**Phase Transformation in Materials**
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Lecture – 35
Solidification: Castings/Ingots

So, last part of the discussion on this liquid solid transformation, is how the solidification happens in a casting or ingot. As you know in the industries, we pore the liquid metal, mostly alloys into a mould, and this mould will be normally a metallic mould or even a sand mould. So, here I am going to tell you some aspects of solidification of this casting. As you know the solidification of the alloys in a casting, is much more complex than what I am going to discuss with you. For details if you want to know, you should look at to different books. Just I am going to give you an very basic idea, how things can happen. So, if a pore, a liquid into a big mould, it may be metallic mould or ceramic mould, like as like sand mold. What will happen? Immediately the liquid will come in contact with the mould wall, and it will start solidifying.

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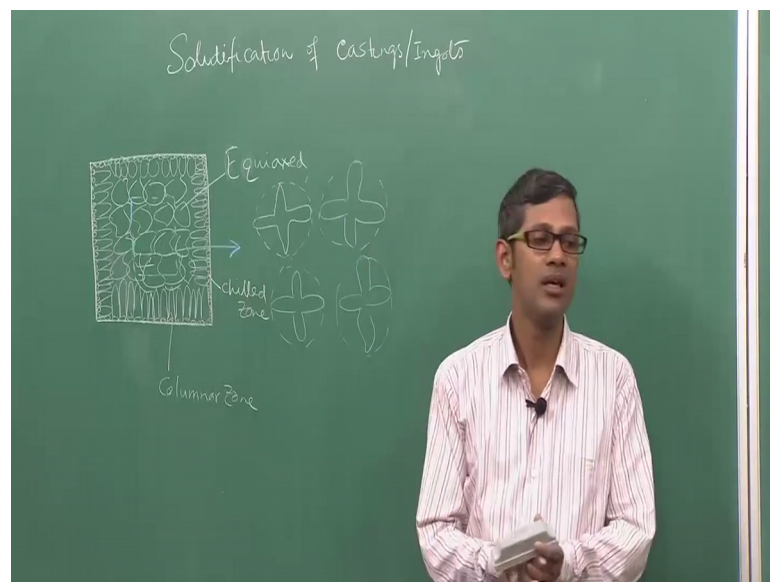
So, what will happen? There will be very small crystal which will form, as you understand at the boundary or the walls. There is no duct of heterogeneous nucleation sites available, large number of heterogeneous nucleation sites available. So, therefore, these crystals will easily form, and they will be very small size, because of the large

under cooling, and also cooling rate, because the liquid which are the very high temperature will be chilled, as its reached the walls of the container, and thus this will be lead to a nucleation, and the very small, large number of nuclei form at the walls, and this nuclear will grow very slowly. Sorry nuclei will go cannot. I will tell remain very small size, because it is chilled, and this zone is known as chilled zone in the casting.

Now; obviously, the important aspect for the solidification to happen further, is the heat transport. The heat, a liquid must get out to the mould wall to the outside. So, to do that, the crystals which will grow in the liquid, must be growing in the direction, such to the heat flow can be maximized. So, what will happen? This crystal which is form on the walls as a small size, all of them will try to go liquid, but as the heat transferred, becomes primarily important, only the crystal which are columnar like this, they will be beaning over than the others. There is a crystal, which is going like that. The heat transfer may not be happening along this axis. So, this may not be the fastest one. So, therefore, it will die out; that is why this crystals will not stay.

So, I am going a very small schematic picture. So, that you can try to see that only few crystals which are present, or which are actually, kind of lying in such a way that heat can pass through very easily, or they actually allow the fastest transfer of the heat. They are the ones which will be growing over than the others. So, out of also, many thousands of the crystal which are present at, in the chilled zone, only few of them will be allowed to grow. And this zone, as its, this is known as columnar zone, because the crystals here looks like columns.

Now, finally, whatever liquid left over the central part of these things, they will be solidifying like a equiaxed grains, why? That is easy to understand also. As you have seen, I have shown you that, for the equiaxed crystals to grow, the temperature gradient from the liquid to solid, solid to liquid must be negative, correct, why? Because if they require very large under cooling in the liquid. So, as you know this will, as the liquid solidifies, lot of solid will be reject into the liquid, because of solid rejection, the constituent under cooling present in the center part of the ingots will be very large, and this constitution under cooling will allow the equiaxed grains to grow.

They do not have any problem nucleation why, because of the fluid flow present in the liquid in. There is a chance there, some of these dendrites or the top part of the dendrites

of this columnar dendrites will break away, and reach the central part of these ingot, and then there will start the growth of these equiaxed crystals into the liquid. This equiaxed crystals will look like this; that is why they are called equiaxed, because they have dendrites arms of equal length, that is why they are called equiaxed grains. So, there will be all present along in the center part of this crystal. So, that is another one you can. Similarly you can draw another one.

So, the central part, if I draw here, if I draw color things that is what is shown here. So, therefore, this zone is known as equiaxed zone. So, in a normal ingots, there will be three zones. There the chilled zone, which is very near to the walls, which have large number of crystals present, because of high nucleation rate, but small growth rate followed by columnar zone, because of the heat transport which is required from the liquidus solid fast, that is why they will go like column crystal, columnar crystals. Another central there will be a, there will be a equiaxed zone. This is the in general picture.

But in many cases you may not see all the zones, many cases you will see columnar zone is present along a chilled zone. The equiaxed zone may not be present, that depends upon how the heat transport, actually happens in the mould from the mould wall, from the liquid to the mould wall to the outside that depends on that, and that depends on the different alloy type also, because the conductivity of the solid will also be dictating, what is the way heat is transported the K l terms or K s terms, which are given in the equations earlier.

So, that is actually happens. Remember this is only in times of dendrites, you can also have eutectic present along the dendrites which is not shown here. Those eutectics also will grow, you know as a last part of the liquid, if the alloy is basically not exactly pretty compositions, then what will happen? There will be dendrites eutectic present in the microstructures, and this eutectic will be solidifying at the end of it, because it is at lowest melting temperature, and they will represent in the in between, in the center part of the castings. So, finally, this is important. Actually, one can actually described a much better heat and the solid balance model for that and that is a part of the solidification courses, which available even on NPTEL perform many of these cases.

But we cannot discuss, settle you know things of these situations in a detailed manner. So, with this one and half, the solidification part of the course, and I will now go to the

next post, part of this course which is basically very large; that is the solid to solids phase transformations. As you know, the most of phase transformations, if you read the books, are solid to solid types and there are large number of this transformations, and we are going to discuss this transformations in detailed manner.

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- Diffusional Transformations
- Diffusionless Transformations

So, solid to solid phase transformations are basically, will be happening forming a new solid inside a old solid; that means, a product phase, you will form product phase which is solid, will form in a parent solid phase.

Depending of the mode of mechanisms of this transformations type of, or is the exact mechanism transformation. We can divide them into two broad classes; one is the diffusional transformation, and other one is basically diffusion less transformation. Diffusional transformations are basically depends on the diffusion of the solids, or actually (Refer Time: 09:33) of the atomic pieces, or the let me say properly, they are the ones which we are dictated the transformation and the kinetics. But there are transformations which will discuss later part of this course, which does not require diffusion of this atomic pieces. They can be happened without diffusion also. They are known as a diffusional diffusion less transformations and they actually happened, because of the shear forces which are present there in transformations, which we will discuss in detail manner. So, first we will take up the diffusional transformations. As you know there are many diffusional transformation solid to solid phase transformation.

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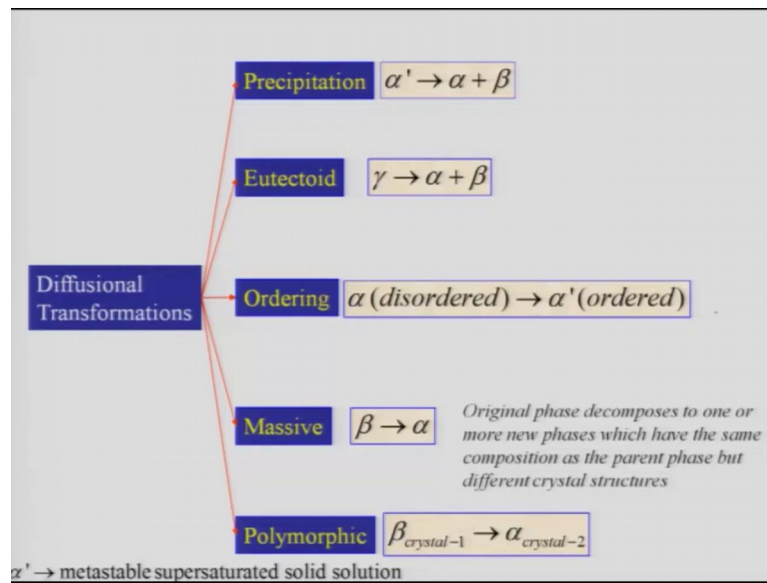
I am going to talk about few of them in this course, but I must inform or tell you, all the basically not all, most of the presence, most of them present in the literature. The first one which is written here is, the precipitation type. Precipitation means a formation of a new phase from a old phase, and that is what you shown here. Alpha prime going to alpha plus beta, where alpha prime and alpha, the same crystal structure, but beta is a different crystal structure. Alpha prime contains more solute than the alpha, then the important transformation is solid state which requires diffusion of this atomic P P C is eutectoid, and the transformation is type, this gamma going to alpha plus beta.

You can also have a transformation known as ordering, where alpha which is a disorder state can go to order state that also needs the moment of the atoms from one part of the crystal to the other part of the crystal. You can also have massive transformation in which there is no compositional change, only the beta goes to alpha, or you can also have a polymorphic transformation, which is very common. Iron is the greatest example of polymorphic transformation. Iron, are room temperature as a body centered cubic structure, pure iron, I am talking about its room temperature and one atmospheric pressure. It has a body centered cubic structure. If you heat up pure 912 degree Celsius, which becomes based on the cubic structure. Again if you heat beyond 1394 degree Celsius, temperature is become delta 1494 degree Celsius, it becomes delta iron.

And then it (Refer Time: 12:00) about 14 and 1539 degree Celsius temperature. So, therefore, iron actually can transformed into different type of crystal structure, depending on the pressure and temperature, and this is known as polymorphic, because there is no computational change. Only thing which is changing is basically crystal structures of function of temperature and pressure.

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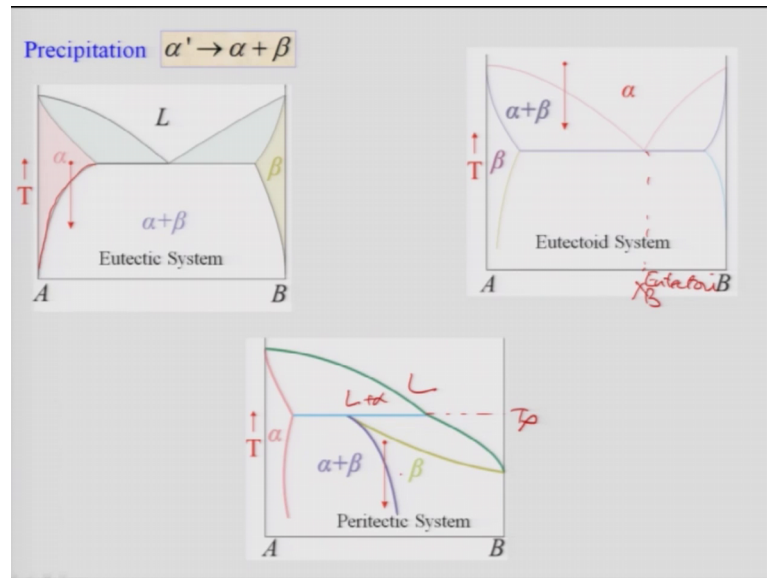
Now, what are the different types of phase diagram? We can attach if with each of these phase, phase transformation. Let us first talk about precipitation. Precipitation as I told you, is like alpha point going to alpha plus beta, and the phase diagram shown is like this eutectics type. We have been discussing this type of phase diagram quite a lot.

Here you see the alpha phase. So, the solid solubility of beta b in alpha, is come, temperature dependent, it keeps on decreasing like this. So, therefore, we can have a precipitation diagram alpha, supersaturated to alpha plus beta; that is what is there you can also have, you know precipitation from alpha to alpha plus beta in eutectoid systems, when the composition is away from the eutectoid. This is the eutectoid composition, but if you go away. If you have less composition than that of mould composition, that in the both the cases your precipitations of alpha or beta phase is possible dependent on the diagram.

Similarly, you can also have a peritectic systems in which beta phase. Here you can see at this A beta, this A peritectic isotherm T P and as a peritectic reaction, here liquid plus alpha going to beta.

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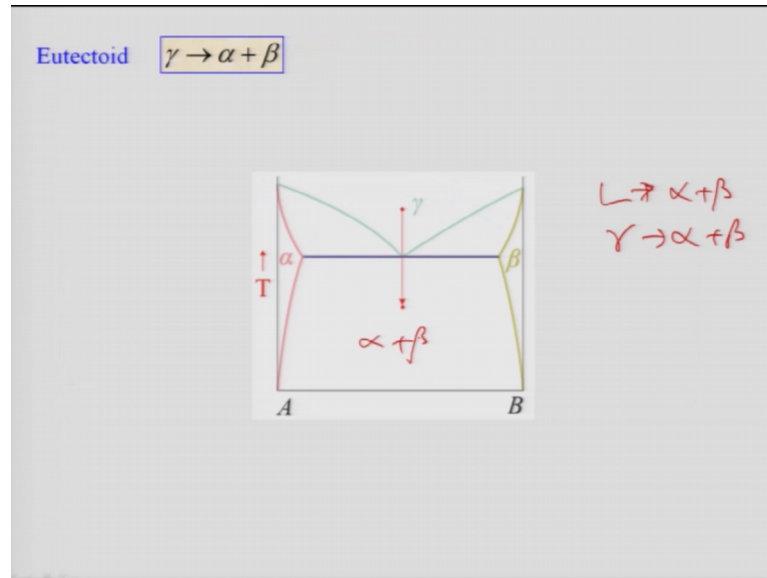
So, this beta phase which is a single solid solutions, can actually transformed to allow plus beta, and lead to precipitation. So, this possible eutectoid is a classical system, which is present in a iron carbon system also, which we will discuss in detail, in which gamma going to transform to alpha plus beta eutectoid, and eutectic reactions look similar. Eutectic is like this; a liquid going to alpha plus beta, eutectic require is like this, and gamma going to alpha plus beta.
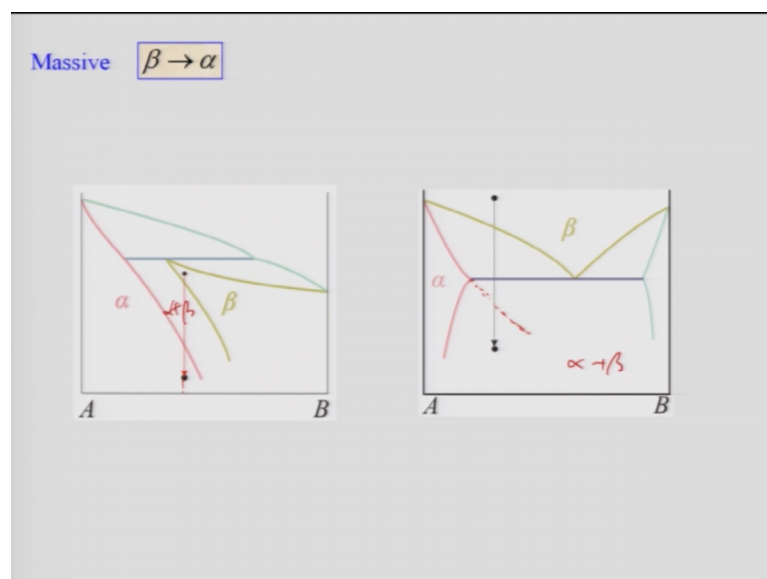
So, only difference between these two reactions is the liquid in the eutectic system reaction is replace to solid gamma phase eutectoid systems. So, anywhere you see toid word, is basically correspond to solid. So, solid transformations, whenever you see a tic eutectic peritectic, you see the tic word tic is present in word; that means, that transformation in both liquid phase, but the moment you see toid in the word; that means, the transformation in solid state. So, eutectoid is a solid state version of the eutectic. As you see the phase diagram will look similar the gamma going to alpha plus beta here, and eutectic is liquid going alpha plus beta.
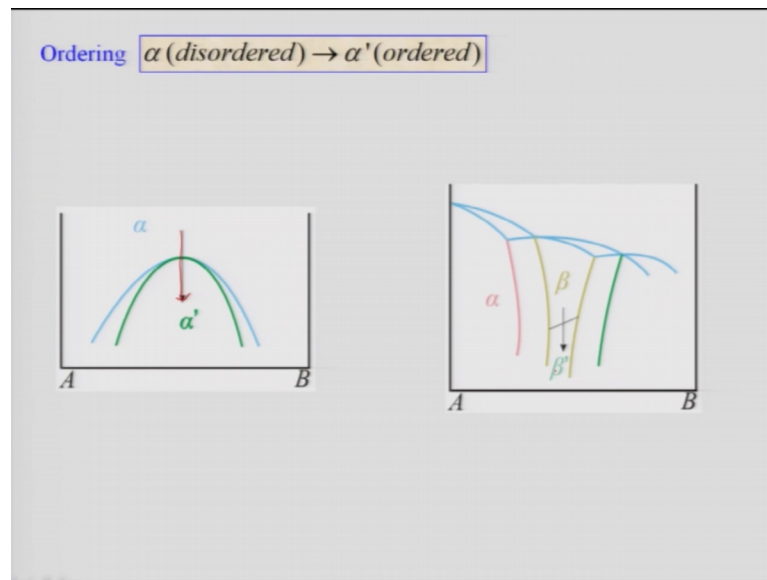
Now, also let me show you few examples of the ordering, as you see here alpha which was a disorder solid solution, as when you cool down it becomes alpha prime. So, that is a order phase of that. The classical system in which, seen is the copper zinc in which the phase diagram is shown here. The beta going to beta prime, as you cool it down, we will have a 200 degree Celsius temperature, beta brass, basically transform in a copper zinc system.

Massive transformations are new, and this requires discussions, but I am just showing you the phase diagram type. As you see here, the beta can directly transformed to alpha without actually transform to alpha plus beta here, without transform to alpha plus beta. Beta can directly go to alpha without any change of composition.

You see here, there is no change of composition on alpha beta, beta transformed to alpha, and this is known as massive transformations. This is same in many cases. This is peritectic systems, you can also have such a transformation eutectoid system; like beta going to alpha. Although we should have done to alpha plus beta, but this is Meta stable, remember that, because we are extending this line or a dotted line in the phase diagram, that equivalent to a Meta stable system.

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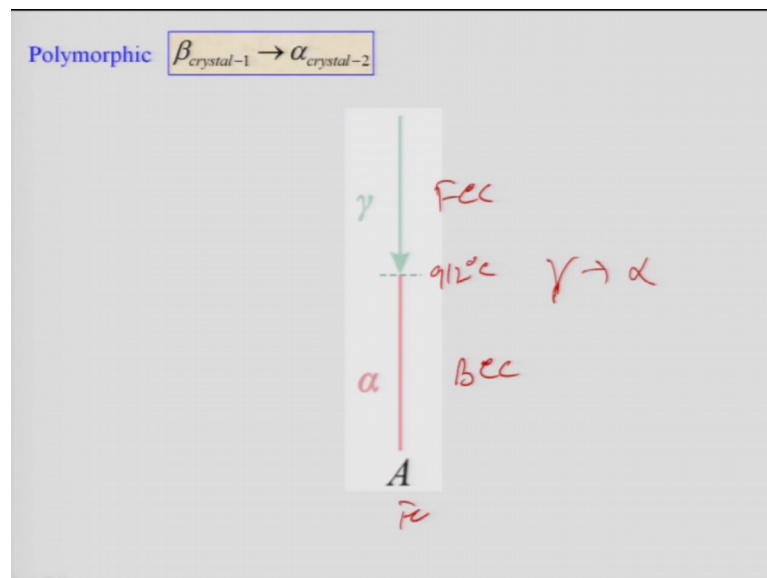
So, we can also have a super situated alpha forming out of beta polymorphic, as I told you is beta going to alpha or gamma, whatever it is, here it strain gamma going to alpha.

Just like pure iron, I will show you gamma to alpha transformation is 912 degree Celsius temperature; gamma is FCC and alpha is BCC in pure iron. So, therefore, this transformation does not require any compositional change. This only happens in pure systems, like you can happen in zirconia also, it can happen in pure iron. You can also have it in sulphur. Sulphur has many types of polymorphs present, and since transformations are known as polymorphic, because it is the same material pure, or let us say compound or it is say metal or metalloid. It is transforming form one phase to other

phase, as the temperature changes at a constant pressure. Iron is a classical example, and we actually use this particular aspects of the transformations of iron in the steel making, or in basically physical metallurgic of steel, which will discuss in a very detail manner in this course itself.

So, now question is this, as you know there is, so many solid state transformations possible, and if I want to discuss each of these things, and there is another one, which I am not discussing here, which is known as (Refer Time: 17:32) composition that also requires diffusion, but different types of diffusion, of ill diffusion, which I have discussed in the diffusion part of my course. So, out of all this transformations, we cannot, we will concentrated on few of them. The first one which will concentrated basically precipitation, because precipitation is a very important phase transformation in the metallic systems, why, because many of the industrial important alloys; like aluminium alloy, copper alloys, aluminium copper magnesium silicon alloys. They are actually the whole transformation depends on precipitation of the particular phase or phases.

So, therefore, it is important that we discuss the precipitation, hardening precipitation, phase transformation in detailed manner. Similarly we will discuss eutectoid transformations as well as the little bit about the (Refer Time: 18:28) decompositions. And as a part of the eutectoid transformations, as I told you that if diffusional transformations are not possible. We can also have diffusional, diffusional less transformations. So, we are going to discuss martensites in the steels. As you see we have seen probably in detail syllabus of the course. So, martensite transformation is also similar like a diffusional less, diffusional less transformation, and we are going to discuss in detail manner about that. Now, as you have seen the precipitation is very important phase transformation. The phase diagram which allows you to understand precipitation type.
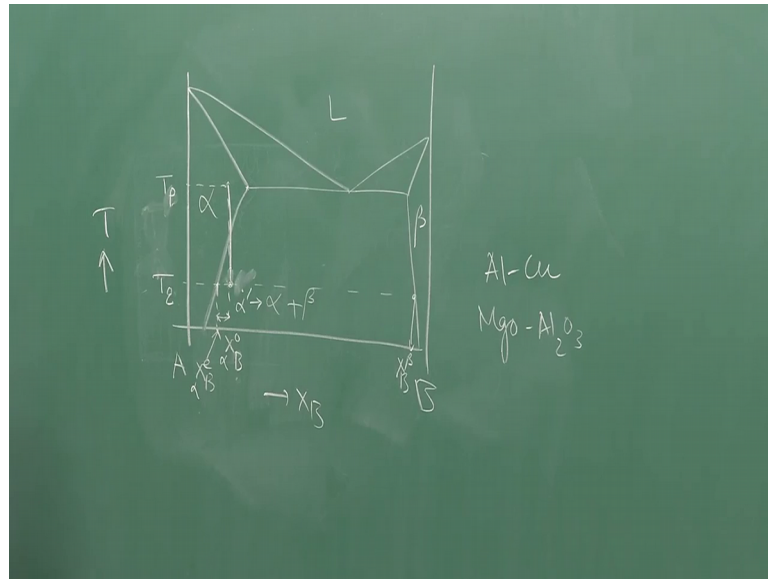
I will just take couple of minutes to describe you that important aspect is that, as I showed you. If you want to have a precipitation, if you want to have a precipitation hardening in a system, you must have, the phase diagram, must satisfies certain things. First of all as you see here alpha is a solid solutions of B in A, and it will have a similar crystal structure as that of pure A. Where A beta is the solid solutions, which is B reach. Now, if I have an alloy composition like this.

Suppose given by this, let us suppose this is the composition of the alloy X 0, later write X B 0 right. Now, if I take this alloy, and at this temperature heat it up. Let us suppose this is at temperature T q T p. Let us suppose at the temperature, it is single solid solution alpha phase, in this at this temperature. Now, if I quench at this, this temperature T q, if I quench, it means if I heat to alloy these temperature T p, and then from the temperature, if I dropped the sample into liquid water or liquid nitrogen; whatever, what will happen. This alpha phase will be retained at temperature T q.

Now, although alpha phase is retained, but as you see here at this temperature, at this temperature alpha phase contains about X B 0 amount of the solid B. On the other hand as per the phase diagram at temperature T q, it can only contain this much amount of X B, e amount of the solid, because the solid solubility of the B in the alpha phase, is slowly going down. So, therefore, the solid solubility at temperature T p was very high.

In fact, it was this value. Now because it has got reduced or quench to T q, the solid solubility has reduce.

So, excess solid, which is present A, which is between these two values must be taken out from the alpha, and this excess solid leads to formation of beta from the alpha. So, the alpha which is quenched is known as super saturated alpha; that is what we have written alpha prime, and this alpha prime actually transformed to alpha plus beta, where alpha will a compositions of X P e, and beta will have a composition of given by this much. This is X P beta. This is; obviously, alpha phase composition in all the cases.

Correct. So, this is exactly known as precipitation hardening. Now, we must have a phase diagram like that in a way. If the solubility of the solid solubility of B in the alpha phase, will slowly, will basically change quite drastically as a function of temperature, then only if its changes slowly, if its changes also very little, then this is not the precipitation, hardening is not possible. So, only in those phase diagrams; like aluminium, copper in case of magnesia aluminium oxide or some other systems. These are the two classical systems, which is metallic on a ceramics that this such kind of a phase diagram exist. So, aluminium copper magnesium oxide, aluminium oxide. These are the two systems, which shows precipitation hardening extensively. So, we are going to discuss mostly on taken the aluminium copper systems, and tell you how actually nucleation and growth happens in the next subsequent lectures.