
UNIT 4 MICROSTRUCTURE OF MATERIALS

Structure

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4.1 INTRODUCTION

In the earlier **Units**, we had been dealing with **materials** which are ideal. We have **seen** them to be absolutely pure and perfectly crystalline. **Ideality** does not exist in **day to day** life and ideal **materials** do not exist at all, Perfection in **crystallinity** is **ideal** and so is an absolutely pure **material**. We will be studying about **the deviations from crystallinity in the next Unit**. In this Unit, we will deal with more realistic **materials**. These are not absolutely pure. They may contain **more than** one "constituent" (**The word "constituent" is used to mean both the elements like metals or compounds**); each of **these** compounds **may** have different **physical form**. Each of these "constituents" may have different physical properties. The material consisting of these constituents may have a set of properties which **may** be different from any of **the constituent** compounds, though we can, at times, **think** of it as a result of contributions from the constituents. We shall deal with this real **material** which is "impure" and a mixture of different "constituents". If we leave a system consisting of different "constituents" together, which may or may not **chemically** react with each other, depending on the "**environment**", and provided sufficient **time** is given, we may end up with a certain combination of compounds with fixed **physical form**. Let us deal with the **rule** governing such an end state of the material. **This rule**, popularly known as "Phase rule" was developed by the mathematical physicist J. W. **Gibbs** in the nineteenth century. Even today, this is one of the most widely applied rules by the Materials **Scientists** and Engineers.

Objectives

After studying this unit, you should be able to:

- understand simple phase diagrams, .
- apply the phase rule to systems,
- calculate the **quantities** of different phases in equilibrium, given the overall **composition** and the phase **boundaries**, and
- explain how the **microstructure** is evolved under slow cooling of preheated materials.

4.2 MONOCRYSTALLINE AND POLYCRYSTALLINE MATERIALS : MICROSTRUCTURE

We had earlier discussed perfectly crystalline materials in Unit 2. We had seen their structures at the atomistic level. We had discussed the perfect periodicity in them. At the very first look we notice how far we are away from the reality. All real materials should have some finite size. Obviously, at the outer surface and in fact nearer the outer surface we should see that the periodicity of the crystalline material should be broken. However, these deviations are small, at least at this level of understanding of Materials Science. The material which is crystalline with complete periodicity within itself (excluding the vicinity of the surface) can be called **monocrystalline** or single **crystalline** material. We often come across mono or single crystalline materials in microelectronic devices, though they are not common in day to day life. If we look at this material under an optical microscope with a magnification of thousand, we may not observe any feature, if we confine our attention (field of view) away from the physical boundaries. If we use a more sophisticated microscope (electron microscope) with a magnification of about a million we may see some features, some defects (see next unit). If we observe one side of the material, by X-ray diffraction, we may see only one peak corresponding to one set of planes, the X-ray beam is exposed to. By rotating the material (single crystal) we may expose different planes and correspondingly, we will observe different peaks, but at no particular direction, we will see more than one set of planes.

Grains and Grain Boundaries

Let us take the piece of material discussed above (single crystal) and powder it using a mortar and pestle. We may see a large number of particles even with the naked eye. When we pick up one particle and observe it under a microscope at sufficiently large magnification, we will find that to be the same as the single crystal. If X-ray diffraction could be performed on your choice of particle, the results mentioned in the earlier paragraph can be observed. This particle is a single crystal, but of smaller size. When we look at the collection of particles made above, under a microscope, we see different facets of the single crystal exposed by different particles. When probed by X-ray, the collection shows multiple diffraction peaks corresponding to different planes. Now, let us compact the powder in a press into a pellet shaped material. Let us do this compaction such that it holds on together as a block. This pellet when observed under a microscope will be seen as a mosaic like structure, The X-ray pattern is more like the one of the powder. The pellet and the powder are the same as the starting material. This pellet consisting of many single crystals is called **polycrystalline** material. The pellet made above may have some voids/pores in between the particles. The overall density of the pellet will be less than the single crystal we started with. By a heat treatment on this pellet, it is possible to remove the porosity and obtain pellet with a density close to that of the single crystal. The heat treated pellet is also **polycrystalline** as it contains many single crystals, however small in their size. Each such Crystal is called a **grain**. The outer surface of the grain is **grain boundary** where it meets the adjacent grain. You have already learnt about the grain boundaries as a two-dimensional defect. Almost all the properties of the material, are grossly influenced by the way the polycrystalline material is structured at the microscopic level. The **architecture** of the material in the **microscopic** scale is called **microstructure** of the material.

We have used a single crystal to make a **polycrystalline** material in this section. You may note that it is difficult to make a single crystal of any material and invariably, one grows the single crystalline material starting with the **polycrystalline** material. Let us take some quantity of polycrystalline silicon. It melts at 1414 °C. The melt is contained in a quartz crucible. A seed (a small single crystal) is inserted into the melt and is slowly withdrawn. At the interface between the single crystal and the melt, growth occurs by freezing of the melt. Crystal growth occurs by successive addition of layers of atomic planes at the **interface**. As a result we get a large sized single crystal. This technique is called **Czochralski technique**. Here, the growth conditions are optimised to get a single crystal. When the conditions are not **optimised** and the melt is rapidly cooled, the melt will freeze into a solid. However, simultaneously several crystallites grow from the melt and we end up in a **polycrystalline** aggregate. In microelectronic circuits, we desire a single crystal in order to reduce the scattering of electrons at the grain boundaries. Nowadays, we use single crystalline **turbine blades** for achieving increased high temperature strength.

Say True or False

- i) X-ray diffraction pattern of the powder and that of the single crystal will be the same.
- ii) In a crystalline materials, periodicity breaks at the grain boundaries.

4.3 PHASE EQUILIBRIA

At the outset, it is worthwhile **learning some** definitions. A **Phase** is a portion of the material, which has physical boundaries within which, its chemical and the physical properties are invariant. In the introductory section we studied **about the** block of a single **crystal**, its powder, and a pellet made of the powder. All these belong to the **same** phase. All have the same chemical composition, the same crystal structure, irrespective of **the size** or **the** number of particles. These **materials** are said to be single phase **materials**. However, if we heat the said materials they melt and we have the same liquid in all **the three** cases (the block of single crystal, its powder, **and** a **pellet made** of the powder). **The structure** of **the** liquid is not **the same** as **that of these** solids. Though, **the chemical composition** of the liquid is the **same** as **that of the** solids, the properties **are different**. The liquid is a **phase** different from **that of the** solids. Further **heating** of the liquid might **result in** the formation of a gas (yet **another phase**). **Let us take this gas** and compress it at the **same temperature**. We are now increasing **the pressure in the system** at **the same** temperature. We observe that the gas is condensed into a liquid at **some** pressure. A phase change has occurred at **this pressure and** at the chosen temperature.

Component **refers** to the chemically distinct species and **the number of components** in a system is the **minimum number** of independent chemical species using **which the** composition of **the** entire system under consideration can be defined. Of course, **when** we say system, we mean what we look into at a given time. We may look at what happens to water as we **cool/heat/vary** the pressure over it. **This** we have already looked into. As we cool, **liquid** water **becomes** ice at 0°C and further cooling does not **alter** the **nature** of ice. As we heat water, it becomes steam (gas) at 100°C . We are doing all **these experiments** at atmospheric pressure. **What** do you think will happen if you **were** to do **the same** experiment on the top of **Himalayas**? Or say, in a vacuum chamber?

We are confining our attention to water **either in the form** of ice or **steam**. **The** composition of all these phases are the same—hydrogen **and** oxygen in the ratio 2:1. Does it **mean** we have a **two-component system**? No. We could have represented the composition of water or ice or steam as H_2O **only**. In other words, one species will do to represent the **composition** of all the **phases** under consideration. It is a one-components system.

In the above experiment what are the independent variables which we have considered? They are only the pressure **and** temperature. We could have as well varied a host of other variables such as gravitational field or electric field or magnetic field. Why? We could have added some **salt** to the water **and** varied the **amount** of salt and studied the effect of **composition** on the phase **transformations**. However, we chose a system wherein only the **temperature and** pressure are varied. So it is what we wish to consider **as** the system with the variables available to the system. The number of variables which we **can** vary independently without altering the number of phases in the system is called the degrees of freedom.

Having understood the meanings of the **terms**, phase, **components** and the degrees of freedom, we can go to a widely used rule relating the above for a system in equilibrium. **This** relationship is known as **Gibb's Phase rule** which can be given as :

$$F = C - P + N \quad \dots(4.1)$$

where, F is the degrees of freedom, C is **the** number of components, P is the number of phases **and** N is the number of variables which we wish to apply to the system. In practice,

we are interested more in the effect of temperature and pressure only on the system. Hence, we may rewrite the above equation as :

$$F = C - P + 2 \quad \dots(4.2)$$

and at times when we consider the effect of temperature at a fixed pressure (say atmospheric pressure) we may write it as :

$$F = C - P + 1 \quad \dots(4.3)$$

Equation (4.1) is a generalised relationship; (4.2) and (4.3) are what we use widely. This is true because variables other than pressure and temperature seem to have effect only on certain materials. Further, the effect of pressure is negligible on most of the materials which the materials scientists encounter and in all those cases we use the relationship 4.3. We need to remember that the later two are specific forms of the former where we fix the number of chosen variables keeping all other variables constant. Pure water can be heated at atmospheric pressure and/or can be pressurised in a certain region of temperature and pressure without changing the phase. We have two degrees of freedom. $C = 1, P = 1$ and $F = 2$, and the phase rule is found to be valid. When we reach 100°C at atmospheric pressure, it boils. We have both liquid water and steam coexisting in equilibrium. If we wish to maintain the two phases, for this one-component system, we cannot independently change pressure and temperature simultaneously. When we raise the temperature above 100°C , at atmospheric pressure, we reach equilibrium only when all the liquid is converted to steam. Or we need to pressurise the system to a value that is fixed by the temperature if we want to attain equilibrium having both liquid water and steam. We can have the freedom to vary one of the two variables (either temperature or pressure independently) if we insist on having two phases. Here again, one can apply the phase rule and find that the degrees of freedom is only one.

4.4 SIMPLE PHASE DIAGRAMS

The above relationships can be more easily condensed in a map called phase diagram. The axis of this diagram are the variables chosen for the system. You may note that conceptually we can think of n variables and the diagram can be an n -dimensional space diagram. However, for simplicity we can use a two-dimensional phase diagram, which can be easily represented in a sheet of paper.

4.4.1 One-component Systems

Phase diagram of one-component systems are the simplest of the phase diagrams. In this, the composition of every phase can be represented using one constituent. In other words, the composition is same throughout the phase diagram. The most common example of such a system is water. Let us look at the phase diagram of water given in Figure 4.1.

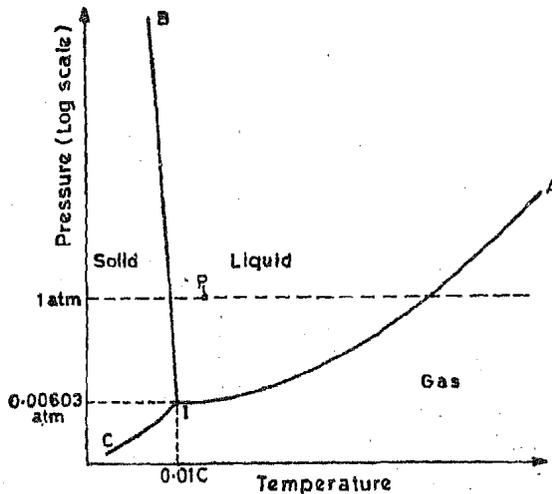


Figure 4.1 : Phase Diagram of Water

The variables chosen are pressure and temperature. It is a one-component system. The regions in this diagram are marked as the region of existence of the phases, namely solid, liquid and gas. The lines in this diagram are the phase boundaries, along which the two phases on either side of the line coexist. You may also note the point I, which is common to the three regions. At this point all the three phases coexist. Now, let us apply phase rule and check whether our observations discussed in the above paragraphs are stated in this diagram. At point P, ($T = 25^\circ\text{C}$ and $P = 1\text{ atm}$), water exists as liquid. When the temperature or pressure is changed by a small amount (say to $T = 27^\circ\text{C}$ and $P = 1.01\text{ atm}$) we still have water. We could change both the variables independently. That means the degrees of freedom, F at point P, is equal to 2. We find the same when we apply the phase rule for this one-component, single-phase system. Similarly, along the line PA, both water and gas coexist. This line shows the variation of the vapour pressure of water with temperature. It means that the pressure is automatically fixed at a given temperature, if we insist that both liquid and gas coexist. In other words, the degrees of freedom is only one along this line. You may find that the phase rule also leads to the same number of degrees of freedom. The point I indicates the temperature and pressure (0.01°C and 0.006028 atm) at which solid, liquid and gas are coexisting. The degree of freedom is zero. This point is called an invariant point in the phase diagram.

SAQ 2

Using the phase diagram of water, given in Figure 4.1, show that the food gets cooked faster inside a pressure cooker.

We may note that the pressure - temperature phase diagram of pure iron, shown in Figure 4.2 is similar to that of water.

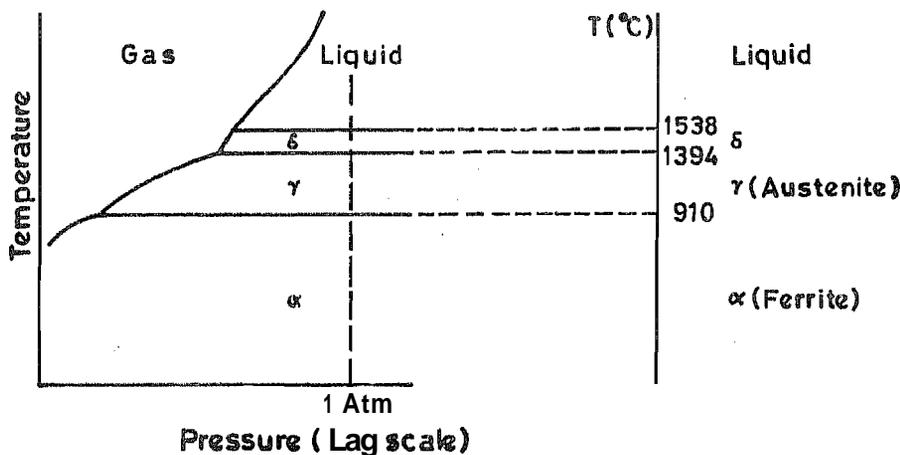


Figure 4.2 : Phase Diagram of Pure Iron

However, we find a few additional features. At one atmospheric pressure, solid iron exists in more than one form. Solid α , popularly known as ferrite, exists upto 910°C and above it transforms to γ form, austenite. Austenite exists upto 1394°C and above this temperature, converts itself into another solid, δ form. This solid melts at 1538°C .

SAQ 3

Identify the invariant points in the phase diagram of pure iron (Figure 4.2). What are the phases coexisting at these points!

phase boundary. Here **it is** the two-phase **boundary (solidus and the liquidus lines)**. If the overall composition has **to be still 20% only** to conserve the mass, the quantity of the two-phases **should be related to the** compositions of the two phases in equilibrium and that of the overall composition. It can be shown that the fraction of the solid will be QC/CD and that of liquid will be QD/CD . This looks like the classical lever with the fulcrum at the point Q. The relationship between the quantities and the lever lengths is called the **Lever Rule**. This rule is applicable to any two-phase region.

SAQ 4

Show from the mass balance, that the Lever Rule is valid.

Eutectic and Peritectic Systems

Let us now consider a case where, the two pure solids under consideration are immiscible in each other. However, in the molten form, they **mix** freely to **form** a liquid solution. These may form a phase diagram similar to one in Figure 4.4. In this Figure, L and M are the melting points of A and B, respectively. The melting points of both A and B **decrease** with the addition of the second component. Accordingly, the **liquidus** line follows the lines LE and ME with a minima at E. Above this line LEM (liquidus line), only a liquid exists. It is a **single-phase** region. Below **the** horizontal line, CED, there is no liquid.

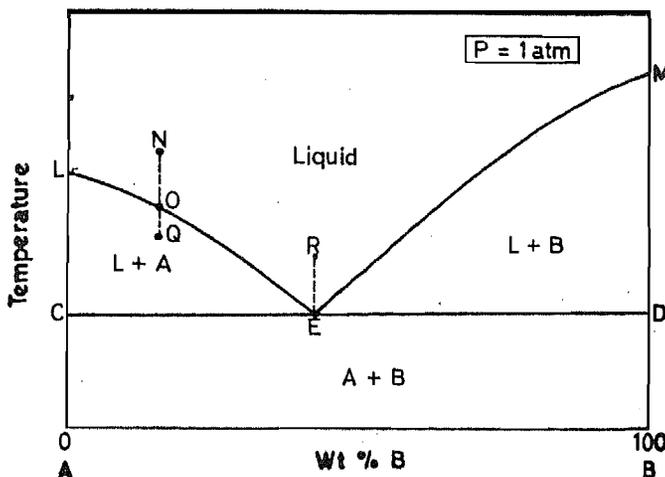


Figure 4.4: Binary Eutectic Phase Diagram without any Solid Solution

It is the **solidus** line. In the region between the **solidus** line and the **liquidus** line, we have a mixture of a liquid and a solid. In the region, between LE and CE, pure A and a liquid coexist and in the **region** between lines ME and DE, we have a mixture of a liquid and pure "B". Below the **solidus** line, the solid consists of two solids, pure A and pure B. (Do you recall that the phases are immiscible?) Now, let us consider what happens if we cool a liquid shown at point R. We have a liquid which remains a liquid **till** we reach the temperature corresponding to E. As we cross the line CD, we cannot have liquid. We should have pure A and B as a mixture of these two phases. What we have now is called a solid with eutectic microstructure with alternate layers of pure **A** and B. If a liquid at point N is cooled, it remains a liquid till we cross the **liquidus** line at O. As we cross, pure A is formed with a liquid richer in B. As we cool further and cross the **solidus** line, we get the eutectic microstructure. Please note that we cool infinitesimally slowly so as to have equilibrium throughout. We will see what happens if we cool rapidly later.

What if the solids are soluble in each other to a limited extent? **The** phase diagram shown in Figure 4.4 is slightly altered into Figure 4.5. You may note that a single phase region has extended from pure A **through** a region with **added** B. This is a single-phase region marked α . A similar situation exists on the other side (that of B). This is another single phase region marked β . Apart from these changes, the phase diagram remains the same. You may note **that**, in the two-phase field, below the eutectic, the two phases in equilibrium are not the **pure** A and B, but solid **solutions** α and β . The compositions of α and β in the **eutectic** solid at equilibrium at a given temperature are given by the points of intersection of the tie line at

that temperature with the boundaries of the solid solution regions. Al_2O_3 and ZrO_2 exhibit such a phase diagram (Figure 4.5).

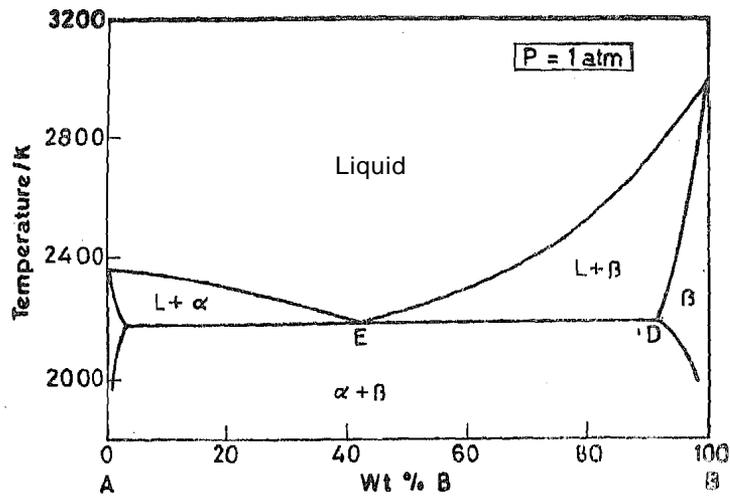


Figure 4.5 : Binary Eutectic Phase Diagram with Limited Solid Solution

So far we have discussed the constituents which do not react with each other. We may come across systems wherein the two constituents react to form a compound. Let us consider a case in which the two constituents, A and B do not dissolve in each other. The phase diagram of such a system with a compound AB is seen in Figure 4.6.

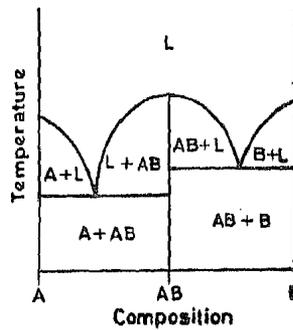


Figure 4.6 : Binary Phase Diagram with an Intermediate Composition

This is a case where the compound melts congruently. In other words, the compound melts without any decomposition and results in a liquid of same overall composition. The liquidus line has a maxima at the melting point of the compound. Here the compound AB is distinctly different from either A or B. If you look at the figure carefully, it is a combination of two eutectic systems put together, those of A-AB and AB-B systems. Each subsystem behaves like a simple eutectic system we had seen earlier in this section.

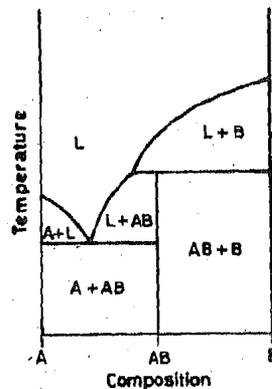


Figure 4.7 : Peritectic Phase Diagram where the Compound AB Decomposes before Melting (Incongruently Meets)

The compounds formed need not melt congruently. In some cases, the compound formed decomposes while melting (see Figure 4.7). In this case, the compound AB formed decomposes at temperature T_1 to give pure B and a liquid which is rich in A. This is a peritectic phase diagram.

SAQ 5

Apply phase rule to points N, Q and E in the Figure 4.4, and find the degrees of freedom at these points.

SAQ 6

Identify the invariant points in Figure 4.7. Identify the phases in equilibrium at these points.

At this stage you should have understood how to interpret the simple phase diagrams. Even the most complicated phase diagrams could be split into smaller and simpler modules and interpreted. In Section 4.6 we will see one of the most important phase diagrams, namely the iron-carbon diagram.

4.5 EVOLUTION OF MICROSTRUCTURE : NEAR EQUILIBRIUM CONDITIONS

In this section let us see how microstructural details of a material slowly cooled from the melt can be predicted from the phase diagram. Here we proceed near equilibrium conditions and the role of kinetics is played down. The slow cooling needs to be emphasised as the rapid cooling is likely to be dominated by kinetic factors.

4.5.1 Homogeneous and Heterogeneous Nucleation

Let us consider an element silicon. When the molten liquid is slowly cooled and when we reach the melting point, we should have both solid and liquid coexisting. But we did not have the solid till we reached the melting point. Further, if a solid crystallite is to be formed, we are increasing the surface energy of the system as we create more interface area between the solid and the liquid. On the other hand we are lowering the energy by the formation of the crystallite. These two considerations are acting in opposite directions as the increase in interface area increases the energy and the formation of the crystallite lowers the energy. The net energy change for the crystallite to nucleate, ΔG_n , is given by

$$\Delta G_n = 4\pi r^2 \gamma + \frac{4}{3}\pi r^3 (\Delta G_v) \quad \dots(4.4)$$

where, γ is the interfacial energy per unit area and ΔG_v is the crystallisation energy per unit volume and r is the radius of the crystallite nucleated. Of course, the nucleation will occur only when the overall energy is decreased. From the equation one can see that for small sized crystallite, called the nucleus, the net energy increases and beyond a certain size, the energy is lowered,

This is shown in Figure 4.8, where the energy changes are shown as a function of the radius of the nucleus. There is a critical size of the nucleus, r_c beyond which, it is stable and

shows a tendency to grow. It can be shown that the critical radius is equal to $\frac{-2\gamma}{\Delta G_v}$. This

process of formation of crystallite from the liquid is called homogeneous nucleation. The maximum energy ΔG_n at the critical size is the barrier for the nucleation.

The interfacial energy, γ , does not vary significantly with temperature, while, the crystallisation energy, ΔG_v , increases in magnitude much faster as the temperature falls. As a result, if we lower the temperature of the liquid well below the freezing point, the nucleation is spontaneous. It is also worth noting that as the temperature falls, the movement of atoms in the melt is slowed down and further growth of nuclei is reduced. As a result the size of the nuclei formed are small. You may note that we can choose the temperature in such a way to get larger size nuclei. When we introduce a seed into the liquid, we have already crossed the critical size requirement and under favourable conditions, the seed grows into a large single crystal.

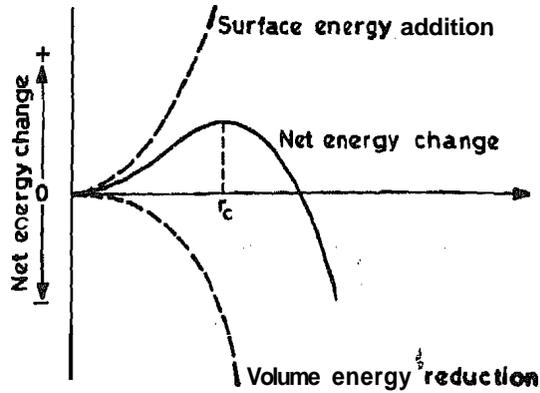


Figure 4.8

In the previous para we considered the case where the nuclei is formed inside a liquid. You might have noticed that the coconut oil solidifies first on the walls of the container in winter. This is because, the solid-liquid interface area increase is smaller when a part of the nucleus is touching the walls. Consequently, the energy barrier is smaller for such a nucleation. This is called heterogeneous nucleation and is more favourable than the homogeneous nucleation due to this reduces barrier.

4.5.2 Microstructural Evolution for Simple Systems

We have seen that even freezing may be controlled to form a fine grained solid or a coarse grained solid or even a single crystal. Here we have a single constituent that is solidifying. In other words, we have seen the freezing in a one-component system. What happens if we cool a liquid solution of A and B? Let us consider the Figure 4.3 as the appropriate phase diagram for the system and let us assume a slow cooling process. Let us consider a situation wherein the liquid solution corresponding to point O in this phase diagram is cooled slowly. Let us observe the system under a microscope as it is cooled. The liquid is featureless as it is uniform. At point Q we have a liquid with crystallites of solid with composition corresponding to point D. As we cool further the crystallites grow and when we reach point below R everything is solidified. We can see the different particles touching each other along the grain boundaries. Figure 4.9 gives the microstructures characteristic of the system

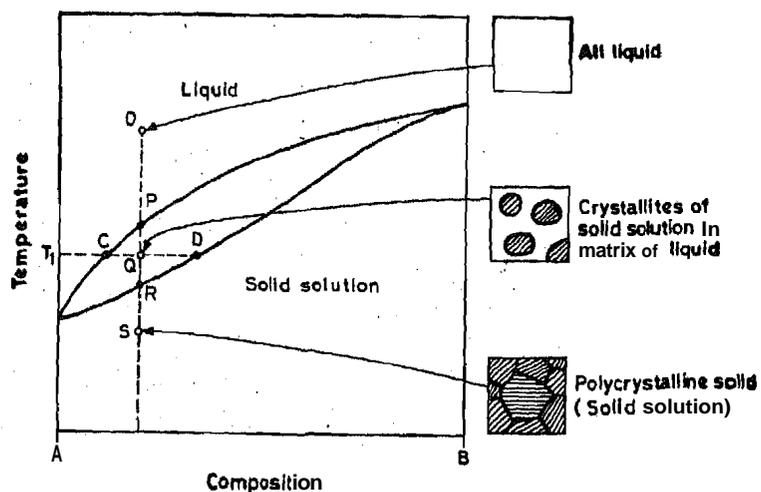


Figure 4.9 : Evolution of Microstructure as the Liquid is Cooled Slowly in a System which Forms Solid Solution

at the said points. This is almost the same as the single-component system as at each stage the readjustment of composition of the solid phase is not observed under the microscope.

Let us consider the case of a system which forms a eutectic without mutual solubility. Pure A or pure B are one component systems and the microstructure will be following the trend of one-component systems. We will find the microstructures numbered 3 and 7 in Figure 4.10. If we cool the liquid of eutectic composition, from point R, the moment we reach the eutectic the entire solid should solidify. But the two components are not soluble in each other. So we end up in alternating layers of A and B in the solid. This is a typical eutectic microstructure (shown as 5 in Figure). If we choose a composition other than eutectic composition but having both A and B, say point N, as we cross the liquidus, the solid A separates out. As we cross the solidus line, whatever liquid present separates out as alternate layers of A and B. This results in grains of pure A dispersed in the eutectic microstructure. This is shown as the microstructure 4. A similar situation prevails if a composition richer in B than eutectic composition is chosen. We get grains of pure B dispersed in eutectic microstructure (Microstructure 6). We will see how the rate of cooling can be exploited further to control microstructure in Unit 9.

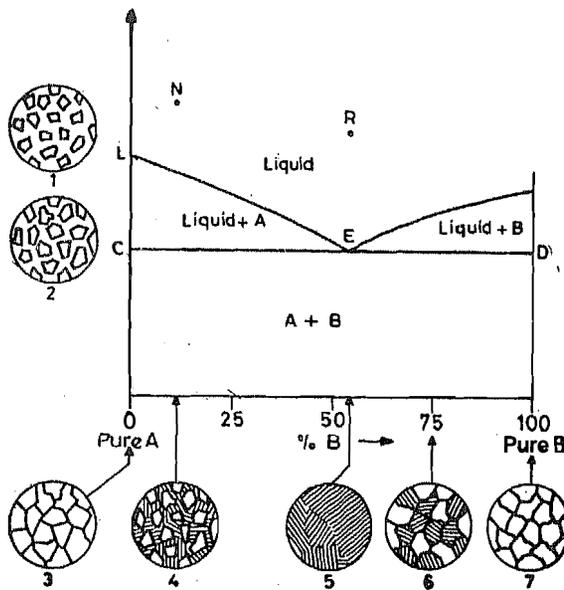


Figure 4.10: Evolution of Microstructure as the Liquid is Cooled Slowly in a Simple Eutectic System

SAQ 7

The melting point of a given solid is 1000°C . When the melt is cooled to 980°C , calculate the critical size of the nucleus. The interfacial energy is 0.64 J/m^2 . The energy of crystallisation is $-3.2 \times 10^9 \text{ J/m}^3$ at 980°C .

4.6 IRON-CARBON PHASE DIAGRAM

A part of the iron-carbon phase diagram is shown in Figure 4.11. It is actually iron-iron carbide phase diagram as it is the most useful part of the system. Though the system is Fe-Fe₃C diagram, the X-axis is not percentage Fe₃C. It is actually marked weight percent carbon. This transformation of scale is simply due to practical applications of weight % carbon in industry.

The main features are as follows: Ferrite (α) is stable till Carbon has a maximum solubility of 0.02 wt% in ferrite (α) at 727°C . Austenite (γ) can dissolve carbon upto 2.11 wt% at 1148°C . Beyond the solubility limits Fe₃C is formed. By suitable heat treatment a host of microstructures can be formed in this system and the properties of the alloy formed can thus be tailored. It is this variety and applicability which has made this into one of the most

utilised phase diagrams. We will look at the control of microstructure of this system by heat treatment in Unit 9.

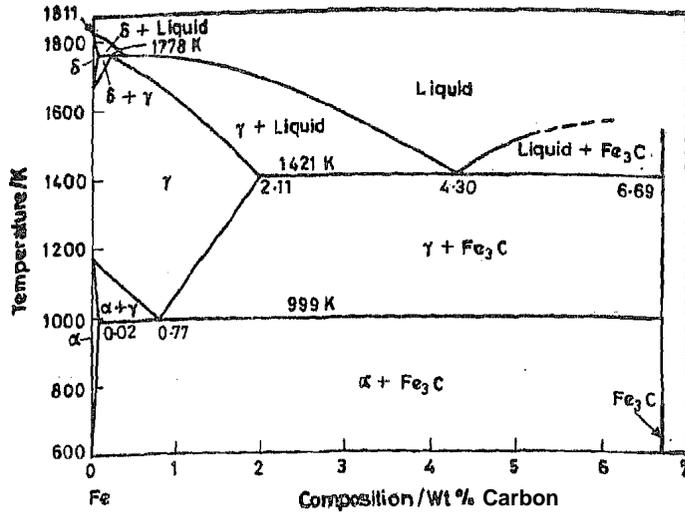


Figure 4.11 : Iron-Carbon Phase Diagram

4.7 SUMMARY

Materials can be single or polycrystalline. They may contain one or more than one phase. Under equilibrium conditions, "phase rule" relates the number of components, the number of phases and the number of degrees of freedom. Phase diagram shows the existence region of different phases which can be formed for a given system. Almost all the phase diagrams can be seen as the combination of some simple phase diagrams. We have learnt to read and understand some of these simple phase diagrams, such as the ones which form solid solutions, compounds, eutectics and peritectic. When a solid is heated to reach a liquid phase and cooled slowly, the microstructure of the solid that is formed can be predicted from the phase diagram. We have learnt to read and interpret the most important phase diagram—that of the iron-carbon system.

4.8 KEY WORDS

- Phase** : A Phase is a portion of the material, which has physical boundaries within which, its chemical and the physical properties are invariant.
- Component** : Component refers to the chemically distinct species and the number of components in a system is the minimum number of independent chemical species using which the composition of the entire system under consideration can be defined.
- The Degrees of Freedom** : The number of variables which we can vary independently without altering the number of phases in the system is called the degrees of freedom.

4.9 ANSWERS TO SAQs

SAQ 1

- i) False. X-ray diffraction of single crystal will show only the reflections from one set of parallel planes which are exposed to X-ray beam. In a powder, all possible planes are exposed in a random fashion, Hence all allowed reflections are seen.
- ii) True,

SAQ 2

Inside the pressure cooker, the pressure is more than one atmosphere and the phases coexisting are water and its vapour. From the phase diagram, the two phases coexist at higher pressures only at higher temperatures. So we are reaching higher temperatures than the boiling point of water and the food gets cooked faster.

SAQ 3

In a one component system, in order to have zero degrees of freedom, one should have three condensed phases in equilibrium (by phase rule 4.2). You may notice three such invariant points in the iron phase diagram (Figure 4.2). These are the points where α , γ and gas coexist, where γ , δ and gas coexist and where δ , liquid and gas coexist.

SAQ 4

Let us look at the point Q in the phase diagram with a complete range of solid solution (Figure 4.3). At this point, a liquid with composition corresponding to C and a solid with composition corresponding to D are in equilibrium. Let us consider a total mass of 100 g in which m_s is the mass of solid and m_l is the mass of liquid.

$$m_s + m_l = 100$$

Let X_l , X_s and X be the compositions of liquid, solid and overall composition at point Q. Mass balance requires

$$X_l m_l + X_s m_s = X (m_l + m_s)$$

This can be rearranged to give relative amounts of each phase as

$$\frac{m_l}{(m_l + m_s)} = \frac{(X_s - X)}{(X_s - X_l)}, \text{ and}$$

$$\frac{m_s}{(m_l + m_s)} = \frac{(X_l - X)}{(X_l - X_s)}$$

These two equations are the representation of the Lever Rule.

SAQ 5

In Figure 4.4, we note that it is a two-component system. At N, there is one phase (liquid) and the degrees of freedom is two.

At Q, there are two phases, a liquid and pure A, the degrees of freedom is one.

At E, there are three phases, a liquid, pure A and pure B; accordingly, the degrees of freedom is zero.

SAQ 6

In Figure 4.7, there are three invariant points.

SAQ 7

0.4 nm is the critical radius.