UNIT 9 MATERIALS PROCESSING

Structure

9.1 INTRODUCTION

Iron and steel are the most widely used structural materials. Steels are alloys of iron and carbon. Along with these two elements, there may be other elements present in steels. The popularity of steels can be attributed to their variety in properties and applications, apart from their abundance and low cost of producing them. In Unit 4, we had seen the iron-carbon phase diagram and noted different phases existing under equilibrium conditions. We know from earlier units that the microstructure can immensely affect the properties of materials. We know how the microstructure is evolved when a melt is cooled under near equilibrium conditions. While, it is easy to study systems under equilibrium conditions, it should be noted that for practical reasons, we often use non-equilibrium conditions. Here, time plays an important role, As we get closer to reality, we may be going farther from equilibrium in processing. Let us see the evolution of microstructure under non-equilibrium conditions in this chapter. Further, let us look at some routine materials processing techniques. Materials processing covers a wide variety of disciplines. However, we shall deal with them from one aspect, the materials aspects. Our emphasis is on steel, as they still are the most widely used materials, though other modern materials are increasingly being used. The domination of steel as a structural material is world wide and is particularly true for the Indian scenario. While a very brief mention of ceramic processing is given, polymer processing is left out.

Objectives:

After going through this unit, you will be in a position to understand

   some important alloys of iron and carbon,

* the effect of time on the microstructure formed in these alloys after a phase transformation,

* the T-T-T diagrams and their applications,

* how heat treatments can be used to alter the properties of ferrous alloys, and

* what happens to steel after it goes through a thermal cycle, in an operation of welding.

9.2 FERROUS ALLOYS

We use steel in our everyday lives. Be it a pin or a needle, be it an axe or a shovel, a door handle or a kitchen utensil, the material it is made of, is steel. Steel is an alloy of iron as a major constituent and carbon as a minor constituent. Along with other elements, iron and

carbon form a wide variety of steels, with a wide variety of properties. In general, iron contains less than 0.05% carbon. Depending on the carbon content we may classify steel as low carbon steels (< 0.2% carbon), medium carbon steels (0.2%-0.6%) and high carbon (0.6% -2%) steels. While cast iron contains more than 2% carbon, wrought iron contains less than 0.03% carbon. Though the carbon content of wrought iron is low, it contains some slag produced during iron making. When there is no other element present, the steels are known as plain carbon steels, and other elements when present steels are called alloy steels. Even among plain carbon steels, it may be noted that the mechanical and other properties of steels can significantly Re varied by the variation of its carbon content and the overall microstructure. Let us look at the iron carbon diagram (Figure 9.1) and learn some nomenclature before we go further.

Fe_3C, a compound formed at 6.67 weight percent carbon is called cementite. The a and β forms which exist near pure iron are solid solutions of iron and carbon and they are known as ferrites; they have a body centered cubic structure. The solid solution of iron wid carbon with the face centered cubic structure is called austenite. It is stable between 723 °C and 1492 °C. The stability region depends on the composition and the range given above is the maximum temperature range. While this region is only for plain carbon steels, addition of alloying elements such as nickel can stabilise the austenite at lower temperatures. Pearlite is an alloy formed by cooling the austenite with the eutectoid composition ($\approx$ 0.8 wt% carbon). The microstructure of pearlite contains fine intimate layers of a-ferrite and cementite. Though the properties of the steels depend on the microstructure as well, let us look at some general properties of some plain carbon steels as the carbon content is varied. Steels with 0.01 - 0.1% carbon are ductile and weldable, those with carbon upto 0.25% are strong, ductile, and weldable; those with carbon in the range 0.25-0.6% are very strong and difficult to weld; those with carbon in the range 0.6-0.9% are strong, less ductile and not weldable. Plain carbon steels with 0.9-2% carbon are wear resistant, brittle and not weldable.

Cast iron has 2 to 4% carbon. While silicon and manganese are present in it some more elements are added to form special form of cast iron. Gray cast iron is a supersaturated solution of carbon existing in a two phase pearlite matrix. Carbon exists as graphite flakes and gives the alloy its machinability and self lubricating properties. Hence, it is used as engine blocks in automobiles. This contains about 2% silicon as well. Another form of cast
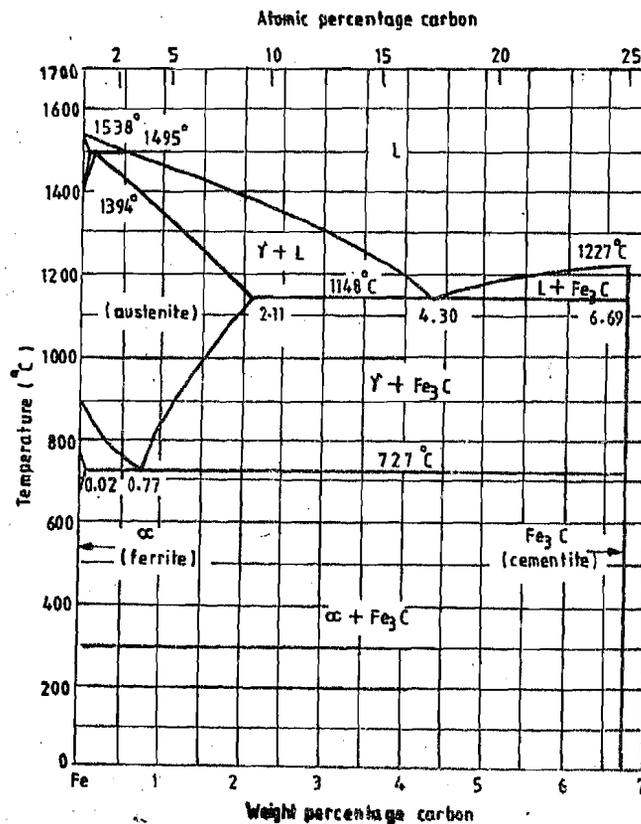

Figure 9.1 : Iron Carbon Diagram

iron is the white cast iron. This has about 3.5 % carbon and almost 0.5 % silicon. Here graphite is not precipitated. This has a mixture of cementite and pearlite. These are brittle and have good wear resistance. These are used in stone crushers. This is the lowest cost cast iron.

Steels with added elements are called alloy steels. When the noncarbon additions is less than 5 weight percent, they are called low alloy steels. When it exceeds 5 weight percent, these are called high alloy steels. These alloying elements usually make the steel better in terms of strength or corrosion resistance. Table 9.1 gives compositions of some popular steels and their code as per the Unified numbering system, and their type.

Table 9.1 : Compositions of Some Alloy Steels

UNI	Composition (wt %)						Type
	C	Mn	Si	Cr	Ni	Mo	
S30400	0.08	2.00	1.00	18-20	8-10.5	--	Austenitic
S31600	0.08	2.00	1.00	16-18	10-14	2-3	- do -
S43000	0.12	1.00	1.00	16-18	--	--	Ferritic

9.3 NUCLEATION AND GROWTH DURING PHASE TRANSFORMATIONS

In Unit 4 on the microstructure of materials, we have learnt the phase equilibria and how the microstructure of the material is evolved as the molten alloy is cooled slowly in such a way that the equilibrium conditions are nearly maintained. Alloys with the structure of pearlite or ferrite could be formed by cooling slowly. Here we need to realise that the closer we want to be near equilibrium, farther it will be from reality. It will take forever to cool down a melt if we want to be close to equilibrium conditions and we cannot afford such a process for making any material. Let us look at the phases formed by a more realistic rate of cooling. There are forms of steel which are formed under non-equilibrium conditions such as martensite and bainite. Let us look at them later in this unit.

SAQ 1

You have learnt how the microstructure is evolved when certain melts are cooled slowly (near equilibrium conditions). Draw the microstructure of the solids at room temperature formed by cooling a melt of iron and carbon with the following compositions : a) 0.5 wt% carbon, b) 0.8 wt % carbon, and c) 3 wt% carbon.

When you do the above SAQ, you will find that depending on the amount of carbon, steel alloys of ferrite and pearlite or cementite and pearlite are formed. These alloys have different hardness and strength. Low-carbon steel has a strength of about 44,000 psi; eutecoid steel (0.8% carbon) has about 112,000 psi. To obtain steel with greater strengths, we must depart from equilibrium conditions primarily in the cooling of the austinite. This departure, in the form of a rapid cooling, is known as quenching. In order to understand what happens during quenching or rapid cooling, let us look at the cooling process microscopically.

Let us look at a molten metal as we cool it. We know, that the melt is not stable below its melting point. The solid can be a large single crystal or polycrystalline with a given distribution of microstructure. What determines the nature of the solid formed- a large single crystal or a polycrystalline material with a certain grain size distribution? Let us imagine what will happen microscopically as the melt is cooled. Though the melt is not stable below the melting point, it is possible to have the material in a liquid form and is

said to be in a supercooled state. In order to form the solid, there should be nucleation of solid centres. (See Unit 4 for finding what is nucleation.) These centres, called nuclei should grow to the size we find in the solid. As the process is dynamic, some small nuclei redissolve and some big nuclei continue to grow. We have seen in Unit 4, the effect of surface energy and the free energy of solidification determining the critical size of the nuclei. We have noted the presence of an energy barrier for the nucleation beyond which the nuclei grow rather than redissolves. In this unit, let us look at the effect of time on the formation of nuclei or nucleation and subsequent growth. While looking at the formation of a nucleus, the rate of nucleation is controlled by two factors which are acting in opposing directions. As we lower the temperature of the melt from the melting point, we are going away from equilibrium and the driving force for nucleation increases. As the driving force increases, the nucleation rate (number of nuclei formed per unit time) increases. Formation of nuclei occurs by the diffusion of atoms to form a cluster, and subsequent rearrangement of them to reach the required structure of the solid. As we lower the temperature, the diffusion coefficients decrease and the formation of the nuclei also should decrease. Hence, as we lower the temperature, the driving force (instability of the melt) increases, while the diffusion rate decreases. The contributions to nucleation by these two opposing factors are marked in Figure 9.2. The product of these two lead to the net nucleation rate which increases as we go down the temperature from the melting point, but decreases again as we lower the temperature further. During the process of solidification, the nuclei which have the size greater than the critical size should grow. The growth of the nuclei is also having an energy barrier and is controlled by the Arrhenius equation of the type

$$U = A \exp\left(\frac{-E_a}{RT}\right)$$

where,

E_a = activation energy for diffusion of atoms in the melt, and

U = the rate of growth of nuclei.

The overall transformation rate should be the product of the nucleation rate and the growth rate. The transformation rate (which is a function of nucleation rate and the subsequent growth rate) is also having a hump, which is shifted towards the melting point (see Figure 9.2).
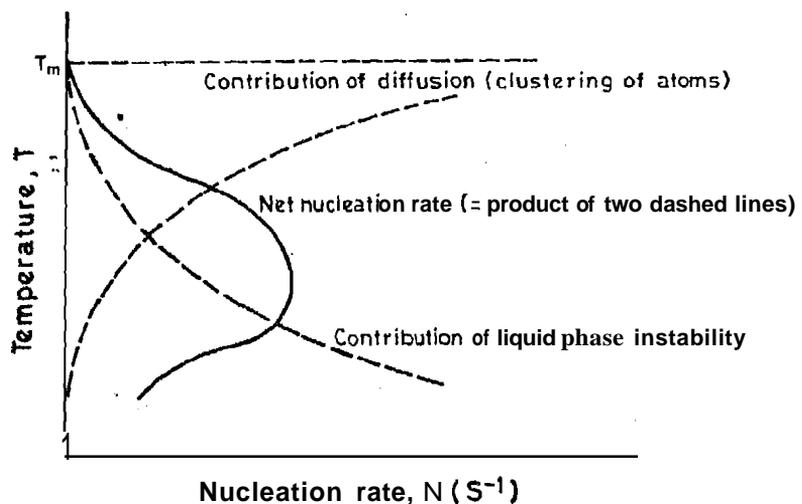

Figure 9.2 : Rate of Nucleation

If we assume that the nucleation occurs randomly in the untransformed phase at a constant rate and that the product phase grows at constant rate as spheres till they meet the adjacent particles, then the fraction X, transformed is given by

$$X = 1 - \exp\left(\frac{-\pi I U^3 t^4}{3}\right)$$

where,

. I = the nucleation rate,

U = the growth rate, and
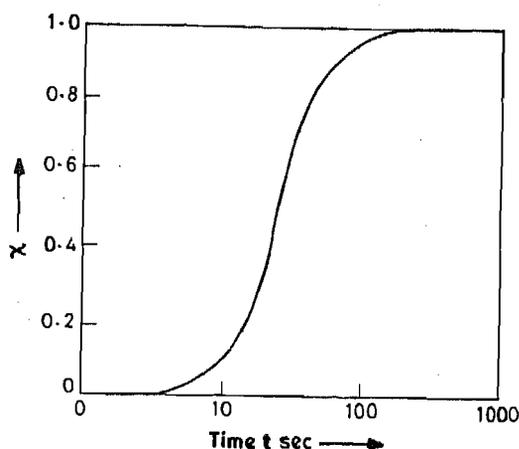
t = the time for the fraction X to be transformed.

Figure 9.3 : Fraction of Phase Transformed versus the Time

Here a plot of X versus t is given by Figure 9.3. The figure is sigmoidal. Again this shows that the rate at which the phase transformation occurs is slow initially, increases and again drops to completion.

9.4 TIME-TEMPERATURE-TRANSFORMATION DIAGRAMS

Most of the phase transformations are thus controlled by the diffusion. However, there are transformations which occur by a diffusionless process. Let us look at them later. In the case of diffusion controlled transformations, we can plot the time required for 100% completion of transformations as a function of the temperature. These curves are known as Time-Temperature-Transformation diagrams or popularly known as T-T-T diagrams. A typical variation of the above is given in Figure 9.4. We may also plot the time taken for
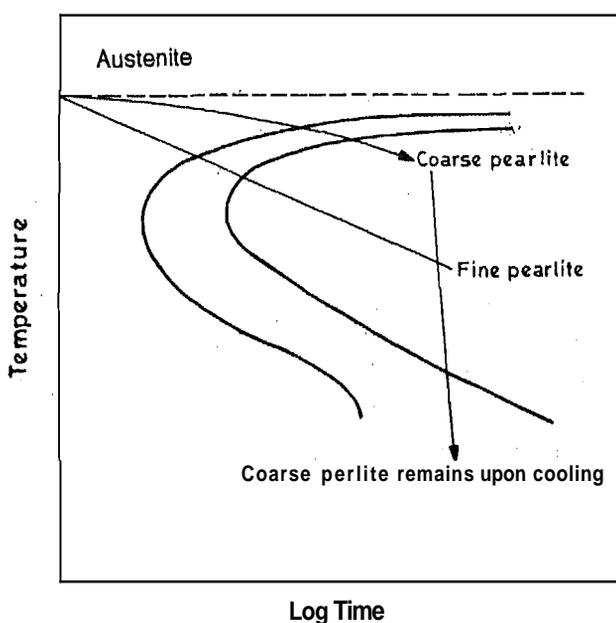

Figure 9.4 : Typical Time Temperature- Transformation Curve

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different stages of completion on the same plot. Let us consider austenite with a composition of 0.778 carbon. Under equilibrium conditions, the temperature should be above 728 °C. As we cool we expect a eutectoid transformation. We expect pearlite to be formed under equilibrium conditions. The iron carbon diagram indicates that indeed the pearlite is formed as we cool slowly. The grains are large, because at small difference in temperature between the transformation temperature and the working temperature at a given instant fewer nuclei are formed. Further, there is enough time for the nuclei to grow. If we cool a little faster, more nuclei are formed and the grains are fine. Whether coarse or fine pearlite is formed, a subsequent rapid cooling, the pearlite phase is retained. Note that we do the rapid cooling after we cross over the 100% transformation line at a temperature high enough, say 400 °C. The crossing of the transformation curve at high temperature has led to the pearlite microstructure. What if we cool the austenite fast enough and we cross the transformation curve at a much lower temperature. Here, we cross the transformation line at low temperatures (say around 400 °C) and the microstructure is much different. We get a mixture of ferrite and cementite as fine needles. This is called Bainite. Here the distribution of ferrite and cementite is much finer than what we see in fine pearlite.
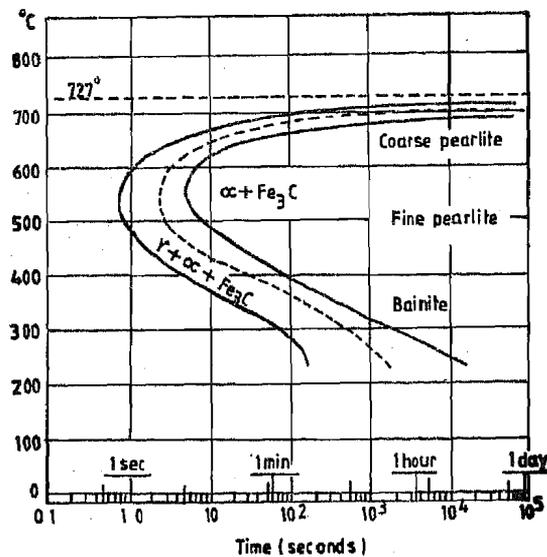

Figure 9.5 : TTT Diagram for Eutectoid Steel. Here the Curved Lanes Correspond to 1, 50 and 100 % Transformation Lines

What will happen if we cross the line below 250 °C. A closer look shows that the transformation curve is stopped at about 250 °C. At such low temperatures, solid stare diffusion is difficult and we have traveled far from equilibrium. That means the solid has become highly unstable. Then a transformation at these low temperatures occur by a fast diffusionless transformation called martensitic transformation. Instead of forming a mixture of ferrite and pearlite, interstitial supersaturated solid solution of carbon in uon having a bct (body centered tetragonal) lattice structure is formed. This occurs in the lattice by a small adjustment of orientation of iron and carbon by a shear-like mechanism. This form of steel is called martensite. It is stable at room temperature. However, on heating, the energy barrier for diffusion is overcome and it can be transformed into more stable phases of ferrite and cementite. The transformation of martensite results from a three-dimensional mechanical shearing action that distorts the structure producing hardness and brittleness. Martensite transformation occurs in other metals and alloys, such as titanium, lithium, iron, nickel and copper-aluminium

To summarize what we have said about equilibrium and non-equilibrium conditions of cooling, our initial step was to heat the basic components of steel (into the austenite-forming region) to produce austenite, a single-phase solid solution of carbon in gamma (γ) iron Once we formed austenite, we could cool it under equilibrium conditions to produce a two-phase mixture of ferrite and cementite called pearlite. The carbon in the cementite distorts this structure, producing qualities of strength and hardness. The ferrite contributes ductility. If we depart from equilibrium conditions and cool the austenite more quickly, we can form pearlite, with greater hardness, If we cool it even more rapidly we produce a transformation product called martensite, which is extremely brittle, strong, and

hard. It far surpasses the hardness and strength of pearlite. Steel with 100% martensite has limited use, due to its sensitivity to fracture by impact.

While we cannot use 100% martensite for the above reason, we may think of a steel with different martensite content, so that we can have the desired set of properties. We may subject the martensite formed to another heat-treatment to selected levels to transform some or all of the martensite to other microstructures with differing properties. This is called tempering or drawing. This process should occur by a process of diffusion of atoms. By this process, varying microstructures and grain sizes are formed with just the correct hardness and strength desired for some industrial application. One application might require a good amount of toughness with very little brittleness; another might demand greater hardness. Depending on the application, a suitable heat treatment can be given and tailor the properties. One serious drawback to this process is the possibility of distorting and cracking the metal as a result of the severe quenching required to form the martensite without transforming any of the austenite to pearlite.

As a metal object is quenched, the outer area is cooled more quickly than the center. Thinner parts are cooled faster than are parts with greater cross-sectional areas. What this means is that transformations of the austenite are proceeding at different rates in a single metal object. As we cool a metal object, it also contracts and its microstructure occupies less volume. Such a situation leads to difficulties in heat treating larger components. How can we overcome such a difficulty? We may quench the austenite from high temperatures to temperatures above the beginning of the martensitic transformation, allow the entire body of the component to reach the temperature, by an interruption of cooling and then continue the quenching to martensite followed by usual tempering process. This process is shown in Figure 9.6 (a) and is called martempering. Alternatively, one can interrupt at a higher temperatures to allow the metal at the center of the part to reach the same temperature as the surface. By maintaining that temperature, both the centre, and the surface are allowed to transform to bainite and are then cooled to room temperature. This process is called austempering (see Figure 9.6 (b)) Austempering produces less distortions as there is no martensitic transformation. Further, one heat treatment for tempering is avoided and saves energy. Here the properties are controlled by controlling the fineness of bainite. However, austempering has the disadvantage of requiring more time even though it requires no tempering treatment. Also, parts with large sections of thickness cannot be processed.
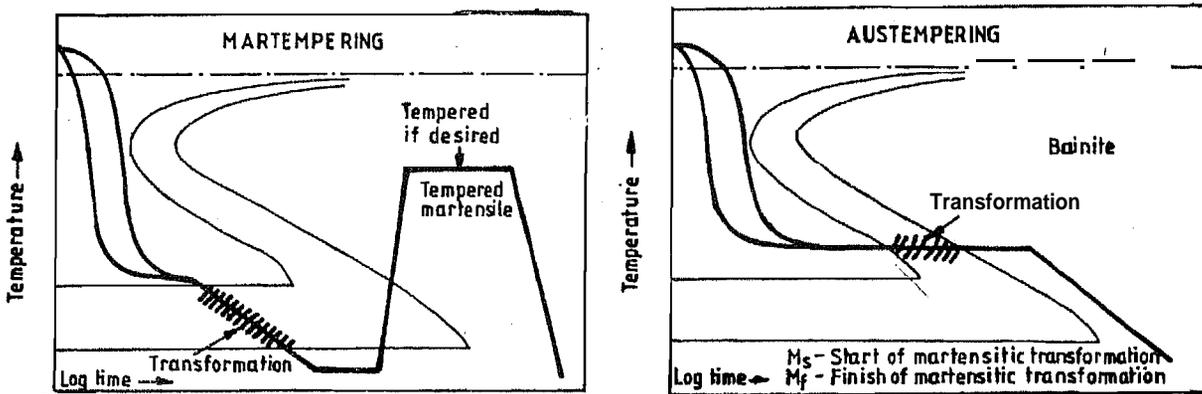
(a) Heat Treatment Process for Martempering   (b) Heat Treatment Process for Austempering

Figure 9.6

SAQ 2

How long does it take to transform austenite to 100% pearlite at 600 °C and 400 °C ?

SAQ 3

What will be the microstructure formed if we cool the austenite (eutectoid composition) from 750 °C to 500 °C at the rate of 250 °C per sec. and subsequently cool it 400 °C at the rate of 100 °C per hour and then quench it to room temperature.

9.5 WELDING AND MACHINING

Weldability is a processing property generally used to describe the reaction of materials to the welding process. Let us consider first the weldability of steels. Our considerations are only going to be materials related and all other aspects of welding are ignored here. When two plain carbon steel pieces are welded together, molten steel is produced. This forms a weld pool between the two pieces. Initially the two pieces were at room temperature and the weld pool at temperatures above 1600 °C, dissipates heat through the two pieces and solidifies. What will happen to a) the weld pool that is made of steel and b) the areas of the plates adjacent to the weld pool as heat is fast dissipated through?
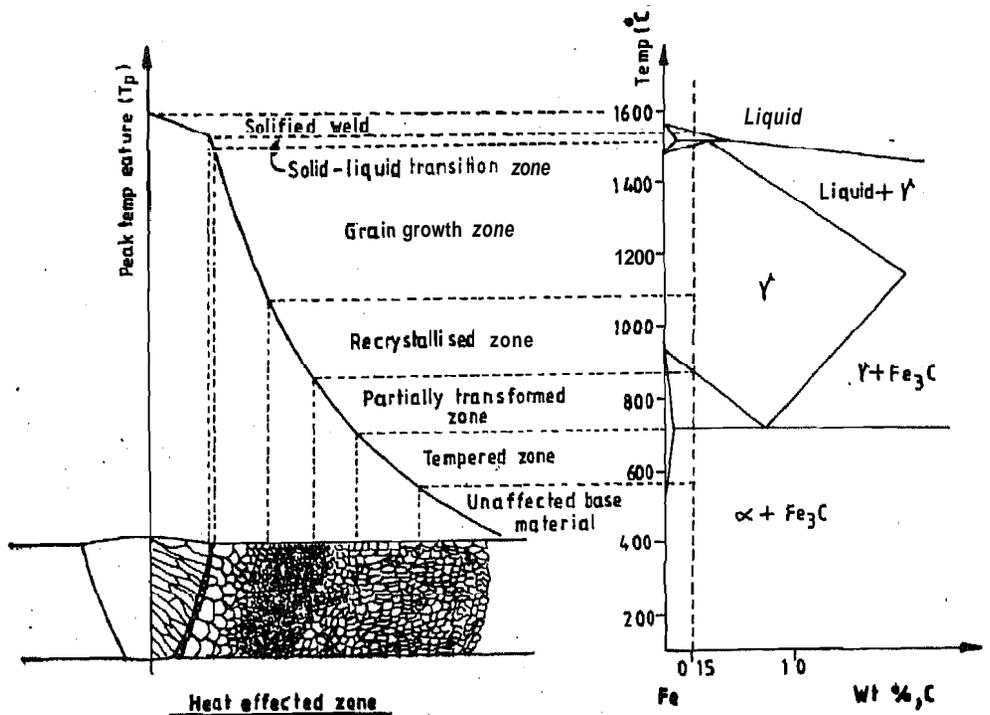

Figure 9.7 : Schematics of the Various Subzones of the Heat Affected Zone for a 0.15% Carbon Steel and the Corresponding Composition Line Indicated in the Iron Carbon Diagram

The material is subjected to severe thermal cycle and the original microstructure of the two pieces and their properties are changed. The heat will raise the temperatures high enough to form austenite phase and as it cools fast may form martensite. This zone is called the heat affected zone. If the carbon content is low, it is not a serious problem. However, if it is more than say, 0.25%, it becomes brittle. This might lead to cracks in the weld. Let us look at the heat affected zone. It can be divided into several subzones as shown in Figure 9.7. Each subzone has different microstructure and consequently, different mechanical properties. The type, and their width are dependent on the thermal cycle. These changes are partly decided by the preweld history of the metal piece that is welded. While the above figure is given to indicate the complexity of the problem, let us look at a simpler

approach and see whether the weldability can be assessed. Carbon content can be used to gauge the weldability of steels.

It is easy to weld low carbon steels, as the transformation temperatures increase with lower carbon levels below the eutectoid compositions (see the iron-carbon diagram) and the ;products formed at these temperatures are soft. As the carbon content increases welding becomes difficult warranting preheating. As the carbon content goes beyond 0.4%, good welding becomes nearly impossible because of the transformation behaviour and the increased hardness of the products.

SAQ 4

How do you think the problem of cracks in weldments of steels with more than 0.25% carbon be solved'?

Machining is a manufacturing process in which the size, shape and surface properties of a component are changed by removing the excess material. The removal of the material may be achieved by locally straining the material to fracture through relative motion of a tool and the work piece. A conventional machining may use a classical tool, while, chemical, electrical or thermal methods may find applications in advanced machining processes. Let 'us look at the conventional process. A tool, in general, should be harder than the work piece. However, since the operating conditions are severe, more constraints are added. Along with liigh hardness, it should have modest toughness at the high temperatures faced by the tool, and be wear resistant. In ferrous based materials, this is achieved by having a matrix of martensite with an excess of carbides of iron, tungsten, molybdenum or chromium. In another variation, sinlered tungsten carbide bonded by cobalt is used. In high speed tools, ceramic tools are emerging as the choice. These are made of ceramics like alumina. A combination of the properties of the ceramic and the classical tools arc achieved by coating the classical tools with a coating of ceramics. Titanium nitride and carbide coatings are increasingly being used to increase the tool life.

Machinability is often used as a vague term to express the relative ease of maching a material. The following comparison will be relevant: tool life or cutting speed for a given cutting condition, cutting forces, horse power required, surface finish, chip disposal and dimensional slability. As quantification of such a term is difficult, it is better to use machinability to mean the cutting speed under standard conditions at which the material can be machined. The physical properties of the material that affect the machinability are mechanical and thermal. Since a lot of heat is generated at the culting edge, and the temperature rise will determine the tool life, the net heal generated and the rate at which il is transferred away are important.

The area under the stress-strain curve is the amount of work done on the material when it is deformed to fracture and this work is converted to heal. Hence, it is a measure of the heat generated during machining. For a good machinability we would like to have this area small. Heat capacity is a factor deciding the temperature rise for this heat input and the thermal conductivity indicates bow this temperature is lowered by the losses due to conduction. Taking all of the above into consideration, some materials are listed according to decreasing order of machinability.

Aluminium, leaded brass, Gray cast iron, Molybdenum, 301 series stainless steel, Inconel.

9.6 CASTING

Casting is probably the oldest process known to mankind for making metallic articles. Archaeological survey bad shown that man knew this as an art or science as early as 4000 BC. Casting is a process whereby the desired material is heated to a liquid state, then poured into a previously prepared mold cavity of proper design, and allowed to solidify inside the mould before being extracted, trimmed and cleaned. In order to determine the castability, we need to consider the following: The relative melting temperatures of the metal and the mould, the solubility and/or chemical reactivity of the metal and the mould material, thermal expansion and conductivity of the metal and the mould, and finally the

cost. Solidification rates during casting operation is usually high. Depending on the type of mould used, we may classify the casting into different types. A number of casting processes use mould materials which are insulating compared to the metal that is cast. In 'sand casting', the mould is made of sand, bonded with clay or a resin. The pattern to form the mould cavity is reusable and may be made of wood or metal. In investment casting, the pattern is not reusable. It is made of wax or plastic. The pattern is surrounded by a slurry of ceramic which settles. This is subsequently dried. The dried mould is fired to give it strength and at the same time, the pattern is burnt out. While the heat flow and the design of moulds are important considerations, let us look at some metallurgical aspects which are worth discussion here.

There are important properties of the material which are relevant. The thermal properties (conductivity, specific heat) of the melt and the solid determine the temperature gradients across the phase boundaries. The solubility of gases in the .liquid and the solid determine the probability for defect generation such as blow holes, voids etc. The expansion coefficient determines the shrinkage of the casting. In case a two-phase material is being cast, there is a possibility of separation of phases, called coring. In a typical casting of a brass (say 70% copper and 30% zinc) a copper rich surface and a zinc rich core is formed. This is a non-equilibrium process called coring.

SAQ 5

Look at the phase diagram (Figure 9.8) which forms a solid solution over a wide composition range and arrive at the compositional variation as the solidification progresses.
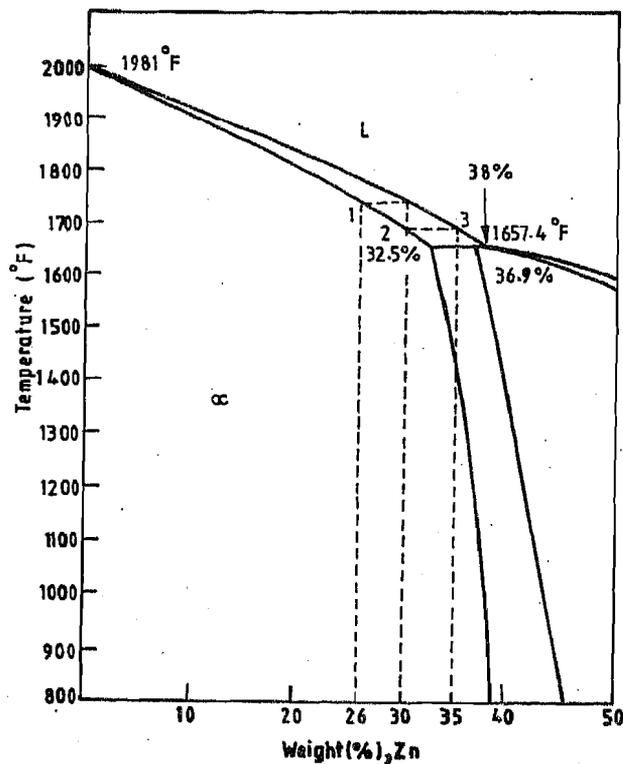

Figure 9.8 : A Portion of Cu-Zn Phase Diagram

9.7 PRECIPITATION HARDENING (AGE HARDENING)

Non-ferrous metals do not undergo the significant phase transformations that we notice in steels. The most effective thermal processing technique for increasing the strength of non-ferrous metals is precipitation hardening, or age hardening. An alloy that exists as a two phases at room temperature is heated to form a single phase (solid solution). This is followed by rapid cooling (quenching) of this single-phase solid solution to form an

unstable supersaturated solid solution. This treatment leads to strengthening of the alloy and is called precipitation hardening or age hardening.

As an example let us look at the Copper-silver system (Figure 9.9). Let us look at the silver rich side, say a composition of 7.5% copper. On heating it to about 770 °C and quenching it, we freeze the system to the a phase as a supersaturated solution of copper in silver. This is quite ductile and can be worked to give a particular shape. This can be compared to the difficult to machine equilibrium two-phase alloy with the same overall composition. Once the shape is formed, a heat treatment is carried out to precipitate copper and cooled, Once this is done the hardness is increased significantly. The precipitates resist the movement of dislocations and that is why the strength increases in such materials.
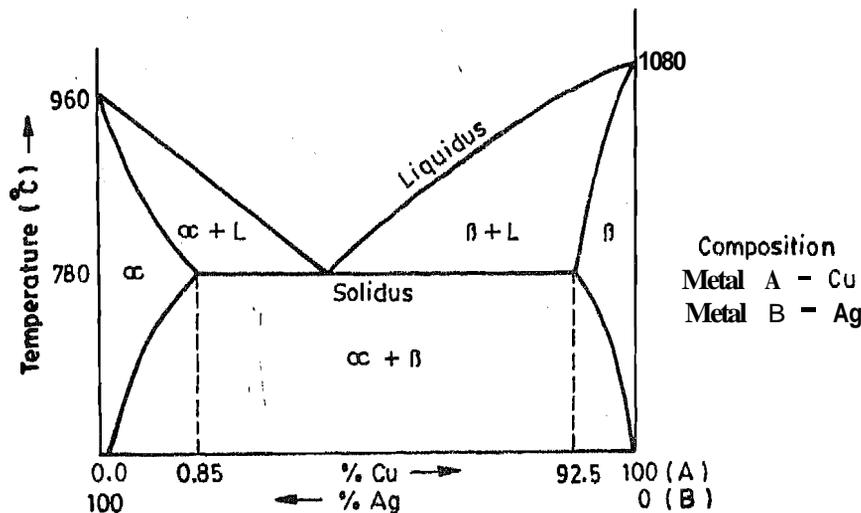

Figure 9.9 : Copper-silver Phase Diagram

9.8 CERAMIC PROCESSING

Ceramic processing has one major problem associated with it. It is difficult to reproducibly achieve same set of properties. As the complexity of the composition, structure and the process increase, uniformity of the product between runs becomes difficult. The most widely used ceramic processing involves preparation of a compact of the ceramic powder, followed by heating it to temperatures below the melting point. The temperature is below the melting point because ceramics have usually high melting points and the problems increase with an increase in temperature. This heat treatment bonds the grains together, giving the component its strength. This process is called densification, or sintering. The bonding between the grains during sintering is a result of many processes, the most important being diffusion. During sinteriug, the pores are removed, grains grow, the apparent density increases along with an increase in strength. The driving force is the decrease in the surface energy due to decreasing surface area. The theoretical density of the material cannot be achieved easily by this process as complete elimination of pores in the ceramic is difficult. Application of pressure at the time of heating leads to improvements in density and this could be achieved by hot pressing and hot isostatic pressing.

9.9 SUMMARY

In this unit we have an introduction to steels as a group of alloys with iron as a major component and carbon as a minor component, We saw that the strength of steels could be varied by the variation of carbon content. As this too has boundaries within which we may achieve strength, we saw that adjusting the microstructure of the steels can give us mother degree of freedom in improving the strength. Non-equilibrium cooling (quenching) of the high temperature phase (austenite) could lead us to materials of controllable microstructure and strength. Just by scheduling the thermal cycle, or designing the heat treatment we

could get coarse pearlite, fine pearlite, bainite and martensite. Since the rate of cooling can change the strength so much, we had a perspective of processes such as casting and . welding which involve high cooling rates from high temperatures (even above melting point). Finally, we had a look at the ceramic processing which involves heating (sintering) as a major step.

9.10 KEY WORDS

α-Ferrite	:	A solid solution of carbon in alpha iron (BCC) which exists below 910 °C.
δ-Ferrite	:	A solid solution of carbon in delta iron (BCC) which exists in the temperature range 1394 °C to 1539 °C.
Austenite	:	A solid solution of carbon in gamma iron (FCC).
Cementite	:	A compound formed in Fe-C system (Fe_3C)
Pearlite	:	Two-phase microstructure formed in steel with 0.8% carbon. It has alternate layers of ferrite (<0.2% carbon) and cementite (Fe_3C) with 6.7% carbon.
Bainite	:	It is a steel with microstructure like pearlite but with a finer structure formed by rapid cooling of austenite. It has very fine needles of ferrite and cementite.
Martensite	:	A form of steel formed by quenching of austenite. It is a metastable supersaturated solid solution of carbon in iron.
Tempering	:	Reheating the martensite to allow diffusional transformation into equilibrium bainite structure.
Martempering	:	A heat treatment process in which the hot steel is quenched to just above the starting temperature of martensitic transformation and then cooled slowly across the martensitic transformation range. Subsequently, it is tempered as above.
Austempering	:	A heat treatment process in which the hot steel is quenched with an interruption just above the martensitic transformation range and allowed to stay there long enough to form the bainite. This avoids the secondary heat treatment.

9.11 ANSWERS TO SAQs

SAQ 2

8 sec, 100 sec (as read from Figure 9.5)

SAQ 3

Bainite (follow the route in Figure 9.5)

SAQ 4

The plates can be preheated to higher temperatures before welding. This will reduce the rate of (cooling) heat loss through the heat affected zone.