Analysis and Modeling of Welding
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Lecture – 16
Solute Segregation Profile - part 2

Let us resume from where we left over, namely in the Solute Segregation Profiles; and we are in the second part of that. And in the second part, what we are going to do is look at the equation that we have derived for this variation which is exponentially decaying in nature, and then see how that would allow has to inspect the kind of micro structure that would be formed in the fusion weldment.

We would like to see how it could guide us to say whether you would have a columnar microstructure or in equi-axial microstructure; and in a weldment, we normally want to prefer equi-axial microstructure. And the way we want to proceed as follows, we have already seen this small domain which is a small part of the weldment aligning in the direction of the maximum temperature gradient. And we are instructing this domain, and seen how the compression profile will be away as we go from the solute to the liquid in the direction of the maximum temperature gradient.

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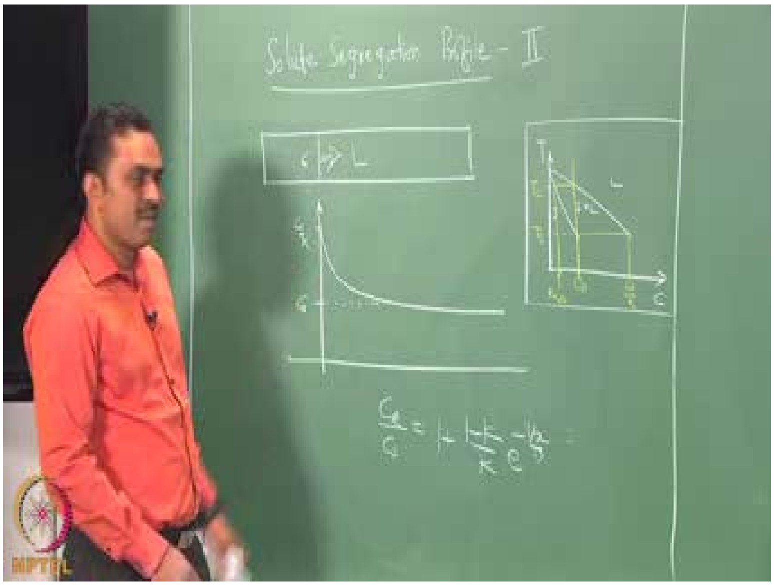

And this profile nature is already given to you in the previous part. We have discussed it as the liquid composition given by this expression, expression decaying. And V is the velocity of the solute liquid inter phase. In the fusion zone, it is related to the torch velocity by its trigonometric function depending on the distance from the surface of the weld to the bottom of the weld, so that is what we know about V. D is diffusivity of the solute in the liquid; and x is the distance from the inter phase into the liquid, that means this is the profile available only for liquid region.

In case, there are situations where in the solid, there is some amount of disquisition that could be accounted for and then you would called as back diffusion and that will be regarded separately later on; but for not that is ignored and we are only looking at limited amount of mixing in the liquid and because of which the profile is there. I am showing you here a simple phase diagram of a dilute alloy, for which we would have done this analysis. And I have would draw the phase diagram showing with the solid region, solid plus liquid region, liquid region. And the composition that we have chosen average composition C naught is here, so where we heat the liquidus that is a temperature we are calling as T L; and where we heat the solid we are calling as solidus temperature.

And the initial, the first solute to form, for a composition of C naught is k C naught, and I would write it here this is k C naught. And the last liquid to solidify from a unlike composition of C naught will be C naught by k. And we have seen already that in this profile, the maximum composition at the interface is C naught by k; for away it is C naught. And so what we do is that in this domain, we want to draw the same plot, but not of compositions but of let us say liquidus temperatures.

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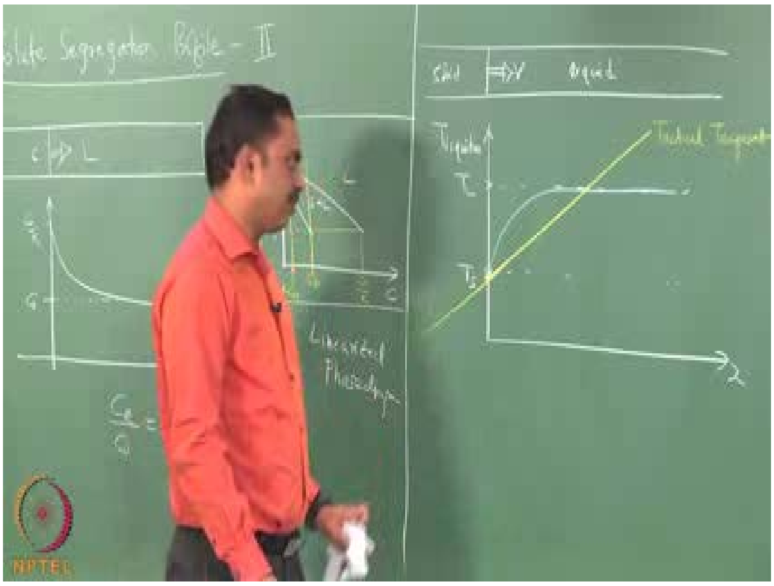

So, how does that look like? What we are doing is liquidus temperature is like a map. We are just converting the compositions into a liquidus temperatures use in the phase diagram, so that we will do like this same distance, they way they have drawn here, the same distance. So, for comparison, let us just ensure that we are looking at the same domain.

So, how does this plot look like? So, what we need to do is at the interface at the at x is equal to 0, the composition of the liquid is given by C naught by k, C naught by k is such that the temperature of the liquidus is very low which is T s and high value is here. Far away, you have got the composition is C naught and C naught composition will have a liquidus which is high which is T L, so this is the T l.

And the variation is an exponential decaying variation for the composition. And if you make an assumption that the phase diagram is linear, linearized phase diagram, it just means that the lines here the liquidus and solidus lines are straight lines. So, if you were assume that these lines are straight then this compositional profile which is exponential will be mapped on to the liquidus profiles as also exponential, which means that the liquidus profile is going to look like that. Now this is how the temperature at which the liquid will start solidifying would look like, what would be the actual temperature actual temperature should be then given by a plot; and that plot, I am drawing in this manner.

It would be drawn something like this; this is the actual temperature. It would be going through the same point here, because at the composition we are talking about to the liquidus temperature is matching as the condition at the equilibrium for the solute and liquid to be there. And therefore, this is how the profile.

Now I am not drawing the temperature profile with any slope changes, the reason being that the thermal diffusivity is about four orders of magnitude higher than the solute diffusivity. So, therefore, the temperature profile is going to be even out much earlier than the solute segregation profile. So, there is for the temperature plot is always drawn in a straight line. Remember, how is the temperature plot in the weld zone.

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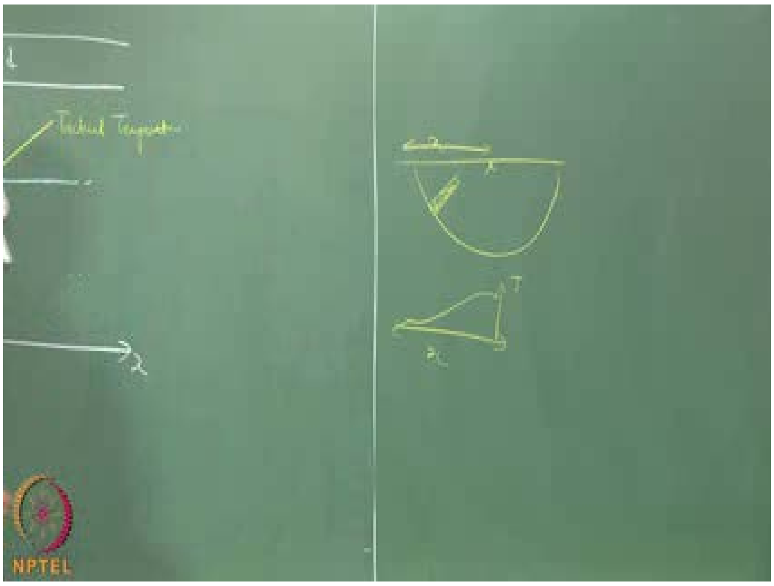

In the weld zone, it looks like this. If you want to look at this distance, over this distance, the temperature profile is going to look, there is a slope change. However, we are not looking at such a distance, we are actually looking at only small distance; and in that small distance, we are going to have the profile fairly linear and that is what we are assuming.

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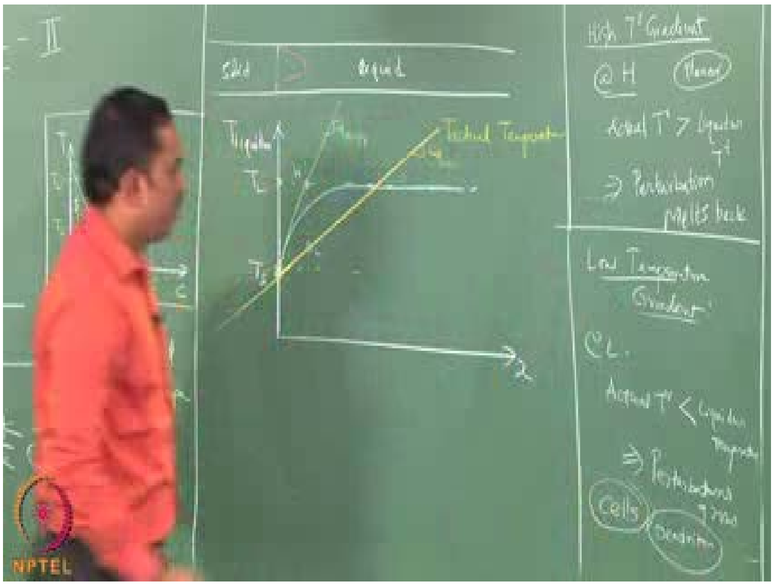

And therefore, this plot we can just also put one gradient G. Now, there are various possibilities that are existing in a real weld. If you have a heat source that is very intense the heat source distribution is very intense then what would happen is that the temperature variation is very steep. So, you may have G value so high that you may have a situation like this, G, I would say high. And you may have a situation like this also G low. Now we can inspect what will be the effect on this solidification mode by looking at these two profiles, when we have a low gradient and high gradient.

What we mean by high gradient is situations like laser welding, electron beam welding. Low gradient we mean situations like gas tungsten arc welding or manual arc welding. So, if you change the heat source intensity, temperature gradients are changed from shallow to narrow, and therefore how you can look at the interface is something that we can do now.

Now, what I want you to imagine is as follows. Imagine that this interface has got a perturbation due to normal vibrations that are there in the system thermal fluctuations etcetera. So, let us say that this interface is not straight, but let us say it has got a fluctuation. Let us say it has got a fluctuation I am exaggerating it because I want to show clearly in the board. So, the fluctuations are generally much, much smaller. So, if that is the fluctuation then how would the temperatures look like at the front of the fluctuation is something known, when you draw this vertical line. And you can see that there are two intersection points, I am putting this point as H, and this point has L.

And we can inspect what is happening at these two points. What is happening at H that is the situation where high temperature gradient, under this situation at H, what is happening is that the actual temperature is higher than the liquidus temperature you can see that the blue line is below to green, which means that actual temperature is higher than the liquidus temperature. So, this implies that this solid which happens to get perturbed and then get a bulge is finding itself at a temperature that is supposed to be in a fully liquid region, so that solute is not stable it suppose to melt back. So, it means that the bump or the perturbation melts back.

So, what it means when you say the perturbation melts back is that the front between the solute and liquid is going to be flat; it means that the growth of the grains from the fusion zone is going to be in a flat manner; that means, that microstructure will not be a cellular and grain, it will be having flat grains and it will be also columnar in nature. So, that is what we mean by a high gradient.

We can inspect the situation it L and C, what would happen. What we would mean by L, we mean by low temperature gradient. If it was low temperature gradient, you can inspect what happens at L, you can say at L, the bump accidentally the perturbation has found itself at a temperature which is below the liquidus.

So, we can see that the actual temperature is less than the liquidus temperature, which means bump is finding itself at a temperature below liquidus means below liquidus you are supposed to have solute growing which means that the bump is actually now in a condition suitable to grow. Which means that this breakage of the planer front of solidification is going to take place, and you are going to have a perturbation that is grow, which means that in this case the growth of the solid is going to be either cellular or dendritic in nature. You can say cells or dendrites; and in this case, you would get the planar.

So, this is how the impose temperature is going to change the microstructure evolution in the weldment as to solidify. And you can see that we are able to make this conclusion only because we know the variation of the liquidus; and we are able to get the variation of the liquidus in the liquid region for the various compositions in the liquid, because we know the composition profile also from solving the equation. So, now, we have this then we can use it further to tell what would happen. What we can do is, we can inspect this height difference, and ask what would happen. This height is basically being giving a name this height is basically the difference between the actual temperature and the liquidus temperature.

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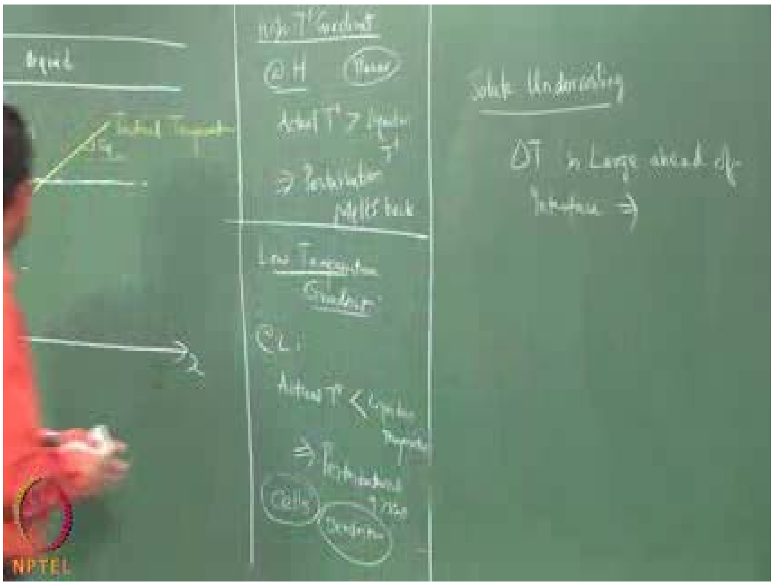

And a temperature below the liquidus where the solidification is enhanced or possible then it is called as under cooling and because this is coming from the solute segregation profile it is called as solute under cooling or solutal under cooling, this delta T.

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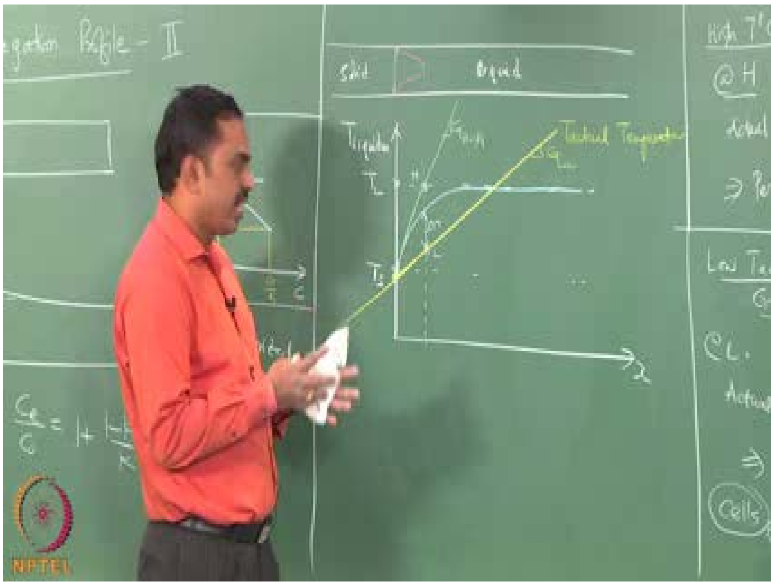

What happens when this delta T is large? What happens when delta is large ahead of the interface, then what happens is that ahead of the interface you have a situation where the liquid is having a composition such that actual temperature is much below the liquidus temperature; that means, it is all fully under cooled it has an of driving force to solidify.

So, you may have situation where nucleation can take place ahead of the interface which means that it is not necessary that the grains of the fusion zone only can grow in, you can have nucleation of fresh grains ahead of the interface.

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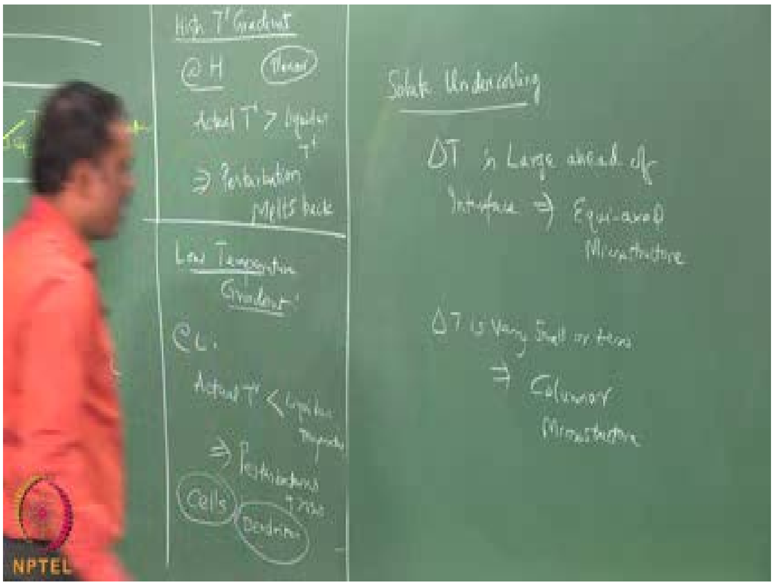

And that means that you could have equi-axial microstructure. And if delta T is very small or 0, if this is very small or 0, in the sense if it is also a situation like this like the very high temperature gradient which is going above the solute segregation profile causing this liquidus temperature profile in the blue line.

If the actual temperature is above that then you have no solute under cooling; and in such situations, what happens is that it is impossible to nucleate a grain ahead of the front and that means, that the grains belonging to the weldment only can grow inside which means that you would have what is called a columnar microstructure.

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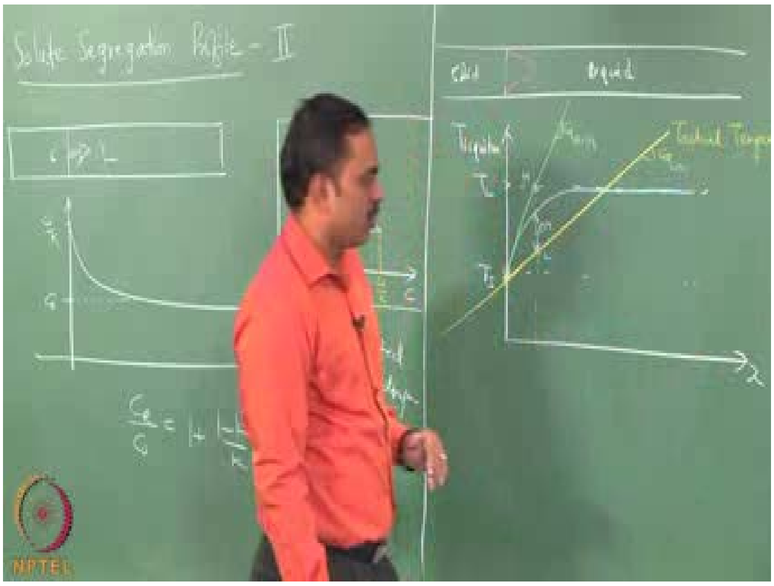

So, this is how we can relate the profile with the under cooling given by the name solute under cooling with the microstructure that is going to be coming out. There are situations already we have seen in the reality; people have worked in welding would know that electron beam welding usually gives you columnar microstructure in the fusion zone. And if you take GTAW, we normally tend to see equi-axial microstructure. So, this again conforming that in electron beam welding, the gradients are very steep and therefore you get columnar microstructure; and in the GTAW or such processes, the temperature gradients is not so steep and you can have under cooling and can have a equi-axed microstructure that can come up.

Now what governs the delta T, and how can we see that change over, the applied temperature gradient is it good to give you the equi-axial microstructure are not, that can be known by seeing with respect to the tangent where we are.

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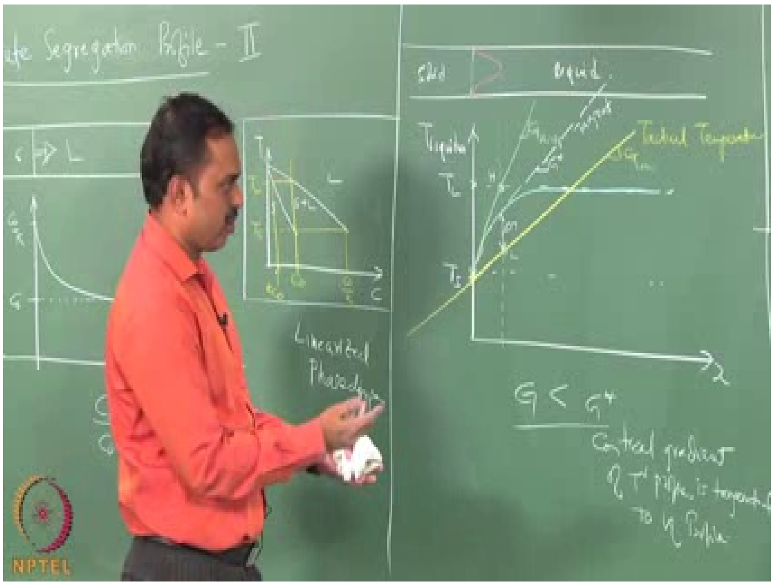

So, I would just draw the tangent in the dotted line. If this was a solute segregation profile, we can draw a tangent. This is the tangent and we can inspect this as a critical slope. And we can ask a question the imposed a temperature gradient if it was less than the critical gradient of a temperature profile that is tangential to this liquidus profile. So, then you have a situation where you have equi-axial grain possible, equi-axial grow possible. So, this criterion is also called as the criterion to know that solute under cooling will be take place. So, it is also call as a solute under cooling criterion.

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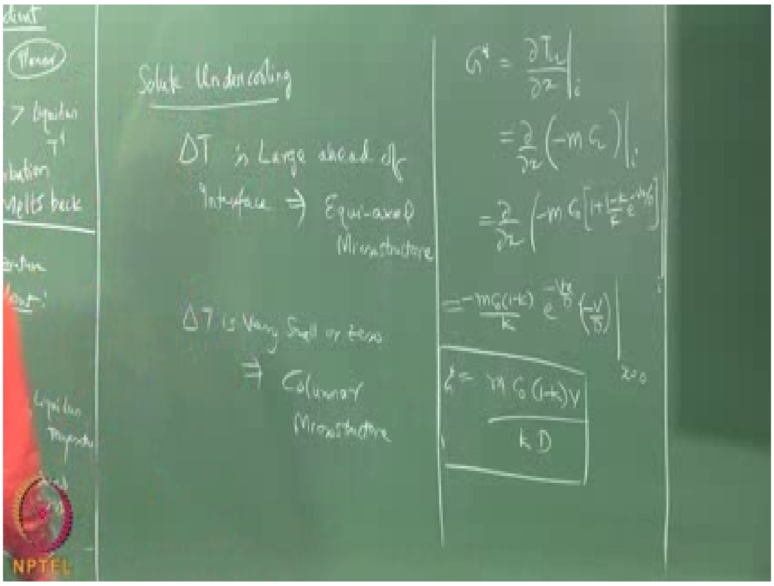

So, what would be the G star is important for us to inspect. Now, G star is nothing, but the tangent to this slope, and tangent to a slope can always be inspected because you already know how to inspect that here. So, we could then write a simple expression and put that value here. And let me just clear the board at one and then show you there. We can show it here. Now what we need to do is basically G star, and G star is nothing but the critical temperature gradient and that means, it is the liquidus temperature gradient like this. T liquids itself is known for us at the interface this itself is known T liquidus.

It is known from looking up the liquid us temperature from the compositions. And if the liquidus is says straight line we can say that it is m that is slope of the line and the solidus and liquidus lines are going down, so it is minus m into the compositional profile. And this already we have the expression there. So, you could write it has dou by dou x minus m and we have got that expression C L is nothing but C naught into 1 plus 1 minus K by K e raise power of minus V x by D and this has to be applied at I interface which is having x is equal to 0.

So, you can then substitute that to see how it looks like then that would be minus m C naught, and 1 is gone because you are differentiated. So, you have 1 minus K by K coming in, and you would have e raise power minus V x by D into minus V by D at x is equal to 0. And you know that x is equal to 0, this function in a way goes to 1, so minus and minus will get cancelled, and you would have a value like this, m C naught into 1 minus K into V divided by K into D, this is the value of G star

What it implies is that once the G star is known like that then you can inspect in an actual weld what is the temperature gradient I am getting at the fusion boundary. If that temperature gradient is less than this value, then I would be having the solute under cooling possible; that means, I will have equi-axial microstructure. And in case, the temperature gradient interface is more, and then I will have a columnar microstructure.

And that value G star depends upon the phase diagram parameters such as the liquidus slope m, the actual composition C naught, and the partition coefficient K, the velocity of the interface V which is related to the torch velocity, and then D is a diffusion which means that related to the process conditions as well as the phase diagram.

Now process conditions are basically coming via the velocity of the interface, because that is related to the torch velocity. And parameters like D, C naught, K and m are coming from the phase diagram; C naught is something that we can choose as a process parameter the alloy composition. So, K, m and D are coming as a property of the material. So, you can see that it is a condition that can be tuned. We can now ask in the assignment various questions what would happen when you change each of those parameters to this condition. So, given two alloys, which of the alloys will have a higher tendency to form, for example, equi-axial micro structure is something that we can ask.

So, you can inspect this relationship with is to all of them and then attempt the assignment problems and you would get in a idea of how this can be interpreted. And I would also show you some videos of a real time visualization of this solidification under these conditions, and you would get an idea of how the microstructure is evolving, and what I actually mean by perturbation, and what does it mean to say a flat interface growing or a interface that is growing as a cellar and dendrite.

So, I would show you some videos which I have planning to upload in the Google website, I will show you that. And then you can also see the microstructures of typical weldments under these two conditions, and then you will appreciate the meaning of this particular concept.

With that, we come to the conclusion of this solute segregation profile. And then if you attend the assignment problems, you will get clarity on this concept further on. So, then we will continue in the next session about the micro structural evolution further. So, with that, we close this lesson.

Thank you.