the grain boundaries, the material in the vicinity of the grain boundary becomes depleted of the dissolved element, creating a difference of potential, and the grain boundary will dissolve preferentially. Often a visual examination of the part will not reveal the extent of the damage and in most cases there is an appreciable loss in mechanical properties. Intergranular corrosion is a severe problem in the welding of stainless steels where it is also termed as weld decay.

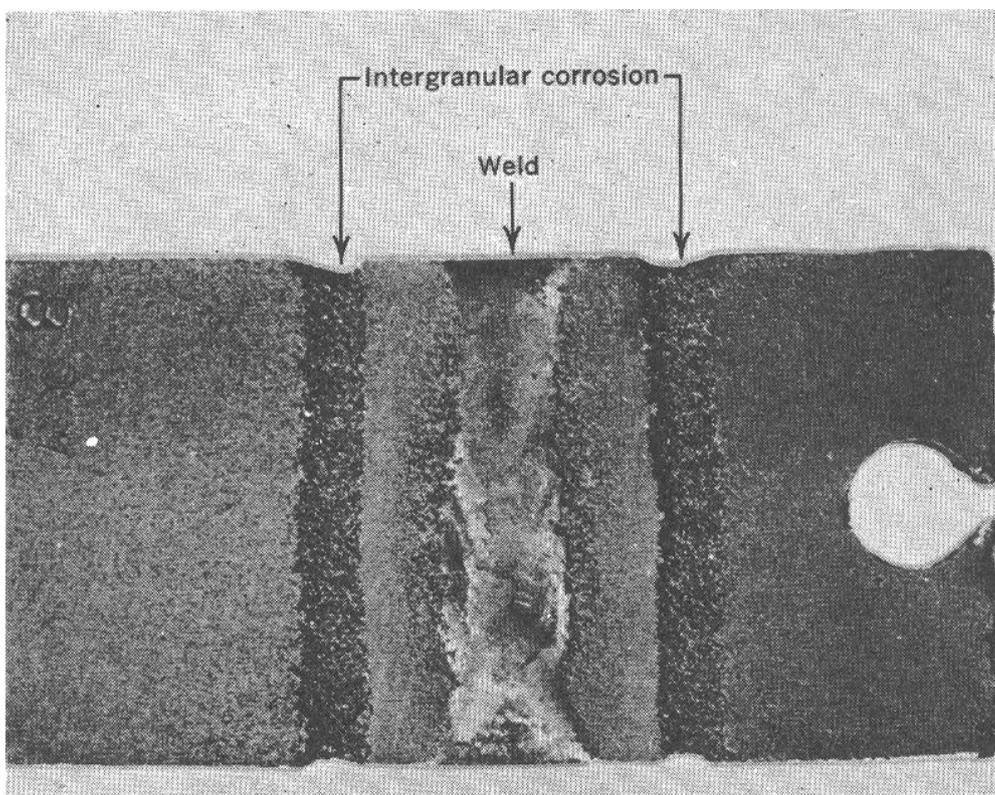


FIGURE 4.32 - WELD DECAY IN A STAINLESS STEEL

Stress-Corrosion: -

Stress corrosion is acceleration of corrosion in certain environments when metals are externally stressed or contain internal tensile stresses due to cold working. The cracks may be transgranular or intergranular or a combination of both. The

magnitude of stress necessary to cause failure depends on the corrosive medium and on the structure of the base metal. Stress corrosion is one of the most important types of corrosion because it can occur in so many metals. Almost any metal can be attacked in certain environments, yet the conditions that cause cracking in one metal will not cause cracking in another. Thus, it is difficult to predict where attack will occur.

Some stainless steels are susceptible to stress-corrosion cracking in the presence of chlorides, e.g. in solutions of sodium chloride, calcium chloride and several others. Stress-corrosion cracking has been recognized as the major cause of austenitic stainless steel failure in processes involving a chloride-containing environment.

Stress-corrosion cracking can also occur in stressed copper alloys when they are exposed to ammonia and its compounds, especially in the presence of oxygen and carbon dioxide. The danger of cracking can be minimized by avoiding residual stresses, by using protective coatings and in the case of brasses, by keeping zinc content below 15% or by proper stress-relieve annealing. Brasses containing 20-40% Zn are highly susceptible to attack.

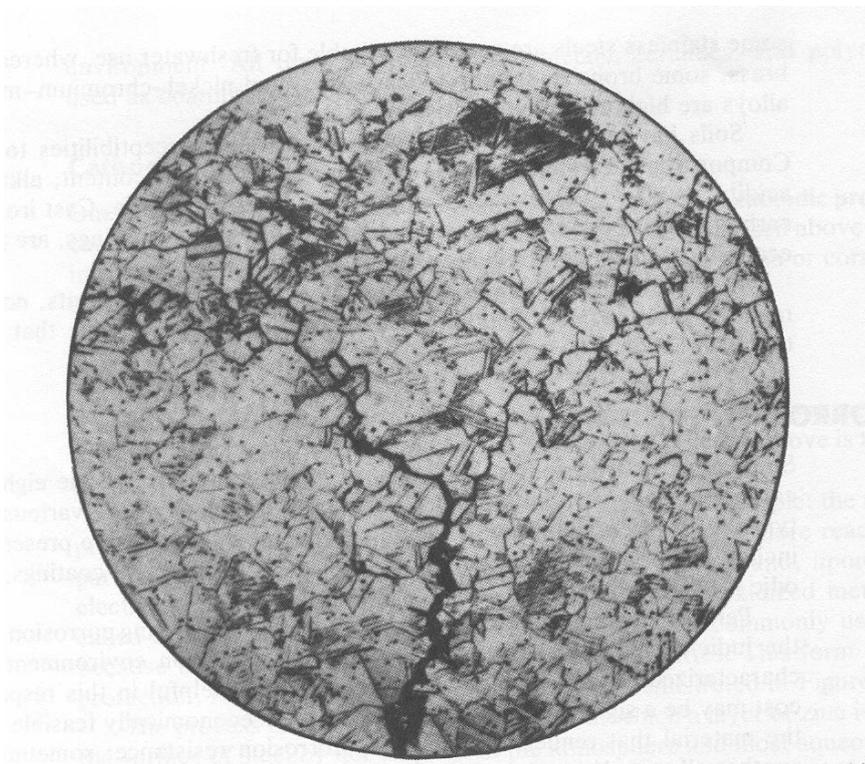


FIGURE 4.33 - PHOTOMICROGRAPH SHOWING STRESS CORROSION CRACKING IN BRASS

Intergranular and stress corrosion have a very serious effect on the mechanical properties of the metal. The reduction in strength is not due to the amount of metal removed but rather due to the stress concentration produced by the fine cracks.

Preferential Corrosion: -

Preferential corrosion of one of the components may even occur in single-phase solid solution alloys. Dezincification in brass is an example of this kind of corrosion.

Galvanic Corrosion: -

It occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte. The more reactive metal in the particular environment will experience corrosion; the more inert metal will be protected from corrosion.

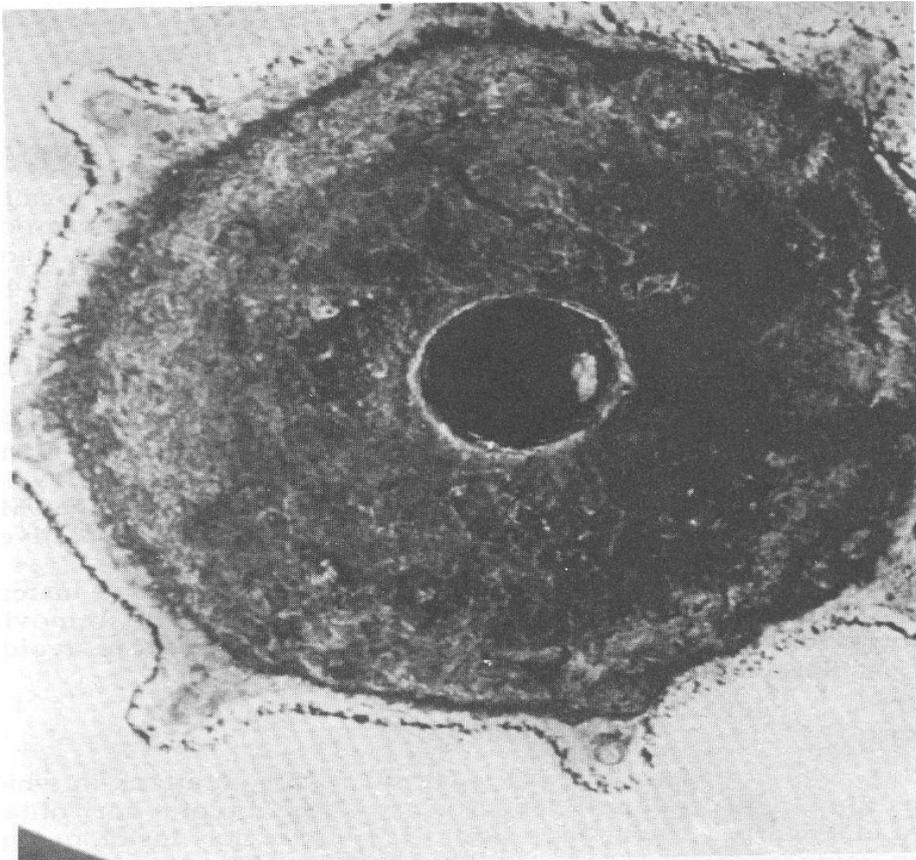


FIGURE 4.34 - GALVANIC CORROSION OF A MAGNESIUM SHELL THAT WAS CAST AROUND A STEEL CORE

Liquid-metal Corrosion: -

In certain types of nuclear reactors for the production of atomic power, liquid metals such as bismuth and sodium are used as heat-transfer medium. The path of the liquid metal is a closed loop with one leg at high temperature in the reactor core and the other leg at lower temperature in a heat exchanger. The

solubility of a solid in the liquid usually increases with the increase in temperature. Therefore, there is a tendency for the solid to dissolve up to its solubility limit in the cooler leg. The hot leg is continually corroded and the cold leg becomes plugged with the deposited corrosion products.

The most effective method of controlling this type of corrosion is by use of inhibitors in the liquid metal. Zirconium has been used as an effective inhibitor in liquid bismuth to decrease the liquid-metal corrosion.

4.10 d) METHODS FOR COMBATING CORROSION: -

Many methods are used industrially to prevent corrosion by selection of the proper alloy and structure or by surface protection of a given material. The most important ones are:

Use of high-purity metals

Use of alloy additions

Use of special heat treatments

Proper design

Cathodic protection

Use of inhibitors

Surface coatings

In most cases, the use of high-purity metals tends to reduce pitting corrosion by minimizing in-homogeneities, thereby improving corrosion resistance.

Alloy additions may reduce corrosion by several methods. For example, austenitic stainless steels are susceptible to intergranular corrosion. This type of corrosion may be avoided either by reducing the carbon to a low value (below 0.03 %) or by converting the carbides to a more stable form. The latter method is more widely used and involves the addition of titanium or columbium.

Heat treatment which leads to homogenization of solid solutions, especially in cast alloys that are subject to coring, tends to improve corrosion resistance. Stress-relief treatments following cold working are widely used to improve the corrosion resistance of alloys susceptible to stress corrosion.

Proper design should keep contact with the corroding agent to a minimum. Joints should be properly designed to reduce the tendency for liquids to enter and be retained. Contacts between metals far apart in the electromotive series should be avoided or, otherwise, the metals should be separated by rubber or plastic to reduce the possibility of galvanic corrosion.

Cathodic protection is obtained by placing the metal that would normally corrode in electrical contact with one that is above it in the galvanic series. The more active metal thus becomes the anode. The metals generally used to prevent this type of corrosion are magnesium and zinc.

Inhibitors are chemical which when added to the corrosive solution, reduce or eliminate its corrosive effect. In most cases, the inhibitor will form a protective layer on the metal surface.

Surface coatings include paints, salt and oxide films and metallic coatings. Metallic coating is mostly use to prevent corrosion. Metallic coatings may be obtained by a variety of methods such as metallizing, hot dipping, electroplating, diffusion and cladding.

4.10 e) WEAR OF METALS: -

Wear may be defined as unintentional deterioration resulting from use or environment. It may be considered essentially a surface phenomenon. Wear is one of the most destructive influences to which metals are exposed.

The displacement and detachment of metallic particles from a metallic surface may be caused by contact with

Another metal (adhesive or metallic wear)

A metallic or a nonmetallic abrasive (abrasion), or

Moving liquids or gases (erosion).

Erosion is usually accompanied by some form of corrosion.

Wear involving a single type is rare, and in most cases both abrasive and adhesive wear occur. Each form of wear is affected by a variety of conditions, including environment, type of loading, relative speeds mating parts, lubricant, temperature, hardness, surface finish, presence of foreign particles, and composition and compatibility of the mating parts involved. Since in most machinery applications wear can rarely be avoided completely even with the best lubrication, it is common practice to use a hard metal and a relatively soft one together. The softer material is used (as in a bearing) for the part which is most economical to replace.

4.10 f) MECHANISM OF WEAR:-

In adhesive wear, also called scoring, galling, seizing and scuffing, tiny projections produce friction by mechanical interference, with the relative motion of contacting surfaces increasing resistance to further movement. If the driving force is sufficient to maintain movement, the interlocked particles are deformed. If they are of a brittle material, they may be torn off. This leads to the conclusion that wear resistance will be improved by preventing metal-to-metal contact and by increasing the hardness to resist initial indentation, increasing the toughness to resist tearing out of metallic particles, and increasing the surface smoothness to eliminate the projections.

Abrasive wear occurs when hard particles slide or roll under pressure across a surface, or when a hard surface rubs across another surface. The abrading particles from the harder object tend to scratch or gouge the softer material. These hard particles may also penetrate the softer metal and cause the tearing off of metallic particles.

The ease with which the deformed metal may be torn off depends upon the toughness. Therefore, hardness and toughness, the same properties that influence adhesive wear also determine abrasive wear. Of these two factors, hardness is probably the more important one.

4.10 g) FACTORS INFLUENCING WEAR:-

Lubrication is an important contributing factor to wear resistance, particularly in adhesive wear. In "thick-film" lubrication, a sufficiently thick lubricating film completely eliminates metallic contact and metallic wear is reduced to a negligible amount.

The dominant frictional factor for metallic materials is believed to be welding. When two clean surfaces of the same metal actually touch each other, they will weld together because of atomic attraction. If, by friction, sufficient pressure is applied to break through any residual separating material such as oil, dirt, or adsorbed moisture, and the surfaces are in sufficient contact to have elastic or plastic deformation occur, then seizing or welding takes place. The softening of metals by high temperatures increases the ease of plastic deformation and facilitates welding. Seizing may cause complete stoppage, or if relative motion is not prevented, pieces of the opposite face may be pulled out. The resultant projection then may cause scoring, galling, and excessive local wear.

Many methods may be used to minimize the danger of seizing. One is to use thin layers of hard surfacing material. The use of at least one metal that forms some sort of lubricating film or thin, tightly adherent oxide, sulfide, or phosphide coating is frequently helpful. Aluminum oxide is very effective in preventing welding.

Impact is a factor in wear, since the suddenly applied load may cause plastic flow and a change in shape. Proper design should provide a surface compressive yield strength above the compressive stress produced by impact and sufficient support so that subsurface flow does not occur.

Fatigue failure is included in a discussion of wear since it is a gradual deterioration due to use. Proper design to eliminate stress concentrations at notches and sharp angles will increase fatigue strength. Since fatigue failures are always due to tensile stress, residual compressive stress at the surface will provide additional protection. This may be accomplished by case hardening, such as carburizing and by shot peening.

4.10 h) PROTECTION AGAINST WEAR:-

Many materials and methods are available for protection against wear. The selection of a particular material and process requires a thorough analysis of the actual service conditions, knowledge of applicability and limitations of the particular material and process, and data concerning the cost involved.

Various techniques for providing surface protection to wear are as follows:

Electroplating

Anodizing

Diffusion

Metal spraying

Hard facing

Selective heat treatment

ELECTROPLATING:-

The wear resistance of a metal part can be improved by electroplating a harder metal on its surface. The metals most often plated on base materials are chromium, nickel, and rhodium. Indium plating has been used to reduce the wear of lead bearings.

Two types of chromium plating used industrially are known as *hard chromium* and *porous chromium*. The hardness of chromium plate is equivalent to 950 to 1050 Vickers. Another factor contributing to the reduction of wear is the low coefficient of friction of chromium plate. Chromium plating is used in the cylinders and piston rings of internal-combustion engines. Non-galling is another useful property of chromium plate. The high corrosion resistance of chromium is also helpful in reducing wear under corrosive conditions.

The hardness of nickel plate is from 140 to 425 Vickers depending upon the nickel plating solution used.

The hardness of rhodium plate is from 540 to 640 Vickers, and its wear resistance is between those of nickel plate and chromium plate.

ANODIZING:-

The formation of an oxide coating by anodizing may be used to improve the wear resistance of certain metals. The anodizing process is usually applied to aluminum, magnesium, zinc, and other alloys. In anodizing, the work is the anode, and oxide layers are built up on the base metal. Since the newest oxide layer always forms next to the base metal in order for the processes to continue, the previously formed oxide layers must be porous enough to allow the oxygen ions to pass through them.

Anodizing aluminum is simply a method of building up a much thicker oxide coating than may be obtained by exposure to air. The films produced are transparent, thicker and more porous than those produced by other electrolytes. Aircraft parts such as hydraulic pistons, guide tracks, gears, cams, screws, swivel joints, and friction locks are made of hard-coated aluminum alloys.

The production of a hard wear-resistant surface by anodizing has greatly extended the uses of magnesium and its alloys. Flash anodic coatings are often used as a base for paint adherence.

Anodizing zinc produces a coating which has greater resistance to wear than chromate films. Anodic zinc coatings are used for cartridge case airplane propeller blades, wire-screen cloth, and refrigerator shelves.

DIFFUSION:-

Several processes improve wear resistance by diffusion of some element into the surface layers. These are:

Carburizing

Cyaniding

Carbonitriding

Nitriding

Chromizing

Siliconizing

The first four of these processes have already been discussed, and only the last two will be discussed here.

Chromizing consists of the introduction of chromium into the surface layers of the base metal. The process is not restricted to ferrous materials and may be applied to nickel, cobalt, molybdenum, and tungsten to improve corrosion resistance and heat resistance.

When it is applied to iron or steel, it converts the surface layer into a stainless-steel case. If the steel contains appreciable amounts of carbon (above 0.60 percent), chromium carbides will precipitate, increasing wear resistance. Chromized high-carbon steels have a hardness of 800 to 1000 Vickers and a low coefficient of friction. Chromizing is used on drop-forging dies, tools, hydraulic rams, pistons, and pump shafts.

Siliconizing consists of impregnation of an iron-based material with silicon. The process is carried out in the temperature range of 1700 to 1850 °F. The work is heated in contact with a silicon bearing material such as silicon carbide, and chlorine gas is used as a catalyst. The case depth ranges from 0.005 to 0.1 in, depending mainly on the carbon content of the base material. Siliconized cases are difficult to machine, although the hardness only Rockwell B 80 to 85. The increase in wear resistance by Siliconizing is due to a low coefficient of friction and non-galling properties. Siliconized cases have been used on pump shafts, conveyor chain links, cylinder liners, valve guides, valves, and fittings for the chemical and oil industries.

Metal Spraying: -

Metal spraying or flame spraying has been used for many years to build up dimensions that are undersize and to repair worn surfaces. It has found increased use for wear-resistant applications.

Sprayed coatings can be applied by several methods: Metallizing; flame-plating, which is used to deposit tungsten carbide and aluminum oxide; plasma arc spraying, which can deposit almost all inorganic materials.

In general, a sprayed metal coating is harder and more brittle and porous than equivalent cast or wrought metal. The wear resistance of sprayed metals is generally very good, but metallizing is not suitable for service involving heavy impact or extreme abrasion or where highly localized loads are applied. Metallizing is best suited for applications involving light abrasive wear, for conditions where boundary lubrication exists, and to provide a wear-resistant or corrosion-resistant surface to inexpensive base materials.

Hard Facing: -

The production of a hard wear-resistant surface layer on metals by welding is known as hard facing. This method is relatively easy to apply, requiring only the hard-facing alloys in the form of welding rods and an oxyacetylene flame or electric arc.

The advantages of hard facing are

It may be applied to localized areas subjected to wear

Hard wear-resistant compounds are available

It provides effective use of expensive alloys and protection in depth

Hard facing can be applied to most ferrous metals, but with a few exceptions it is not advisable to face nonferrous alloys having melting points below 2000 °F.

Hard facing is most extensively used where systematic lubrication against abrasion is impossible, as on oil-well drilling tools, agricultural and earth moving equipment, mining tools, engine valves and refinery or chemical processing equipment. Hard facing also extends the life of lubricated parts such as metal working dies and areas of machine parts that have a high wear rate. Hard faced surfaces are usually more wear-, heat-, and corrosion-resistant than case-hardened or flame-hardened surfaces.

There are more than 150 different compositions of hard-facing materials commercially available, ranging from steels containing only about 2 % alloy content to nickel-base and cobalt-base alloys and tungsten carbide. Tungsten carbide hard facings have the highest hardness and best wear resistance.

Selective Heat Treatment: -

The methods used for selective heat treatment are induction hardening and flame hardening. These are essentially shallow-hardening methods to produce a hardened case and relatively tough core. These methods have already been discussed in detail under "Case Hardening".

5. MECHANICAL METALLURGY

5.1 INTRODUCTION: -

Mechanical Metallurgy is the area of metallurgy, which is concerned, primarily with the response of metals to forces or loads. The forces may arise from the use of the metal as a member or part in a structure or machine, in which case it is necessary to know something about the limiting values, which can be withstood without failure. This section has been discussed earlier to some extent under Physical Metallurgy. On the other hand, the objective may be to convert a cast ingot into a more useful shape, such as flat plate, and here it is necessary to know the conditions of temperature and rate of loading which minimize the forces that are needed to do the job. There are many other metal shaping/metal fabrication techniques such as casting, welding, brazing, soldering etc.

Classification Of Metal Forming Processes: -

The importance of metals in modern technology is due to the ease with which they may be formed into useful shapes such as tubes, rods, and sheets. Useful shapes may be generated in two basic ways:

By plastic deformation processes in which the volume and mass of metal are conserved and the metal is displaced from one location to another.

By metal removal or machining processes in which material is removed in order to give it the required shape.

Major emphasis is given to plastic deformation processes. Hundreds of processes have been developed for specific metal working applications. However, these processes may be classified into only a few categories on the basis of the type of forces applied to the work piece as it is formed into shape. These categories are:

Direct-compression-type processes

Indirect-compression processes

Tension-type processes

Bending processes

Shearing processes

In direct-compression processes the force is applied to the surface of the work piece, and the metal flows at right angles to the direction of the compression. The chief examples of this type of process are forging and rolling shown in figure below. Indirect-compression processes include wire drawing and tube drawing,

extrusion, and the deep drawing of a cup. The primary applied forces are frequently tensile, but the indirect compressive forces developed by the reaction of the work piece with the die reach high values. Therefore, the metal flows under the action of principal directions. The best example of a tension-type forming process is stretch forming, where a metal sheet is wrapped to the contour of a die under the application of tensile forces. Bending involves the application of bending to the sheet, while shearing involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear.

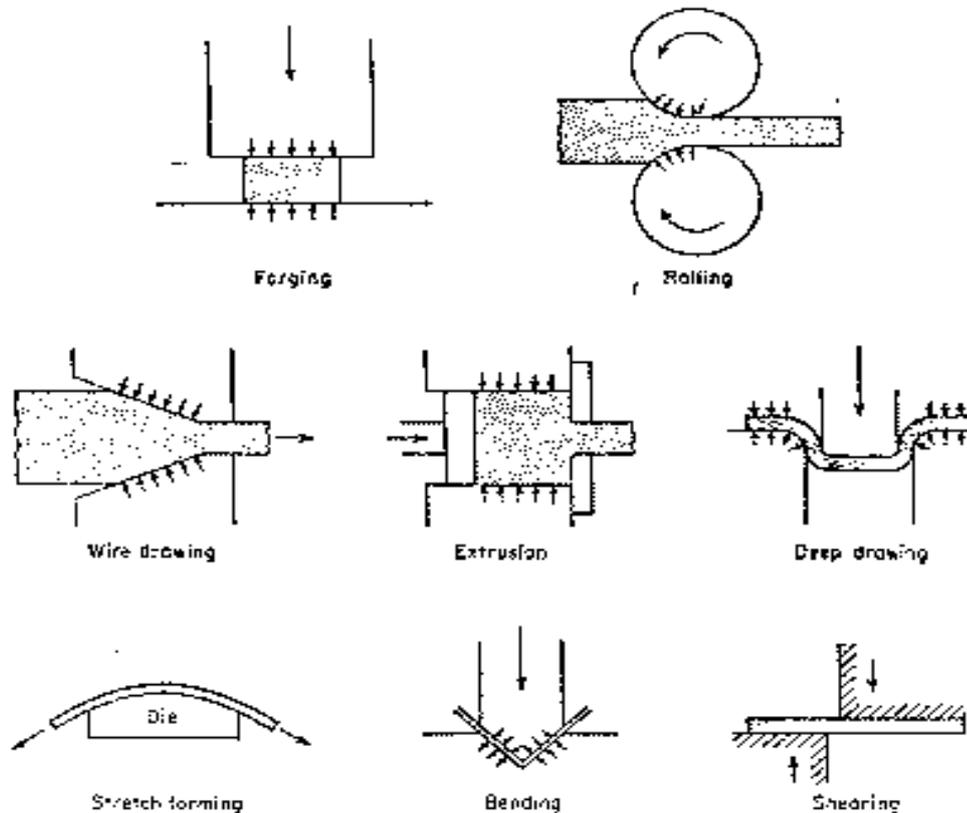


FIGURE 5.1 - VARIOUS FORMING OPERATIONS

TEMPERATURE IN METAL WORKING: -

Forming processes are commonly classified into hot-working and cold-working operations. Hot-working is defined as deformation under conditions of temperature and strain rate such that recovery processes take place simultaneously with the deformation. On the other hand, cold-working is deformation carried out under conditions where recovery processes are not effective. In hot-working the strain hardening and distorted grain structure produced by deformation are very rapidly eliminated by the formation of new strain-free grains as the result of re-crystallization. Very large deformations are possible in hot-working because the recovery processes keep pace with the

deformation. Hot-working occurs at an essentially constant flow stress, and because the flow stress decreases with increasing temperature, the energy required for deformation is generally much less for hot-working than for cold-working. Since strain hardening is not relieved in cold-working, the flow stress increases with deformation. Therefore, the total deformation that is possible without causing fracture is less for cold-working than for hot-working, unless the effects of cold-work are relieved by annealing.

It is important to realize that the distinction between cold-working and hot-working does not depend on any arbitrary temperature of deformation. For most commercial alloys a hot-working operation must be carried out at a relatively high temperature in order that a rapid rate of re-crystallization be obtained. However, lead and tin re-crystallize rapidly at room temperature after large deformations, so that the working of these metals at room temperature constitutes hot-working. Similarly, working tungsten at 2000°F, in the hot-working range for steel, constitutes cold-working because this high-melting metal has a re-crystallization temperature above this working temperature.

HOT WORKING: -

Hot-working is the initial step in the mechanical working of most metals and alloys. Not only does hot-working result in a decrease in the energy required to deform the metal and an increased ability to flow without cracking, but the rapid diffusion at hot-working temperatures aids in decreasing the chemical inhomogeneities of the cast-ingot structure. Blowholes and porosity are eliminated by the welding together of these cavities, and the coarse columnar grains of the casting are broken down and refined into smaller equiaxed re-crystallized grains. These changes in structure from hot-working result in an increase in ductility and toughness over the cast state.

However, there are certain disadvantages to hot-working. Because high temperatures are usually involved, surface reactions between the metal and the furnace atmosphere become a problem. Ordinarily hot-working is done in air, oxidation results, and a considerable amount of metal may be lost. Reactive metals like titanium are severely embrittled by oxygen, and therefore they must be hot-worked in an inert atmosphere or protected from the air by a suitable barrier. Surface decarburization of hot-worked steel can be a serious problem, and frequently extensive surface finishing is required to remove the decarburized layer. Rolled-in oxide makes it difficult to produce good surface finishes on hot-rolled the dimensional tolerances for hot-worked mill products greater than for cold-worked products. Further, the structure and properties of hot-worked metals are generally not so uniform over the cross section as in metals which have been cold-worked and annealed. Since the deformation is always greater in the surface layers, the metal will have a finer re-crystallized grain size in this region. Because the interior will be at higher temperatures for longer times

during cooling than will be the external surfaces, grain growth can occur in the interior of large pieces, which cool slowly from the working temperatures.

The lower temperature limit for the hot-working of a metal is the lowest temperature at which the rate of re-crystallization is rapid enough to eliminate strain hardening in the time when the metal is at temperature. For a given metal or alloy the lower hot-working temperature will depend on such factors as the amount of deformation and the time that the metal is at temperature. Since the greater the amount of deformation the lower the re-crystallization temperature, the lower temperature limit for hot-working is decreased for large deformations. Metal which is rapidly deformed and cooled rapidly from temperature will require a higher hot-working temperature for the same degree of deformation than will metal slowly deformed and slowly cooled.

The upper limit for hot-working is determined by the temperature at which either melting or excessive oxidation occurs. Generally the maximum working temperature is limited to 100°F below the melting point. This is to allow for the possibility of segregated regions of lower-melting-point material. Only a very small amount of a grain-boundary film of a lower-melting constituent is needed to make a material crumble into pieces when it is deformed. Such a condition is known as hot shortness, or burning.

Most hot-working operations are carried out in a number of multiple passes, or steps. Generally the working temperature for the intermediate passes is kept well above the minimum working temperature in order to take advantage of the economies offered by the lower flow stress. It is likely that some grain growth will occur subsequent to the re-crystallization at these temperatures. Since a fine-grain-sized product is usually desired, common practice is to lower the working temperature for the last pass to the point where grain growth during cooling from the working temperature will be negligible. This finishing temperature is usually just above the minimum re-crystallization temperature. In order to ensure a fine re-crystallized grain size, the amount of deformation in the last pass should be relatively large.

COLD WORKING:-

Cold-working of a metal results in an increase in strength or hardness and a decrease in ductility. When cold-working is excessive, the metal will fracture before reaching the desired size and shape. Therefore, in order to avoid such difficulties, cold-working operations are usually carried out in several steps, with intermediate annealing operations introduced to soften the cold-worked metal and restore the ductility. This sequence of repeated cold-working and annealing is frequently called the cold-work –anneal cycle. Figure below schematically illustrates the property changes involved in this cycle.

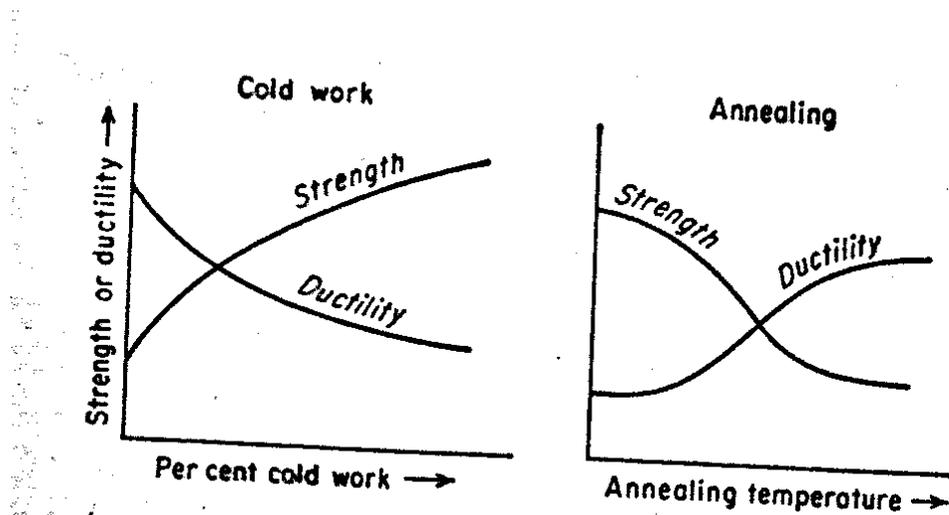


FIGURE 5.2 VARIATION OF STRENGTH & DUCTILITY IN COLD WORK-ANNEAL CYCLE

Although the need for annealing operations increases the cost of forming by cold-working, particularly for reactive metals which must be annealed in vacuum or inert atmospheres, it provides a degree of versatility which is not possible in hot-working operations. By suitably adjusting the cold-work-anneal cycle the part can be produced with any desired degree of strain hardening. If the finished product must be stronger than the fully annealed material, then the final operation must be a cold-working step with the proper degree of deformation to produce the desired strength. This would probably be followed by a stress relief to remove residual stresses. Such a procedure to develop a certain combination of strength and ductility in the final product is more successful than trying to achieve the same combinations of properties by partially softening a fully cold-worked material, because the re-crystallization process proceeds relatively rapidly and is quite sensitive to small temperature fluctuations in the furnace. If it is desired to have the final part in the fully softened condition, then an anneal follows the last cold-working step.

It is customary to produce cold-worked products like strip and wire in different tempers, depending on the degree of cold reduction following the last anneal. The cold-worked condition is described as the annealed (soft) temper: quarter-hard, half-hard, three-quarter-hard, full-hard, and spring temper. Each temper condition indicates a different percentage of cold reduction following the annealing treatment.

5.2 FORGING PROCESSES:-

Forging is the working of metal into a useful shape by hammering or pressing. It is the oldest of the metal working arts, having its origin with the primitive black smith of Biblical times. The development of machinery to replace the arm of the smith occurred early during the industrial revolution. Today there is a wide

variety of forging machinery which is capable of making parts ranging in size from a bolt to a turbine rotor or an entire airplane wing.

Most forging operations are carried out hot, although a certain metals may be cold-forged. Two major classis of equipment are used for forging operations. The forging hammer, or drop hammer, delivers rapid impact blows to the surface of the metal, while the forging press subjects the metal to a slow speed compressive force.

The two broad categories of forging processes are opened-die forging and closed-die forging. Open-die forging is carried out between flat dies or dies of vary simple shape. The process is used mostly for large objects or when the number of parts produced is small. Often open-die forging is used to form the work piece for closed-die forging. In closed-die forging the work piece deformed between two die halves which carry the impressions of the desired final shape. The work piece is deformed under high pressure in a closed cavity, and thus precision forgings with closed dimensional tolerances can be produced.

Open-die Forging:-

The simplest open-die forging operation is the upsetting of a cylindrical billet between two flat dies. As the metal flows laterally between the advancing die surfaces, there is less deformation at the die interfaces because of the friction forces than at the mid height plane. Thus, the sides of the upset cylinder become barreled. As a general rule, metal will flow most easily toward the nearest free surface because this represents the lowest frictional path.

The effect of friction in restraining metal flow is used to produce shapes with simple dies. Edging dies are used to shape the ends of the bars and to gather metal. As shown in Fig below, the metal is confined by the die from flowing in the horizontal direction but it is free to flow laterally to fill the die. Fullering is used to reduce the cross-sectional area of a portion of the stock. The metal flows are outward and away from the center of the Fullering die. An example of the use of this type of operation would be in the forging of a connecting rod for an internal combustion engine. The reduction in cross-section of the work with concurrent increase in length is called drawing down, or drawing out. If the drawing down operation is carried out with concave dies so as to produce a bar of smaller diameter, it is called swaging. Other operations which can be achieved by forging are bending, twisting, extrusion, piercing punching and indenting.

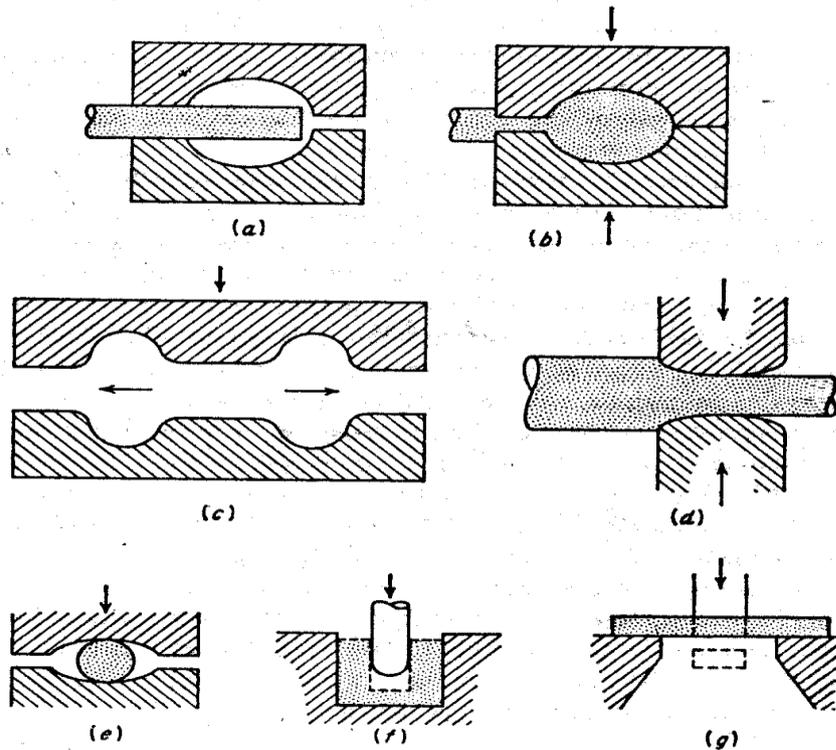


FIGURE 5.3 - FORGING OPERATIONS

CLOSED-DIE FORGING:-

Closed-die forging used carefully machined matching die blocks to produce forgings to close dimensional tolerances. In closed-die forging the forging billet is usually first fullered and edged to place the metal in the correct place for subsequent forging. The pre-shaped billet is then placed in the cavity of the blocking die and rough forged to close to the final shape. The greatest change in the shape of the metal usually occurs in this step. It is then transferred to the finishing die, where it is forged to final shape and dimensions. Usually the blocking cavity and the finishing cavity or machined into the same die block. Fullering and edging impressions are often placed on the edges of die block.

It is important to use enough metal in the forging blank so that the die cavity is completely filled. Because it is difficult to put just the right amount of metal in the correct places during Fullering and edging, it is customary to use a slight excess of metal. When the dies come together for the finishing step, the excess metal squirts out of the cavity as a thin ribbon of metal called flash. In order to prevent the formation of a very wide flash, a ridge, known as a flash gutter, is usually provided as shown below in figure. The final step in making a closed die forging is the removal of the flash with a trimming die.

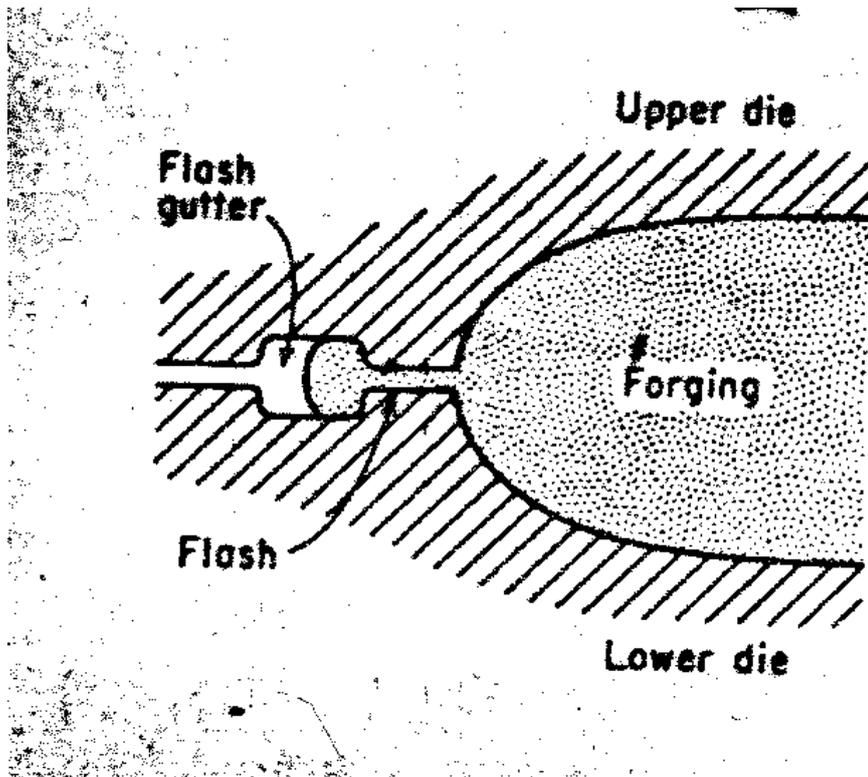


FIGURE 5.4 - CLOSE DIE FORGING

The flash serves two purposes. As described above, it acts as a "safety valve" for excess metal in the closed die cavity. Of more important, the flash regulates the escape of metal, and thus the thin flash greatly increases the flow resistance of the system so that the pressure builds up to the high values to ensure that the metal fills all recesses of the die cavity.

In closed-die forging it is particularly difficult to produce parts with sharp fillets, wide thin webs, and high ribs. Moreover, forging die must be tapered to facilitate removal of the finished piece. This draft allowance is approximately 5° for steel forgings.

FORGING EQUIPMENT: -

Forging equipment may be classified with respect to the principle of operation. In *forging hammers* the force is supplied by a falling weight or ram. These are energy restricted machines since the deformation results from dissipating the kinetic energy of the ram. *Mechanical forging presses* are stroke-restricted machines since the length of the press stroke and the available load at various positions of the stroke represent their capability. *Hydraulic presses* are load-restricted machines since their capability for carrying out a forming operation is limited chiefly by the maximum load capacity.

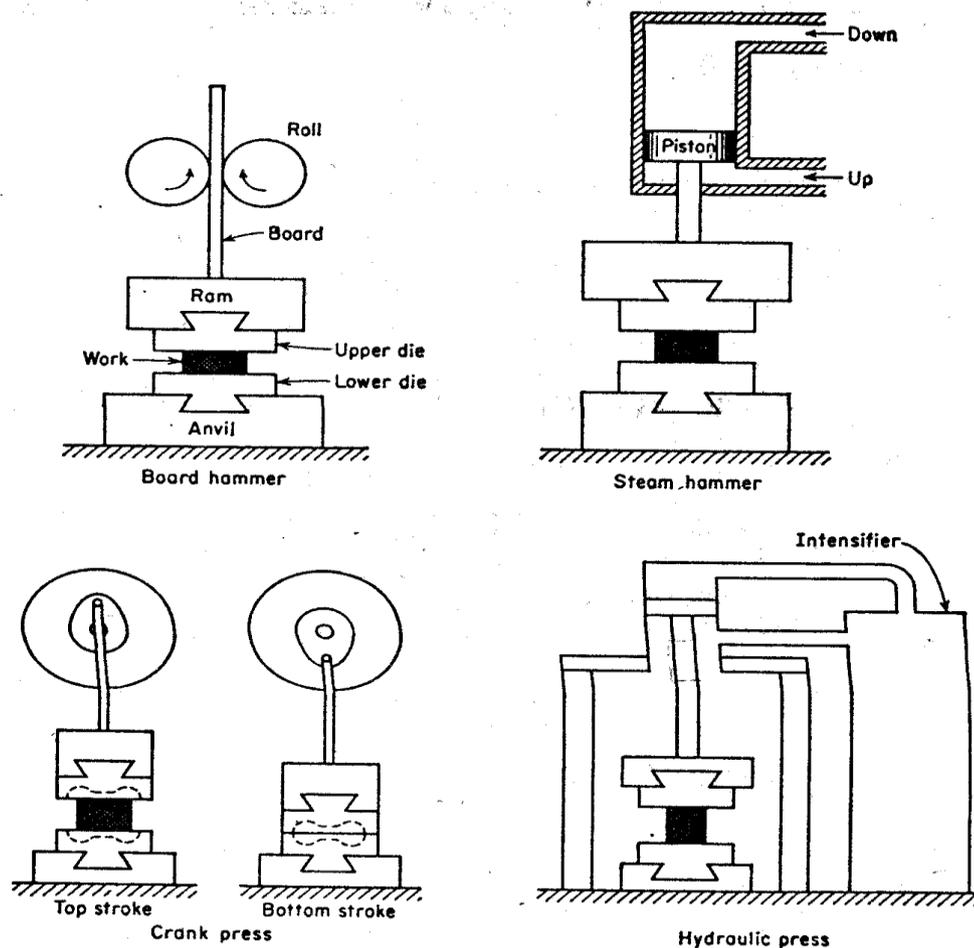


FIGURE 5.5 - FORGING EQUIPMENTS

FORGING HAMMER: -

The most commonly used piece of forging equipment is the forging hammer. The two basic types of hammers are the board hammer and the power hammer. In the board hammer the upper die and ram are raised by friction rolls gripping the board. When the board is released, the ram falls under the influence of gravity to produce the blow energy. The board is immediately raised again for another blow. Forging under a hammer usually is done with repeated blows. Hammers can strike between 60 and 150 blows per minute depending on size and capacity. The energy supplied by the blow is equal to the potential energy due to the weight of the ram and the height of fall.

Greater forging capacity is achieved with the power hammer in which the ram is accelerated on the down stroke by steam or air pressure in addition to gravity. Steam or air also is used to raise the ram on the upstroke.

An important feature of the power hammer is that the energy of the blow can be controlled, whereas in the board hammer the mass and height of fall are fixed.

Power hammers are preferred over board hammers for closed-die forging. This equipment ranges in size from 1,000 to 50,000 lb and can produce forgings ranging in weight from a few pounds to several tons. The forging hammer is the cheapest source of a high forging load.

FORGING PRESSES: -

Forging presses are of either mechanical or hydraulic design. Presses are rated on the bases of the force developed at the end of the stroke. The ram stroke is shorter than in a hammer or hydraulic press, so that mechanical presses are best suited for low profile forging. Mechanical presses with load rating from 300 to 12000 tons are available. The blow of a press is more like a squeeze than like the impact of a hammer. Because of this, dies can be less massive and die life is longer than with a hammer. However, the initial cost of a press is much higher than that of a hammer, so that large production runs are needed. The production rate is comparable to that of a hammer, but since each blow is of equal force, a press may be less suitable for carrying out preliminary shaping and finishing operations in the same piece of equipment.

HYDRAULIC PRESSES: -

Hydraulic presses are load-restricted machines in which hydraulic pressure moves a piston in a cylinder. A chief feature is that the full press load is available at any point during the full stroke of the ram. This feature makes the hydraulic press ideally suitable for extrusion type forging operations. The ram velocity can be controlled and even varied during the stroke. The hydraulic press is a relatively slow-speed machine. This results in longer contact time, which may lead to problems with heat loss from the work piece and die deterioration. On the other hand, the slow squeezing action of a hydraulic press results in close-tolerance forgings. Hydraulic presses are available in ratings from 500 to 18,000 tons, although several presses with ratings of 50,000 tons have been built. The initial cost of a hydraulic press is higher than that of a mechanical press of equal capacity.

FORGING DEFECTS: -

INCOMPLETE PENETRATION: -

If the deformation during forging is limited to the surface layers, as when light, rapid hammer blows are used, the dendritic ingot structure will not be broken down at the interior of the forging. Incomplete forging penetration can readily be

detected by macro etching a cross section of the forging. To minimize incomplete penetration, forgings of large cross section are usually made on a forging press.

Surface Cracks: -

Surface cracking can occur as a result of excessive working of the surface at too low a temperature or as a result of hot shortness. A high sulfur concentration in the furnace atmosphere can produce hot shortness in steel and nickel. Cracking at the flash of closed-die forgings is another surface defect, since the crack generally penetrates into the body of the forging when the flash is trimmed off. This type of cracking is more prevalent the thinner the flash in relation to the original thickness or by relocating the flash to a less critical region of the forging. It also may be avoided by hot trimming or stress relieving the forging prior to cold trimming of the flash.

Cold Shut / Fold: -

Common surface defect in closed forgings is the cold shut, or fold. A cold shut is a discontinuity produced when two surfaces of metal fold against each other without welding completely. This can happen when metal flows past part of the die cavity that has already been filled or that is only partly filled because the metal failed to fill in due to a sharp corner, excessive chilling, or high friction.

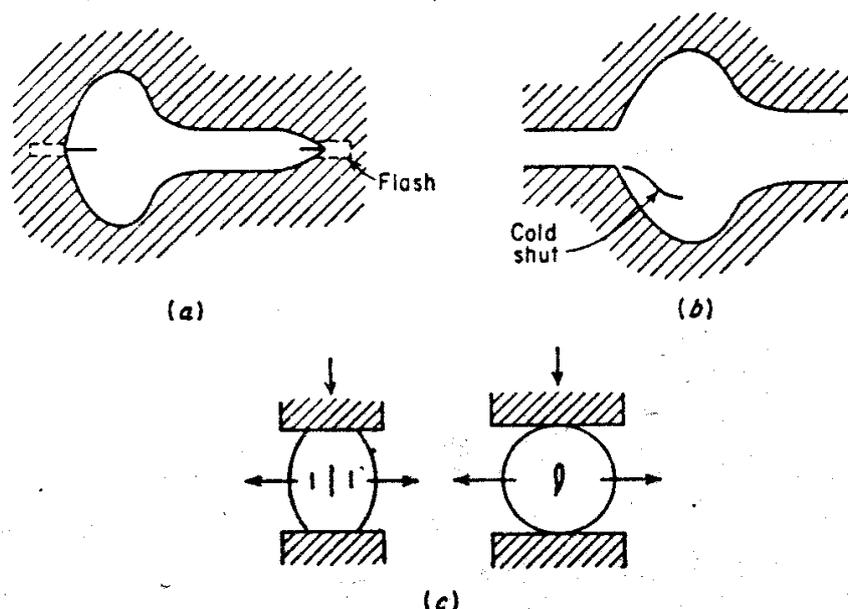


FIGURE 5.6- FORGING DEFECTS

Scale Pockets: -

Loose scale or lubricant residue that accumulates in deep recesses of the die forms scale pockets and causes underfill. Incomplete descaling of the work piece results in forged-in scale on the finished part.

Internal Cracks: -

Secondary tensile stresses can develop during forging, and cracking can thus be produced. Internal cracks can develop during the upsetting of a cylinder or a round, as a result of the circumferential tensile stresses. Proper design of the dies, however, can minimize this type of cracking. In order to minimize bulging during upsetting and the development of circumferential tensile stresses, it is usual practice to use concave dies.

5.3 ROLLING PROCESSES: -

The process of plastically deforming metal by passing it between rolls is known as rolling. This is the most widely used metal working process because it lends itself to high production and close control of the final product. In deforming metal between rolls, the work is subjected to high compressive stresses from the squeezing action of the rolls and to surface shear stresses as a result of the friction between the rolls and the metal. The frictional forces are also responsible for drawing the metal into the rolls.

The initial break down of ingots into blooms and billets is generally done by hot-rolling. This is followed by further hot-rolling into plate, sheet, rod, bar, pipe, rails, or structural shapes. The cold-rolling of metals has reached a position of major importance in industry. Cold-rolling produces sheet, strip, and foil with good surface finish and increased mechanical strength, at the same time maintaining close control over the dimensions of the product.

CLASSIFICATION OF ROLLED PRODUCTS: -

The terminology used to describe rolled product is fairly loose, and sharp limits with respect to dimensions cannot always be made for steel making terminology. A bloom is the product of the first break down of the ingot. Generally the width of a bloom equals its thickness, and the cross-sectional area is greater than 36 in². A further reduction by hot-rolling results in a billet. The minimum cross-section of a billet is about 1½ by 1½ in. It should be noted that in nonferrous metallurgical terminology a billet is any ingot, which has received hot-working by rolling, forging, or extrusion, or the term may refer to a casting which is suitable for hot-working, as an extrusion billet. A slab refers to a hot-rolled ingot with cross-sectional area greater than 16 in² and with a width that is at least twice the thickness. Blooms, billets, and slabs are known as

semi finished products because they are subsequently formed into other mill products. The differentiation between plate and sheet is determined by the thickness of the product. In general, plate has a thickness greater than $\frac{1}{4}$ in, although there are exceptions to this limit, depending on the width. Sheet and strip refer to rolled products which generally have a thickness less than $\frac{1}{4}$ in. In general strip refers to the rolled product with a width no greater than 24 in, while sheet refers to the product of greater width.

ROLLING MILLS:-

A rolling mill consists basically of rolls, bearings, a housing for containing these parts, and a drive for applying power to the rolls and controlling their speed. The forces involved in rolling can easily reach many millions of pounds. Therefore, very rigid construction is needed, and very large motors are required to provide the necessary power.

Rolling mills can be conveniently classified with respect to the number and arrangement of the rolls. The simplest and most common type of rolling mill is the two-high mill. Rolls of equal size are rotated only in one direction. The stock is returned to the entrance, or rear, of the rolls for further reduction by hand carrying or by means of a platform, which can be raised to pass the work above the rolls. An obvious improvement in speed results from the use of a two-high reversing mill, in which the work can be passed back and forth through the rolls by reversing their direction of rotation. Another solution is the three-high mill, consisting of an upper and lower driven roll and middle roll which rotates by friction.

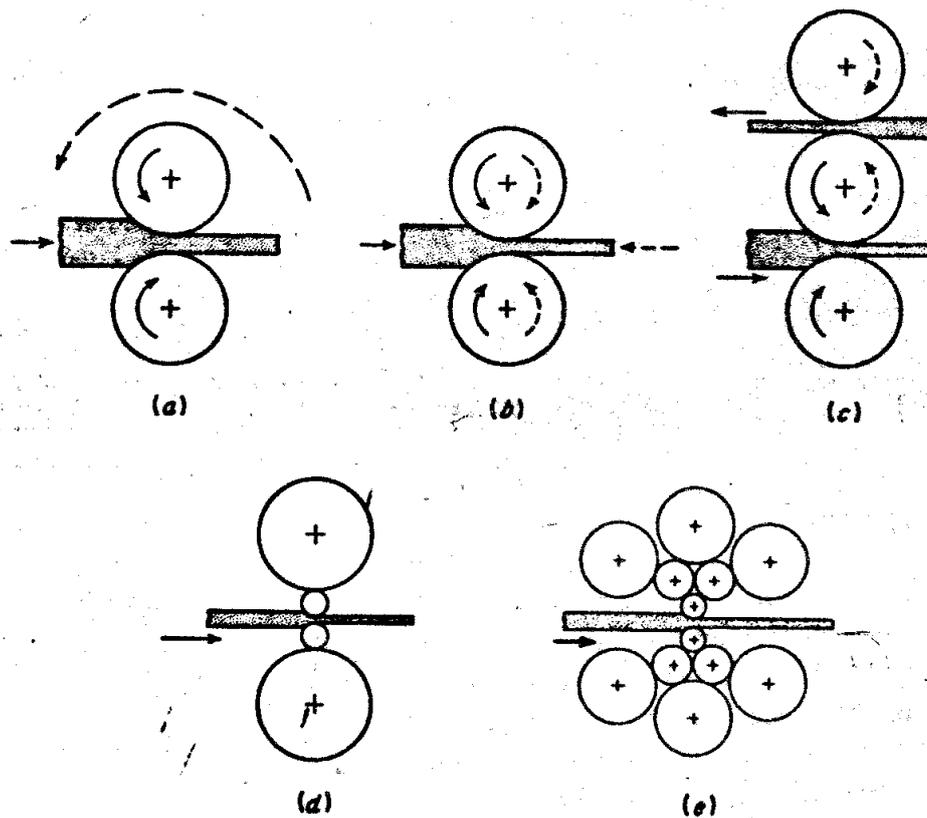


FIGURE 5.7 - ROLLING MILLS

A large decrease in the power required for rolling can be achieved by the use of small-diameter rolls. However, because small-diameter rolls have less strength and rigidity than large rolls, larger diameter backup rolls must support them. The simplest mill of this type is the four-high mill. Very thin sheet can be rolled to very loose tolerances on a mill with small diameter work rolls. The cluster mill, in which two backing rolls support each of the work rolls, is a typical mill of this kind. The Sendzimir mill is a modification of the cluster mill, which is very well adapted to rolling thin sheet or foil from high-strength alloys.

For high production it is common to install a series of rolling mills one after another in tandem. Each set of rolls is called a stand.

HOT ROLLING:-

The first hot-working operation for most steel product is done on the primary roughing mill (sometimes called blooming, slabbing, or cogging mills). These mills usually are two-high reversing mills with 24- to 54-in-diameter rolls. They are designated by the size of the rolls, as for example, a 45-in slabbing mill. The objective of this operation is the breakdown of the cast ingot into blooms or slabs for sequent finishing into bars, plate, or sheet. Heavy scale is removed initially by rolling the ingot while lying on edge, while the thickness is reduced by

rolling after the ingot has been turned 90 so as to be lying flat. There is appreciable spreading of the ingot width in hot-rolling of ingots. To maintain the desired width and preserve the edges, the ingot is turned 90° on intermediate passes and passed through edging grooves in the rolls.

The production of slabs from cast ingots by hot-rolling can be eliminated by using continuous casting to produce the slab directly from the molten steel. Another method is to produce slabs by bottom-pressure casting.

Plates are produced by hot-rolling, either from reheated slabs or directly from ingots. Rolling between straight horizontal rolls and then trimming all edges produce sheared plate.

The general distinction between strip and sheet is that strip usually is less than 24 in wide. However, irrespective of width, the equipment for producing these products is known as a continuous hot-strip mill.

In hot-rolling steel the slabs are heated initially at 2000 to 2400°F. The temperature in the last finishing stand varies from 1300 °F to 1600°F, but should be above the upper critical temperature to produce uniform equiaxed ferrite grains.

COLD ROLLING:-

Cold-rolling is used to produce sheet and strip with superior surface finish and dimensional tolerances compared with hot-rolled strip. In addition, the strain hardening resulting from the cold reduction may be used to give increased strength. A greater percentage of rolled nonferrous metals is finished by cold-rolling compared with rolled-steel products. The starting material for cold-rolled steel sheet is pickled hot-rolled break down coil from the continuous hot-strip mill. Cold-rolled nonferrous sheet may be produced from hot-rolled strip, or in the case of certain copper alloys it is cold-rolled directly from the cast state.

High-speed four-high tandem mills with three to five stands are used for the cold-rolling of steel sheet, aluminum, and copper alloys. Generally, this type of mill is designed to provide both front and back tension. A continuous mill has high capacity and results in low labor costs.

The total reduction achieved by cold-rolling generally will vary from about 50 to 90 percent. In establishing the reduction in each pass or in each stand, it is desirable to distribute the work as uniformly as possible over the various passes without falling very much below the maximum reduction for each pass. Generally the lowest percentage reduction is taken in the last pass to permit better control of flatness, gage, and surface finish. One rational procedure for developing cold-rolling schedules is to adjust the reduction in each pass so as to produce a constant rolling load.

ROLLING DEFECTS:-

A variety of problems in rolling, leading to specific defects, can arise depending on the interaction of the plastically deforming work piece with the elastically deforming rolls and rolling mill. Under the influence of the high rolling forces the rolls flatten and bend, and the entire mill is elastically distorted. Because of mill spring the thickness of the sheet exiting from the rolling mill is greater than the roll gap set under no load conditions. In order to roll to precise thickness it is necessary to know the elastic constant of the mill. The elastic constant for most screw-loaded rolling mills is 4,000 to 8,000 tons/in, while hydraulically loaded mills may exceed 10,000 tons/in.

Elastic flattening of the rolls with increasing roll pressure results in a condition where the rolls eventually deform more easily than the work piece. Thus, for a given material and set of rolling conditions, there will be a minimum thickness below which the sheet can be reduced no further. Thinner gage sheet can be produced with small diameter rolls.

The roll gap must be perfectly parallel, otherwise one edge of the sheet will be decreased more in thickness than the other, and since volume and width remain constant, this edge of the sheet elongates more than the other, and the sheet bows.

Problems with shape and flatness are brought about by in-homogeneities in deformation in the rolling direction of the sheet. Other forms of in-homogeneous deformation can lead to problems with cracking.

Edge cracking is minimized in commercial rolling practice by employing vertical edge rolls, which keep the edges straight and thus prevent a cumulative build up of secondary tensile stresses due to barreling of the edge.

Defects other than cracks can result from defects introduced during the ingot stage of production or during rolling. Internal defects such as fissures are due to incomplete welding of pipe and blowholes. Longitudinal stringers of non metallic inclusions or pearlite banding in steels are related to melting and solidification practices. In severe cases these defects can lead to laminations which drastically reduce the strength in the thickness direction. Because rolled products usually have a high surface to volume ratio, the condition of the surface during all stages of production is of importance. In order to maintain high quality, the surface of billets must be conditioned by grinding, chipping, or burning with an oxygen lance to remove surface defects such as slivers, seams, and scabs. Scratches due to defective rolls or guides must be guarded against in cold-rolled sheet.

5.4 EXTRUSION PROCESSES: -

Extrusion is the process by which a block of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure. In general, extrusion is used to produce cylindrical bars or hollow tubes, but shapes of irregular cross section may be produced from the more readily extrudable metals, like aluminum. Because of the large forces required in extrusion, most metals are extruded hot under conditions where the deformation resistance of the metal is low. However, cold extrusion is possible for many metals and has become an important commercial process. The reaction of the extrusion billet with the container and die results in high compressive stresses, which are effective in reducing the cracking of materials during primary break down from the ingot. This is an important reason for the increased utilization of extrusion in working of metals difficult to form, like stainless steels, nickel-based alloys, and other high-temperature materials.

The two basic types of extrusion are direct extrusion and indirect extrusion (also called inverted, or back, extrusion). Fig (a) illustrates the process of direct extrusion. The metal billet is placed in a container and driven through the die by the ram. A dummy block, or pressure plate, is placed at the end of the ram in contact with the billet. Fig (b) illustrates the indirect extrusion process. A hollow ram carries the die, while the other end of the container is closed with a plate. Frequently for indirect extrusion, the ram containing the die is kept stationary, and the container with the billet is caused to move. Because there is no relative motion between the wall of the container and the billet in indirect extrusion, the friction forces are lower and the power required for extrusion is less than for direct extrusion. However, there are practical limitations to indirect extrusion because the requirement for using a hollow ram limits the loads, which can be applied.

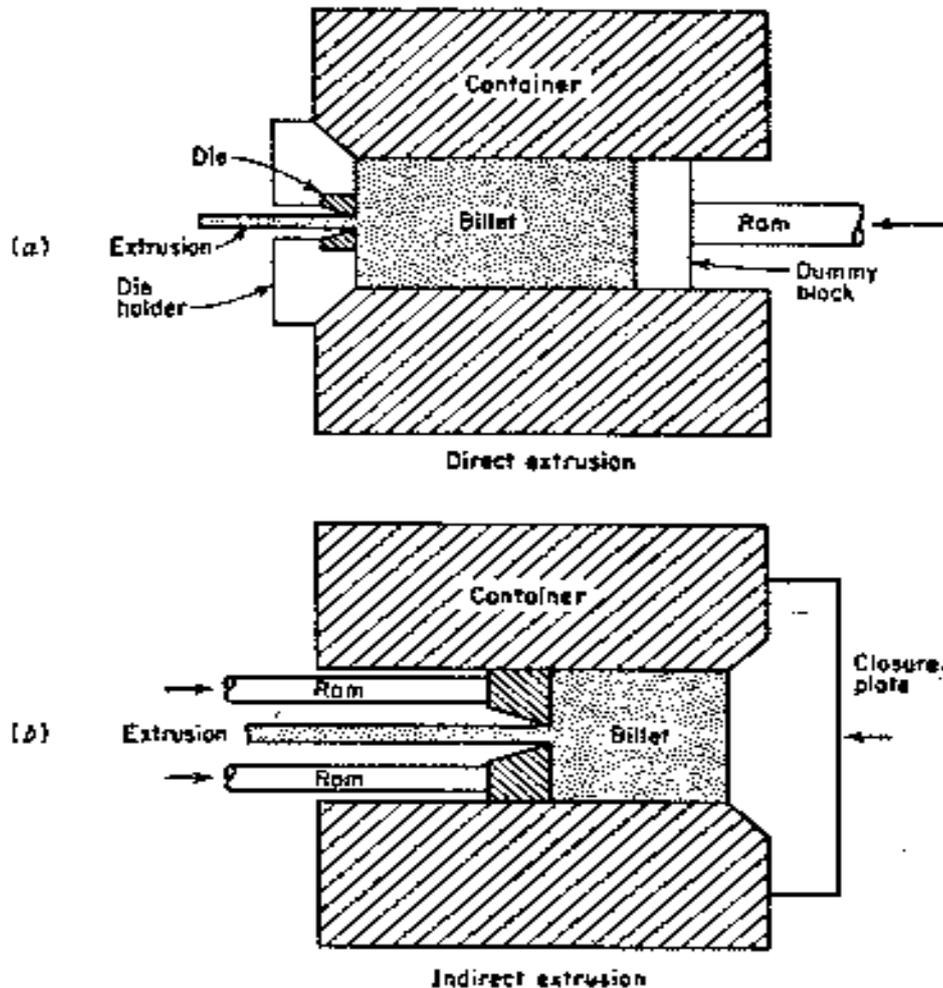


FIGURE 5.8 - TYPES OF EXTRUSION

Tubes can be produced by extrusion by attaching a mandrel to the end of the ram. The clearance between the mandrel and the die wall determines the wall thickness of the tube. Tubes are produced either by starting with a hollow billet or by a two-step extrusion operation in which a solid billet is first pierced and then extruded.

Impact extrusion is a process used to produce short lengths of hollow shapes, such as collapsible toothpaste tubes. It may be either indirect or direct extrusion, and it is usually performed on a high-speed mechanical press. Although the process generally is performed cold, considerable heating results from the high speed deformation. Impact extrusion is restricted to the softer metals such as lead, tin, aluminum, and copper.

EXTRUSION EQUIPMENT: -

Most extrusions are made with hydraulic presses. Hydraulic extrusion presses are classified into horizontal and vertical presses, depending upon the direction of travel of the ram. Vertical extrusion presses are generally built with capacities

of 300 to 2,000 tons. They have the advantages of easier alignment between the press ram and the tools, higher rate of production, and the need considerable headroom, and to make extrusions of appreciable length, a floor pit is frequently necessary. Vertical presses will produce uniform cooling of the billet in the container, and thus symmetrically uniform deformation will result. In a horizontal extrusion press the bottom of the billet which lies in contact with the container will cool more rapidly than the top surface, unless the extrusion container is internally heated, and therefore the deformation will be non-uniform. Warping of bars will result, and non-uniform wall thickness will occur in tubes. Presses with a capacity of 1,500 to 5,000 tons are in regular operation, while a few presses of 14,000 tons capacity have been constructed.

The ram speed of the press can be an important consideration since high ram speeds are required in high temperature extrusion where there is a problem of heat transfer from the billet to the tools. Ram speeds of 1,000 to 1,500 in/min may be used in extruding refractory metals, and this requires a hydraulic accumulator system with the press. At the other extreme, aluminum and copper alloys are prone to hot shortness so that the ram speed must be restricted to a few inches per minute. In this case, direct-driven pumping systems are adequate

HOT EXTRUSION: -

The principal variables which influence the force required to cause extrusion are

The type extrusion (direct vs. indirect)

The extrusion ratio

The working temperature

The speed of deformation

In Fig shown below, the extrusion pressure is plotted against ram travel for direct and indirect extrusion. Extrusion pressure is the extrusion force divided by the cross sectional area of the billet. The rapid rise in pressure during the initial ram travel is due to the initial compression of the billet to fill the extrusion container. For direct extrusion the metal begins to flow through the die at the maximum value of pressure, the break through pressure. As the billet extrudes through the die the pressure required to maintain flow progressively decreases with decreasing length of the billet in the container. For indirect extrusion there is no relative motion between the billet and the container wall. Therefore, the extrusion pressure is approximately constant with increasing ram travel and represents the stress required to deform the metal through the die. While this appears to be an attractive process, in practice it is limited by the need to use a hollow ram which creates limitations on the size of the extrusion and the extrusion pressures which can be at the end of the stroke the pressure builds up rapidly and it is usual to stop the ram travel so as to leave a small

discard in the container. This discard often contains defects which are unwanted in the product.

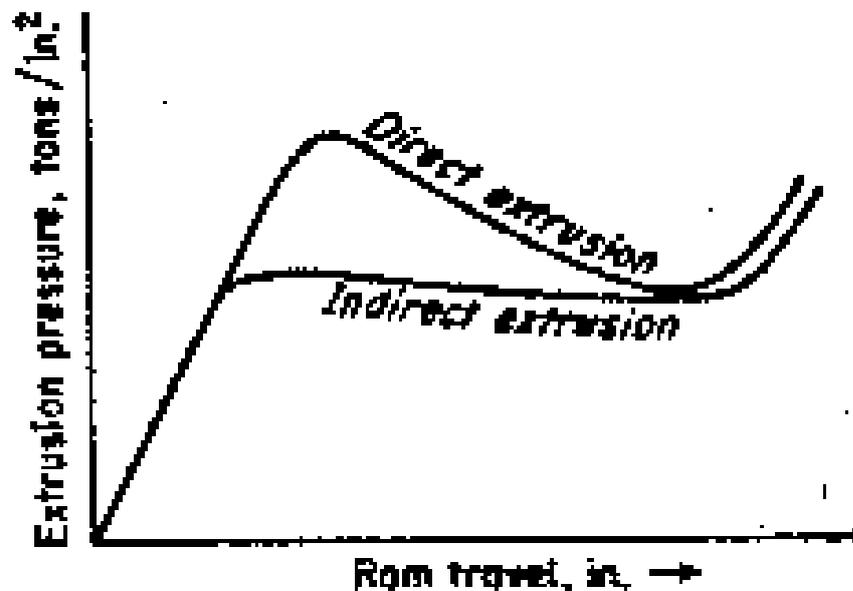


FIGURE 5.9 - TYPES OF EXTRUSION

The extrusion ratio is the ratio of the internal cross-sectional area of the billet to the final cross-sectional area after extrusion, $R = A_0/A_f$. Extrusion ratios reach about 40:1 for hot extrusion of steel and be as high as 400:1 for aluminum. It is important to note the distinction between the fractional reduction in area, $r = 1 - A_f/A_0$, and the extrusion ratio R , $R = 1/(1-r)$. For large deformation R is more descriptive parameter. For example, the change in fractional reduction from 0.95 to 0.98 appears relatively minor, yet it corresponds to a change in area ratio from $R = 20:1$ to $R = 50:1$.

Most metals are extruded hot so as to make advantage of the decrease in flow stress or deformation resistance with increasing temperature. Since hot-working introduces the problems of oxidation of the billet and the extrusion tools and softening of the die and tools, as well as making it more difficult to provide adequate lubrications, it is advantageous to use the minimum temperature which will provide the metal with suitable plasticity. The upper hot-working temperature is the temperature at which hot shortness occurs, or for pure metals, the melting point. Because of the extensive deformation produced in extrusion, considerable internal heating of the metal also results. Therefore, the top working temperature should be safely below the melting point or hot shortness range. For a given deformation, higher working temperatures are generally possible with extrusion than can be used in forging or rolling because the high compressive stress minimize cracking.

Increasing the ram speed produces an increase in the extrusion process. A tenfold increase in the speed results in about a 50 percent increase in pressure. Greater cooling of the billet occurs at low extrusion speeds. When this becomes pronounced, the pressure required for direct extrusion will actually increase with increasing ram travel because of the increased flow stress as the billet cools. The higher the temperature of the billet, the greater the effect of low extrusion speed on the cooling of the billet. Therefore, high extrusion speeds are required with high strength alloys that need high extrusion temperatures. The temperature rise due to deformation of the metal is greater at high extrusion speeds, and therefore problems with hot shortness may be accentuated. The selection of the proper extrusion speed and temperature is best determined by trial and error for each alloy and billet size.

COLD EXTRUSION / IMPACT EXTRUSION: -

Great advances have also been made in cold extrusion, a family of processes more commonly known as Cold / impact extrusion. Figure below illustrates the basic principles of several variations, *forward & backward* using both open and closed dies. These processes were first used to shape low strength metals such as lead, tin, zinc and aluminum in to products such as collapsible tubes for tooth pastes, medications and other creams; small "cans" for shielding electronic components; zinc cases for flash light batteries; and large cans for food and beverages.

HYDROSTATIC EXTRUSION: -

It is another type of cold extrusion. Here high pressure fluid surrounds the work piece and applies the force necessary to extrude it through the die. The product emerges into either atmospheric pressure or low pressure fluid filled chamber. The process resembles direct extrusion, but the fluid pressure surrounding the billet prevents any upsetting. Since the billet does not come in to contact with the surrounding chamber, billet-chamber friction is eliminated, and the pressurized fluid can further act as lubricant between the billet and the die.

While process efficiency can be significantly greater than most other extrusion processes, there are problems related to the fluid and the associated high pressure, which typically range between 900 and 1700 MPa. Temperatures are limited since the fluid acts as a heat sink and the pressurizing fluids burn or decompose at moderately low temperatures. Seals must be designed to contain the pressurized fluid without leaking, and measures must be taken to prevent the complete ejection of the product, often referred to as *blowout*. Because of these features, hydrostatic extrusion is usually employed only where the process offers

unique advantages that cannot be duplicated by the more conventional methods.

DEFECTS IN EXTRUSION: -

There are a number of defects, which must be guarded against. Because of the in-homogeneous deformation in the direct extrusion of a billet, the center of the billet moves faster than the periphery. As a result, the dead metal zone extends down along the outer surface of the billet. After about two-thirds of the billet is extruded, the outer surface of the billet moves towards the center and extrudes through the die near the axis of the rod. Since the surface of the billet often contains an oxidized skin, this type of flow results in internal oxide stringers. This defect can be considered to be an internal pipe, and it is known as the extrusion defect. On the transverse section through the extrusion this will appear as annular ring of oxide. The tendency toward the formation of the extrusion defect increases as the container wall friction becomes greater. If a heated billet is placed in a cooler extrusion container, the outer layers of the billet will be chilled and the flow resistance of this region will increase. Therefore, there will be a greater tendency for the center part of the billet to extrude before the surface skin, and the tendency for formation of extrusion defect is increased.

One way of avoiding the extrusion defect is to carry out the extrusion operation only to the point where the surface oxide begins to enter the die and then discard the remainder of the billet. This procedure may have serious economic consequences since as much as 30 percent of the billet may remain at the point where the extrusion defects are encountered. An alternative procedure, which is frequently applied in the extrusion of brass, is to use a follower block which is slightly smaller than the inside diameter of the extrusion container. As the ram pushes the follower block forward, it scalps the billet and the oxidized surface layer remains in the container.

When extrusion is carried to the point at which the length of billet remaining in the container is about one quarter its diameter, the rapid radial flow into the die results in the creation of an axial hole, or funnel, in the back end of the extrusion. This hole may extend for some distance into the back end of the extrusion, and therefore this metal must be discarded. The length of this defect can be reduced considerably by inclining the face of the ram at an angle to the ram axis.

Surface cracking, ranging in severity from a badly roughened surface to repetitive transverse cracking called fir-tree cracking can be produced by longitudinal tensile stresses generated as the extrusion passes through the die. In hot extrusion this form of cracking usually is inter granular and is associated with hot shortness. The most common cause is too high a ram speed for the extrusion temperature. At lower temperatures where hot shortness cannot occur

transverse cracking is believed to be caused by momentary sticking in the die land and the sudden building up of pressure, and then break way.

Center burst, or chevron cracking can occur at low extrusion ratios. It is related to the influence of frictional conditions on the zone of deformation at the extrusion die. In this instance high frictional restraint at the tool-billet interface produces a sound product while center bursts occur when the friction is low.

Because of the non-uniform deformation produced in extrusion, considerable variation in hot-worked structures and properties, or in properties after heat treatment, may be expected. A common problem is variation in structure and properties from front to back end of the extrusion in both the longitudinal and transverse directions. Regions of exaggerated grain growth often are found in hot extrusions. These coarse-grain regions appear on the surface or towards the center, depending on the deformation conditions.

5.5 DRAWING PROCESS: -

INTRODUCTION: -

Drawing operation involve pulling metal through a die by means of a tensile force applied to the exit side of the die. Most of the plastic flow is caused by compression force which arises from the reaction of the metal with the die. Usually the metal has a circular symmetry, but this is not an absolute requirement. The reduction in diameter of a solid bar or rod by successive drawing is known as bar, rod, or wire drawing, depending on the diameter of the final product. When a hollow tube is drawn through a die without any mandrel or plug is used to support the inside of the tube, this is known as tube sinking. When a mandrel or plug is used to support the inside diameter of the tube as it is drawn through a die, the process is called tube drawing. Bar, wire, and tube drawing are usually carried out at room temperature. However, because large deformations are usually involved, there is considerable temperature rise during the drawing operation.

ROD AND WIRE DRAWING: -

The principles involved in the drawing of bars, rod, and wire are basically the same, although the equipment that is used is different for the different sized products. Rods and tubes, which cannot be coiled, are produced on draw benches. The rod is pointed with a swager, inserted through the die, and clamped to the jaws of the draw head. The draw head is moved either by a chain drive or by a hydraulic mechanism. Draw benches with 300,000 lb pull and 100 ft of run out are available. Draw speeds vary from about 30 to 300 ft/min.

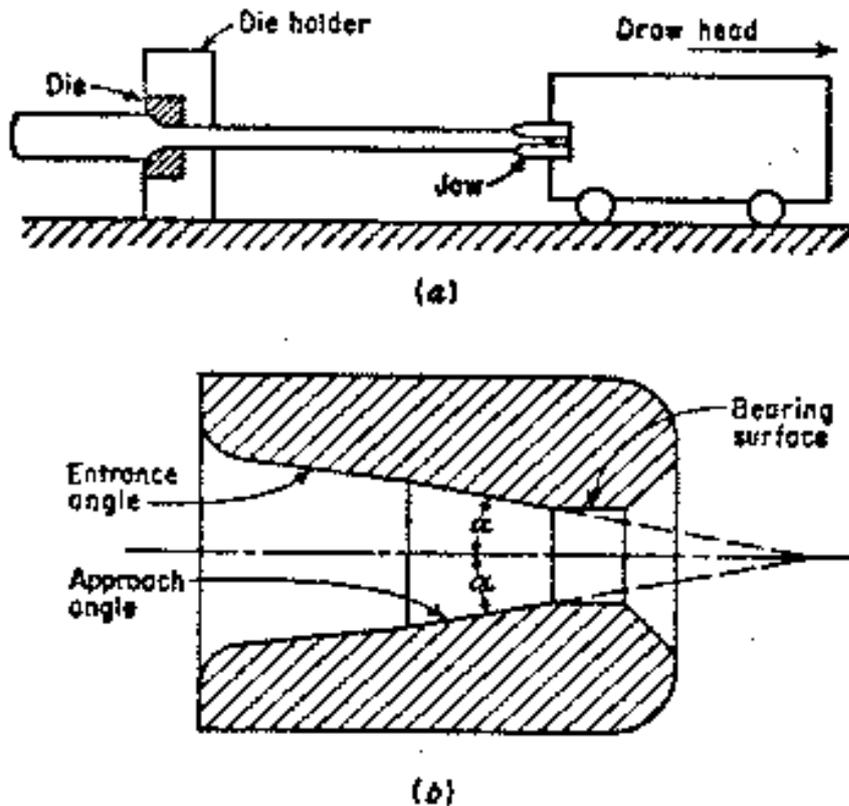


FIGURE 5.10 - DRAWING DIES

The cross section through a typical conical drawing die is shown in Fig (b). The entrance angle of the die is made large enough to allow space for the lubricant that adheres to the die. The approach angle is the section of the die where the actual reduction in diameter occurs. The bearing surface serves to guide the rod or wire as it exits from the die. An important characteristic of a drawing die is the half-die angle, denoted by α . At the present time most drawing dies are made from tungsten carbide because it provides long die life.

Wire drawing starts with hot-rolled wire rod. The rod is first cleaned by pickling to remove any scale which would lead to surface defects and excessive die wear. For the production of steel wire the next step consists in coating the wire rod with lime or plating it with a thin layer of copper or tin. The lime serves as an absorber and carrier of the lubricant during dry drawing, and it also serves to neutralize any acid remaining from pickling. In dry drawing the lubricant is grease or soap powder, while in wet drawing the entire die is immersed in a lubricating fluid.

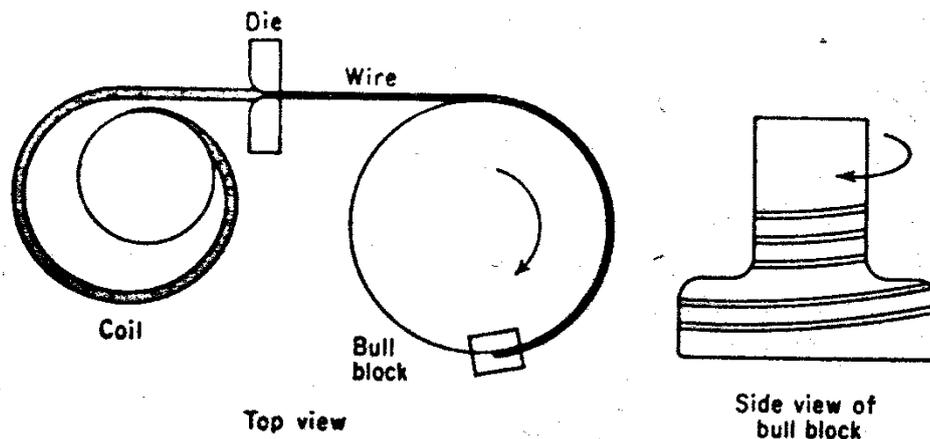


FIGURE 5.11 - WIRE DRAWING EQUIPMENT

Long lengths of thinner bar or wire (usually below $\frac{1}{2}$ -in diameter) are produced by drawing with a bull block. For coarse wire a single bull block is used, but for fine wire a large number of draw blocks are required, with the wire passing through a number of dies until it is reduced to its final size in one continuous operation. For fine wires reductions per pass of 15 to 25 percent are used, while for coarse wires the reduction per pass may 20 to 50 percent. Drawing speeds of modern wire drawing equipment may exceed 5,000 ft/min.

Non-ferrous wire and low-carbon steel wire are produced in a number of tempers ranging from dead soft to full hard. Depending on the metal and the reductions involved, intermediate anneals may be required.

DEFECTS IN ROD AND WIRE DRAWING: -

Defects in rod and wire can result from defects in the starting rod (seams, silvers, and pipe) or from the deformation process itself. The most common type of drawing defect is center burst, or chevron cracking. This also is called cupping. This center burst fracture occurs for low die angles at low reductions, and as α increases the critical reduction for freedom from center burst increases. For a given reduction and die angle, the critical reduction to prevent fracture increases with the friction.

TUBE DRAWING: -

Hollow cylinders, or tubes, which are made by hot-forming processes such as extrusion or piercing and rolling, often are cold finished by drawing. Cold-drawing is used to obtain closer dimensional tolerances, to produce better surface finishes, to increase the mechanical properties of the tube by strain

hardening, to produce tubes with thinner walls or smaller diameters than can be obtained with hot-forming methods, and to produce tubes of irregular shapes.

The three basic types of tube drawing processes are sinking; plug drawing, and material drawing. Since the inside of the tube is not supported in tube sinking, the wall thickens slightly and the internal surface becomes uneven. Because the shearing at the entry and exit of the die is large, the strain is higher for sinking and the limiting deformation is lower than for other tube producing processes.

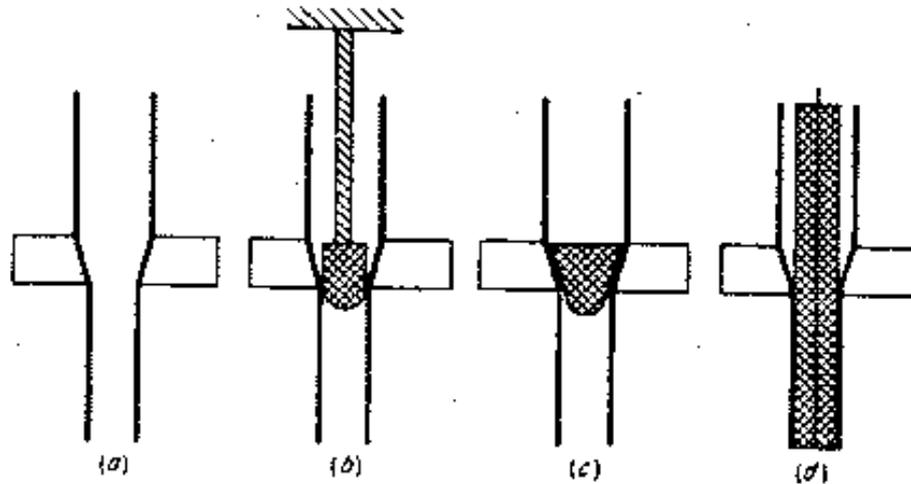


FIGURE 5.12 - METHODS OF TUBE DRAWING

Both the inner and outer diameters of the tube are controlled in drawing on a plug. The plug may be either cylindrical or conical. The plug controls the size and shape of the inside diameter and produces tubing of greater dimensional accuracy than in tube sinking. Because of the increased friction from the plug, the reduction in area seldom exceeds 30 percent. The situation where a carefully matched plug floats in the die throat is shown in Fig (c). Properly designed floating plugs can give a reduction in area of 45 percent, and for the same reduction the drawing loads are lower than for drawing with a fixed plug. An important feature of this design is that it is possible to draw and coil long lengths of tubing. However, tool design and lubrication can be very critical.

Problems with friction in tube drawing are minimized in drawing with a long mandrel. The mandrel consists of a long hard rod or wire that extends over the entire length of the tube and is drawn through the die with the tube. In tube drawing with a moving mandrel the draw force is transmitted to the metal partly by the pull on the exit section and partly by the friction forces acting along the tube mandrel interface.

5.6 CASTING:-

INTRODUCTION: -

Casting is the oldest process for metal forming. It consists of introducing the molten metal into a cavity or mould of the required form and allowing the metal to solidify. Casting is the most versatile, flexible, and cheapest method of metal shaping. There is practically no limitation to the size, shape & alloy of casting that may be made. It is possible to cast intricate and complex which are difficult to produce economically by any other manufacturing process. Cast parts range in size from a fraction of a centimeter and a fraction of a gram (such as individual teeth on a zipper) to over 10 meters and many tons (such as the huge propeller). Moreover, the casting processes have distinct advantages when the production involves parts having hollow sections or internal cavities, parts that contain irregular curved surface, very large parts or parts made from metals that are difficult to machine. The process is also suitable for mass production resulting in decrease in cost per part.

Despite all these advantages, there are some inherent defects in casting associated with the solidification process. These include:

Shrinkage

Segregation

Gas porosity

Low hot strength

Cold shuts

Cracks

The various casting processes are distinguished primarily by the mould material (whether sand, metal or other materials) and by pouring methods (gravity, vacuum, low pressure or high pressure).

CASTING PROCESSES: -

The most commonly used casting processes are as under:

Sand Casting

Die Casting

Permanent Mould Casting

Centrifugal Casting

Investment or Lost Wax Casting

Shell Moulding

1. SAND CASTING: -

In this case a sand mould is used for casting the desired shape of the required alloy. A sand mould may be defined as a preformed sand container into which molten metal is poured and allowed to solidify. In general sand moulds are destroyed as the casting is removed from them. Sand moulds make it possible to cast complex shapes that might not be possible otherwise.

Different types of sand mould can be made for making different castings. Green sand moulds are made from moist sand and are used for particularly all ferrous and non-ferrous castings. They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause certain defects in the castings. Green sand moulds may be provided with a dry sand on the surface to give 'skin-dry moulds'. Purely 'dry-sand moulds' can also be made by adding to the sand a binder instead of moisture. Its main advantages include a greater resistance to metal erosion, increased strength and a lessening of the tendency in the casting to acquire moisture related defects. In some cases, silica sand bonded with Portland cement may be used to make the moulds.

Methods of preparing sand moulds include 'bench moulding', 'machine moulding', 'floor moulding' and 'pit moulding'. Bench moulding is used for small castings. This is usually a slow and laborious process since hand ramming with loose pattern is usually used. Small and medium moulds may be made even with the aid of a variety of machines which are usually faster and more uniform than bench moulding. Medium to large moulds are made directly on the foundry floor. Very large moulds made in a pit constructed for the purpose are called 'pit moulds'.

The sands most commonly used in 'sand casting' contain silica sand which is usually from 50 – 90 % of the total material in any moulding sand, zirconate and olivine etc. The most important properties and characteristics of such sands are permeability, cohesiveness and refractoriness. Permeability is a condition of porosity and is related to the passage of gaseous material through the sand as well as to the density of sand grains. Cohesiveness can be defined as the holding together of sand grains or strength of moulding sand and depends upon the size and shape of the sand grains. The property of cohesiveness may be improved by adding to the sand some binders such as clay, resins, gums and drying oil. The third important characteristic of the moulding sand is refractoriness which is its ability to withstand a high temperature without fusing. Pure silica sand can withstand a temperature as high as 3148 °F. The property of refractoriness can be affected by the impurities like metallic oxides.

Mould cavities may be produced by packing the mould material around patterns. The patterns may be made from wood, metal or other suitable materials. There

are a variety of these patterns used in the manufacture of castings. Another important part of the casting process is the core box which is a structure made of wood, metal or other suitable material, containing a cavity with a shape of a desired core. Making a sand mould involves the proper packing of moulding sand around the pattern. After the pattern is removed from the sand and the gating arrangement completed, the mould cavity is filled with molten metal to form the casting. Principal steps for making sand casting process are shown in Fig below.

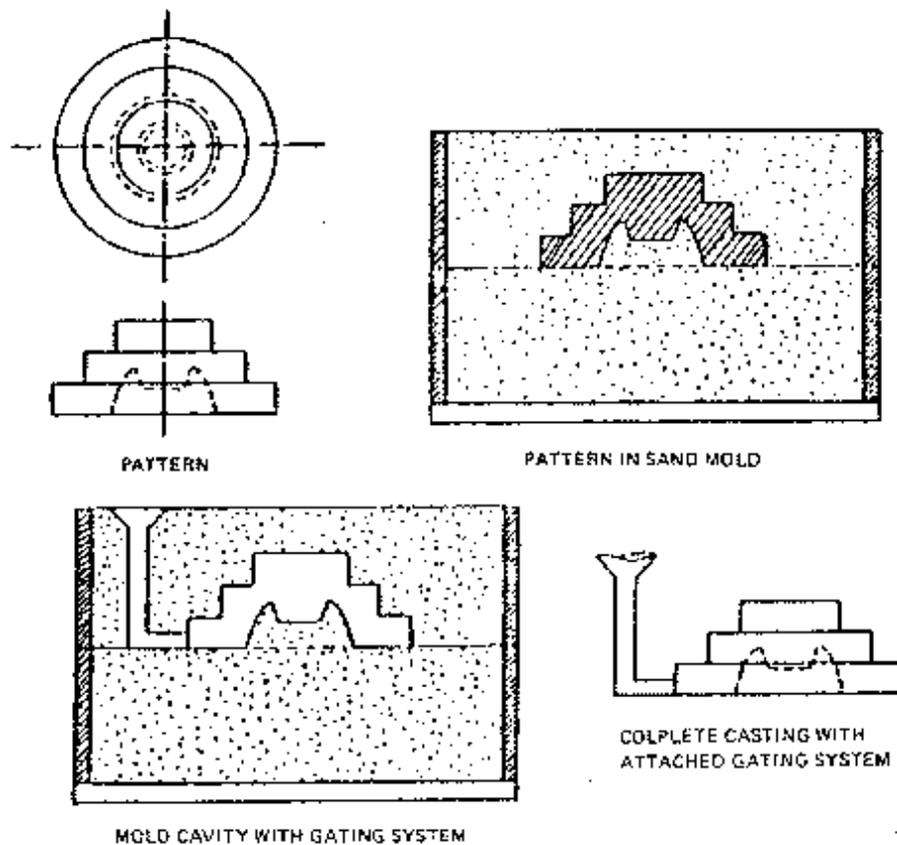


FIGURE 5.13 - MAIN STEPS INVOLVED IN SAND CASTING

DIE CASTING: -

It may be defined as the use of a permanent mould (die) into which molten metal is introduced by means of high pressure (1000- 100,000 psi). The term pressure die casting is another name for this method of casting. This pressure is obtained by application of compressed air or by pneumatically or hydraulically operated pistons. This process of casting can be sub divided into two types.

Hot Chamber Die Casting

Cold Chamber Die Casting

Hot Chamber Die Casting:-

The melting unit is an integral part of the hot chamber machine, and molten metal is introduced directly from this melting unit, by means of plunger mechanism in to the die cavity. The process is further characterized by a normal amount of super heat in the metal and the need for a lower casting pressure. Pressure on the molten metal in hot chamber die casting machine may vary from approximately 500 – 6000 psi (3.5 -41 MPa) An average of approximately 2000- 2500 psi (14-17 MPa) is common. Air injection pressures are normally limited to about 6000 psi (4 MPa).

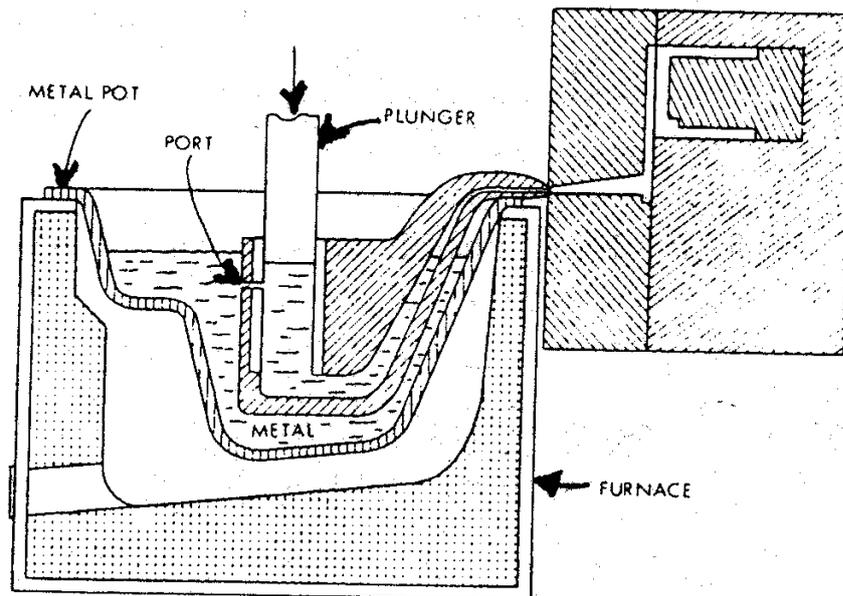


FIGURE 5.14 - HOT CHAMBER DIE CASTING

Unfortunately, the hot chamber design cannot be used for the higher melting point metals, and it is un-attractive for aluminum since there is a tendency for molten aluminum to pick up some iron as a result of the extended time in contact with the casting equipment. Hot chamber machines, therefore, see primary use with zinc, tin and lead based alloys.

Cold Chamber Die Casting:-

Cold chamber machines are usually employed for the die casting of materials that are not suitable for the hot chamber design. These include alloys of aluminum, magnesium, copper and high aluminum zinc.

The melting unit is usually separate in this case, and molten metal must be transferred to the injection mechanism by ladle. Further distinctive characteristics of the process are, very high metal pressures and the fact that

the casting alloy may be at a temperature somewhat less than normal super heat; the melt may even be in a semi molten condition. Pressure on the casting metal in the cold chamber die casting machines may vary from 3000 psi (20.5 MPa) to as high as 25000 psi (172 MPa) and in some cases may reach 100,000 psi (690 MPa).

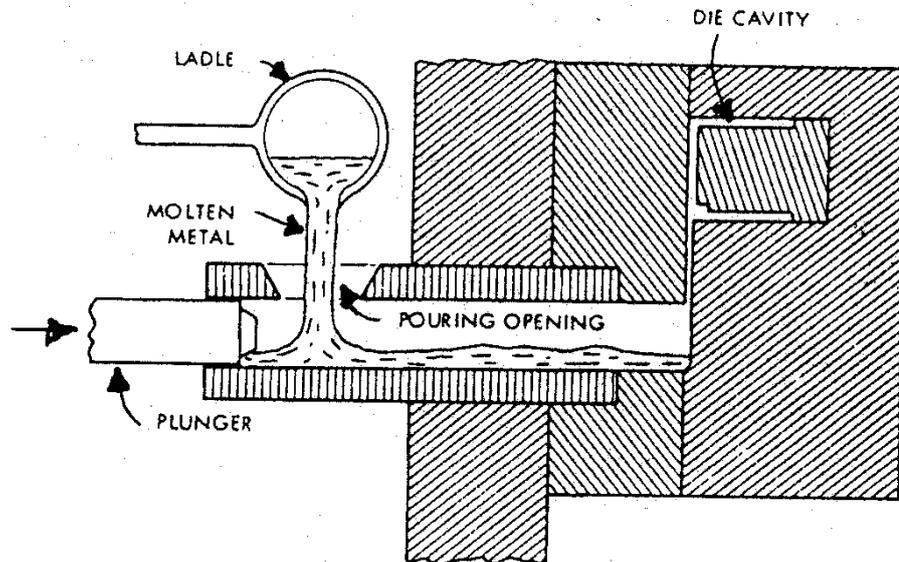


FIGURE 5.15 - COLD CHAMBER DIE CASTING

Metallic alloys cast in a semi molten condition require greater pressure to compensate for the reduced fluidity resulting from low pouring temperature. Lower working temperature and high pressures produce castings of dense structure, free of blow holes and porosity related to dissolved gases. A piston type plunger mechanism is commonly used to force the semi-molten alloy, which has been introduced through the injection port, into the die cavity. The lower temperatures of the melt reduce the possibility of excessive damage to machine parts from thermal shock.

Advantages of Die Casting Process:-

Very high production rates are possible, e.g. in the hot chamber type 300-350 castings per hour and in the cold chamber type 75-150 castings per hour. Cycle time varies from 3 seconds to 12 seconds in modern die casting machines.

Close dimensional control can be maintained. In zinc, a tolerance of ± 0.025 mm for each additional 25mm can be easily achieved.

Thin sections can be cast. Under favorable conditions, minimum thicknesses are about 0.50mm for size and 0.80mm for aluminum.

Details are reproduced faithfully with a high degree of precision.

Surface finish of 0.8 microns (Ra value) can be obtained. It may vary from 0.8 micron to 3 microns according to the types of cast metal and the controlling parameters.

Die casting dies retain their accuracy and usefulness for a long time. Dies for zinc alloys may produce as many as 5 million castings.

The saving of labour and time and the elimination of machining renders it extremely economical for large scale production.

Disadvantages of Die Casting Process:-

Only certain non-ferrous alloys (Zn, Al, Mg, Cu, Sn, Pb) can be economically die cast.

The maximum size is limited by the size of the dies and the capacity of the die casting machines available. So far, the max. sizes reportedly cast are 90 Kg in Zn and 30 Kg in Al using a locking force of about 2.0 Tonnes.

The high cost of dies and die casting equipment require sufficiently large production quantities to make the process economically feasible. The minimum economical quantity for die casting is considered to be about 20000.

Die castings usually contain some porosity due to entrapped air.

3. PERMANENT MOULD CASTING: -

In this casting, the molten metal is poured in a metallic mould and around metallic core. The moulds are generally made of cast irons, alloy steels or non-ferrous alloys and last for long period, permanently; and hence the process is known as permanent mould casting. In this process, the metal flows in to the mould under the action of force of gravity and no external pressure is applied; and hence this process is sometimes called Gravity Die Casting. The metal used for the moulds or cores should have such a composition as to withstand high temperatures. Inner surfaces of the mould are coated first with a refractory and then with a lamp black or core oil, to reduce the chilling effect on the cast metal and to facilitate the removal of casting. The moulds are generally made in two halves, which are hinged at one end and clamped at the other. For hollow castings, metal cores are used but dry sand cores may also be used for complicated shapes having varying diameters.

The ferrous and non-ferrous metals may be cast by this process but it is generally used for non-ferrous metals and their alloys. The castings are usually annealed to relieve any strain that may remain.

Advantages of Permanent Mould Casting:-

Dense, fine grained structures, free from shrink holes or blow holes

Superior in mechanical properties – stronger, harder

Economical process- low tool cost, low mould cost

Better surface finish and closer tolerances

Less space required

Less labour, less skill, less rejection

Low production cost with increasing lot sizes

Disadvantages of Permanent Mould Casting:-

Suitable for small and medium size castings, impractical for large castings

Suitable for non-ferrous castings, impractical for alloys of higher melting temperature

Suitable for large scale production due to high cost of metal mould. Not suitable for small production lots

Difficulty in ejection of casting after solidification due to rigid nature of the mould

Production rate is slower than for the same parts made by other metal mould methods

Yellow brasses, which are high in zinc, are difficult to utilize because zinc oxide fouls the mould dies

Several defects like stress and surface hardness occur due to surface chilling effect

4. CENTRIFUGAL CASTING: -

In centrifugal casting, the molten metal is poured in the mould and allowed to solidify while the mould is revolving, thus the molten metal is subjected to centrifugal force due to which it flows in mould cavities and result in the production of high density castings. This process is most suited for mass production. Cylindrical parts and pipes are mostly cast by this process.

There are three types of centrifugal castings:

True Centrifugal Casting

Semi Centrifugal Casting or Profiled-Centrifugal Casting

Centrifuged or Pressure Casting

a. True Centrifugal Casting: -

In this process the castings are made in a hollow cylinder mould which rotates about an axis common to both the casting and the mould. The axis of rotation may be kept horizontal, vertical or inclined. Due to the centrifugal force, the metal remains with the mould boundary and hence the thickness of the casting is governed by the quantity of molten metal that is poured in the rotating mould. Thus the mould does not require any core. The most common parts which are produced by this process are cast iron pipes, levers, bushes, barrels etc. True centrifugal casting is used only on symmetrical shaped objects.

b. Semi-Centrifugal Casting: -

This process is just like the true centrifugal casting with the only difference that a central core is used in it to form the inner surface. The casting of the particular shape is produced by the mould and core shapes and not by centrifugal force. However, the centrifugal force feeds the molten metal in the cavities of the mould and produces the casting of high density. Armed wheel is the good example of casting produced by this process. In this process the axis of spin is always vertical. With this process also, only symmetrically shaped objects can be cast.

c. Centrifuged Casting:-

Non-symmetrical castings having intricate details are produced by this process. Due to the centrifugal force, the molten metal is fed into the mould cavity. The mould cavity is not rotated about its own axis but about the axis of a central down sprue common to the axis of rotation, which feeds the metal into the mould cavity through the radial gates. The process is possible only in the vertical direction. The moulds for centrifugal castings can be made of sand, metal, graphite or combination of three materials. The surface of all moulds is given adhesive material wash to improve finish to increase mould life and to facilitate the removal of the casting. The wash generally consists of lime, silica and clay graphite or oil.

In centrifugal castings the speed of rotation should be selected properly, as the force exerted on the molten metal depends upon the speed. If the centrifugal force is more, longitudinal hot tear will produce in the outer surface of the casting and if it is less, slipping of molten metal will occur during the casting.

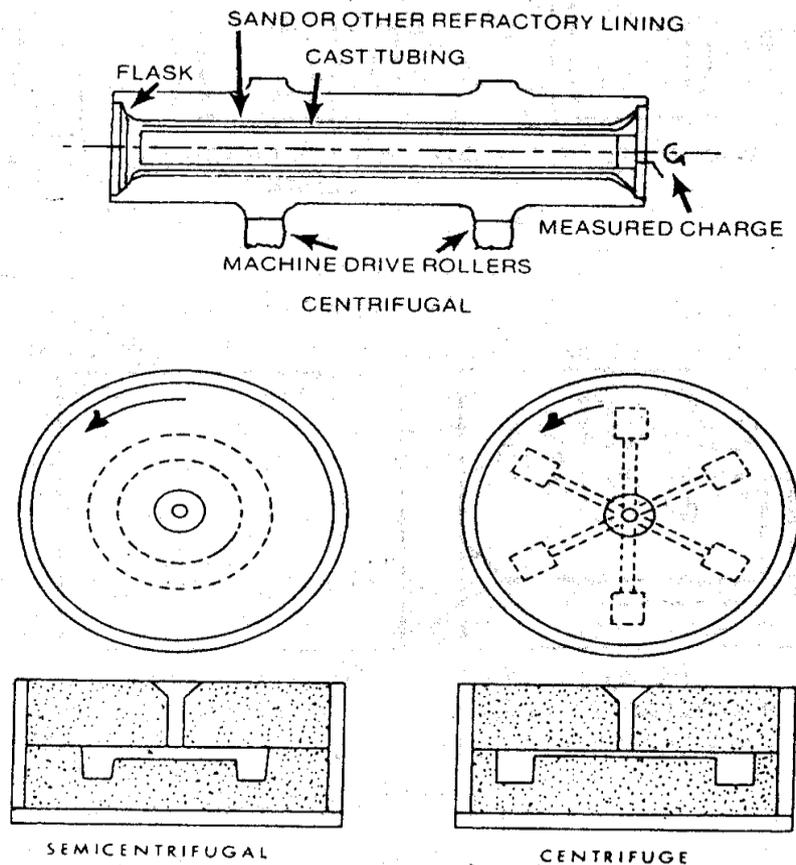


FIGURE 5.16 - CENTRIFUGAL CASTING

Advantages of Centrifugal Casting:-

- Casting of high density are produced
- Good surface details are obtained
- Use of runner and core is eliminated
- Mass production is obtained with less rejections
- Both ferrous and non-ferrous metals can be cast

Disadvantages of Centrifugal Casting:-

- Process is limited to only cylindrical parts with a limited size range
- It requires high initial cost and skilled labour

5. INVESTMENT CASTING:-

It is also known as lost wax, lost pattern, hot investment and precision casting. This method is used to manufacture engineering castings of many types from metals which were not amenable too fabrication by other casting methods. For many years, it was neglected but it has now come into favor with dentists, jewelers, and orthopedic surgeons.

In this method the pattern is made of wax, plastic, tin or frozen mercury. Suitably gates and risers are attached to it, and the assembly, or tree is placed inside a container, usually a stainless steel cylinder open at each end. The tree is pre-coated by dipping in a refractory slurry, and is then dusted with refractory sand. Now the investment, a coarse refractory is more viscous slurry, of suitable binder plus alumina, silica, gypsum, zirconium silicate or mixtures of these and other refractories is poured over the pre-coated pattern. After the investment has set, the container is placed in an oven at low heat, the investment becomes harder. As the temperature of the oven is raised steadily, the pattern melts and flows from the mould if it is wax, or volatizes if made of plastic. The mould now contains a cavity in the identical form of the original pattern. The molten metal is poured into the hot mould to get the required casting.

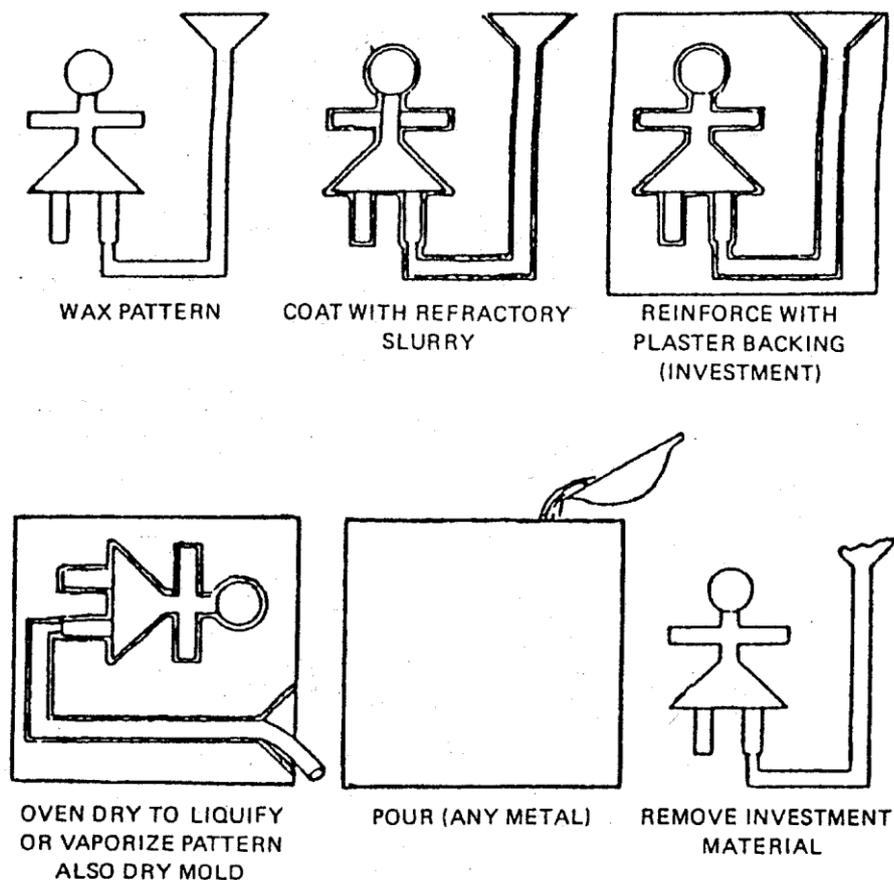


FIGURE 5.17 - INVESTMENT CASTING

ADVANTAGES OF INVESTMENT CASTING:-

Castings made by investment casting process possess:

Excellent details

Smoother surfaces

Close tolerances (of ± 0.003 mm / mm)

- 2) Castings do not contain any disfiguring parting line
- 3) Some machining operations can be eliminated thereby attaining considerable saving in cost
- 4) With suitable heat treatment, the investment castings attain physical properties comparable to those of forged or rolled sections of same metal.
- 5) Castings produced are sound and free from usual defects
- 6) Intricate shapes can be cast
- 7) Irregular parts which cannot be machined may be cast by this method
- 8) Sections as thin as 0.75 mm may be cast
- 9) Since molten metal is poured in pre heated moulds, the resultant cooling rate thus being slow, produces large grain size as well as sounder and denser castings.

Disadvantages: -

Process is relatively slow

The use of cores make the process more difficult

Production of wax pattern and thus investment moulds etc make the process relatively expensive as compared with other casting processes

Size limitations of the component parts to be cast. Majority of castings produced weigh less than 0.5 Kg

Pattern is expandable; one wax pattern is required to make one investment casting

The economic value of this process lies in its ability to produce intricate shapes in various alloys that could probably not be produced at all by any other casting process.

Applications: -

Milling cutters and other types of tools

In dentistry and surgical implants

For making jewellery and art castings

Parts of gas turbine used in locomotive propulsion

Jet aircraft engine outlet nozzle

Buckets for super chargers

Parts for sewing machines, locks, rifles, beer barrels and burner nozzles

To fabricate difficult to machine and difficult to work alloys into highly complex shapes such as hollow turbine blades

Impellers and other pump and valve components in stainless steel and non-ferrous alloys, wave guides, die inserts and parts for gun mechanism

Corrosion resistant and wear resistant alloy parts used in diesel engine, textile machines, motion picture projectors, pulverizing equipments and chemical industry equipments.

Parts produce from satellite, vitallium etc for use in automotive and aircraft industry and for plastic moulding dies, extrusion and drawing dies, refrigerators and power plants

6. SHELL MOULDING: -

it is the newest of the casting processes. It was developed in Germany during World War II by J. Croning and is sometimes therefore known as Croning or C Process also. It was first publically announced in 1947 and since then it has undergone rapid developments. Shell moulding replaces conventional sand moulds by shell moulds made up of relatively thin rigid shells of approx. uniform wall thickness. The same technique also replaces conventional solid rammed and baked cores by what is known as shell cores.

Steps Involved: -

Various steps involved in making casting using this method are as under:

A metal pattern having the profile of the required casting is heated to 180-250 ° C in an oven maintained at 300-400 ° C.

Pattern after being heated is taken out of the oven and straight with a solution of a lubricating agent or release agent containing silicon. It is necessary to prevent the shell from sticking to the metal pattern.

Metal pattern (made up of iron or steel) is then turned face down and clamped over the open end of the dump box. The dump box contains sand resin mixture i.e. 4 to 6 Kg of phenol-formaldehyde resin to each 100 Kg of sand.

The dump box is inverted so that dry sand-resin mixture falls on to the face of hot metal pattern. The resin sand mixture in contact with the pattern gets heated up, the resin softens and fuses to form a soft and uniform shell of about 6 mm thickness on the surface of pattern. Heat first causes to become sticky; then additional heat cures or hardens it.

As the dump box is turned to its original position, excess sand-resin mixture falls back into the dump box leaving a shell adhering closely to the pattern.

The pattern along with the shell adhering to it is passed directly in to an oven for 1 to 2 minutes when the resin in the resin-sand mixture cures and the shell acquires rigidity.

The shell is then stripped from the pattern plate with the help of ejector pins which are an integral part of the metal pattern.

After the shell so obtained have cooled, two mating shells are securely fastened together to form a complete mould.

Shell moulds may be poured either by keeping the parting surface vertical or horizontal. The heat of the molten metal starts burning resin binder of the mould and the gases evolved escape through the permeable shell walls. By the time shell casting has solidified, the binder has completely burnt out and on tapping, the shell mould disintegrates easily. The loose sand is removed from the casting and the casting is sent for finishing.

Advantages: -

Shell mould made castings possess excellent surface finish.

Shell moulding reproduces details with sharp clean edges thereby rendering fettling and machining unnecessary.

Shell moulding produces smoother surfaces of the casting.

Less foundry space is required for shell moulding.

Castings as thin as 1.5 mm can be cast satisfactorily.

Since shell is an excellent heat insulator, there is no surface chilling or skin hardening of castings.

Cooling rate of cast metal being slow, casting possess grain sizes larger than those obtained in green sand moulds.

Tolerances of the order of 0.002 to 0.003 mm / mm are possible to obtain in shell mould castings.

Semi skilled operator can handle the process.

Shell moulding can be mechanized.

Shell can be stored for a long time before use.

Disadvantages: -

Shell moulding is uneconomical for small scale production.

Low carbon steel castings made by shell moulding may show depression on their upper surfaces.

The comparatively small amounts of breakdown sand from shell mould is not normally recoverable economically.

Resin costs are comparatively higher.

Shapes in which proper parting and gating cannot be obtained are not suitable for production with this method.

The max. size of the casting is limited by the max. size of the shell which can be feasibly produced and poured. Castings weighing up to 10 Kg may be cast by shell moulding.

Applications: -

Shell moulding is ideal for mass production of small castings.

It is suited to ferrous and non-ferrous alloy casting in the range 0.1 to 10 Kg.

A no. of small hydraulic casting in stainless steel and copper alloys are produced by shell moulding.

For casting automotive rocker arms and valves

Various alloys which can satisfactorily be cast by shell moulding are, Al alloys, Cu alloys (including brasses, phosphor bronze and gun metal), Cast Irons (gray and specially malleable), Stainless steels.

Other components cast by shell moulding are small pipes, camshafts, bushings, valve bodies, spacers, brackets, manifolds, bearing caps, shafts and gears.

5.7 WELDING, SOLDERING & BRAZING:-

WELDING:-

Welding can be defined as metallurgical method of joining. It consists of joining two parts of metal by establishing a metallurgical atom to atom bond. This metallurgical bonding is achieved by heating the metal to above its recrystallization temperature with the application of pressure or heating the metal to above its fusion temperature with or without pressure.

Many welding processes require the presence of heat or pressure, or both, to produce a suitable bond between the parts being joined; in making a joint two parts of the same chemical composition may be welded together using no added metal to accomplish the joint. This might be termed as "autogenous welding". A metal is of the same composition as the parts being joined may be added, in which event, the process would come under the general heading "homogenous welding". Finally, an alloy quite different from that of which the parts are made may be used or alternatively the parts themselves may differ significantly in composition. Then this process is called "heterogenous welding". Almost every imaginable high energy density heat source has been used at one time or another in welding. Externally applied heat sources of importance include arcs, electron beams, light beams (lasers), exothermic reactions (oxyfuel gas and Thermit), and electrical resistance. Welding processes that acquire heat from external sources are usually identified with the type of heat source employed.

American Welding Society (AWS) has classified the various welding processes as shown in fig below, and has assigned short letter symbols to facilitate their designation.

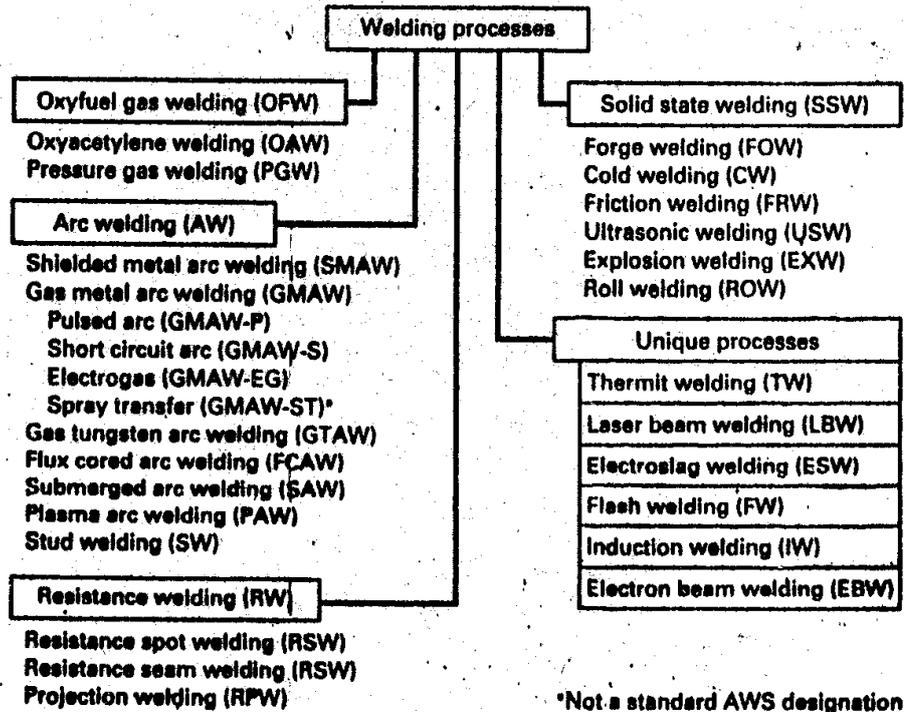


FIGURE 5.18 - CLASSIFICATION OF WELDING PROCESSES

The welding processes which are commonly used for the welding of metals are described in the following sections,

SHIELDED METAL ARC WELDING (SMAW):-

It is an early arc welding process. It is one of the simple and versatile processes for welding ferrous and several non-ferrous base metals. Basically, it is a manual welding process in which the heat for welding is generated by an arc established between a flux covered consumable electrode and the work. The electrode tip, welded puddle, arc and adjacent area of work piece are protected from atmospheric contamination by a gaseous shield obtained from the combustion and decomposition of the flux covering. The process is illustrated in fig shown below.

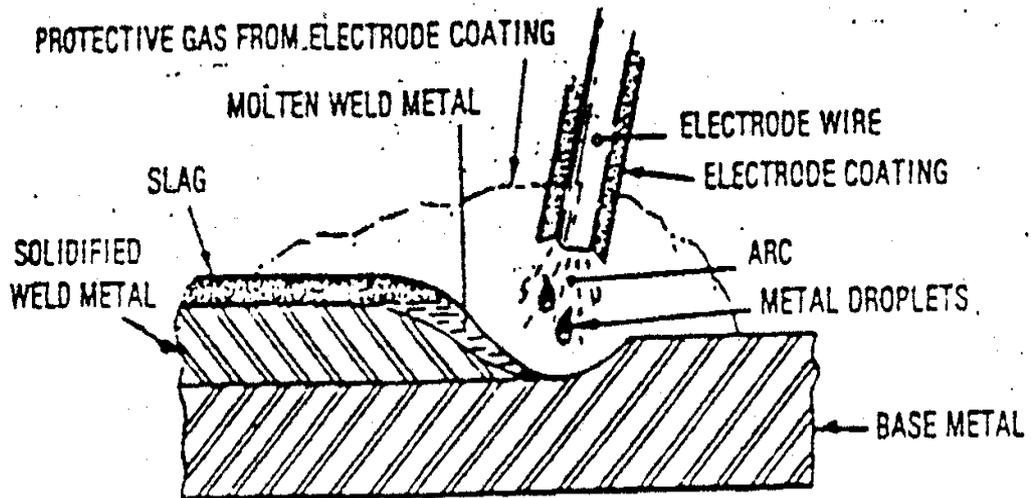


FIGURE 5.19 - SMAW

The bare section of the electrode is clamped in an electrode holder, which in turn is connected to the power source by welding lead (cable). The work is connected to the other power source terminal. The arc is initiated by touching the electrode tip against the work and then withdrawing it slightly. The heat of the arc melts the base metal in the immediate area, the electrode metal core, and the electrode covering. The molten base metal, core wire, and metal powders in the covering coalesce to form the weld.

Covered electrodes are produced in a variety of diameters normally ranging from 1/16 to 5/16 inches (2-8mm). The smaller diameters are used with low currents for joining thin sections and for welding in all positions. The large diameters are designed for conducting high currents to achieve greater deposition rates in the flat and horizontal positions. Special alloy filler metal composition can be formulated with relative ease by the use of metal powders in the electrode coating.

The SMAW process has several advantages. Using the process, job shops can handle many welding applications with a relatively small variety of electrodes. Other advantages are the simplicity and lightness of the equipment, and its relatively low cost. Also, welds can be made in confined locations or remote from heavy power supplies.

SUBMERGED ARC WELDING (SAW):-

In this process, the arc and molten metal are shielded by an envelop of molten flux and a layer of unfused granular flux particles as shown in Fig.

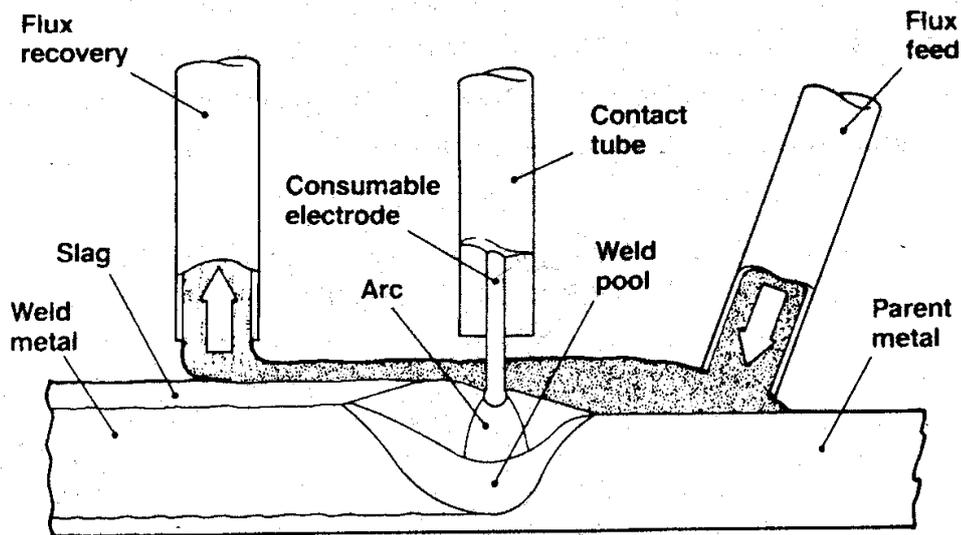


FIGURE 5.20 - SAW

When the arc is struck, the tip of the continuously fed electrode is submerged in the flux and the arc is therefore not visible. The weld is made without the intense radiation that characterizes an open arc process and with little fumes.

The SAW process is used in both mechanized and semiautomatic operations, although the former is by far more common. High welding currents can be employed to produce high metal deposition rates at substantial cost savings. Welds can only be made in the flat and horizontal position.

The SAW process is useful for welding both sheet and plate. In welding relatively thin materials, speed of up to 200 in./min (84mm/s) can be achieved. In thick section applications, high metal deposition rates of 60-100 lb/h (27-45kg/h) and reliability are the key advantages.

The process is most widely employed for welding all grades of carbon, low alloy, and alloy steels. Stainless steel and some nickel alloys are also effectively welded or used as surfacing filler metals with this process. Various filler metal-flux combinations may be selected to provide specific weld metal properties for the intended service. The flux may contain ingredients that when melted react to contribute alloying additions to the weld metal. Approximately 1 pound of flux is consumed for every pound of electrode used.

GAS METAL ARC (GMAW) AND FLUX CORED ARC WELDING (FCAW):-

GMAW and FCAW are two distinct processes, but they have many similarities in application and equipment. Both processes use a continuous solid wire or tubular electrode to provide filler metal, and both use gas to shield the arc and weld

metal. In GMAW, the electrode is solid, and all of the shielding gas (argon, helium) is supplied by an external source.

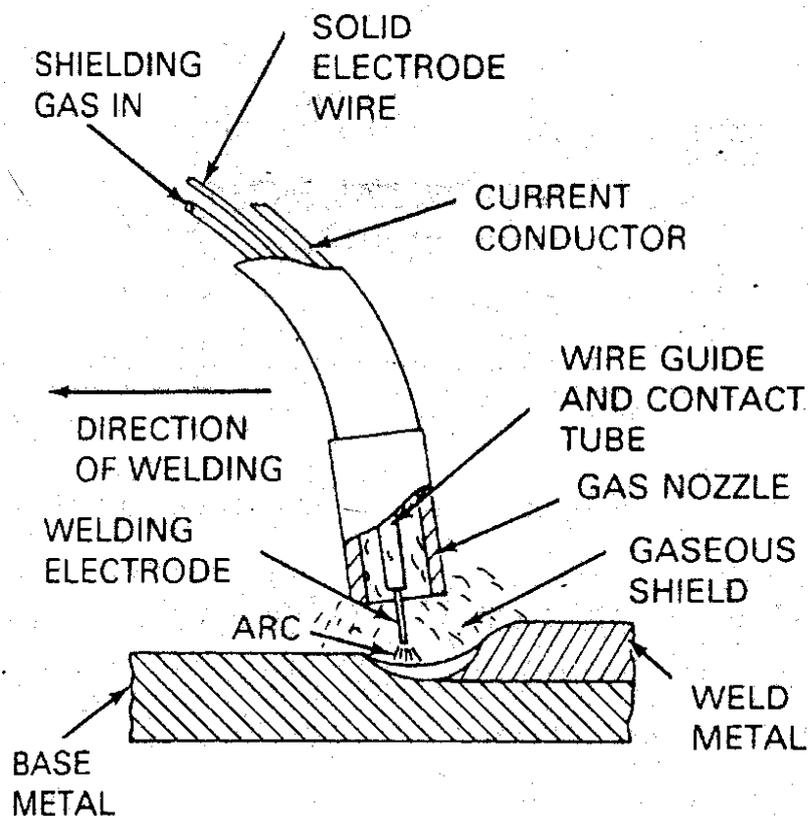


FIGURE 5.21 - GMAW

The original gas metal arc process consisted of a continuous operation requiring high current densities to achieve a smooth transfer of molten metal. Two modifications of this original spray-type arc have been developed for various applications. These are shorting arc and pulse-spray arc techniques. The shorting arc technique is essentially the same as the basic spray arc method, except that the welding cycle consists of alternating periods of arcing and short-circuiting. Metal transfer occurs during the short circuit phase of the cycle in the form of a molten, but relatively cold droplet. The process is characterized by relatively low heat inputs, controlled penetration, and good out-of-position capability.

Another variation of the gas metal arc process is pulsed-spray arc technique. In this process, the current is pulsed between high and low current densities, which cause a semicontinuous arc. Metal transfer occurs during the cyclic pulses of higher current. The process permits welding with minimal splatter, uniform penetration and good out-of-position capability. With FCAW, the electrode is tubular and contains core ingredients that may supply some or all of the shielding gas needed. This process may also use auxiliary gas shielding,

depending on the type of electrode employed, the material being welded and the nature of the welding involved.

Flux cored arc welding (FCAW) uses cored electrodes instead of solid electrodes for joining ferrous metals. The flux core may contain minerals, ferroalloys and materials that provide shielding gases, deoxidizers and slag forming materials. The addition to the core promotes arc stability, enhanced weld metal mechanical properties and improved weld contour. Many cored electrodes are designed to be used with additional external shielding. Carbon dioxide-rich gases are the most common. Weld metal can be deposited at higher rates and the weld can be larger and better contoured than those made with solid electrodes, regardless of the shielding gas.

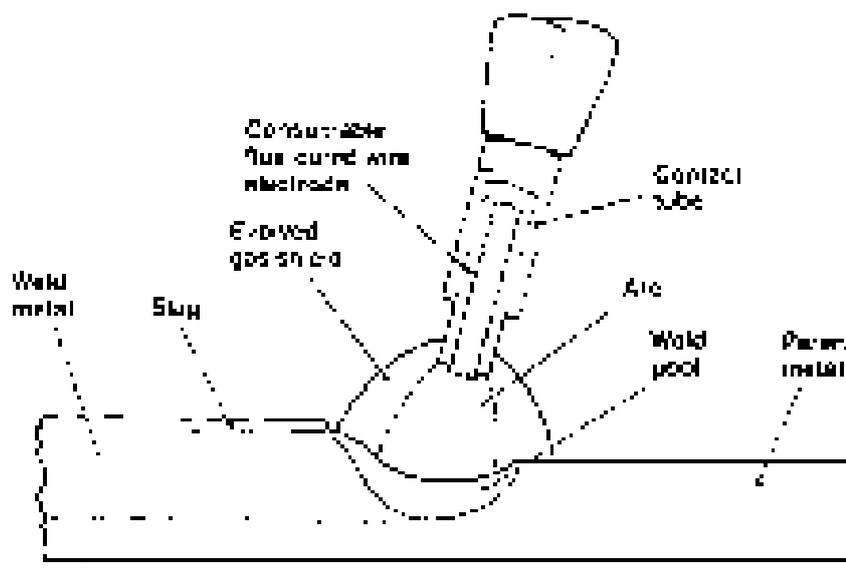


FIGURE 5.22 - FCAW

GAS TUNGSTEN ARC WELDING (GTAW):-

Gas Tungsten Arc Welding GTAW uses a non-consumable tungsten electrode which must be shielded with an inert gas. The arc is initiated between the tip of the electrode and work to melt the metal being welded, as well as the filler metal, when used. A gas shield protects the electrode & the molten weld pool and provides the required arc characteristics.

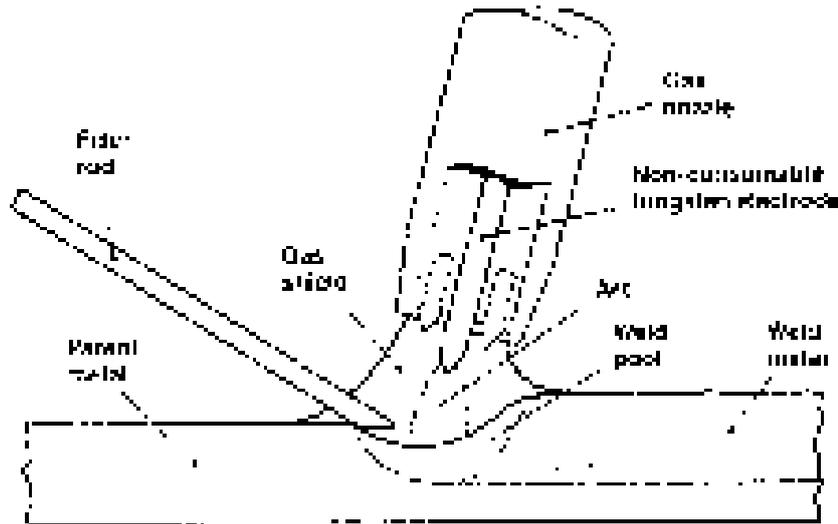


FIG 5.23 GTAW

Several types of tungsten electrodes are used with this process. Thoriated and zirconiated electrodes have better electron emission characteristics than pure tungsten, making them more suitable for dc operation. The electrode is normally ground to a point or truncated cone configuration to minimize arc wander. Pure tungsten has poor electron emission characteristics but provides better current balance with arc welding. This is advantageous when welding aluminum and magnesium.

The equipment needed consists of a welding torch, a welding power source, a source of inert gas with suitable pressure regulators and flow meters, a welding face shield and protective clothing. Electric power requirements depend upon the type of material and the thicknesses to be welded.

PLASMA ARC WELDING (PAW):-

This process provides a very stable heat source for welding most metals from 0.001 to 0.25 inches. This process has advantages over other open arc welding processes, such as SMAW, GMAW & GTAW, because it has greater energy connection, improved arc stability, higher heat content and higher welding speeds. As a result, PAW has greater penetration capabilities than SMAW, GMAW & GTAW.

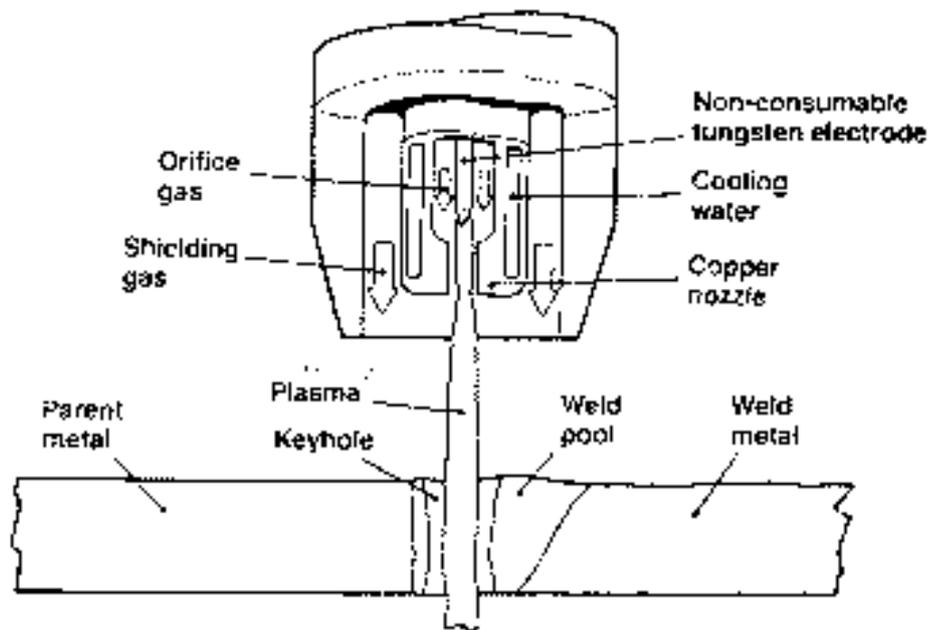


FIGURE 5.24 - PAW

A small flow of argon is supplied through the orifice to form the arc plasma. Shielding of the arc and weld zone is provided by gas flowing through an encircling outer nozzle assembly. The shielding gas can be argon, helium or mixture of argon with either hydrogen or helium. The plasma is initiated by an internal low carbon pilot arc between the electrode and the orifice. The pilot arc ionizes the orifice gas to ignite the primary arc between the electrode and the base metal. The arc plasma is constricted in size by the orifice around the electrode and is called a transferred arc. If filler metal is used, it is fed in to the arc as in the GTAW process.

Two welding techniques are possible with the PAW process: melt-in, and keyhole. The melting technique is normally used when welding thin sections in the range of 0.001 to 0.062 inches. Narrower welds can be obtained with PAW rather than with GTAW because of the constricted arc. Manual welding of very fine sections of 0.01 inch and under is very difficult with the GTAW process but practical with low power PAW.

High current manual PAW can be done in the melt-in mode. Melt-in welds on 1/32 to 1/8 inches thick butt joints or lap joints can be used to join most materials. Titanium and other reactive metals can be joined using helium as a shielding gas.

ELECTRON BEAM WELDING (EBW) AND LASER BEAM WELDING (LBW):-

These methods are generally utilized for precision assemblies requiring high-quality welds. The procedure is conducted by focusing an electron beam or laser beam on the joint interface and causing melting and fusion of the metal. Beam welds require that the mating of the components to be welded be fitted closely since there is no filler metal. The weld joint is created by the fusion of the material penetrated by the beam, therefore, the mating surface should be geometrically prepared so that they are in intimate contact over the entire joint surface.

Electron beam welds are usually made in a vacuum while laser welding is conducted using an inert gas surrounding the laser beam. At the present time, electron beam has the capability for welding thicker specimens (up to 200 mm in steel), but is limited by the size of the vacuum chamber.

RESISTANCE WELDING (RW):-

Resistance welding (RW) is a group of processes in which the heat for welding is generated by the resistance to the flow of electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates which may have different thicknesses. A pair of electrodes conducts electrical current to the joint. Resistance to the flow of current heats the faying surfaces, forming a weld. These electrodes clamp the sheets under pressure to provide good electrical contact and to contain the molten metal in the joint. The joint surfaces must be clean to obtain consistent electrical contact resistance to obtain uniform weld size and soundness.

The main process variables are welding current, welding time, electrode force and electrode material and design. High welding currents are required to resistance heat and melt the base metal in a very short time. The time to make a single resistance weld is usually less than one second.

There are three major types of resistance welding processes:

Spot Welding (SW)

Projection Welding (RPW)

Seam Welding (RSEW)

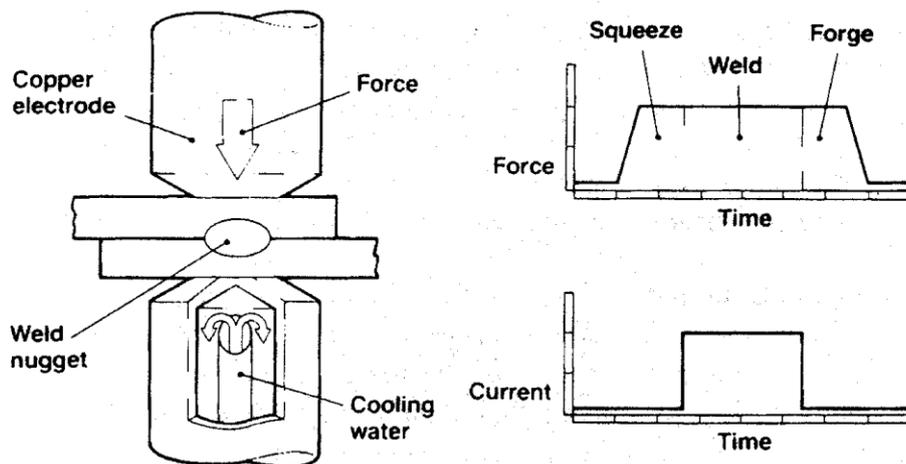


FIGURE 5.25 RSW

In resistance spot welding (RSW), the welding current is concentrated at the point of joining using cylindrical electrodes. Spot welds are usually made one at a time. In RPW, a projection or dimple is formed in one part prior to welding. The projection concentrates the current at the faying surfaces. Large, flat electrodes are used on both sides of the components to produce several welds simultaneously. As an example, a stamped bracket may have three or four projections formed in it so that it can be welded to a sheet with one welding cycle. Resistance seam welding (RSEW) is similar to spot welding except that the spots overlap each other or the spots are spaced at short intervals making a continuous weld seam.

FLASH WELDING (FW): -

Flash welding (FW) is classified as a resistance welding process, but it is a unique process. Heat for welding is created at the faying surfaces of the joint by resistance to the flow of electric current and by arcs across the interface. When the faying surfaces are heated to welding temperature, force is applied immediately to consummate a weld. Molten metal is expelled, the hot metal is upset and a flash is formed. Filler metal is not added during welding.

The usual flash weld joins rods or bars end to end or edge to edge. Both components are clamped in electrodes which are connected to the secondary of a resistance welding transformer. One component is moved slowly towards the other and when contact occurs at surface irregularities, the current flows and initiates the flashing action. This flashing action is continued until a molten layer forms on both surfaces. Then the components are forced together rapidly to squeeze out the molten metal and dross, and upset the adjacent hot base metal.

This produces a hot worked joint free of weld metal. The mechanical properties of flash welds are often superior to other types of welds.

Flash welding is usually an automatic process. Parts are clamped in place by a welding operator who simply presses a button to start the welding sequence.

OXYFUEL GAS WELDING: -

Oxyfuel gas welding (OFW) includes a group of welding processes that use the heat produced by a gas flame for melting the base metal and, if used, the filler metal. Pressure may also be used. Oxyfuel gas welding is an inclusive term used to describe any welding process that uses a fuel gas combined with oxygen to produce a flame having sufficient energy to melt the base metal. The fuel gas and oxygen are mixed in the proper proportions in a chamber which is generally a part of the welding torch assembly. The torch is designed to give the welder complete control of the welding flame to melt the base metal and the filler metal in the joint.

Oxyfuel gas welding is normally done with acetylene fuel gas. Other fuel gases, such as methyl acetylene propadiene and hydrogen, are sometimes used for Oxyfuel gas welding of low melting metals. The welding flame must provide high localized energy to produce and sustain a molten weld pool. With proper adjustment, the flames also can supply a protective reducing atmosphere over the molten weld pool. Hydrocarbon fuel gases such as propane, butane, natural gas and various mixtures employing these gases are not suitable for welding ferrous materials because the heat output of the flame is too low or the flame atmosphere is oxidizing.

Although the hydrogen flame temperature is about 4800 °F (2660 °C), hydrogen has limited use in OFW because the total heat content of the flame is low. The use of hydrogen is further complicated because the flame is essentially colourless. The lack of a visible cone makes the hydrogen-oxygen ratio very difficult to adjust. Oxyhydrogen welding (OHW) is used primarily for welding low melting metals, such as lead and to a limited extent thin sections and small parts.

Manual welding methods are most commonly used and require minimal equipment. A suitably sized torch, hoses, regulators, oxygen in a pressurized cylinder, fuel gas in a pressurized cylinder, welding rods, goggles and protective clothing are needed.

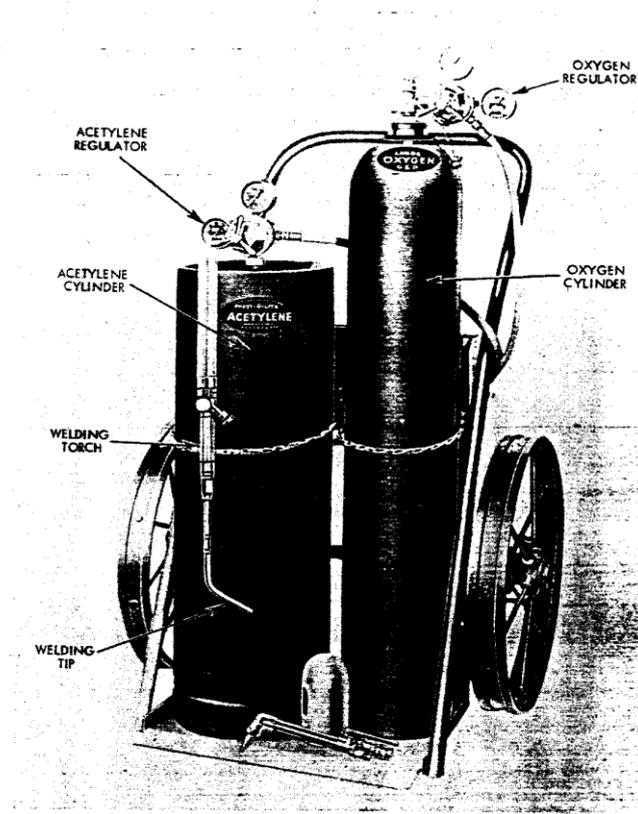


FIGURE 5.26 - OFW

Oxyfuel gas welding can be used for joining thick plate, but welding is slow and high heat input is required. Welding speed is adequate to produce economical welds in sheet metal and thin-wall and small diameter piping. Thus, OFW is best applied on material of about 6 mm maximum thickness.

SOLDERING:-

Soldering is a process of joining two pieces of metal by using a non-porous filler metal having melting temperatures below 840 °F (450 °C) and below those of the base metal. The filler metal is called solder and is distributed between the surfaces by capillary attraction.

Soldering is used to join surfaces where they are not subjected to high strength forces since solder has a relatively low tensile strength. Soldered joints are also not suitable where temperatures approach the melting point of the solder.

Soldering is a simple operation providing the following five basic requirements are met:

The right type & amount of solder and flux are used for the base metal being joined.

The pieces being soldered fit tightly together.

The pieces are absolutely clean.

The pieces are held together until the solder solidifies

The correct amount of heat is applied to the seam.

Soldering alloys are known as soft solder. Most soft solder are alloys of tin (Sn) and lead (Pb). The %age of each metal determines its melting point and other characteristics. The melting range is from 370 °F for a mixture of 70 % Sn and 30% Pb to about 590 °F for a 5 % Sn and 95 % Pb. The most common general-purpose solders is known as half-and-half or 50-50 solder. It contains 50% Sn and 50% Pb and melts at about 475 °F.

In general alloys with a low Sn content have higher melting points and do not flow as readily as the high Sn alloys. The low-tin alloys are less expansive and find application where large volumes of soldering are done. Solders with a high amount of Sn have better wetting properties and produce less cracking. High Sn solders are used considerably in electrical work.

Special solders are also available or specific purposes. Thus a tin-antimony solder is designed to solder food-handling vessels where lead contamination must be avoided.

Solders are available in bar, cake, solid wire, flux-core wire, ribbon and paste forms. Flux-core wire solder has an acid or resin flux in the center of the wire. With these solders no additional flux is required.

Metals when exposed to air form oxides and rust on their surfaces. Solder will not adhere if such impurities are present. By applying a flux the oxide is removed and the formation of new oxide during the soldering process is prevented. Fluxes also increase the wetting action enabling the solder to flow more freely.

Fluxes come in paste, liquid, powder and cake form. Some are general-purpose fluxes usable on most metals. Others are special fluxes such as those for aluminum soldering.

All fluxes are classified as corrosive or non-corrosive. Although the corrosive types are most effective, they must be washed from the metal after soldering. They should never be used for electrical or electronic work. Rosin is the most common non-corrosive flux. Zinc chloride is the most frequently used corrosive flux.

The application of heat to the surfaces to be joined may be by soldering iron, torch, molten bath, induction or resistance methods or by wiping. The metal surfaces must be heated to the melting temperature of the solder and held at that temperature only long enough to allow uniform "wetting" or "tinning" of the previously prepared surface. An excessive soldering temperature or time at temperature promotes the formation of intermetallic compounds in many alloy

systems which tend to weaken the resulting joint. Since little or no alloying takes place at the relatively low temperatures involved in soldering operations, the bond is only as strong as the soldering alloy. Thin solder films of the order of 0.003 to 0.005 inches thick are, therefore, preferred for the best joint strength. Where higher strength is required, it is often desirable to incorporate mechanical aids, such as crimping, riveting, seaming etc.

Copper, iron, lead, nickel, tin, zinc and many of their alloys may be soldered. Aluminum and the stainless steels, however, require special techniques in view of the stable and tenacious oxide films that are formed.

BRAZING:-

According to the American Welding Society (AWS) brazing is defined as a group of welding processes where joining is achieved by heating to suitable temperatures above 840 °F (450 °C) and by using a non-ferrous filler metal having a melting temperature below that of the base metals. The filler metal is distributed between the closely fitted surfaces of the joint by capillary action. Most commercial metals can be brazed. Although a brazed joint has a relatively high tensile strength, this method of joining is not recommended when the full strength properties of a joint are required. An important characteristic of brazing is that there is less danger of destroying the mechanical properties of the base metal since lower bonding temperatures are used than normally required for regular fusion welding. This process is especially adaptable for joining dissimilar metals.

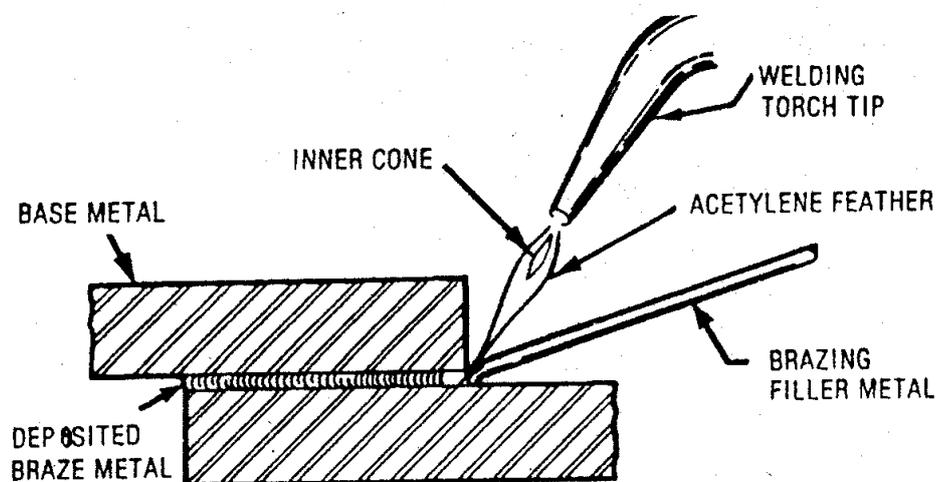


FIGURE 5.27 BRAZING PROCESS

The success of any brazing operation depends on joints having relatively small clearances and surfaces that are free of oxide and other contaminants. Cleaning is accomplished by coating the surfaces with a special flux which when heated is

capable of dissolving all foreign matter. Once the surfaces are properly fluxed a brazing filler metal is melted at some point along the seam. Capillary action then draws the molten brazing metal between the surfaces of the joint. Upon cooling to room temperature the solidified brazing metal forms a solid bond at the interface of the work piece. During heating and cooling, precautions are taken to prevent any movement of the surfaces. Ordinarily, for most production work, some type of fixture is used to hold parts in alignment during the brazing process.

Brazing filler metal can be any metal that melts between 450 °C & the melting point of the metal being joined. Brazing filler metal should meet the following requirements.

Sufficient fluidity so the metal will flow evenly by capillary attraction.

Good melting action to form a sound metallurgical bond.

Melting point consistent with the type of metal to be joined.

Brazing filler metals fall in to seven groups: Silver, Aluminum-Silicon, Copper-Phosphorus, Gold, Copper and Copper-Zinc, Magnesium and Nickel.

Any form of oxide on the surface of a metal will inhibit a uniform flow of the brazing metals. Accordingly a flux of some kind is necessary to eliminate the oxide. The common commercial fluxes are in paste, liquid or powder form. Fluxes have as their main ingredients borates, fused borax, boric acid, fluorides, chlorides and fluborates. There is no single flux which is applicable for all brazing operations. All traces of flux residues must be removed after brazing to prevent corrosion.

In some situations, where mass production is involved the application of fluxes is a time consuming task. Consequently, controlled atmospheres are used to remove oxide and prevent the formation of oxide during brazing. In a controlled atmosphere a gas is continuously supplied to a furnace and circulated within it at slightly higher than atmospheric pressure. Gas may consist of high purity hydrogen, carbon dioxide, carbon monoxide, nitrogen, argon, ammonia or some form of combusted fuel gas.

The application of heat for brazing purposes is accomplished by a variety of methods depending on the kind of material to be brazed, quantity of production and sizes of parts to be joined. Mostly following techniques are used: Torch Heating, Furnace Heating, Induction Heating & Dip Brazing.

6. 6. POWDER METALLURGY

6.1 INTRODUCTION:-

Powder metallurgy, designated by P/M may be defined as "the art & science of producing metal powders and using them to make serviceable objects." It may also be defined as material processing technique used to consolidate particulate matter i.e. powders both metals and / or non-metals.

A metal powder is characterized by the size (ranging from 0.01 – 1000 microns) and its geometrical shape and high specific area. Powder metallurgy development started with the sponge iron production (in the absence of fusion) before 1800 A.D and making of platinum ingot from reduced platinum powder in 1930. Complex multiphase materials have developed through P/M during 1900-1940 and from 1940 onwards more classical parts in larger quantities for automobile, aircraft, light engineering industry have been economically manufactured.

Powder metallurgy is an improved alternative method as compared to industrial metallurgy being more economical for large production with precision of design and saving of energy, material & labour. Further it is unique method for producing cermets, cutting tools, nuclear fuel elements, self lubricating bearing, copper-graphite brushes etc.

ADVANTAGES OF P/M FOR STRUCTURAL COMPONENTS:-

These may be classified into two main advantages

Cost Advantages: -

It includes Zero or minimal scrap, avoiding high machining cost in mass production as irregularly shaped holes, flats, splines, counter bores, involute gear teeth, key-ways can be moulded into the components, extremely good surface finish at very low additional cost after sizing and coining, very close tolerance without a machining operation, assembly of two or more parts can be made in one piece

Advantages due to specific property of sintered components: -

It includes achieving up to 95% density thus the mechanical and physical properties of parts is comparable with cast materials and in certain case with wrought materials, plating is also possible directly at 90% density and after impregnation of the pores at lower densities, damping out vibrations and noise property with controlled residual porosity, ability to retain lubricants such as lead, graphite, oil and PTFE giving less wear and longer life to bearings, achieving a close control of porosity to give a specified balance between strength and lubrication properties (a superiority over wrought materials), improved

surface finish with close control of mass, volume and density, components manufactured are malleable and can be formed and bent without cracking.

LIMITATIONS OF P/M FOR STRUCTURAL COMPONENTS: -

There are number of limitations for the P/M as an alternate route for the production of structural components. The process is captive intensive and high initial costs mean that the production ranges in excess of 10,000 are necessary for economic viability. However if components are to be machined considerably otherwise when manufactured by industrial metallurgy, the economic production range by P/M could be much lower. The configuration of the component should be such that it can be easily formed and ejected from a die, undercuts and re-entrant angles cannot be moulded and have to be machined subsequently. The capacity and stroke of the compacting press and the compacting pressure required limit the cross-sectional area and length of the component. Sphere cannot be moulded and hence a central cylindrical portion is required

DESIGN CONSIDERATIONS FOR P/M COMPONENTS: -

- i) Avoid sharp corners and thus the corners have to be chamfered.
- ii) As under-cuts and re-entrant angels cannot be moulded into the component, these have to be machined subsequently.
- iii) To prevent excessive wear of the tools chamfers greater than 45 degrees are preferred, but in case of less than 45 degrees land are required.
- iv) Punches less than 1mm be avoided.
- v) Large sectional changes should be avoided as far as possible as they may lead to the cracking of green component at the change in section.
- vi) The practical minimum diameter which can be easily moulded is about 2mm and holes running parallel to the direction of pressing should normally have a length to diameter ration of 4:1
- vii) Grooves are generally moulded into the top face of the component and these should not extend to more than 30% of the total height.
- viii) Tolerances on sintered component can be improved by sizing at extra cost as per design requirements.

The main factors for using P/M are

- a) Economical involving cost savings and achieving large productivity and high precision
- b) Its unique use for special alloys production and their typical microstructure otherwise difficult to be evolved and production of composites
- c) Its captive use for refractory and reactive materials which cannot be otherwise produced and processed.

6.2 POWDER PRODUCTION METHODS:-

This is the first step in P/M and there are numerous basically different methods for the production of metal powder. Many typical modifications have been developed for each method. The requirements of particle size, shape, microstructure, chemistry and cost of production are involved for the choice of a specific technique for powder production. As a matter of fact, all the production techniques can be classified into three basic categories of production methods.

PHYSICAL METHODS:-

- i) Water and gas atomization
- ii) Special atomization methods
- iii) Atomization as a rapid solidification processing technique

MECHANICAL METHODS:-

- i) Milling
- ii) Cold stream process

CHEMICAL METHODS:-

- i) Thermal decomposition and reduction of compounds
- ii) Electro deposition of powders

In addition to these main approaches, several special techniques are also used like rapidly solidifying technique, rotating electrode process and spinning-pulverization techniques. Almost all metals and alloys can be made into powders. The formation of a powder involves the delivery of energy to the material to create new surface area. It is also important to consider the process efficiency, energy content, type of feed stock and possible source of contamination. Various properties of metals and alloys are also to be considered.

Table below gives the various methods for the production of powders of various metals.

Table: Basic Methods for the Manufacture of Metal Powders

1. Machining

Usually produces a relatively coarse particle size.

2. Milling

In ball mills, attritor mills, impact mills, gyratory crushers,

eddy mills and others, result in fine powders of brittle materials.

3. Atomization

By breaking up a stream of molten material in gases or liquid media.

4. Condensation of metal vapour

By deposition on cooler surfaces.

5. Reduction of metal compounds

In reducing mostly oxide powders in solid or gaseous media.

6. Decomposition of metal hydrides

Vacuum treatment of hydrides which results in powder of fine particle size

7. Decomposition of metal carbonyls

Liquid or gaseous metal carbonyls are decomposed and form a fine powder.

8. Electrolytic deposition from salts or solutions

Seldom forms powder directly, but an adherent mass of the material which has to be mechanically comminuted

9. Precipitation of a metal from solutions of its salts

Kroll process for titanium and zirconium

PHYSICAL METHODS: -

These methods are employed for metals and alloys with comparatively less reactivity. The most popular technique under this category is "Atomization". This physical phenomenon involves the formation of powder from molten metal using the spray of droplets. Both elemental and pre-alloyed powders can be formed by such processes.

Atomization: -

It is defined as the breakup of a liquid metal into fine droplets, typically smaller than 150 μm . The breakup of liquid metal stream by the impingement of high pressure jets of gas or water is referred to Gas or Water Atomization respectively. Other types of atomization techniques are based upon the kind of energy being used in the process. The use of centrifugal force to break up a liquid stream is called "Centrifugal Atomization". Atomization into a vacuum is

known as "Vacuum Atomization" and the use of ultrasonic energy to breakup is referred to as "Ultrasonic Atomization". The shape of the particles can be spherical, acicular, spheroidal, irregular or splatted.

For powder production by atomizing of low melting point metals, the molten metal is held in the liquid state in a tank and is raised by the suction produced by the atomizing medium through a pipe to the atomizing nozzle. For higher melting point metals and alloys such as copper, iron, nickel alloys, a stream of molten metal is issued from the orifice at the bottom of tundish and this stream is then broken up by a jet of atomizing fluid.

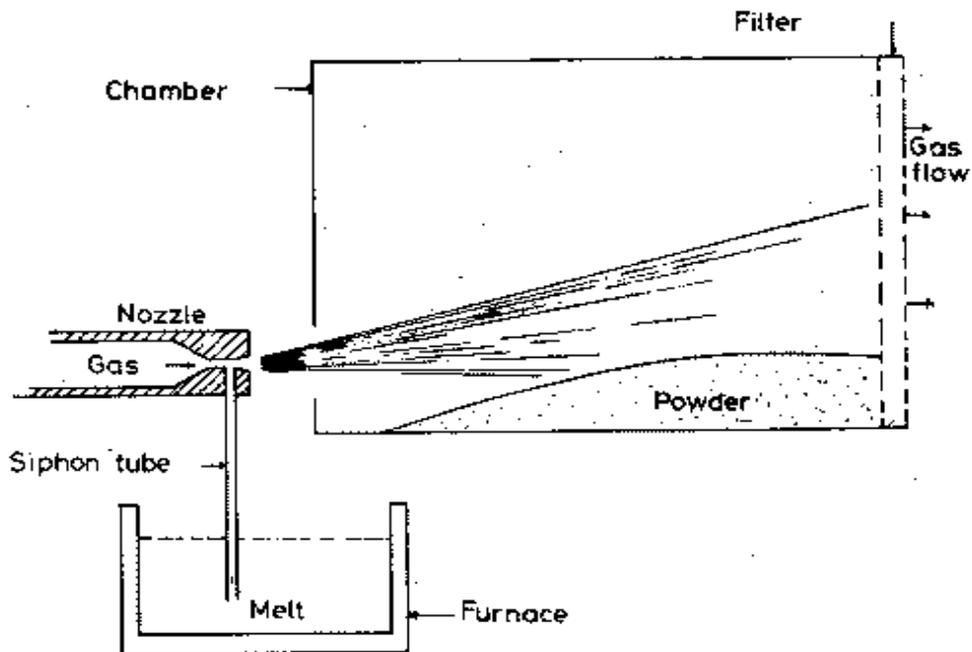


FIG 6.1 - HORIZONTAL ATOMIZATION

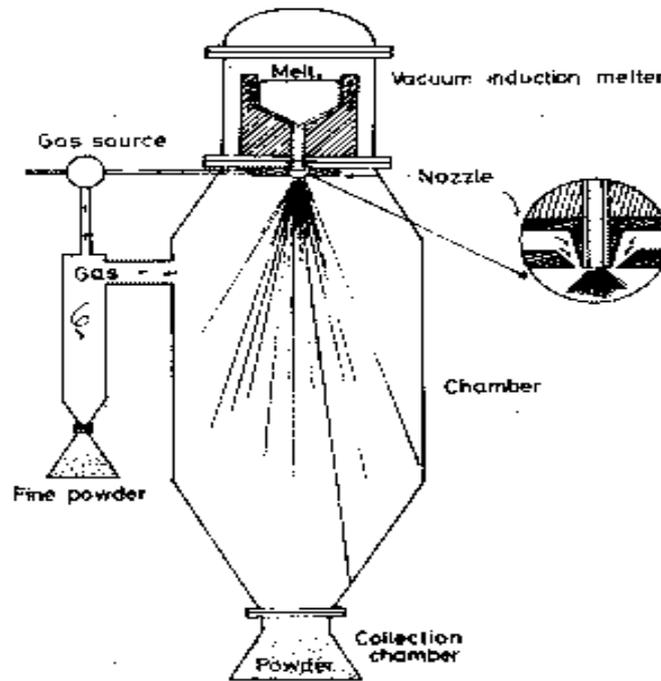


FIGURE 6.2 - VERTICAL ATOMIZATION

GAS ATOMIZATION: -

In this method the liquid metal stream is disintegrated by rapid gas expansion out of a nozzle. This gas may be air, nitrogen, helium or argon depending upon the purity needs of the powder. The major components involved in gas atomization include a melting furnace facility, an atomizing chamber usually 5 to 6 meter high and gas jet compressor network. Pure metals and alloys are melted and degassed in a vacuum induction furnace at the top of the facility. Metals having higher vapour pressure can be melted under inert gas atmosphere. Normally the metals are heated slightly above the melting points which is called super heating temperature. When the desired temperature of molten bath is achieved, it is poured into a tundish having a nozzle at its base. The nozzle controls the shape and size of molten stream and directs it through the atomizing nozzle system. The angle of atomizing nozzle is arranged such that the metal stream is disintegrated into fine droplets by high velocity atomizing medium. The pressure of the gas determines the fineness of the particles. It is generally found that as the gas pressure and gas flow increases or the jet to metal distance decreases, the average particle size decreases. Finer particle size is also favored by:

- a) Low metal viscosity
- b) Low metal surface tension
- c) Degree of superheat
- d) Small nozzle diameter

- e) High velocity atomizing fluid
- f) Short metal stream and short jet length

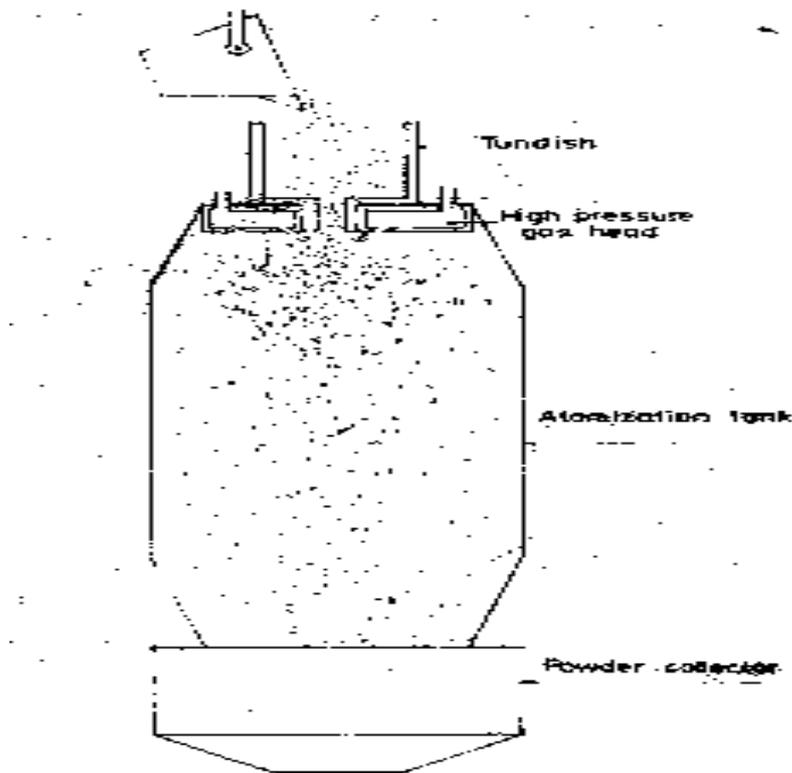


FIGURE 6.3 - GAS ATOMIZATION UNIT

In gas atomization mostly spherical powder particles are produced. Surface tension forces also tend to spheroidize an irregular liquid droplet. As the droplets are away from the point of high turbulence, surface tension forces becomes operative if the droplets are not solidified at this stage.

WATER ATOMIZATION: -

It is the most common technique for the production of powder from metals and alloys, which melt below 1500 °C and are not much reactive. The water atomization tank is similar to gas atomizing but it is slightly smaller in height. Metal is melted in the furnace and poured in the tundish for controlled flow through its bottom nozzle. The water is directed by a single jet, multiple jets or annular ring around the bottom nozzle of tundish. The process is similar to gas atomization except in water atomization, the rapid quenching of particles occurs. High pressure water jets are directed toward the melt stream which forces disintegration and rapid solidification.

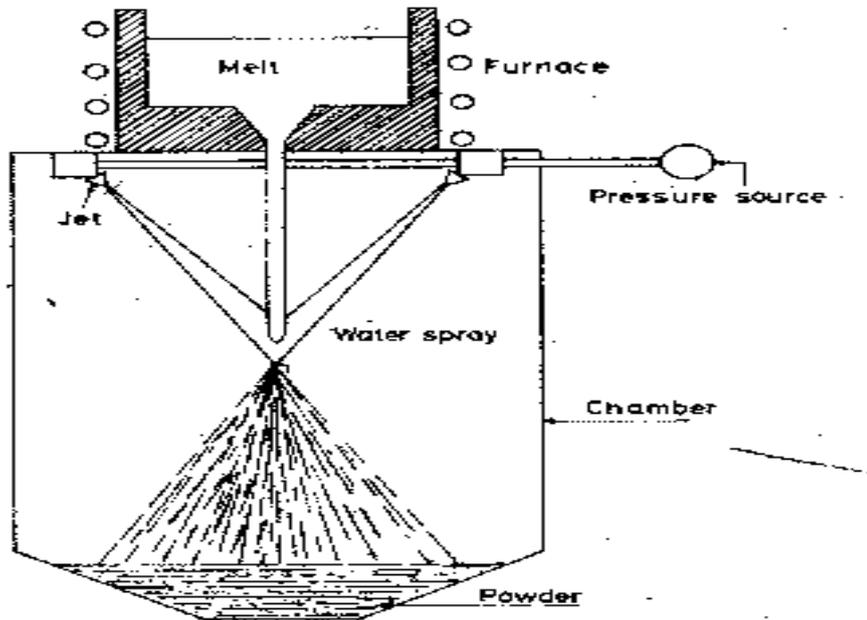


FIGURE 6.4 - WATER ATOMIZATION UNIT

Pressure of water is main process variable in water atomization. Higher pressures result in higher water velocities and finer powder particle size. The nozzle to melt stream distance has less influence in water atomization than in gas atomization. Water-atomized powders are irregular in shape and have relatively high surface oxygen contents. In gas atomization on the other hand particles are more spherical or rounded in shape and if atomized in inert gas, they have very low oxide contents. For high volumes and low cost powder production, water atomization is generally preferred over gas atomization provided powder characteristics are compatible with the application.

VACUUM ATOMIZATION: -

When the molten metal supersaturated with gas under pressure is suddenly exposed to vacuum, the gas expands, comes out of the solution and caused liquid metal to be atomized. There are two vertical sections – lower chamber is the vacuum induction furnace for melting and upper one is atomization chamber with powder collection pot. Metal and alloys are melted in the induction furnace where molten metal is saturated with soluble and non-reactive gas. The molten metal stream is atomized by introducing gas-saturated metal stream through a ceramic transfer tube and nozzle in a reduced pressure (vacuum) chamber. It is also called the melt-explosion technique because the high pressure stream and gas cause the melt to literally explode into the vacuum chamber. All powder handling operations are performed under inert gas or vacuum atmosphere with clean room areas. All equipment of powder handling is specially designed to prevent powder contamination. Alloy powder based on nickel, copper, iron, cobalt and aluminum can be vacuum atomized with this technique. Also the

powders of super alloys and titanium can be produced by this method. Powder produced is spherical, clean and of a high purity with respect to other techniques. With the modification of the process variables, particle size of the powder can be varied from coarser to finer size distribution.

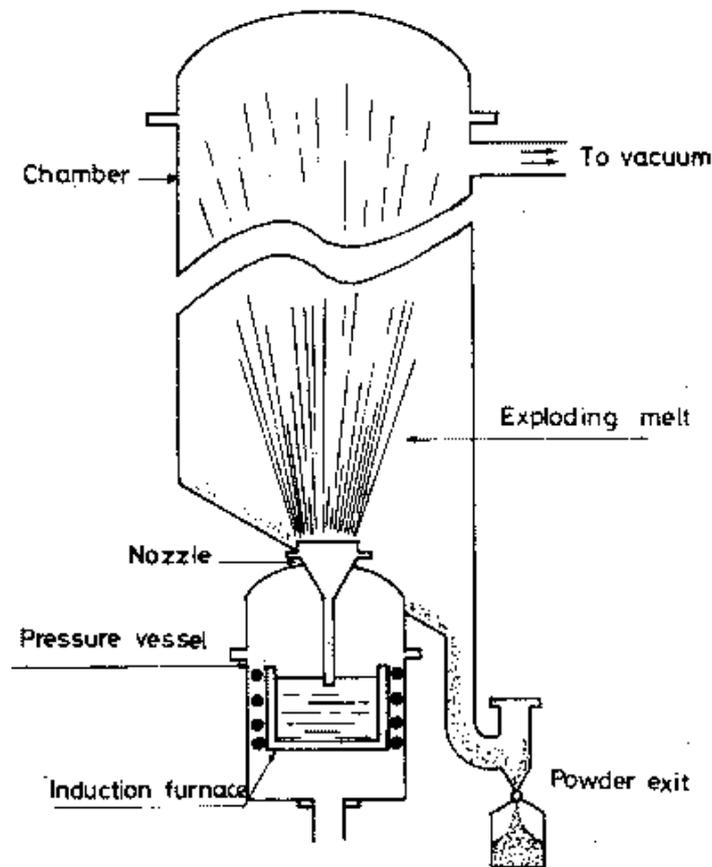


FIGURE 6.5 - VACUUM ATOMIZATION UNIT

Principle application of vacuum atomized powder is the production of gas turbine discs. Also this process is used for coating of turbine blades and vanes.

OTHER ATOMIZATION TECHNIQUES: -

In addition to above mentioned methods, several other mechanisms of atomizations are being practiced. Some examples are "Roller Atomization", "Rotating Disc Atomization" & "Plasma Atomization".

The roller atomizer uses a high velocity rolling mill to quickly break up the melt stream, as a result flake shaped powder is produced. Coarser powders from low melting point metals can be produced using a rotating disc atomizer. In plasma atomization wire, rod or bar is fed into a plasma torch where melting and rapid acceleration of particles occur. As a result fine powder is sprayed out of the torch.

MECHANICAL METHODS: -

Powder production by mechanical comminution process generally is used for brittle materials. There are four different techniques i.e. machining, ball milling and cold stream process. Examples of mechanically comminuted alloys used in powder metallurgy are iron-aluminum alloy used in permanent magnets (alnico). Ferro-silicon powders are used in producing soft magnets and Ferro-phosphorous powders for structural parts. For mechanical comminution, various metals and alloys are embrittled by heat treatment processes. However ductile metals can also be comminuted into powder when they are available in wire, sheet or ribbon form.

MACHINING: -

A large amount of machining scrap is produced in machining operations. This scrap in the form of chips and turnings can be further reduced in size by grinding. It is useful for small scale production. However, its disadvantages are the lack of control on the powder characteristics, including chemical contamination such as oxidation, oil and other metal impurities. The shape of the powder is irregular or coarse. Presently the machined powder is used with high carbon steel and some dental amalgam powders.

BALL MILLING: -

The use of hard balls for mechanical comminution of brittle materials is classical approach to size reduction for powders. The basic apparatus for this technique is the ball mill which mainly consists of a rotating drum (jar) with hard balls in it. As the jar rolls on its side, the balls continuously impact on the material, crushing in into the required powder. Milling is not useful for most of the metals because of their ductility, cold welding and low process efficiency. Under optimum conditions, rotation speed of the jar is adjusted for maximum impact velocity. The rotation speed is kept fast enough to carry the balls to the top of the jar before falling back on the bed of material being ground. The optimum speed of rotation for a grinding mill varies with the inverse square root of the jar diameter. The comprehensive effect of milling upon a powder depends upon the physical and chemical properties of the powder and the milling conditions.

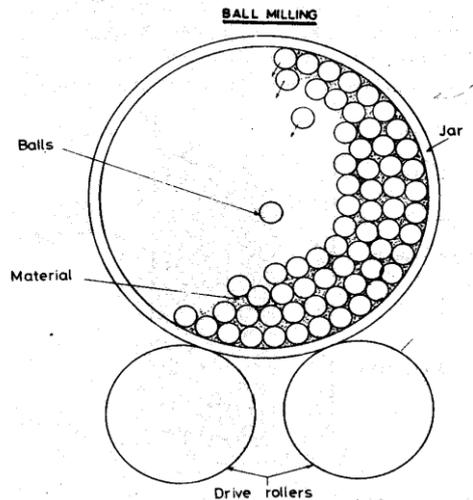


FIGURE 6.6 - BALL MILL

The size and density of the milling medium is selected according to the deformation and fracture resistance for metals. For hard and brittle material the fracture resistance is the only criteria of selection. Large, dense grinding medium is used for milling larger and stronger particulates whereas smaller diameter medium is used for finer grinding. Lubricants and surface active agents are used to nullify the welding forces which cause agglomeration. Corrosion of material in grinding fluid also facilitates comminution.

ATTRITION MILLING: -

In this method a very high efficiency ball mill is agitated by a vertical rotating shaft with horizontal arms. The milling action is done by impact and shear forces. The charge is impacted by balls traveling in various trajectories that collide within the area. In these mills the rotational speeds are nearly 6-80 rpm while the size of medium used is 3- 6 mm. Power is used to rotate the agitator and not the vessel as in case of ball mills.

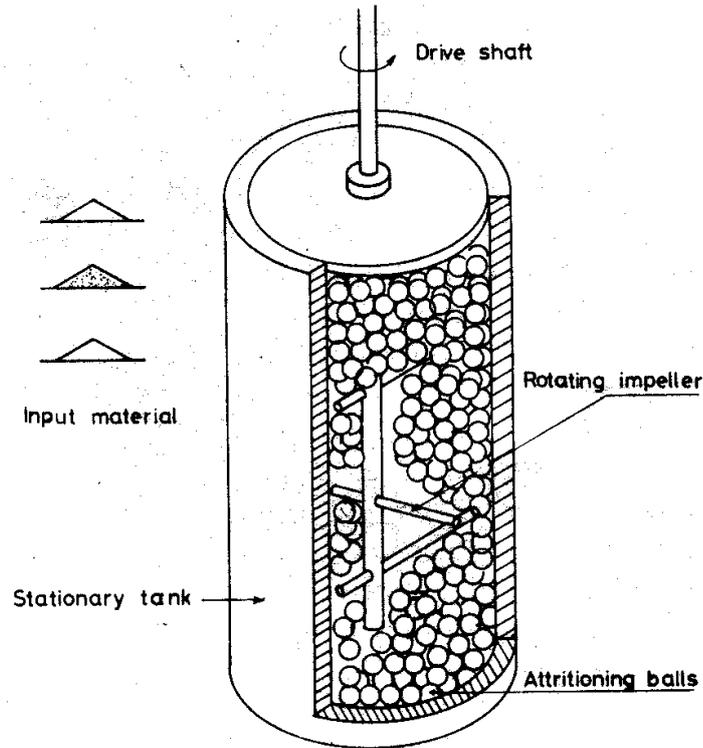


FIGURE 6.7 ATTRITION MILL

In these mills impaction is caused by constant impinging of grinding medium due to irregular movements. Shearing action is produced by random movement of balls in different rotational directions which exert shearing force on adjacent slurry. There also exist continuous attrition mills consisting of a tall, narrow, jacketed chamber through which well premixed slurry is pumped in at the bottom and is discharged at the top. Powders of very hard materials such as ceramics, carbide and hard metals are being produced by this technique. To avoid possible contamination, the balls, stirring rods and the tank may be made from the same material as the powder. The particle size becomes finer with increasing milling time and the shape of particle is angular.

COLD STREAM PROCESS: -

In this process high velocity gas streams are used which impinge at an angle upon the metal particles as they are entrained in the venture shaped stationary target in the classifying chamber. As the material has struck the target and shattered, it is removed from the chamber by suction and classifier allows the oversized products to move through a discharge port. The process is used for relatively expensive metals like tungsten carbide, tungsten alloys, tool steel, molybdenum, beryllium and their alloys.

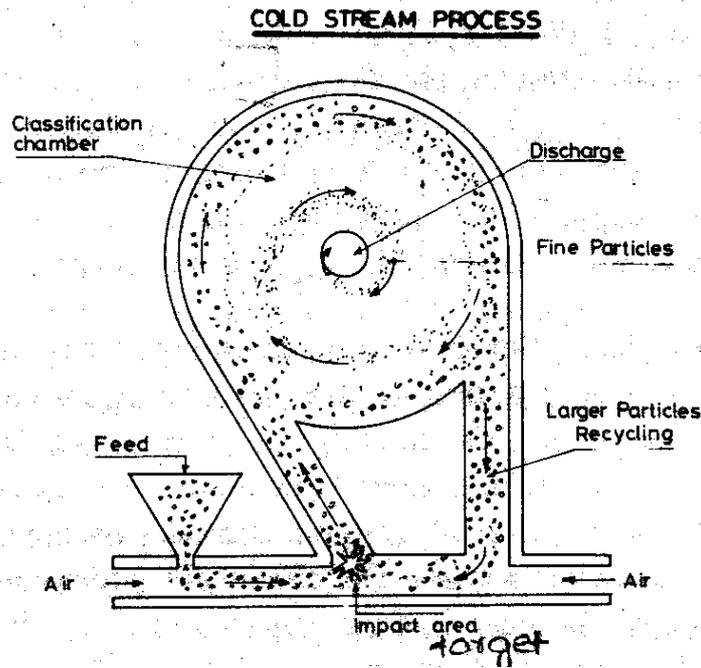


FIGURE 6.8 - COLD STREAM PROCESS

CHEMICAL METHODS: -

In these methods the powder is produced by chemical decomposition of compound of a metal. Almost all metals can be fabricated into powder by this technique. A wide variety of processing variables and production parameters are now available which permit close control of particle size and shape. Major techniques available for this purpose are reduction of oxide, precipitation from solution, hydride decomposition and electro deposition.

REDUCTION OF METAL OXIDE: -

Oxides in the form of finely divided solid powder may be reduced to the metal powder as in case of tungsten oxide to tungsten powder and of copper oxide to copper powder with hydrogen. These powders are spongy and exhibit pores. This sponginess is useful for good green strength and sintering properties. Oxide reduction is achieved by thermo chemical reaction involving reducing gases such as carbon monoxide and hydrogen. A low temperature reaction produces fine powder and sometime spongy in shape. A high temperature increases the reduction rate and particles produced are dense with polygonal. The operating temperature is selected to optimize the reaction kinetics and the type of powder formed.

PRECIPITATION FROM SOLUTION: -

In this method the metal powder is produced by the precipitation of the salts as insoluble hydroxide, carbonates or oxalates etc. On heating, these compounds decompose into metal or metal oxides and gaseous products. The examples of this technique are the production of uranium dioxide, platinum, selenium, silver, nickel and cadmium oxides. The chemically precipitated powders can have high purity and have fine particle size and a tendency towards agglomeration. The particle shape is irregular or cubic or sometime it is sponge like. In some cases, powder is produced by gaseous reactions i.e. metal chlorides, fluorides or oxides of vanadium, niobium, tungsten, uranium, titanium and zirconium are reduced with sodium, magnesium or hydrogen. The reaction product is leached with dilute hydrochloric acid to remove sodium and magnesium chlorides. The resulting powder is spongy like with irregular shape.

HYDRIDE DECOMPOSITION: -

By using this process, titanium, uranium and zirconium hydrides are formed by heating metal turnings or chips in hydrogen. The brittle hydride is milled into fine powder and then dehydrided under vacuum at elevated temperature.

ELECTRO DEPOSITION: -

A few metallic powders are produced by electrolytical methods. The quantities of powder produced are also very limited. There are two known methods of obtaining powder by electro deposition.

- i) Direct deposition of loosely adhering powder or spongy deposit that can easily be disintegrated mechanically into fine powder.
- ii) Deposition of a dense smooth, fine and brittle layer that can be ground into powder.

This process produces high purity metal powders with excellent properties for conventional P/M processing. However, the production technique involves the control and manipulation of many variables. Also it is more expensive than other techniques. Presently only copper, silver and iron powders are produced by this method.

6.3 PRODUCTION OF IRON POWDERS: -**INTRODUCTION: -**

Iron powders are used commercially for a large number of applications such as fabrication of structural parts, welding rods, flame cutting, food enrichment and electronic and magnetic applications. The classical technique for the production

of iron powder is the reduction of iron oxide and mill scale however other methods like atomization, electrolytical and fluidized bed reduction are also used.

REDUCTION OF IRON OXIDE: -

It is the oldest process of production of iron powder from iron ore by using carbon as the reducing agent. The basic technique is the Swedish sponge iron process which was developed by M/s Hoganas in 1900. In this process pure magnetite (Fe_3O_4) is used. Coke breeze is the carbon source used to reduce iron oxide. Additionally limestone is used to react with the Sulphur present in the coke. The mixture of coke and limestone (85% + 15%) is dried in a rotary kiln and crushed to uniform size.

The ore and coke-limestone mixture is charge in to ceramic tubes (Silicon Carbide) with care so that ore and reduction mixture are in contact with each other but not intermixed. It can be achieved by using accentric charging tubes with in the ceramic tube. Charged ceramic tubes are loaded on the kiln cards (36 tubes on each) and cars are pushed into 170 meter long tunnel kiln where the reduction occurs. The total time a car is present in the kiln is 68 hrs. Gas burners heat the 150 meter tunnel at a temperature of 1200 °C and remaining length is cooled by air circulation. Within the hot zone, several chemical reactions occur and metallic iron is formed in the form of sponge cake. This cake is removed from ceramic tube and dropped into a tooth crusher where this is broken into pieces. Afterwards these pieces are ground to desired particle size. During grinding the powder particles are considerably work hardened. The powder is annealed at 800 °C in the atmosphere of dissociated ammonia. The powder is loosely sintered, but requires only light grinding and screening to produce a finished product.

PRODUCTION OF IRON BY THE PYRON PROCESS: -

In this process mill scale is used for reduction instead of ores. Mill scales from different steel mills which produced sheets, rods, wires, plates and pipes is magnetically cleaned to remove dust, dirt or other non magnetic impurities. The mill scale is ground upto desired particle size in a continuous ball mill. Oxidation of the mill scale at 980 °C converts FeO and Fe_3O_4 to ferric oxide (Fe_2O_3). This process is essential to ensure the uniform properties of Pyron-Iron powders. Reduction of ferric oxide by hydrogen is done in an electric furnace 30-40 meter long. Hydrogen is supplied by ammonia cracking plant and reduction is done at 980 °C. The reduction product is ground and mechanically densified to make it suitable for production of structural parts.

ATOMIZED IRON POWDER: -

In this process the free falling molten metal stream is impinged upon by high velocity water jets at about 1200 psi. The jet angle is usually 40 ° and metal flow

rate is 70 kg/min. To protect against excessive oxidation during atomization a shield surrounds the stream of melt and an inert or reducing gas is introduced. The atomized powder is quenched and collected in a water-filled tank. Powder is then magnetically separated, dewatered and dried. Powder is then heated in hydrogen atmosphere at 800-1000 °C to lower down the oxygen contents. These powders are used primarily in conventionally pressed and sintered parts with moderate density.

STAINLESS STEEL POWDERS: -

S.S powders are normally used for structural parts and for filter applications. These are produced by water atomization. Austenitic stainless steel of the composition 303L, 304 L and 314 L and martensitic steel 410 L are produced by this method.

Raw materials: Armco-iron, electrolytical nickel, low carbon ferrochrome and ferromanganese are melted in a high frequency induction furnace under a protective cover of slag. The melt is poured at 1650 °C into preheated tundish with 6-10 mm bottom hole. The water jets which intersect the molten stream at an angle of 40-45° in the chamber, atomize the steel melt. The atomized steel droplets fall to the bottom of atomizing chamber filled with water. The slurry of powder is dewatered, dried and screened. Austenitic steel powders are used without further treatment and martensitic steel powders must be annealed in a protective atmosphere. These powders are flake type with 100-300 mesh. The spherical powders of stainless steel can be produced by argon or nitrogen gas atomization.

6.4 CHARACTERIZATION OF METAL POWDER:-

Prior to the processing of powder in to compact shapes and sintering, following two steps are involved.

- a) Powder characterization and testing
- b) Powder mixing and blending

POWDER CHARACTERIZATION AND TESTING

The performance of the material during processing as well as the properties of the finished product depends to a large extent upon the basic characteristics of the powder material. Aside from the chemical composition and purity, the basic characteristics of a metal powder are particle size and size distribution, particle shape, particle surface and apparent density.

Metal Particle Size and Size Distribution:-

Metal powders may be divided into sieve and sub sieve size ranges. Those in the sieve-size class are usually designated according to the finest mesh through which all the powder will pass. If all the powder passes through a 200-mesh screen, it is designated as a minus 200-mesh powder, etc. The size of these particles may be specified by averaging the actual dimensions as determined by microscopic examination. Particle size distribution is important in the packing of the powder and will influence its behavior during moulding (compaction) and sintering. In general a finer powder is preferred over a coarser powder, since finer powders have smaller pore size and large contact areas, which usually results in better physical properties after sintering. Particle-size distribution is specified in terms of a sieve analysis, that is, the amount of powder passing through 100-, 200- etc mesh sieves. It should be apparent that sieve analysis will yield significant results regarding particle size and distribution only when the particles are spherical in shape. Inaccurate information will be obtained if the particles are irregular or flaky.

Particle Surface:-

The nature of the surface of individual particles is also an important powder characteristic. Powders produced by chemical reduction of oxides usually have a highly roughened surface which is easily observed, whereas atomized particles have a much finer degree of surface roughness. The character of the surface will influence the frictional forces between particles, which is important when powder is flowing or settling or during compaction. Since any reaction between particles or between the powder and its environment is initiated at the surface, the amount of surface area per unit of powder can be significant. The surface area is very high for powders made by reduction techniques.

Particle Shape:-

Particle shape is important in influencing the packing and flow characteristics of powders. Spherical shaped particles have excellent sintering qualities and result in uniform physical characteristics of the end product but give poor green strength as compared to irregular particles. Irregularly shaped particles have been found superior for practical moulding. By water atomization, particle shapes ranging from near spherical to highly irregular can be produced. High melting metals/alloys (above 500 °C) have tendency to form spherical particles because of long freezing times. While very short freezing times for low melting metals/alloys (e.g. Pb, Zn) tend to form highly irregular particles. Thus a silver-tin alloy (m.p 630 °C) produces near spherical particles and the particle shape of lead (m.p 327 °C) is highly irregular. But it is possible by the variation of the atomizing parameters to vary the particle shape of a given metal / alloy over a certain range. The use of minor alloying additions in many cases can influence particle shape up to a great extent.

Apparent Density:-

Apparent density may be defined as the weight of a loosely heaped quantity of powder necessary to fill a given die cavity completely. Increasing the specific gravity or density of the solid material increases the apparent density of the powder. The packing of powder particles is greatly influenced by particle size and shape. For example a given space can be completely filled only by the same size of cubes exactly aligned. Any particle shapes that are curved or irregular cannot completely fill a space and this leads to the presence of porosity. An effective way to increase the apparent density is to fill the spaces among particles with smaller ones. This leads to a filling arrangement known as interstitial packing, however even the smaller particles cannot completely fill the pores. It is even possible for the addition of small particles to decrease the apparent density by an effect known as "bridging". The apparent density of a powder is property of great importance for both moulding and sintering operations. Powders with low apparent density require a longer compression stroke and deeper cavities to produce a briquette of given size and density. The tendency of the compact to shrink during sintering seems to decrease with increasing density.

POWDER MIXING AND BLENDING:-

The metal powder directly after production may not have the necessarily required physical and / or chemical characteristics for immediate use. The requisite characteristics may be attained by mechanical, thermal or chemical treatment or by alloying. The impure, wet powder may be washed, dried and purified by a reducing anneal in a hydrogen gas atmosphere. The required shape, size and size distribution may be achieved by sieving, mixing or milling. Mixing or milling may give the required uniformity of physical and chemical characteristics. The mixing may involve various powders to give the required chemical composition and other additions such as binders or lubricants to assist the processing with required green strength and ultimate controlled porosity.

The process of mixing and milling may require several hours to a few days with may be carried out in air or under controlled atmosphere or under a suitable liquid medium to minimize oxidation or segregation. The powder mix thus produced is immediately transferred to the press hopper or stored in a liquid medium or as such or under vacuum in sealed containers. Various problems of powder mixing are

- i) Filling the powder in to the mixer
- ii) Determination of optimum amount of the powder
- iii) Grinding action and agglomeration during mixing
- iv) Oxidation
- v) Addition of impurity by abrasive action
- vi) Determination of optimum mixing time

- vii) Extraction of the mix
- viii) Sampling difficulties
- ix) Evaluation of mixed ness

6.5 METAL POWDER PROCESSING TECHNIQUES: -

It involves two important processes

- i) Compacting / Pressing
- ii) Sintering

COMPACTING: -

The most important operation in powder metallurgy is compacting or pressing. The ability to obtain a satisfactorily pressed density often determines the feasibility of manufacture by powder metallurgy. Most compacting is done cold, although there are some applications for which compacts are hot pressed. The purpose of compacting is to consolidate the powder into the desired shape and as closely as possible to final dimensions taking into account any dimensional changes that result from sintering; compacting is also designed to impart the desired level and type of porosity, to provide adequate strength for handling and to provide particle to particle contact which is necessary for sintering. Compacting techniques may be classified into following two types:

i) **Pressure Techniques**, such as die, isostatic, high energy rate forming, forging, extrusion, vibratory and continuous

ii) **Pressureless Techniques** such as slip casting, gravity and continuous.

Die compaction

This is the most widely used method. The usual sequence of operations in die compacting consists in filling the die cavity with a definite volume of powder: application of the required pressure by movement of the upper and lower punches toward each other and finally ejection of the green compact by the lower punch.

The pressure commonly employed range from 19 to 50 tons per sq. in. The pressure may be obtained by either mechanical or hydraulic presses. Mechanical presses are available with pressure ratings of 10 to 150 tons and speeds of 6 to 150 strokes/min. The important features of mechanical presses are high speed production rates, flexibility in design, simplicity and economy in operation and

relatively low investment and maintenance costs. Hydraulic presses have higher pressure ratings up to 5000 tons but slower stroke speeds generally less than 20 / min. These presses are used for higher pressure more complicated powder metal parts. Dies are usually made of hardened ground and lapped tool steels. The punches are made of die steel heat treated to be slightly softer than the die, since they are usually easier to replace than the die. They must be perfectly aligned and very closely fitted.

Isostatic Compacting

This technique is used extensively for ceramic materials rather than metals. In this method, pressure is applied simultaneously and equally in all directions. The powder is placed in a rubber mold which is immersed in a fluid bath within a pressure vessel. Since pressure is applied uniformly, it is possible to obtain a very uniform green density and a high degree of uniformity in properties.

High Energy Rate Forming

These may be mechanical, pneumatic or explosive or spark discharge methods applied in a closed die. The advantage of these methods is the short time and high pressures that can be attained. It is also possible to use low grade and very cheap powders and some parts due to increased strength of the green compacts may be used without subsequent sintering. Disadvantages include high punch and die wear, limited tolerances and high cost.

Forging & Extrusion

These techniques have been used only to a limited extent. In either case the powder is "canned" or placed in some kind of metal container. The sealed container is heated or evacuated and then forged or extruded. After forging or extruding, the container material is removed either mechanically or chemically. Both techniques yield compacts of extremely high density and usually do not require sintering.

Vibratory Compaction

In this method, pressure and vibration are applied simultaneously to a mass of powder in a rigid die. Compared with ordinary die compaction, this method allows the use of much lower pressures to achieve a given level of densification.

Continuous Compaction

It is applied primarily for simple shapes such as rod, sheet, tube and plate. Most of the commercial techniques involve flowing loose powder between a set of vertically oriented rolls. The roll gap is adjusted to give a compact of desired properties. In general, the speed of powder rolling is much less than that of conventional rolling operations.

Slip Casting

Slip casting is widely used for ceramics but only to a limited extent for metals. The process consists of first preparing a "slip" containing the powder suspended in a liquid vehicle and additives to prevent particle settling. The slip is then placed in a mold made of a fluid absorbing material (such as Plaster of Paris) to form the slip casting. After removal from the mold, the slip casting is dried and sintered. This technique is attractive for materials that are relatively incompressible by conventional die compaction, but the process does not lend itself to high production rates because of the long time required for the liquid to be removed through the porosity of the mold.

Gravity Compaction,

In this method, the die is filled with loose powder which is then sintered in the die. The die is usually made of an inert material such as graphite. Since pressure is not used, parts are generally more porous. Commercially this method is used for the production of P/M filters.

Continuous Pressureless Compaction

This method is used to produce porous sheet for electrodes in nickel-cadmium rechargeable batteries. The powder may be applied in the form of a slurry (similar to the slip in slip casting) to be coated on a metal screen or solid metal sheet to produce unusual composites.

The green compact density is a most useful property, since it is an indication of the effectiveness of compaction and also determines the behavior of the material during subsequent sintering. Green density seems to increase with increasing compaction pressure, increasing particle size or apparent density, decreasing hardness and strength of particles and decreasing compaction speed.

SINTERING: -

Sintering is the heat treatment of the powder compact for strengthening and densification and bonding of adjacent surfaces of particles. The sintering process is usually carried out at a temperature below the highest melting constituent. In some cases the temperature is high enough to form a liquid constituent such as in the manufacture of cemented carbides, whereas sintering is done above the melting point of the binder metal. In other cases, no melting of any constituent takes place.

Sintering furnaces may be either the electric resistance type or gas or oil fired type. Close control of temperature is necessary to minimize variations in final dimensions. The very uniform and accurate temperature of the electric furnace makes it most suitable for this type of work.

Since bonding between particles is greatly affected by surface films, the formation of undesirable surface films, such as oxides, must be avoided. This

may be accomplished by the use of a controlled protective atmosphere. Another function of the atmosphere is to reduce such films if they are present on the powders before mixing and briquetting. The protective atmosphere should not contain any free oxygen and should be neutral or reducing to the metal being sintered. A dry hydrogen atmosphere is used in the sintering of refractory carbides and electrical contacts but most commercial sintering atmospheres are produced by the partial combustion of various hydrocarbons. Natural gas or propane is often used for this purpose.

Sintering is essentially a process of bonding solid bodies by atomic forces. Sintering forces tend to decrease with increasing temperature, but obstructions to sintering—such as incomplete surface contact, presence of surface films and lack of plasticity— all decrease more rapidly with increasing temperature. Thus elevated temperatures tend to favor the sintering process. The longer the time of heating or the higher the temperature the greater will be the bonding between particles and the resulting tensile strength.

Despite a great deal of experimental and theoretical work on the fundamental aspects of sintering, there is still much of the process that is not understood. The sintering process starts with bonding among particles as the material heats up. Bonding involves diffusion of atoms where there is intimate contact between adjacent particles leading to the development of grain boundaries. This stage results in a relatively large increase in strength and hardness, even after short exposures to an elevated temperature. During the next stage, the newly formed bond areas called “Necks” grow in size, followed by pore rounding. The last stage is pore shrinkage and eventual elimination. This stage is rarely complete, since the temperatures and times necessary are too impractical.

HOT PRESSING: -

This method consists in applying pressure and temperature simultaneously. Molding and sintering take place at the same time, which results in higher densities and greater productions. The advantages of hot pressing as compared with cold compacting and sintering are a reduction in shrinkage effect, along with higher strength, hardness, elongation and density. Hot pressing is used only to a limited extent, primarily for the production of very hard cemented- carbide parts. The principal disadvantage of this method is the high cost of dies to stand up under pressure at elevated temperatures.

6.6 POST SINTERING OPERATIONS: -

For applications that require higher density or close dimensional tolerances, sintering is followed by a cold working operation known as Coining or Re-Pressing. Coining serves the purpose of condensing the sintered compact. It is possible to obtain considerable plastic deformation within the die, resulting in more complex shapes than may be made directly from powder. The restricted

plastic deformation within the die also allows close dimensional tolerances to be held without the necessity of costly machining.

In some cases resintering after repressing will increase the mechanical properties considerably. As compared with straight sintered metal, resintering may increase the tensile strength of copper by about 60 % and of iron by about 30 %. Despite the increase in strength, resintering may result in large grain size and loss of dimensions due to shrinkage. This may require another sizing operation, which will increase the cost of the part.

Depending upon the particular application, the sintered compact may be heat-treated to obtain certain desirable properties. The heat treatment may be a stress relief or annealing treatment. Suitable nonferrous alloy compositions may be age-hardened. Steels may be quench-hardened or case-hardened by carburizing, cyaniding or nitriding.

Various finishing operations may be carried out to complete the manufacture of powder metal parts. These include machining, shearing, broaching, burnishing, straightening, deburring, grinding and sandblasting. Protective surface coatings may be applied by electroplating and metal spraying. The structural parts may be impregnated with a lubricant. The impregnation is the means used to fill the internal pores in the sintered compact. This is carried out primarily to improve antifriction properties, as in the self lubricating bearings. Oil impregnation may be accomplished by dipping the parts in a container of hot oil or by first drawing the air out of the pores by vacuum and then forcing the oil in to the pores under pressure. Waxes and greases may also be used as impregnants.

6.7 POWDER METALLURGY APPLICATIONS: -

Powder metallurgy techniques are used for the production of refractory metals, composite metals, porous metals and metal-nonmetal combinations and as a more efficient production method for certain parts. The high melting points of the refractory metals make it impossible to use the conventional melting and casting techniques. P/M offers the only practical method of producing molybdenum, tantalum and other metals of the same group.

One of the outstanding uses of powder metallurgy is the combination of hard materials in a metallic matrix, which serves as the basis for cemented carbide products. In the production of cemented carbide cutting tools, a suitable mixture of the carbides of tungsten, tantalum and titanium with cobalt as a binder is compacted and presintered. In this condition, the materials can be cut, machined and ground to the final shape. The compact is then subjected to a high temperature sintering operation during which the liquid cobalt binds the hard carbide particles into a solid piece. Cemented carbide tools are noted for high compressive strength, red-hardness and wear resistance. Since they are

relatively brittle, they are usually employed as brazed on tips to a steel tool. They are also used as liners for wear-resistant applications.

Other examples in this classification are diamond-impregnated grinding wheels, drill-core bits and dressing tools. These consist of diamonds embedded in cemented carbides or more plastic metals and alloys.

Metal-nonmetal combinations have found wide use in the manufacture of friction materials such as clutch facings and brake linings. These materials contain a metallic matrix of copper or bronze for heat conductivity, lead or graphite to form a smoothly engaging lining during operation and silica or emery for frictional purposes. Iron is sometimes added to increase friction. Copper-graphite combinations are used as current-collector brushes and in porous bronze and iron bearings.

Composite metals are metal combinations that retain the characteristics of each metal for particular applications. Powder metallurgy is particularly useful for alloys of metals that are not soluble in the liquid state. Casting tends to produce a two-layer alloy unless special techniques are used, whereas homogeneous mixtures are easily produced from powders. The electrical industry makes use of composite metals in the production of heavy-duty contacts which combine the high resistance to abrasion and arcing of a refractory metal such as tungsten with the high conductivity of silver or copper. Similarly the lubricating qualities of lead are combined with the load-carrying ability of copper in the copper-lead bearings.

Controlled porosity of powder metal parts has led to the production of porous bearings, gears and filters. Self lubricating bearings are made of bronze powder with controlled porosity after sintering. The pores are subsequently filled with oil. In operation, the load on the bearing and the increased heat set up by the moving part within the bearing force the oil out of the pores to provide automatic and uniform lubrication. Self lubricating bearings are used extensively in the automotive industry and in washing machines, refrigerators, electric clocks and many other types of equipment. Porous-metal gears are used in oil pumps for their lubricating properties. Metal filters used in the chemical industry are similar to the ceramic type but have higher mechanical strength and resistance to both mechanical and thermal shock.

Finally in many applications the use of powder metallurgy techniques results in more economical manufacture of the part. Where load conditions are not severe, small gears, cams, levers, sprockets and other parts of iron, steel, brass or bronze may be molded from powders to reduce greatly or completely eliminate expensive and time consuming machining and other forming operations. For example, the gears of a gear-type oil pump must have accurately formed involute teeth or the pump will be inefficient. The machined gear is cut from a cast blank by a skilled machinist with about 64 % of the metal lost in chips. On the other hand, any semiskilled man can fill a hopper and operate a press which

can turn out hundreds of these gears with dimensional accuracy and with less than 1 % of the metal as waste.

Small Alnico permanent magnets containing aluminum, nickel, cobalt and iron may be made from powders or by casting. The cast alloy is difficult to machine and finishing to dimensions must be done by tedious grinding. These magnets may be molded of powders directly to size and shape and their dimensions held to acceptable tolerances during sintering. In addition, a finer grain size and greater mechanical strength are obtained in the sintered magnets.



FIGURE 6.9 - VARIOUS PARTS MANUFACTURED FROM POWDER METALLURGY

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Q.9 In any solid solution if atoms of solutes substitute for atoms of solvents in the lattice structure then the solution is called interstitial solid solution.

A) True

B) false

Q.10 The heat treatment that is used to negate the effects of cold work is called process annealing.

A) True

b) false

10. ANSWER KEY

1. **A** B C D

2. **A** B C D

3. **A** B C D

4. A **B** C D

5. Zinc

6. Hot Working

7. Solid 1+Solid 2

8. Pearlite

9. F

10. T