Fundamentals of Materials Processing (Part–1)

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Lecture Number 13

Heat Flow (Solidification of Alloys)

In this lecture we will start with discussion on 'Solidification of Alloys'. So far whatever we have discussed has been about pure materials, pure metals if you will. So, the topic is 'Solidification of Alloys' from the point of view of heat flow; so the overall topic is still heat flow, but we are now talking about.

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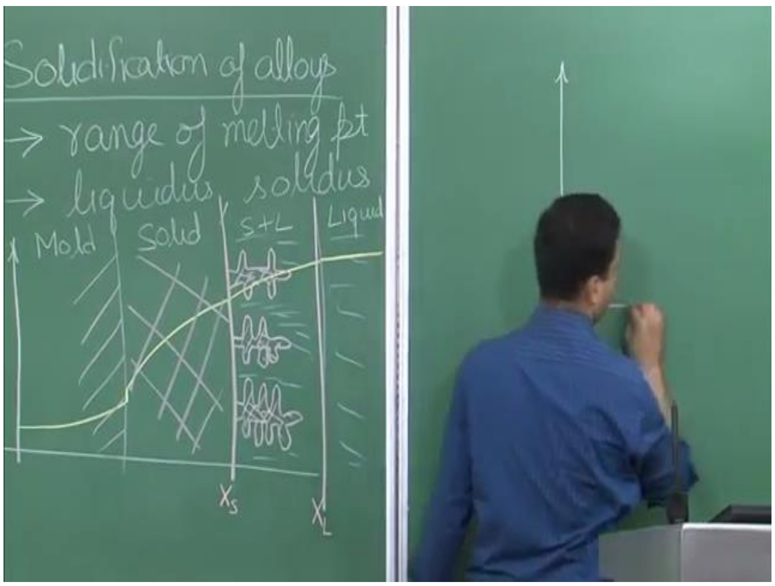

So the first question comes to mind is 'how is the solidification of alloys different from what we have been discussing so far, which is pure material?' So for that, what you need to realize, is that whenever we are talking about alloys, it has not one melting point, not a unique melting point; it always has a range of melting point, range (())(01:15). What do I mean by range of melting point? Remember it has a liquidus, it has a solidus, and in between these two temperatures, the material remains or co-exists as liquid and just solid; and therefore we can say that the all the temperature range between the liquidus and solidus is the range of melting point. So how will that make a difference?

So again first start with how the temperature profile would look like. Now here, there will be a difference. So far we were talking only about mold, solid, and then used to come liquid. But here, we will have another phase, where we have both solid and liquid, and then comes the liquid. So, the temperature change, even if you are taking about these four layers, the temperature profile would look like; so there will be, we are assuming again the most general case; so there will be probably a temperature heat resistance interface resistance over here, and then; now here, and so on.

So what do you see? That the temperature in the most general case, there will be temperature dropping mold, there will be temperature drop at the solid and mold interface; there will be temperature drop in the solid, in the solid plus liquid, and even here if we assume liquid at TM, that is without superheat, that is not going to be a problem, or that will not take away any kind of information away from us. But still it looks like a very difficult problem to track. So again, we will not look at what or how to derive for, in fact there is not, I am not aware of any analytical solution for a case like this. But what we will look at is, what the solidification rate people have observed experimentally, and we can we can relate it with what we already know.

Now, if you are drawing this, then also let me draw what exactly these look like. This is your mold, now this is your solid, this is your liquid, and in between solid plus liquid, what do we have? Here you have some growing solids which exists along with the liquid. So here, these this is your solid part, and let us say, let me use a different colour; so this is liquid; and this is the solid part, so if we have. So here is the mold, here is the region, where there is only solid, and here is a region where you have both solid and liquid; and here is a region where you have liquid.

So now you can clearly see that there is a interface, where, upto which only solid exists. So, that is your solidus line, and we can call it XS. This is a line beyond which you have only liquid. So, this will become your liquidus line, and let us call it XL. So now when we are looking at solidification rate or basically S versus t plot, we will not be looking at only one line. Remember earlier we had only solid-liquid interface, so we used to draw only one plot; but now, we have two things to look at, XS and XL, the solidus line and the liquidus line. So let us draw how this will look like.

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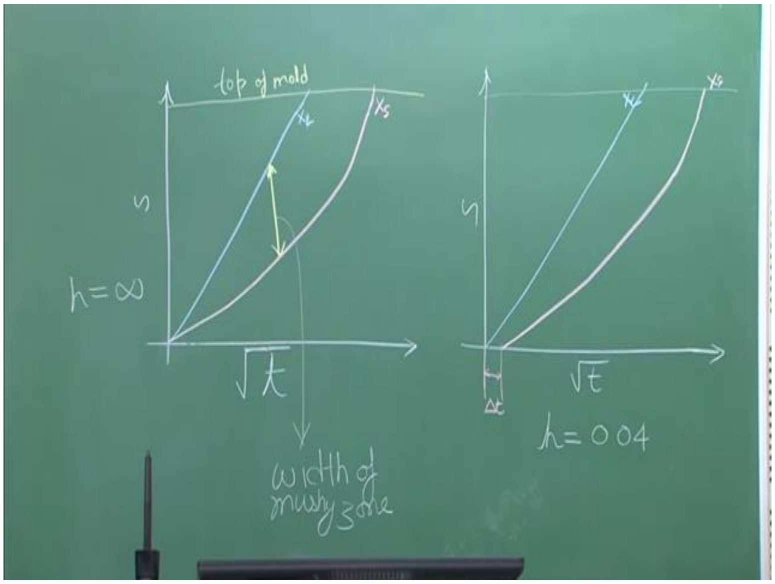

So S is the length which has crossed or which has solidified in the terms of liquidus or solidus, and now, this is let us say the top of the mold. So now for the solid first, the first interface to reach the top of the interface top of the mold would be liquidus, a you can see, it is ahead of the solidus. So in terms of time, it will be below or it will reach this point earlier to solidus, and it comes out something like this. And for the solidus, you get lot; so this is how this plot looks like and there is just one modification, this has to be root t, because we are assuming a insulating mold kind of condition. Whenever we have a sand mold like this, then the condition is like that of insulating mold, and insulating mold, you remember, S is proportional to root t.

So remember that I had earlier mistakenly wrote it at t; it is not t, it should be root t. So S will be S and root t you see a straight line. Now there are few things that you can look at this plot and understand. One is that the liquidus, so now this is your XS line, and this is your X; no this is your XL, it has reached the liquidus reached the top of the mold earlier; and this is the solidus line. So as you can see, liquidus has reached the top of the mold, or it has reached the end earlier; solidus has reached after that, we already know from this from here; this will reach earlier, this will reach later on.

Another thing is that XL (fol) follows a straight line between S and root t, so it very nicely follows the S versus root t plot. Therefore it is very much you can say agrees to the insulating mold condition. On the other hand, XS which is the solidus curve, it shows some variations.

Although it is straight line to the, to most of the extent, towards the end, it becomes, or it rises very sharply. So there is some some changes occur towards the end and you can understand that once the liquidus has solidified then suddenly the concentration and we will see that more when we talk about composition, that towards the end, the composition rises abruptly, and that may be what is leading to this change in the plot over here.

Now another thing is that when we are doing this, we are assuming that h is equal to infinity. What does h equal to infinity mean? That this is 0, there is no gap over here, or there is no interface resistance. If, on the other hand, we take h as a some small quantity, it means that there is some amount of interface resistance, and that will lead to some change. What changes we will see? So, the first change is, in terms of liquidus, you so not see much change; the liquidus remains as it is. So this is S, this is root t. But when it comes to solidus, you see a shift over here. Overall plot remains same, but, over here, because of the presence of interface resistance; so whenever there is a interface resistance between the solid and the mold, you would see that the XS which is the solidus plot, gets shifted a little bit in time. It starts a little later.

And remember, we talked about it when we said that the S is equal to a root t minus b kind of has the experimental form that is that what people have observed, and that delay, one of the reason was, suggested was that that is because the interface resistance, because in the, in some even in the materials or in the configuration where you are saying that there is no interface resistance, there is still some finite interface resistance, and which is what leads to that minus b term. And this is what is we can see over here. Here we have some finite interface resistance, and this leads to delay in the solidus curve. So these are the two different kind of S versus time plot that you will see, for the alloys.

Now, there are few more things that we should look at. If you look at this gap, what does this gap represent? For any particular time, what it is saying is that the your solidus is that this point and the liquidus is at this point. So, what it is saying is that, let me erase this part; what it is saying is that, in that region, both solid and liquid exist, co-exist. So let us call it, let us give it some (term) name; and it is called ‘width of mushy zone’. It is not the name, it is not a name I am giving it, it is what it is called; it is called ‘width of mushy zone’. So this vertical distance, that vertical gap that we get, it represents ‘width of mushy zone’. And why is it called the why why is it named like this? Because it is in this region, both liquidus, liquid and solid co-exist.

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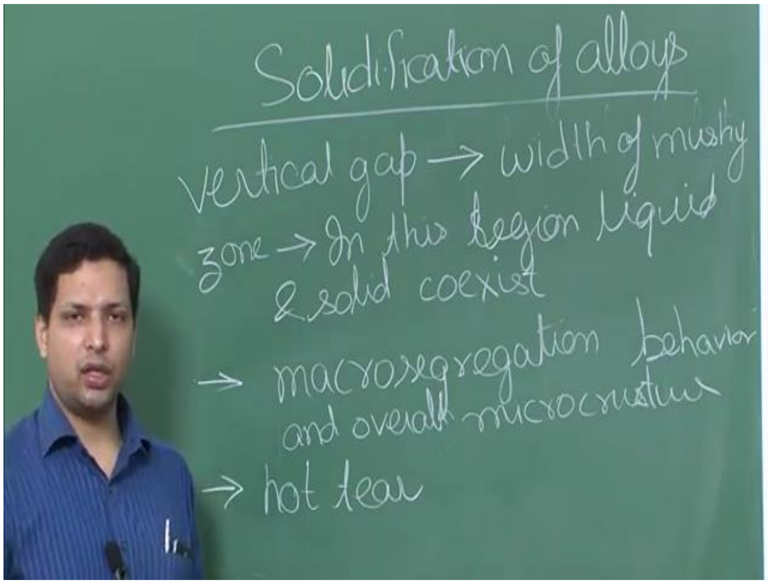

Okay? So, it is, if you look at this particular time, this is where the liquidus is, this is where the solidus is, and therefore it represents from your original plot; this was the region where both solid and liquid exist, so it will be present, the width of that region; and therefore it tells you the width of the mushy zone. Now there are several important points that you must be aware when we are talking about this width of mushy zone. One, it determines what is the macro-segregation, it determines the overall macro-segregation behaviour. And not only macro-segregation, since it is (diff), it is influencing macro-segregation, it also influences and micro, overall microstructure. It can also influence overall microstructure.

Now when the liquid solid part solidifies first, or the solidus liquidus has reached, and then there is some solid and liquid left, then what happens is that by remaining part, or the outside region is solid, but in between we have some liquid remaining. Now if that liquid is remaining and once once it starts to solidify, it will contract, and because of that it leads to stresses, and and even lead to hot tear. So this width, it is this width that determines also the hot tear in the alloys. So, larger the width, we have larger the chances of hot tear; smaller is this width, smaller are the chances for this hot tear.

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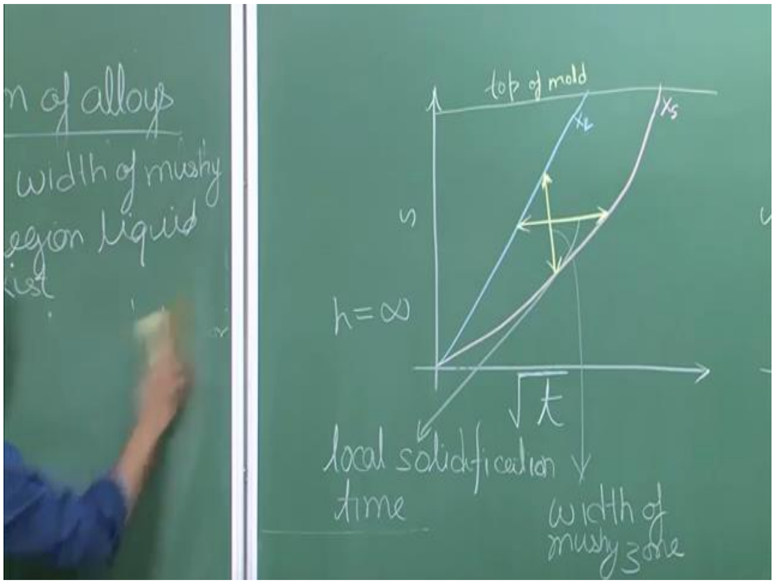

Now as you can see, that is one aspect of the plot, which is the width of the mushy zone; other is this one. You also see a gap over here. What it is representing is that if there is a particular point in your uni-directional solidification of the alloy, then, what is the total time that it takes, first from the point that the liquidus crosses it to the solidus to cross it. So it is at this point liquidus crosses it, and it is at this time solidus crosses it. So if these two, as you can see it is the (vert) horizontal axis, or horizontal axis will represent time.

So it represents the time for, the time difference between the liquidus and solidus curve to cross. And therefore, it is termed as ‘local solidification time’. So this region is the ‘local solidification time’. So this represents the local solidification time, as I mentioned over here, that is the time that at a particular point after what after the liquidus has crossed, how much it will take for the solidus to cross. Now that time is also again of importance when we are talking about alloy solidification.

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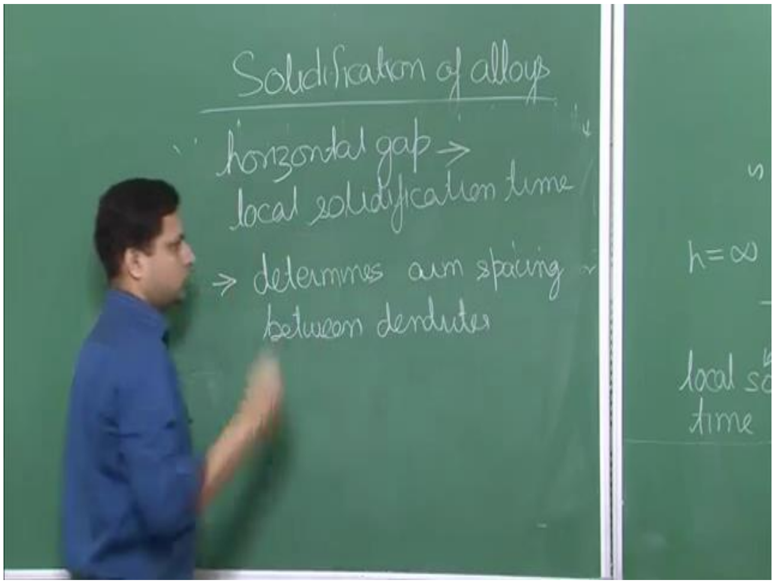

So let us again put some of these points in perspective. So this horizontal gap is called; this is the horizontal gap; what does it represent? It represents local solidification time; and, like the vertical gap, it also determines some of the characteristics. What are those characteristics? It determines the arm spacing between the dendrites. So both of these gaps have importance. So if you can get this plot experimentally, then, based on the horizontal gap that you are getting, and the vertical gap that you are getting, you can say or understand a lot about the behaviour of the material that you will obtain after solidification. Now that is the solidification in general the solidification of alloy in general.

Now there is one thing in particular that we can still get from this; although we are not looking at the heat flow equations and all those details, but, let us say that we were looking at solidification of alloy in a very very insulating mold. How will that, so we are still looking at solidification of alloy, but now we are looking at insulating mold.

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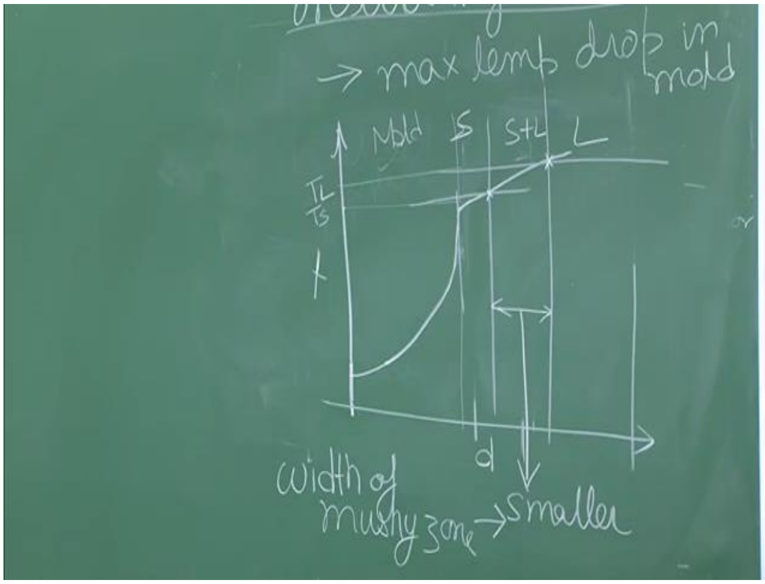

We should not have erased the part solidification of alloys because it is still there. We are looking at insulating mold condition. Now remember what was the implication of insulating mold. When we are talking about insulating mold, it means that maximum temperature drop takes place in mold. Right. So the maximum temperature drop has to take place in mold. So how will it change? Again, let us start from our temperature profile; this is your temperature, this is your distance, and, this is the mold, this is a solid. Now if the maximum temperature drop, if this is now your TM, actually we should not call TM over here; we will have T liquidus and solidus, and since liquidus is higher this is T liquidus, this is T solidus.

So the region you get below which you will get only solid, you will be calling it (liqui) solidus. Now over here, we will have maximum temperature drop taking place in the solid, sorry in the mold. And then we have the solidus, solid over here. Now this, this represents our solidus, this represents our liquidus because in this region, we have below this you have only solid, above this you have only liquid. And in in over here, you have solid plus liquid. So now this is one plot; actually what I wanted to draw was a little bit different; I should have; since we have insulating mold, our temperature drop should be even larger in the mold part. So, let us bring it over here. And therefore; now what is happening here?

You see, this is this becomes your solid part, this becomes your solid plus liquid part. So let me clean it a little bit, so that you can clearly see. So what is the difference that we have now, compared to what we had earlier? The difference is that, because the maximum temperature drop is taking place in the mold, there is a very small range of temperature change to take place in the solid and the solid plus liquid part, which means, the width of this zone which is more important than any other (zone) width; this width becomes smaller.

So when we are talking about insulating mold condition for solidification of alloys, the solid plus liquid region, or the width of mushy zone becomes smaller. So now we have a smaller width of mushy zone, which means, that as soon as the liquidus reaches the end, the solidus will also reach the end, or in terms of this plot, if we look at it.

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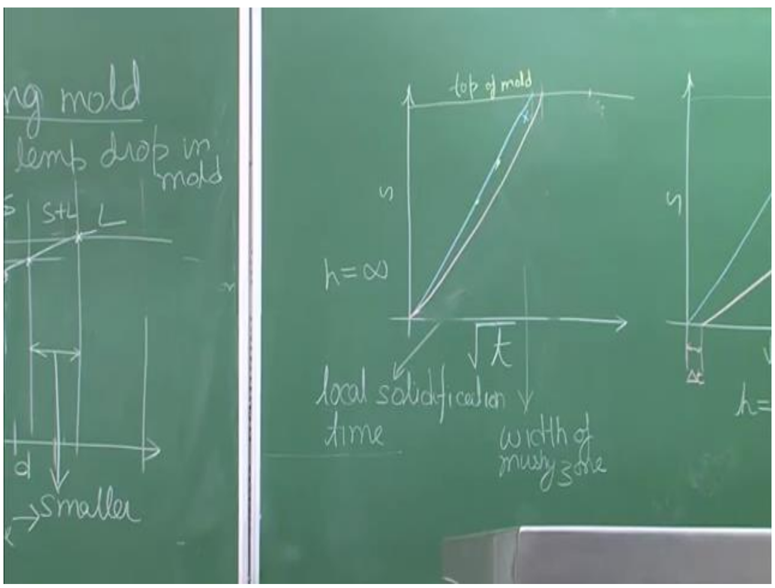

So you see, the total time that we have over here, the difference between the time becomes very small. As soon as the liquidus reaches the top, solidus also reaches the top; and therefore it starts to behave like a pure metal. And therefore what we will have is that the total overall equations that we derived for pure metal can also now be applied for something like this. So when you have a very insulating mold where maximum temperature drop is taking place in the, inside the mold, and not inside the solid and solid plus liquid part, it means the material will behave very much similar to what we have discussed for pure metals.

The only difference would be that this temperature that we have at the mold-solid interface, it will keep changing, although in a very small narrow temperature range, which will be only this much, but it will change with time, which we did not have when we were talking about pure metals. But otherwise, all the equations that we derived for pure metals, you can apply it for solidification of alloys, when you are using a insulating mold. So with that, we will come to end for the solidification of alloys, and it is at this time, good it will be a good idea to let us review what we have done for the heat flow component.

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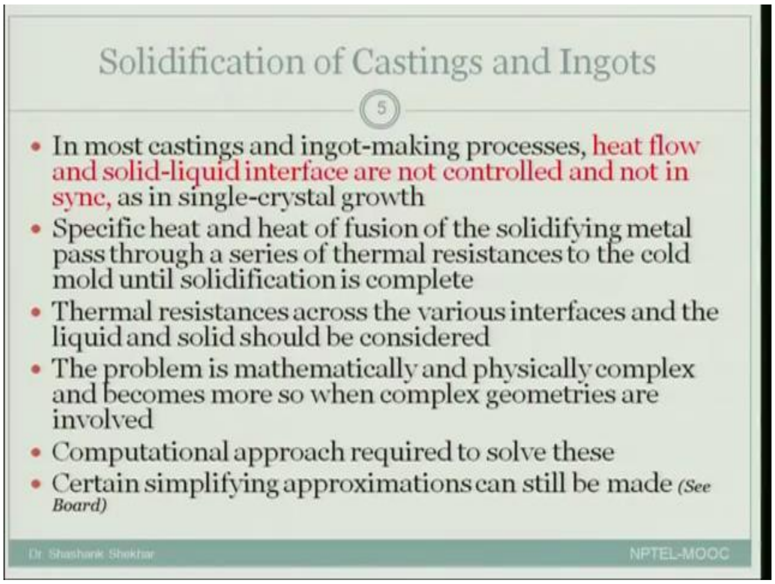

So let us summarize what we know. So we talked about the solidification of casing and ingots, and said that the overall equation are always very complicated but we need some simplifications and therefore and for that, first we need is a heat flow equation, and we saw that for, the heat flow equation comes from the conservation of energy, which is from the, which gives us the Fourier law, and from that we get that heat equation.

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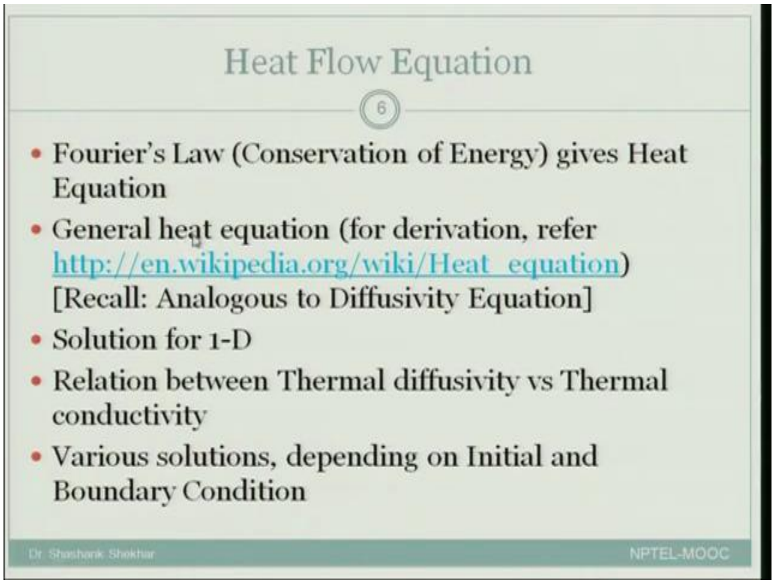

Actually you can go to some of these Wikipedia type of websites and get some more detailed information about the heat equation; and in (parti) in this particular course, we solved 1D solution for some two very simple conditions for two very simple cases; one was the insulating mold, the other was the interface resistance. And then we also showed you the solution for two difficult cases, although we did not go through the mathematics of it. We showed you that there is a relation between thermal diffusivity and thermal conductivity, and various solutions were discussed.

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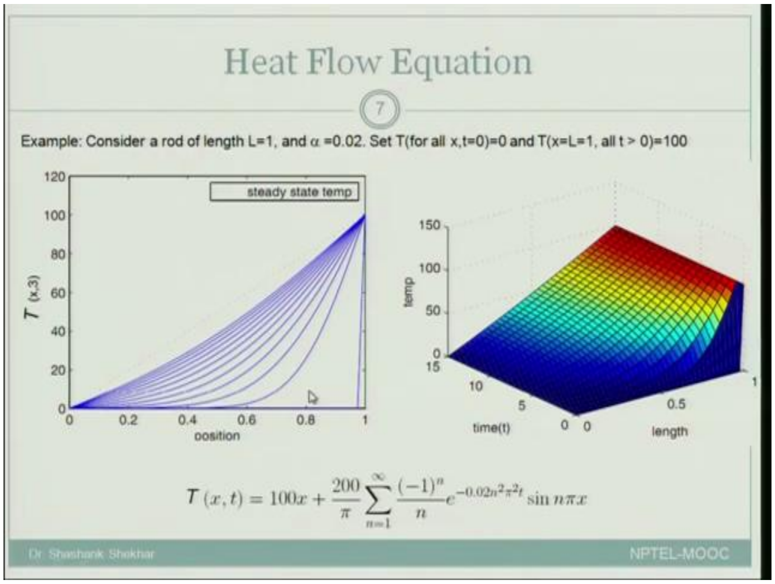

And at this point, I would again like to emphasize, we discussed two different important conditions, or two different temperature profile that we have discussed. One was the semi-infinite insulating mold condition, Over there you remember we said that outside temperature remains constant, but not because we are fixing it or not, because we are enforcing it. It is because the mold size is assumed to be so large, that the temperature rise will take place after such a long time that before that solidification would have taken place.

The other extreme case that we were talking about where where you will see that you can impose or where you have imposed a external temperature, is this one. See this is the kind of solution that you will obtain, and this is also a standard set of solution, when you impose temperature from the outside. So you can assume that this is the mold, and this is the TM temperature in some units and this is the room temperature. So here you have fixed the room temperature over here, and it is, to begin with, the temperature profile looks like this, it goes with increasing time; it is looking like this. But, in here, the outside temperature will never increase beyond the ambient temperature that has been fixed.

And the steady state will be this dotted red line; at this steady state, whatever amount of heat is coming in, is the amount of heat going out and the amount of heat is being absorbed; and this looks like, this is how the plot will look like on the right, that you have shown with increasing time. So this is starting time, and then you when you keep going, at some point, it will become steady state. So this is the steady state. But this is not the insulating mold condition; I have shown it so that you can appreciate the difference between insulating mold condition where we have invoked semi-infinite mold, and the condition where you have enforced a temperature, some temperature, which is ambient temperature.

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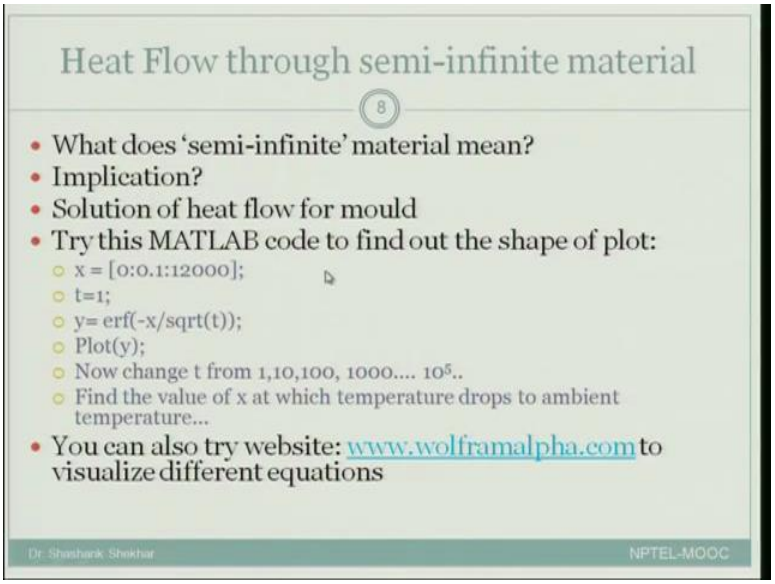

So we talked about what does semi-infinite mean, and, if you are interested in some kind of computation for this, there is a very simple MATLAB code, that you can use to plot, and we will show the plots that you have; this is a very simple plot for the semi-infinite mold, and here is the equation that is that we have for the semi-infinite mold condition, and this is what is given over here. You can, in case you do not have a MATLAB, you you may even try this website which is the parent company of MATLAB and over here you can simulate some of the simple programs.

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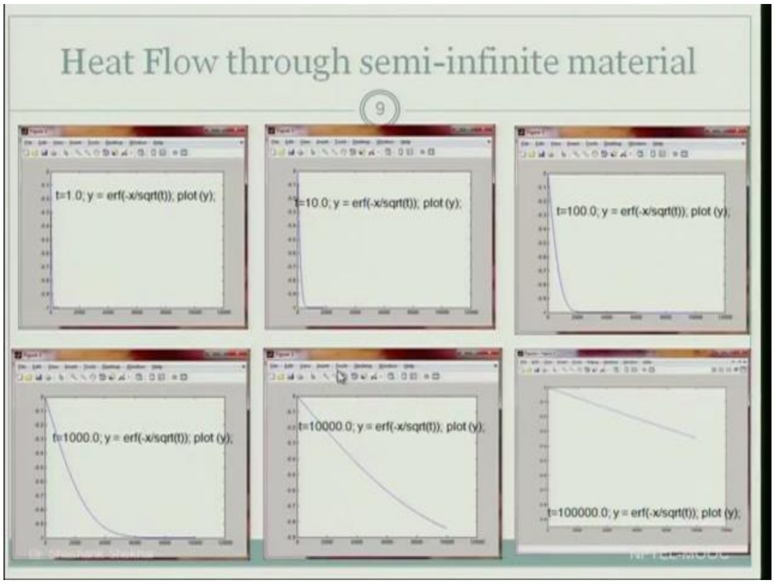

And this is the plot I have shown over here for different times. So see, over here, time is equal to 1, 10, 100, 1000, 1000, and I have kept the total distance constant and this in some unit, this is the temperature. So what do you see? As the time increases, this is how the temperature plot looks like; so this, you can assume this is TM, this is T0; so this temperature profile of the mold is increasing at increasing distance, and this is how it looks like. After some time this is, at some point at this like this, and after some time you start to see a increase in the overall temperature. If you see now, if you keep giving it the temperature or the temperature at the inside remains constant at TM, the outside temperature may even rise and get to up value very close to the TM temperature.

So, we will leave it at this, and we will come back and summarize the some more of this and solve some problem related to this, and then we move on to what is the, the next part of the course which is compositional variations when you do solidification. So, we will meet in next lecture. Thanks.