Phase Transformation in Materials
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Lecture - 27
Growth

So, after discussing about nucleation in liquid in the solid, we are going to start the subset of solidification, but I have already discussed nucleation part of the solidification. Therefore, the things which needs to be discussed is basically how is solid nucleonic liquid grows, and form the complete solid. But before you do that it is better that I tell you why solidification is so important. And the aspects which you need to consider while dealing with solidification. As a phase transformation so as we know casting is normally synonymous with solidification and major industries in the world they produced different kinds of castings industrially as well as even small scale.

So, when a casting is made liquid metal is pour into a mold.

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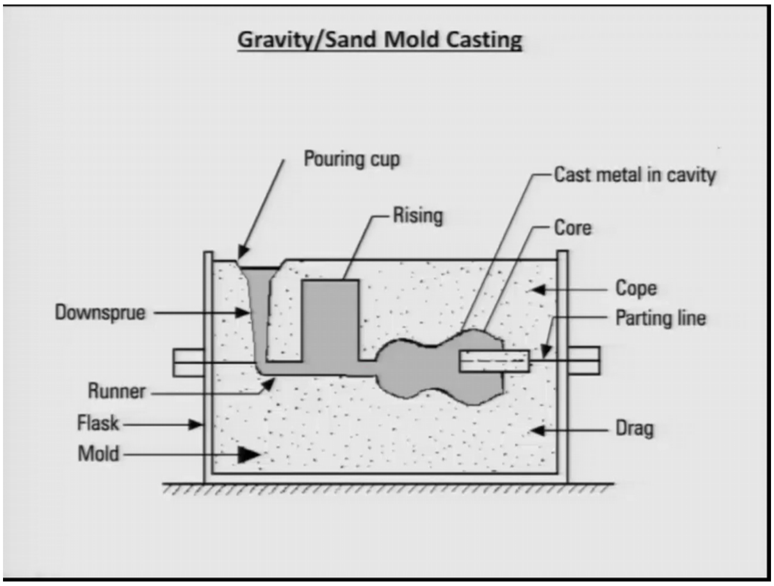

So, picture here shows the same thing there is a mold made of sand and the cavity is made inside the mold for the object whos shape has to be made by the solid. Therefore, to put the liquid metal, it can be pure metal it can be alloy normal it is an alloy we need to have a system to reach the metal at we pour and transported to the cavity. Since you see here this is the cavity and this is the pouring cup and the metal actually poured here slowly travels through this and this cavity as most of the materials in the metallic materials shrink during solidification because of a change of density.

So, we need to take care of that that is done by a riser using a riser which will allow us to keep hot metal as extra, source if at all as a shrinkage in the casting that can be taken care of by this riser, but I do not want to give a complete lecture on how the castings are made that is the different course all together, but let me tell you the basic is important aspects the liquid which is pour in the pouring cup travels to the cavity and then starts certifying. And because of sand mold so therefore, walls were sand actually acts as heterogeneous nucleation sites.

And once a nucleation happens in the surface or the walls of these mold in your sands are present the solid grows into the liquid. So, our effective of phase transformation in solidification is basically, to understand how the nucleation happens and the growth followed by it can be whether understood or not. So, nucleation is mostly heterogeneous type that is I mentioned in last lecture.

Therefore, all the theories which I have discussed in the last lecture can be used to explain in nucleation aspect of that. So, this is basically known as a gravity or sand mold casting which is predominantly used in industries to make different objects, but that is not the all well this is basically after the casting is made there you see this is the casting, there is a hole in the casting this is what is the core and these are the riser and pouring cup.

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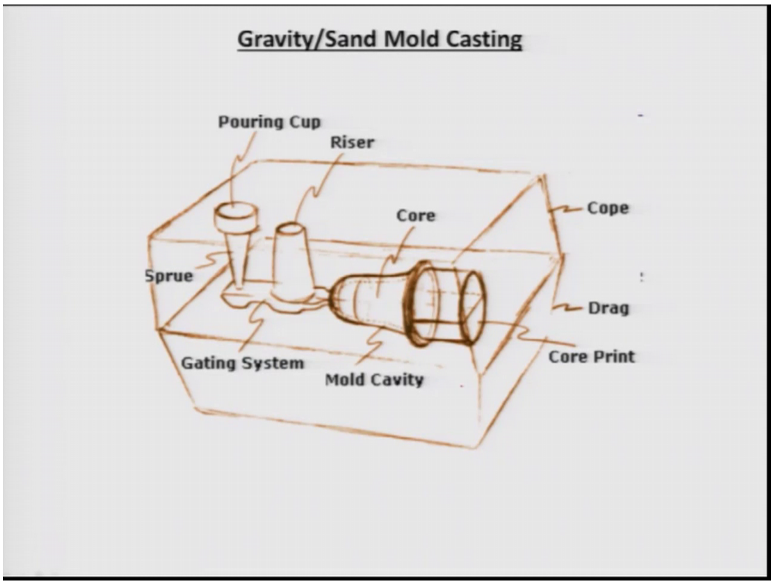

So, after the casting is made these 2 pieces are cut off by using some acetylene flame and the casting is separated.

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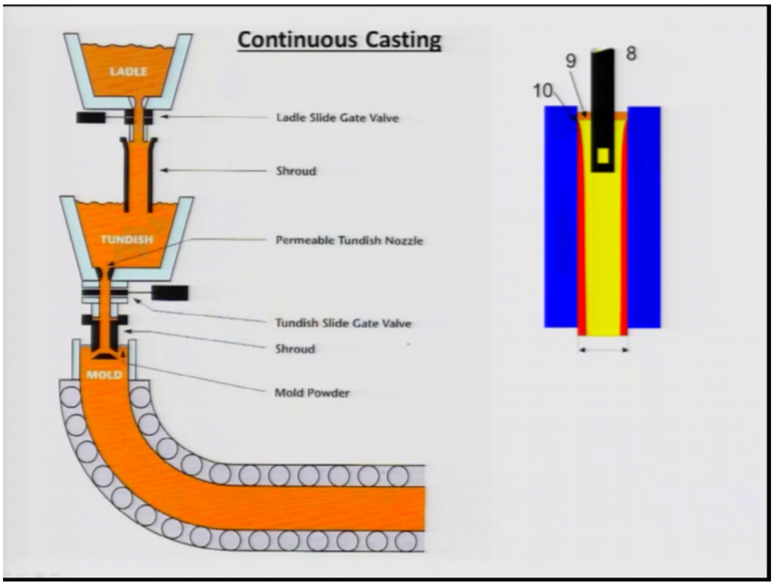

Now, there are many techniques when which solidification is used extensively. One such is basically known as continuous casting. This is used extensively steel and aluminum industry in which we pour liquid metal in a ladle is a reserve wall, and for the ladle liquid metal is sorry from the ladle liquid metal expanded tundish is the reserve one not ladle. So, ladle actually used to transport the liquid metal from smelting sop or aluminum melting holam cells. And then this is this is fed into a tundish keeps the liquid metal in a steady state conditions. On the tundish, it is pour into a mold open mold basically it is a water cooled copper open mold and basic picture is shown here, as the liquid metal is pour into the water cold copper mold a thin layer is solidified or scheme solidified at the interface and inside still remains in hot liquid conditions.

So, therefore, again the nucleation happens at the interface between this solid copper mold. And the liquid and this is again heterogeneous time nucleation. So, as this is basically chilled zone in which the liquid metal has been solidified very rapidly because a copper and water cooled. So, there heat transport is very high. So, number of nucleation number of sights on replaces on it is nucleation happened is also very large. Not only that because it is a rapid process cooling process therefore, the size of these screens which may form along this interfaces very small. Subsequently as the liquid metal as these you know piece of the liquid metal piece flows by this by the convel belt water is spread on to the surface. So, that heat can be extracted and everything is solidified at the end. So, this is a mass scale production process in which solidification is extensively used.

Therefore, it is important that to understand, how actually heat transport under solidification happens in such a situation.

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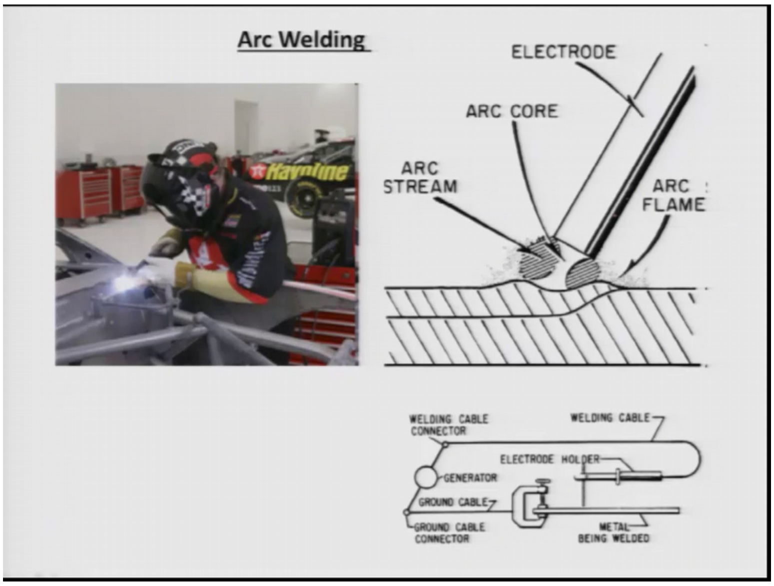

Well not only that there are welding techniques in which solidification is taking place every time your weld is made. So, as you see here there is a welding of basically arc welding in which arc electrical arc is used to join 2 pieces of metal basically is nothing but an transtant electrode normally it is it can be actually used to generate only the heat. And then sometimes you also use a feeder feeding electrode which will melt and allows to join the 2 metals here, you see there actually 2 pieces of metal joined together and using a arc flame. So, in this situation only liquids small amount of liquid is generated, between the 2 pieces of the metal. And because of that liquid is contact with the 2 pieces of metal that there is a empty number of heterogeneous nucleation sites based on the both surfaces.

Solidification is actually starts with the heterogeneous nucleation of these grains. The important aspect is this how the grains than grow because this welding torch moves at a certain velocity during welding process. As you probably seen many of these welders when they do welding of the pipes or some other objects in very different places. So, therefore, the basic purpose basic you know aspects which are more important as a growth how the growth of this solid happens in the liquid.

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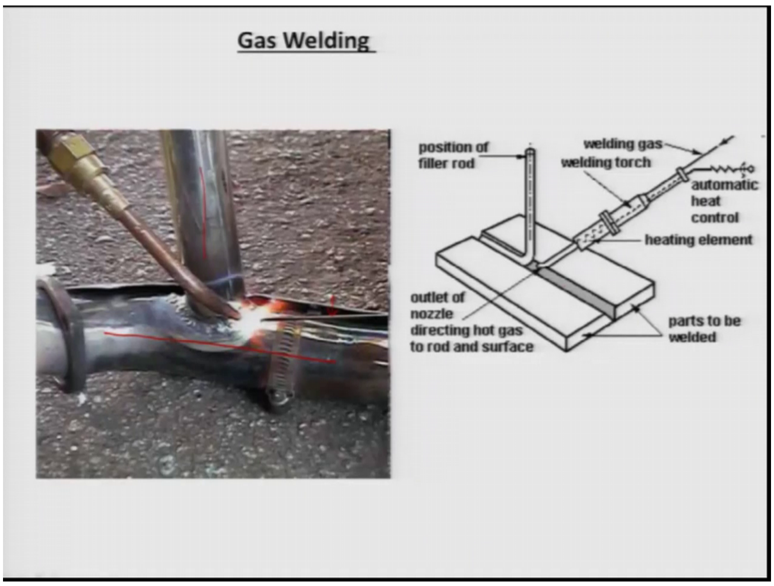

This is the gas welding which is also used you can use excessive flame to create a heat source. As you see here this is basically a one pipe here, and this is another pipe they are getting joined and you see a filler rod this is a filler rod filler rod is nothing but a again an metal alloy which will allow us to make a nice joint. So, schematic pictures show right side that there is a 2 pieces of a metal to be welded and filler rod is placed like this. And the flame which is placed at the intersection of these filler rod and the 2 metal pieces melts down of melts down. The both these 3 things actually 2 pieces of a metal as well as a filler rod and creates a liquid pull and there is liquid then solidifies.

Again because the 2 pieces are solid most of because welding is happening only small region. So, of this pieces remains solid therefore, there is empty number of heterogeneous nucleation sites presence on a surface. So, only you say the how this solid sorry nucleating a solids grow into a liquid.

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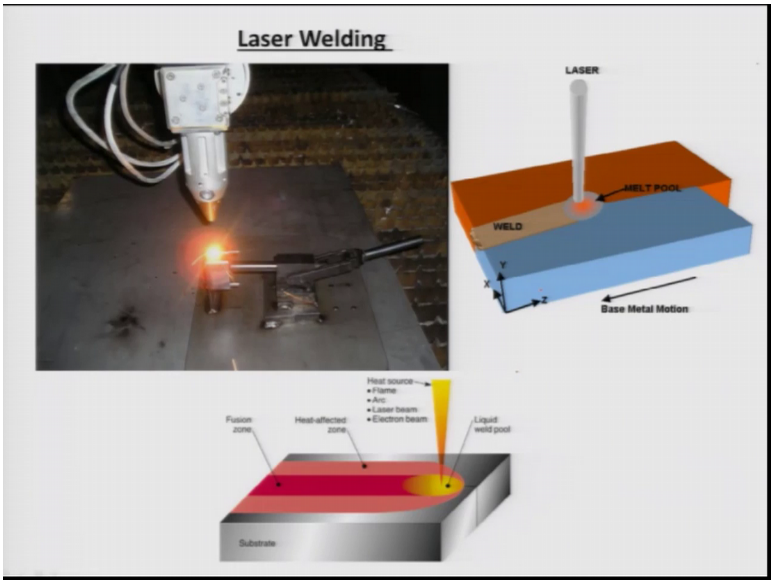

So, that is my basic aspects. One can use laser also instead of a arc or a gas welding torch one can use a laser. Laser is the clean source of heat. So, that is what it can be actually focus on certain spot also, unlike the other 2 cases held shows that how things happens you have a 2 pieces in the metal. And as the laser actually falls on in between a 2 pieces it melts both the pieces because of that there is a weld pooled or liquid pool generated. And as the laser moves or the basically that sample moves laser cessionary the position of the laser beam on the surface also moves because of that the pools get solidified at a certain rate.

So, that is why the growth of these things, those of these nucleating phase which are forming at the 2 2 joining surfaces is the most important aspects.

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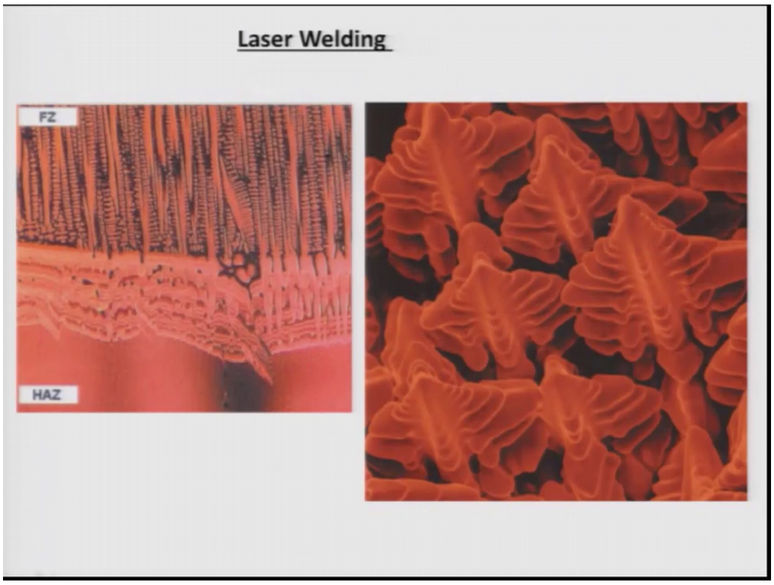

So, all these industrially aspects this is shown here, again all the industrially important processes requires you to understand the solidification you see here this is a basically a different zones of the welded. This is the fusion zone in which you forms certain geometrically feature important features known as dendrites, those we will discuss later on dendrites is a steel like structure and this is forms at the at the interface between the solid metal and the liquid and then it grows inside the liquid.

So, their basic aspect is that how this dendrites which is shown in a bigger picture. Here you see here these are the dendrites of super alloy nickel base super alloy going into the melt, how this actually grow into the liquid that is the question we needs to understand more.

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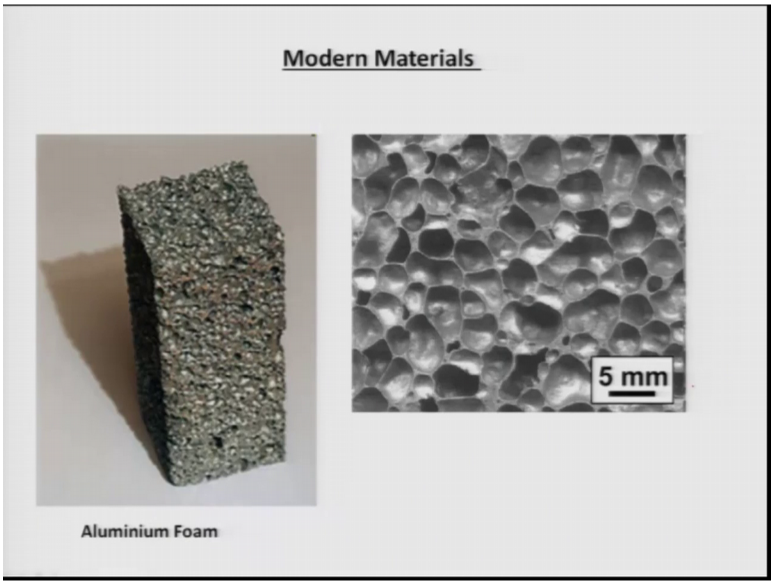

Now, it is people actually all talking about metallic foams, foams actually were important industrially because foams are used in the as a soft cabs absorber in the cars or even the you know different applications, where you need a ballistic things to protect it protect ballistic armor basically to protect from the bullet us. So, foams actually also made from liquid basically the foams are made.

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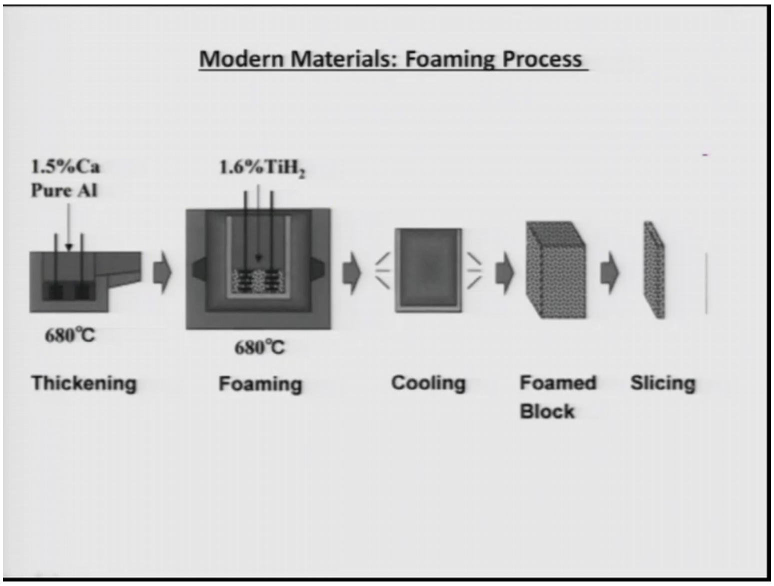

This is aluminum as a foam, you can actually have aluminum melt with little bit of calcium and then calcium actually stabilizes the foam basically foam is nothing but when you take as you know puts soap into a bucket and then started staring, it you will generate foam, but you know something else which stabilizes these foams metal is little bit difficult than an a common example I gave you. So, what happened actually calcium actually stabilizes the foam surface. So, once it is similar to 680 degree Celsius temperature this is known as thickening means it is makes a liquid (Refer Time: 10:46) that is why actually this foams gets stabilized.

Then we add little bit amount of titanium hydrate TiH2. So, what happen titanium hydroid in the liquid aluminum reacts and hydrogen gas is produced this hydrogen gas creates a bubble. And this bubbles are nothing but foams and because it is a discuss liquid and calcium is presents. Therefore, the foam walls are basically gets stabilized because of this calcium present in the liquid. So, once this gets completely bubbled up just like a bucket you put water and then soap. And then stare it will be full with foams then you can simply cool it down, the solidified that is how the foams actually formed and then you can cut and use it. So, foams are important, but basic thing what I am talking about to you is that again here the solidification is very important.

Remember nucleation of this bubbles is not a big problem, because hydrogen is basically bubbling up or because hydrogen has certain amount of hydrogen can get inside the liquid metal rest cannot. So, the once you put more amount of hydrogen, it will create bubbles it will try to come out and the process it creates more bubble and this bubbles actually grow. So, that place growth of that liquid into a bubble form that is what an important aspects in the foam formation; so these all industrially important processes.

Another important as the individual process in which, now a days is very coming up is known as what is known as additive manufacturing or rapid laser manufacturing.

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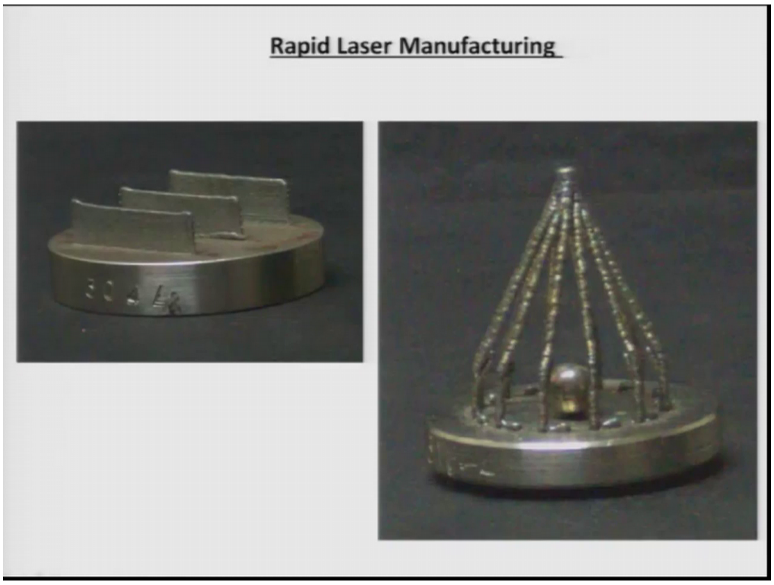

If you want to produce an objects and to see, whether it is possible to have you know particular shape and it has it has market need or not normally rapid prototyping is used. So, rapid prototyping is just a routine technique. Now a days for any objects whether you are wearing a shoe or wearing a goggles, it what rapidly prototype fast and send to the market and then based on the market feedback mass scale production is done. So, in that case this is actually used. Now a days for metals use laser as a layer steps you can see here the laser beam has been used to produce such a kind of structure in which everything is produced layer wise and this is again done using solidification, because we use powder as a source melt it down and then produce this layer structures.

So, that is rapid prototype is the metals actually are using solidification as a tool to create different kinds of structures. So, these are all examples, where I have seen you how solidification is so important in the day to the life because, we need to produce different objects for our need. So, therefore, solidification must be used and this is the probably on the cheapest technique in which liquid metal can be given any shape.

So, that is it is important as a part of course, of phase transformation that you understand what actually happens, atomistically, atomistic mechanism growth is what is important because atomistic mechanism nucleation have already discussed with you. Know when we talk about atomistic mechanism of growth, you have to understand growth means what growth means basically growth of the stable nucleus, which is already form in a liquid and that growth happens. Because of the attachment of the atoms from the liquid to solid the atoms on the liquid they jump across the interface and join the solid and become part of the solid. That is how the growth happens basically any very rudimentary way I can we can say that, but it is not. So, simple that is; what is the basic purpose of discussing today in the lecture?

So, any solidification process is; obviously, categorized in 2 steps nucleation and growth. Once a nucleation forms the growth is nothing but bigger making the nuclear bigger in size. So, how we can make it bigger by simple attaching more atoms to it? So, that atomic attachment kinetics becomes the most important aspects in the solidification in the group process during solidification. And this atomic attachment actually depends on the type of surface, we have type of interface basically we have between the solid and liquid; obviously, because atoms will jump on the liquid because of the thermal vibration.

And then they will join solid surface therefore, the interface between solid and liquid you will dictate what kind of process will happen any way there are 2 types of interfaces normally present in a solid liquid solid actually one is known as atomically smooth.

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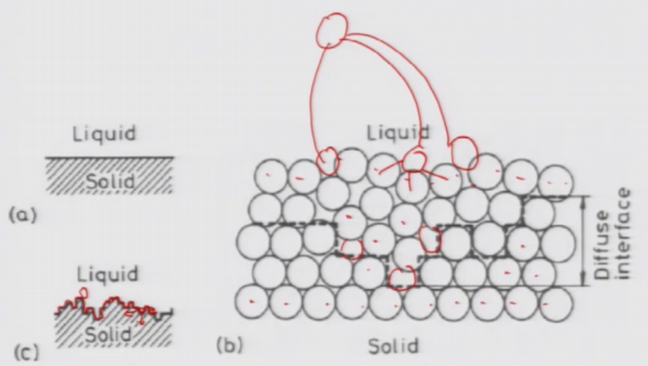

Fig. 3.63 Solid/liquid interfaces: (a) atomically smooth, (b) and (c) atomically rough, or diffuse interfaces. (After M.C. Flemings, *Solidification Processing*, McGraw-Hill, New York, 1974.)

This is directly taken from this picture and then taken from the protocols telling book you can read it, if you have the book otherwise you can actually available on different internet sites also.

So, there are 2 types of surfaces created one is known as atomically smooth what is shown as other one is atomically rough. These are very confusing terms for the students atomically smooth means it is smooth, what do we mean by smooth a smooth we means that it is a very you know nice surface and rough means we assume as basically lot of jeggard things are there. So, as you see here basically in a atomically smooth surface atomically smooth surface is a and actually b and c are actually atomically rough and atomic diffuse interface.

So, in a let us first discuss about the b which is basically diffuse or atomically rough surface. So, as you see here that in atomically rough surface you have a diffuse interface what do you mean of diffuse interface; that means, there is a you know large number of atoms at present at the interface these atoms neither part of the solid nor part of liquid. Why? Because in the solids atoms are nicely order in the liquids atoms are random there is no order in it and in between atoms are actually somewhere, there order here somewhere there rough somewhere there not order.

So; that means, they neither part of completely part of solid nor completely part of the liquids when you such a kind of interface, you can clearly see there is a atom in a liquid bulk of the liquid. And the atom needs to come and jump and join the solid what it can do it can basically come and sit over here nicely. Or you can easily come and sit over there nicely or you can easily come and sit over there nicely and then satisfies bonds 1 2 3 bonds can be satisfied right. Then slowly these atoms can migrate because it is in very high temperature because surface in count of the liquid the diffusion is in very fast diffusion coefficients are very large here.

So, these can easily migrate and reach these places even if it is finely travelling, it can easily occupies these positions nicely and finally, it is all bonds can be satisfied. So, therefore, in a atomically you know rough surfaces or diffuse interface there are empty number of large number of places, where the atom can easily jump and sit and become part of the solid, but that is normally happens for the metals most of the metals silicon dioxide titanium dioxides type of things in silicones and ceramics.

But there are other things like silicon germanium metalloids, where the surface is not actually like that surface. Basically you know what is known as jaggard what is the meaning of that if you carefully look at the surface is basically faceted it is like this is no longer rough enough, but it faceted when you faceted surfaces; obviously, atoms cannot go and sit on every positions because if atoms sits here. Suppose it sits here it is only satisfying only one bond rest of bond are remaining dangling.

Therefore, energetically that is not favorable one another, and if the atom actually goes here in this deep wells they can satisfy many bonds because they can satisfy bonds this way they can satisfy bond this way this way. So, therefore, in this kind of interfaces atoms has to go to a particular place to sit it nicely to becomes part of solid. That is why all the jumps atoms will make from the liquid will not be successful one to become part of the solid some other jumps will successful some other jumps, will unsuccessful; that means, some jumps atoms will basically come from the liquid join, the solid and it can go back if is not avail to lower it is energy completely.

Well that is the basically way things happens, but you know let us do it in the board with a little bit of analysis. How the things happen actually I will assume a simple potential barrier from a solid liquid.

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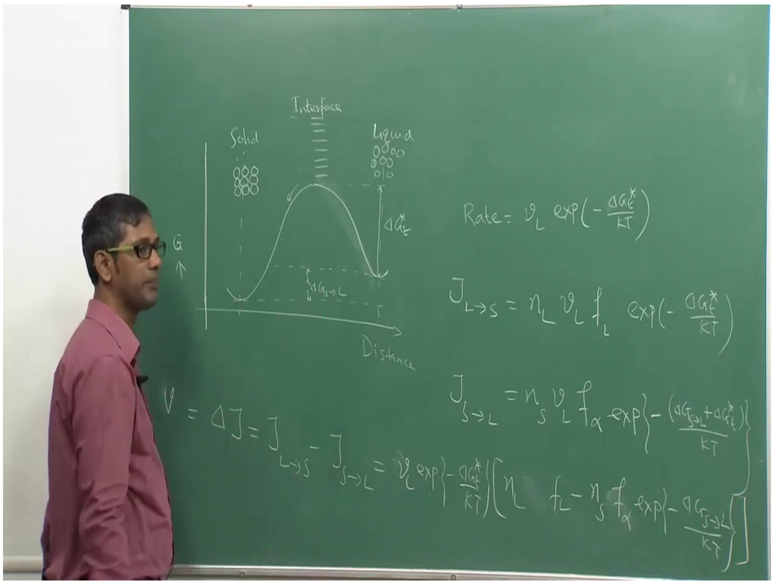

So, let us let me just draw. Let us not consider those interfaces right now simple you consider there situation where you are dealing with this is the distance access and this is free energy g. And suppose this is my solid this is my liquid and this is the interface right this is the interface. Remember atoms in the solids actually in order manner therefore, most of the bonds are satisfied. So, therefore, the potential of the atom basically potential means is it is a energy of atom basically low compare to the liquid the liquid atoms are moving happens just bonds and nuts are satisfied.

Therefore, you know in a solid, if I mark this is solid this is liquid solid will have always low energy then the liquid always because solid atoms are order. And that bonded, but you know at the interface energy will be high why because at the interface atoms are neither atoms are under being a jump. Basically that is why that is the main reason they will have energy at the interface.

Now, these difference between the solid and liquid this. What is I can define as a delta g solid to liquid this is the energy gain, when the atoms actually jumped from the liquid to the solid and this energy which is shown as a pick from here to the liquid is basically known as basically term as delta g star transport t. So, what does this mean this means that this is just like a gain moun in migration or basically atom will be you know from one place diffusion actually from one place to other. Basically this solidification is also can be considered as a atomic migration from the liquid to solid.

So, therefore, it is a diffusion one way one kind of diffusion that is not only diffusion, but it will something else so; that means, this is an activation you know activation control process, when you have activation control process if this is activation control process. Then what is the rate of the process is basically can be easily define as a the frequency of they are to be jumped from the from the liquid to the solid. There is suppose this is mu l multiplied by sorry multiplied by p to the part delta g star by k t. While g star is basically the transport barrier or the barrier height in per atom divided by the thermal energy per atom that is k t.

So, this is what is basically give you the rate, because this is related to the frequency of jump it makes jumps and this is the probability that they can cross the barrier. So, all atoms may not have sufficient energy to cross this height some of atoms will have some atom will not have once is cross this barrier basically the atom slide down or basically atom basically slide down along the energy you know energy gradient and become the part of the solid that is what happens whenever solid. So, in the solid actually atoms are nicely order manner, but in the liquid they are not there happened that in the liquid, they happened at. So, that is why actually things are happen now using this concept 2 different of the interfaces let me explain.

So, I can actually, then do the I can do a flux calculations from liquid to the solid from the liquid to the solid and explain you how the flux can be calculated; obviously, as you as I told you that when you are talking about the net growth net growth means net atoms getting attached from the liquid to solid. We need to consider both the jumps from the liquid to solid, which is not the forward jump forward jump and also backward jump from solid to liquid. Because some atoms such say do clearly may jump come to the solid, but may not feel energetically energy has been reduced because what type of interfaces you have and then go back that is always possible. Because if they are not setting at a very nice positions where most of his bonds are satisfies the solid it can go back.

So, therefore, we need to consider both the flux from the liquid to the solid and flux from the solid to the liquid both. So, what is the flux depends on; obviously, flux will depends on total number of atoms yes if liquid has any number of patterns they all can jump multiplied by the frequency and then; obviously, the factor which comes is that not all the jumps will be successful. Therefore, that it will jump and it can come because some of the atoms may not be able to cross even those barriers they will go back to the liquid that is possible. So, there are 2 types of things one is that atom jumps cross a barrier is a solid do not feel comfortable go back that is what it has jump.

Second one is that atoms try to jump, but may not be able to cross this barrier. So, fraction of liquid atoms of n l multiplied by this frequency into exponential minus delta g t star divided by k t is what if it is flux in the forward direction. That is from the liquid to solid to liquid; obviously, n l be defined n l will be substituted by n s number of atoms (Refer Time 22:30) again the frequency you can write down frequency as solid also, but does not matter because frequencies. Now of the (Refer Time: 22:40) almost same.

And then not all atoms may not be able to go back because there have to go back they have to again cross the barrier so that fraction has to multiplied, but this will be defined exponential, because the barriers now is these plus this together. So, why have to write down delta g delta g solid minus solid to liquid plus delta g star t divided by k t everything here is per atom basis therefore, there is no item dividing by that.

Now, I can actually do a flux balance calculation flux plus calculation tells you liquid minus solid, solid minus solid to liquid. As you clearly see I can take common of mu l exponential minus delta g t star divided by k t. Again take the common this factor and I can write down this as n l mu l mu l. So, n l mu l is what is that aptical. This (Refer Time: 24:09) out right. So, all the factor I can take out this. So, n l v l f l minus n s sorry v l can be taken t s v l can be taken out, is a common and f alpha this will be exponential minus delta g solid to liquid by k t. Thus basically is my next flux and that is nothing but the growth set, so that is nothing but v for a any kind of interface you can talk about it.

So, you can clearly see it is basically has a t exponential term that depends on the frequency of the vibrations that depends on the barrier height. This barrier height for the jump and then it depends on something else depends on these number of sites available how many of the jumps successful on that liquid to solid. Similarly for the solid to liquid and also on the solid to liquid sides we have exponential term related to these parts that is the difference of energies between solid and liquid well.

We will keep these equation intact and discuss further because where it requires some more discussion we will do that.