Fundamentals of Materials Processing (Part–1)
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Lecture Number 03
Solidification (Welding)

Okay welcome back! So we were discussing some of the processes related to solidification. Before getting into the (scien) fundamentals of solidification, we want you to take a look at some of the processes which will utilize this science or with the fundamentals. So we looked at casting, several kinds of casting, but that is not the all the kind of casting that you will see. Here are couple of more casting processes that you may encounter or you will come to know about. So let us look at those.

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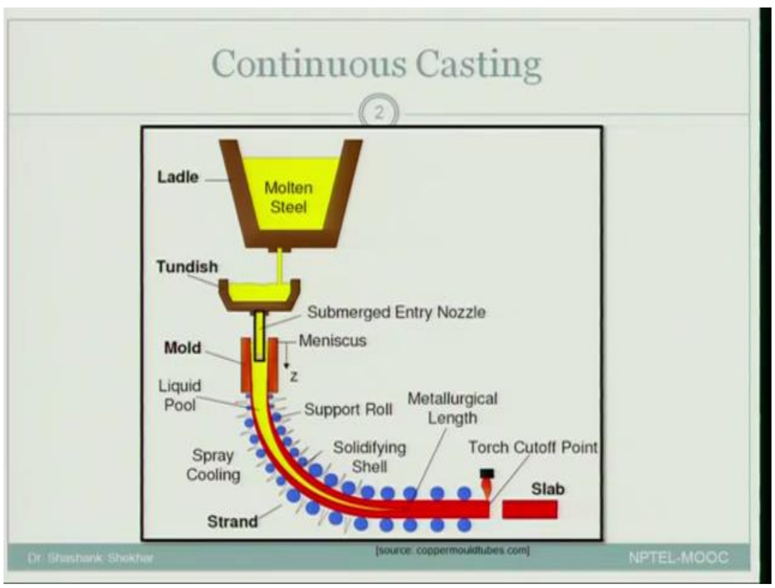

One of it is continuous casting. So as the name suggests, casting is taking place continuously, okay; most of the time when we say casting, you in your mind it will come that you have a batch process, where you cast one block, another block and so on, but not in continuous casting. As you can see in the picture, molten steel is being poured into a tundish, and then from there into a mould; but this mould is not closed from the bottom and the liquid metal goes all the way from over there into a continuous strand. And, what is being done here is that the mould is aligned, some amount of solidification onto the walls. Once these walls are solidified, they will hold the structural integrity and allow the continuous flow of these solidified material.

Although the liquid metal which is shown in liquid will still exist and may be upto a good length, and the red region that you see over here is the solidified region, and you can keep pulling it out at the rate at which it is getting solidified. The biggest advantage is that you do not have to disrupt the process; it will go on continuously, molten steel many a times in in a industry you may be producing continue, you may be producing in batches which you can pour it into here, and then this particular ladle will be always filled, you can bring it in batches over here; but the process of casting would continue to be continuous.

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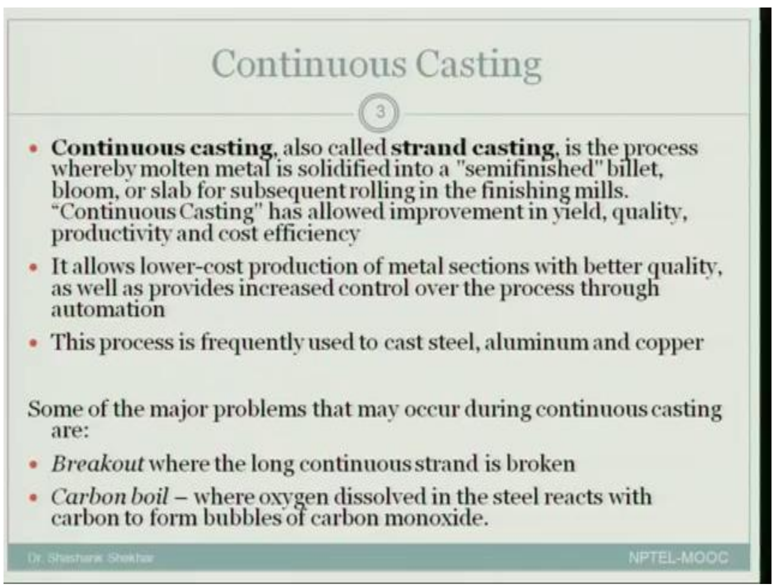

So, just what I said. Continuous casting, also called strand casting, is the process where the molten metal is solidified into semi-finished billet. So you will saw that, you saw in the previous slide, what the outcome we were getting was some slab. So you can also get it in the form of billet or bloom or slab, whatever you like, for subsequent rolling into finishing mills. Continuous casting has allowed improvement in yield, quantity (prod) quality, productivity and cost-efficiency, because here now, you are not doing batch processes, you are able to get continuous output. So cost and efficiency both improve. It also allows lower cost production of metal sections with higher quality, as well as provides increased control over the process through automation.

This process, this continuous casting is frequently used in cast steel, aluminum, and copper and many other systems. But, this also has some of the drawbacks; one of them is breakout, meaning, although you saw the continuous or the ideal process, but it may happen that some time the structural integrity is not maintained and the two and it may break from somewhere in the middle. That will be called the (break) the breakout, where the long continuous strand is broken. Another problem is carbon boil, where oxygen dissolved in the steel reacts with carbon to form bubbles of carbon monoxide; so those bubbles are not good. So this, this can also be another problem with continuous casting.

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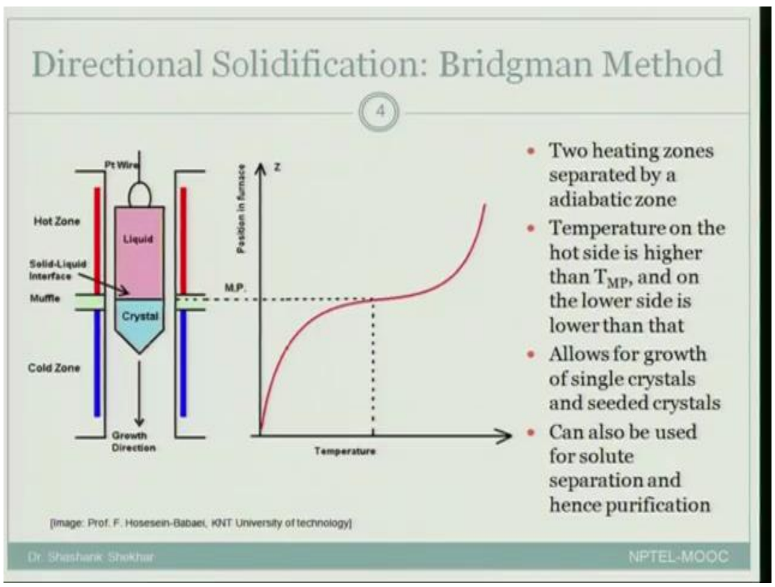

So these are the usual casting that are very commonly observed. But there are also some special kind of casting; although you may not see it very commonly, but they are, they are also very widely used in particularly in this specialized components. One of these is Bridgman method; in fact the next two methods I am talking about, it can be (ca), it can be put together in a common class called 'directional solidification'. So first one is Bridgman method.

Now in this, what you have, you have two zones of furnace; one is kept at higher temperature, the other is kept at lower temperature. And the temperature profile is kept such that in the upper zone is somewhere above the melting point of the material, and lower zone is below the melting point of the material. And inside you will have a crucible into which you will have the (liqui) in which you will put the metal, or the material, whatever you want to melt and solidify in a directional way.

In, since it is higher than the, since it will be in the top zone in initially, it will be in the molten state because here the temperature is above its melting point, and then slowly, at a very very slow rate, let me give you an idea, it will be of the order of may be 5-6 millimeter per hour; that kind of slow speed this crucible is pulled down. So what will happen is that a very small region first will enter a range, a region below the melting point; so some solidification will take place. And since a very small amount has solidified, what will happen is that it will have one particular orientation, meaning it will be a single crystal in nature.

Now the next layer that forms, it will preferentially like to form a one layer above that surface, okay; so because of that small one layer getting onto the top of the waters, what is already solidified, what you will get is another layer of that crystal. So, slowly what you see because of this shape of the crucible, you get a single crystal; so you, this blue region that is demarcated over here, is a single crystal which is now below the melting point, and the and the pink region is above the melting point which is in liquid state and you keep slowly pulling it down; so this is called the Bridgman technique, and it is very commonly used to grow single crystals. Usually what you will get like this would be a random crystal; you do not, you do not have much say on what particular orientation you will get. However there are some methods which are called seeded crystal methods, where you can obtain crystals of desired orientation.

Now, directional solidification, both Bridgman and Czochralski method, which I will discuss next, can also be used for solute separation. What this means is that it can also be used as a purification process, also called as zone refinement, which we will look at when we get into solute partition. So there are two purposes of these directional methods; one, to grow single crystals, and second, to get zone refinement or purification.

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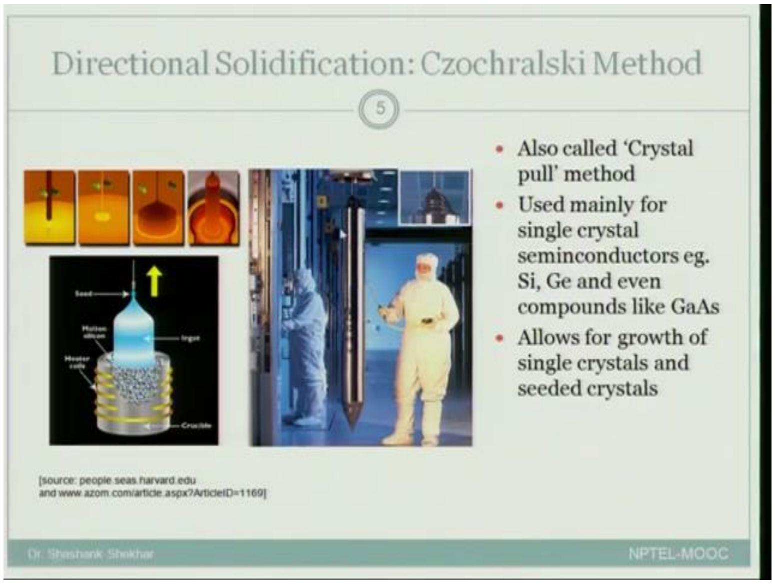

So this is the second directional solidification method which is very very common in electronic industry. Here what you see is a very long single crystal; mind you, it is a single crystal of silicon. So this is a very long single crystal, you see this, there is a human being standing nearby; so it is this single crystal may probably be of the length 10 feet. So that is the kind of length we are talking about and may be one or two sheets in diameter. So that is the kind of size that you can get using this Czochralski technique. So what is this Czochralski technique?

Here you have the liquid material, in this case silicon, so which has a very high melting point, so you can imagine what will be the temperature over here. And then, you slowly pull out, you basically first what you do is put a seed over there, meaning a silicon solidified silicon of known orientation, because the wafers that are used for electronic industry, they have a preferred orientation or a particular orientation. Only then you can get desired properties in the electronic material, electronic system.

So, to get those oriented single crystals, you put a seed in there, and then you put the seed and then slowly pull it out. Basically the seed touches the liquid and then you slowly pull out the solid, the seed. And what you get is a conical initial conical zone like this, and thereafter you will get a cylindrical zone. And hence it will form something like this. So here is another picture which shows there is a seed over here, it is being pulled out at a very slow rate; again it will be of the order of some few millimeter per (se) per hour, and in here there is a molten silicon, and this is the ingot which has been solidified.

So because it is being pulled out, it is also called as crystal pull method. And it is very widely used, like I said for semi-(conduc) electronic materials, meaning semi-conductors; for example silicon, germanium, and even compound materials, which is kind of very difficult but still possible using this technique, compounds like gallium arsenide. It allows for growth of single crystals and seeded crystals; so that is that is possible in both the directional solidification. So those were, that is directional solidification.

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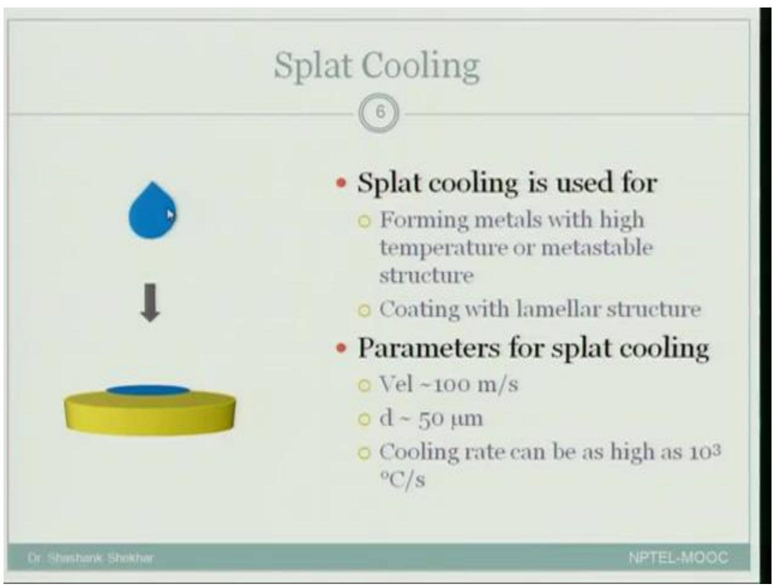

Apart from that, there is again another class of solidification that you may encounter. It is called ‘splat cooling’. Now what is done here is that there are big droplets, which are thrown onto a substrate, which the substrate is at very low temperature, may be at room temperature or even lower, and this liquid and this is a liquid metal or material, any even can be ceramic. So this is at very very high temperature.

Now suddenly, this is thrown into it at a high velocity; so velocity is given here, of the order of 100 meter per second; and then it splashes onto the substrate. So this is, this yellow region is a substrate onto which it splashes; and since it splashes, it becomes very thin, and because it is thin, it will be able to release its (ene) heat energy very quickly. So there is a very quick release of heat into into the substrate, and so quenching rates of the order of 10 to the 3 degree celsius per second can be achieved.

Because of that you get, you may even get amorphous state of the material, or you can also get some metastable structures or some other high temperature structures. This method is also used for coating. Now you can see, that these were droplets, now these have become lamellar; so if you keep forcing these kind of droplets or particles onto the substrate, you get thin lamellar layer. Now this thin, these thin lamellar layer, they have the ability to reduce or reduce the heat transfer coefficient greatly.

So these can be used as thermal barrier coating and this is, these are one of the method that is used for thermal barrier coating; for example, in your aeroplanes that you see, that their, there are some of these may be using splat cooling for coating. So like I said, the parameters for splat cooling are velocity of the order of 100 meters per second, and the dimensions for these splash the splashes that you see here, are diameter may be of the order of 50 micrometer. And you can get cooling rate as high as 10 to the power 3 celsius per second.

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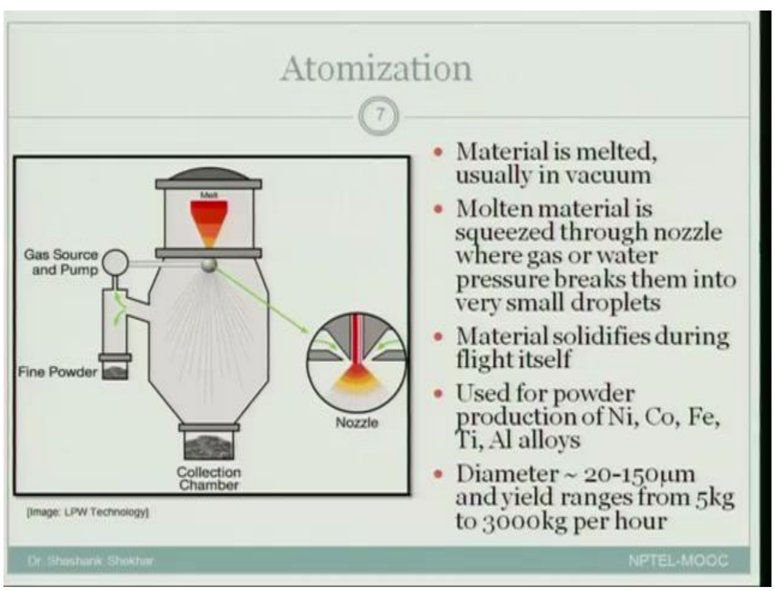

Now this solidification, we are not yet over, and there is still another place where you can get, where you can encounter solidification, and that is 'atomizaion'. you have, you all must have heard of powder processing technique, I also discussed it in the previous lecture. So in the powder processing techniques, how do you actually make the powders? Now those powders are not made or not always made by mechanical methods; some of those powders are made by atomization technique.

What we do here in this method is that you melt the material, usually in a vacuum, and then you squeeze the metal through a nozzle. Now just when it is coming out, you force a gas or a air or or water, just at the tip of the nozzle. So what this does is this amount, large amount of energy because of large pressure difference causes the material metals or whatever material that you are trying to produce, to break into very very small droplets.

So you see these are not clearly shown as droplets, but these become very very small droplets; and the, since it is being squeezed out, it is, it starts to move into the important direction. And, we most of these atomization techniques, the solidification takes place during the flight itself. So (whe) it starts at this point as liquid, and by the time it somewhere before it hits one of the walls, it may have solidified.

So you can see that it does not you may assume that in most of these cases, you would get what is known as homogeneous nucleation, because it is not encountering any additional preferential point for nucleation. So these atomization techniques are very commonly used for production of metallic powders like nickel, cobalt, iron, titanium and aluminum alloys. You can get diameter in the range of 20 to 150 micrometer, and, in this kind of process, you can get a yield ranging from 5 kg to 3000 kg per hour. So those are the very wide variety of (solidi) casting or you can say one application of solidification which is casting.

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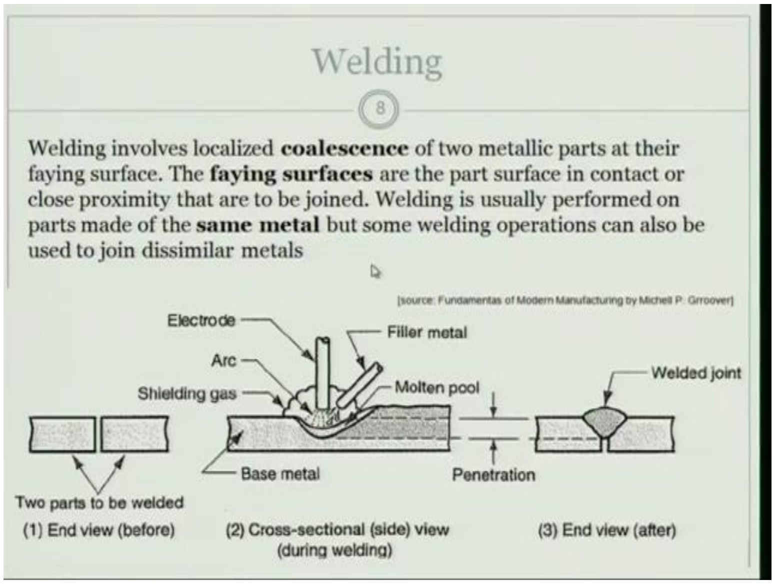

Another application that I have been repeating from beginning, is welding. Although welding also involves lot more other physics, but the microstructure is greatly influenced because of of the molten state of the material near the welding zone and the heat that flows through it. So science of solidification is also to a great extent applicable to welding technique. So let us look at, let us try to understand a little bit of welding. Now welding involves localized coalescence of two metallic parts at their faying surface; so for example, if these are the two metallic parts, so (ano) before I get into there, first thing is that it is used for metallic parts. So these are, welding is used for metallic parts, not for any other material. So, for example you cannot use it for ceramics, or anything like that.

Now, when you have two metal, metallic parts, there will be two faying surfaces or the regions that you want them to be joined. So for example if these are the two metals, and these are the two faying surfaces that needs to be welded. And here we are looking at from the end point view. Now what you do is the the faying surfaces are the part surface in contact or close proximity; most of the time there will be some proximity but it will not be touching each other.

Now welding is usually performed on the parts made of the same metal. So, usually what you will see is that, for example we talked about the two pipes; now the two pipes would always be made of the same material, and you would be, you would like to join the two parts. But it is also possible in some, certain specialized application that you may need to join two different materials, dissimilar materials, and that is lot more involved technique for welding and joining.

But let us keep things simple, and let us look at only let us only concentrate where we are trying to join two different materials metals, not two different metals but two different components of same metal. So we want to join them. Now here is one technique that is shown here in the middle figure. This is arc welding technique. There is a electrode over here, there is a filler material which along with the (sol) the base metal, a filler metal also melts, and it fills in the gap, and then it, it is the melting of both of these that forms a pool of liquid, and then when it solidifies, it joins the two parts; so that is how the melting takes place. And if you look at it from the end view again, after welding, this is how it will look like, this is the welded zone. So here, your base metal has welded, and the filler material has welded and pooled a liquid pool was formed over here, and then it solidified to look like this.

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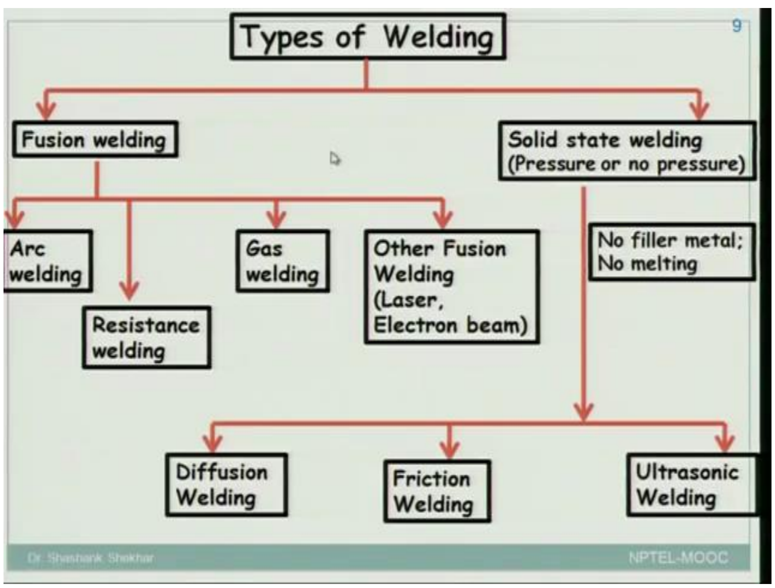

Now let us look at what are the types of welding, not all types of welding require solidification. Only, if you look at it, there are two major classes: fusion welding and solid state welding. So as the name suggests, only the fusion welding uses solidification, or where melting is actually taking place. Now as the other process, and again as the name suggests, it is a solid state welding, meaning no real melting is taking place. There it may be because of pressure, and even without pressure, people have been able to get welding, that is joining of the two components, for example in diffusion welding. So again, when we are talking about welding with respect to solidification, we will be limited to fusion welding.

Now in fusion welding, the material, to be more precise, metal is being moltened, or melted. So there must be some energy being provided. These energy can be provided in wide variety of ways. It can be provided by arc, it can be because of resistance, it can be because of gas, or may be other source of energy like laser, electron beam. So these all will cause the base metal to melt or fuse; so it is called the fusion welding.

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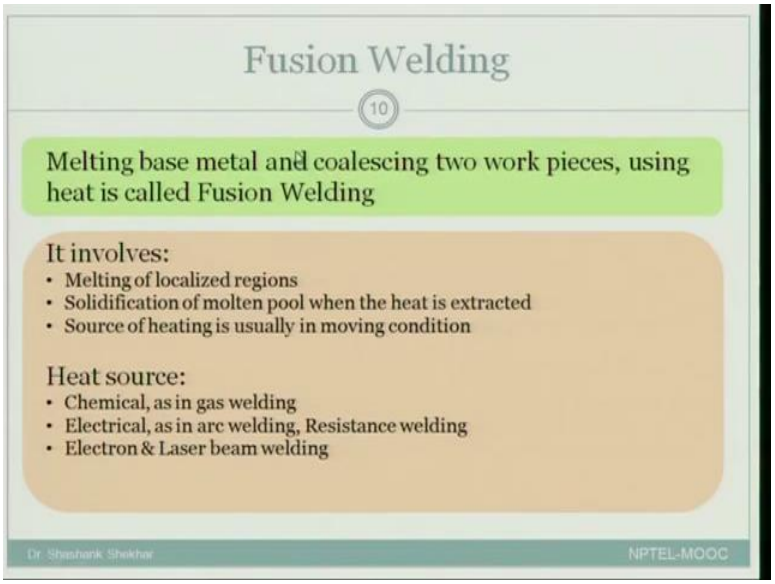

Okay, so we are saying fusion welding fusion welding, so why not describe it in one line? So melting base metal and coalescing two work pieces using heat is called fusion welding. So now that clearly differentiates it from the other counterpart which was the solid state welding (melt) welding, because over there, the base metal was not melting. Also, as the definition says, it involves melting of localized regions, solidification of molten pool when the heat is extracted; so that if there is a (soli) melting taking place, then of course solidification has to take place, and source of heating is usually in moving direction. So, unlike in casting, in the welding, source of heating is also moving. So for example, you remember a welder, he has a torch and he keeps moving along the gap that has to be sealed or joined.

Now in fusion welding, the heat (source) there can be several kind of heat sources; some of which are listed here. Chemical, as in gas welding; electrical, as in arc welding or resistance welding, and there can also be some more refined heat source; for example, electron and laser beam welding. The razor that we use, actually the blades are joined to the base using this laser beam welding, because it is able to do that precise amount of welding or melting of the base metal. If you were to use any other method, you will probably be melting the whole blade, which is not desirable.

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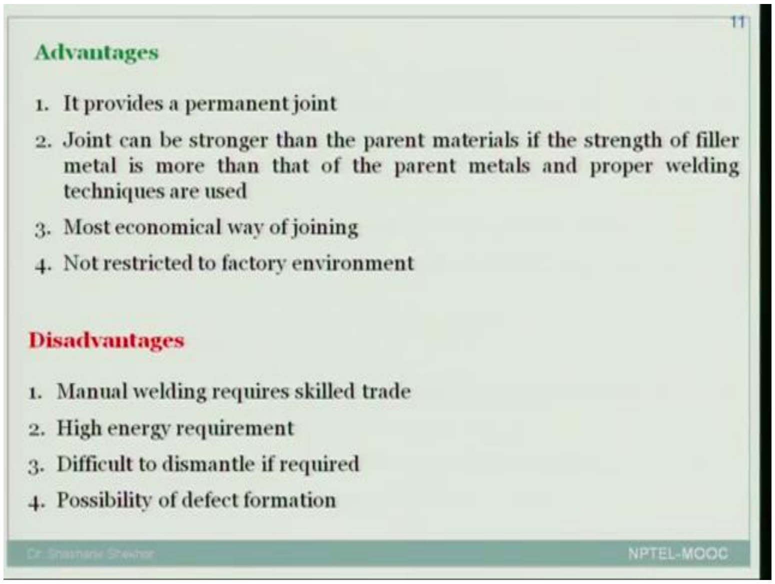

So let us now look at some of the advantages that we, that is there in the fusion welding. In fusion welding, since you are melting and then rejoining the two components, it provides a permanent joint. It is not like bolting two things where you can unbolt it. It has molten, it it was melted, and then it was solidified; so it is now a permanent joint. And, depending on how well you are doing and what is the filler material, the joint can even be stronger than the parent materials; so you are taking two metals, and joining it, it is quite possible if you do it the right way and use the right right filler material, you will be able to have strength in the joint higher or better than the base metal, which is always desirable. You do not want that to be your weak point. It should be atleast as strong as your base metal.

This is the most economical way of joining. Now whenever you have two components to be joined, this will become in a permanent way, this becomes the most economical way, because you have to just get a filler metal and wherever you have the welding capability, you can melt the base metal along with a filler metal, and join these two. And, the (advant) another very important advantage is that it is not restricted to factory environment; you can even in a very small workshop, you can get the setup, and do welding and joining of the materials like this.

There are also some disadvantages associated with this technique. Some of these are listed here. manual welding requires a skill trade. If any of you have tried in your undergraduate days, welding, you would know that it is not easy to get the right welding, particularly if you would have tried arc welding, the filler metal which is also acts as a electrode, gets stuck with the base metal. So, you do, you are not able to get very good control on the gap and the at the same time, the movement of your electrodes. So manual (weld) welding requires a skilled trade, not everyone and anyone can do it, atleast it will require some amount of training.

High energy requirement. So you are providing energy using electric arc, so you need to provide very high voltage and high current. Difficult to dismantle if required. Well this is also a advantage, because you wanted to join as a permanent joint, so it also becomes difficult to dismantle if required. For example if it did not get joined properly and you want to dismantle, it becomes really a problem and a pain. So, it is you can also call it as disadvantage, but if it is done right, then it is a good advantage.

Possibility of defect formation. Now the defects can also be formed during welding, because if we will have time to discuss some other physics of welding, we will (so) show that there is a critical velocity at which you should be moving the electrode. If you move it at a faster rate, then you are not welding it properly or you are, you are not joining the two components. If you are moving at a very slow rate, then the heat is a lot of heat is getting absorbed into the base metal.

So, the possibility of defect formation is large, and you need to have a proper control to avoid these kind of defects. Even otherwise, even if you are doing it right, if you do not select the filler material properly, or if the material that you are joining forms some deleterious phases at high temperature, then again you can you can get into some trouble with the performance of the material after welding.

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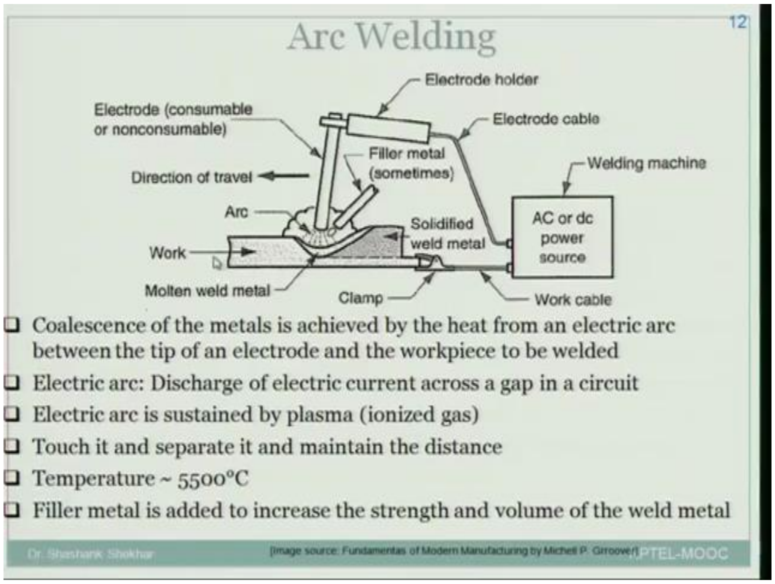

Here is an example of arc welding process. So what are the things over here? Lets us look at it in a in a little bit more detail. So here is the workpiece and this particular, this particular arc welding is being moved from this direction to this direction; so this is the solidified weld metal, and in this direction it will move, so this part will weld, or melt and then get welded. This is the electrode holder, and this is the electrode. Now in many a cases, the electrode may itself be the filler material, in some the electrode may be different and the filler metal may be have to be provided separately. And this is the power source. So one of the power source uhh, since you are creating arc, so one of the power source has to be connected to the base metal, and one of them has to be connected to the electrode.

And, when you bring them together, a spark will get created, and when you just displace them by a small gap, an arc will get created. Why is that arc created? Because the gas ions over there get ionized; and, in that ionized layer, the current starts to flow. So you see that arc, and it is that arc which allows the melting or which has allowed large amount of energy, which causes the heating of the material. In fact the temperature in the metal can reach as high as 5500 degrees celsius. And, this is really good enough to melt the material, so this will, the melting will take place and the (melti) and then after that you will have solidification.

Along with it, you will also be adding filler metal, because if you remember from the previous diagram, there is always a gap, and that gap is always required. It is not that you can keep the two components that you want to join together, and expect that you will do the welding just on top of it, and you do not need the filler metal; that is not the way it happens, because in those cases you will get even lower strength. You always need some amount of gap and then some amount of filler material to fill it. So, lot lot amount of large amount of studies have been done to find out what is the optimized gap and what is and what is the right way to do these kind of welding techniques.

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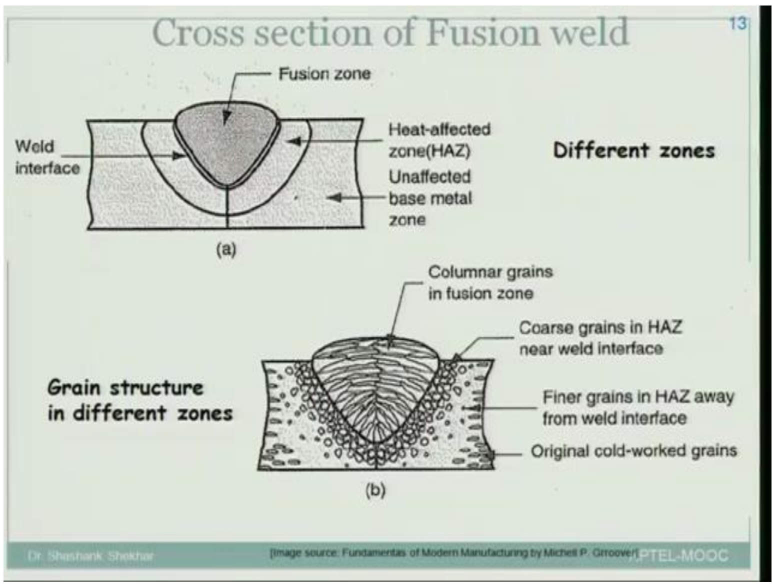

So now let us look at what happens in welding. Now there are so many other sciences also involved. Like I said, energy, what is the power rate, what is the heat rate dissipation etc. But one of the things that is (more) most important is, because of the heat there will be microstructural changes. So, first let us look at the, what are the different zones that get formed. One is, the fusion zone. Fusion zone is the region where actual solidification took place. So here, you have some original metal that melted, and also the filler metal that melted. So this is the fusion zone.

Just nearby, there is a heat-affected zone, and in between these two you can say there is a weld interface. This heat-affected zone is the region again which will, where a lot amount of heat which was dissipated or carried away from solidification goes into, over here in the heat-affected zone, and that will affect the microstructure, and at a much greater distance from the fusion zone, you will have the unaffected base metal zone. Over here, not much actually changes. So this is a safe region, where you can say okay not much change has taken place. But these are the two regions, the fusion zone and heat-affected zone where most of the microstructural changes take place.

For example, if you look at this fusion zone, and look at the microstructure, in most of the cases, you would see columnar grains. Why would you see columnar grains? Because heat is (be) heat is moving in normal direction to this interface, and therefore, growth takes place in a columnar direction normal to this interface. Now, the heat is also going into the heat-affected zone which is over here, and over here, at some distance over here, where some small amount of heat has gone, recrystallization has just taken place, and the grains have not been able to grow. So you see very fine grains little distance away from heat-affected the interface.

And as you get closer to the interface, the recrystallization took place and thereafter (nucl) green growth took place. So the grain size has become even coarser. So these are new recrystallized grains and which have grown in size. And very far from it, you would see where you have the base metal region, or the region which have not got affected the original cold-worked region.

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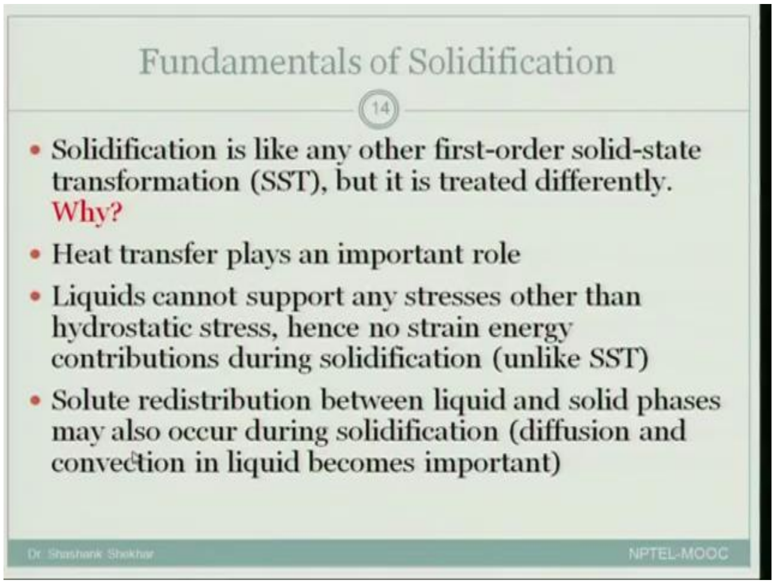

So, based on our discussion so far, we can talk about some fundamentals of solidification, or something which why some of these fundamentals are important. First thing we should realize is that solidification is like any other first order (trans) solid state transformation; but it is still treated differently. You must ask yourself why. We will be able to answer these questions later on, but this is a question for you to think and ponder over it. You saw that heat transfer plays a very important role, what is the kind of microstructure forms, whether it is welding, or whether it is casting, depending on whether you are doing what, which kind of casting, permanent casting, mould casting. The heat transfer plays a very important role, and based on that, you will get different microstructure and hence different properties.

Now the liquid cannot support any stresses other than hydrostatic stresses, hence no strain energy contribution during solidification, unlike solid state transformation. In solid state transformation, because the stresses will have to be accommodated, there will be there may be some stresses getting generated inside solid state transformation, but in liquid to solid transformation, which is solidification, such stresses and strain energy would be minimal. Another very important is, (soli) redistribution between liquid and solid phases. Now in solid state transformation, the diffusion is the only process for redistribution. But in but in solidification, convection and diffusion both of them are very and liquid, and therefore, they play a very important role in solid redistribution. So that again becomes very important.

So in fact I have partly answered the question that I asked over here, which is why solid state transformation and solidification are different in some sense, although they are first order solid state (trans) first order transformation.

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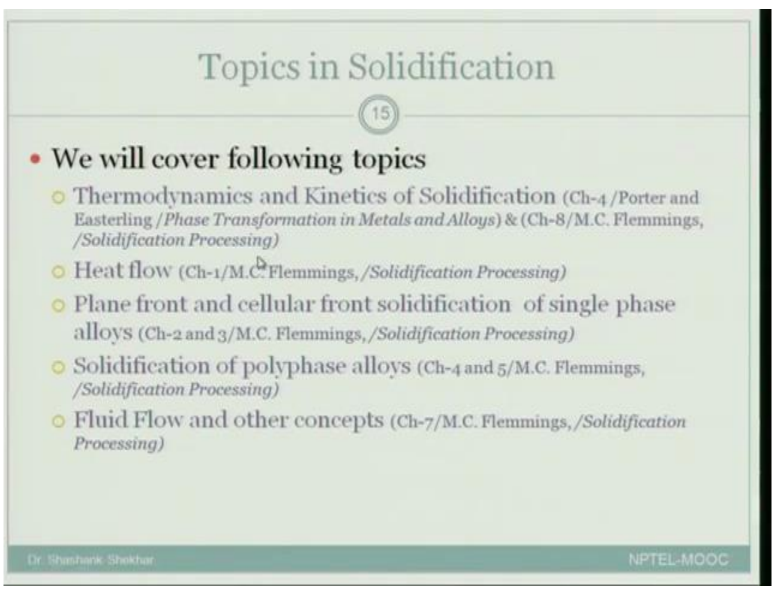

So with next at this point we will conclude, and we will say that these are the topics that we will cover, based on our understanding of the various processes. So we will cover what are the thermodynamics and kinetics of solidification, and along with the chapters that you may refer to in the books that have been prescribed. Then we will cover heat flow, then plane front and cellular front solidification of single phase alloys, then solidification of polyphase alloys, and time permitting, we may even cover fluid flow and some other concepts. Thank you.