Analysis and Modeling of Welding

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Lecture - 20
Dissimilar Welding

Welcome to the lesson on dissimilar welding. In this lesson, we would be defining what we mean by Dissimilar Welding.

We will look at various aspects of dissimilar welding, namely the metallurgical, the thermal, the fluid flow the mixing aspects. And then we will also in the end highlight some of the issues where research has to be done. Let us first define dissimilar welding as follows; we will be using the same terminology as we have been using till now in various lessons in this course.

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Let us say we have a domain, in which we would like to join two types of materials. And if we have the two pieces of the same material, and if you have, for example, the fusion zone in which we added a filler which is heterogeneous, namely it is of a different material let us say filler B, then here you have B plus A, and so this is the situation where you have A plus B melt which is in contact with a base material with A. So you could think of this as one very simple situation of dissimilar welding.

And then as we proceed further you may have a situation, where you have the second part not as the same of the first part. And you may have B and then filler can be also different from that. So we will in which case you would have for example, melt which will be A plus B plus C melt, and in addition to being in contact with A, it is also in contact with B. And in a situation which is somewhere in between namely autogenous welding between these two, you would have a situation like that. So you can see that these are the various scenarios that would be considered under the broad subject of dissimilar welding, namely a melt that is different composition from the two base materials.

And a melt that would be having for example, filler also, so you could have basically three different materials coming in a weldment together that is the reason why you would call it as a dissimilar welding. Now this definition can then be seen to extend the discussion in two even other related processes.

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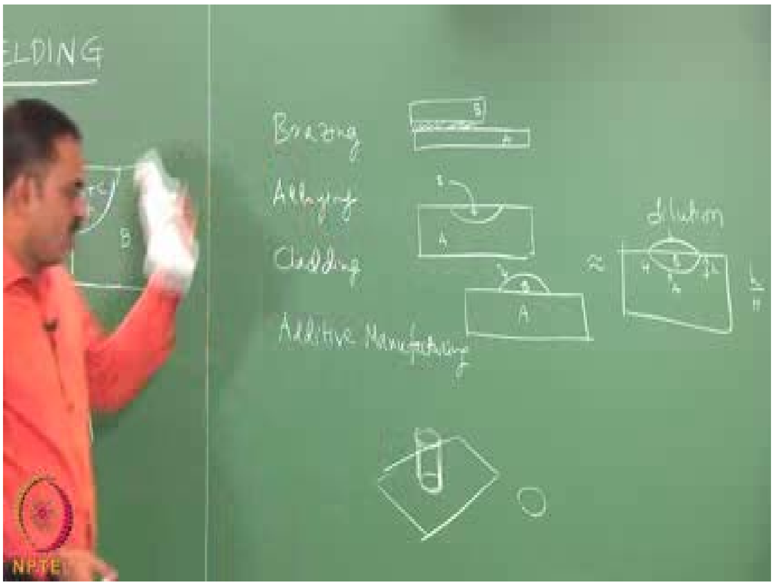

For example, let us take brazing and surface alloying, and we have cladding, and even a newly emerging subject called additive manufacturing. In all these things, you would be basically encountering situation that is very close to dissimilar welding discussion as follows. In the case of brazing, you normally have a requirement that the filler, this filler is going to be different; it is going to be molten when A and B are not molten yet, so this is the situation where you have a dissimilar joining that is possible.

Alloying is a situation, where you have on the surface of a material, a molten pool that is created and you want to add a particular element into it. So you would like to add B and an element B into a base material A, so that the surface layer would have for example, enhanced corrosion resistance or enhanced abrasion resistance etcetera. So you have situations where you want to alloy only the surface and that would also constitute a geometry which would be similar to what we have discussed in the dissimilar joining.

Cladding is the situation, where you are going to have a weld over lay; in such a situation, where you want to deposit a material B on the top of a surface of material A, so that you would like to have a surface that is having better properties again for perhaps oxidation or corrosion or abrasion resistance etcetera. You normally would not be able to distinguish between alloying and cladding as two separate processes, because most of the ways by which you can deposit these are the same processes called as weld over lay.

So, you would have a situation actually in this manner, where you have some amount of alloying and some amount of cladding. And more alloying you would be coming into this situation, and more cladding you will be coming to this situation. And what is the parameter that would distinguish between these two, it is basically a parameter called as dilution that is basically how much of thickness of the material has been alloyed when you want to actually clad and that parameter you could call it as the extent of dilution during this processes.

Additive manufacturing is a process whereby you may want to build a part, and this part may be then made by sequential deposition. And in this case, I want to make, for example, a cylindrical tube on the surface of a plate, and this is made by layer by layer deposition where each layer is basically like a circle, and you build the material on top.

So, you can see that additive manufacturing encompasses in each layer what is happening for example, in a cladding process. So, in that sense, you can see that in a variety of other alloyed processes also, you would have a scenario where dissimilar welding is being discussed and so the wide applicability of this subject is now evident.

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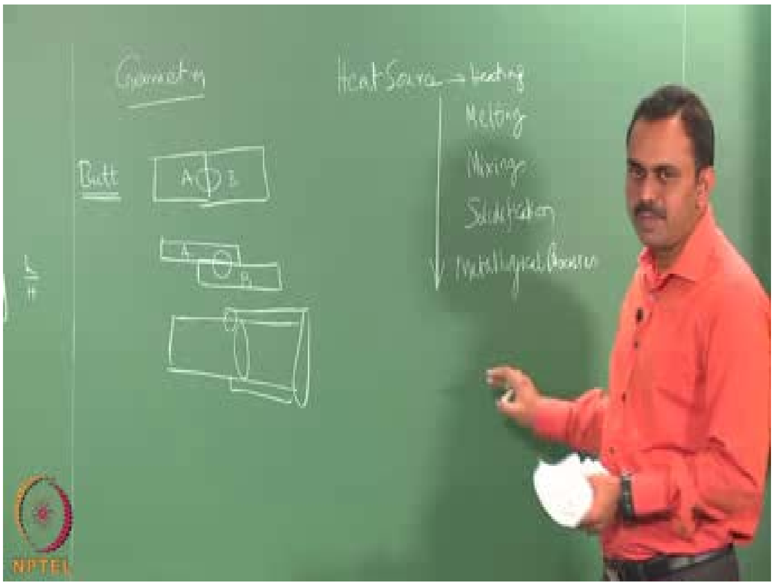

We would go further by looking at various aspects of dissimilar welding as follows. So dissimilar welding is practiced in multiple geometries, we would look at a very simplified geometry as follows. You normally would encounter butt geometry or lap geometry. And you will also encounter this lap geometry in the different geometries in these manners also.

So you will have situations where you want to join a pipe to another pipe or plate to another plate or a thick plate to another thick plate, in all these geometries you can actually visualize what would happen in a small region and then you would see that you can always think of that as just a pair of two materials that are being joined. So you can actually take the case of butt geometry and then analyze the process and then see that the physics is happening in a very similar manner in the rest of the geometries also. So we would limit our discussion to butt geometry for this lesson, because that would illustrate adequately what we need to understand in dissimilar joining.

Now, what are the various aspects of dissimilar joining that we are going to cover there as follows. Basically, what is happening is that you have basically a heat source that is going to be present to melt. So you would have this is going to affect heating; and then we would have melting, and then you would of mixing of those molten regions. And after the mixing is happening, then when the heat source is moving away you would have solidification of the mixed region that is in between the two different materials, so you would have basically solidification.

This solidification of this melts is different from normal welding, because the solid part over which it has to grow is not the same as what is the molten region. So, it is not same as for example, the melt is not the same as the solid from the where grains can grow, so that is the very different thing.

And after the solidification is over you have usually the metallurgical processes such as precipitation of a various phases that would be coming because of the alloy that you have chosen and then different morphologies of those phases as they evolve. And then the stresses because of any shrinkage of the different phases, the two different extents as the cooling are happening. So these are all the various stages how a dissimilar weld is going to form and come up to room temperature. And then in this process, there can be many things that can go wrong at various stages, so the success of a dissimilar weld it depends very strongly on each of this processes happening the way we would like to have.

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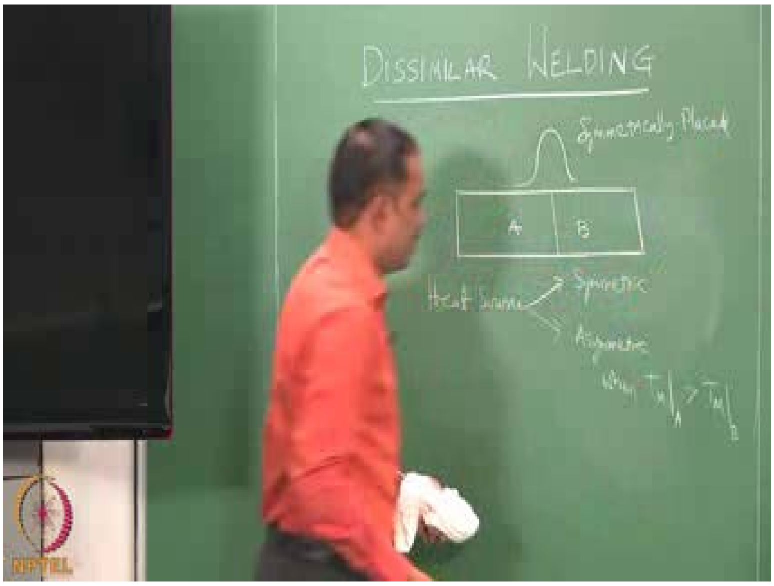

So, let us look at the heating process during dissimilar joining. For illustration, we would take butt geometry and put two materials side by side, and then look at how the heating could be different during the dissimilar joining. The first thing that we must know is the placement of the heat source earlier when you are joining the same material, the placement is with respect to this center line and that would not be playing a very significant role as long as the air gap between them does not alter the thermal characteristics. However, in this case, now you have got two materials that are different, so the placement of heat source is very important. So, the placement of heat source can be in the following manner, it can be symmetric or asymmetric.

Why would you like to consider the case of asymmetric placement, it is for example, when the melting point of A is for example, very, very different from that of B. So if a melting point of A is a very large compare to that of B, then what would happen is that if you were to place the heat source towards the B side then B would melt a lot, and before even A would start melting, and you may have a situation where you have a braze welding kind of a process. So, you may want to choose a variant of the dissimilar welding by the choice of the materials that are at hand, so the heat source is not always symmetrically replaced.

If you want to do braze joining, you may want to place it on the side where middle is going to be molten faster, so that that is what is being brazed on to the relatively refractory metal which is on the A side. Otherwise, normally if you want to look symmetric side, symmetric placement of the heat source, then we will see what will happen. So, let us say symmetrically placed.

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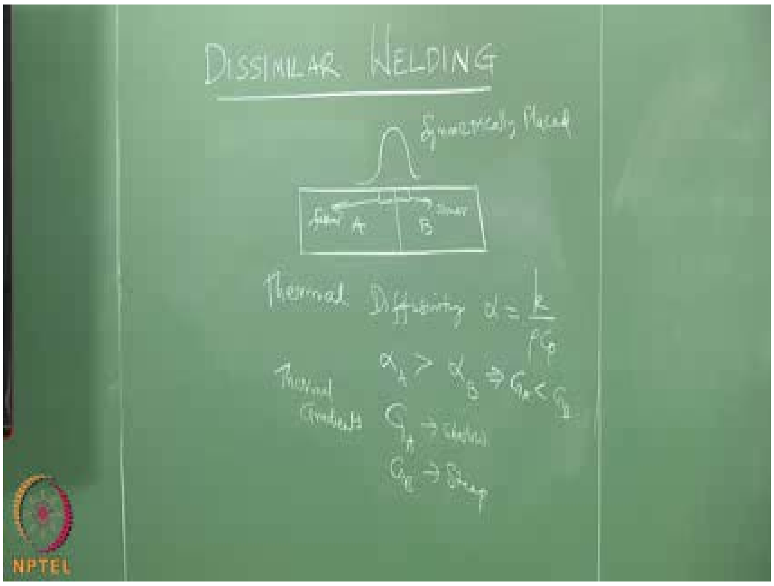

If it was symmetrically placed then what would be changing. Essentially, you have to see that you have got two different materials in what way are the different. So very often if you were to take two different alloys that are not very different in their composition, let us take for example, two different carbon steels with a small change in the carbon content then the thermal properties of A and B are not very different. So, as for as heating is concerned, then they are not dissimilar adequately dissimilar enough; however, you may have a generic situation, where these two can be having very different thermal properties.

And the most important thermal property which would distinguish the heating process between them is the thermal diffusivity. So, it is basically ratio of thermal conductivity, the density and the heat capacity of that material.

What would happen when you have this property very different? Let us take the case of alpha A, for example, more than alpha B. What happens when the thermal diffusivity of A is large, what would happen is basically the same amount of heat is placed on both sides, but the heat is placed on A side would actually be getting removed much faster. So, relatively the same amount of heat is going away slower on B side and faster on A side. This would have an implication that the location that is far away from the center line is going to get heated up faster on the A side than B side, which would mean that is the gradients, so the thermal gradients on the A side are going to be shallow on the B side is going to be steep. In other words, you could think of this.

So the material which as poorer thermal conductivity is going to experience sharper temperature gradients that is because you have basically different amount of the diffusivity of the heat on both sides and this is going to result. Now, this is the first thing that would be changing the way the molten region is going to form. Now it is not obvious that just because the thermal diffusivity is different, the molten region is not going to be the same way. There is a discussion that is required before we see which one would melt.

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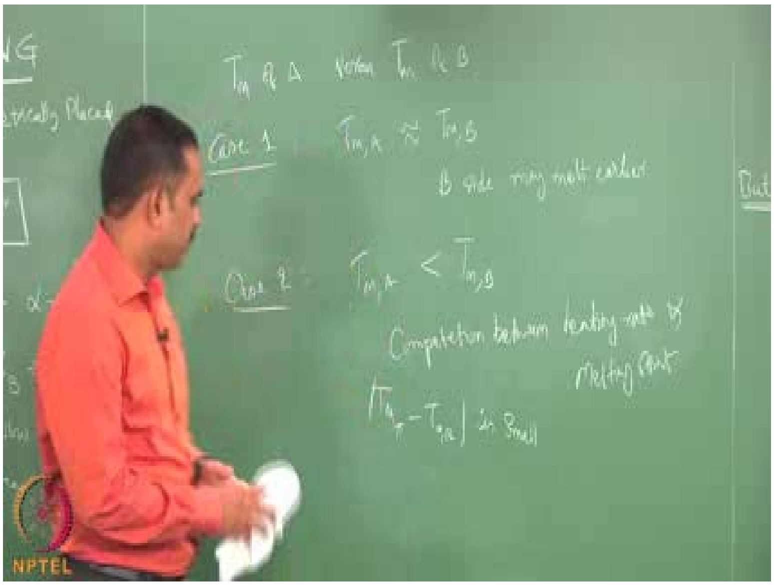

And let us just take the following example. So, as you can see that here as the heat is being applied the heat is accumulated on B side more than on A side. So, if we have a situation that the melting point of A versus the melting point of B; case 1, if they were very close by, if they were very close by, then you would see that on the B side the heat is not going away fast so it is getting heated up faster at the central line. And therefore, you would see that the melting may initiate on the B side.

Now, let us take the case 2; let us take A to be less. Now if A were to be having a lesser melting point, it is not obvious that A would melt first. The reason is as follows; there is a competition between the heating rate and the melting point. If the melting point difference is small, if it is small, by small, what we mean is couple of 100 degree centigrade, and then you would see that if the heating rate on the B side is faster, then B would still melt though the melting point of B is higher. So, it is not obvious that what is lower melting would actually melt earlier; it could also be that what is higher melting can melt earlier when its thermal diffusivity is quite poor.

The competition between these two can be resolved only numerically when we simulate the process of heating and melting on both sides by giving the same amount of heat. And then seeing which would melt fast, because this is a competition of how much of heat is removed versus how much of heat is available for it to rise upwards.

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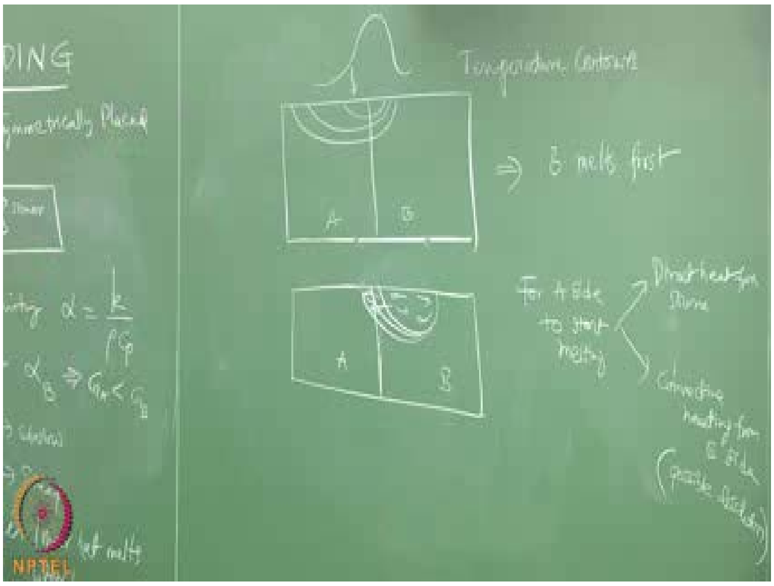

So, the once the materials have reached to the melting point, then you would see that there will be a competition of the melt formation also on both sides. And we would see that unlike in similar welding, you may not have the same way of melting on the both sides, by that what we mean is as follows. Let us take one of the cases for our analysis. Let us take the case of whatever you have written, so that a melting point if A is slightly lower, but melts later. You can have that situation and what would happen that is illustrated as follows. You can have a situation here, then that the contours are going to be widely separated here and narrowly separated here. These are all basically temperature contours.

And you would see that the gap between them is a measure of the temperature gradient, and wider gap would mean shallow gradient and lesser gap means steeper gradient. So if you have A and B, and alpha of B is less which would mean that you have the heat being removed bit slowly on the B side, so you would see that heat is accumulated on B side. So, it would actually mean this would actually mean this kind of a situation would mean that B melts first. If B were to melt first, then you would see that the molten region would appear like this. The first region that would melt is like this. And the heat is still being applied symmetrically on top.

Now you can see that for the A side, you have got two modes by which melt can initiate. For the A side to start melting, it has two modes; one is direct heat from the source, and another way of heat this is first direct heat what is coming down from the heat source that is one way of making the A side melt. There is another way that is from the liquid that as formed on the B side so that is basically convective heating from B side. So, I can actually explain that by exaggerating this geometry to indicate this phenomenon, basically let us make this very big so A is not molten B is molten and we have got on the B side, so some kind of an advection is always there in the melt pool.

So you can see that the heat is being brought towards A side by the advection within the molten pool, so as it would grow and you can see that heat coming laterally is also aiding in the melting of A. So apart from what is heat is coming from the top, you also have lateral heat coming in and therefore, from the A side the melting is actually in two fold.

And because it is a molten B that is coming in contact of A, then you can say that the way A would melt is not by melting directly, it also is by dissolving into B. So, you also have possibility that this may indicate possibility of dissolution, so that it can start melting and mixing. So you have got this kind of a twofold mechanism for the A side if the thermal conductivity of A is high because of which it would melt later on.

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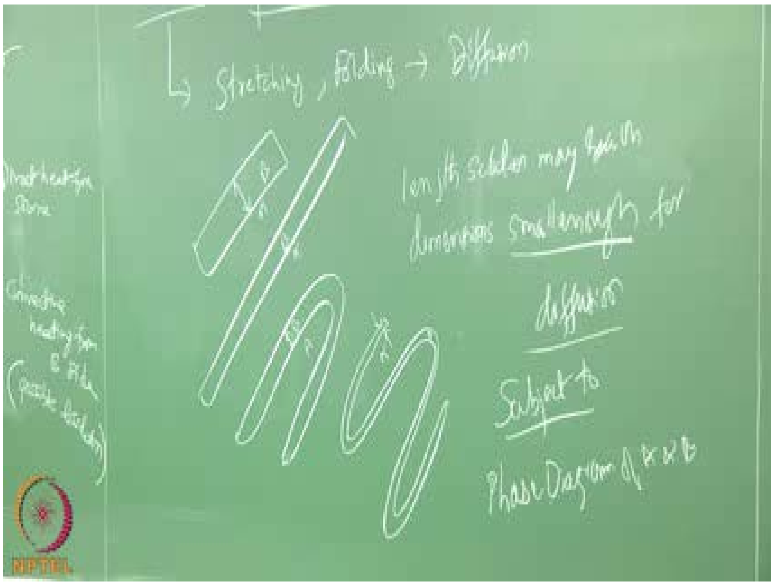

Now, once the molten regions are available how do they mix? So, this is possible for us to analyze as follows, the mixing process can be analyzed as follows. So, mixing is only when we actually have both the sides molten to some extents, so the initial point for mixing let us take the situation, where basically you have got some amount of A and some more amount of B molten. This entire thing is basically liquid.

Now you know that due to various driving forces namely the buoyancy, the Marangoni convection, and also depending upon the heat source, the electromagnetic forces, there are various driving forces because of which the molten pool would be having an advection and that advection would tell whether or not A and B would mix.

So, how any two materials would mix, we can analyze as follows. You can actually think of mixing as a process of stretching and folding followed by diffusion what I mean by that is as follows. If you have a region, let us say a small amount of B is being advected into the A side then you would see that this is going to be stretched. So what I mean by stretching is that like this; and because of the advection, this layer is then going to be folded so you would then see that.

Now you see that the thickness over which this is A, and this is B, this is b, this is A. The thickness over which the diffusion as to take place is now shrunk, and if this were to proceed further, you may have a situation like this, so that the thickness over which the diffusion needs to take place between A and B is shrunk as the stretching and folding is going on and this stretching is mainly because of the velocity gradients that are present in the pool. And the folding is because of change of velocity directions. And this process would mean that at some point the length scale may be small enough length scales may reach dimensions which are small enough small enough for diffusion.

Small enough for diffusion in the sense, you know already that the solutal diffusivity is generally very poor it is about three to four orders of magnitudes smaller than thermal diffusivity. So, normally we do not want to think of ability of mixing between A and B over such a large length that is not the fact. But when the layers of B are going to penetrate into A and then are going to be stretched and folded you would have a situation where the distance over which the mixing is suppose to take place is very small.

And then it would happen if the diffusion would permit because length scales are now small. Now would they still mix or not is depended upon actually a metallurgical reason so this is subject to the kind of phase diagram between A and B, so are the elements A and B or the alloys a and b miscible or not is something that we can deduce from the phase diagram, and that is what is going to tell us whether after even this much of process would they still mix or not.

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And we can come to the categories of those alloys as follows. We have got the categories as follows A and B fully miscible, you may have them partially miscible. And usually when they are partially miscible it also implies that you have compound formation. And these are the situations where the dissimilar welding is struck off as a not feasible; fully miscible is a situation where you can say that dissimilar welding is possible and there is no problem in joining them. And the other extreme is fully immiscible and you then would have two more possibilities it is immiscible, but without compounds and with compounds formation.

And you could see that the situations which are very straight forward for us to have joining process taking place, you can say that in this situation it is very possible and again in this case is very much possible. And you always have a problem when these are the situations where whether it mixes little bit or does not mix at all and then you have a compound formation. And how these compounds would form between the layers of those mixed stretched and mixed layers, where they are going to form whether they are actually going to withstand the kind of stresses thermal stresses during the cooling of the weldment. And if they do not with stand that is when we are basically have the dissimilar joining failing.

So, basically you can see that metallurgical compatibility must be looked at. Now some examples are suitable at this point. We can say that situations like copper nickel or let us say gold nickel etcetera, where you have fully miscible phase diagrams, and therefore, there is no problem in joining them. And you also can think of fully miscible regions as two different alloys of slightly different compositions, so they are also can be thought of as fully miscible.

Let us take for example, two steels of slightly varying carbon content or two aluminum alloys of slightly varying copper content or silicon content, so such situations can be thought of as fully miscible situations. And you also have fully immiscible situations without compounds for example, iron and copper or for example, steel and brass, so you have those situations coming here and you have the remaining cases for example, between important technical alloy categories such as super alloys and aluminum alloys, titanium alloys and aluminum alloys or super alloys and titanium alloys. So, you those common agents, where you have got later mental compounds that are forming, and you normally have difficulty in dissimilar joining.

So you can see that after the mixing process is over you can see whether the diffusion will take place or not. And you can see that the diffusion will takes place in these two regions, and it will not take place here. So it is not obvious that mixing is actually going to happen or not. You may a have a situation where mixing is not at all happening in spite of stretching and folding; or mixing is happening, but fully.

Now looking at the extent of mixing possibility, we can choose what kind of modeling technique is possible. And we normally will have several types of modeling techniques that are possible whenever you have two different liquids A and B, what a kind of modeling technique is suitable can be decided based upon this kind of a analysis looking at the phase diagram of that relevant elements.

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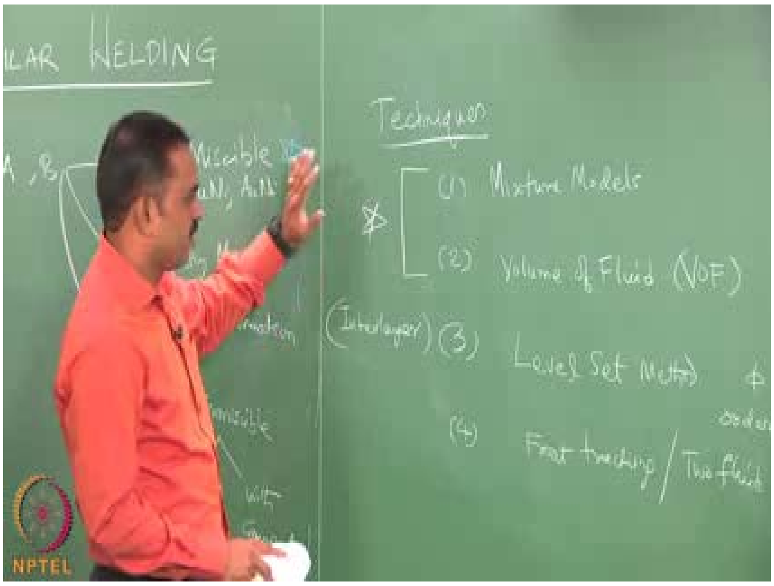

So, let us look at what are the modeling techniques available, whenever you have this kind of a situation. So the techniques available are as follows. The first technique is basically the assumption that these two liquids are going to be fully miscible in each other, and therefore, there is no problem in considering the both the fluids A and B - the molten A and molten B as fully miscible. So, you may have a situation of mixture models.

In other words, the properties of any control volume are taken basically as an average mixture of the properties of A and B knowing how much of A and how much of B are mixed in that particular location. So, in other words, you can actually go ahead and extend the control volume formulation, which we have discussed in the last several lessons; and we can basically replace the properties with mixture properties and then go ahead and use.

The other methods that are available are as follows. You have for example, volume of fluid approach, this approach is where in the control volume you keep track of how much of volume of each of the two phases are present, and then try to conserve the total volume and advecting each of those phases across the control volumes. So, you basically you have conservation taking care quite well, and you can actually handle situations of partially mixed or immiscible regimes using this kind of an approach. So, level set method is again one more approach, where you basically think of a parameter phi which is basically the level set parameter. It has a similarity with respect to what is called as an order parameter.

So, it is like an order parameter, which is telling you where the interface, and interface between the two phases alpha A and B is, which are molten regions. And you can set saying that when phi is equal to 0.5 or phi is equal to 0 is the interface between these two liquids. And this is actually very good method to track the regions whenever they are not being mixed very well. And the last method of course, is what is called is the front tracking or two fluid approach. So, in this approach, we basically populate the domain with particles or marker locations and then we want to track where the interface between the two regions is.

And this is very suitable in situations, where you have completely no possibility of mixing. And it is also quite complicated, because you normally will have to handle how the interface is going to split the domain or join two domains. And that would require lot of book keeping with respect to the location of the interface re-meshing etcetera. So, we have basically a variety of methods that can handle a variety of mixing possibilities.

And what is very suitable for dissimilar welding for metallic materials particularly the kind of alloys that we normally encounter in structural engineering scenarios, basically we will have requirement only to look at these approaches. The reason being, that most of the metallic materials that we are looking at are either fully mixing with each other, or partially mixing with each other. So you normally do not have situations where they are totally not at all mixing with each other. So you may not require to go to the situation of a front tracking methods at all.

You will have a situation when you have a inter layers that will not be mixed to a large extent, so in the case of inter layers, you may want to use level set method to know the location of the inter layer, if it was to melt and move a little bit away from its original location. So, you have situations where the mixture model is going to be the used maximum and front tracking or two fluid approach is used minimum in the context of a dissimilar metal joining the modeling aspect as for as the metallurgical scenario is concerned.

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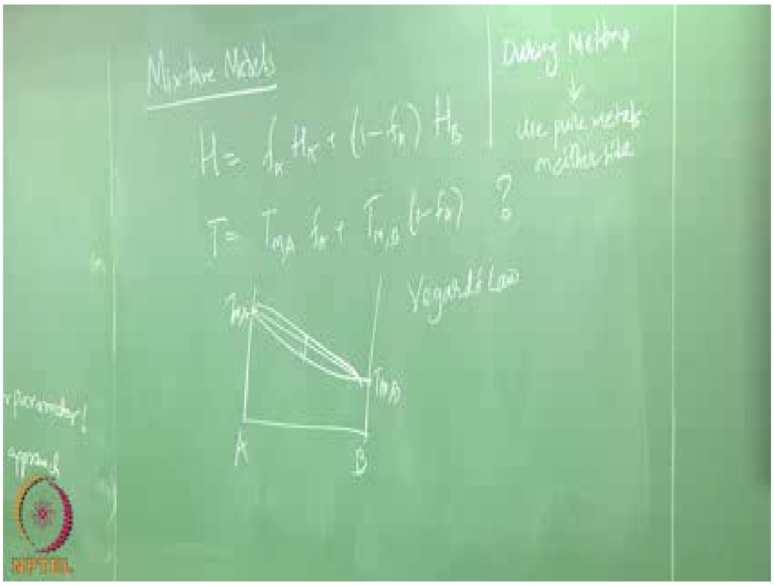

Let us go to some additional details of the mixture model, because that is what we have seen as a very suitable for dissimilar joining for most of the metallic materials. So, we will go to some more details of that what we mean by that etcetera. So what are the things that you are going to be mixed? So, enthalpy for example, you could always take it as a fraction, so you could think of the enthalpy as a mixture quantity, if you have A and B that are being joined then the enthalpy of A and B can be thought of as mixed within the controlled volume. And the fraction of A and fraction B that is present in that control volume can be taken and then you can average it out, and you can say that f A and f B sum of it is 1. So, therefore, instead of f B, I can write 1 minus f A.

Now this kind of a method would actually also see whether the enthalpy change at the melting can be taking it as the same way. Can we write the melting point also like this or rather 1 minus f A, can we write like this? The answer is no, the reason is as follows. If you take the phase diagram of elements A and B, and let us take the melting point of A is here, and the melting point of B is here, then this kind of a mixture model assumes that the melting point of any region in between is going to just an averaged value between the two.

So, it means that the melting point of any alloy in between is given by this law. Now this is basically Vegard's law, which need not be applicable for engineering applications. And you can see that even a very well mixed system like copper-nickel would show that in between you would have situation like that, so you will have a freezing range that is coming up and the melting points are not given by the straight line approximations.

So, you can see that already we can see that we have a deviation from the mixture model that we need to account for, so one should not blindly put this for everywhere. It is also not true that we need to apply the mixture model in the entire domain upfront, because during the melting you have a situation that what is melting is only a pure material. So, you can say that during the heating and melting, you can say that you do not have to apply the mixture model. So, you could use the pure metals properties on either side and really the mixing is happening only after their molten, so you can actually see that only for the liquid domain you start seeing the mixture model is required, so up to the point of melting you do not have to apply.

So, you can actually delay the melting point averaging until the point that both sides have some amount of molten region; and after that, you can actually substitute the averaging of melting point with the phase diagram information, if you have it readily and then use that information instead of averaging the rest of it. So, similarly the other parameters also should be averaged carefully such as for example, the thermal conductivity, or heat capacity etcetera. So, we always need to look up the data bases for information about the property averaging whether it is correct or not, but otherwise by default, if you use a mixture model like this then you would get a numbers that are not very far away.

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So, once we have used this mixture model to start looking at the mixing of the two liquids, then you would encounter a situation as follows. You have basically the regions that are molten A and B to different extents. Now we already said that in the case study we have taken B has a lower thermal diffusivity, and it meant that B melts first. And you already saw that we took the example where the melting point of B is higher, so which means that as you are cooling B also starts to solidify last.

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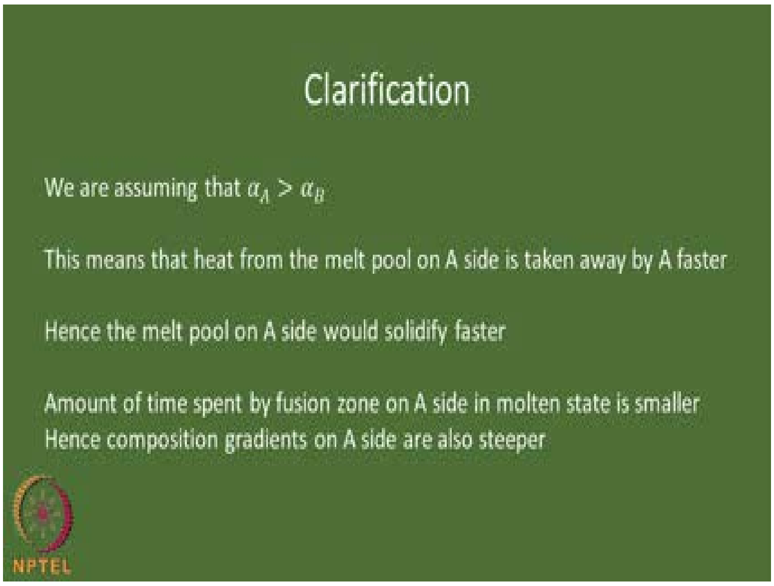

Clarification

We are assuming that $\alpha_A > \alpha_B$

This means that heat from the melt pool on A side is taken away by A faster

Hence the melt pool on A side would solidify faster

Amount of time spent by fusion zone on A side in molten state is smaller
Hence composition gradients on A side are also steeper

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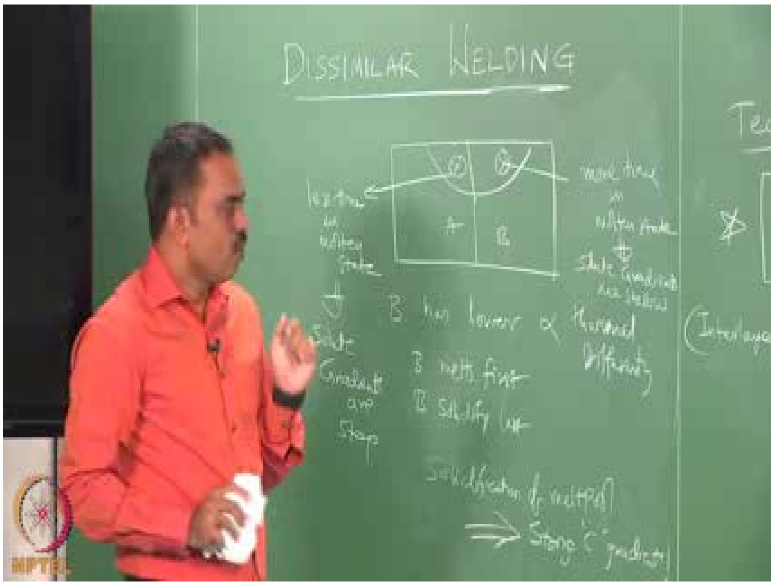

So what this means is basically this region is spending less time in molten state, and this region is spending more time in the molten state. So even when we assume that the stretching and folding, and the diffusion process is taking place, you saw that that process is actually given more time on one side, and less time on the other side.

And what is the conclusion from the amount of time that is available for stretching and folding and diffusion, even assuming that they are both fully miscible, if it has less time then basically the gradients are sharp. So you can say that this would imply that the solute gradients are steep, and this would imply that the solute gradients are shallow.

So, clearly we can see that already based upon our discussion that when you have two different materials that are being joined, and then we have thermal properties that are different, we already see that they both may not melt same time. And if they were to melt in such a way that one of them is melting earlier, then you may have a situation where that region may spend more time and then that is also leading to different gradients.

Now, once the heat source is moved on, and this region is now going to solidify. This region when it is going to solidify, how does it happen, does it happen the same way as we have looked at in the welding of similar metals, does it solidify the same way, namely the grains of A or B side can they grow straight into the melt. Now that is where actually interesting thing is possible. Essentially the problem when you have dissimilar welding is now converted to a problem where you have got the solidification of the melt pool in the presence of strong composition gradients.

So, it is not the same as in the similar welding, where you have got the melt of the same compositions as the solid, and then solid is growing into the melt; and then as long as there is a heat removal then the solidification will proceed. But this is not that case, you have got a situation, where the solid is having a different composition from the melt and that melt is not having the uniform composition, it has a very steep gradient. So, under what circumstances such a situation would actually lead to solidification or is it possible that the grains may not grow fully in, and it may require nucleation of fresh new grains in the melt, so that you may not have actually a continuous growth of the solid. So you will have those scenarios coming up.

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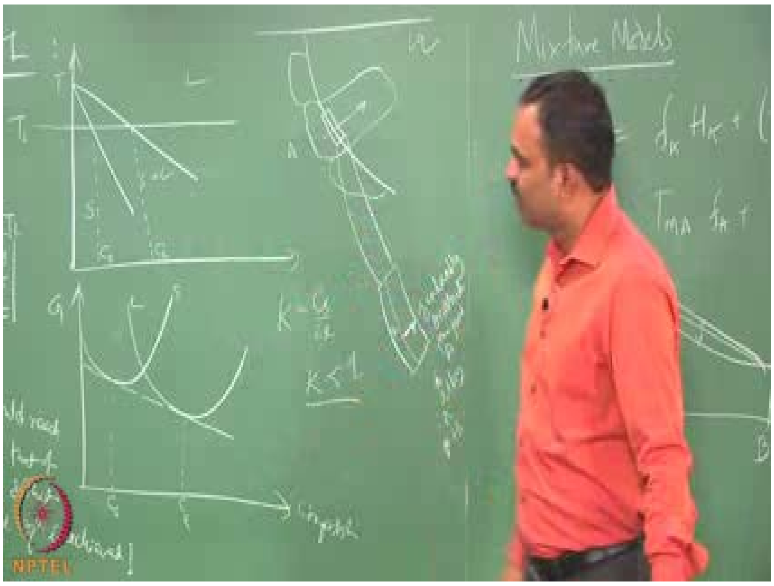

And let us just take two very different kinds of possibilities and analyze, what is going to happen here. So let us take the case as follows. The case 1, first case is taking the phase diagram to behave in this manner. Let us take that it will have this kind of a possibility. And let us take the temperature for our analysis as left. And if this was the case then how would the scenario look like.

At this scenario, if you want to look at the so called Gibbs energy versus composition plots, more information about this can be obtained from physical metallurgy text books, but for now you can just look at what I am analyzing. You can see that the temperature T i is where these two compositions are at equilibrium, so this is basically the solidus composition and this is the liquidus compositions that are in equilibrium with each other as solid and liquid. And you can see that that is actually example is given by this situation, the solid composition and the liquid composition that are in equilibrium, so that there is a common tangent construction that is possible.

And how is the region that is looking like here, if look at this region then you have a situation where pure A is in contact with alloy melt, this is the situation. And you see that what is in contact with alloy melt, alloy melt, let us take the composition of alloy melt of C l and let us take the temperature to be T i. Then you can see that what is in equilibrium with an alloy of the composition C l is thermal numerically a solid of a composition of C s, but then what is actually in the welding scenario is actually pure A. Which means that at this location composition should reach C s from that of pure A so that local equilibrium is achieved. So, you can see that what is in equilibrium with a liquid melt in the melt pool is having a composition of C l.

So, what is in equilibrium with that kind of a melt pool is actually a solid of composition that is may be for example, 4 percent or 5 percent of B for example. And that is not in contact with the melt actually, what is in the contact with melt is pure A, so you can see that if the pure a composition can change by diffusion, so this thing can through diffusion. If it can change through diffusion to a value C, s and then locally it could be miss possible after that if you then try to bring the temperature down, then the solidification can take place as we would normally understand in the physical metallurgy.

So, you can see that the growth of grains from pure A in to alloy melt is possible, but only after some amount of diffusion is taking place. So, how the micro structure would be, let us draw like this A; we are looking at these grains. Can they grow, we see that, if they want to grow then there will be region here that I would like to expand A, the composition in this region is gradually enriched from pure A to alloy of A plus B. So, as the grains of were trying to grow into the melt, you have to expect that the composition locally has to change, and then only the growth is possible. Now such a change in the composition is possible provided the temperature as come down, so with the small amount of under cooling you can expect that this is possible.

And therefore, you can expect that on the side of the dissimilar joining where the partition coefficient K C s by C l. The partition coefficient K is less than 1; that is, when the phase diagram is going downwards. So on that kind of a side it is possible for us to imagine that through a small amount of diffusion at the interface the local equilibrium can be achieved following that the grain growth the growth of these grains into the liquid can take place to complete the solidification. So, you may expect a micro structure very similar to that of a similar welding on one side that is one case that we are looking at.

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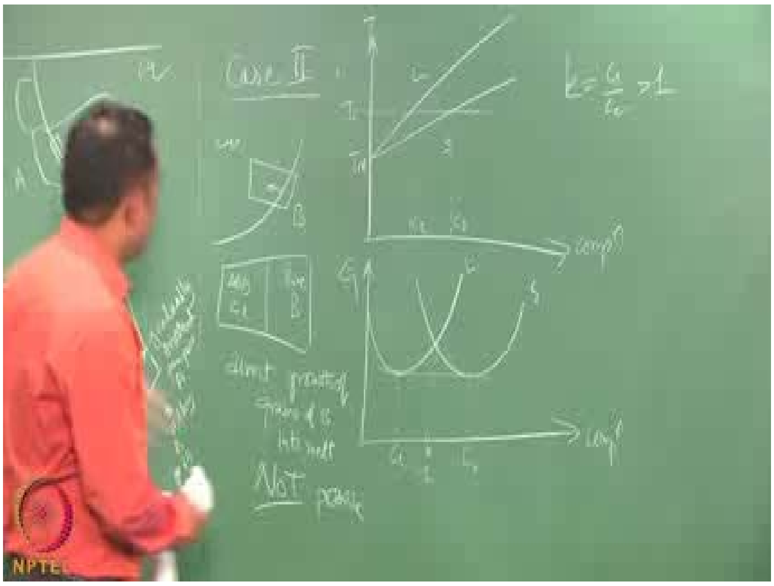

Let us look at the other case where this is not possible that is case 2. For case 2, we then take the phase diagram. In the other way, and we would then have a situation like this. And this a melting point, and this is T i, so you would have a phase diagrams like this. This is composition. And you have a situation where the partition coefficient is greater than 1 and; that means, the phase diagram is going upwards, there it is going downwards; both are possible in various alloy categories. And you have a situation where exactly the same kind where the B is now facing it the liquid. And we are now seeing whether it is possible for this fellow to grow or not ok. Now, what is facing B, you can say that pure B is facing alloying melt. And let us take that alloy C l like this.

Now you can see that what is in equilibrium with C l is actually a much enriched form of B with lot of A, which is having a composition of C l, and you can see that B is actually molten you can see that is liquid that is in equilibrium with that kind of a thing. So, you can see that until you reach this composition C s star, you do not have a situation where the solid is actually having any stability with through the liquid.

For all the compositions where the pure B is going to get enriched with A, you see that it is only the liquid which is stable only after it as crossed this composition. So, you can say that C l or C s only when you cross the composition, you can see that solid is stable compared to the liquid and solidification can start taking place. So, in other words, you can see it is not possible for B grains to grow, because it is it is possible only beyond a very high amount of composition. So, you can see that this growth that is direct growth, direct growth of grains of B into melt not possible.

Now if B were not able to solidify then how would the liquid on that side freeze, it would happen basically by nucleation of solid in the region, and that would actually normally take some amount of under cooling. Which means that on the B side you will not see a micro structure similar to the similar welding situation, where the grains are growing into the melt instead you would see that this interface is only going to be what is molten and then the grains here will not have any relation with the grains of B. So, you can see that you have very, very different situations. And you also saw that on the B side, you will have perhaps more amount of gradients and you also see that more amount of unmixed region is possible on B.

So, you can see that in a dissimilar case, the way the melt pool is going to solidify can be very different on both sides; on one side, it may be achieving the micro structure similar to the similar welding; on the other side, it may not able to take place at all. And that is reason is basically motivated from partition coefficient being less than one or more than one and looking at the situation of a pure metal in contact with alloy melt in the presence of a gradient.

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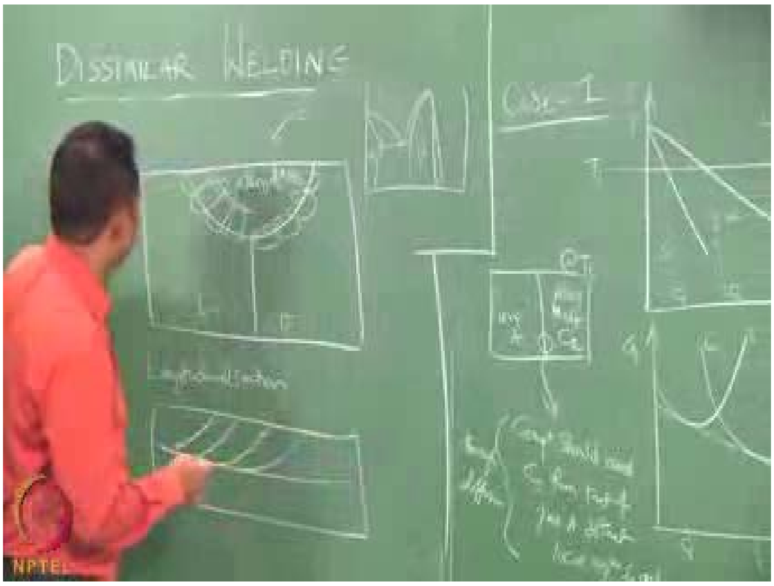

So, at this juncture then we would then see what would happen further. As the solidification is then taking place whether directly from the melt or not, then this is the situation that would happen. And you have got the region; this is the alloy of A, B and may be even C, because some addition of C is possible.

Now you would see that on one side, it may be possible for the grains to grow in; and on the other side, it may not happen at all, and you see that some other grains are forming. And you would see that as this is going on, you would have also situation where the composition is gradually changing. And you will have a region where the composition may be such that certain inter metallic and form. And what would be the shape of such inter metallic region; it would be the same shape as that of the fusion zone. And in a longitudinal section, it would look like this. You would see that there will be regions that would be containing different inter metallic; and these inter metallic will be basically coming from the phase diagram which ever are all possible.

So, if you have a phase diagram like this. So, you have some inter metallic here this beta for example, is appearing when you have composition that is enriched, so you may have regions containing B appearing in this kind of a passion located in a region that is basically following the shape of the fusion zone. And these regions are going to be subjected to stresses, because of the shrinkage of the material as the temperature is brought down and whether they are able to withstand the stresses or not will tell whether the cracks will actually form or not.

So, a lot of discussion is possible when we look at what are all the components that are going to form, we will not do that because that is specific to a particular alloy category. But at this juncture we would say that there are so many things that would change from the point where you have got the heating, and then later the initiation of melt, and then you have got the mixing, and then the solidification.

At each stage there are different things that will be happening compare to the similar welding situation and therefore, you may expect the final result to be either successful or not depending upon the properties of the kind of compounds that can form and also the properties of the rest of the two materials that are being joined. At this juncture, I would like to close by giving some remarks about how we proceed to understand further.

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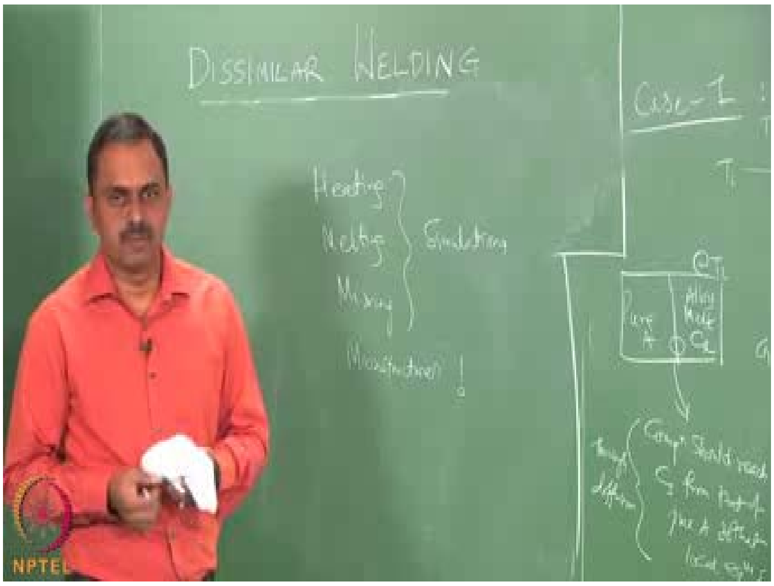

So what we planned to do is as follows. It is possible to understand how this entire processes, namely the heating, melting, mixing, these thermal processes can be understood through simulations. So, what I planned to do is following the two part lesson on numerical simulations to thermal field, and fluid flow in welding, I would like to show you some slides on how the evolution of a thermal field and fluid flow will take place.

And then we will also then combine with this lesson to show, if the material properties were to be different then how those profiles would look different when you have these three stages. So, we would actually combine them to make a slide presentation shortly in a later lesson to show how the difference will be happening. And regarding solidification, we will actually be able to see the difference only when we look at the micro structures. So, few microstructures can also be shown to see the difference of solidification on both sides when dissimilar welding is happening.

Now, how close is the analysis that we are applying to the alloyed problems such as brazing or brazed welding or cladding or there is surface alloying or additive manufacturing, this is a problem that is to be seen, and we will take that as a separate lesson where, we can look at only a geometrical variation; and rest of the discussion, wherever you have got the difference of properties playing a role, then we will refer back to this lesson where we have discussed them in detail.

With that, we will close this topic of dissimilar welding, and then we will continue further with simulations of dissimilar welding for illustration purpose.

Thank you.