Welding Metallurgy
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Lecture - 03
Introduction to Phase Diagrams

Welcome to the lecture on introduction to phase diagrams. So, while discussing the welding metallurgy course, we very much need to know about the phase diagrams. Now, I hope that you must have some introductory knowledge about the phase diagrams in your initial courses related to material science and engineering or physical metallurgy. So, we will have an overview about the phase diagrams.

And in the subsequent lectures, we will also discuss about the phase diagram of ferrous system especially the iron carbon system as well as some of the important non-ferrous system also.

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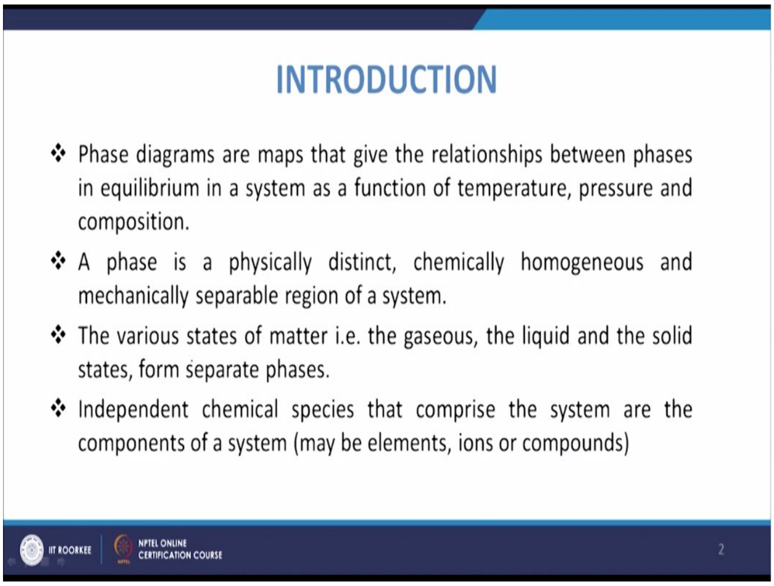

INTRODUCTION

- Phase diagrams are maps that give the relationships between phases in equilibrium in a system as a function of temperature, pressure and composition.
- A phase is a physically distinct, chemically homogeneous and mechanically separable region of a system.
- The various states of matter i.e. the gaseous, the liquid and the solid states, form separate phases.
- Independent chemical species that comprise the system are the components of a system (may be elements, ions or compounds)

So, coming to the introduction about the phase diagrams, as you know the phase diagrams are the maps that give the relationship between phases in equilibrium in a system as a function of temperature, pressure and composition. So, what we you know expect from phase diagram, what information do we expect, basically we are in need of engineering alloys. We know that in most of the cases, the pure metals or pure elements are less significant; having less significance as far as the engineering you know use is concerned.

So, what we do is we normally make alloys, we have to add a certain element to the parent atom you know element and then we have to see that how it will behave, how they are going to behave when they are combined and how the there is strengthening effect or which kind of reactions take place.

So, all that basically as a function of temperature, pressure and composition, so with the change in composition of one element or with the variation of temperature and pressure what you know what kind of phases we are going to get in the equilibrium condition. So, basically phase diagrams depict about all these things. Coming to you know definitions of the different terms like a phase.

So, phase is defined as the physically distinct, chemically homogeneous and mechanically separable regions of a system. So, that is you know the definition of a phase and you know now if we talk about the gaseous state or you know liquid state or solid state that is what the different states of matter is. When we talk about the gaseous phase, so since there is mixing at the atomic level, so we call it as a single phase.

Similarly, if you have a liquid solution, in that case we also call it as a single phase. Now many a times, so that is what we have that is gaseous, liquid and the solid, they are forming the separate phases. You have also independent chemical species, so we will talk about you know components, what is component, so the independent chemical species that comprise the system are the components of a system.

So, that is what is the definition for a component and it may be elements, ions or the compounds. So, basically there is a well-known rule given by the Gibbs and he has given the rule like $F=C-P+2$. So, that is you know the degree of freedom is defined as F so F is equal to C, so number of components minus P, so that is number of phases in the system and plus 2 but we will see that how that changes.

Because when we are dealing with these elements, what happens that many a times with change in temperature you know, we will see that how you know at one point you will see that there are many phases in equilibrium. So, you know and if you change the parameters like you have the external variables like pressure or temperature or composition in that case, how these changes in phases you know are incorporated that gets reflected from the phase diagrams.

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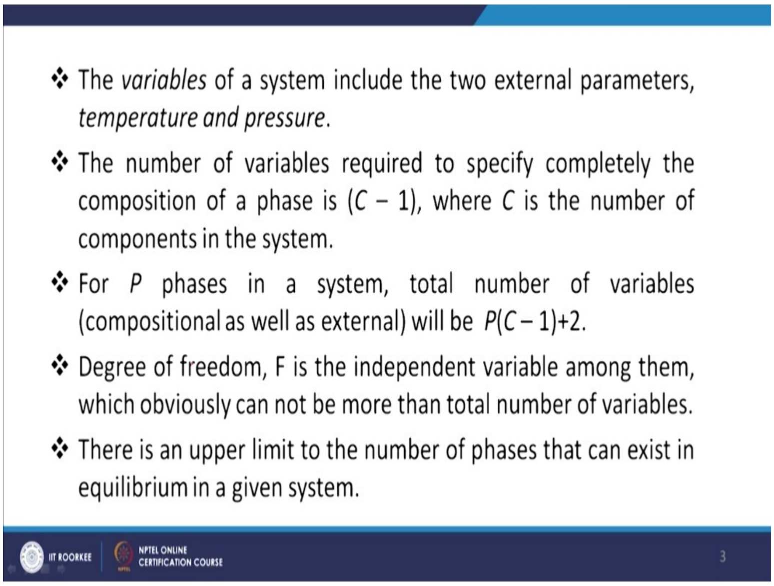

- The *variables* of a system include the two external parameters, *temperature and pressure*.
- The number of variables required to specify completely the composition of a phase is $(C-1)$, where C is the number of components in the system.
- For P phases in a system, total number of variables (compositional as well as external) will be $P(C-1)+2$.
- Degree of freedom, F is the independent variable among them, which obviously can not be more than total number of variables.
- There is an upper limit to the number of phases that can exist in equilibrium in a given system.

So, what we see that normally you have the variable of a system, you have normally two external parameters that is temperature and pressure. Now, if C is the number of component in the system, then the number of variables which are required to specify completely, the composition of a phase $=C-1$. So, if there are P phases in the system, then in that case that will be $P(C-1)$.

$C-1$ means that if you know the $C-1$you know components, then certainly you know the last component, so that is why the number of variables which are required to specify completely the composition of a phase that will be $C-1$and for P phases you will have $P(C-1)$ and if you take the other two external parameters that is temperature and pressure, then it becomes $P(C-1)+2$.

Now, degree of freedom that is defined as F, so it is the independent variable among them and this degree of freedom F it cannot be more than this total number of variables that is you know $P(C-1)+2$.

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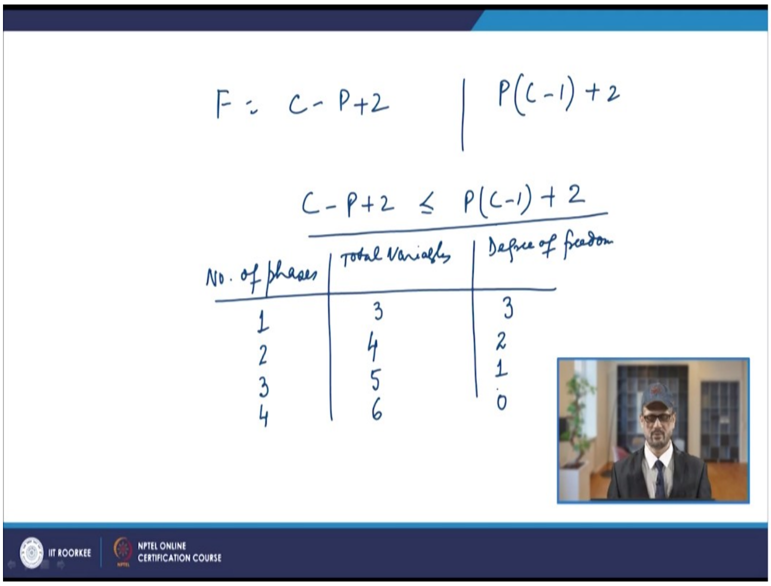

$F = C - P + 2$ | $P(C-1) + 2$

$C - P + 2 \leq P(C-1) + 2$

No. of phases	Total Variables	Degree of freedom
1	3	3
2	4	2
3	5	1
4	6	0

Now, according to Gibbs rule basically F is so Gibbs has given this $F = C - P + 2$ and here you get this $F = P(C-1) + 2$. So, basically this degree of freedom in that case so this cannot be more than total number of variables. So, basically $C - P + 2$, this cannot be more than $P(C-1) + 2$. So, what we can make out from this that if there is only one phase present that is P=1, in that case what you see that so in that case degree of freedom is equal to the total variable.

So, in that case, degree of freedom here it will be $C - 1 + 2$ so $C + 1$ and in this case also if P is 1, so it will be $C - 1 + 2$ so $C + 1$. So, degree of freedom will be equal to the total number of variables and as you increase the number of you know variables, so number of phases, so in that case if you increase that you know if these number of phases in that you must have you will see that there is an upper limit to the number of phases that can exist in the equilibrium.

So, basically when you will analyze these equations, you will see that how in the multi-component system, we have single component system or multi-component system, then in that case using this formula basically you can see that at any condition, at any temperature or pressure, you know what will be the degree of freedom. So, basically how you can change either, either you can change pressure or you can change temperature or you can change nothing of them.

Because in that case, the conditions will change, so that is basically being depicted by these phase diagrams. So, what we will see next will be if you look at this, so what we have got from here, so if you try to see that if you have if you try to analyze if you see that if your number of phases is suppose 1, in that case your total number of variables, so total you know variable that is $P(C-1)+2$, so you will have you know 3.

And if you have you know the degree of freedom, so you will see that degree of freedom value will be 3. Now, if you go for the number of phases as 2, so you know it will be so number of phase becomes now 2 here and in that case your this one for a two component system, it will be $2(2-1)+2$, so it will be 2+2 that is 4 and for a two component system if you take 2-2+2, so it will be 2.

So, normally for 3 phases, you will have the total variables is 5 and your degree of freedom becomes 1 and similarly you will have for the 4 phases, you will have 6 is the total number of variable and the degree of freedom becomes 0. So, that is how you can see that how many phases can be there and at some point you will have the degree of freedom as becoming 0.

So, we will see that how you analyze the single component system or the multi-component system and how you can discuss about you know the different traits of these phase diagrams.

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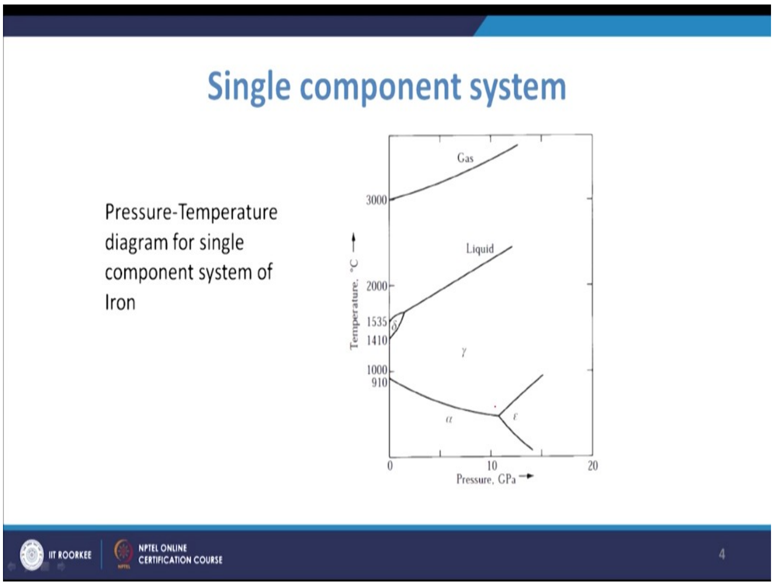

Single component system

Pressure-Temperature diagram for single component system of Iron

So, coming to the single component system; now in this there is no compositional variable and this is basically the pressure-temperature diagram for the single component system of iron and what you see that you have different phases that is α, epsilon, γ, δ and all that that is shown in such cases and now in the case of single component system, you can see the different points.

And you can find that what will be the degree of freedom at different points, so if you talk about so what you see is here this is for the iron and this is very clear that you have these are the solid phases and then you have liquid phase here and then you have gaseous phase at the top. So, when you are in this region you know in that case P is 1 and this is single component system.

So, if you go to the single component system and when your phase is 1, so degree of freedom will be C-P+2, so C is also 1 and P is also 1. So, in that case, you will have F as 2. It means your the degree of freedom is 2. So, basically you can independently vary as long as you are in that single phase region that is in this region or this region or this region or this region. So, you can basically vary either pressure or the temperature independently.

And you know you do not have you know you will be in that phase itself. Now, if you come to when your two phases are in equilibrium suppose and that is normally along a boundary suppose solid and liquid phase is there on that. So, now in this case, you will have two phases in equilibrium, so your P will be 2. Now, F will be C-P+2, C is 1 and P is 2. So, 1-2+2, so your degree of freedom becomes only 1.

Now, that means that if you are changing, you can independently change the temperature but then the pressure will automatically change, so that you are still in that phase that is your two-phase region that is around normally along the boundaries. Now, if so in that case degree of freedom becomes 1. Now, if you talk about you know three phase equilibrium, so three phase equilibrium suppose it is at this point suppose say, now in that case your phase is 3.

So, C-P+2, so P is 3, C is 1 and so 1+2-3, so in that case it becomes basically F is 0. It means your degree of freedom is 0, so if either of you know these parameters if you change either temperature or pressure, in that case you are basically going into the different phase region. So, you will not be at that point, so normally that is indicated by a point, so that is you know three-phase region. So, this is about the single component system.

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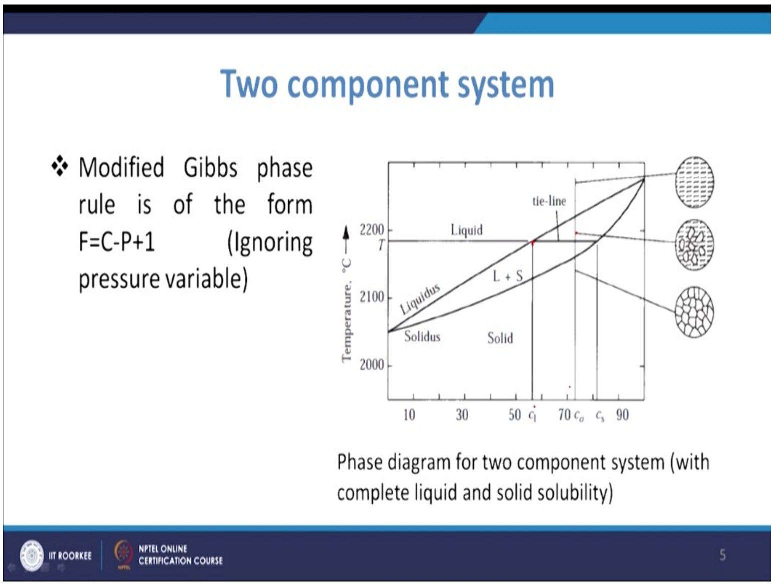

Two component system

- Modified Gibbs phase rule is of the form F=C-P+1 (Ignoring pressure variable)

Phase diagram for two component system (with complete liquid and solid solubility)

Now, if you come to a two component system, now in this case basically you will have 3 you know components which are to be looked into as simultaneously. One will be temperature, another is pressure and the third is composition. Now, that can be seen only on the 3-dimensional graph. So, what we do normally is that we ignore the pressure; we take only temperature and composition.

So, basically the Gibbs phase rule that is F=C-P+2, so in that case that +2 will be replaced with +1 because we are ignoring the pressure because pressure does not, pressure is seem to not do much of the changes. So, ultimately you know for two-component system, the phase diagram looks like this. So, F=C-P+1. Now, what we see is that normally we can go for a phase diagram of one system where there is complete liquid and solid solubility.

So, in that case, this is how the phase diagram looks like. So, what we will see that what we are seeing here that in this case, you have this as the liquidus line and this is the solidus line. This is the liquid and this is the solid, so normally this is typically for that type of phase diagram where the two materials, two components you know have the solid as well as the liquid complete solubility in them.

Now, what is you know clear from this you can see that when you are decreasing the temperature from this point, at this point the whole you know domain is liquid. Now, when you come to this zone, this is the liquidus line and this is the solidus line, so the solidus line is separating that solid part with the liquid plus solid zone and the liquidus line is separating the liquid part with the liquid plus solid zone.

So, when it is coming you know below this, the temperature is coming below this point, in that case the solid will crystallize out and so what we see is that apart from liquid you have also crystallized solid you know phases and then you have liquid also and once the temperature reaches below this solidus line, in that case it completely becomes solid state. Now, what we need to know in this case is that you can see that you have two components.

One component has the melting temperature at this point; another component has melting temperature at this point and as this component percentage increasing you can see that its liquidus temperature will be going on changing. Now, in this case, we need to know a few things, one is you know when we are coming to different points, then the solid which will crystallize and now this solid will have what composition and also what will be you know its fractional you know part that is formed.

So, basically this is known as the tie-line and this tie-line is basically talking about the composition. So, the tie-line will tell you what will be the composition of the liquid and what will be the composition of the solid. So, based on the tie-line you know so tie-line is you know meeting here and at this point liquidus point here and the solidus point here.

So, depending upon the tie-line touching, your liquid and the solid compositions will be so that is what you see, if you have the melt of composition C_0, when it reaches to this point, at this point this tie-line is touching the liquidus line at this point, so corresponding to this point this is the composition of the liquid. So, at this point, you have liquid as well as the solid zone.

Now, the liquid zone will have the composition C_l and the solid formed will have the composition C_s and accordingly when you are coming at this point is completely solidified, it will have the composition of C_0. So, the tie-line will tell you the composition of the phases. Now, another thing is that what will be the amount of solid formed at a particular temperature.

So, that is you know being calculated with the help of lever rule. Now, the lever rule tells that you know if you have this point you take as a fulcrum of the lever, so the fraction this upon whole will be the you know part of this solid and the fraction this upon the whole will be telling you about the part of the liquid which is there. So, basically the line it is you know touching the liquidus line.

So, this part this fraction will be the fraction of the solid form and this fraction will be equal to the fraction of the liquid. So, that you know these are the two things which we know from these you know phase diagrams. The tie line and the lever rule, these two you know principles are used to find the composition as well as the amount of the solid or liquid you know phases which are there, so that is formed.

Now, in this case also, we can apply this Gibbs phase rule to find the degree of freedom and if you look at the region that is if you take the single-phase region that is either solid or liquid, in that case you know that is if you put component is 2, so 2-1+1, so that will be degree of freedom will be 2, so you can independently vary either pressure, so you will have 3 variables here.

So, temperature, composition of phase 1 and composition of phase 2, so you know you can vary any of the two independently you know so that it is there. Whereas if you go to the two-phase region, again in the two-phase region basically you will have 2-2+1, so there will be only once if you vary one, so one of the compositions will be changed. So, it is in the same way it can be interpreted as you know we have seen in the case of binary system.

Now, in this case of complete solubility in the binary system, you do not see a point where the degree of freedom is 0, so that is what is seen. Now, when we talk about these you know binary systems, now in such cases what we see that we see many a times the invariant reactions and you know.

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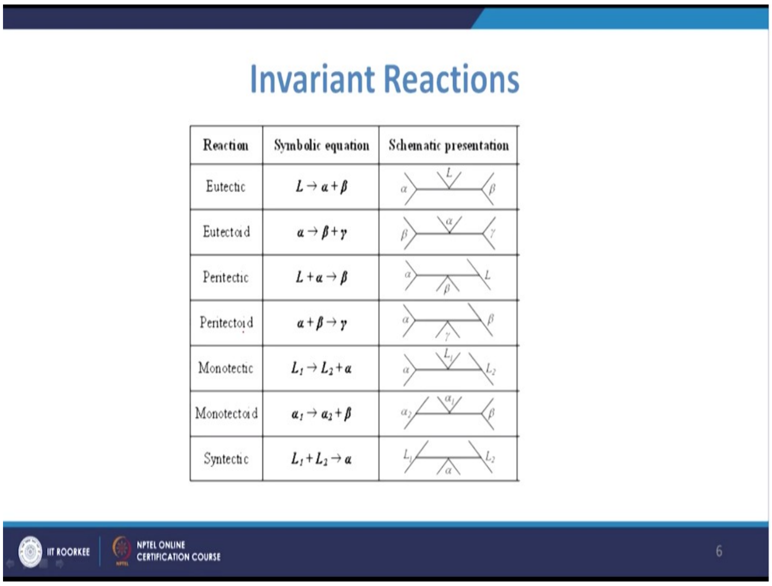

Invariant Reactions

Reaction	Symbolic equation	Schematic presentation
Eutectic	$L \rightarrow \alpha + \beta$	α L β
Eutectoid	$\alpha \rightarrow \beta + \gamma$	β α γ
Peritectic	$L + \alpha \rightarrow \beta$	α L β
Peritectoid	$\alpha + \beta \rightarrow \gamma$	α β γ
Monotectic	$L_1 \rightarrow L_2 + \alpha$	α L_1 L_2
Monotectoid	$\alpha_1 \rightarrow \alpha_2 + \beta$	α_2 α_1 β
Syntectic	$L_1 + L_2 \rightarrow \alpha$	L_1 L_2 α

So, what happens that if you look at the phase diagrams, these are the different invariant reactions which are taking place at a particular temperature and you have the different invariant reactions like eutectic, eutectoid, peritectic, peritectoid, monotectic, monotectoid and syntectic. So, mostly you will have the first 5 which you will normally be looking at. Now, in this case, you will have you know transformation from one phase to others.

So, liquid will be converting to α+β that is in the case of you know this you will see at many places, you will have the eutectic reaction taking place, the liquid is there and it will be solidifying at a particular temperature and it will make mixture of two you know solid phases α and β. So, normally what you see is in the case of iron-carbon system, it is at about 1137 °C or 1140 °C.

In that case, the liquid is basically so if you look at so we will deal with you know the iron-carbon system and what we will see so.

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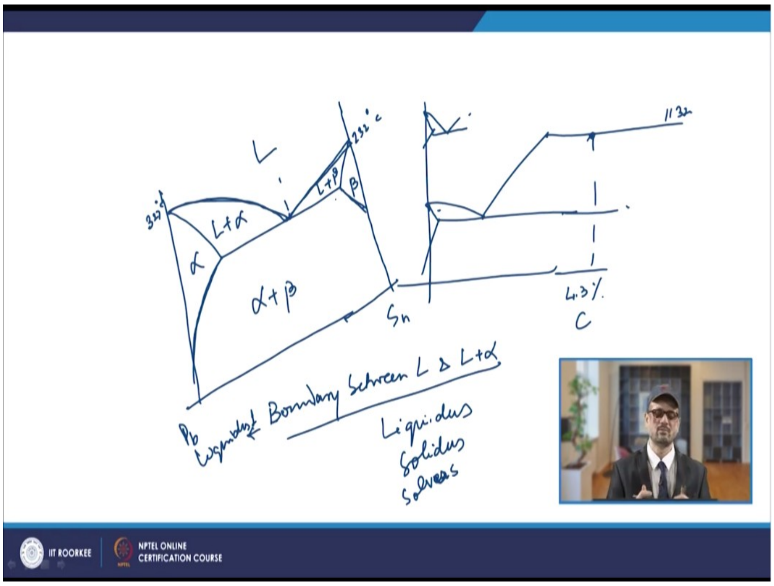

Now, in this case, so this way you know so this is 1137 °C. Now, in this case here this is at 4.3% of carbon. So, here basically you will have the austenite plus cementite these two mixtures. So, in this side you will have γ and in this side you will have Fe_3C. So, that will be formed and you will have this side as the liquid, so that is your eutectic reaction and in many cases in many systems you will come across.

So, while cooling the liquid will be converting to two solid you know mixtures, liquid is converting to α+β. Similarly, when you heat the α+β will be heated and ultimately at a particular temperature your liquid will be formed. Similarly, in the case of eutectoid reaction, you will have α converting to β+γ. You have a solid phase and this when you are cooling, so it is giving you the β+γ phase.

So, this is happening in the case of iron carbon system also and in this case you know austenite while being cooling; it will lead to the ferrite+cementite. So, that is how you know you have these eutectoid reactions taking place. Apart from that, you have peritectic reaction where the liquid+α, so that upon cooling will so liquid+one solid phase will give you the another solid phase.

And while if you heat, the solid phase will you know be converting to one liquid+one solid phase. So, that is your peritectic reaction. Similarly, in peritectoid reaction, you will have two solid phases and that will be once you cool, in that case it will be giving you another solid phase and reversibly it will be going on for the while you heat it.

So, accordingly as you see you know you must have the understanding about these things that when you are cooling, so in this case at this point these reactions take place and you are getting liquid to α+β, α to β+γ, so α+liquid to β, similarly α+β to γ, α+liquid will be to α+another liquid, α 1 is α 2+β and similarly liquid 1+liquid 2 will be on cooling will be making you the α.

So, these are you know different invariant reactions and they will be you know we will be facing these invariant reactions you know as we discuss the different types of you know the phase diagrams either be it for the ferrous system or the non-ferrous system. Now, you will also, you may also come across certain type of phase diagram when the solid solubility is limited in that case and also the melting point of the you know components they are not vastly different.

In that case you know eutectic type of phase diagram will be obtained and that will be so if you can have the typical example which you can see will be basically the lead-tin phase diagram and what you see in this case, the phase diagram will be like this. So, what you see here, now in this case you will have so this is type of you know phase diagram which is there for the lead-tin.

So, you will have Pb and Sn. Now, in this case what you see this is the example of the, so this point what you see, so you will have this is the α phase and this is your β phase. So, what you see is your this point, so this is your liquid and this is something like 327 °C and you will have this case is this is to 232 °C. Now, in this case, what you see is this portion will be liquid+α and similarly this will be liquid+β.

Now, in such systems and here it will be α+β. Now, this point as we discussed, this point will be your eutectic point because this liquid composition when it comes at this point, so after this point when it solidifies, it will make you the α+β. Now, in these cases, you have liquidus line, so liquidus line will be the line between the liquid and the liquid+α zone.

So, your this line that is boundary between L and L+α, so boundary between L and L+α, so that will be you know the liquidus 1. Similarly, liquidus 2 will be boundary between L and L+β. So, that will be your liquidus 2. Similarly, you will have solidus line and solidus line will be basically solidus 1 and solidus 2. Now, solidus line is normally between α and you know L+α.

So, you will have α and L+α, similarly β and L+β that will be your solidus line. So, this is your liquidus line, this is your solidus line. Apart from that, you have also solvus lines, so you will have liquidus line, you will have solidus line and also you have solvus line and the solvus line is basically, so solvus line is basically boundary between α and α+β.

So, these lines α and α+β or β and α+β, so these lines are known as the solvus lines. So, normally you must know that in such cases what these lines are known as, so these will be your liquidus lines, L and L+α, similarly L and L+β you will have liquidus lines, similarly you will have the α solid phase and L+α that line, so that will be α and L+α will be your solidus line, here also you have solidus line.

And then if you talk about you know the α and α+β zone or β and α+β zone, in that case these lines will be talking about the solvus lines. So, these are some of the characteristics of the phase diagrams and we will be discussing about the phase diagrams of ferrous system as well as non-ferrous system because we need to have you know some overview or you know you must be able to refresh what we have studied in our earlier years.

And then this basically knowledge will be utilized when we talk about other welding metallurgical considerations or points when we go and study the different phenomena. So, that is about you know phase diagram and we will further read about, we will further study about you know or interact about these phase diagrams of ferrous as well as non-ferrous systems in our subsequent lectures. Thank you very much.