Analysis and Modeling of Welding
Prof. Gandham Phanikumar
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

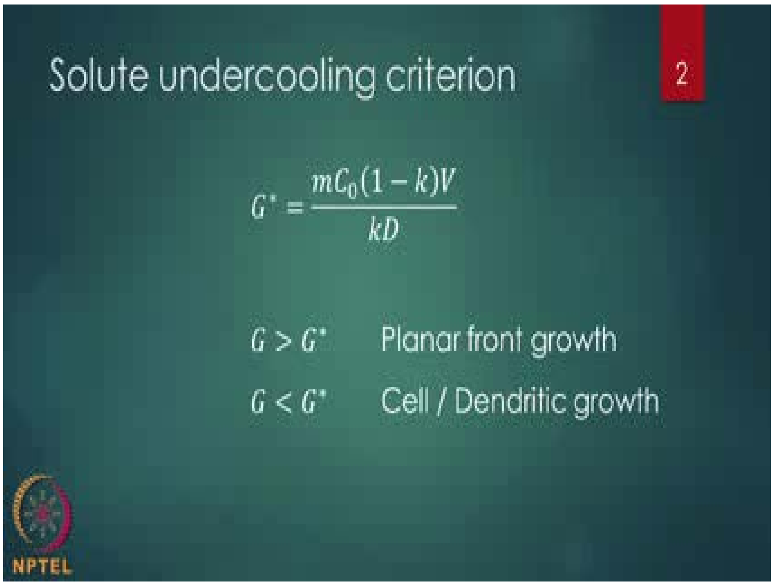
Lecture -17
Microstructure Formation in Fusion Welds

Welcome to the lesson on Microstructure Formation in Fusion Weldments.

(Refer Slide Time: 00:10)

In this lesson, we will be discussing how the grain structure will be evolving, whether the microstructure will have only grains or the grains with cellular or dendritic kind of appearance and whether the segregation channels are going to be appearing at the center line or not. So, this lesson is going to build up on the concepts we have discussed in the previous lesson about the so called solute undercooling. So, we will revise some of those as we go along, and look at how the microstructure formation will happen.

(Refer Slide Time: 00:52)



So, just recap of what we did in the previous lesson, I am writing this expression which we have derived earlier; and we are going to manipulate this expression to look at the meaning of those terms little closer.

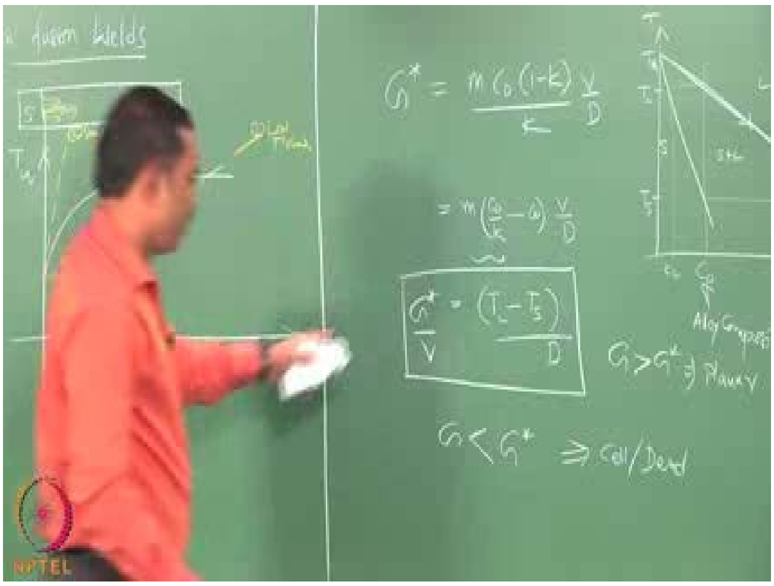
(Refer Slide Time: 01:12)

So, let us just take this expression and see how this is coming about. So, the idea we did was that if we had a domain which is oriented in this direction then in that domain we are looking at how the solid is going to grow into the liquid and how the segregation profile in the liquid is going to affect the microstructure formation. So, we said that we are plotting the liquidus temperatures along the y-axis with distance along the x-axis and; we saw that the profile is going to look experientially and going flat.

And then we asked a question what happens when the imposed temperature is going to be having a gradient that is either shallow or steep. So, if it is shallow, low temperature gradient; and if it is steep, this is steep temperature gradient. So, in both the situations, we were discussing earlier; and we said for the first case of low temperature gradient, we would have what is called the solute undercooling because of which this planar front would be growing with a broken interface where perturbations are stable.

So, they would be going in this manner. And we said that if it was having a steep gradient, then such a thing is not possible, so it would be growing as a flat interface. So, what we would see is that the transition is happening at a critical temperature gradient given by the tangent to this liquidus locus of points. And we draw the tangent here and that tangent will have a slope G star - critical gradient, and that is what is the expression that we have written.

(Refer Slide Time: 03:02)



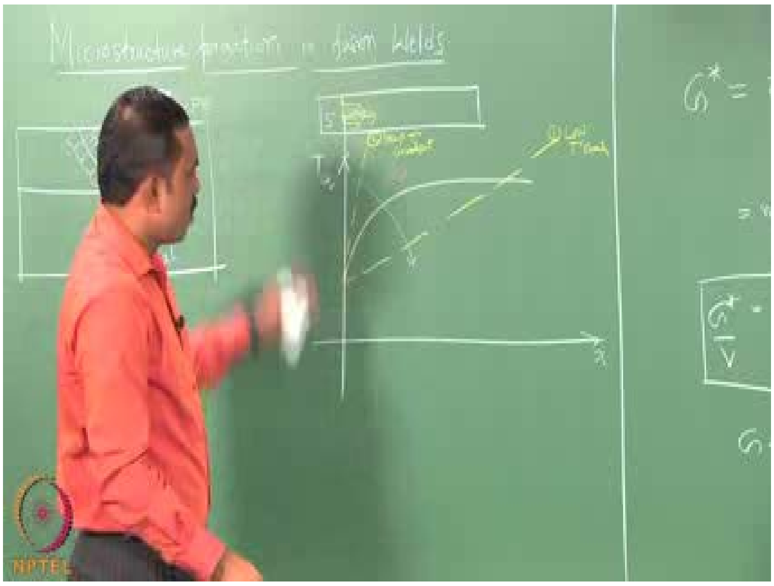
So, we have written the G star as follows. G star, we have written is as m C naught into 1 minus K by K to V by D. So, this expression is to be seen related to the idealized phase diagram as follows. So, the phase diagrams itself we have drawn earlier as a simple dilute alloy phase diagram as follows. And this is the melting point. And if the alloy is here then we said that this is going to be C naught by K, and this is going to be K C naught and we said that this is L and this is T S, two temperatures. So, compared to this, let us just also finish the labeling. So, this is alloy composition that is being welded.

So, we will look at this expression, and see how that would change. So, we are writing it as m into C naught by K minus C naught into V by D. Now if you see this term m C naught by K is, nothing but the difference between this point and this point, because m into the liquid composition is going along the liquidus line is the liquidus line. And if the composition is C naught by K; that means, the m C naught by K is this distance and then m C naught is basically this distance.

So, what we are doing here is this distance minus this distance which means that it is nothing but these two differences of the temperature, and we could then bring the V down here and then see how it would look like which is very popular in the textbooks. So, this is how a expression would look like, which means that whenever G star by V is greater than a particular constant which is given by the phrasing range divided by the liquid diffusivity, then you would have a situations where the undercooling is large enough, and then not large enough, and therefore, the planar front will be stable.

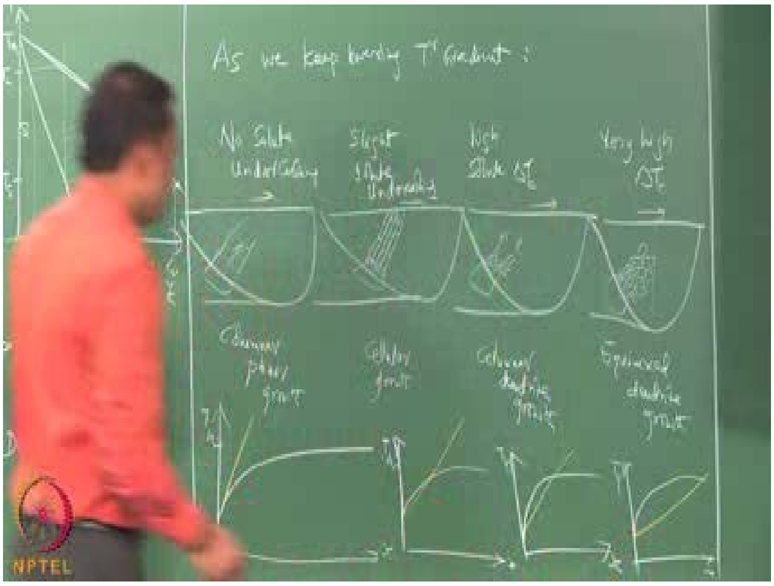
And when G is less than G star that is lower, then it implies the cell or dendrite. So, this is a conclusion we have drawn. So, we can see that though this expression has many terms; finally, it turns out that the ability of the solidification to grow as either as a planar front or as cells or dendrites is basically depended upon the freezing range and the diffusion coefficient of the solute within the liquid.

(Refer Slide Time: 06:32)



Now, this would actually allow us to make what is called as a map the map of how the solidification is happening; and that map would tell us overall the picture of how the microstructure will be in the fusion zone. Before we make the map, you just look at the situation step by step as we go from the temperature gradient at a high value to a low value as we keep decrease in the temperature gradient what is happening.

(Refer Slide Time: 06:40)



So, we can write it here. As we keep lowering the temperature gradient, what is happening is that there is a point up to which there is no solute undercooling. In that case, what happens is that in the microstructure of this weldment would look like this, it is a base material grain, this grain would just keep growing straight down in a planar fashion; that means, at any point, it would have an interface which is just flat. So, that is what is a situation as it goes.

Now when you go further, when you have slight amount of solute undercooling, the same microstructure would look slightly different to grain would have this front would break down and form what are called cells, and then these cells are growing. So, you would see that the microstructure will start having features that are much finer. And these features can be seen in most of the alloys by etching out because the region between the cells has high concentration of the solute.

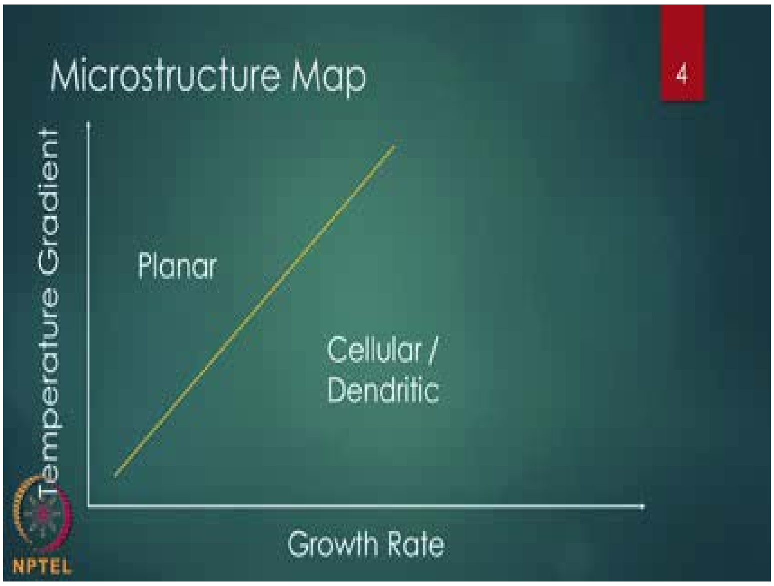
And you may have high solute undercooling then it goes further up; schematically, it has situations like this these are cells and you would have dendrites growing. And these would then keep going further which means that the microstructure scales is further refined; and when you have very high solute undercooling. In all the situations, we are looking at the longitudinal section. And what you would see that is as it increases the undercooling, you no longer have long dendrites that are growing; each of these will have lot of dendritic appearance. So, you see that there will be what is called equi-axed dendrite growth appearance.

This will be long dendrite or columnar dendrite. Here you will have basically cellular growth, cellular columnar both. And you have columnar and planar growth which means that the microstructure will have least amount of features in this situation. And it will have a very fine microstructure with lot of features in the last section. So, this is how the microstructure is evolving.

And as it is evolving, how would is the lines are looking like when a superpose, those also we can draw and compare here. And we will just draw with the yellow line; this is the situation when you are like this. And here, so we are at situation where there is some amount of undercooling, but not too much; and here in the situation little bit more; and here, it will be lot of undercooling, and that is why the grains are able to nucleate inside the liquid metal ahead of the front.

So, this is how as you keep change in the temperature gradient to very shallow, from a very steep then the microstructure evolution will be happening. And this kind of evolution can be seen as a map, a map of the gradient and the velocity. And remember this velocity is a velocity of the front and it is related to the torch velocity by cos theta, where theta is the orientation between the normal to this interface with the horizontal. So, we can make a map out of these arguments also as follows.

(Refer Slide Time: 11:45)



The map requires basically looking at this condition and looking at how we would interpret and we will do that with the gradient and the velocity along the two axis.

(Refer Slide Time: 12:05)

So, along the x-axis, we have got the growth rate; and along the y-axis, we have got the temperature gradient. And we have seen is that the ratio of these two must be some number, so that this transition can happen, which means that you are looking at some kind of a straight line, if you were to take log plot, you basically have a 45 degree line that will be coming.

And if you want to interpret what happens for these two ranges of parameter basically look at what is happening at a given velocity and you would see that when the temperature gradient is high then you should get planar. So, you would write that here; and when the temperature gradient is low, you are supposed to get cells or dendrites, so that is what you write here.

Now, once you have made this kind of a map, then you also have an ability to draw the regions for the remaining regimes that are there, and that we could draw here as other lines ahead, so which also would come out to be like that. So, these how are they going to look like then you can say that here is where we have got cells; and here is where we have got dendrites; and here is where we have got equi-axed growth. Which means that for any given torch velocity if you have very steep gradient like an electron beam welding, you would have grains without much features.

And as you keep decrease the velocity, and then you start seeing the cellular microstructure and then dendritic microstructure and then equi-axed microstructure. So, by the time you come to a welding process such as GTAW, you are basically in the in this regime. So, you normally will have equi-axed growth. And you can use this map to decide what kind of a microstructure we want for a given welding. Most of the engineering welds we require equi-axed microstructure because we would like the impact toughness of these welds to be good.

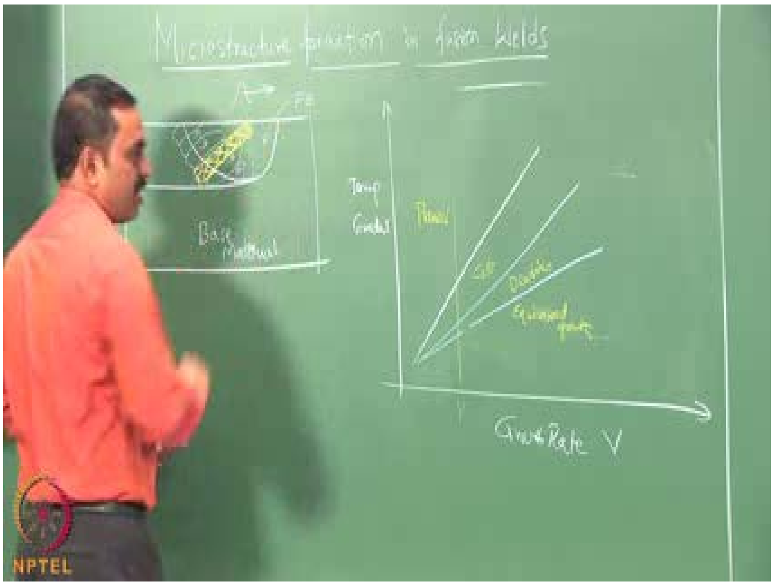
However, in the case of repair of super alloy blades which normally have in oriented grain growth or grain structure or a single crystal structure, then you do not want these kind of features to come, because they may lead to what is called stray grain formation, you normally want a planar growth. So, you can see that if you want to do repair then you would have actually either very, very slow growth rate, and very high gradient which is what is used for the production of the blades itself. However, during the repair these kinds of conditions are very difficult to achieve, and we will see that something else is possible at the other end of the spectrum. So, at this point, I would say this is how the map of the process conditions is going to look like.

(Refer Slide Time: 15:00)

And at this juncture, I would like to also show some videos to see how these microstructure evolutions are going to look for a real alloy. And I will be showing you videos that are that are taken from the European Synchrotron Radiation Facility by my collaborators and researchers who I met during a Prof. Billia and Prof. Gastaldi, they have kindly shared these videos for education purpose. I will be showing some of them and there are analog material videos also, which I have myself in IMTNP lab under the guidance of Prof. Billia; and those also are included here.

So, you can actually see using these techniques of synchrotron as well as the analog setup, how the microstructure is appearing. And these videos are actually for directional growth, but are you see the layout here is such that the directional growth is already present. So, you can imagine whatever domain I am showing as what happening along this box in this particular longitudinal section.

(Refer Slide Time: 16:00)



So, you can see that that is the domain in which we are going to look at the microstructure evolution.

(Refer Slide Time: 16:12)

So, let us look at some of these videos now. In the first video, we are showing a vetch shaped sample, where at the bottom we have the initial solid, and it is going to grow towards the vertical direction upwards because of a temperature gradient that is also driving the heat flowing the vertically in downward direction. So, the growth is going to be vertical upwards as we see it. And I am going to play it, and then you would see that these grains that are at the bottom half of the sample are going to grow. And as they grow initially it was planer, now you will see that it is actually cellular.

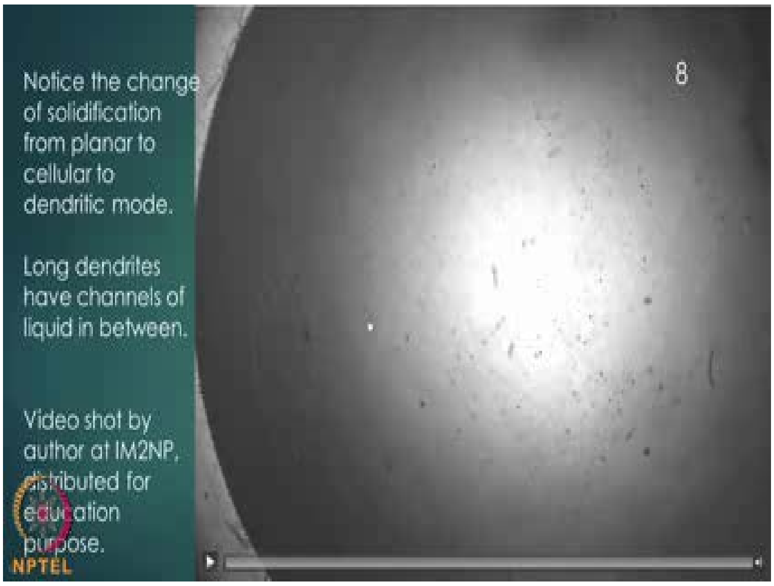
And what I mean by cells is basically these protrusions which are appearing in the direction of growth. Now you see that some of those protrusions have gone ahead and they have also taken side arms and these can then be called as dendrites. So, this is what we mean by a planar to cellular to dendritic transition of morphology.

So, as you see the growth, now you can see that the dendritic growth is quite fast, the side arms are also looking like the primary arm of the dendrite. So, it has the self similar kind of an appearance. So, you can look at the video once more to just see these features more clearly; follow the cursor to see that now the transition is happening from planar to cellular and then to dendritic, and dendrite growth is happening in this direction, these are the side arms.

(Refer Slide Time: 17:45)

In the second video, what we are seeing is basically this kind of a dendrite growth, but which is sustained for a long length, which means that it is representative of what is called columnar dendritic growth, where the dendrites are very long. Now these dendrites are going to live last to solidify liquid between their primary arms and are going to play a role in the cracking tendency of large freezing range alloys. So, again, we will play once more to just see that the dendrite is growing quite long and the channel is going to be on either ends of the dendrite.

(Refer Slide Time: 18:22)



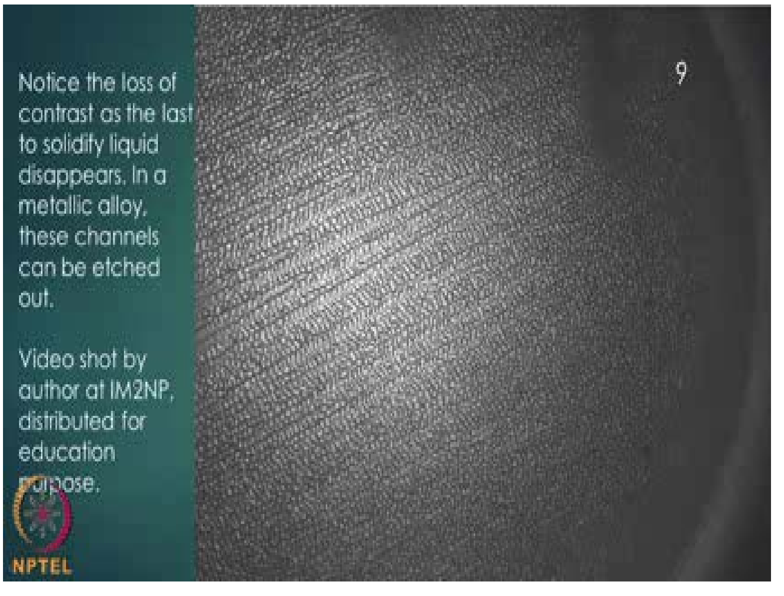
And here is a video of analog system to again show you, how the channel formation happens between the grains; and what I am showing you here at the center on the left hand of the domain is a set of grains which are going to grow laterally outward. So, let me play the video, and to show you how it looks like. You can that the growth is happening in laterally outward; and very soon the morphology is appearing to be dendritic.

And just let me pause the video, and then show you that this is what is called one primary arm of a dendrite, and there are the side arms that are forming sidewise, you may not be able to resolve a very closely in this video, but you could make out that there are several arms on the side. And there many such primary arms and in between them is liquid channel. And once it grows further up, you can make out the liquid channel quite clearly.

So, this is actually one boundary that is coming between the dendrites, there will be a channel of liquid that will be present. So, here all these lines are basically having some liquid channel that is present. So, this is a microstructure how it would appear for example, when you hatch an as certified weldment in the fusion zone, and all these appearances are basically because of fine side arms that are coming from the dendritic morphology. They are actually not grains by themselves. The grains themselves be much larger. And you can actually see the grains itself only in either orientation imaging or when you use imaging techniques that is sensitive to the grain orientation and not by just compositional contrast.

Let me just play you this video once more to show you, how the morphology changing from planar to a cellular to dendritic. And then the dendritic then sustains throughout the growth mode in the entire liquid. And you can see that lot of them will be growing parallel to form liquid channels in between.

(Refer Slide Time: 20:22)

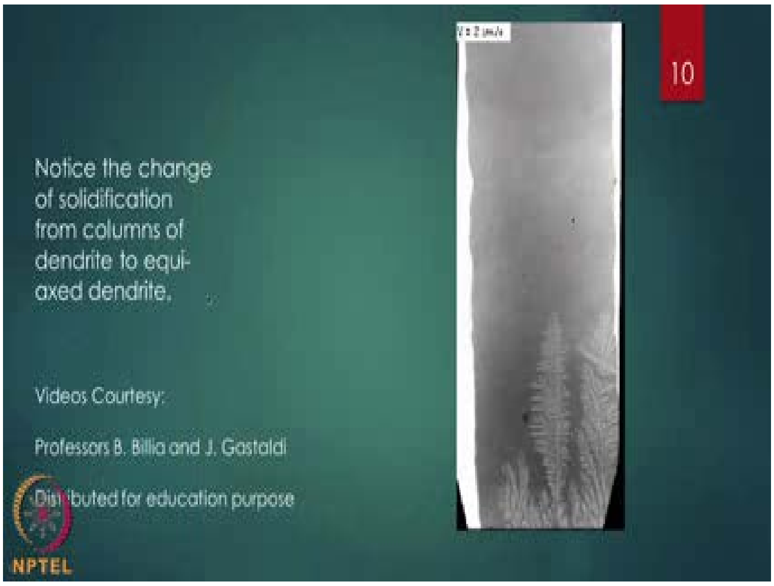


Now, what happens to this liquid channels as we along to complete the solidification will be clear when we see this video this is at this video where it is coarsening is happening and which means that the last two solidified liquid which is there in between the dendrite arms is solidifying. So, here you can see the video, and as you keep watching what is happening is basically the features are becoming more and more clear. And then slowly, slowly you would see that there is a channel that is appearing as line set of parallel lines, and then these patterns are going to become dots, and then finally, those dots are also going to disappear.

So, essentially the last two solidified liquid is being solidified in this particular run. And you see some boundaries that are remnant of the last solidified liquid which will be evident when you hatch a metallic sample. This is an inorganic sample; in which, we are able to see the microstructure evolution as the refractive index change is going to give us the morphological features for a visible light.

So, let me just play you once more where I can then highlight with my cursor to highlight what is happening. So, basically, these lines what we are seeing are channels of liquid that are not yet solidified when the growth is complete; and these are going to take some more time to solidify. And these are fairly long if the dendrite growth is sustained for a lot of distance. And you can see that these long distances are covered by the liquid channel, and this is going play a role in the solidification cracking as we would analyze later on.

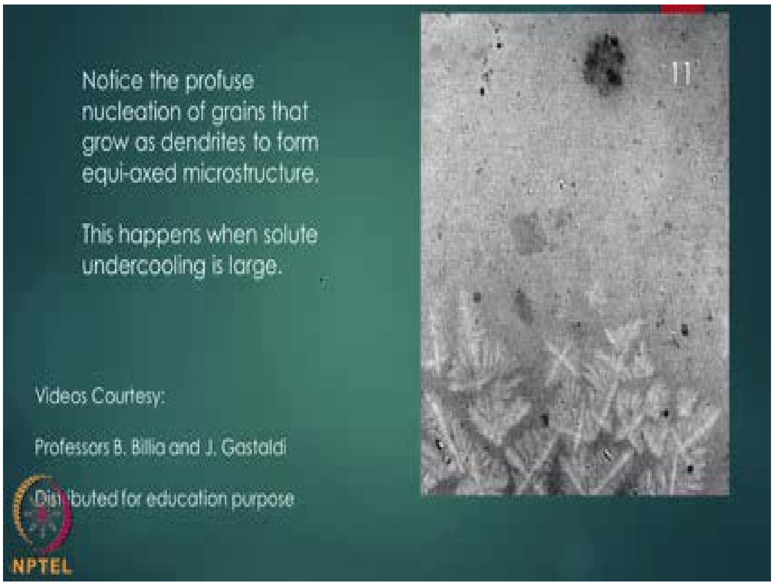
(Refer Slide Time: 22:03)



In this video, what we are actually going to show you is a transition from a columnar to equi-axed microstructure formation. We have already seen that as we increase the solute undercooling this kind of a transition will happen. At the top, you see that the velocity is going to be changed; and when the velocity changes to a higher value, you would see what is happening. And let me play the video for you. This is initially a dendritic growth, but then soon you see that in nucleation of dendrites is happening in the liquid ahead of these primary dendrites, and you see that very soon there is equi-axed growth of the solidification.

So, which means that as we increase the velocity to 14 micrometers per second as it is done in the synchrotron facility, you see that the microstructure is changing from a columnar dendritic to equi-axed. So, from 2 to 4 as it keeps going up 6 micrometer per second and then 8 and then 14, then you see that most of the solidification is happening in the equi-axed mode.

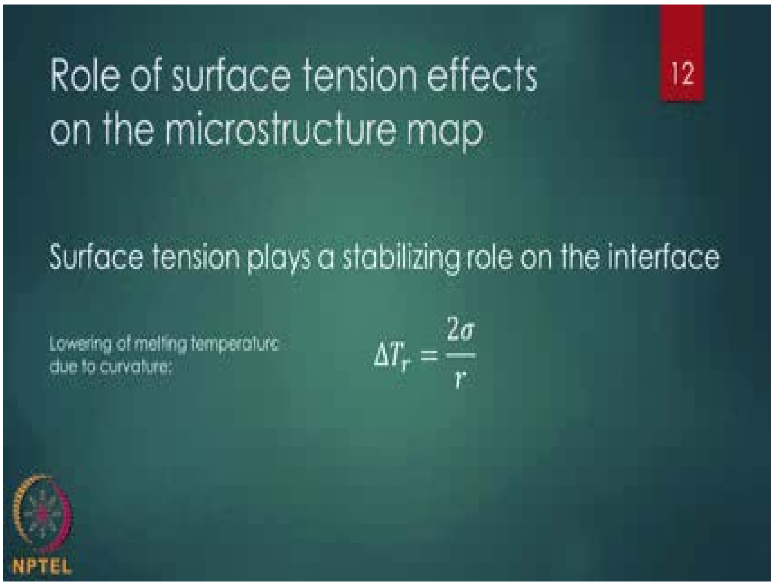
(Refer Slide Time: 23:06)



So, we can look at the equi-axed mode again a bit closer in a smaller domain by enlarging it. And you can see that essentially what is happening is that in the liquid, these dendrites are being nucleated and then they are growing up to a particular extent, and then settling down; and each of these dendrites may become one grain. And because they are growing roughly equal in all directions you see them as equi-axed.

And as you can see that grain boundary around these dendrites is going to be giving you a much smaller grain as compared to a long dendritic growth. So, these grains are generally small and also good for the impact toughness of the weld which solidifies in this kind of a mode.

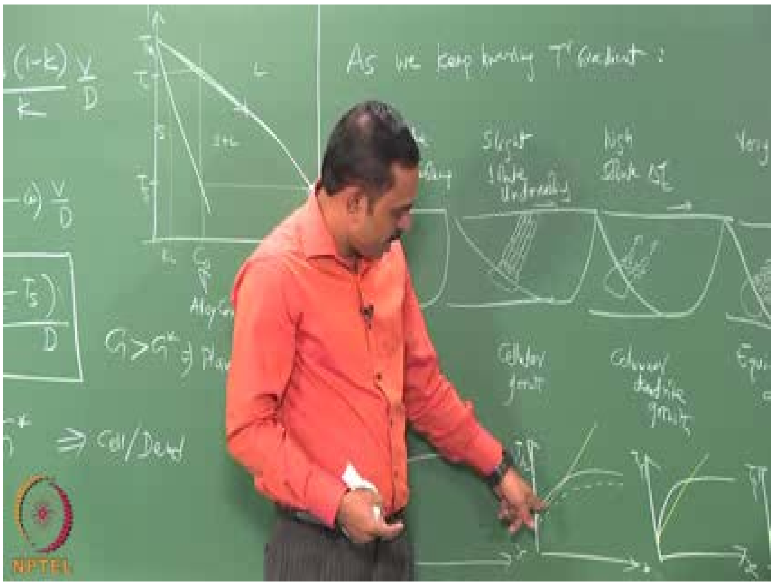
(Refer Slide Time: 23:46)



So, at this juncture, let me then come back to the analysis. So, here is the analysis to tell you that the map that we have drawn is not the complete story. The reason being that, as we increase the velocity we are saying that for a temperature gradient - you should be having equi-axed growth or dendritic growth for any large velocity and that is not going to happen - The reason is as follows.

What happens as we keep increasing the velocity is that the amount of time available for any pattern formation at the solid liquid interface is limited; and as we go to higher and higher velocities, we reach those regimes where the perturbations are going to be very, very fine. And when the perturbations are fine, it means that the curvature effect is going come in; and this curvature effect is shown in the slide as the curvature undercooling, which means that the melting point of the solid is going to come down because of the curvature effect.

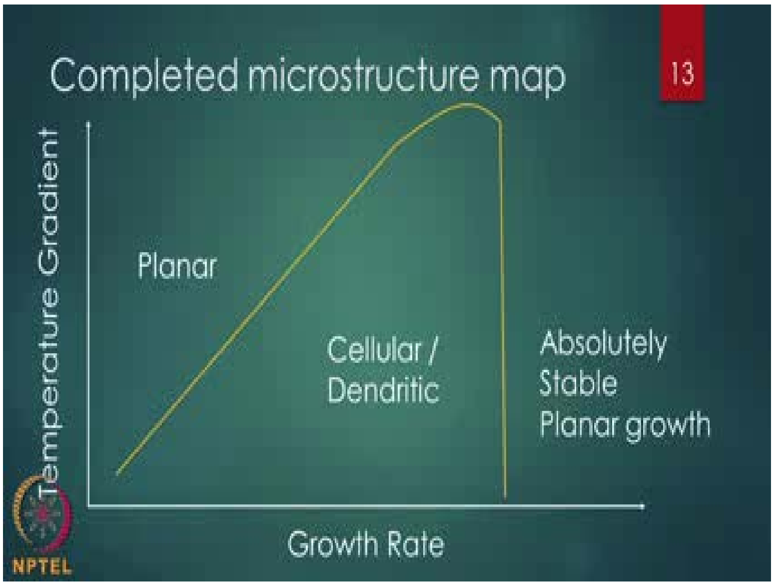
(Refer Slide Time: 25:02)



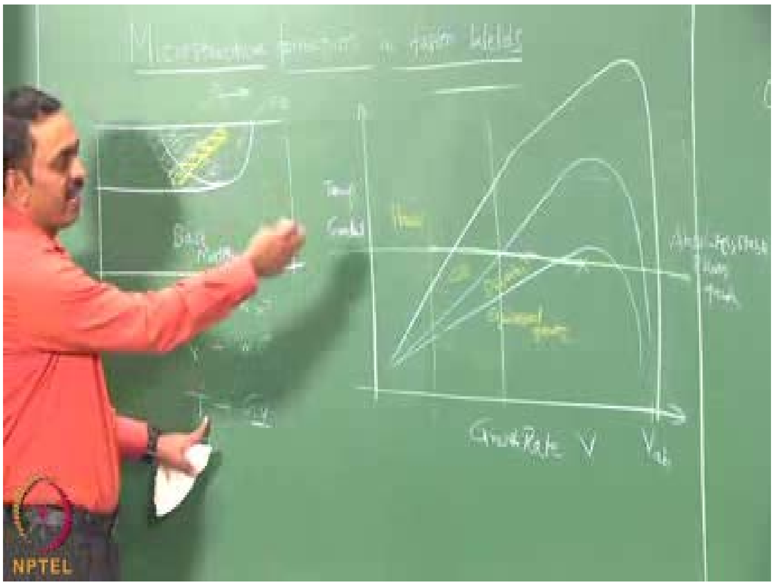
We have already seen that in this analysis the as you can see here the melting point, if it were to come down because of the curvature effect then you could see that what was actually giving you some undercooling, if the plot is going to come down then you no longer have that undercooling, which means that the effect of the undercooling which happens because of a fine curvature effect that is at the interface the surface tension effect is going to basically reduce the temperature of melting of any solid.

And if that is significant then what was a temperature gradient that would give an undercooling will no longer give you that which is means that the surface tension is going to play stabilizing effect. Now this is going to have a change in the microstructure map and then we would see that now.

(Refer Slide Time: 25:39)



(Refer Slide Time: 25:43)



So, what is going to happen is that there will be a velocity at a very high value; at beyond which, no longer you would have the possibility of any pattern formation namely it will be having absolute stability of the flat. Which means that these lines is cannot go on up to infinity, but then they will have to take a turn and come vertically down.

Showing you that all the morphology we are talked about is going to be only in this domain; and this is going to be also true for all other situations that we have discussed. Which means that at any at any gradient, if you go to high enough velocity, then you can always get a planar front growth; and the vice versa also. For any velocity, as you keep increasing the gradient, then there will be a gradient above which you would have planar growth; and this gradient will be higher and higher values, as you go to higher and higher velocities.

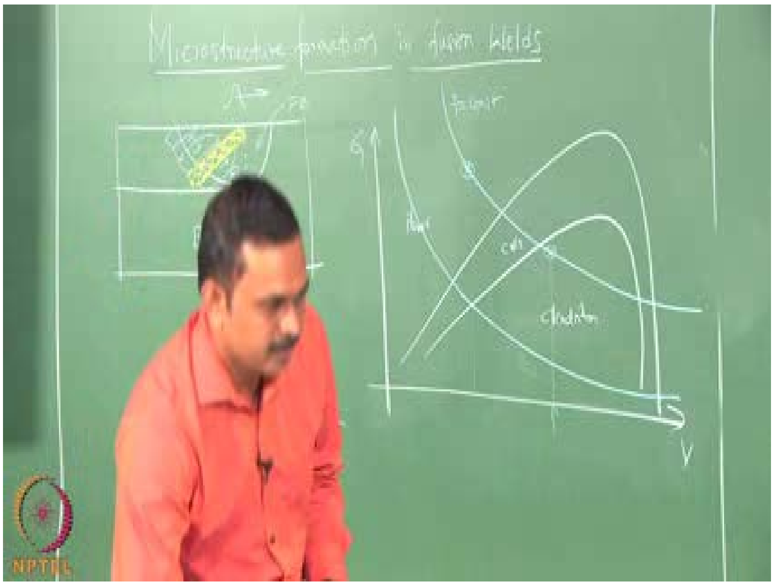
Now, what we have seen in the videos is that as we increase the velocity, this is what we have seen, as we increase a velocity cells have come, dendrites have come, and then equi-axed microstructure has come same thing is possible as we go downwards by keeping the velocity same, but decrease in the temperature gradient. So, this kind of a map is called as a solidification microstructure map to show you what is happening to the microstructure. So, this planar can be written on the other side as absolute planar stability absolutely stable planer growth. And all the microstructure is only happening in some intermediate range of parameters namely for the velocity and the gradient.

Now we can ask what kind of a domain we are in when we are doing the welding. Luckily, we are actually in this kind of a domain, where a rich amount of features is going to form. And this domain is basically where you have single crystal growth and this domain is when we have very, very fast growth rate because of laser scanning, and situations where the velocity is very high and in the order of several meters per second which is not very common in the weldments. So, casting is also in one corner. So, you can see that this kind of a map is showing you what would happen to the microstructure for different, different parameters. And on this map, if you want to super pose what would happen if you have a constant cooling rate then we can do that and then analyze.

For that we just need to look at only one small expression and that is as follows. You see that the gradient has these units, we have got temperature per meter; and you have got velocity, you have got meter per second. So, if you have cooling rate basically that is nothing but G V, because this is supposed to have Kelvin per second and this is going to give you that you needs. And if the process condition is coupling these two then this is what is going to happen. So, which means that if you want to analyze what happens when you change the cooling rate, essentially what you see is changing T dot and look at how it is happening, but T dot is nothing but G V which means that look at curves that correspond to G V is equal to constant.

Now, considering that the G is along the y-axis and V along the x-axis what we are trying to do is that look at curves of x, y is equal to constant curves and analyze what is happening. And x, y is equal to constant kind of curves are nothing but hyperbole that are super pose here. So, let me super pose neatly and then show you how it will happen.

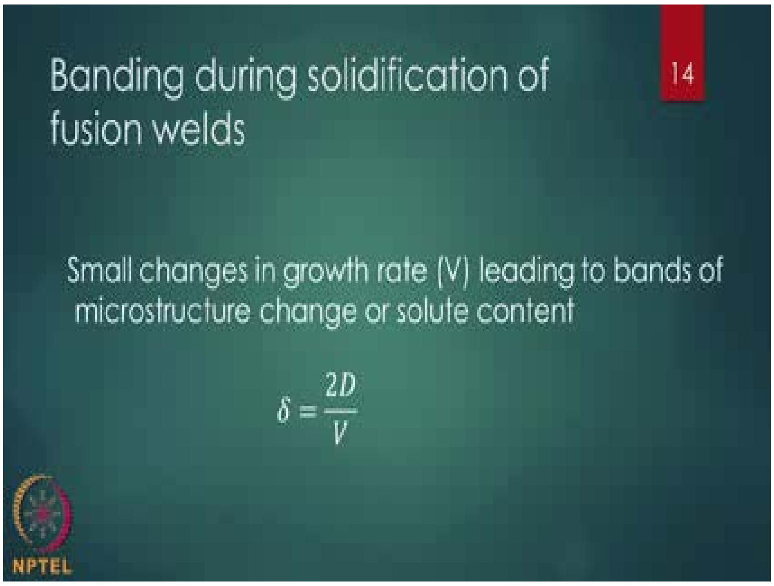
(Refer Slide Time: 29:40)



So, this is how we are going to superpose. The hyperbole is going to there want to look like that at large or small values, they are going to look like that. So, constant cooling rate curves are going to look like that. So which means that if you have a location in the fusion weld which is undergoing constant cooling rate then basically you are going along this line and then you can ask if it is a constant cooling rate, and if there was a cooling rate with a process condition of particular kind of a velocity which is going to give you a microstructure that you do not desire.

And you would like to make dendritic then keep in the constant cooling rate what should you do you can see that you can trace this path and find out what would be that velocity, and that is a velocity at which the torch has to move to give an equivalent increase in the growth rate. So, that you are in the regime where dendritic microstructure is going to come. And this can be done for various cooling rates. So, whatever is the cooling rate, you can actually find out the conditions where the microstructure is going to change from planar to cellular to dendritic.

(Refer Slide Time: 31:19)

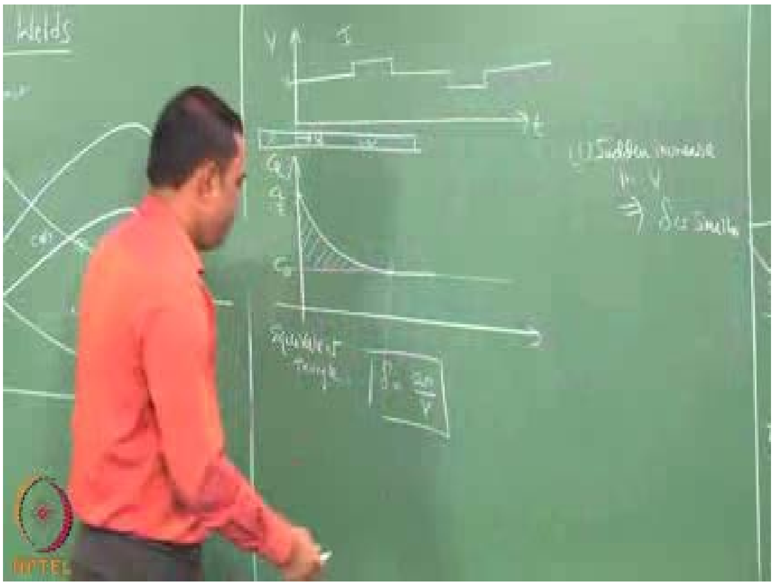


And whenever the microstructure is changing by all this variations, we are also interested in for example, are they small changes that are going to give us a indication that the there will be microstructure variations within the fusion zone. So, that is where we will address what is called as a banding. And banding is a phenomenon that occurs in weldment mainly because of the reason that the traverse rate of the torch is usually with disturbances, you never usually have absolutely constant velocity of the torch, there will be always disturbances.

And also the fact that on the surface of the weld pool, you have undulations that are caused by the interaction between the motion of the fluid as well as the front that is solid-liquid front which is moving. So, interaction between them will always give you rippling effects which are also going to cause some amount of disturbances in the growth rate.

So, whenever this V parameter is going to be disturbed that how does it manifest; you can already see that whenever V parameter is disturbed you see that you may actually keep changing from different microstructures from cell to dendrite and back, or in the dendrite itself going from columnar dendritic to equi-axed dendritic back etcetera. So, minor changes in the velocity can always give a microstructural change as a signal.

(Refer Slide Time: 32:55)

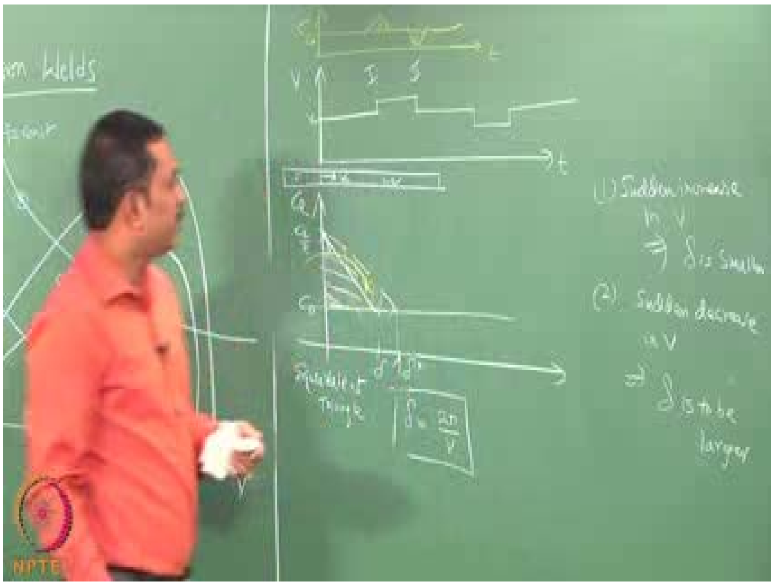


We can also analyze it to see what would happen using a small schematic. So, the way we analyze the schematic is as follows. Let us say as a function of time, the growth rate is supposed to be kept constant, but for whatever it has not been kept constant. And let us say it took a high value and then came back to the same value. And then after sometime, we took a low value and came back to the same value.

All through, you can say that there was a average velocity that is supposed to have. how such small variations in the velocity, how are they going to effect the microstructural pattern formation within the fusion weld is what is our interest now. Now for this, what we do is basically analyze the solute segregation profile ahead of the front, you saw that this was the profile we derived. And we said that this the amount of solute to be carried by the interface as it keeps moving at the velocity V; this is V naught let us say if the solid is going to grow at the velocity V naught then there is such an amount of solute that is supposed to be carried ahead.

And we already gave an exercise in the previous lesson for a home work, and asked if this where to be approximately to be a triangle then what would be the delta. So, the delta for an equivalent triangle, keeping the height same, what would be the width that would be have the same area you see that that will be 2 D by V. And this would tell us what will happen, what happens is that at a point like this the first transition when you suddenly increase. So, we will just look at the case, a sudden increase in V implies, what it does it imply, it implies that V is increasing; that means, delta is supposed to be smaller. So, delta is supposed to be smaller which means that we can just convert this into a triangle and then analyze what is happening quite easily.

(Refer Slide Time: 35:12)



This is the amount of solute you are supposed to have, and suddenly when V is increasing you are supposed to have lower amount of delta, which means that this is the amount of solute that it can take. And what can happen to the rest this region where will it go.

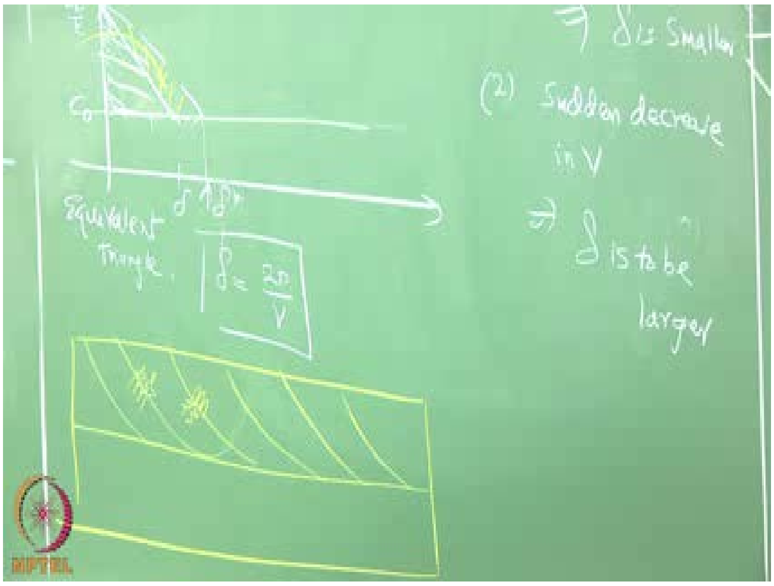
So, in order that at increased velocity also, you again for a long duration have a steady state then it requires that the excess solute has to be dumped in the solidification that is happening behind, which means that if you were to then along this direction, if you were to plot C as a function of time behind the front, then at this point - exactly at this point, you must see that the solid will have a dumped that will have an excess composition, which means that, as this front is moving, there would be an excess solute that is going along this direction as the velocity suddenly increased.

The same analogy can be used to know what will happen when a suddenly decrease at this point. Suddenly, when you decrease, where it is at a steady state and then come down to the value, it implies that V is now suddenly decreased which means that delta has to be increased. If the delta is to be larger, it implies as follows.

This is large delta, but for stable growth, you are supposed to have this required the new delta, and which means that where is this solute come coming from, it has to come in and it will come from depletion of solute behind, which means that you would have at this region, a lower bump which means that it will have a lower composition - which means that as this front is growing, if you have a sudden increase in the velocity, then you would see a small increase in the composition; and sudden decrease in the velocity, you see a small decrease in the composition.

And as we have seen from this expression which we have derived this line the composition is playing a role in the position of this line itself. So, which means that we are actually if we are at a particular position, V may be out or in to the dendritic region depending upon the extent of the variation in the arc, which means that as you keep disturbing the front, you may have disturbances in the microstructure.

(Refer Slide Time: 37:58)



And how does that manifest, it manifests in the longitudinal section as follows. This was the trace of the fusion zone, which means that you may have at every disturbance traces that come to it microstructure changes or composition changes. So, when you sketch a longitudinal section you would see that for example, cells that are supposed to grow may actually start becoming dendritic locally or what was growing as a dendritic may start growing as cell and vice versa.

So, you see a microstructural change corresponding to every disturbance in V that you have had. And these are microstructural features that can tell you also the shape of the fusion zone in the longitudinal section, which is valuable because you can actually analyze the growth rate and the segregation based upon those profile, but it also tells you that the microstructural changes are actually capture in the process conditions quite closely.

So, with this actually, we will come to the end of this lesson on microstructural variation in the fusion zone because of the so called solute undercooling concept. And we have seen in this lesson a microstructural map; and then we have also seen how different microstructural will come as the undercooling is changed from zero to a very large solute undercooling. And we have used that also talk about different regimes within this map.

We can actually now see also microstructures of real welds and understand under what conditions in this map they might have been weld, so that they have that kind of microstructure.

Thank you. .