1 IRON AND STEEL MANUFACTURE

1.1 IRON

1.1.1 Indirect Method

When ores containing iron are heated under certain conditions, metallic iron is produced. Some ores that contain iron are Magnetite Fe_3O_4, Hematite Fe_2O_3, Siderite $FeCo_3$, Pyrite FeS_2 and Limonite $HfeO_2$. This list of iron producing ores is more extensive and can be classified as Oxides, Carbides, Silicates and Sulphides. Magnetite and Hematite contain about 70% iron, Siderite about 60%, Limonite about 35% and Pyrite about 45%.

1.1.1.1 Blast Furnace Production

A medium sized blast furnace is about 30m high and 10m in diameter at its widest part. It is covered on the outside with steel plates, some of them water cooled, enclosing a refractory lining. Most iron ore is mixed with sand, earth, clay, and stones that contain silica.

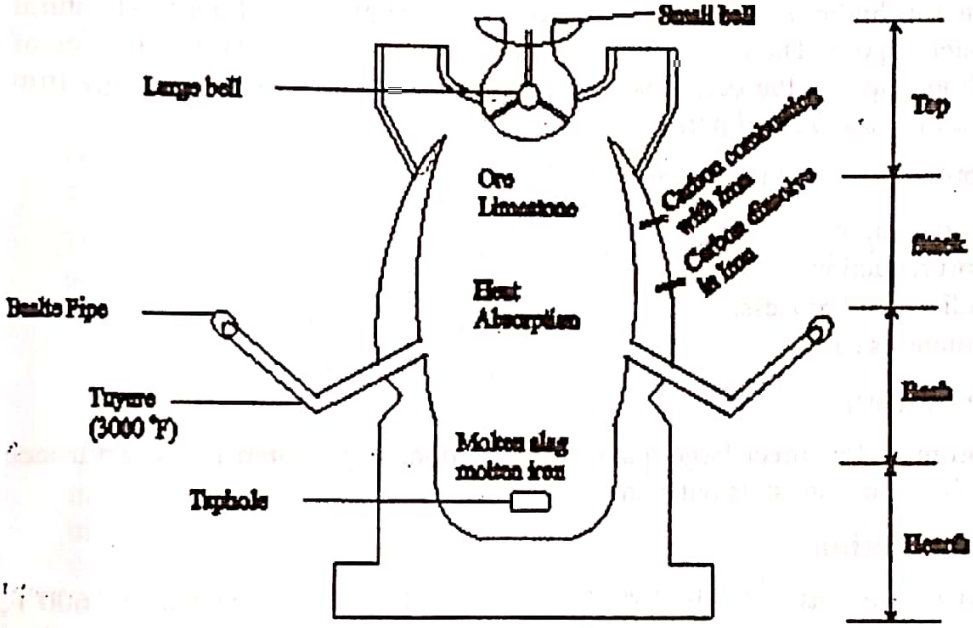

Fig.1.1 Blast Furnace

During smelting a great deal of the iron ore would combine chemically with the silica. It is, therefore, necessary to introduce another material, which will combine with silica, thus preventing it from uniting wastefully with the iron. Limestone has this property, forming slag - used in cement, insulating and roofing materials, fertilizer and paint.

Slag subsides down the blast furnace being lighter than iron; it then floats above the layer of molten metal, which is accumulating at the bottom.

A blast of hot air is blown through a number of nozzles called tuyeres. There are between 12 and 24 of these distributed evenly round the circumference but placed about 2½ meters above the bottom of the furnace in order to leave a space in which the molten iron and slag can accumulate.

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The ore, coke (fuel) and limestone (flux) are given the collective name "charge". The charge is hoisted to the top of the furnace and dumped onto a double bell and hopper arrangement. As the charge works its way down to the bottom of the furnace, carbon monoxide is formed by the combustion of air and coke. The temperature of the charge increases to about 3000°F, which is enough to melt the ore.

When the level of the iron and slag has risen to approach the tuyeres, the slag is drawn off and the metal is tapped.

The molten iron is run into moulds - Pig iron or conveyed molten into steel. Ratio of each components of the charge is ⅔. Iron ore, ¼ coke, and $^1/_{12}$ flux. Constituents in pig iron vary considerably but a common approximate composition is 3.5% C, 2% Si, 1% S, 1.5% Mn, 1% P. Pig iron, may be either **basic** or **acidic** depending on phosphorus level. *Cast iron is refined pig iron.*

1.1.2 Direct Method

This involves the reduction of iron ore to a spongy form of iron. This could then be converted into steel. A gas rich in hydrogen and carbon monoxide is manufactured from local natural gas mixed with water vapour. The conversion of iron ore to metal takes place in a series of four reactors. Without melting the ore, it is converted by the gases into solid spongy iron lumps or pellets to a high standard of purity.

There are various processes of achieving this:

- Kiln reduction.
- Retort reduction
- Fluidized bed process.
- Continuous casting.

1.1.2.1. Kiln Reduction

This has a good promise for direct large quantity production. A gas fired rotating furnace with a water spray directed against its outer shell is used.

1.1.2.2. Retort Reduction

This uses reformed natural gas 73% H_2, 16% Co, 7% Co_2, 4% CH_4, preheated at 1600°F, injected into the retort. Processes involved are, charging, primary reduction, secondary reduction and cooling.

1.1.2.3. Fluidized Bed Process

This uses heat of partial combustion of preheated air and natural gas for the reducing reactions. Reducing gas -- 21% Co, 38% N, 41% H_2. It is a batch process and operates at 1500°F and atmospheric pressure.

1.1.2.4. Two Stage Continuous Casting using H_2 as fuel

Iron ore is preheated to 1700°F.

1st phase $Fe_2O_3 \longrightarrow$ reduced FeO at 1300°F

2nd phase H_2 at 207 N/mm^2 preheated to 1550°F.

$\longrightarrow$

FeO reduced Fe at 1200°

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1.2 STEEL

The production of steel is essentially a process of the purification of pig iron and the introduction of impurities in the form of alloys to impart the desired characteristic.

1.2.1 Methods

Bessemer, Open hearth and Electric furnace. The refining of steel by Bessemer and Open hearth removes impurities form pig iron by iron oxide and by the O_2 of the air; most of the impurities being taken into the slag.

1.2.1.1 Bessemer/Open Hearth

The Open-hearth method is labour intensive. In the production of steel O_2 has been found to be of great importance, that the L –D method was evolved - Linz Dusenverfahren method. Here a jet of almost pure O_2 at high pressure and traveling at supersonic speed is passed into the surface of molten iron held in a converter.

However, in steel production, the type of furnace lining used is one important means of controlling impurities introduced in the form of alloys to impart the desired characteristics of the steel.

The 2 linings used are acid and basic lining. Carbon, Si, Mn may be removed by either lining. The removal of phosphorus P and Sulphur S is accomplished with lime, which forms a basic slag. Liquid steel contains dissolved O_2 which can be removed by adding strong deoxidants eg, Al, Si,.

Three basic ingot styles are made, depending on the mode of solidification, which is governed by metal composition, and the extent of the use of deoxidants. They are known as **killed, rimmed** and **semi-killed steels**.

In the production of killed steel virtually all the dissolved O_2 is removed and the liquid solidifies without any evolution of gas. The resulting ingot contains no porosity and is used where high strength and resistance to impact are essential.

In contrast to killed steels, the manufacture of rimmed steels takes advantage of the chemical reactions, which take place when a non-deoxidized steel is allowed to solidify. The dissolved O_2 combines with carbon to give Co gas, which is released at the solidification front.

The evolution of this gas gives the ingot a characteristic clean outer skin or rim. Sheet metal products requiring good surface quality are made from rimmed steel ingots, like car bodies and "tin" cans. The 3rd class of products is called semi killed and as the term indicates, it is only partially deoxidized prior to solidification. Some structural steel products are made from it.

1.2.1.2 Electric Furnace Steel

Where a fuel is burnt in the furnace some contamination is unavoidable and this led steel makers to realize that electric melting was likely to be technically more desirable than the methods of the Open hearth and Bessemer processes.

1.2.2. Modern Steel Making

Two main processes in use today are Basic Oxygen Steel making (BOS) and Basic Electric Arc (BEA) but considerable amount is still made by Open Hearth (OH) process.

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In BOS the converter is charged with scrap together with molten iron direct from the blast furnace. This is then refined by the chemical action of oxygen. Any alloy additions are made either to the charge before the blow or to the ladle during teeming.

The BEA process is primarily used to make alloy and special steels. At the start of the process the furnace is charged with scrap that is then melted by the heat generated by an electric arc struck between the electrodes through the scrap.

In the OH process, scrap and molten iron ore heated by gas and impurities removed with the aid of slag making fluxes. Because of restricted heat input, it is a slow process. As a result of the use of O_2 in steel making, the steel as poured is saturated with dissolved O_2. The O_2 combines with some carbon to form CO, which escapes as gas bubbles at the solid liquid interface of the cooling steel. By careful control of the carbon /oxygen reaction, solidified ingots having 3 different types of internal structure can be produced. These are rimmed, semi-killed and killed steels.

- Low C, good surface - rimmed steel
- Construction steel -semi-killed steel
- Engineering steels deoxidized with Al., Si, - killed steels

When molten steel has solidified it is rolled or formed into 3 basic shapes.
The basic 3 shapes produced in 7 – 10m lengths.

- **Slabs** (typically 75 – 200mm thick and up to 2000mm wide.
- **Blooms** 150 – 300mm square.
- **Billets** 50 - 150 mm square.

1.2.3 Steel Products

Principal methods used for forming products

- **Rolling**
- **Forging**
- **Extrusion**
- **Casting and Drawing.**

1.2.3.1 Rolling

Hot rolled to produce ***Sections*** and ***Flats***.

1.2.3.1.1 Sections

Round, H, square, hexagon shapes supplied with a black mill scaled finish which is pickled to remove the mill scale, annealed and cold rolled to produce a bright finish.

1.2.3.1.2 Flats

These comprise heavy plates of 10 to over 150mm in thickness and 4m wide. Light plates 3 – 10mm thick. Sheet 1.2-10mm thick but width up to 1.8m.

1.2.3.2 Forging: gives bars and bill

1.2.3.3 Extrusion: for sections and hollows; complicated ones to be produced by rolling.

1.2.3.4 Casting: from cast ingots or continuous casting.

1.2.3.5 Drawing: wire drawing, pipes etc.

Commonly used alloying elements Mn, Si, Ni, Cr, Mo, V, and W.

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1.3 Tutorial Worksheet One

1 Describe the indirect method of manufacture of iron.

2 Differentiate between indirect and direct methods of iron production

3 Describe the Electric furnace steel production method

4 Distinguish between killed, semi-killed and rimmed steels

5 Distinguish between slabs, blooms and billets

6 What product types can be derived from Rolling, Forging, extrusion and Drawing?

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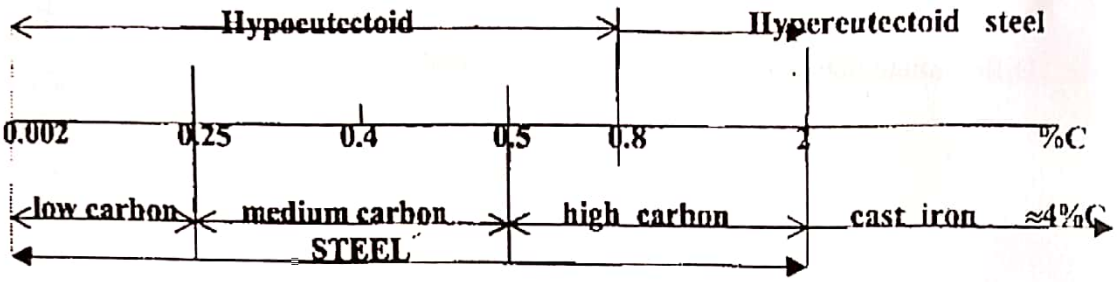
2 STEELS and THEIR TYPES

Steel is essentially an alloy of iron and carbon. Its remarkable properties and the ability to control these properties stem from the presence of carbon.

2.1 Plain Carbon Steels

These are split into Low carbon, Medium carbon and High carbon.



They are called plain carbon because they contain very small amounts of impurities or alloying elements. In addition to carbon, other elements such as Mn, Si, P and S, which are introduced unintentionally during manufacture, are present in small amounts. The main advantages of the unalloyed steels is their low cost of production and the fact that they are used successfully where strength and other requirements are not too severe. For example, at ordinary temperatures and in atmospheres that are not of a severely corroding nature, plain carbon steels will be highly satisfactory.

2.1.1 Division of Plain carbon steels

Low carbon steels (0.002- 0.25% C) account for a large proportion of the total output of steel. In this form they are used for automobiles, furniture, refrigerators, tinplate and roofing etc.

In between 0.15 and 0.25%C content is the structural steel because it is mainly used for structural purposes; beams, channels and angles for construction.

Medium carbon s teels are the heat treatable steels. They are used for the production of machine parts, bolts, crankshafts, gears and railroad rails.

High carbon steels (Tool steels)

Much cheaper than alloy steels and used in general engineering where service condition is not particularly severe. Depending on the carbon content, six groups are recognized.

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THE SIX GROUPS OF HIGH CARBON STEELS

Carbon Content %	Typical Application
1.3 - 2.0	Extra hard planning, slotting, turning tools, drills, razors.
1.2- 1.3	Lathe tools, small cutters, cold chisels.
1.1 - 1.2	Turning tools, cutters, punches.
0.9 - 1.1	Hot shear blades, picks and dies.
0.7 - 0.9	Miner's drill
0.6 - 0.7	Hammers, stamping and pressing tools.

2.1.2 Limitations of Plain Carbon steels

1) **Low Hardenability**: This limits the strength that can be attained except in relatively small x - section. Water quenching, with its danger of distortion and cracking must always be used and even this drastic quench is incapable of fully hardening most carbon steel bars greater than 3cm in diameter.

2) **Loss of hardness on tempering:** One of the purposes of tempering hardened steels, is to decrease the internal stresses that may have been produced in the quenching operation. Plain carbon steels exhibit softening during tempering. Ideally a steel should stress relieve without softening.

3) **Low Corrosion resistance:** This is a problem in most low temperature and elevated temperature environments.

4) **Low Strength at elevated temperature:** The creep strength falls off rapidly with temperature and the maximum temperature at which they can be used is 500^0C or less.

2.2 Alloy steels

As we have seen, carbon steel as made commercially always contain certain amounts of other elements such as S, Mn, P, Si. Steels to which further elements have been added (and those steels with greater than 1% Mn, or greater than 0.3 %Si) are known as alloy steels. This definition is quite arbitrary.

The purpose of using alloying elements is to mitigate the disadvantages listed already of plain carbon steels and to strengthen steels, which cannot be subjected to quenching.

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The alloying elements commonly employed for the purpose of securing hardenability, are:

Manganese

Chromium

Molybdenum

Vanadium

Nickel

Silicon

Various combinations of these elements are used resulting in numerous types of alloy steels. Included in these groups are alloys of:

1. Iron and Chromium varying from about 12 to 30 percent.
2. Iron, Chromium and Nickel, with chromium varying from 18 to 32 percent and nickel from 8 to 20 percent.
3. Iron, nickel, and chromium, with nickel varying from 33 to 41 percent and chromium from 13 to 21 percent.
4. Iron and nickel with nickel varying from 58 to 68 percent.

The properties of alloy steels are controlled largely by the effects of the specific alloys or the allotropic transformation characteristics, especially under the influence *of* rapid cooling of the steel, and are not dependent to any great degree on any intrinsic property that the particular alloy might confer. The only complicating factor is that many of these alloying elements also combine with carbon to form solid solutions or a carbide phase.

Solid Solution Hardening

Some alloying elements can improve the mechanical properties by assisting the quench hardening process. Also those that form carbides can cause increased strength and hardness in the same way as Fe_3C does in carbon steels. One important useful benefit can be obtained from those elements, which dissolve readily in ferrite in which they can produce enhanced hardness and strength. This effect is termed *solid solution hardening.*

There are two ways of doing this:

First the solute atoms do not fit into the solvent lattice so they replace the atoms *of* the solvent atoms by a substitutional solution reaction.

Interstitial atoms, which are normally smaller in size, can produce similar effects by fitting into the interstices of the solvent lattice. Such distortions or local imperfections in the symmetry of the crystal tend to hinder dislocation movement.

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Consequently the presence of interstitial or substitutional atoms produces solid solution hardening.

Secondly solute atoms tend to migrate to dislocations because in doing so the strain energy associated with a given dislocation is reduced. When dislocation slips, the strain energy of the crystals increases because the solute atoms do not move with the dislocations. This energy must come from the forces acting on the dislocation. Therefore the stress required for slip is raised from the atoms have a dislocation pinning effect.

2.2.1 Division of Alloy steels

Depending upon the amounts of alloying additions present, these steels can be divided into **High or Low alloy steels.** The high alloy steels are often called *stainless steels*.

Low alloy steels contain less *than 10%* alloying additions.

Nickel steels: The principal advantage that is obtainable from Ni is the higher tensile strength that can be obtained without reduction in area and % elongation. They can contain anything up to 5% Ni and are used for carburising application - can develop hard surface with tough cores. Such steels are used for boiler and bridge structures.

Chromium steels: The addition of Cr. to plain carbon steels improves hardenability, strength, wear and corrosion resistance. Cr steels however, have the disadvantage of being temper-brittle - usually containing 0.15 to 1.6% Cr and are used for cutting tools and bearings.

Nickel-Chromium steels: A proper combination of Ni-Cr will improve the general serviceability of the steel. The improvement in ductility and toughness upon the carbon steels by the addition of Ni can be combined with the increased strength, surface hardness, depth of hardening and corrosion resistance produced by addition of Cr. The optimum ratio of Ni: Cr. is 2.5:1, the steel containing up to 4% Ni

Molybdenum steels: When molybdenum is added to carbon steel, improved high temperature strength and creep resistance results. Consequently, 1/2% Mo steels with 0.1 % C are used in power plants for steam pipes, superheated tubes and turbine components. The microstructure of such steel is identical to plain carbon steel. The improved creep strength is associated with the production and stability of MO_2C particles, which confers resistance to high temperature deformation when the steel is correctly heat-treated.

Chromium-Molybdenum steels: These contain up to 9% Cr and up to 1% Mo. Applications for these steels are broad based. Corrosion resistance is a predominant requirement of the Petroleum and Chemical Industries and this led to the initial use of the higher Cr. alloys in this group. One of these, 2 1/4% Cr., 1 % Mo steel, was later adopted for steam power plant by virtue of its good creep strength. Other steels such as 3% Cr, 1/2% Mo type are of use in general engineering, while the 1% Cr, 1/2% Mo evolved from high temperature engineering requirements.

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The microstructures are again similar to carbon steels depending upon the carbon content (0.1 to 0.4%), Cr. content and the operative cooling rates. The creep strength of these materials is thought to be partly attributable to solid solution hardening of the ferrite by Mo and also by the precipitation of complex Mo and Cr. carbides after suitable heat treatment procedures.

Chromium- Molybdenum- Vanadium steels: Usually contain 1 - 3% Cr., 1% Mo, 1/4 - 3/4% V. Also have good creep strength and have been extensively used in power plants for steam pipes, turbine rotors and casings. The resistance to high temperature deformation of these alloys is, thought to be, due to the αFe being hardened by the Mo and Cr. with additional benefits from a dispersion of fine particles of V_4C_3 within the αFe (ferrite).

High alloy steels – *Stainless Steels*

Steels containing about 10% or more of Cr. are of great interest to the engineer because they are more resistant to corrosion and stronger at elevated temperature than the low alloy steels. Such steels are often called stainless steels and are used for aircraft, missiles and nuclear energy fields where stringent corrosion and thermal problems arise. Although Cr. is the principal alloying element, many other elements are added such as Ni, Si, Ti, Nb for various reasons.

Depending upon the characteristic microstructure the stainless steels can be divided into ***martensitic, ferritic and austenitic steels.***

Martensitic (or hardenable) Steels

These contain 12 - 14% Cr and (0.1 - 0.3%) C and can be hardened by austenite martensitic transformation --since at 950 - 1050^{0}C this composition lies between the γ loop in the iron - Cr. equilibrium diagram. Typical applications of these alloys are cutlery, surgical instruments, syringes, turbine blades and in chemical plants. The corrosion resistance of this material is due to the formation in most low and high temperature environments on the surface of the components of a thin passive film of Cr_2O_3. This insulates the metal from corrosion when broken by scratching or indentation. Some commercial alloys in this group exhibit good creep resistance at 450 - 600^{0}C. An example is an 8% Cr 3% Mo 1 % Ti steel whose creep strength is considered to be due to the solid solution strengthening of the ferrite together with the formation of complex carbide.

Ferritic Stainless Steels

Binary iron - Cr alloys with more than 13% Cr are ferritic at all temperatures. With carbon present (as in commercial materials) more Cr. is ready to give an α structure at all temperatures. Clearly such ferritic steels will not respond to heat treatment. In practice, these alloys tend to be fairly coarse grained and brittle so that their principal engineering application lies in the field of corrosion resistance conferred by their high Cr content. Another useful feature is their softness, which allows them to be cold worked to a greater extent than other stainless steels and enables them to be pressed and deep drawn. On the other hand they are difficult to weld without loss of properties and their creep strength is poor.

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Austenitic Stainless Steel

These steels which constitute by far the greatest proportion of stainless steel output contains between 16 - 25% Cr. together with sufficient Ni to enable the austenite to be retained on cooling to room temperature. There are also other elements usually added in low concentrations. The effect of the additions of various levels of Cr to Fe - Ni system is known. Quen[illegible] annot harden austenitic steels, but the austenite structure provides an inherently high [illegible] resistance, toughness and strength particularly above 600^{0}C. Moreover increased strength can be obtained by cold working. In the soft condition the tensile strength of an 18% Cr. 8% Ni steel is 689 MN per m^2 and with 60% reduction by cold work, this can be almost doubled.

Applications:

The 18/8 steels have good corrosion resistance in a wide range of environments and are generally the cheapest of the austenitic steels. They are used for domestic utensils and in chemical plants involving generally corrosive liquids. They are also used where high temperature strength and resistance to corrosion are important. They have been utilised for generator steam tubes operating up to 550^{0}C. The addition of slightly more Ni say 10-12% to the steel containing 18% Cr. produces somewhat greater creep resistance due to enhanced solid solution hardening. Further benefits are obtained if Ti or Nb are present due to the precipitation of Ti or Nb carbides during high temperature use, which reduces dislocation mobility. Such steels have satisfactory creep strength up to 625^{0}C. More complex austenitic stainless steels have been developed, many of which contain several % of Mo together with Nb or Ti. The Nb contents are quite high. The other elements added are Cu, Al, Mn, and Co. These materials can be used up to 700^{0}C in creep application. Their high temperature strength is thought to be partly due to the solid solution hardening together with the hardening due to precipitation of complex carbides and inter metallic compounds such as Fe_2Ti, Ni_3Ti and Ni_3Al.

Limitations of Cr. content of Alloy Steels:

The maximum operational temperature from the point of view of creep resistance for the various steels has been indicated earlier. Unfortunately these maximum temperatures are often unattainable in practice for other reasons. The most serious limiting factor is often corrosion-resistance particularly in sulphurous atmospheres such as in conventional power station boilers and some chemical plants. There is evidence that the high temperature corrosion of stainless steels increases with Cr content, thus some commercial steels containing greater than 18% Cr. exist but this introduces two problems.

First, if austenitic steel is desired, then the Ni content must be raised and this increases the cost of the alloy.

Secondly and more seriously is the occurrence of a sigma phase of the Fe - Cr. alloys of high Cr. content. When sigma phase is present in the microstructure, the mechanical properties of the alloy fall off --- in particular the material becomes brittle. This dictates a limiting Cr. content of steel to about 25 % Cr.

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2.3 Tutorial Worksheet Two

1 What is responsible for the versatile use of steels?

2 Differentiate between low, medium and high carbon steels

3 Why are high carbon steels called Tool steels?

4 Is cast iron, steel? Explain

5 How would you overcome the limitations in the use of plain carbon steels?

6 What are stainless steels?

7 Differentiate between Ferritic, Martensitic and Austenitic stainless steels.

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3 HEAT TREATMENT OF STEELS

This is a process in which steels are subjected to one or more temperature cycles to confer certain desired properties. Heat treatment can alter the size and shape of the grains and micro constituents of steel. The shape of the grains are altered by heating the steel to a temperature above that of re-crystallization, the size of the grains are controlled by the temperature and duration of heating and the speed at which the steel is cooled after heating. Heat treatment is only effective with certain alloys because it depends upon one element being soluble in another in the solid state in different amounts under different circumstance.

Reasons for heat treatment.

1 To change the strength, hardness, ductility and other properties of the material.

2 To improve machinability of the parts.

3 To remove or reduce irregular structures.

4 To transform the structures.

Heat treatment process - *Hardening and softening*

The hardening one produces non-equilibrium conditions, which leads to strengthening of the materials and the softening process produces equilibrium conditions.

3.1 Hardening non-Equilibrium Process

This involves mainly alloys; such as alloy steels which when heated to temperature T are maintained at this temperature for a while and then cooled. This cooling could be under atmospheric conditions or in water. The high temperature phase of steel is the face centred cubic phase (austenite), which can contain up to 2.1%C in interstitial solid solution. On slow cooling, 2 phases form, cementite that contains nearly all the carbon and ferrite, which is almost pure α iron. This change involves diffusion of carbon atoms and so requires time --- it is time dependent. But if the austenite is quenched (rapidly cooled by plunging into oil or water) the above processes are suppressed and the f c.c. structure changes by a shear-type transformation to a body centred tetragonal (BCT) structure. This is in effect a body centered cubic structure distorted to make one cube edge longer than the other two.

This happened because the C atoms have not had time to diffuse out of the lattice that wants to be ferrite and have distorted the would be ferrite lattice. As a consequence of this distortion, the lattice would not permit the free flow of dislocation and the material is said to be very hard and non- ductile. The structure produced by quenching is called *martensite* and is meta- stable - it hasn't arrived at its position of equilibrium.

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Different types of Hardening- *Coherent and Incoherent*

When hardening is enhanced by the boundary between particles and the matrix, it is called *coherent hardening.*

Incoherent or aggregate hardening occurs when particles of incoherent boundaries merge with the primary phase. Dislocations are impeded only partially by these particles. Dislocations move by bowing in between the particles.

3.2 Softening Equilibrium Process

This involves the following procedures: *Tempering, Annealing, Spheroidising, Surface Hardening and Normalising.*

Tempering

Since martensite does not represent the stable state of the alloy it tends with time to revert to the more stable structure of ferrite + cementite. It does this by a diffusion process in which carbon is expelled from the supersaturated martensite and precipitated elsewhere as distinct crystals of ferric carbide while the tetragonal lattice of the martensite shrinks slowly to the cubic lattice of the ferrite. At atmospheric temperature diffusion is so slow in hardened steels that martensite persists indefinitely. As would be expected from its effect upon diffusion rate, even a small temperature rise would accelerate the decomposition of martensite into ferrite + cementite. At temperatures of a few hundred degrees, martensite may be completely eliminated in just a matter of minutes. ***This process of eliminating martensite by the application of heat is called tempering.***

The importance of tempering is that as-quenched martensite steel is very brittle for most practical purposes. Tempering process produces a more stable, less distorted structure through which dislocations can move easily. Thus tempering increases the ductility and toughness above that of the as quenched steel and decreases the hardness. The extent of these changes depends on the temperature and time of the tempering process.

Annealing

This is the heating to and holding at a suitable temperature above re-crystallisation, followed by cooling at a suitable rate in a switched off furnace for such purposes as inducing softness and enhancing cold work.

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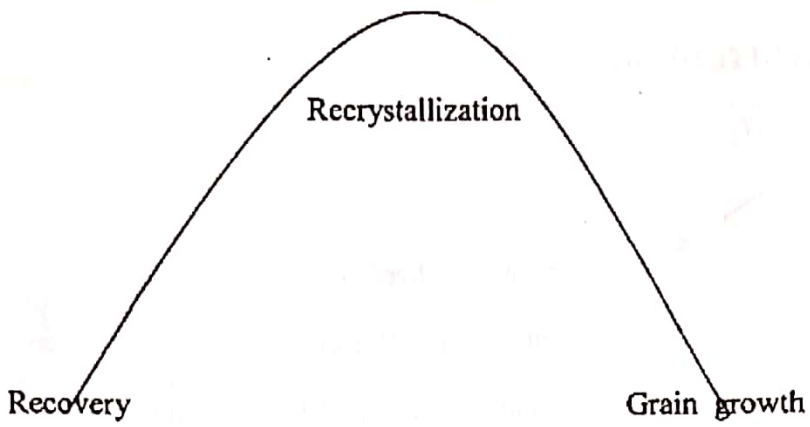

Spheroidising

The structure of steel after tempering consists of an extremely fine dispersion of Fe_3C in ferrite. If martensite is reheated to temperatures just below the eutectoid (723°C), the cementite particles become more and more spheroidal and the particle size increases. This occurs by a process involving dissolution of carbon from the smaller particles, its diffusion through the ferrite matrix and its reprecipitation as Fe_3C to further enlarge the larger particles. Eventually, a spheroidised structure is obtained, consisting of coarse cementite spheroids in a ferrite matrix -- a structure which is outstanding in machinability and which if the carbide particles are not excessively coarse still allows the steel to take and retain a sharp hard cutting edge. Razor blades and thin sectional cutlery are commonly made of spheroidised steel containing about 1% C.

Surface Hardening

For some applications, such as rotating shafts, it is desirable to have a very hard outer surface to minimise wear but a tough internal core. This combination is obtained by heating a low C steel to ≅ 900°C in the presence of carbon (either as CH_4 gas or Co gas or as graphite chips).

The carbon diffuses into the outer regions of the component (using $Co \rightarrow C + O$). Then the component is quenched to produce hard martensite in the outer 'rim' whilst the core (still low C) is not hardened and retains the ferrite/pearlite structure – **CABURISING.**

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Alternative process is **NITRIDING**

Heat in $2NH_3 \rightarrow N_2 + 3H_2$

Ammonia gas

diffuses into and hardens steel by

1) Interstitial diffusion to sites of dislo

and makes them difficult to move

2) Precipitates a fine dispersion of nitr

Nitriding is more suitable for low alloy steels (containing Cr, AI, Mo) be formed are near the surface and dense, where as plain carbon steels tend t greater depths thus embrittling the material.

Normalising

Here the steel is heated to a temperature slightly above re-crystallisation, depends on the carbon composition of the steel) allowed to soak up the he time corresponding to steel specimen thickness and cooled to room ter

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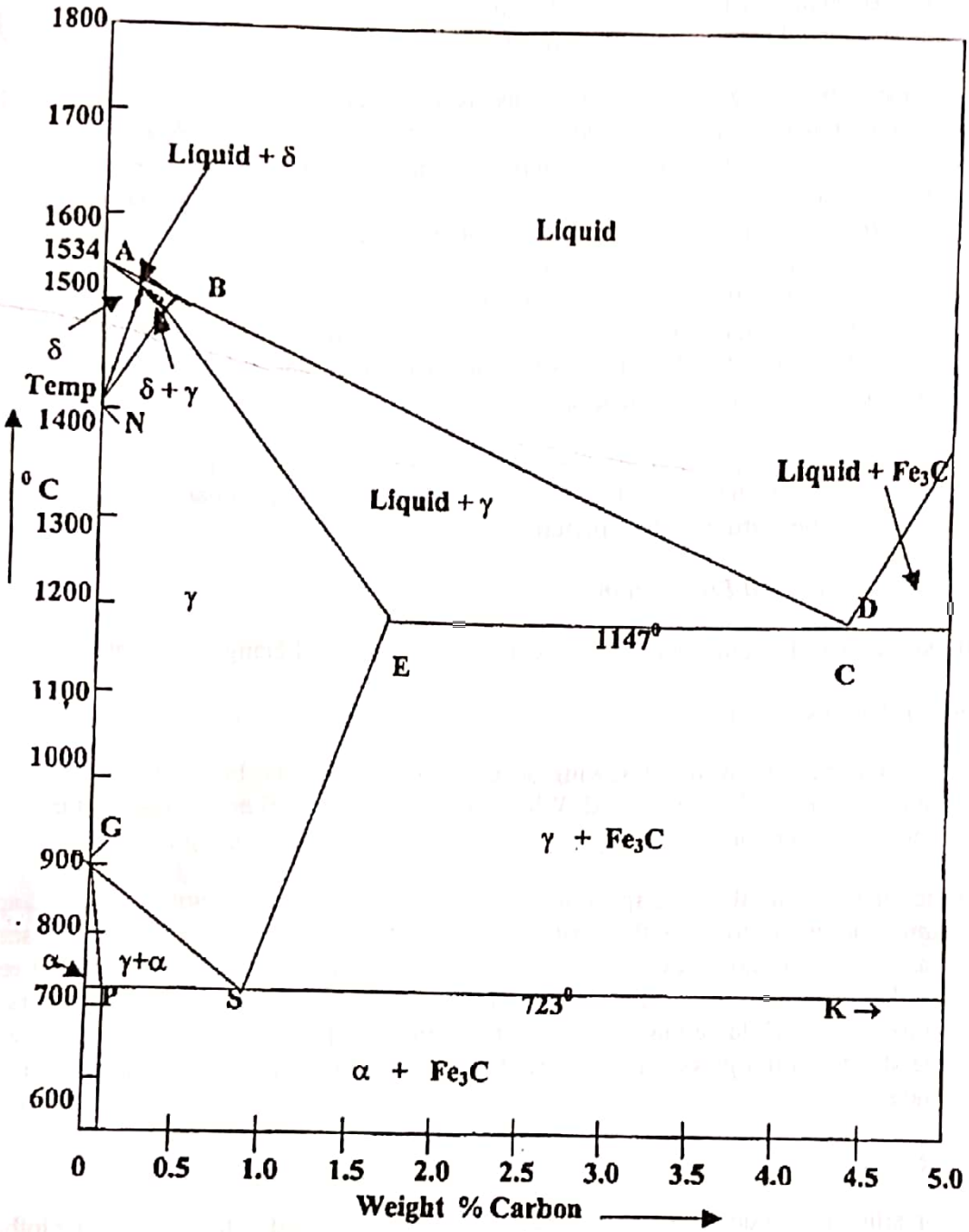
3.3 The Iron-carbon equilibrium Diagram



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3.4 Metallography

This is the technique for the examination of metals for structural and surface features. Metal structures are studied for a number of purposes; Macro and micro examination.

When object is to study structure of metals by microscopic methods the surface will be prepared by sectioning, grinding and polishing. Metallographic specimens are normally prepared for examination under the microscope by cutting out the specimen, carefully removing the disturbed surface layer and then rubbing the surface with successively finer abrasives until a smooth polished surface is obtained, sensibly free from disturbing effects from the cutting and grinding. Etching reagents, which reveal the structure of the metal, then attacks the clean smooth undisturbed surface chemically or otherwise. Any mechanical method of cutting or smoothing the surface produces distortion of the metal near the surface; the object is to make the disturbed layer successively thinner at each stage until it is negligible or can be removed by etching.

The early stages of preparation are common to most metals and types of specimen. Fine polishing may have to be varied to suit the metal. Etching is peculiar to the metal under examination and the feature of the structure to be investigated.

Specimen Selection and Preparation

It is important that the specimen selected represents the material being investigated.

Sectioning and Mounting

Sectioning may be carried out by sawing or breaking. Care should be taken that the original condition of the material is not altered. When specimens are small or of irregular shape, they may be mounted in hot or cold setting plastics or held in special clamping devices.

The basic method is to place the specimen face down in a die, cover it with plastic and apply the treatment necessary to make the plastic set. Thermosetting, thermoplastic and cold setting plastics are used. Thermoplastics such as polymethyl - methacrylate and thermosetting resins such as Bakelite are convenient for routine work because they are available as powders, but they require a press. Cold setting resins may be formed simply in a container consisting of a short tube standing on a glass plate and are therefore suitable for occasional use and for odd shapes and sizes.

Grinding

Emery or silicon carbide clothes and papers are normally used. These strips of cloth and paper are laid flat on plates and the specimen is rubbed to and fro on the strips. You start with the roughest cloth (240 grit) and rub until all traces of saw cuts are removed. Turn through 90° and rub on the next (finer) paper (320 grit) until the previous scratches are removed. Next grind on the (400 grit) and then on the final one (600 grit) each time turning through 90°.

Mechanical Polishing

This is often done in two stages, with a coarse and a fine abrasive or polishing agent respectively. The specimen is usually held against a horizontal rotating wheel, covered with a short - pile cloth fed with a suspension, slurry or cream of the polishing agent.

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Examples of polishing agents are α - alumina, γ - alumina, MgO, Cr_2O_3, proprietary metal polishes and diamond dust.

Etching

This consists essentially of either submerging the specimen in, or swabbing it, with a chemical reagent that removes the surface layer produced on polishing and then attacks preferentially, grain boundaries and second phase precipitates.

<u>For steels</u>

2% Nital is 2% by volume of concentrated Nitric acid in alcohol. Always add the acid to the alcohol and not vice versa. The carbide will show darkened.

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3.5 Tutorial Worksheet Three

1) What range of percentage of carbon present in plain carbon steel is most amenable to the heat treatment of steel?

2) Using the Fe-C equilibrium diagram, show the various transformation ($\alpha \rightarrow \gamma \rightarrow \delta$) temperatures of steel with respect to 0.5% changes in carbon content.

3) What are the uses of the Fe- C equilibrium diagram?

4) Differentiate between Annealing, Normalising, Spheroidising and Tempering.

5) What kind of microstructures would you expect to find when the following heat treatments are applied to a 0.4%C steel?

a) Quenching b) Tempering c) Annealing d) Normalising e) Carburising. Explain how these structures arise.

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6) How would you prepare the steel specimens for micro structural examination?

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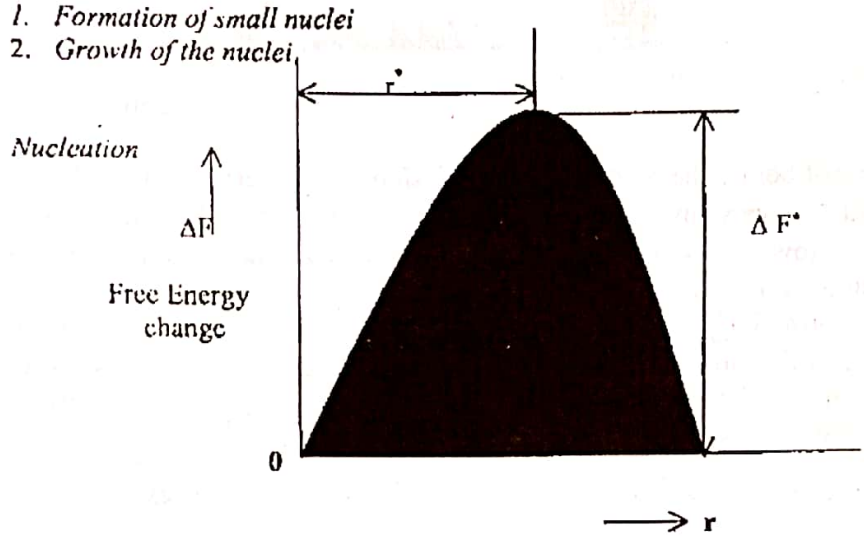
5 PHASE TRANSFORMATION

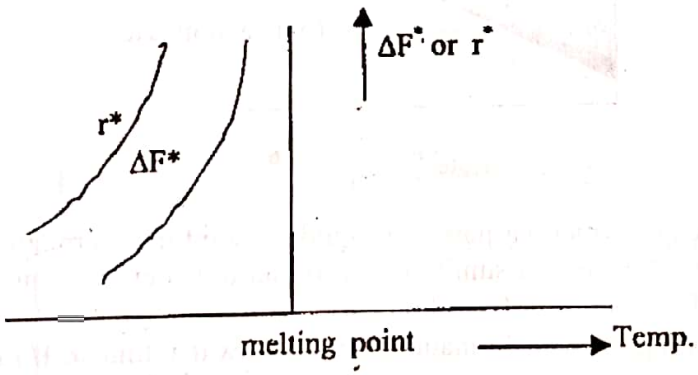
5.1 The Kinetics

The liquid phase α now moves to the solid phase β. At the melting point $F_\beta = F_\alpha$ i.e. the free energies are equal, which means the system is at a state of equilibrium. But below the melting point, $F_\beta < F_\alpha$ ∴ the solid phase is more stable than the liquid phase (on thermodynamic grounds) and should form. The important point, however, is at what rate does solidification take place? This is our immediate concern. For this reason solidification is broken into two parts.

1. *Formation of small nuclei*
2. *Growth of the nuclei*



The shaded region shows the system as unstable because it has +ve ΔF ∴ it tends to re dissolve to the molten state. When r tends to r*, the nuclei are unstable and therefore tend to re dissolve but the tendency for small nuclei to re dissolve decreases as the temperature falls further and further below the melting point. Nucleation rate is affected by temperature.



But nucleation also involves diffusion of atoms and since diffusion is a thermally activated process, then the rate of nucleation is very temperature dependent.

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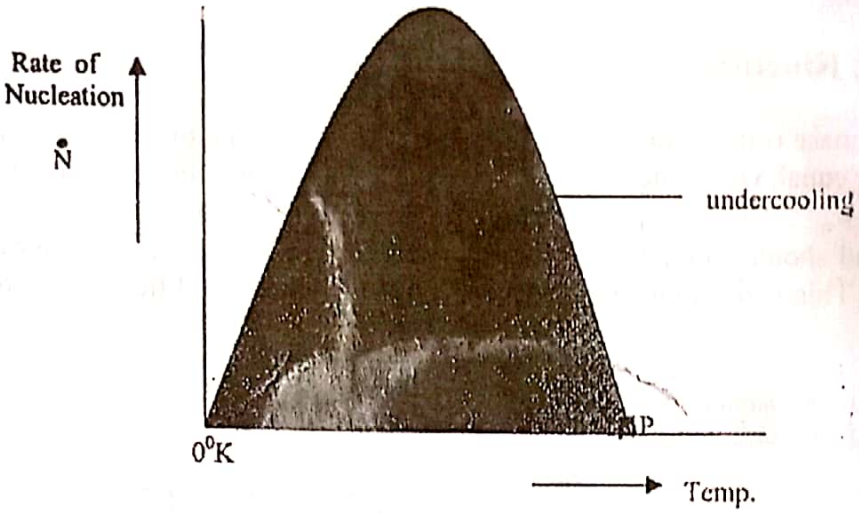
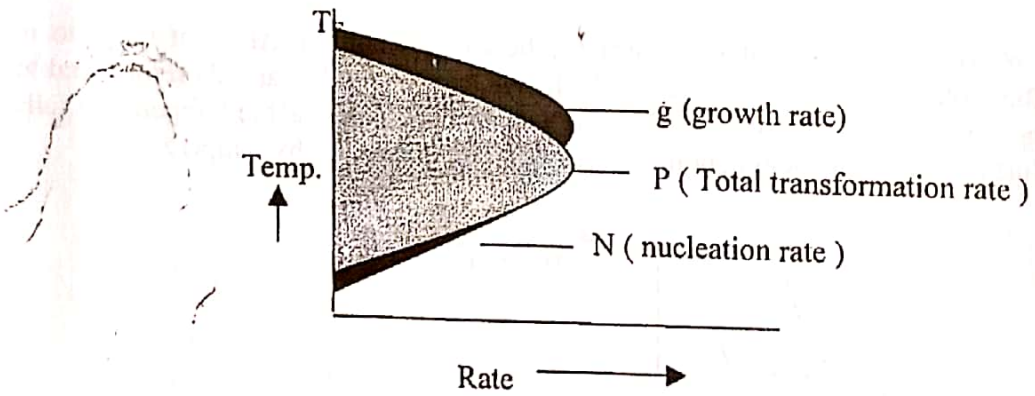


At temperature just below the melting point diffusion rate is very rapid, ΔF^* and r^* are very large. ∴ Ň must be very low. At very low temperatures ΔF^* and r^* are low but diffusion rate is also very low. ∴ Ň must be very low. Maximum nucleation rate is therefore at intermediate temperatures. These results are *applicable to the solid-solid* transformation, but solid-solid transformation occurs at a much slower rate. This is evident from the fact that diffusion rates in solids are much slower than in liquids. ΔF^* for solid phase > ΔF^* for liquid phase, because this diffusion in solids is slow. Ň for solid-solid transformation is often so slow that meta-stable phases can exist in between the transformation.

Growth of Nuclei



T_E = equilibrium temp. = melting point for liquid → solid transformation. The temperature dependence curve of ĝ follows a similar curve to that of Ň but maximum in ĝ is at a lower temperature. Therefore total transformation curve will be similar. We are often interested in the time required for a given transformation and we know that time ∝ 1/ rate.

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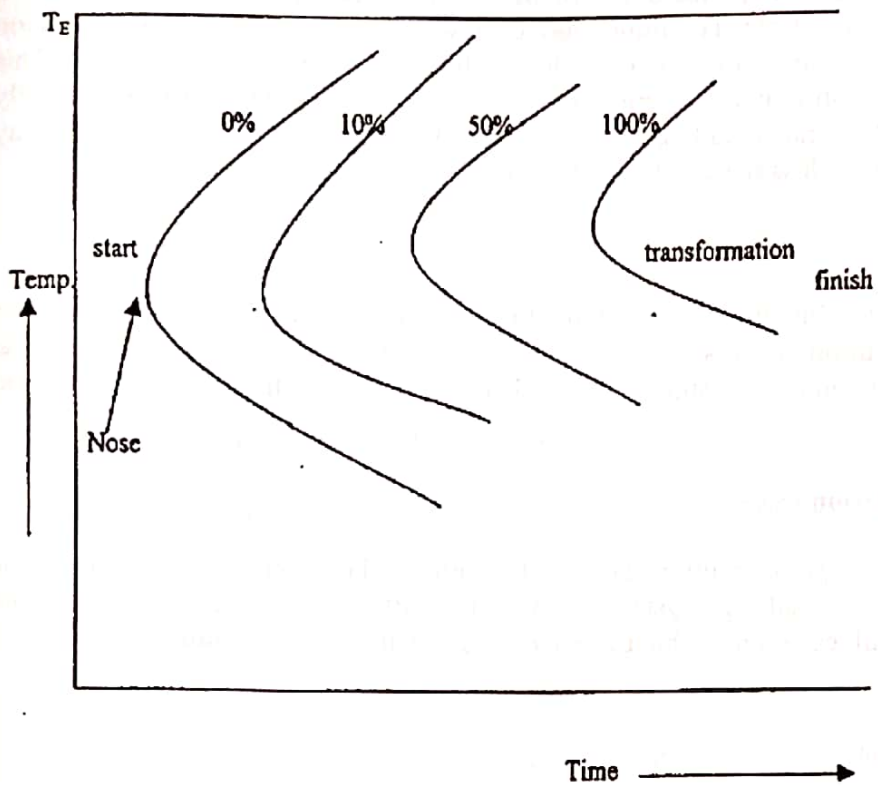
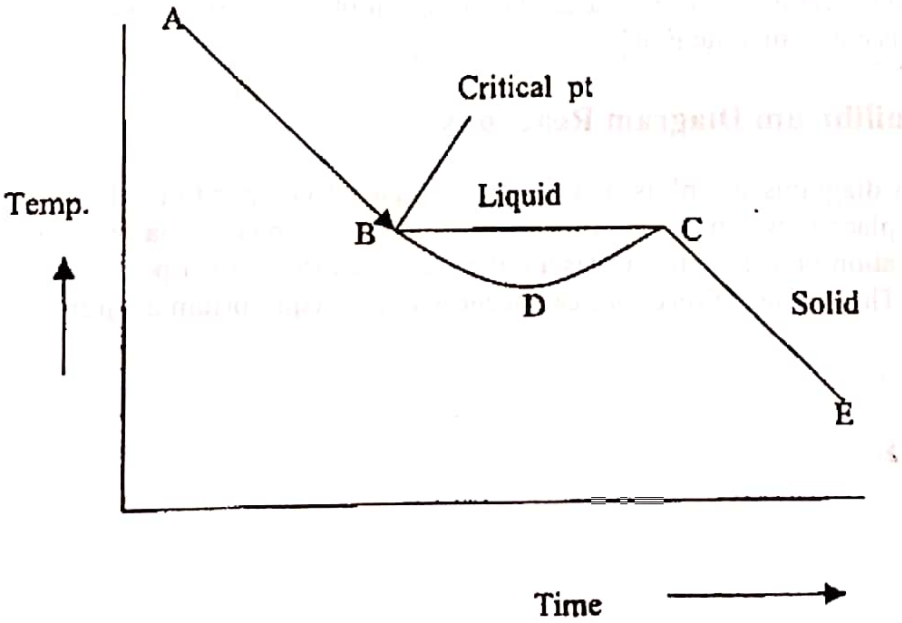


The combined effect of temperature and available free energy on a transformation is called **isothermal transformation curves.** These may also be called **C curves** because of their shapes or **TTT Curves.** The nose of TTT curves is the temperature at which Ň equals ĝ.

5.2 Cooling curves of alloys

It is an exception rather than a rule for alloys to yield the same types of cooling curves



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A cooling curve is a time-temperature curve or plot, which records the temperature of a cooling body over a period of time. The figure above shows a simple cooling curve. A region of depression on the curve shows a period of under-cooling (or suffusion) of the liquid. This occurs because solidification is not uniform over the entire molten metal phase. It normally starts around the impurities and spreads gradually so that the latent heat of solidification may be released at a gradual rate, less than that of heat loss.

Solid solutions

In true solid alloys, the solute metal is contained in the solvent-based metal in a manner comparable to liquid solution. This is called a *solid solution*. The solute is atomically sparse through out the solvent, and the nature of this dispersion determines the type of solid solution.

Substitutional solid solution (SSS)

This is the most common type of solution. The solute atoms replace some of the atoms in the lattice of the solvent. The resulting crystal has the same lattice pattern as the solvent but contains foreign or dissolved atoms, which replace some of the native atoms -- alloying of steel.

Interstitial solid solution

When the solute atoms are much smaller than the atoms of the solvent, they may fit between the interstices of the solvent atoms rather than replace them. The crystal patterns of the solutions are the same as that of the solvent e.g. austenite is a solid solution of carbon in iron. Solutions of H_2, N, C, and B with metals are also examples.

Intermediate Constituents

In many important alloy systems the crystal structures of the solid phases formed differ from those of any of the constituents. In many cases, these phases contain the constituent atoms in certain definite ratios. In other cases the composition of these phases can vary between certain limits e.g. cementite Fe_3C.

5.3 Equilibrium Diagram Reactions

Equilibrium diagrams are plots of temperature against composition, showing the changes, which take place between these variables and the various phases that exist during and after the solidification process. The curves are the loci of all the critical points of all the alloys in the system. Three types of reactions can occur within an equilibrium diagram.

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1) *Eutectic reaction:* A doubly saturated liquid solution freezes isothermally into a fine-grained mechanical mixture of two solid phases.

Properties of Eutectics

a. They are mechanical mixtures of two solid phases and usually have a characteristic banded or lamellae structure.

b. They have a constant chemical composition even though they are not chemical compounds

c. They freeze and melt isothermally

d. They have the lowest freezing of any alloy series

e. Their fine grains make them to display the best mechanical properties of any alloy in the series.

2) *Peritectic reaction:* The solid crystal that precipitated from a liquid solution reacts isothermally with that liquid to form crystals of a different solid. The reaction continues until all the liquid or the initial solid solution is consumed.

3) *Eutectoid reaction:* A doubly saturated solid solution decomposes isothermally into a fine-grained mechanical mixture.

Iron exists in three allotropic forms α,γ and δ. Carbon is quite soluble in γ but only slightly in α and δ. There are four solid phases-The primary solid solutions of carbon in α, γ and δ and the intermetallic compound-cementite.

The solid solution of carbon in δ iron contains a maximum solubility of 0.08% C. It cannot exist below 1400^0 C. The solid solution of C in γ iron is called *austenite* and has a solubility of 1.7% C and cannot exist in equilibrium below 723°C. *Cementite* contains 6.67%C and exists at all temperatures, but shows a magnetic change at 200°C. The solution of carbon in α-iron is called ferrite. Since the solubility of carbon is very small, ferrite is practically considered to be pure α-iron. Pearlite is the eutectoid of ferrite + cementite. It has a lamellar structure and contains 0.8%C.

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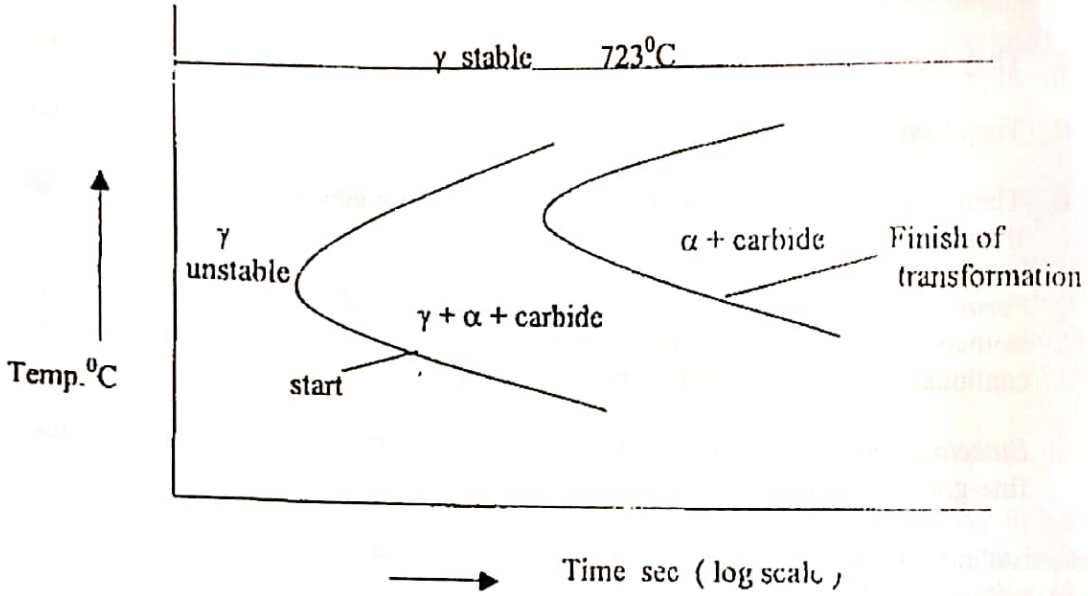
These reactions occur slowly both at relatively low temperatures and temperatures close to transformation. At intermediate temperatures more rapid transformation occurs due to

1) Sufficient force to help nucleate the new phases

2) Because thermal diffusion is still quite rapid

With extremely fast cooling, severe quenching, it is often possible to miss the knee (nose) of the transformation curve.



Small samples of steel were heated into the austenite temperature range sufficiently long to assure complete transformation to austenite. These samples were then quenched to a lower temperature (620°C -- about nose of C curve) and held there for varying lengths of time before being quenched further to room temperature. The times required for the transformation of steel could be contrasted with that required for the transformation of glass. The "C" curves are very similar except for the abscissa scale.

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5.4 Tutorial Worksheet Five

1 Show how diffusion affects the kinetics of phase transformation.

2 What is responsible for the existence of meta-stable phases in betw phase transformation?

3 What are "C" curves? How are they derived?

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4 What is an equilibrium diagram?

5 (i) What types of reactions can occur within an equilibrium diagram?

(ii) Describe them

(iii) Use the Iron-Carbon equilibrium diagram to locate these reactions.

6 Why is the rate of a solid reaction most rapid at intermediate temperatures?

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6 ISOTHERMAL TRANSFORMATION PROCESSES

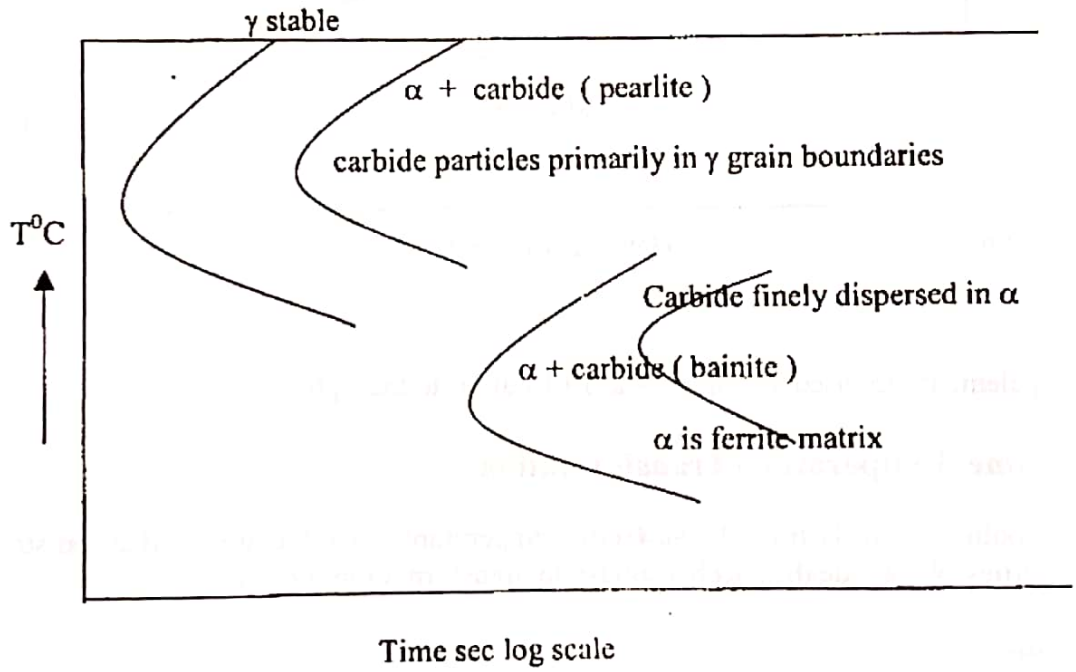
At higher temperatures, isothermal transformation produces coarse pearlite structures, the properties so produced are identical with those produced by the process of annealing.

Isothermal transformations at lower temperatures produce finer pearlite because of reduced thermal activity to assist the diffusion of carbon from the areas forming ferrite to all areas forming carbide.

If transformation occurs isothermally at a temperature below the "knee" or "nose" of the isothermal transformation curve, the resulting microstructure is not pearlite. Assume temperature of knee = 620°C. Instead of developing a lamellar structure, the carbide is finely dispersed in a ferrite matrix forming a microstructure called "BAINITE"

High temperature transformation produces coarse microstructure and hence softer metal. Bainite and tempered martensite have rather similar structures and their properties are similar. The production of Bainite has been developed into a commercial venture called AUSTEMPERING. The cooling which must be sufficiently rapid to avoid transformation to pearlite is usually accomplished in a molten lead or a fused salt bath maintained just about $M_s \approx 320°C$. This process has a major advantage of not developing brittle martensite in high carbon steels. Therefore quenching cracks are not likely to develop from the differential thermal contraction between the surface and the centre of the steel. The carbide particles within the bainite microstructure nucleate at many locations within the original austenite grain. Where as in pearlite formation the carbide particles nucleate primarily at the austenitic grain boundaries.

Pearlite forms in less time than bainite.



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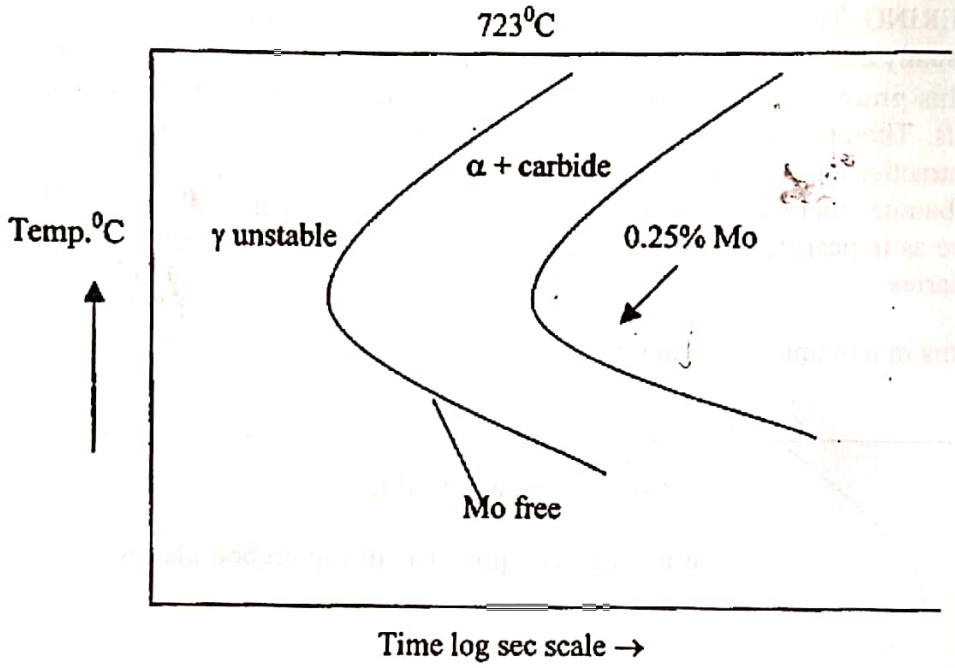
6.1 Control of reaction rates

1) By temperature regulation
2) By control of nucleation sites
3) By modification of diffusion rates
4) Grain sizes

Fine γ grain size will give rise to faster transformation reaction than steel with coarser γ. In the earlier case, there are more grain boundary regions for reaction to occur, so that more nucleation can occur in a given interval (achieved by the use of Mn).

The most significant effect of the addition of alloying elements to steel is to retard the reaction γ→ α + carbide by reducing rate of diffusion of the carbon atoms to the reaction site.



Alloying elements are used to displace the TTT curves to the right.

6.2 Time-Temperature-Transformation

Rate of cooling of steels from the austenitic temperature range has great effect on structure and properties. We are dealing with a solid-state transformation process

$\gamma_{Fe} \rightarrow \alpha_{Fe}$

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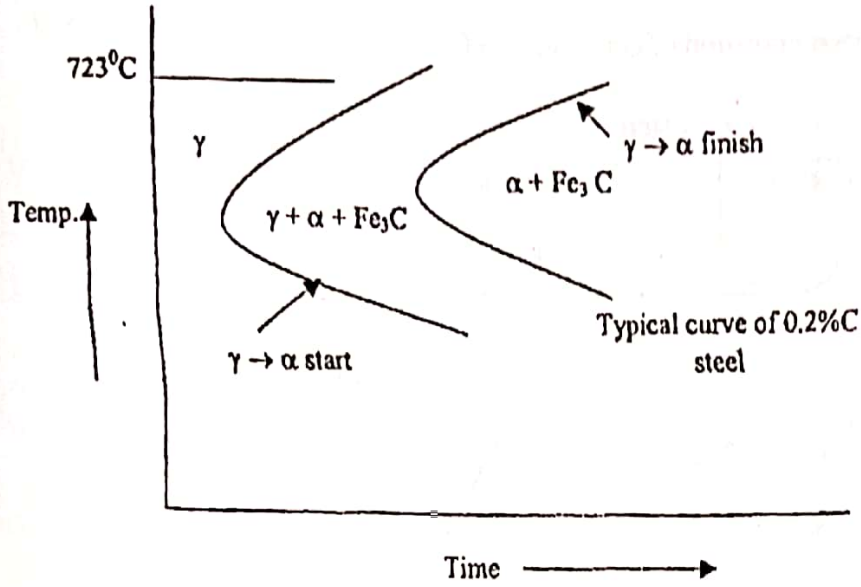
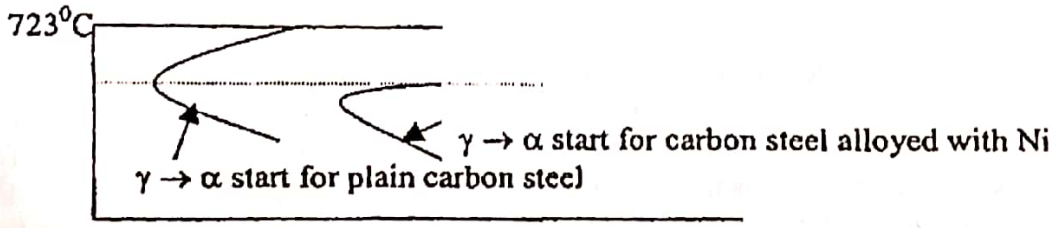


Fast cooling rate allows phase transformation to occur at lower temperatures and thus produces a finer grain structure than does slow cool. Thus steel cooled slowly have coarser microstructure and since yield strength increases with decreasing grain size, a faster cooling rate increases strength.

Another way of refining $\alpha + Fe_3C$ grain structure is to reduce the transformation temperature $\gamma \rightarrow \alpha$ i.e. to stabilise γ. $\gamma \rightarrow \alpha$ at 910°C for pure Fe, γ is stable to 723°C when 0.8%C is present. ∴ C is a γ stabiliser. Other austenite stabilisers are Ni, Mn.

For any given cooling rate if the transformation takes place at lower temperatures where diffusion rates are low, the microstructure will be finer.



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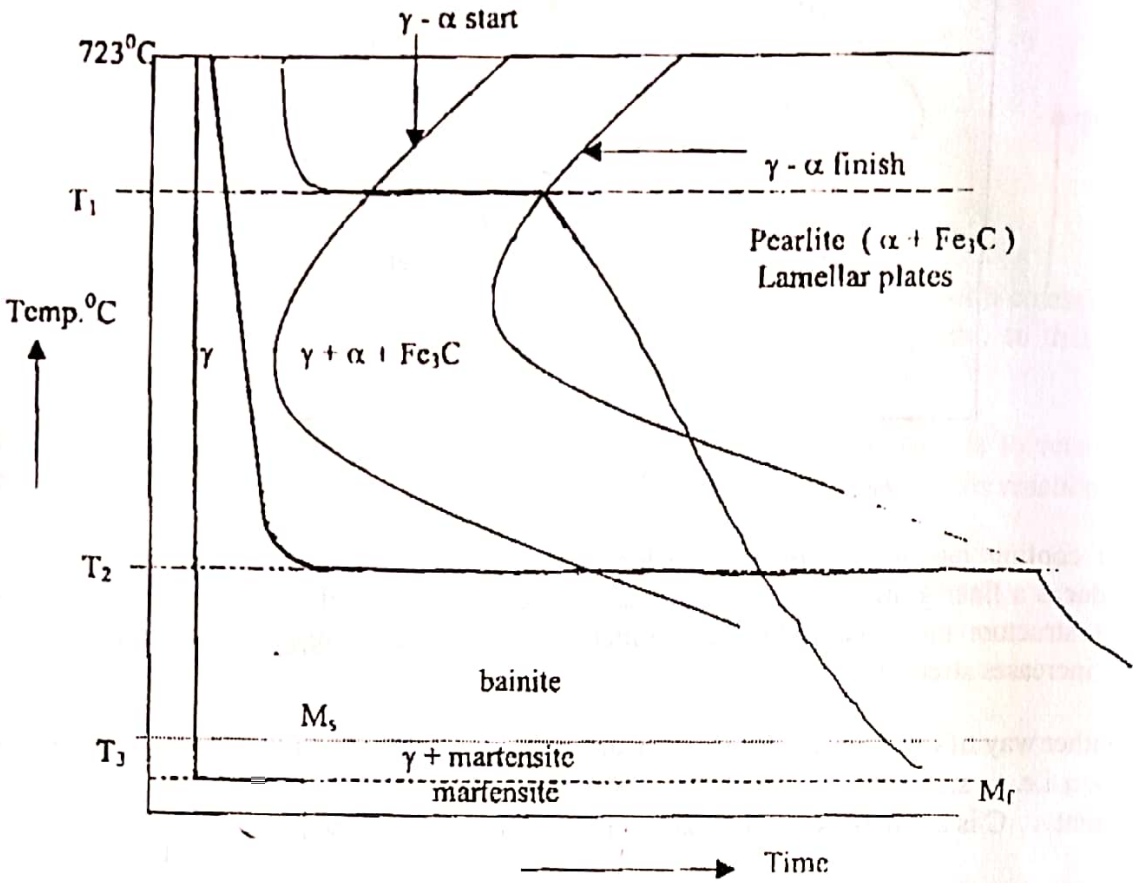
Consider the austenite decomposition of eutectoid steel 0.8%C



In the TTT diagram above, if a sample is quenched from the austenite range to a temperature T_1 (above the nose of the curve) and then isothermally transformed, all the austenite will transform in the time indicated by intersection with $\gamma \rightarrow \alpha$ finish curve and the product will be pearlite.

Now if steel is quenched and transformed at a temperature T_2 (below the nose) corresponding to a rapid cooling rate, the α and Fe_3C no longer form the plate like pearlite structure, instead the Fe_3C appears as finely dispersed particles in the ferrite matrix. This mixture of α and Fe_3C is known as "bainite". The reason for this is that at these low temperatures, the diffusion rates are so slow that the carbon atoms do not have enough time to diffuse over sufficient distances to form a Fe_3C plate. Instead they agglomerate over short distances and appear as fine particles, since the resulting ferrite grain size is small as well, bainite microstructure has high strength and toughness.

If the steel is quenched to an even lower temperature T_3; without intersecting the γ - α start curves then at this temperature the diffusion rates are so slow that Fe_3C cannot precipitate from the γ even as tiny crystals. Consequently the diffusion-controlled decomposition of austenite, cannot take place and what happens is a diffusionless transformation of $\gamma \rightarrow$ "martensite" --body centred tetragonal crystal structure of iron supersaturated with carbon. Since martensite formation is a diffusionless transformation, it is independent of time and provided the cooling rate is fast enough to reach the martensite start temperature M_s without intersecting the $\gamma \rightarrow \alpha$ curves, some martensite will form. If temperature M_f is reached the whole structure is martensite.

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6.3 Tutorial Worksheet Six

1 Using the Fe-C Equilibrium diagram, show how you can produce a) coarse pearlite b) fine pearlite c) bainite d) martensite, by isothermal transformation.

2 What is the effect of the rate of cooling of steels on their structure and properties?

3 What is the effect of the transformation temperature on steel structure?

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4 What is the significance of the "knee" or "nose' of a C curve as far as isothermal transformation is concerned?

5 Discuss the factors that control reaction rates. How can they be manipulate advantageously?

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7 IMPERFECTIONS IN SOLIDS

Real crystals are never perfect. They have a considerable amount of various defects and imperfection that profoundly affect the physical and mechanical properties of engineering materials. Defects and imperfection especially affect structure - sensitive properties such as yield strength, fracture strength, plasticity, thermal conductivity, electronic properties and corrosion resistance. The presence of defects also plays a very important role in various technological processes and in phenomena such as annealing, precipitation, diffusion, sintering, oxidation, and others. The influence is not always adverse, and often-specific characteristics are deliberately fashioned by the introduction of controlled amount or numbers of particular defects, as evidenced in semiconductor processing (doping) and in work hardening of structural materials.

Classification of crystalline imperfections is frequently made according to geometry or dimensionality of the defect. In this scheme we find that all defects can be classified into one of the following groups.

1.	Point defects	-	Zero dimensional imperfections
2.	Line defects	-	One dimensional imperfections
3.	Interfacial defects	-	Two dimensional or planar imperfections
4.	Bulk defects	-	Three-dimensional imperfections

7.1 Point Defects

Point defect in pure crystalline materials are defects of atomic dimensions that usually result from the presence of an impurity atom, the absence of a matrix atom, or the presence of a matrix atom in the wrong place, as shown in fig 7.1

An impurity atom that occupies a normal lattice site is called a **substitutional impurity atom,** and an impurity atom found in the interstice between matrix atoms is called an **interstitial impurity atom.** Whether a foreign atom will occupy a substitutional or interstitial site depends on the size of the atom relative to the size of the site. Small atoms are usually interstitial impurities, while larger atoms are usually substitutional impurities. Normally, the maximum allowable concentration of interstitial impurity atoms is low (less than 10%) since very small impurity atoms are ordinarily larger than the interstitial sites, and as a consequence, introduce some lattice strains on adjacent atoms. Appreciable quantities of substitutional impurities are accommodated if the difference in atomic radii between the two atom types is less than about $\pm 15\%$. Carbon, for example forms an interstitial solid solution in iron; the maximum concentration is about 2% whilst up to 35% zinc dissolves in copper forming a substitutional solid solution.

A vacant site is referred to as a **vacancy** and a matrix atom in an interstitial site is called a **self-interstitial.** Vacancies are formed during solidification, and also as a result of atomic vibrations, which can cause the displacement of atoms from their normal lattice sites. They are important because they control the rate of matrix or substitutional atom diffusion. Self - interstitials generally do not occur naturally, but may be introduced into a structure by irradiation. For example, high-energy neutrons from atomic fission can knock atoms from their regular lattice sites into interstitial sites creating vacancy - interstitial pairs.

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The equilibrium number of point defect N_d for a given quantity of material depends on and increases with temperature according to

$$N_d = N \exp\left[-\left(\frac{\Delta E_d}{KT}\right)\right] \tag{7.1}$$

where N = the number of atomic sites per cubic metre or per mole

ΔE_d = the activation energy necessary to form the defect

T = the absolute temperature

K = the Boltzmann constant (= 1.38×10^{-23} J/atom - °K)

Vacancies are the main point defects in metallic systems as their energy of formation is relatively low.

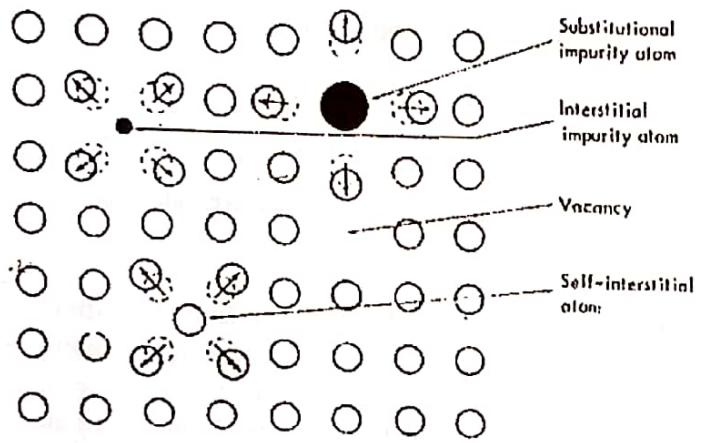

Fig. 7.1 Point Defects in Crystalline Materials

Point defects in ionic structures differ from those found in pure elements because of the charge neutrality requirement in ionic solids. For example, in a pure monovalent ionic material, a cation vacancy must have associated with it either a cation interstitial or an anion vacancy to maintain charge neutrality. Similar requirements hold for anion vacancies. The vacancy pair defect is called a **Schottky imperfection**, and the vacancy - interstitial pair is called a **Frenkel imperfection**. These imperfections are shown in fig. 7.2a.

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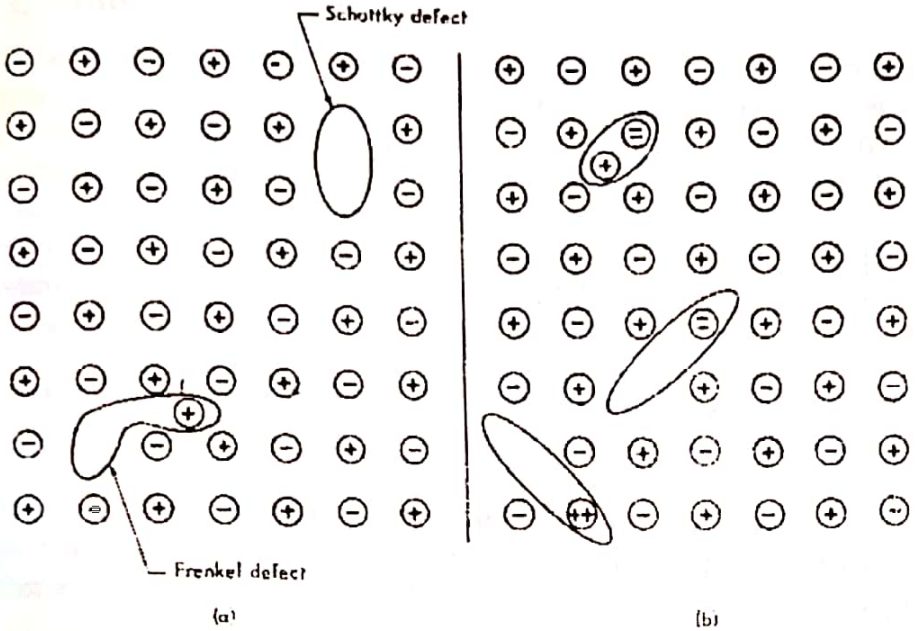

Fig. 7.2 (a) Imperfections in Pure Crystals, (b) Imperfections caused by Impurity Atoms

Foreign atoms in ionic crystals produce defects that also must maintain charge neutrality. For example, in NaCl a monovalent cation such as lithium may simply replace one of the sodium ions as a substitutional impurity. But a divalent cation, such as calcium, replacing a sodium ion must be accompanied by either a cation vacancy or an anion interstitial if charge neutrality in to be maintained. Correspondingly, monovalent impurity cations in a divalent structure, (e.g. Na in MgO) must be accompanied by an appropriate number of cation interstitials or anion vacancies (fig 7.2b)

7.2 Line Defects

Line imperfections, or **dislocations,** in crystalline solids are defects about a line. To visualize the geometry of these defects consider a material with a simple cubic crystal structure shown in Fig 7.3. Let us slice this crystal along the plane ABCD and displace the top part of the cut relative to the bottom part by one inter atomic distance in a direction parallel to both the plane of the cut and a cube edge (<100> direction). This squeezes the top part of the crystal causing its distortion about a line AB, as shown in fig. 7.3(b). The line AB is thus called a **dislocation line,** while the plane ABCD is known as the **slip plane.**

A similar situation exist if we slide the crystal in manner shown in Figs 7.3(c) and 7.3 (d), although it is clear that the nature of the atom displacements along the dislocation line depends very critically on exactly, how we displace the atoms relative to the line AB.

(1) If the atoms are displaced in a direction perpendicular to AB we call the resulting defect **an edge dislocation,** since the defect resembles the edge of an extra half plane of atoms.

(2) If the atoms displacement is parallel to AB we have a **screw dislocation.**

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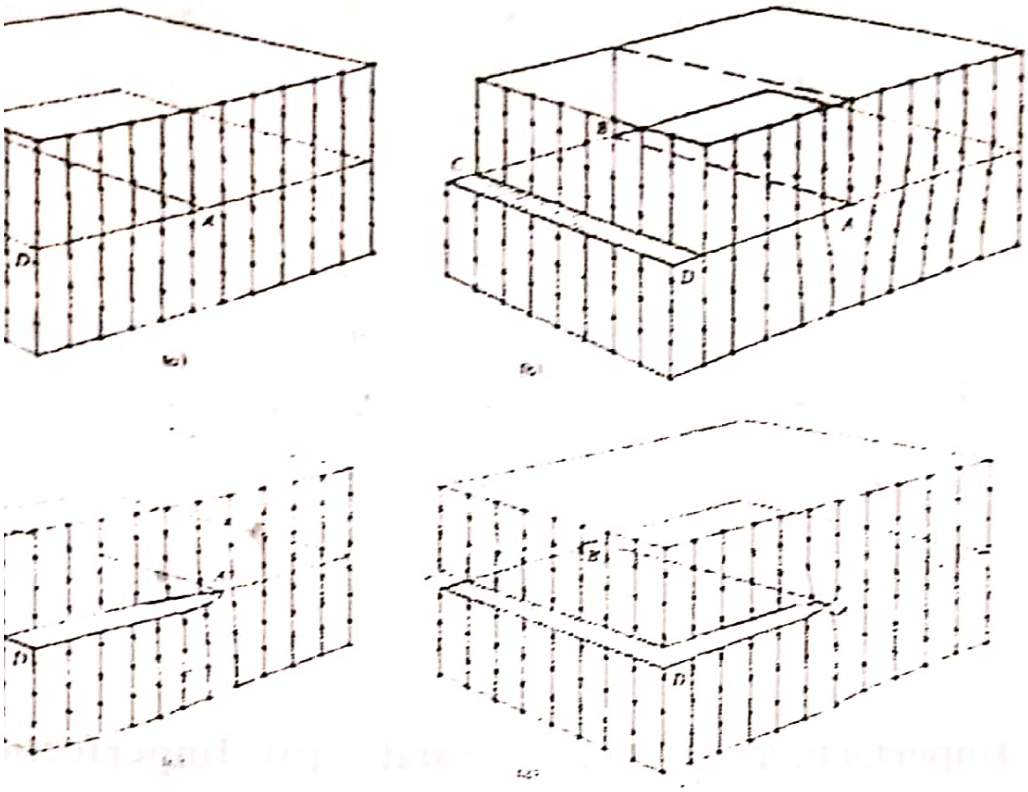

Geometric illustration of dislocations

on may be represented by the symbol ⊥, which also indicates the position of the
is symbol is used to denote a **positive edge dislocation** (extra half - plane above the
is used to represent a **negative edge dislocation** (extra half plane below the slip
dislocation does not have an extra half plane associated with it. It can however be
or left-handed, depending on the nature of the twist.

icinity of a dislocation is a strongly disturbed region with considerable strain energy.
e dislocation, the presence of the extra half plane causes the atoms above the slip
n compression, while those below the slip plane are put in tension. The screw
ensile or compressive stresses all stresses are pure shear.

has passed all the way through a crystal, or swept out its entire slip plane, the portion
e the slip plane has shifted one atomic distance relative to the portion below the slip
rds, the motion of the dislocation has caused the crystal to change its shape, or
n.

lline materials contain some dislocations that were introduced during solidification,
mation, and as a consequence of thermal stresses that result from rapid cooling. The

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7.3. Interfacial Defects

Interfacial or planar crystalline defects have two dimensions. The most obvious is the external or **free surface**, which is considered to be an imperfection inasmuch as it represents the boundary along which the crystal structure terminates. Surface atoms are not bonded to the maximum number of nearest neighbours, and are therefore in a higher energy state than the atoms at interior positions. The bonds of these surface atoms that are not satisfied give rise to a surface energy. To reduce this energy, materials tend to minimize, where possible, the surface area. This is why liquids tend to assume a shape having a minimum surface area (droplets become spherical). However this is not possible with solids, as they are mechanically rigid.

Another planar defect of significance is the **grain boundary**. The grain boundary separates two small grains or crystals having different crystallographic orientations in polycrystalline materials. Grain boundaries have an interfacial energy because of the disruption in atomic periodicity. In the vicinity of the boundary and the broken bonds that exist across the interface. This interfacial energy is generally less than that of a free surface because the atoms in a grain boundary are surrounded on all sides by other atoms and have only a few broken or distorted bonds.

Boundaries separating phases where there is a change of chemical composition and atom aarrangement across the interface are called **inter-phase boundaries.** The nature of the interface separating various phases is very much like a grain boundary. Boundaries between two phases of different chemical compositions and different crystal structure are similar to high-angle boundaries, while boundaries between different phases with similar crystal structures and crystallographic orientations are analogous to low-angle grain boundaries in both energy and structure.

Interfaces between regions where there is a change in electronic structure but not in atomic arrangement, known as **domain boundaries.** Domain boundaries are typically associated with semiconductor and magnetic devices

7.4. Bulk Defects

Bulk defects are generally found in materials for one of two reasons - either the defect has been introduced during the processing of the material (e.g. extraction) or it has been introduced during the fabrication step (e.g. casting, forging, etc.). These defects include pores, cracks, foreign inclusions, and other phases.

The most common bulk defect introduced during the production (or processing) of materials are unwanted second - phase particles called inclusions. These particles usually originate during the initial refining operations when the metal is molten, and since they are generally insoluble in the metal, they may be entrapped within the bulk metal during the process of solidification. In metallic materials the most common example of an inclusion is an oxide particle. Sulphides, hydrides, etc. are sometimes also found.

Bulk defects introduced during the fabrication of materials usually occur as casting defects, forging defects or joining defects. Casting defects usually originate from volume contraction accompanying solidification (shrinkage cavities) or from the evolution of gases during the solidification process (gas holes). Shrinkage cavities are usually found at the center of castings where solidification occurs and the hot molten material is not available to fill the void created by the volume change from liquid to solid. Dissolved gases in the molten material that are evolved and entrapped during solidification cause gas holes in castings.

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The bulk defects introduced during forging or welding operations are usually in the form of cracks. During forming operations cracks originate in areas where the material is severely deformed (e.g. sharp bends) or where a previous defect exists. Cracks in welds commonly occur because of large thermal stresses set up as the weld metal rapidly cools.

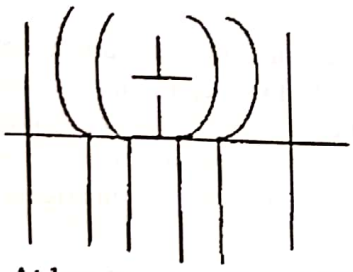
7.5 Elementary Theory of Dislocations

7.5.1 Movement of Dislocation

Four types of movements

1. Glide
2. Climb
3. Slip
4. X slip

Glide: dislocation moves in the surface defined by its line & Burgers vector



At low temperatures where diffusion is difficult and in the absence of non-equilibrium concentration of point defects the movement of dislocation is restricted almost entirely to glide. An edge dislocation shortens its extra half plane of atom and glides. The atoms of the extra half plane diffuse into the lattice vacant sites. The slip plane then moves up after diffusion has occurred over a whole line of atoms.

Climb: However, at higher temperatures an edge dislocation can move out of its slip plane by a process called CLIMB. Positive climb can occur by either diffusion of vacancies or by the formation of an interstitial. Negative climb can occur either by an interstitial diffusing to an atom site or by the formation of a vacancy. All these processes require mass transport by diffusion and therefore climb requires thermal activation. The most common climb processes involves the diffusion of vacancies either towards or away from the dislocations. This is so because at higher temperature, there is a high concentration of vacancies in the lattice and so greater chance of diffusion.

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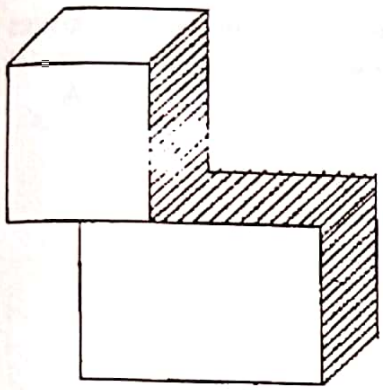
Slip: Slip occurs in a material by shearing across a plane of atoms. The theoretical stress is very much greater than experimental stress.



Here movement of dislocation involves a shift of atom I from atom 2 and requires energy to shift from atom 3 moving close to atom 4.

The net energy to move dislocation is very small, in other words the shear stress required to move dislocation is less than the stress to shear plane of atom over each other.

Planes on which dislocations move are slip planes and are those that are most widely separated. These are closed packed planes in crystals. Slip direction is the direction of the Burgers vector of the dislocation on the slip plane. Slip planes are not unique; they depend strictly upon temp.

X- Slip

Screw dislocation cannot change plane like edge dislocations by climb but only by X slip. X slip does not involve vacancy movement and it is not a high temperature process. Shear stress is needed to move dislocation on X plane. ∴ X slip is stress dependent.

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7.6 TUTORIAL WORKSHEET SEVEN

1 The energy of formation of a vacancy in copper is 0.9 ev. Estimate the fraction of vacant sites at 1250 and 300°K. What would be the fraction of vacant sites at 300°K if the copper were quickly quenched from 1200 to 300°K? Comment on the results.

2 Calculate the activation energy for vacancy formation in silver, given that the equilibrium number of vacancies at 800°C is 3.6×10^{23} m^{-3}. The atomic weight and density (at 800°C) for silver are, respectively 107.9 and 9500kg/m^3

3 The vacancy concentration at equilibrium at 600°C for magnesium is 3.5×10^{23} m^3 Calculate the formation energy of vacancies in electron volts and in kilojoules per mole. The density of magnesium is 1740kg/m^3.

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4 Determine the number and type of vacancies produced by the following substitutions in substitutional solid solutions: $MgCl_2$ for LiCl, MgO for FeO, LiCl for $CaCl_2$, CaO for ZrO_2, Al_2O_3 for NiO.

5. Show how two edge dislocations of opposite sign on the same slip plane can annihilate each other. Can two screw dislocations of opposite sign also annihilate each other?

6 The motion of dislocations is known to proceed by slip, climb, and cross slip. Account for each of these and specify the type of involved in each case.

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8. ATOMIC DIFFUSION

Atoms in gases, liquids and solids move around by making individual jumps. These are random events but, in the presence of a concentration gradient, we usually get a net flow of atoms *"atomic diffusion"*.

Similar laws to describe diffusion of atom as that of heat electricity

FLUX → No. of atom/unit time
FLUX → Amount of heat/time
FLUX → Amount of charge/time

Flux = (Conductivity) (Driving force)

For Heat	thermal conductivity	ΔT
Electricity	^{1}/Resistance	ΔV
Atom	Diffusivity D (Diffusion coeff.)	ΔF

For atomic diffusion

$$\text{Flux of atom} = -D\frac{dF}{dx} = -D\frac{dc}{dx}$$

No. of atoms moving/sec

$$\frac{dc}{dx} = \text{Concentration gradient in x – direction}$$

Diffusion is a thermally activated process is strongly dependent on temp.

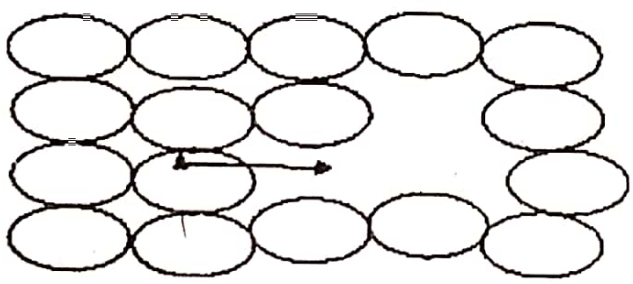
$$\therefore D = D_o e^{-\frac{\Delta E_D}{KT}}$$

D_o = const [frequency factor] ΔE_D = activation energy for diffusion.

8.1 Mechanism

There are several ways in which atoms can migrate thru' crystalline material.

1. By mean of **"Vacancies"** all materials contain



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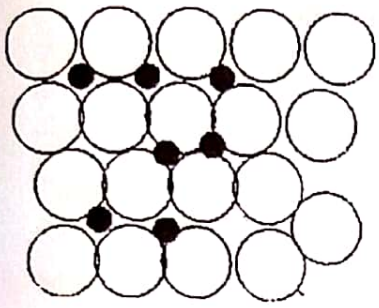
2 By means of **interstitials**



Impurities or alloying elements of small atomic size often reside in between the parent atom.

Vacancies and interstitials play an important role in atomic diffusion. A neighbouring atom can move into a vacancy. After one such move the new vacancy can receive another atom, and the process is continued.

For atom to move from one site to another bonds must be broken and the lattice distorted. Hence, activation energy is required. The numbers of atoms, which have the necessary activation energy, increase exponentially with the reciprocal of temperature.

8.2. Factors Affecting Diffusion Coefficients

(a) The activation energy for diffusion is lower with a small interstitial solute atom than with a larger substitution solute atom.

(b) The activation energy for diffusion is lower in a solvent with a low melting point than in a solvent with a higher melting point.

(c) The activation energy for diffusion is lower through a structure with a low atomic packing factor than through a structure with more dense packing.

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8.3 Tutorial Worksheet Eight

1. Even under equilibrium condition, a metal contains vacant lattice sites. Explain why this is so and discuss briefly two examples of metallurgical phenomena in which vacancies play a prominent part.

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9 EFFECTS OF ALLOYING ELEMENTS ON STEEL

When nickel is added to steel, there is a decided improvement in the steel's tensile, impact, and fatigue strengths. When steel is alloyed with chromium, molybdenum, silicon and other elements, many desirable properties are obtained.

Chromium is one of the most valuable elements to alloy with steel when one wishes to obtain resistance to corrosion and heat.

Molybdenum added to steel helps to reduce grain growth and leads to a fine grained pearlite structure.

Manganese added to steel is a powerful deoxidizer; it also renders sulphur inactive.

9.1 The Principal Effects of Major Alloying Elements in Steel

ELEMENT	PERCENTAGE	PRIMARY FUNCTION
Manganese	0.25 - 0.40	Combines with sulphur to prevent brittleness
	> 1%	Increases hardenability
Sulphur	0.08 - 0.15	Contributes to ease of machining metal but gives harmful effects on toughness and ductility.
Nickel	2 - 5	Acts as toughener
	12 - 20	Improves corrosion resistance
Chromium	0.5 - 2	Increases hardenability
	4 - 18	Improves corrosion resistance
Molybdenum	0.2- 5	Forms stable carbides, inhibits grain growth.
Vanadium	0.15	Forms stable carbides, increases strength while retaining ductility.
Boron	0.001 - 0.003	Acts as powerful hardening agent.

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nformation Concerning the Steel Alloy Elements

Aluminium

ting point 660°C

ons restricts grain growth.

Boron

ting point 2040°C

leep hardening of constructional steels.

Beryllium

lting point 1283°C

lium alloys are very hard and corrosion resistant; used in surgical instruments.

Carbon

foremost alloy element of steel and it has the farthest- reaching influence on it. content increases, the mechanical strength and the hardening properties of the but its elasticity, forging, welding and cutting properties decrease. The carbon bstantially no influence at all on the corrosion resistance to water, acids and hot

Calcium

lting point 850°C

Silicon, in the form of Calcium Silicide, is used for de-oxidation.

Cerium

lting point 775°C

de-oxidant and promotes de-sulphurising. Improves the hot working of high l also the non-scaling properties of heat resistant steels.

Cobalt

lting point 1492°C

m carbide. It hinders the grain growth at higher temperatures and greatly resistance to tempering. If subjected to neutron rays it forms a strong radio- Cobalt 60 for which reason it is undesirable in steels for atomic reactors.

Chromium

lting point 1920°C

dness and strength and only minimally reduces the elasticity. With higher nt the steels become corrosion resistant and with carbon forms a high wear ide. The welding properties deteriorate in pure chromium steels with increasing ntent. Chromium is a strong carbide former.

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Mn Melting point 1244°C **Manganese**

Manganese improves the strength properties of steel, while only slightly impairing its elasticity; further more, manganese has a favourable influence on the forging and welding properties. A higher content of manganese in the presence of carbon increases the wear resistance very substantially. With up to 3% of Mn the tensile strength of the steels is increased by about 10 kg/mm^2 for every % of Mn; with Mn content about 3 to 8 % the increase rises more slowly and at more than 8% of Mn it drops off again.

Mo Melting point 2610°C **Molybdenum**

Molybdenum improves the tensile strength and especially the heat resistance and it has also a favourable influence on the welding properties. Molybdenum is frequently used in conjunction with chromium. Molybdenum has a strong tendency to form carbide.

N Melting point-210°C **Nitrogen**

In austenitic steels nitrogen stabilises the structure. Nitrogen allows the achievement of high surface hardness through nitride formation during nitriding.

Ni Melting point 1453°C **Nickel**

Nickel raises the strength of steel less than does Silicon or Manganese with the elasticity dropping only insignificantly. Ni ensures good through hardening, especially so when the steel contains also chromium. Nickel does not impair the welding properties.

S Melting point 118°C **Sulphur**

Makes steel brittle and is therefore harmful. Contents of 0.025% or 0.03"/o are permitted. Exceptions are the free- machining steels to which are added up to 0.03% so that the small distributed sulphide inclusions disturb the metallic cohesion and therefore contribute to the formation of short turnings.

Si Melting point 1410°C **Silicon**

Like Manganese Silicon is present in all steels since the iron ores used in their manufacture contain a varying amount of it. Further Silicon stemming from the refractory lining of the furnace is introduced into the melt during the manufacture of steel. The term "Silicon steels", however, includes only steels having silicon content above 0.40%. Si is not a metal but rather a so-called metalloid like, for example phosphorus and sulphur. Maximum phosphorus level permissible is 0.03 - 0.05% because it is harmful to steel. High silicon content (about 14%) enables steel to resist chemical attacks but it can no longer be forged.

Ti Melting point 1812°C **Titanium**

A very hard metal that forms strong carbide. It is an alloying element mainly in stainless steels for the stabilising against inter-granular corrosion; apart from this it has grain-refining properties.

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V Melting point 1730°C **Vanadium**

A very small addition improves the hot hardness and reduces the grain growth. Var acts especially favourably in structural and tool steels. Vanadium is strong carbide f Vanadium is preferred in combination with Chromium in structural and heat resisting and in combination with tungsten in high-speed and hot worked steels.

W Melting point 3380°C **Wolfram**

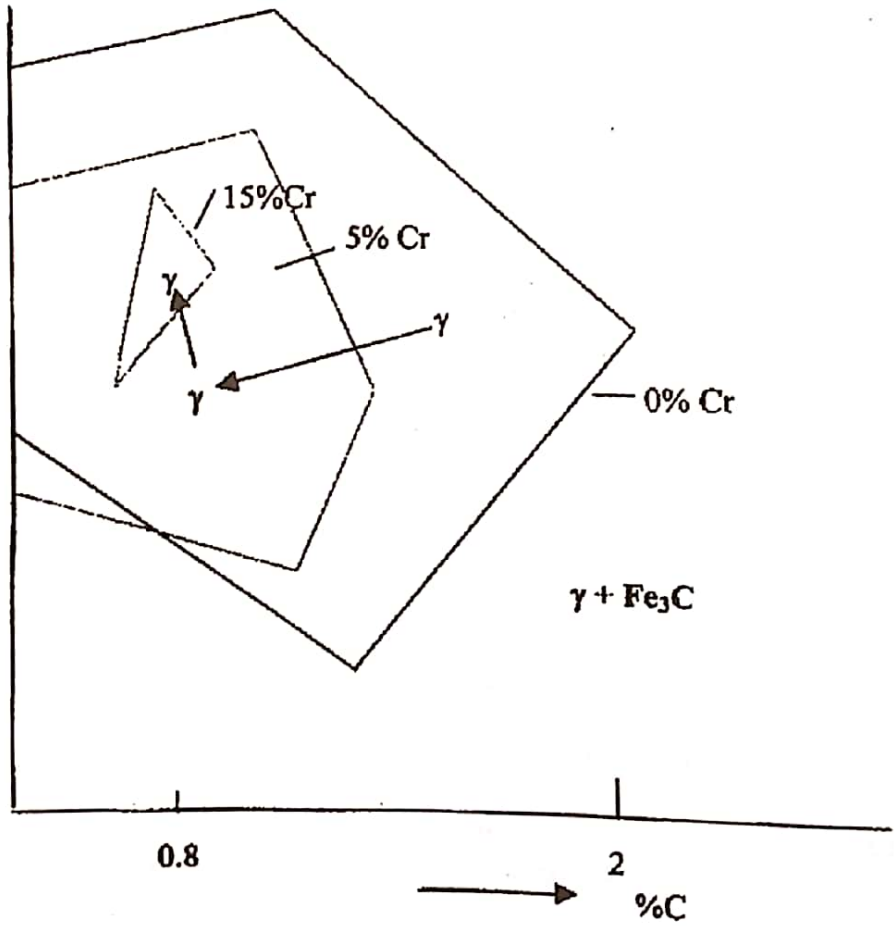
Tu **Tungsten**

Tungsten improves the strength properties. It increases substantially the hardness and t of cutting edges and is also responsible for high heat resistance values. It has a very tendency to form carbide and is primarily used in heat resistant steels.

Zr Melting point 1860°C **zirconium A**

Carbide former. It is used for de-oxidation, desulphurisation and eliminating nitro leaves minimal de-oxidation products. Increases the life of heat conducting steels

9.3 Effects of Alloying Elements on Fe-C Equilibrium Diagram



BCC elements such as Cr, Mo, V are more soluble in α Fe than in γ Fe and they increa stability range of ferrite by raising the eutectoid temperature and expanding the α field.

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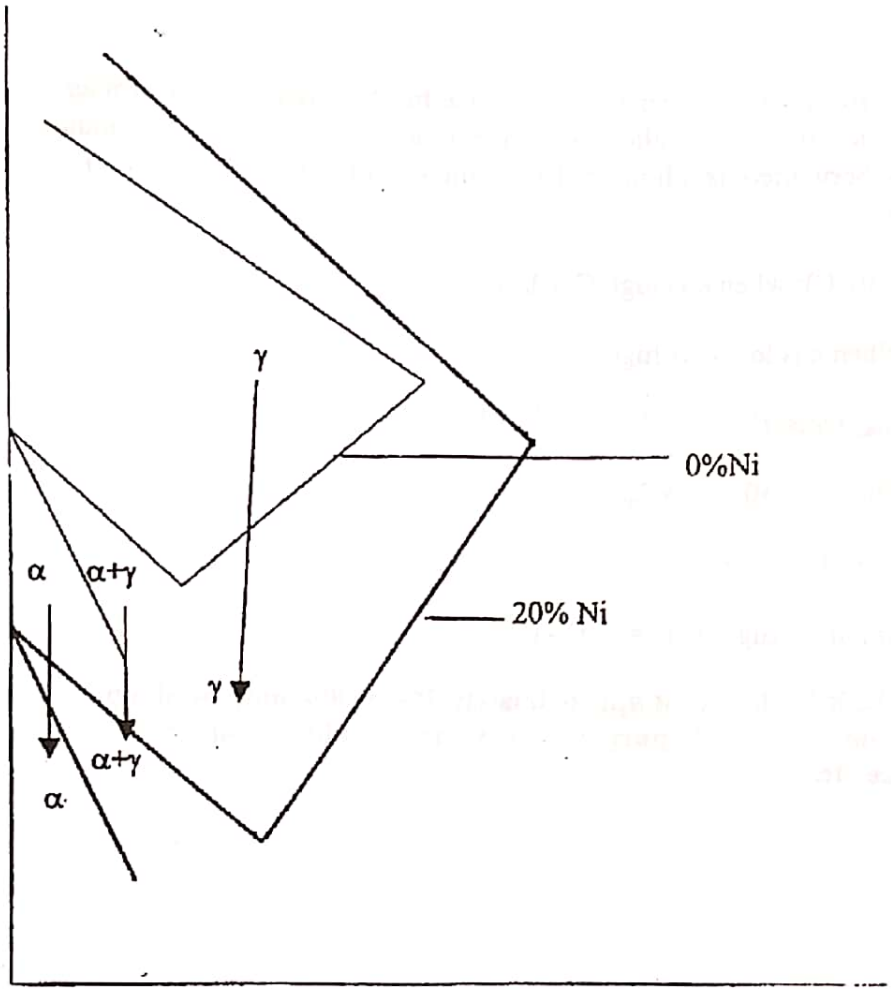
When much BCC elements is present e.g. (> 15% Cr); ferrite persists up to the melting point and such steels are non hardenable.

On the other hand FCC elements such as Ni, Mn and Cu are more soluble in γfield and tend to stabilise the phase by lowering the γ→α transformation temperature and raising the γ→δ temperature.



If sufficient FCC element is present then γ - α transformation temperature is depress... room temperature and the alloy consists of austenite at room temperature and will the... be non- hardenable.

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ıeory

Parent lattice atom	radius r
Alloy atom	radius r_o

ıl which atom is bigger. What matters is the difference between the size. This ɜs rise to a misfit parameter ε

gave the shear stress (τ) value for the misfit parameter ε as $\tau = 2\varepsilon CG$ where C ntration of alloying element and G is the shear modulus. According to y, there is a limit to the magnitude of C; If $\varepsilon > 0.15$ or < -0.15 solid solubility is

C); when ε is high C is low

ε is low C is high

vhen $\varepsilon \approx C$

$\varepsilon \rightarrow 0$, $C \rightarrow C_{max}$

).15, $C \rightarrow 0$

n strength ε, C = 0.07 - 0.08

t is clear that approximately 7% or 8% only of alloying element is needed ım strength purposes. Any extra could be for other things e.g. corrosion ıc.

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9.5 Tutorial Worksheet Nine

1 Why do we add alloying elements to steel?

2 Which alloying elements have very significant effects on steel? How do they impart these effects?

3 Using the Hume- Rothery rule; what percentage of alloying clement is needed for maximum strengthening of steel?

4 How are alloying elements used to control phase reaction rates?

5 What are the effects of alloying elements on Fe-C equilibrium diagram?

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10. STRENGTHENING OF STEELS

Strength in steels arises from several phenomena, which usually contribute collectively to the observed mechanical properties.

The heat treatment of steels is aimed at adjusting these contributions so that the required balance of mechanical properties is achieved. Fortunately the γ/α phase change allows great variations in microstructure to be produced, so that a wide range of mechanical properties can be obtained even in plain carbon steels.

The additional use of metallic alloying elements, primarily as a result of their influence on the transformation, provides an even greater control over microstructure, with consequent benefits in the mechanical properties.

Steels can be strengthened by several basic mechanisms, the most important of which is the movement of dislocations past obstacles.

Obstacles here are:

a) Other sessile dislocations → Work Hardening

b) Foreign solute atoms → Solid Solution Hardening

c) Precipitates → Age and Dispersion Hardening

d) Grain boundaries → Refinement of grain size

All these obstacles give rise to different strengthening mechanisms.

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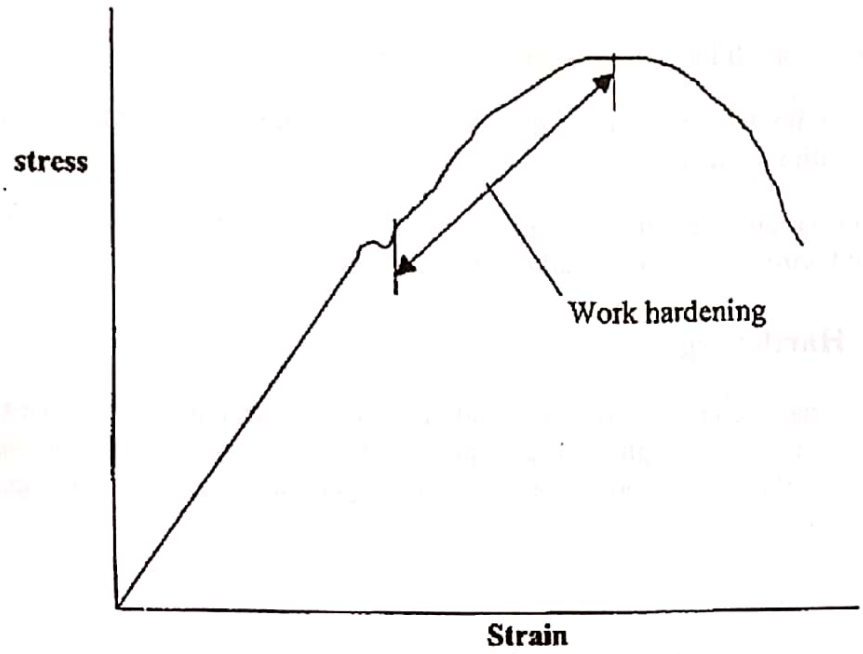
10.1 Work Hardening



Here the obstacles are other sessile dislocations ie dislocations that are not moving.

Sources of sessile dislocations

a) "Grown into" the lattice from cast state, the burger's vector $\vec{b}$ doesn't lie in the slip direction

b) From intersection of two moving dislocations (primary)

The stress required to maintain deformation at any given strain, the flow stress, σ_f can be related to the dislocation density

$\sigma_f = \sigma_i + k\sqrt{\rho}$ where ρ is the dislocation density

σ_i is the yield stress of a single crystal

k is a constant

The flow stress increases as the density of dislocation increases. The rate of this increase termed work hardening rate; depends on the rate at which ρ increases with strain.

The relationship between stress and strain during a tensile test is often stated to obey the equation $\sigma_f = k\varepsilon^n$

Where σ_f = true flow stress, ε = true strain, k = constant, n = work hardening index

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In steels, however, it has been observed that the true-stress true-strain curve more often obeys a relationship

$$\sigma_f = a + b \ln\varepsilon + c(\varepsilon) \quad \text{where a, b, c are constants.}$$

This equation confirms with the observation that the work hardening rate decreases to a constant limiting value with increasing strain.

Work hardening is an important strengthening process in steel, particularly in obtaining high strength levels in rod and wire, both in plain carbon and alloy steels.

10.2 Solid Solution Hardening

It is a well-known fact that the introduction of solid solution solutes into steel causes an increase in strength. The intensity of solid solution strengthening is dependent upon ----the difference in size between the solute and solvent atoms. In general the rate of change of strength with concentration is given by

$$\frac{\partial \tau}{\partial c} \propto \left(\frac{1}{a} \cdot \frac{\partial c}{\partial a}\right)^n$$

where τ = shear stress, a is the lattice parameter of the solid solution and c is the solute concentration.

Generally, substitutional solutes cause symmetrical distortion of the solvent lattice and this leads to relatively moderate strengthening effects. The overall effect of substitutional solutes has been shown to influence strength by a factor proportional to the square root of concentration (C)

$$\sigma \propto C^{1/2}$$

where σ = flow stress.

In dilute solutions, as is frequently the case for most steel, the last equation can he simplified to a linear dependence of solid solution.

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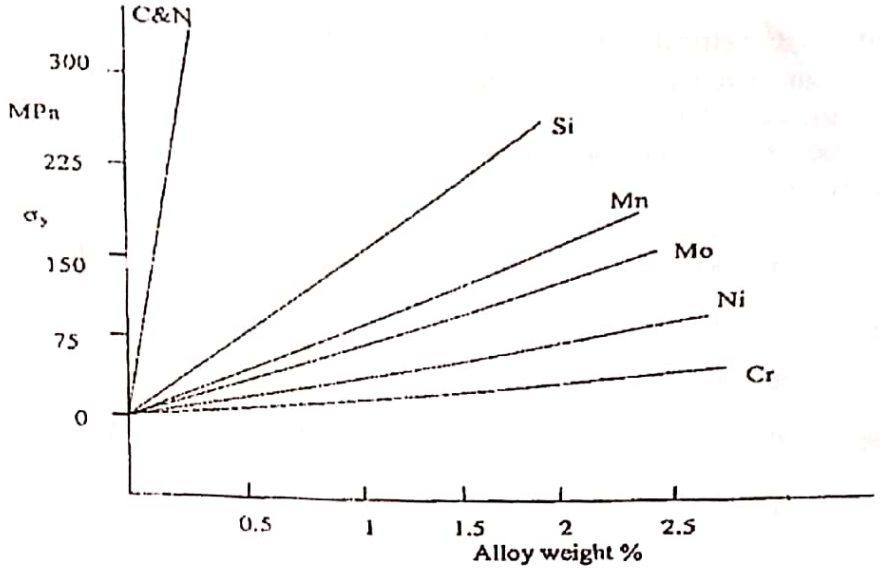
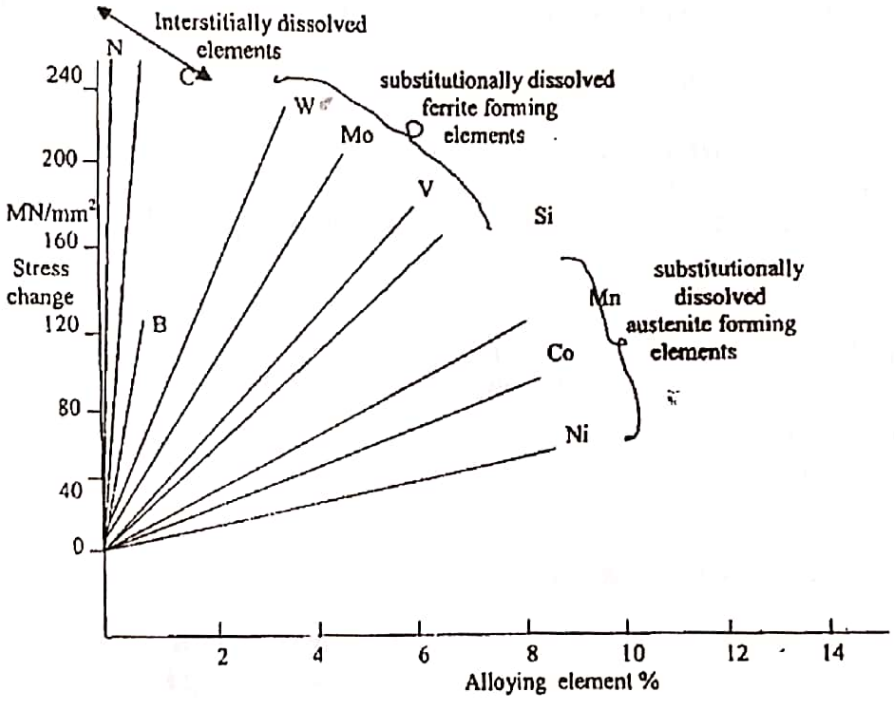


Change in yield stress due to Solid Solution Hardening effects in low carbon ferritic steels



Change in 0.2% proof stress due to Solid Solution Hardening effects in austenitic stainless steels.

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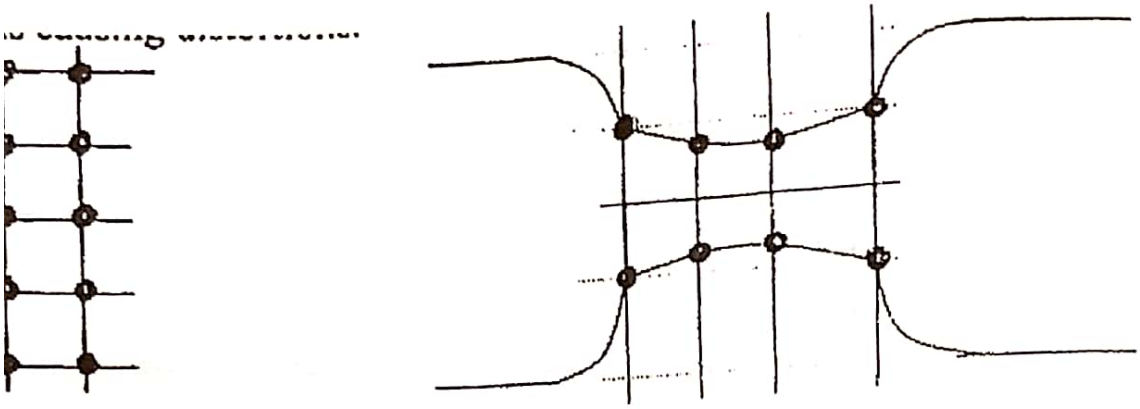
nmetrical lattice distortion, interstitial solutes such as carbon and nitrogen :h greater strengthening effect than substitutional solutes. This is further ery strong interaction that occurs between the interstitial solute atoms and :d with the fact that solute atoms tend to segregate to the dislocations



:reate a large number of strain field centres. Dislocation movements are ıd strain field centres because the lattice lines here are curves; high stresses ɔped leading to large elastic strains around the obstacles.

Dispersion Hardening (Second Phase Particle Hardening)

: *Particle Hardening*

cut deformable particles such as partially coherent precipitates. The ıe to work done by the plastic strains, dislocation by pass mechanism and cipitate and the creation of new precipitate matrix interface.

Deformable Particle Hardening

due to the difficulty of dislocations either shearing or bypassing of the :rent obstacles. The dislocations loop between the precipitates and the st be sufficient for this to occur. Orowon first showed how this stress (τ) ɔortional to the inter-particle spacing (λ); $\tau \propto 1/\lambda$.

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SUMMARY

	Amplitude/Size of Obstacle (r)	Wavelength (λ)/Distance Apart of Obstacles	Nature	Comment	Strengthening mechanism
SSH	0.3 Nm	0.05 nM	Obstacles perfectly coherent with matrix	$\lambda << r$	Elastic strains around obstacles
AH	>2.5Nm	5nM	Partial coherency	$\lambda \approx r$	Plastic strains, bypass & shearing
DH	>15nM	200nM	Complete incoherence	$\lambda >> r$	Difficulty in shearing / by pass

SSH-- Solute Solution Hardening; AH –Age Hardening; DH –Dispersion Hardening.

10.4 Grain Size Refinement

Probably the best-documented strengthening process in steels is that associated with a refinement of grain size; one of the most important strengthening routes in the heat treatment of steels.

The first scientific analysis of the relationship between grain size and strength, carried out on ARMCO iron by Hall Petch, led to the Hall - Petch relationship between the yield stress σ_y and the grain diameter d.

$$\sigma_y = \sigma_i + K_y d^{-1/2}$$

where σ_i = friction stress opposing the movement of dislocation in the grain

K_y = constant or stress required to move free dislocations along the slip planes or yield stress of a single crystal (intercept on the stress axis)

The unique feature of grain size strengthening is that it is the only strengthening mechanism, which also increases the toughness.

In practical terms, the finer the grain size, the higher the resulting yield stress.

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10.5 Strengthening Mechanisms

10.5.1 Solid Solution

Alloying additions can harden materials that cannot be hardened by t
process. The alloy addition is called the solute and the material the solve

When the solute and the solvent are of comparable atomic radii (R ar
solute displaces the solvent atom by a substitution solution process. Th
the new alloy is similar to that of the solvent.

However, the strengthening mechanism is achieved by the disparity in
solute and solvent atom as shown in section 9.4.

10.5.2 Precipitation and Dispersion

This phenomenon is found in those alloys whose solid solubility decre
temperature. Thus by heat treating an alloy at a temperature where it ex
and rapidly quenching it from that temperature, meta-stable solid solu
unsteady solid solution tends to revert to its lowest energy state, that of a
solution and the equilibrium precipitate. Therefore during ageing, solute
supersaturated solution to form a very high density of small 2nd phase p
the strength of the alloy to increase.

The driving force for this precipitation reaction is the reduction in free e
of the following:

$\Delta G = \Delta Gv + \Delta Gs + \Delta G_E$.

ΔG_v = Volume free energy of phase change

ΔG_S = Free energy of precipitate / matrix interface.

ΔG_E = strain free energy caused by misfit between precipitate and matri

ΔGv always takes negative value but ΔGs and ΔG_E can have large
therefore oppose the phase transformation. For the case of the formati
precipitate directly from the supersaturated solution, the surface free en
therefore the activation energy for the process will be high. The cons
formation of transition precipitates in the ageing sequence. These ha
coherent or partially coherent with matrix and therefore have no values
of these phases is much easier than the formation of the equilibrium pre

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Age hardening, which creates increase in strength and hardness due to time storage after heating and quenching initially has improved the scope for Al usage - leading to the development of special Al. eg. RR58 containing 2% Cu, 1½ % Mg, 1½ Fe and 1% Ni - used throughout the structure and surface cladding of Concorde. Age hardening, due to resistance to slip of the crystals and increase in lattice strain gave rise to alloy, Al - 3.5% Cu - 0.5% Mg,

Cu Al_2 is precipitated. If quenched alloy is heated to about 175°C for a few hours, hardening is increased.

Reason for ageing:

Aging disperses 2nd phase precipitates and hence reinforces the matrix.

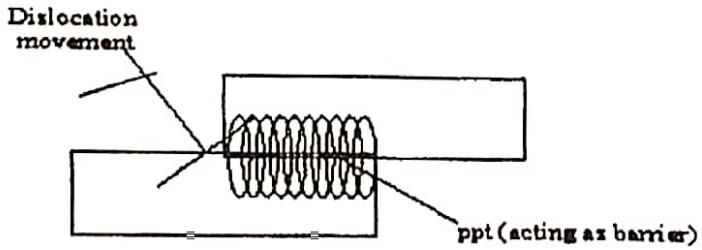
In most age hardening alloys the formation of the transition precipitate causes a greater increase in strength than the formation of either GP zones or the equilibrium precipitate. For the equilibrium precipitate they are too large. The strengthening may arise from the following mechanisms.

a. As a result of chemical hardening whereby the precipitates are sheared by dislocations, which cause the number of solute atom bonds to increase.

b. Because of interaction between strain field of a dislocation and the coherency strain field surrounding a precipitate. This is referred to as internal strain hardening.

c. The presence of non-deformable particles, which cause the dislocation to loop, round them.

d. A most effective resistance to dislocation movement is achieved when the precipitate lies across or normal to the slip planes (ie. It will form a sort of barrier to dislocation movement) of the matrix.



This form of strengthening mechanism gives rise to **Dispersion hardening.**

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10.6 Tutorial Worksheet Ten

1 What factors affect the yield strength of steel? How can the yield strength of steel be increased?

2 What is the role of alloying elements in the strengthening of steels?

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3 How does grain size affect the strength of steels? What is grain size refinement?

4 How do dislocations affect the strength of steels?

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5 Differentiate between precipitation and dispersion hardening of steels

6 What are the effects of coherent and incoherent precipitates on the strengthening of steels?

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7. Describe the characteristics of the formation of homogeneous and heterogeneous nucleation of transition precipitates in an age hardenable alloy and state briefly the role of precipitates in connection with dislocations in structural components.

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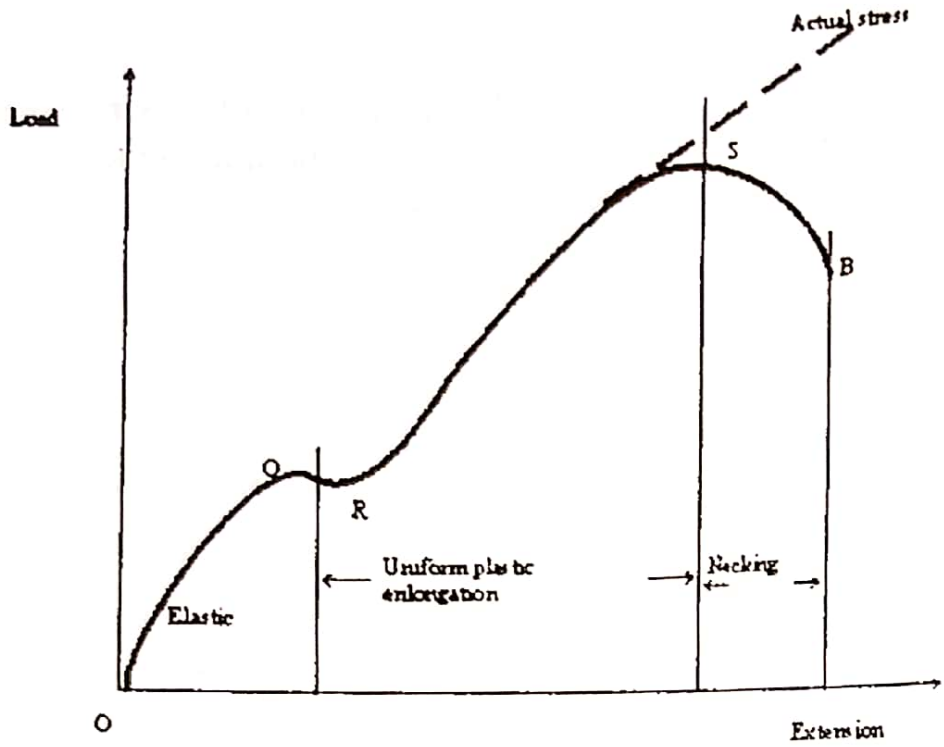
21. ELASTIC AND PLASTIC DEFORMATION



If original length = L

Cross sectional area = A

Load applied = P

Extension = l

For Elastic range Hooke's law is obeyed

$$\frac{stress}{strain} = \text{Const} = E \text{ (Young's modulus of Elasticity)}$$

$$\frac{P/A}{l/L} = \frac{PL}{Al}$$

21.1 Elastic

If at any point in the part of the curve 0Q the load is removed, the test pie original length. The extension is then said to be entirely elastic. On at deformation is interpreted as producing small displacement of rows of atom

21.2 Plastic

As the load in increased, a point Q is reached when the curve begins to straight line. Beyond Q, the material will not return to its original length removed and the material is said to have acquired a permanent set. proportionality. From R onwards the specimen stretches plastically. If metal does not return to original shape. This must involve atoms "slipping"

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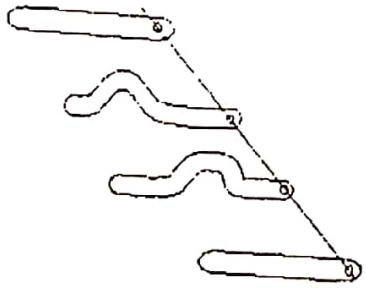
If we do the calculation for "block Slip"; i.e. large blocks of atoms sliding relative to one another, we find that the stress necessary to allow all the atoms to break their bonds with neighbouring atoms simultaneously is 1000 times greater than stresses observed in practice to produce plastic deformation.

Therefore, there must be some kind of imperfection present in crystals to allow plastic deformation at low stresses. Theory and experiments have shown that certain line defects known as "dislocations" are present. A calculation of stress necessary to produce a movement of a dislocation through a crystal to produce permanent deformation gives about the same answer as found in practice. This is because, to move a dislocation, only few atomic bonds are broken at a time – not all the bonds as in movement of whole blocks of atoms.

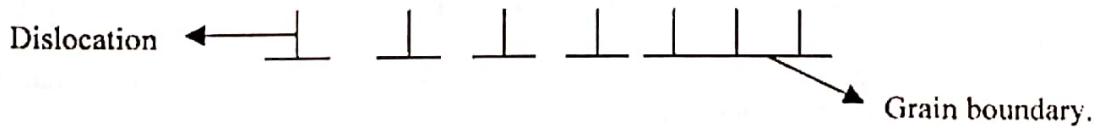
The permanent deformation produced by dislocations moving through a crystal is analogous to motion of a caterpillar. However, the resistance to deformation increases as amount of plastic strain increases. This is known as work "hardening" due to cold work.



Most metallic materials are produced by melting various alloying components together, pouring into ingots – then working ingots into required shape – forging, rolling, drawing. These working operations can be done "cold" or "hot".

Work hardening occurs because of dislocation multiplication under action of stress and many dislocations moving in different directions start to intersect one another - get tangled up and then are more difficult to move.

Dislocations pile up at obstacles – such as grain boundaries or large inclusion or other particles.



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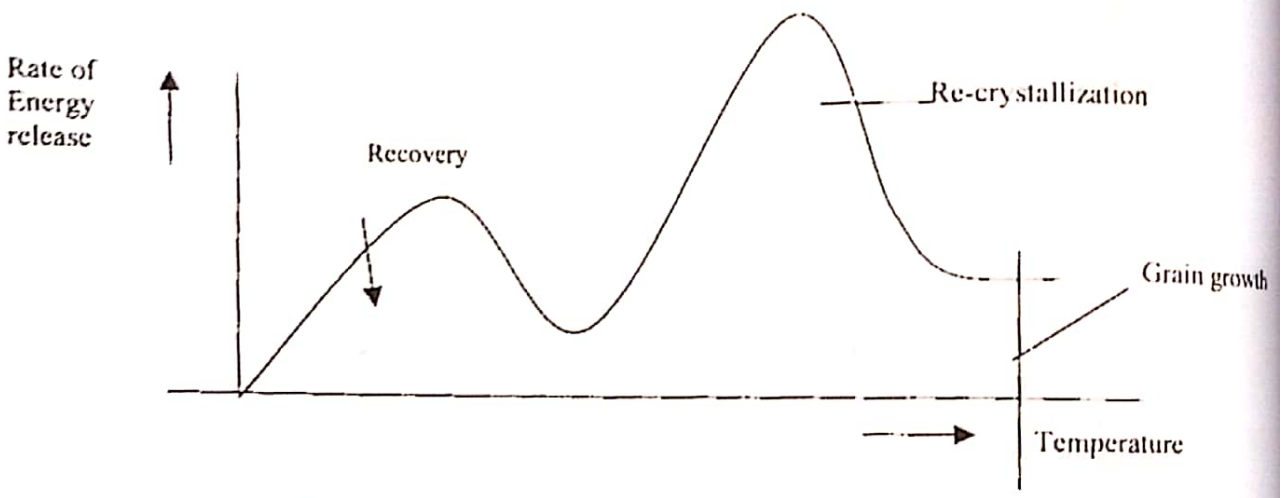
21.3. Practical Importance of Work hardening

It becomes more and more difficult (and hence more and more expensive) to fabricate metals by cold work. This is overcome either by hot working or cold working with intermittent annealing.

There are cases where we do want to cold work a metal (perhaps to get high strength or for a good surface finish) but because of work hardening we can only do a small amount of cold work before it becomes difficult. In such cases we can re-soften a material by "annealing" it – then we can do more cold work and so on.

21.4 Effects Of Heat / Temperature On Cold Work Materials

A cold worked metal when heated up to a high temperature for a sufficiently long period of time would form new unstrained grains that in time would supplant the cold worked structure. The most immediate effect of exposure of cold worked material to elevated temperature is the rearrangement of dislocations into lower energy configurations known as *recovery*.



As the material is maintained at this elevated temperature, a small region of nearly perfect crystals, capable of sustained growth in at least one direction into the deformed metal is developed. As this continues, however, dislocation climb and dislocation interaction result in a decrease in the dislocation density and dislocation arrays are formed. These arrays, which constitute the walls of the sub grains of the recovery metal, have lower energy than the dislocation tangles which made up the walls of the cells in the cold worked metal.

As with all such growth processes, the release of stored energy of the deformed material must be larger than any increases of free energy associated with the growth of grain boundary area surrounding the growing nucleus. It is now widely acknowledged, however, that re-crystallization does not involve nucleation in the classical sense, but is a continuous process of growth. Several suggestions have been put forward for a cold worked matrix to generate a re-crystallized grain by growth. These include:

1. A high local stored energy, which provides the driving force.
2. A steep spatial gradient of stored energy that allows the development of local instability.
3. A sharp lattice curvature that enables a growing embryo to quickly achieve a high angle grain boundary. These conditions achieved; re-crystallization then readily generates growth. Re crystallization in essence is the rearrangement of atoms into an entirely new set of

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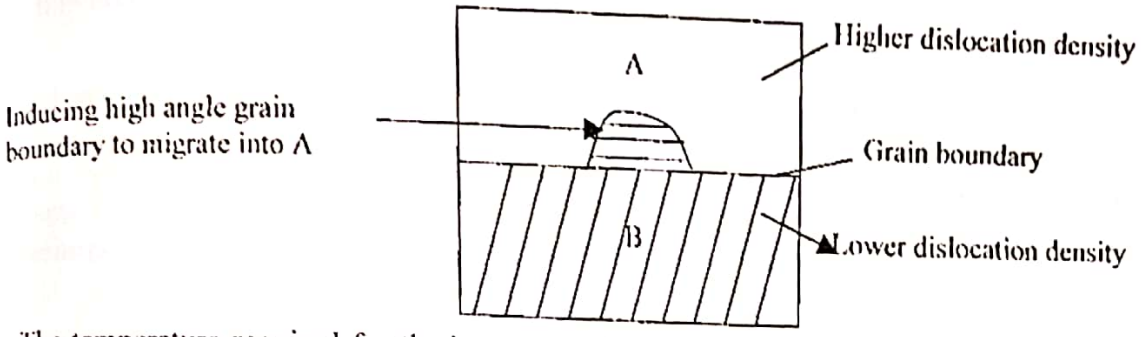
crystals; the crystals grow from very small "nuclei" until they impinge on each other, absorbing the intervening non re-crystallized material.

This process is accomplished by the outward movement of crystal boundaries into material containing high concentration of dislocations. The boundaries act as reaction fronts that sweep out dislocations in their path and leave strain free grains behind.

Local differences in dislocation density across a boundary cause it to bulge into the region of higher dislocation content and to produce a dislocation free area behind it.



The temperature required for the beginning of re-crystallization is determined by the degree of deformation. The higher the degree of deformation, the lower the re-crystallization temperature. This is so because a certain amount of deformation energy is necessary for re-crystallization to occur. The greater the prior deformation, the higher the available energy and the latter will be able to initiate the formation of new nuclei with an addition of less energy in the form of heat.

According to Bochrar, the minimum re-crystallization temperature of commercial pure metals, subject to high degrees of deformation is

$T_r = 0.4T_m$

T_m is the melting point temperature

T_r is the re-crystallization temperature.

Of several factors, which affect the re-crystallization temperature, the following are essential.

1. Severity of plastic deformation
2. Grain size prior to plastic deformation
3. Temperature at which plastic deformation was performed

In his paper Jeffries stated that the rate of heating through the temperature range in which re-crystallization takes place is an important factor determining grain size. It is this rate of heating that determines in particular whether grain growth will occur.

Grain growth is normally used to cover that phenomenon involving an increase in size of strain free single-phase polycrystalline structures, with second phases being considered only in so far as they modify the basic pattern of the process.

Grain growth often caused by the difference in surface energy of adjacent grains. The smaller the grain, the greater the surface energy and the less stable the grain, so that the larger grains will grow at the expense of the smaller ones. Owing to the small amount of energy available for grain growth to occur, both the time and the temperature of heating usually have

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to be greater than is necessary for complete re-crystallization of a deformed metal. Grain growth is characterized by a decrease in grain boundary area per unit volume and the associated decrease in grain boundary energy provides the driving force.

The kinetic theories of grain growth that have been proposed proceed from the consideration that the growth velocity V is a linear function of the driving force P, such that

$V = M*P$

Where M = mobility, specifying velocity change per unit driving force associated with the atomic transport mechanism involved.

The linear relationship between velocity and driving force follows from a consideration of the atom flux across an interface possessing an activation barrier.

Available evidence supports the view that grain growth kinetics is characterized by low velocity behaviour. At first sight this appears surprising, [Grey & Higgins], in view of the variations in boundary velocity that occur during grain growth. However, on reflection it is evident that though high velocities must develop during the final annihilation of a small grain; it is the gradual readjustment and slow boundary motion preceding such terminal stages that control the kinetics.

The grain boundary mobility depends upon:

1. Temperature
2. Orientation of two grains.
3. Nature of grain boundary.
4. Impurity concentration in grain boundary.

21.5 Hot Working

Intuitively, we know that heating a piece of metal makes it easier to deform.

Consequently, hot working methods (hot rolling, forging etc) are used extensively to fabricate metals. But heating up large pieces of metal is not cheap. Also components are heavily "scaled" after hot working and need to be de-scaled in acid.

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21.6 Tutorial Worksheet Twenty-One

1. Discuss in detail the processes, which occur during heating of a cold-worked metal below the re-crystallization temperature.

2. "Grain growth and re-crystallization are not stages of a single solid state reaction, in contrast they are competitive processes". Comment on this statement by comparing the kinetics of grain growth and re-crystallization

In annealed steel with an average grain diameter of 100μm, there are a few grains of 150μm diameter. Is grain growth a possibility? Give reasons for your answer.

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22. PRODUCTION PROCESSES

A working knowledge of tools, machines and processes is imperative in working towards the goals of improved production methods and lower manufacturing costs.

The selection of a given production is influenced by several factors including:

a. Quality product.
b. Cost of labour.
c. Cost of raw materials.
d. Number of units produced.

Although many items may be produced by several methods, there is usually one method that is best for a given set of variables.

22.1. Classification of Metal Working Processes

There are five different categories of metal processing.

a. Processes used to change shape of materials.
b. Processes used for machining parts to a fixed dimension.
c. Processes for obtaining a surface finish.
d. Processes for joining parts.
e. Processes used to change physical properties.

We are most interested in (a). Which includes casting, forging, extruding, rolling, drawing and powder metal forming.

22.1.1. Foundry/ Casting

This is the process of forming objects by putting liquid of viscous material into a prepared mould or form.

A *casting* is a product formed by allowing the material to solidify.

A *foundry* is the collection of the necessary materials and equipment to produce a cast.

Practically all metals are initially cast. The ingot from which a wrought metal is produced is first cast in an ingot mould. A *mould* is a container that has cavities of the shape of the cast.

Good castings cannot be produced without good moulds. Because of the importance of the mould, casting processes are often described by the material and methods employed by the mould.

22.1.1.1. Characteristics of Good Mould

1. Strong enough to hold weight of metal.
2. Resist erosive action of the rapidly flowing metal during pouring.
3. The mould must generate a minimum amount of gas when filled with molten metal.
4. The mould must be constructed so that any gases formed can pass through the body of the mould itself rather than penetrate the metal.
5. The mould must be refractory enough to withstand the high temperature of the metal and strip away cleanly from the casting after cooling.

22.1.1.2 Behaviour of Metal Casting.

When molten metal is poured into a mould the casting begins to cool inwardly through the mould from all boundary surfaces because the heat can only flow outwardly through the mould. The metal on the surface is more or less chilled because at first the mould is relatively

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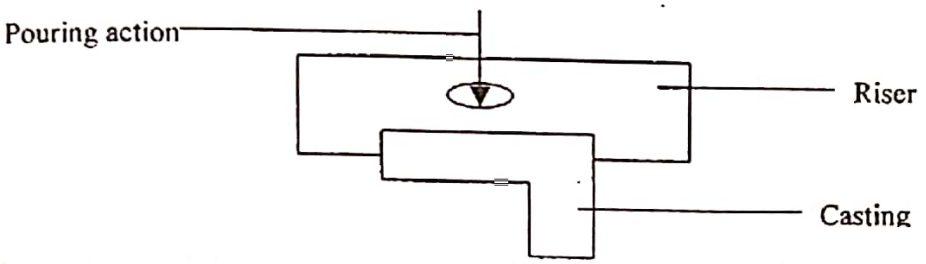
cold. Under usual conditions a fine close grain structure occurs near the surface and coarser grains towards the center where cooling is slower.

If a section is thick, enough metal may be withdrawn by contraction from the center before it cools to leave a void or cavity. To avoid this defect, a supplementary mass of metal called a RISER is provided adjacent to the casting. The purpose of the riser is to feed liquid metal by gravity into the body of the casting to keep it full, the riser is cut off after the casting has cooled.



If a section is too thin, metal flowing through the narrow passage may be frozen before it has a chance to fill in the wall completely.

The practical lower limit of section thickness depends upon design of castings and the fluidity of the metal. Phosphorus increases fluidity but weakens iron. Sections of different thickness cool at different rates, that leads to difficulty if a casting is not designed with uniform thickness throughout. Walls that shrink at different rates pull at each other and set up residual stresses.

22.2. Powder Metallurgy

This is the manufacture of products from finely divided metals and metallic compounds. The powders are loose in some application and pressed into pieces and parts in others.
Aluminium and Bronze powders are mixed into paints for metallic finishes. Metal powders add strength and wear resistance to plastics. Metals in powder form in fireworks burn with colourful effects.

22.2.1. Reasons for Powder Metallurgy in Industry

1. Only feasible means of fabricating some materials eg Melting point of refractory metals, tungsten (6,200°F), Tantalum (5400°F) Molybdenum (4800°F) are so high that they are hard to work in appreciable quantities with available equipments. Other substances such as Zirconium (3,452°F) react strongly with and are contaminated by their surrounding when melted. Powder metallurgy is a practical way of refining and fabricating such metals. It is also the only feasible way to consolidate and form the super hard tool material such as cemented carbide and sintered oxides

2. Combination of metals and non-metals not obtainable economically in other ways can be made by powder metallurgy. This is of particular value to the electrical industry. Motor brushes and contact points must have proper conductivity but must be resistant to wear and arcing. Brushes are made from powder of copper, graphite and sometimes tin and lead. Points require combinations like tungsten and copper or silver. Permanent magnets can be made by densely packed and finely dispersed particles of suitable substances and be held to small tolerances, others are clad or duplexed parts such as rods and slugs for nuclear reactors, Bimetallic units for thermostats and coated

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welding rods. A class of materials of growing importance made possib
metallurgy is known as "CERMETS".

As the name implies, they are combination of metals and ceramics with the
metals or alloys and the abrasion and heat resistances of the metallic compo
ceramics.

22.2.2. Cermets

These were developed in Germany in 2nd world war for possible jet eng
examples of their wide spread applications are in corrosion.

a. Resistant chemical apparatus.
b. Nuclear energy equipment. Heavy duty pumps for severe services, a
handling rocket fuels.

22.2.3. Porosity of Metals

Metals can be made porous by powder metallurgy. Applications are bron
stainless steel filter elements, more shock resistant than ceramic and beari
pump motors.

22.2.4. Importance of Powder Metallurgy

Many machines and structural parts can be made most cheaply by powder met
true of intricate precision parts that can be produced in two quick steps by pow
instead of by several costly machining operations eg gears, cams, valve an
brackets. Powder metal preforms make for simple dies and fewer strikes and
cost of forging some parts. In some cases, higher purity, more variety and b
properties can be achieved by powder metallurgy than by melting and ca
temperature.

Powder metallurgy encompasses the preparation of the powders, their co
useful articles; basically the powder is compacted to the shape desired
strengthen the compact.

22.2.5. Preparation of Metal Powders

The most used compositions of metal powder is the copper base and iron ba
and steel for structural parts and bronze are used for bearings. Others of import
lesser amounts are stainless steel, aluminum, nickel, tin, tungsten, copper, zirco
and metallic oxides and carbides.

The chief characteristics of a powder metal are particle size, size distributio
structure, density, flow rate and compressibility.

Most metal powders are obtained by reduction of refined ore, mill scale or prep
carbon monoxide or hydrogen. The grains tend to be porous; particle size can
uniform. Metals may be atomized in a stream of air, steam or inert gas. Some

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22.3. Industrial Forming Methods

In the manufacture of metallic components, it is very necessary to produce the required shape and dimensions by the most suitable and economic method.

22.3.1. Forging

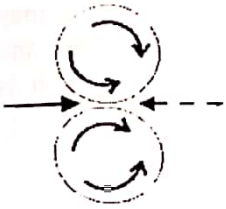
This is used extensively for helping large castings and alters their general properties.

The method involves either hammering, where the blow has high velocity or pressing, where the force has a low velocity. Forging is often a hot working process in which the yield stress is a function of the strain- rate used and high friction values are found.

22.3.2. Rolling

Initially ingots are broken down into blooms or slabs as a hot working process in a cogging mill which usually has two large rolls.

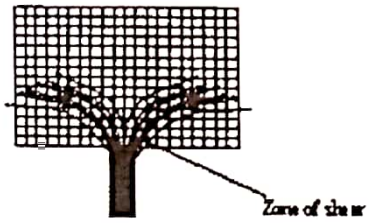
Refining the grain size and removing any as cast structure improve the properties of the cast metal. This leads to more homogeneous structure and higher strength and toughness.



It is not a batch process but is continuous and can produce slabs, plates etc. The tension must be controlled between close limits to maintain an even thickness. As the thickness of the metal is reduced, the length increases, since the volume of the metal remains constant.

22.3.3. Extrusion

This method of deformation differs from rolling and forging in that the zone of deformation is not fixed but gradually extends towards the container wall by progressive thickening of zones of heavy shear.



A simple representation of extrusion pressure P can be given

$P/y = a + b \log R.$

Where,

y = mean yield stress in tension.

R = extrusion ratio, a, and b are constants.

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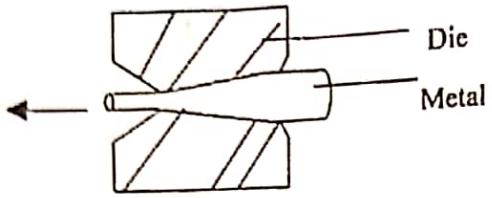
22.3.4. Drawing

This involves the reduction of cross section and increasing the length by pulling through a series of conical tapered dies.



Excessive speeds lead to cracking and faulty dies and dirty lubricants often lead to grooves or scratches in the drawn material.

22.3.5. Pressing and Spinning

Hollow articles often of symmetrical shape, may be produced from sheet or strip by pressing or spinning. Pressing operations include shearing, cupping, and deep drawing and may produce articles of irregular shape. Spinning can produce only symmetrical shapes and consists in holding a circular blank against a spinning chuck. As the blank rotates, it is formed into shape by the application of pressure from blunt steel.

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22.4 Tutorial Worksheet Twenty-Two

1. Discuss the significance of Powder Metallurgy in the manufacture of products. How are metal powders produced?

2. Write short notes on the following industrial forming methods:
   a) Forging
   b) Rolling
   c) Extrusion
   d) Drawing
   e) Pressing

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