Basics of Mechanical Engineering-2

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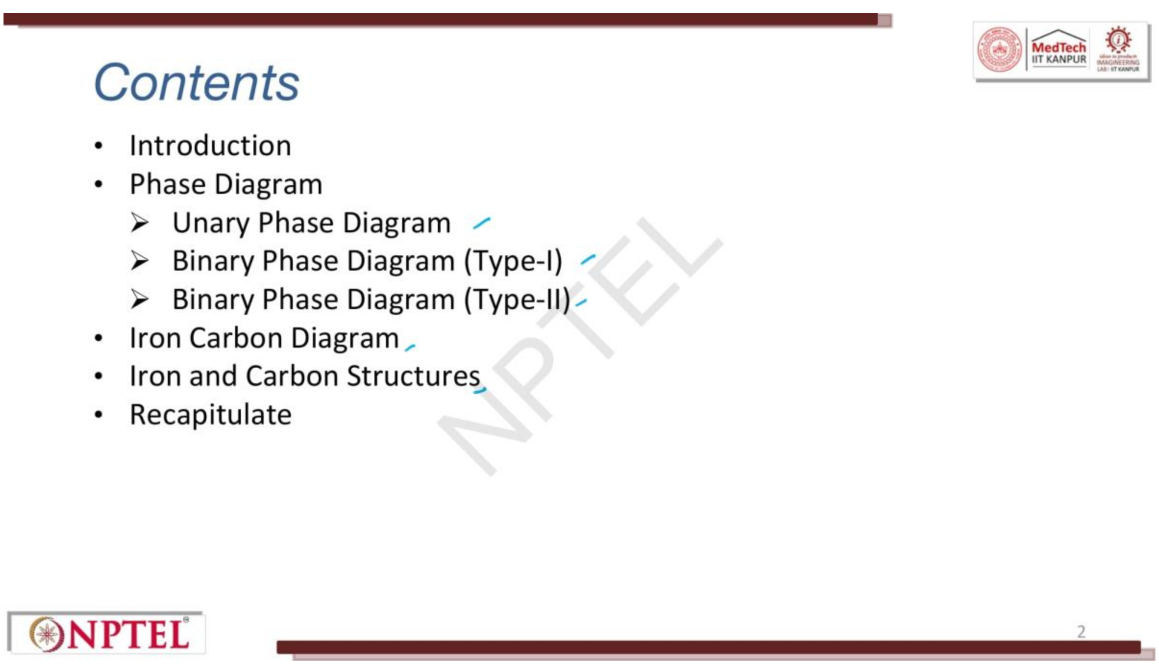
Week 02

Lecture 06

Phase Diagrams

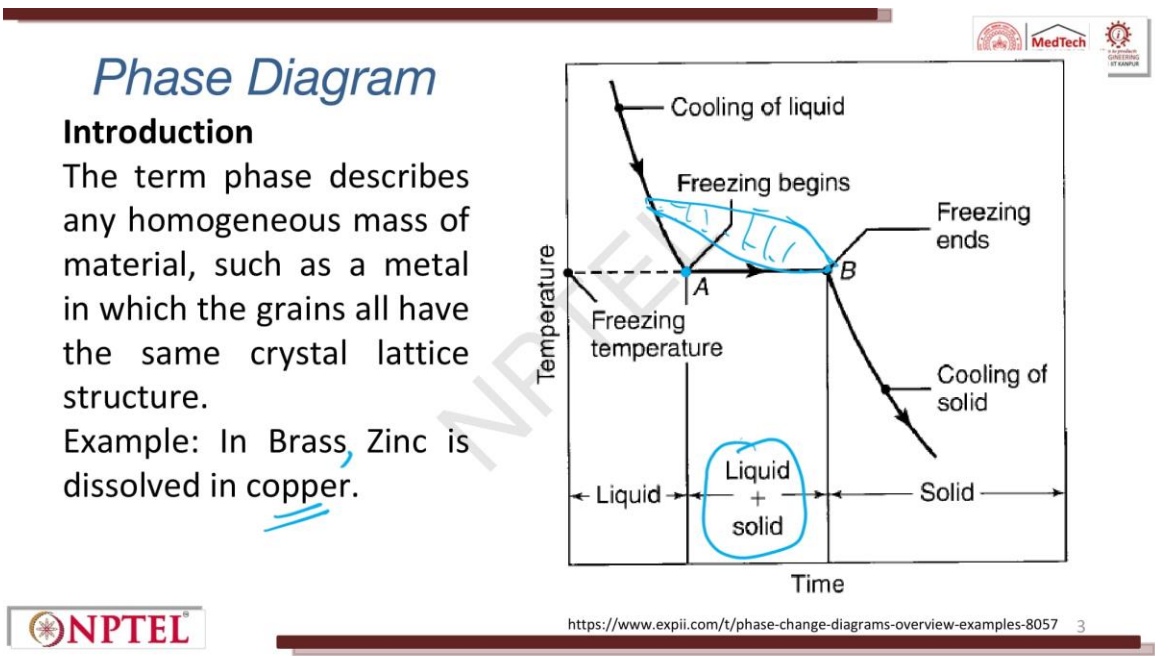
Welcome to the next lecture on Phase Diagrams. In the previous lecture, we were more focused on atoms, the arrangement of atoms, the atomic packing factor, coordination number, and all the Bravais lattices, the seven different types of Bravais lattices. We were trying to understand more from the atomic or microstructural level. Now, let us try to move towards different phases.

What will happen when the same metal is taken to a higher temperature? It gets into a liquid phase, then it gets into a solid phase on cooling. So this is also an important lecture when we try to understand the processes in the future.



In this lecture, we will try to have an introduction. Then, there are several phase diagrams, but we will try to categorize them into three simple ones and try to take Unary Phase, Binary Phase Type 1, Binary Phase Type 2. The Iron-Carbide Diagram is the most popular phase diagram which is being used in academia.

So we will try to see the Iron-Carbon Diagram. Then, Iron-Carbon Structures. Finally, we will try to have a recap.



If you look at this graph, you will try to see there is an overlap of information with the graph which we saw in the previous class. Volume divided by unit weight with respect to temperature.

Do you remember that? Where we had a sharp change in the melting point. So, the same curve, when plotted with respect to temperature versus time for a pure metal, you will see a response like this. So, the melting point starts here, right? Above this, when you try to increase the temperature, the metal will be in liquid form.

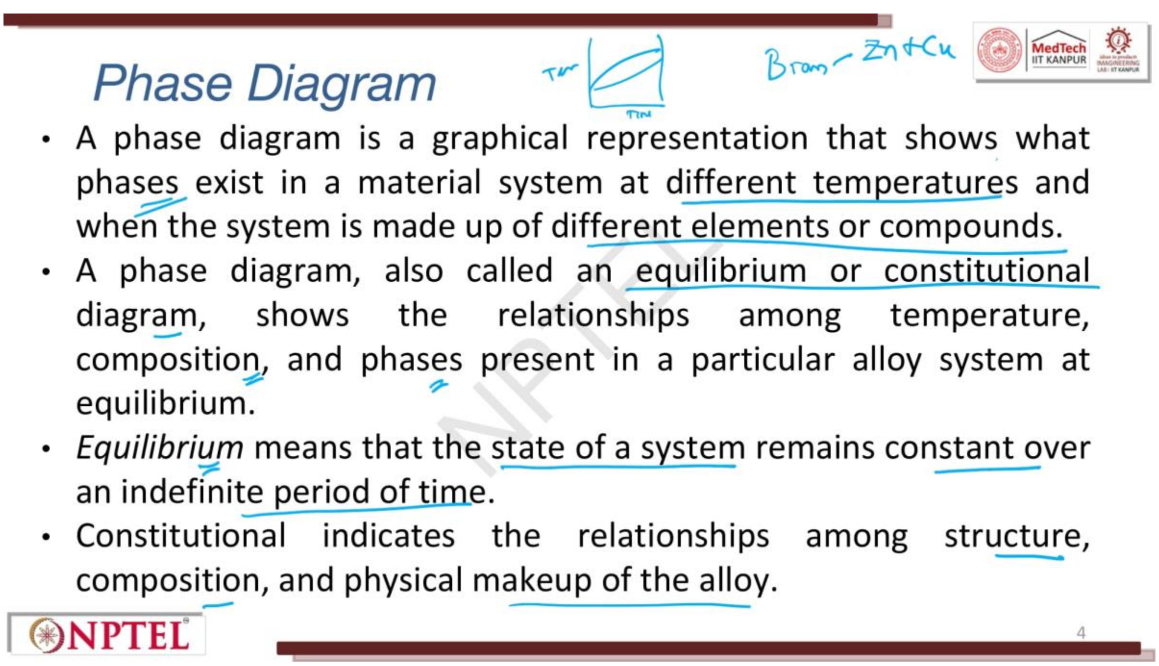
Then, after this point, it starts solidifying. When it starts solidifying, you will have a mixture of liquid and solid. When it crosses the freezing end, it becomes solid. So now, in the liquid phase, you will not have much discussion about crystal structure and other things. But, once it enters from the freezing beginning to the freezing end, you will have a mixture of liquid and solid.

When you try to make sugarcane syrup, you will observe as it solidifies from liquid to solid. So, basically, how do you make sugar syrup? You take solid sugar, add water to it, and boil it. The moment the water boils, the sugar dissolves, and then you have something like a viscous material. When this viscous material is allowed to solidify, it will have a mixture of liquid and solid.

You would have seen on the skin, on the top, right? Liquid, something like that, a solid will be floating on a liquid. So, a similar thing will happen when it tries to solidify. So, you will try to have liquid plus solid. So now, what are the phases which happen there, and how is it going to bring a difference, is what we will try to see.

So this graph is for a pure metal. When you have an alloy, you will not have a sharp response, but you will have something like this response. The melting point, you will have a zone, not like a discrete point. The term 'Phase' describes a homogeneous mass of material such as metal in which the grains are the same crystal structure. For example, in brass, zinc is dissolved in copper.

This is an alloy. The phase describes any homogeneous mass of material. Such as metal in which the grains all have the same crystal lattice structure. The Phase Diagram. So this, temperature versus time, this we will try to see is a phase diagram.



A phase diagram is a graphical representation that shows what phase exists in the material system at different temperatures and when the system is made up of different elements or compounds. In a phase diagram, you will try to have temperature versus time. What are all the different phases that are getting formed? A phase diagram is a graphical representation that shows what phase exists in a material system. In a material system, we saw brass, in which you have zinc plus copper.

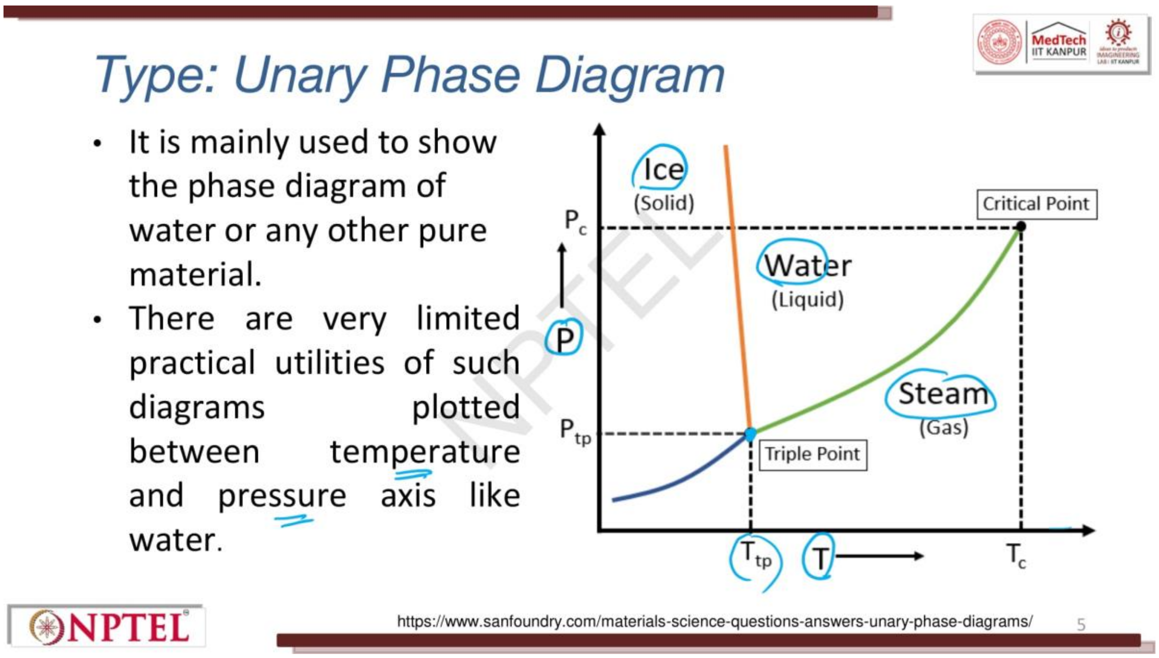
Then, the system is made up of different elements or compounds. A phase diagram is also called an equilibrium or constitutional diagram. So, a phase diagram is sometimes called an equilibrium or constitutional diagram. Why is it said constitutional? We will try to see solid, liquid, and what are the phases coming there.

It shows the relationship among temperature, composition, and the phase present. Why is composition important? Because if, let us take an example of carbon and iron. Now, what is happening? At the carbon, atoms are small.

The iron atoms are large. When you see the unit cell, the carbon atoms diffuse into the unit of iron. So that is the amount, that is the composition. So at various temperatures, the composition and phase present in a particular alloy system at equilibrium will be seen from the phase diagram. We keep on repeating the term called equilibrium.

What does equilibrium mean? Equilibrium means that the state of a system remains constant over an infinite period of time is called equilibrium. The state of a system remains constant. The state, right? The state of a system.

The constitutional diagram indicates the relationship among the structure, composition, and physical makeup of the alloy. So, understanding the phase diagram is very important. Because it is going to give you the time-temperature relationship for different elements. And then, it also tries to tell in a particular alloying system what it tries to say. Then, constant over an infinite period of time.



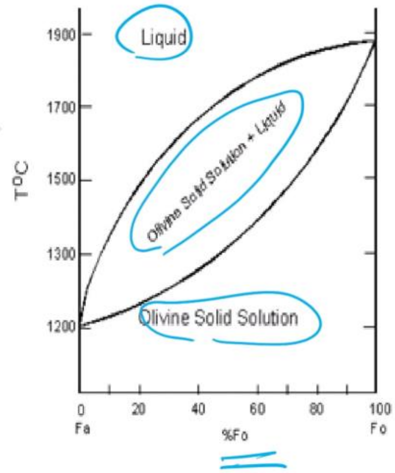
Unary Phase Diagram. This is a very famous phase diagram in which ice gets converted into water, and then that gets converted into steam. The x-axis is temperature. So you have Tp (Triple Point) here and Tc, the critical point here. So this is pressure.

So ice, as you increase the temperature, the solid becomes a liquid. That liquid becomes water, and then steam. So if you see that, there is something called the triple point. This triple point is always very important because we try to play with pressure. It is mainly used to show the phase diagram of water or any other pure material.

There are very limited practical uses of such diagrams plotted between temperature and pressure. Because when you change the pressure, water also gets converted into steam. So this is just an example, or this exists only for water and some other pure materials. Very seldom do we use it from the materials perspective or the manufacturing point.

Binary Phase Diagram

- It is used for two components.
- These diagrams are further divided into 3 categories.
- The materials which are completely soluble in the liquid as well as solid state.
- The material that is completely soluble in the liquid state but partially soluble in the solid state (Eutectic phase diagrams).
- The materials which are completely soluble in the liquid state and completely insoluble in the solid state.



https://www.sanfoundry.com/materials-science-questions-answers-unary-phase-diagrams/

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Binary Phase Diagram means there are two components, Bi, there are two. These diagrams are further divided into three categories. The material which is completely soluble in liquid as well as in solid state. So liquid. So here, it is olivine solid solution. So here, it is olivine solid solution plus liquid.

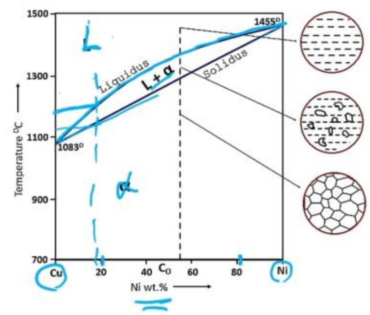
So here, it tries to talk about temperature with respect to some percentage. So the material which is completely soluble in liquid as well as in solid state. The material that is completely soluble in liquid state but partially soluble in the solid state is called a eutectic phase diagram. So here, it will be completely liquid, here it will be completely solid. So here, it will be liquid plus solid.

The material which is completely soluble in liquid state and completely insoluble in solid state. So you can exist in three.

Binary Phase Diagram

Type-I

- The materials which are completely soluble in the liquid as well as solid state.
- The line that separates the liquid phase from the mushy zone is called liquidus.
- The line that separates the mushy zone from the solid phase is called solidus.
- On such a phase diagram solidification takes place over a range of temperatures.



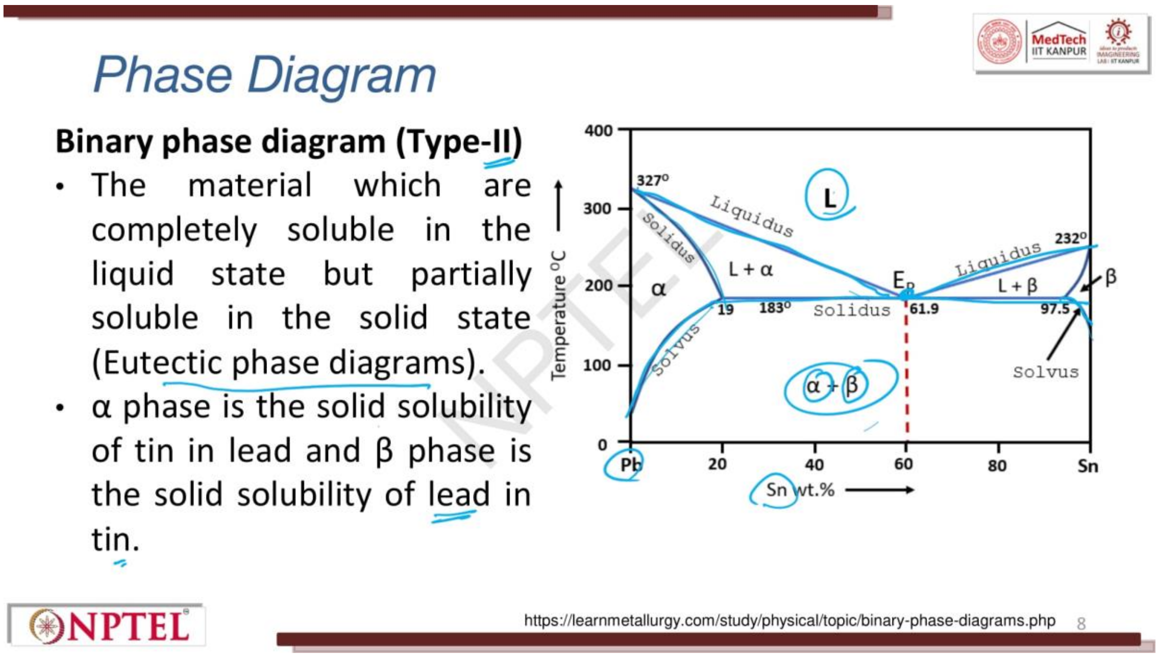
So in binary phase diagram, type 1. So temperature versus composition we have taken. So here, we are trying to take copper, here we are trying to take nickel.

So the nickel weight percentage is observed. So a nickel weight percentage of 20 means 80% is copper. If it is 80% nickel, it means 20% is copper. So we are trying to understand at what temperature, what composition, and what microstructure phases you can observe. The materials that are completely soluble in both liquid and solid states.

The line that separates the liquid phase from the mushy zone is called the liquidus line. So this line is called the liquidus line because it is liquid, and at this line, it tries to distinguish itself into liquid plus α, right? And this is the start of the mushy zone. The end of the mushy zone is where you get the solidus line. So inside this mushy zone, you will always have liquid plus solid.

So the liquid is L, the solid is α, then L plus A is the mushy zone, L plus α. So, at varying temperatures, we know, for example, I can try to take 20%, you will have around 20%, when the nickel is 20%, around 1200 or 1150 or 80, if you try to heat it, it will form a liquid. And when it goes around 1120 or 30, you will see the solidus line forming. When the composition changes, you see the temperature offset happens, and you can see the mushy zone also trying to form. The line that separates the mushy zone from the solid phase is called the solidus line.

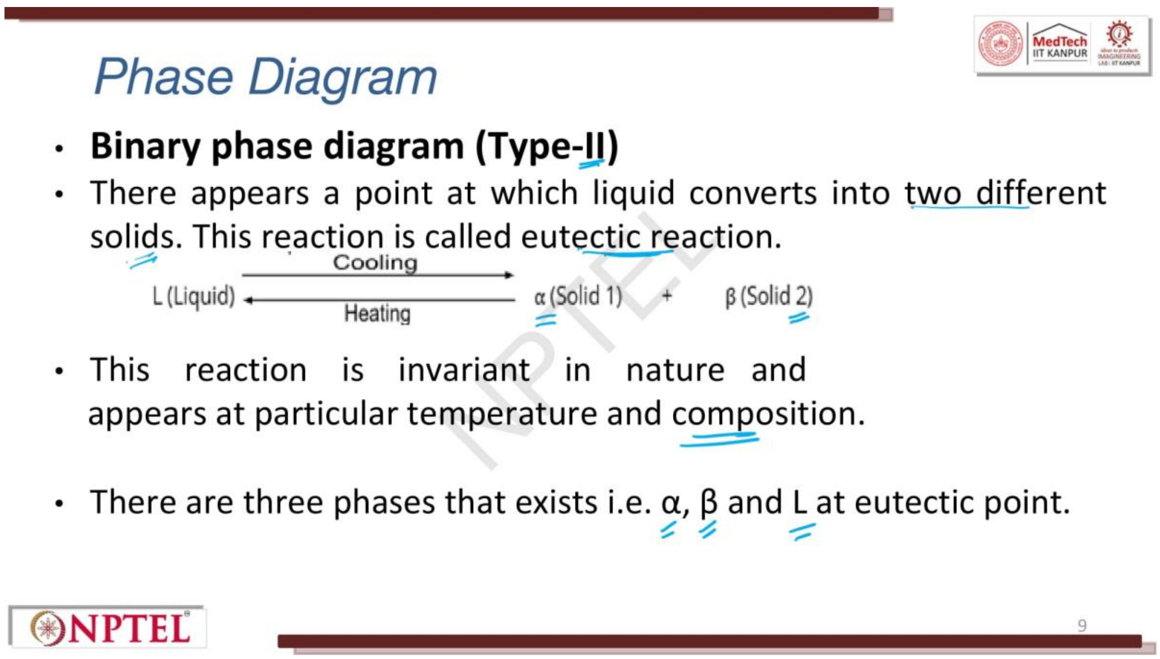
On such a phase diagram, solidification takes place over a range of temperatures. This is what I said: solidification takes place over a range. In a pure metal, it will be a straight line, one point. But here, it will be a range.



So when we try to take a binary phase diagram type-2, you can see here like solid, this is a liquidus line, this is a liquidus line, right? And this is a solidus line.

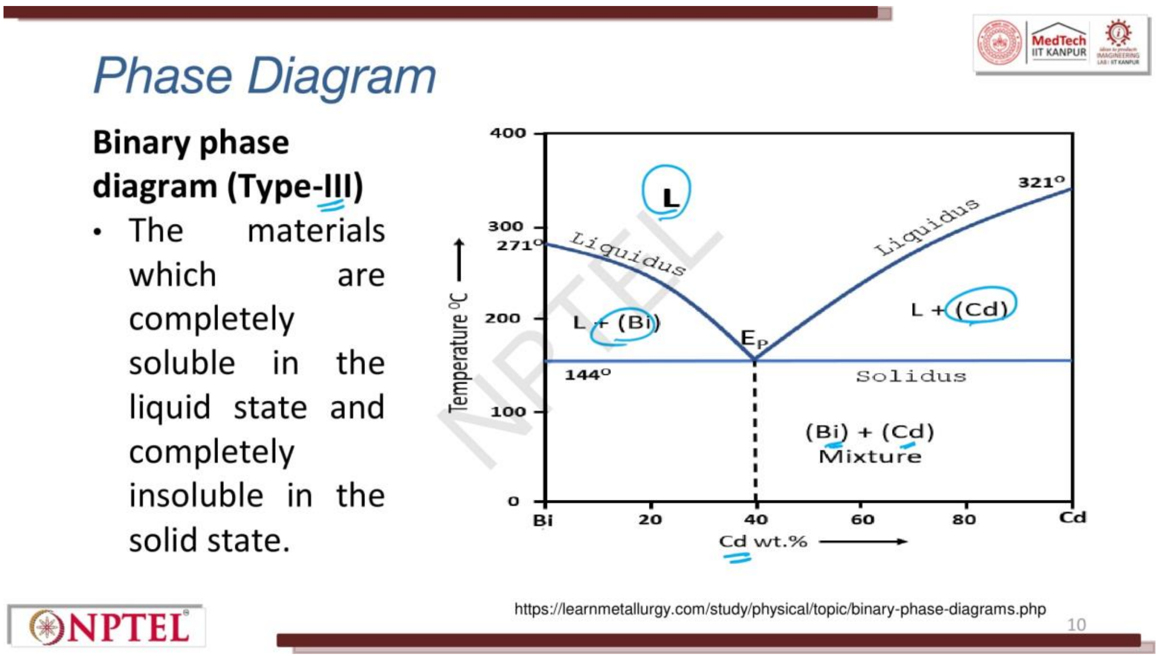
So, from here, you can see the solidus, and then you can see up to here, and the solvus you can see here. Above the liquidus line, you have a liquid form; below the solidus line, you have a solid. So let us now look into detail. So you have a temperature on the y-axis. Then, you have the tin percentage changing. This is lead. So the tin percentage is changing. So that is on the x-axis.

The materials which are completely soluble in the liquid state but partially soluble in the solid state are called eutectic phase diagrams. I repeat, the materials which are completely soluble in the liquid state but partially soluble in the solid state are called eutectic phase diagrams, and they have a eutectic point also. The α phase is the solidus solubility of tin in lead, and the β phase is the solid solubility of lead in tin. So you can see here α, β.



So in binary phase diagram 2, there appears a point at which liquid converts into two different solids. So the reaction is called a eutectic reaction. So liquid on cooling leads to solid 1 and solid 2, which are α and β. While heating, it gets back into this.

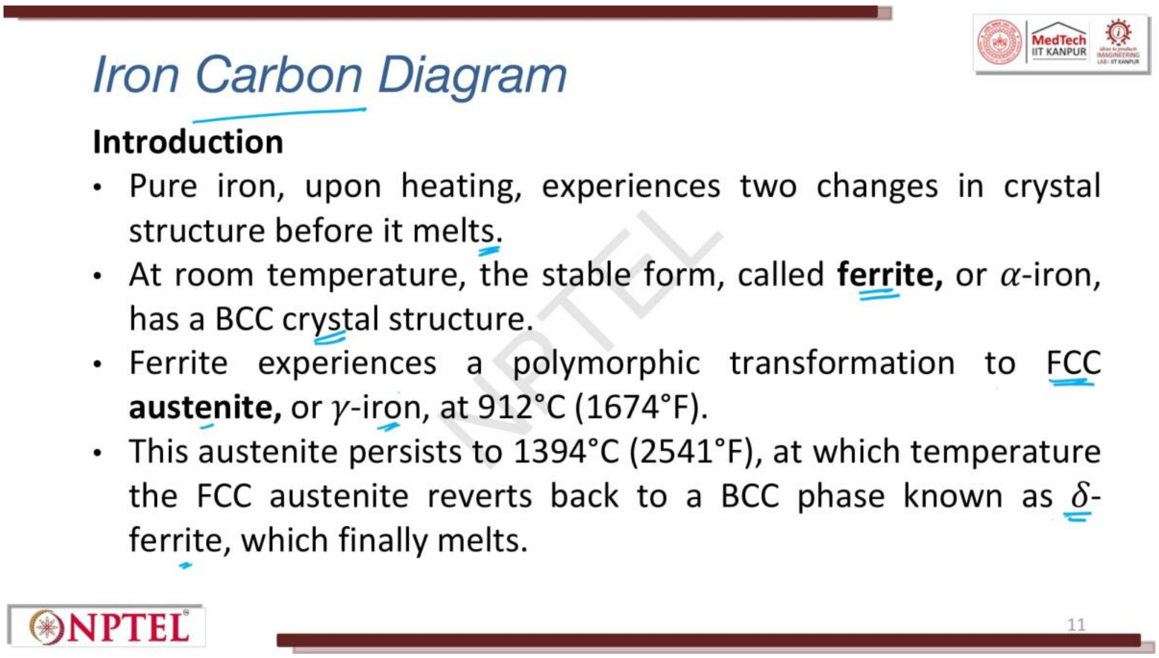
This reaction is invariant in nature and appears at a particular temperature and composition. There are three phases: α phase, β phase, and liquid at the eutectic point. Where is the eutectic point? This is the point. Liquid leading to two solids, eutectic.



When we go to type III, So we try to take cadmium. We try to take bismuth. So temperature versus composition. You can see here the materials which are completely soluble in the liquid state are completely insoluble in the solid state.

So, you can see here there is a liquidus line. There is a liquid. So, liquid plus bismuth. Liquid plus cadmium, right? So, they have a solidus line.

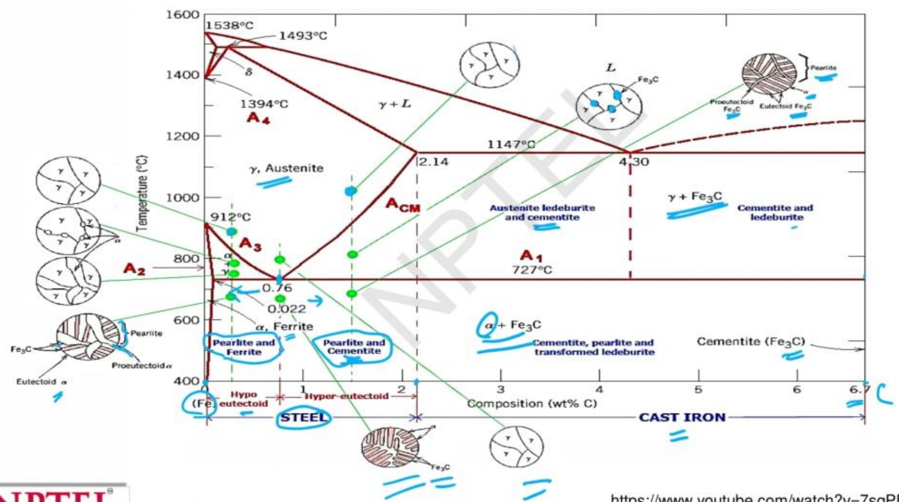
So, below this line, they will have a Bi and Cd mixture. So, the material which is completely soluble in the liquid state and completely insoluble in the solid state.



Now, let us move to the Iron-Carbon Diagram. Pure iron, upon heating, experiences two changes in crystal structure before it melts. At room temperature, the stable form, called ferrite or α iron, has a BCC structure.

So, as the temperature increases, the crystal structure also changes. The ferrite experiences a polymorphic transformation to FCC austenite or γ iron at 912 degrees Celsius. This austenite persists up to 1394 degrees Celsius, at which temperature the FCC austenite reverts back to the BCC phase known as γ ferrite, which finally melts.

Iron Carbon Diagram



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So now, let us try to understand the iron-iron carbide diagram in detail. So, on the x-axis, you will try to have iron plus carbon.

So it is 0% carbon; here it is 6.7% carbon. So we have seen in the first week itself that up to 2.1% approximately, if you have iron plus carbon, it leads to steel. Anything above 2.1% will lead to cast iron. So cast iron will have a higher amount of carbon, and steel will have a lower amount. And here, we again saw low carbon steel, medium carbon steel, and high carbon steel.

Again, depending upon the proportion of the percentage, this can change. Now, let us try to understand what all the different phases are. You have austenite γ. So if you look at the microstructure, you will see there is a γ phase. When this γ is mixed with a liquid phase, and you try to solidify it from a higher temperature, it comes down to a lower temperature.

Now, we are trying to look at a microstructure at this point. So you will have a γ phase. When it is trying to slowly cool down, right? If you see here, along with the γ phase, you also have Fe3C present. And further, when you cool down, you will see here there is a pearlitic structure where Fe3C in the eutectoid and pro-eutectoid portions are seen. We will see eutectoid and pro-eutectoid quickly.

So now, when you see there, as and when the solidification happens, you will get a pearlite and a cementite structure. Now, let us try to drop down. See here, this portion, when you move towards zero, it forms hypo-eutectoid. When you move from 0.76 towards 2, it forms hyper-eutectoid. We have seen what is eutectoid.

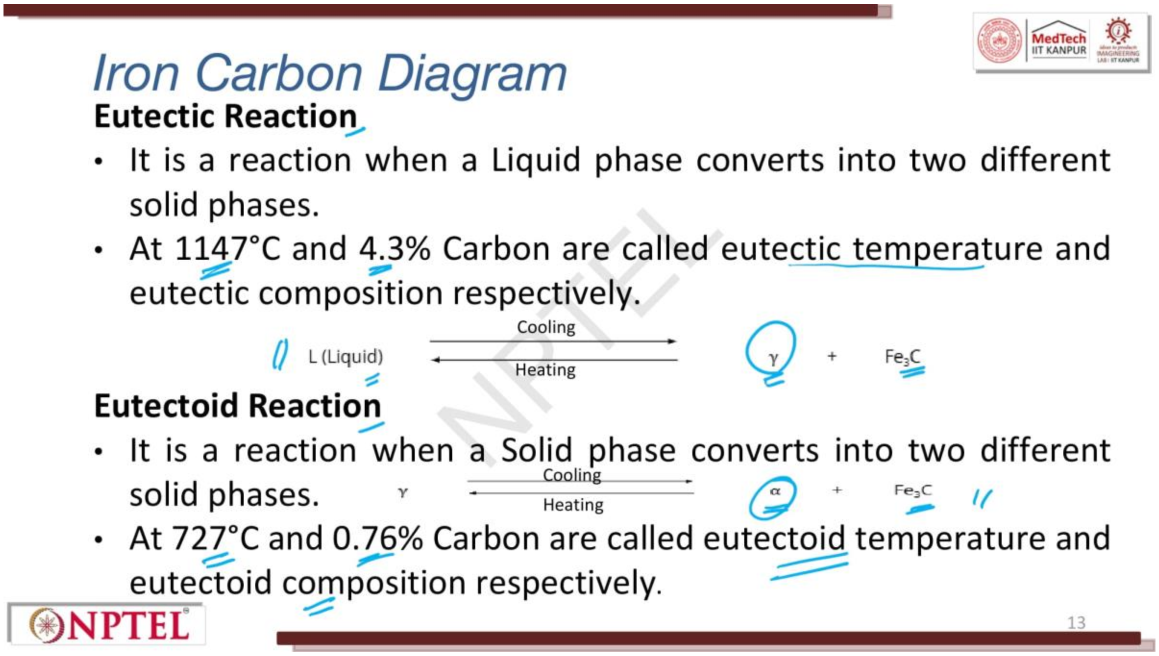
So now at 0.76, you drop down. You see a γ phase which is already here. Then, when it goes down, you will see α, plus you will see this α, which you saw here, α plus Fe3C. When you try to cool down and drop your line in the hypo-eutectoid region, you will see at 912 degrees Celsius, you will form a γ phase. Then, when it slowly cools down, you will have α plus γ.

What is γ? Γ is austenite. So if you want only the γ phase, you just have to take the composition and drop down the temperature at this point. You will get only α ferrite when you do exactly here. So when we try to do at this portion, you will get ferrite plus pearlite.

When you try to do it at this point, above the start of hypoeutectic or in the hypoeutectic region, you get pearlite plus cementite. So you get ferrite or you get cementite. Pearlite plus ferrite or pearlite and cementite. So if you see here, you will try to see how the microstructure is getting formed. You can see here Fe3C, and you have eutectoid α there.

And, this structure is a pearlitic structure. And, you have an intermediate which is called hypoeutectoid α. So, eutectoid α or hypoeutectoid α. So, in this diagram, you can try to see by changing the composition of carbon in iron, you try to get varying compositions. So if you look at this zone where γ and Fe3C are there, you have cementite and ledeburite getting formed.

When you try to see at this portion above A1 and AC critical at this portion, you have austenite, ledeburite, and cementite getting formed. When it goes down below the temperature of 800 degrees Celsius, you get α plus Fe3C. And at 0.67, you get this Fe3C. So you see here at this point, you get α, plus you get Fe3C which is cementite, pearlite, and transformed ledeburite will be there. So in this diagram, it clearly talks about iron-iron carbide, with varying phase and composition what all different types of microstructures can be formed.

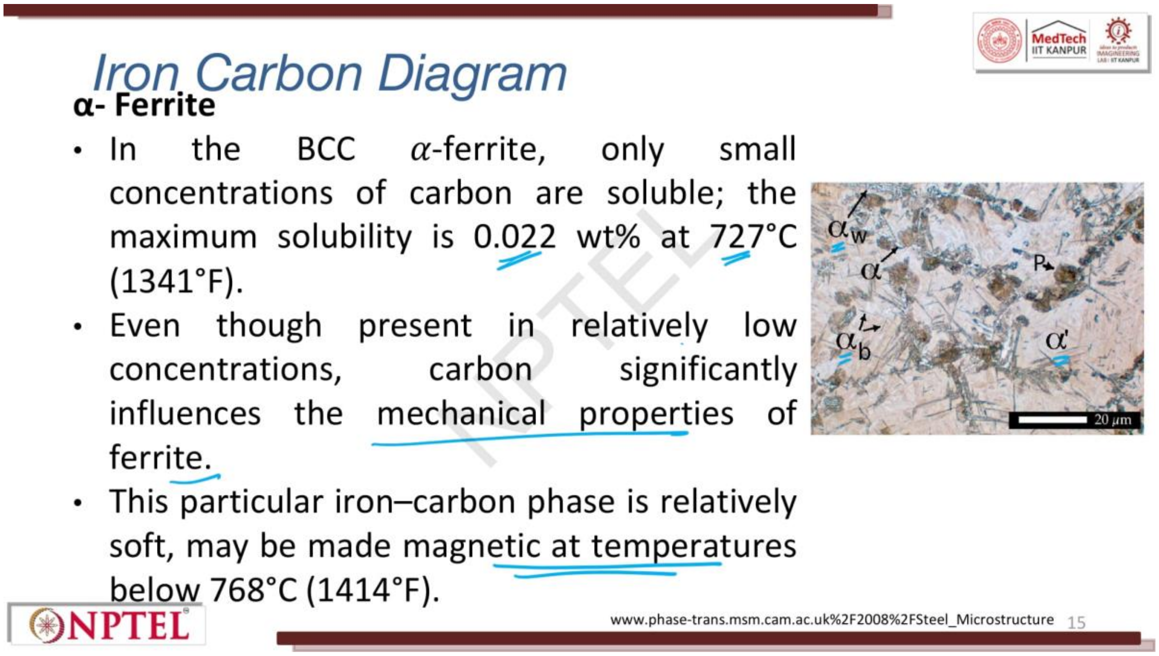


So these are the two reactions: eutectic reaction and eutectoid reaction. In a eutectic reaction, you will have a liquid leading to γ plus Fe3C. When it is cooling, you will get γ plus Fe3C. When it is heating, you get into a liquid. When you talk about eutectoid, you will see γ forms α plus Fe3C. So the difference is this.

So in eutectoid, it is a reaction when a liquid phase converts into two solid phases. At 1147 degrees Celsius and at 4.3 percent carbon, you are called the eutectic temperature and eutectic composition, respectively. So you look at the temperature and look at the composition. When you talk about eutectoid at 723 degrees Celsius and at 0.76 composition, what you get is a eutectoid temperature and a eutectoid composition. So eutectic and eutectoid can be clearly seen from this phase diagram.

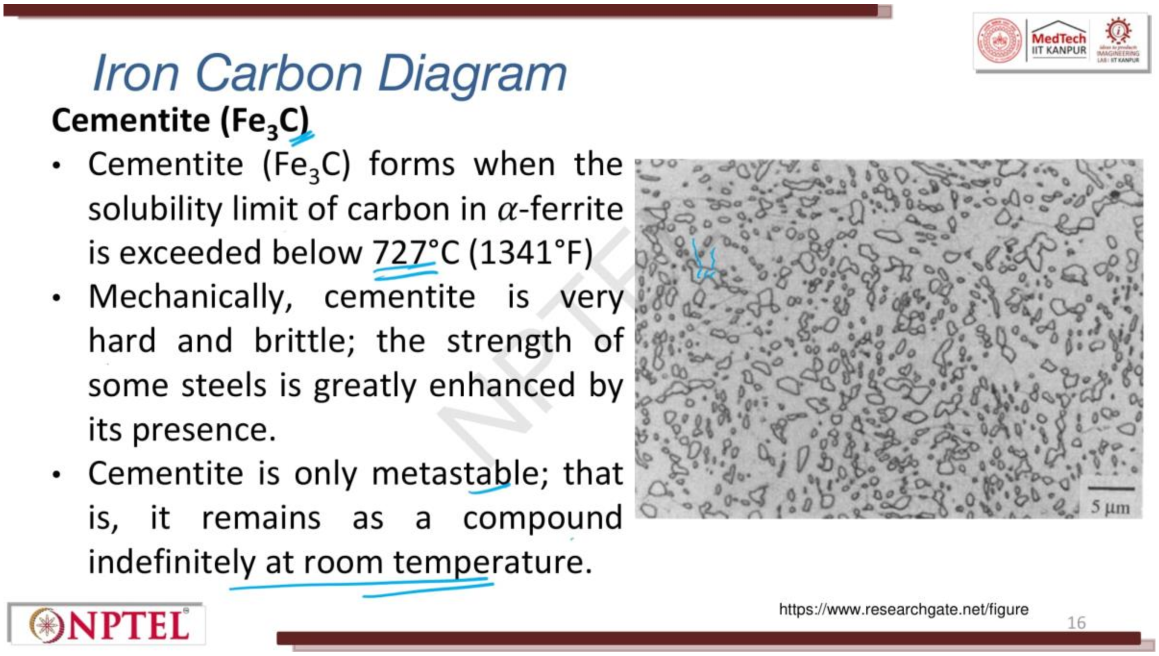
There is peritectic also getting formed in this diagram. It is a reaction when a liquid phase and a solid phase convert into one solid. So liquid plus solid converts into one solid. It is called a peritectic reaction. If you go to this diagram, you can see eutectic and peritectic.

So the microstructure generally formed in the iron and steel diagram includes α ferrite, cementite (Fe3C), austenite, which is nothing but γ, and delta ferrite. You also have pearlite, which has an alternation of α and Fe3C, called the pearlitic structure, and you also have ledeburite. These are some of the microstructures that are formed. Now, you can clearly understand that if I want to change the composition, if I want to change the output I desire, I can do so by altering the composition I add and adjusting the temperatures.



So let us look at the microstructure; then you can understand more because what we showed here was a schematic diagram. So here, let us see in a little more detail. So, in the BCC α ferrite, only a small concentration of carbon is soluble. The maximum solubility is 0.02 weight percentage at 727 degrees Celsius. If you go below that, nothing is going to happen.

Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite. So you can see here, these are α, which are present, right? So this particular iron carbide phase is relatively soft, which makes it useful for magnetic applications at temperatures below 768. So below that temperature, this carbon gets diffused. So now, this material can be used for its magnetic properties.



When we try to look at cementite (Fe3C), what is it? These are the phases which are in the α phase. Then, we are now trying to see the cementite phase. Fe3C forms when the solubility limits of carbon in α ferrite are exceeded below 727 degrees Celsius. It forms this cementite phase.

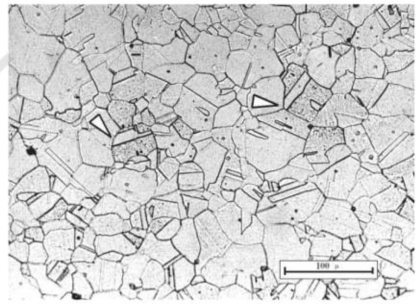
The cementite phase is a hard phase. Mechanically, cementite is very hard and brittle. So, if you see, if there is a soft material and a hard material, if there is a crack, it gets arrested. And when it is hard, it is also brittle. So, you do not have much ductility.

So, the strength of the steel is greatly enhanced in the presence of carbon. Cementite is only metastable; that is, it remains as a compound indefinitely at room temperature. So, if you want Fe3C, if you go back to this diagram, you can try to take Fe3C alone and then try to get it. So, you get cementite. So, for example, cementite.

Iron Carbon Diagram

Austenite (γ)

- A face-centered cubic (FCC) structure, more ductile and formable.
- On cooling below 723°C it starts transforming into pearlite and ferrite.
- It is normally not stable at room temperature. But, under certain conditions, it is possible to obtain austenite at room temperature**.**
- It is a non-magnetic allotrope of iron.



https://www.metallurgyfordummies.com/austenite-gamma-iron.html

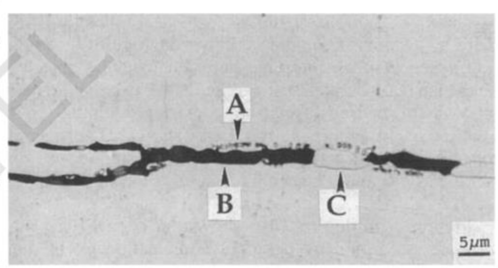
Now, let us look into austenite. An FCC structure, where more ductility and formability is present, which is always γ, austenite is present. On cooling below 723 Celsius, it starts transforming into pearlite and ferrite. It tries to form γ. So, trying to form γ, right?

So, this is what we are trying to see here. It is normally not stable at room temperature, but under certain conditions, it is possible to obtain austenite at room conditions. They are all non-magnetic allotropes of alloys. If you want, you can try to get austenite, but you have to make some changes in the heat treatment to obtain austenite. So, α is ferrite. A ferrite is virtually the same as γ ferrite.

Iron Carbon Diagram

δ- Ferrite

- The δ-ferrite is virtually the same as α-ferrite, except for the range of temperatures over which each exists.
- The δ-ferrite is stable only at relatively high temperatures.
- It has body centered cubic (BCC) crystal structure.
- Delta iron doesn't become magnetize.



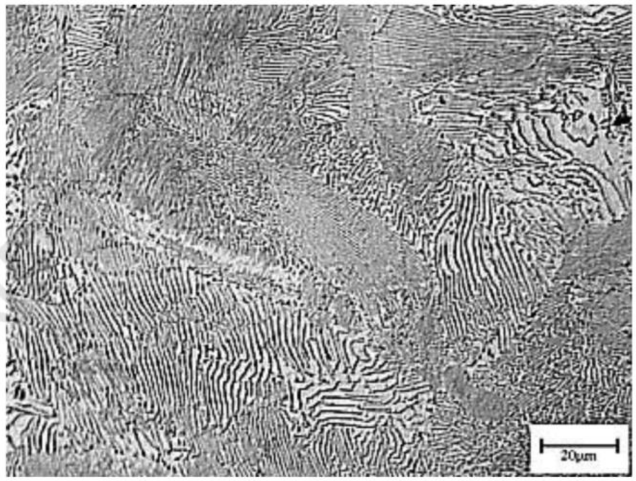
https://www.researchgate.net/figure/Microstructure-of-delta-ferrite-in-a-specimen-aged-at-720-for-57-h-Arrows

Delta ferrite is virtually the same as γ ferrite except for the range of temperatures over which it exists. Delta ferrite is stable only at relatively higher temperatures. It will have a BCC structure. The delta iron does not become magnetized.

Iron Carbon Diagram

Pearlite

- Carbon diffuses through the lattice structure and produces alternate plates of α and Fe_3C.



https://www.sciencedirect.com/topics/engineering/pearlite-microstructure 19

Iron Carbon Diagram

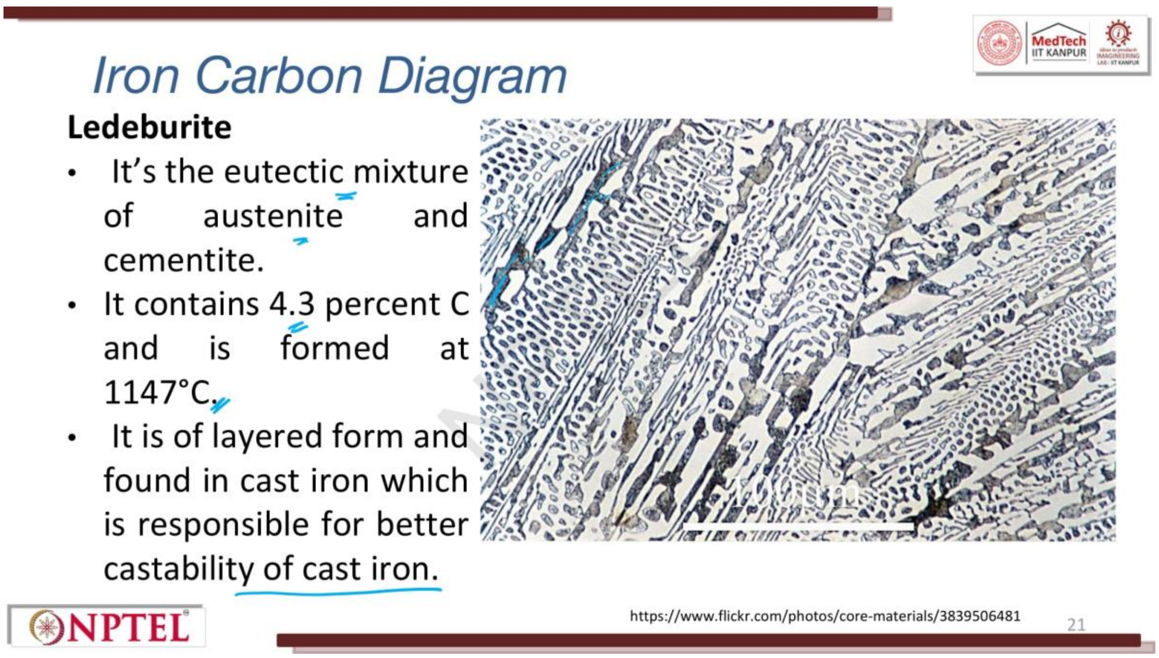
Pearlite

- This structure is called pearlite and it is produced by diffusion. So pearlite is not a phase, it is a phase mixture of α and Fe_3C.
- The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae, most of which appear dark.
- Pearlite has properties intermediate between those of the soft, ductile ferrite and the hard, brittle cementite.

https://www.sciencedirect.com/topics/engineering/pearlite-microstructure 20

Pearlite, which is again a microstructure, carbon diffuses through the lattice structure and produces alternating plates of α and cementite, that is pearlite. So you can see from the figure very clearly. Pearlite, the structure is also called pearlite, and it is produced by diffusion. Pearlite is not a phase; it is a mixture of α plus Fe3C. The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae, most of which appear as dark.

So you can see here dark, which is there or there. The pearlitic has properties intermediate between those of soft and ductile material and hard and brittle phase material.



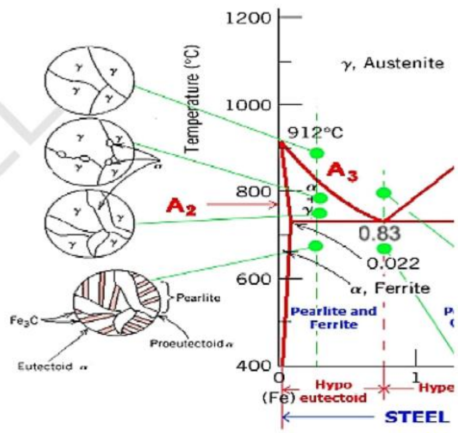
This is ledeburite. It is the eutectic mixture of austenite and cementite. Around 4.3 percent of carbon, it is formed at 1147 degrees.

It is of layered form and found in cast iron, which is responsible for better castability in cast irons. These ledeburite, black these are all carbon which are there, which is used for lubrication.

Development of Microstructures

Hypo-eutectoid Steel

- When steel with 0.83% carbon (the eutectoid composition) is cooled slightly below the eutectoid temperature, austenite undergoes a phase transformation.
- It decomposes into a mixture of ferrite (with 0.02% carbon) and cementite (with 6.67% carbon) through a process called diffusion.



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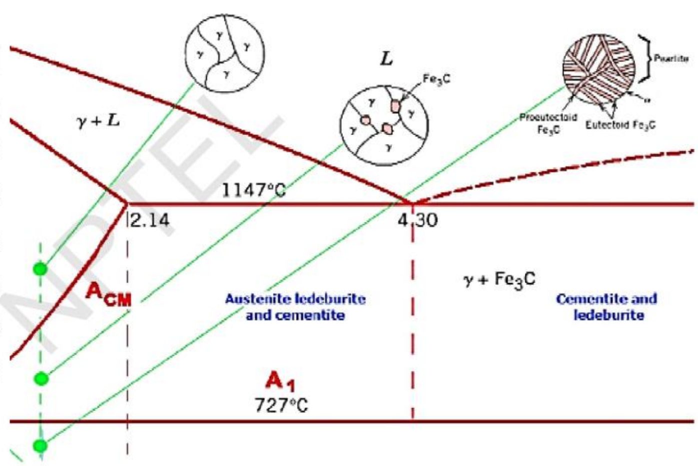
Hypoeutectoid steel. When the steel with 0.83% of carbon is cooled slightly below the eutectic temperature, austenite undergoes a phase transformation. It decomposes into a mixture of ferrite and cementite through a process called diffusion.

Development of Microstructures

Hyper-eutectoid Steel

- In hypereutectoid steels (carbon content above 0.76%), pro eutectoid cementite appears along the grain boundaries as the temperature decreases.



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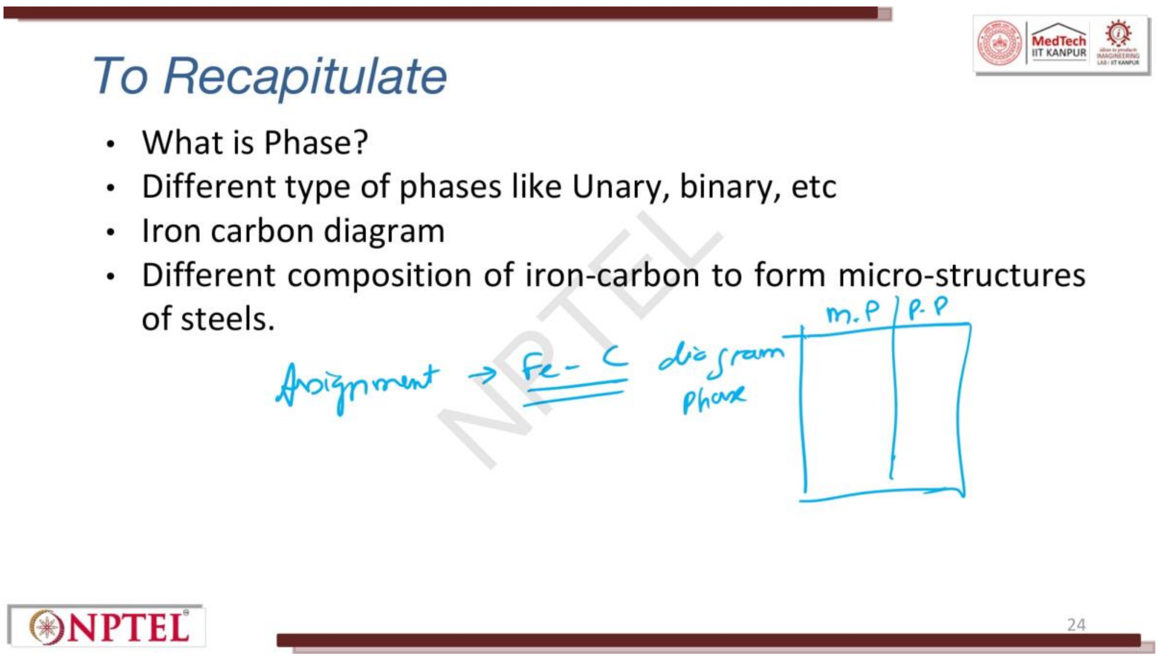
So, hypereutectoid, you can see here. When the carbon percentage is 0.83. So, it should be somewhere here. It is cooled, you get this. So, γ, you get this, you get eutectoid. So, when we talk about hypoeutectoid steel, we are trying to talk about hypoeutectoid, and then we are trying to talk about, this is 0.83 hypoeutectoid.

When we are trying to talk about hypereutectoid, it is formed, the hypereutectoid steel, the proeutectoid cementite appears along the grain boundaries as the temperature decreases. So, this is what it is.



So, in this lecture, what we saw was? We saw what is a face, what are the different types of faces, iron-iron carbide diagram, and different compositions of iron-iron carbide diagram to form the microstructure of steel. Now, there is an assignment which I would ask you to go through. So, to read the iron-iron carbide diagram in detail, and now, you will try to write down the mechanical properties, physical properties of different phases of material.

And see, what is the relevance or understanding with respect to the microstructure and mechanical properties and physical properties.

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These are the references which we have used in preparing the slides. Thank you so much.