Fundamentals of Materials Processing (Part–1)

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Lecture Number 23

Plane Front Solidification of Multiphase Alloy

So we looked at cellular solidification of single phase alloys. Next we wanted to look at the planar solidification of poly phase alloys. But before that, again there is one thing that I missed in the previous lecture that is relevant when we are talking about cellular solidification of single phase alloys and that is to talk a little bit about microsegregation. So you see we said that there is a concentration distribution between the cells and whatever the composition difference is taking place in the cells is because of the difference in the tip.

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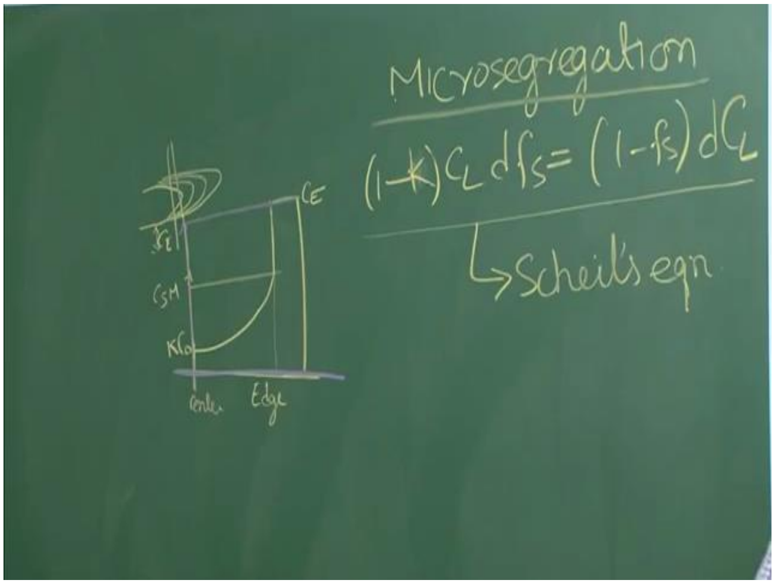

So we said some, we had a model like this; so you the cells are growing like this and like this; and therefore if you look at it, there is a composition difference, over here and here. So there will be some composition difference. So if we look at from the centre of the tip. So let us say this is centre, this is the edge; so there will be some concentration difference in the tip. Now what is that concentration difference? So this and this difference is microsegregation, so the segregation is taking place at a very small length scale; , so inside the 10 micron length which is of the tip which is of the order of the size, or the distance between the cells; so we can say some less than

10 microns is the size of the width of the cells. So it is segregation taking place in that length scale.

Now people have shown that if you try to get the equation for this, which is not very difficult, because we know the concentration of liquid at the tip of the cells, and from that you can find the concentration of the solid that is forming at that particular point and then keep changing the concentration in particular, in this particular direction, then you can get the concentration profile inside the cell; and the differential form of the equation in a simplified with some assumption and simplification, comes out, so this is K. If you look at the differential form of the equation after some simplifications; we are not going into that simplification and assumptions; but this has been shown so. But the what is what is the important point that I am trying to convey here is that if you look at this differential form of the equation, you will see that it is very familiar. Why is it familiar?

We know it from Scheil's equation; and where was it valid? It was valid for single crystal growth. Remember we were talking about single crystal growth, and where there is no diffusion in solid and complete mixing in the liquid, then this is the form of the equation that you obtain. And, surprisingly, we get similar kind of equation if you are looking for the solidification concentration distribution inside the cells. So each of these cells are actually, you can see it can be treated very much like a single crystal. So, it should not come as a surprise that the two equations are the same form.

But that is not the only surprising part. What you would see is that if you look at the concentration distribution, so this is how it will change. So somewhere over here, it will have KC0, where C0 was your concentration of the overall solid, or the overall alloy; this would be your CSM; and just outside it after solidification, the liquid which is present in over here, this would have reached or over time, it would have enriched to a concentration equal to CE. So this is how this will be the concentration CE.

So even in this cellular solidification of single phase alloys, we do get a poly phase region which is this eutectic region. Just like we got it, we got in the single crystal growth. But here, at each and every you can say cell length scale, we are able to see a single phase region, and then this eutectic region. So, this is the kind of microsegregation that you would expect and you can see that even with a very simple models that we have been using, we are able to find out or describe microsegregation. So having said that, it is time for us to move on to a little bit higher complexity of the problem, which is planar solidification of poly phase alloys.

So now we are looking at more than one phase; but still it should have a plane front of solidification, a very simple polyphase composition that you can obtain is at eutectic. Over there, even in a binary system, you would get a eutectic with more than one phases. So let us take for this purpose, we will take a simple phase diagram.

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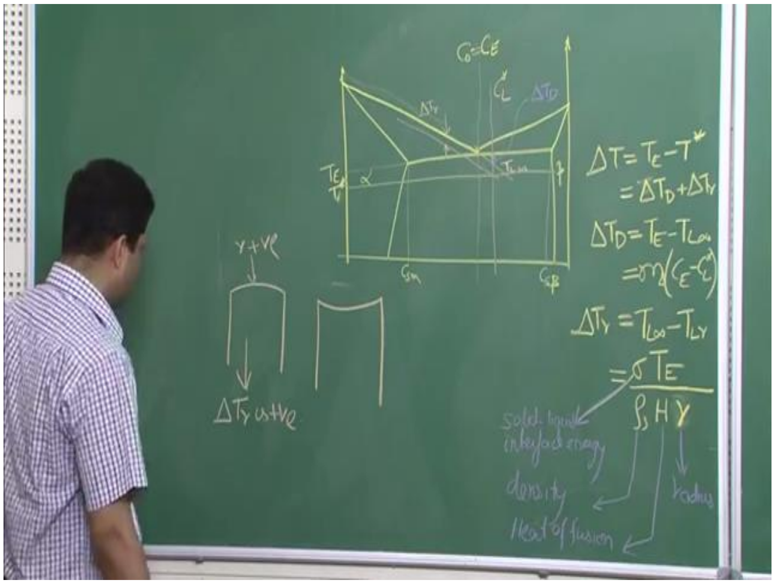

And, to make matter simpler for us, we would also assume that we are talking about concentration of liquid approximately equal to CE. So, the concentration of liquid; to begin with, we will be talking about a (con) CE. So this is CE, this is, that is your also equal to your C0; here is your alpha, and here is your beta; so we can give this the concentration CS alpha, here the concentration can be given as CS beta, and this is your temperature TE. Now, we will look at some more complexity; but before that, let us understand qualitatively what is going on.

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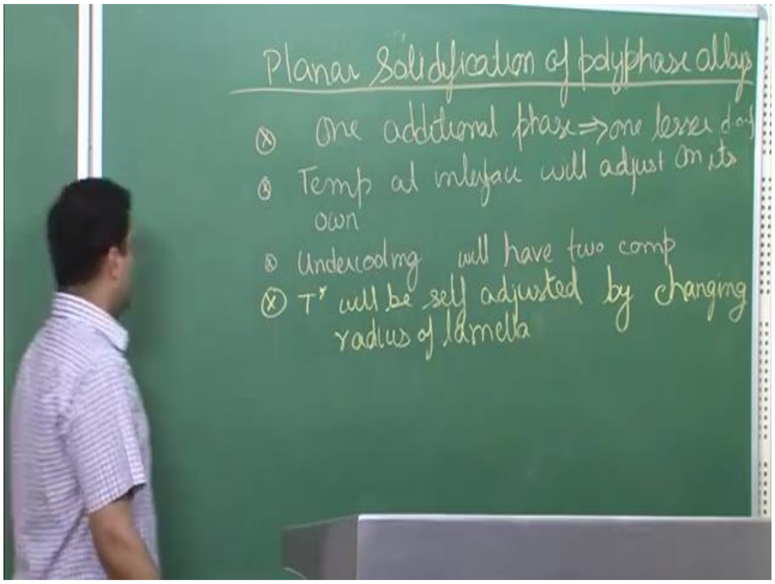

Planar Solidification of polyphase alloys

- ⊗ One additional phase ⇒ one lesser d.o.f
- ⊗ Temp at interface will adjust on its own
- ⊗ Undercooling will have two comp
- ⊗ T^r will be self adjusted by changing radius of lamella

So in the planar solidification of polyphase alloys, as compared to single phase alloys, we have one additional phase. If you have one additional phase, it would mean that we have; so one less degree of freedom. So one additional phase implies one lesser degree of freedom. So we have now, when we are doing the solidification, there will be one less degree of freedom. Now what is that one less degree of freedom? It is the temperature. So the temperature at the interface will not be adjusted or will cannot be adjusted externally. It will be self adjusted. Temperature at interface will adjust on its own.

Now this temperature that we are talking about is a small amount of under cooling. Now what is that under cooling? So that under cooling will have two components here; the under cooling will have two components. Now let us look at that what we mean when we are saying this. And his is a straight line although I have not drawn it very nicely; it will be better if I redraw this particular line to make it look straight because that is important assumption in our case. So now, let us say the lamellas, lamellas of each of the phase that are growing, they have infinite radius, meaning they are, they are completely flat; then this will be TL infinity.

However, if there is a finite radius of these lamella, then there will be some amount of under cooling and the liquidus temperature would have dropped a little bit. So this difference is termed as delta Tr, because of the radius. So there is some under cooling taking place because of finite radius of the lamella that are growing. Another is because we have the liquid composition, which will be little bit different from what we have assumed which is our C0 equal to C; so let us say our liquid composition comes out to be here; so this is our liquid composition at that particular point of time ahead of the lamella that is growing. So if this is the liquid composition, so now that liquid composition different from the eutectic composition and because of that difference in composition, there will be another super cooling or under cooling, which is given as delta TD.

So now you can see we have two different constitutions or two different components in the under cooling, temperature under cooling part. So that is another fact or understanding that we should be aware of when we are talking about planar solidification of polyphase alloys. So now still another fact that we need to look at is let us say that the overall temperature of the interface is T star. So now we have said that there is one additional phase and therefore one less degree of freedom and temperature at the interface is not being externally controlled but it is self adjusted.

It means that the temperature T star will be self adjusted, and how will it be self adjusted? It will be by changing the radius of lamella. Okay, so this is your T star; let us say this is the temperature that is maintained at the interface. This has two component: delta Tr and delta TD. Delta TD component is because of what is the liquid composition; so that liquid composition will be varying along the surface. Which means this value will not be constant; so this would have meant this value overall this T star changes but we know that T star has to be constant, it is a planar solidification and at the planar solidification temperature is being controlled by the system, so how is this controlled?

We know that there is another component which is delta Tr; so delta Tr is what is again varying to adjust and to make sure that the total temperature drop remains delta T, which is; so delta T is equal to TE minus T star, which is equal to delta TD plus delta Tr. Here we can write that delta TD is equal to this we know it is equal to TE minus TL infinity; it is the temperature between T eutectic and at that particular liquidus, if we assume it is a infinite radius, so that temperature difference is what is given by delta TD, and this can also be written as m, because we know the slope, so mL CE minus CL star; the CL star, let us put a star over here because it is a particular value we are looking at. So mL times CE minus CL star.

So we know the delta TD from here, and we know delta Tr is equal to delta, is equal to TL infinity minus TLr. So it is, it can be written like this. And if you want to look at in more detail, this can actually be further written like this; where sigma is the solid-liquid interface energy. TE we know, it is the eutectic temperature, rho S is the density, H is heat of fusion, r is the radius. So you can see, other parameters are constant, only r changes, and which is obvious, we are talking about delta Tr. So, if you, if the delta Tr has to change, r must change, and that is how delta Tr will change when delta TD changes, so that delta Tr plus delta TD remains constant and keeps that TE minus T star equal to delta T.

Now we have the radius; so how does the radius changes? So for example let us say this is one lamella that is growing. If it is like this, it has a positive radius of curvature, this positive radius of curvature can also change to some value, but it can when become negative, and it can become something like this. So whenever you have radius of curvature like this, then the liquidus will have a. So when you have r as positive, let us say this is, when r is positive, delta Tr is positive; when r is negative, delta Tr is negative; and it can also have values in between.

So even in positive it can have different magnitude to change delta Tr magnitude even though it will be positive; similarly r can be negative and different magnitude to change the overall magnitude of delta Tr. And that is how it will be able to again, like I said, able to adjust the temperature difference. So now it is time to look at the overall mechanism of the growth of the planar front solidification.

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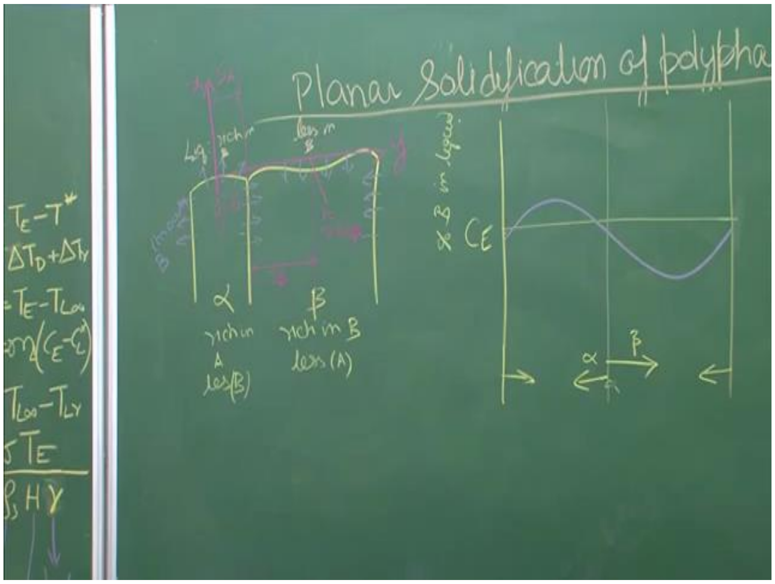

So let us say, we are talking about lamella; since there are two phases, we need to draw them together; so let us say this is one lamella that is growing and let us say this is the lamella of alpha, and these are our components A and B. So let us say this is alpha and just by side of it; and you will see why I have drawn like this when we have completed this overall formulation. But for now, just accept with me that this is how the shape is looking like. So this is our alpha lamella, this is our beta lamella; now alpha is rich in A and it is poor in B. So this is rich in A and less B; let us not write poor; and if this is the other way round, this is rich in B and less A.

So if we look at the B component, over here, the solid, this alpha whenever it is growing, it must throw out B; because initially it was at composition CE; from CE it has come to CS alpha, so it must reduce the B amount, and it will reduce the B amount by throwing out B. On the other hand; so this is throwing out B. If we look in terms of B, for the beta phase that is forming over here, then this will actually take in B from everywhere, because this is rich in B, and this has less B, so it has to be less B by diffusing out or throwing out, ejecting out B. This will be rich in B, because whatever B comes in, it will absorb and it will assimilate; so this has higher amount of B.

So now if we look at the liquid, the liquid at this point and the liquid at this point, in terms of B composition, the B liquid at this particular composition, it will be rich in B. This will be less in B, or it will have smaller amount of B, because it is throwing B, so the B amount is over here larger. This one is absorbing B, so it will reduce the amount of B in the liquid and therefore there is less amount of B over here. And therefore, if we had if we were able to draw the composition variation; so let us say this is CE, and we are looking at percentage B, then the percentage B would have in the liquid, so we are percentage B in liquid. So liquid just ahead. So we are looking at the liquid at the interface; so this is our interface and it is almost planar; we are talking about less than a micron difference in the height over here because of the radius of curvature.

So those are some of the things that must be kept in mind. So overall it is still a planar growth, and we are looking at the liquid composition just ahead of it, and it would look like, let us say this is where alpha region ends, and so this is alpha over here, this is beta over here, and this is our C eutectic over here. So you were to look at the composition, so let me this one in the liquid. So this much is beta, this much is alpha. So now we see that ahead of the alpha phase or the alpha lamella that has formed, B is rich in liquid for most of the places; there are small pockets where it is small.

On the other hand, this is less in B content for most of the region. So this is how the composition would look like. And now if you know the composition, you know that we can also find T equivalent for it, or the liquidus temperature for it. And if we know the T liquidus that means you will be able to find the delta TD component. So we can plot it, it will be best if I draw it over here, and we also need to establish our co-ordinates at this point of time. So let me use even a different colour of chalk. So let us use red to define our co-ordinates.

So this is x equal to 0, y equal to 0, and this is our x direction, this is our y direction; and we will say this is the distance S alpha. So this is half, S alpha, y equal to S alpha is the width, half the width of the alpha lamella. Similarly, S beta would represent half the width of beta lamella. So in terms of x, this point will become S alpha plus S beta. So we also have a co-ordinate system defined over here. So now let us look at the delta TD and delta Tr component, and if that is the way the temperature plot or the composition plot would look like, then the temperature plot would look like, I may have to redraw a little bit of the plot that I drew over here, because we need to have a, we need to align it together.

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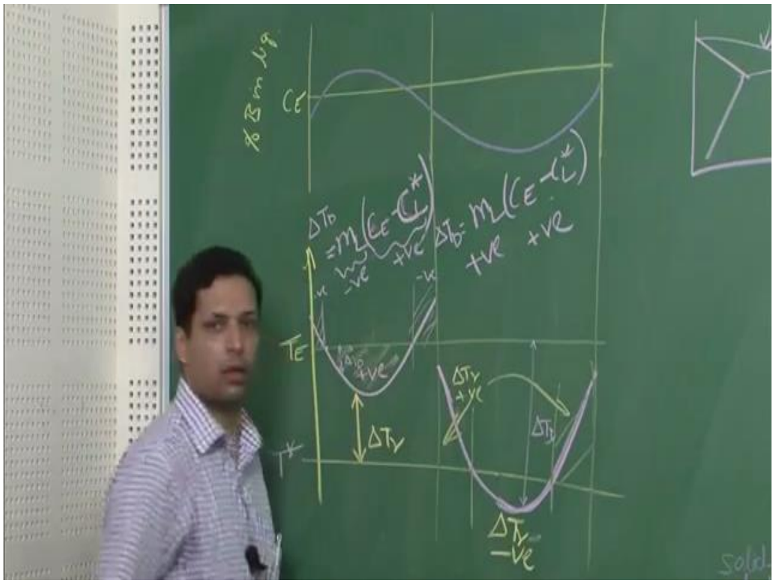

So let us say this is how the composition is varying; this is CE, this is percentage B liquid. Now we will below this, we will draw the temperature plot, and approximately this is how it is, and if we were to draw the delta TD. So wherever we have CE, at that point you will have TE as actual temperature; so we are trying to draw the liquidus temperature. So this is the, at this point and this point, it must be TE; and if you look at delta TD. Now you see, at this particular point, the composition in B is higher, and therefore, we are looking at a higher composition which means this is the liquidus temperature is actually lower than the TE, and therefore there is a constitutional super cooling.

So this plot represents delta TD. And remember what was delta TD equal to; it was equal to mL CE minus CL star. So this is the way it is, and now if you look CE minus CL star, so over here, CE minus CL star, this quantity is positive; but what is mL? mL is negative. Therefore delta TD overall in this particular region comes out to be negative. Similarly over here, delta TD is negative. Over here, your mL is negative and CL minus CE minus CL star is negative; so delta TD becomes positive. So we have delta TD equal to positive over here.

Now let us look at the other part. We are now looking at the beta part. Over here, if you were to draw, it would come out something like. Now you would say over here, CE minus CL star is positive, and if we take mL equal to negative, then this overall thing should have been negative, but it is coming out to be positive. For the beta part, then you have to look at the fact that when we are talking about this particular composition which is the beta phase, for that we have to use the other slope. You remember we have two slopes. So far we have only been using the; we have been only using this, so we said mL is negative.

But when you look at this one, mL is actually not negative, it is positive. So here, mL is positive, and positive positive it is overall positive. So, in this particular case, it is positive delta TD for the beta phase also. Now, this is delta TD, and if this was our T star, which is the temperature of surface, it means that the overall surface temperature must remain T star; so delta TD and the other temperature delta T component which is equal to delta Tr, it should vary like this. So delta Tr is all the way positive, for this part, delta Tr for the beta phase however has different values at different points. For example, (over) from this region to this region, delta Tr is positive, so it is in this particular region; but what about this part? Over here delta TD itself has exceeded T star, it means delta TD must be negative to adjust for this extra long, and therefore when it is negative then the overall temperature will come down to T star.

So in this region, delta Tr must be negative. So we have the distribution for delta TD and delta Tr for both alpha phase and the beta phase. And what we see is that delta TD is negative in some region and positive in some region. The way we have taken the schematic, it need not always be the case, it can change from configuration to configuration. In fact we will be able to predict it, and over here delta Tr was positive delta TD was positive throughout, but when it came to delta Tr, which adjusts by the changing radius, it was positive throughout for the alpha; in the beta it was positive for two parts and negative for the central part. So we will come back to this picture in the next lecture. Thank you.