Principles of Casting Technology

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Lecture - 03
Solidification
Solidification of pure metals and alloys

Welcome to the lecture on Solidification of pure metals and alloys. So, in the last lecture we discussed about how nucleation starts, under what condition it starts and then further it grows, so that there is complete transformation from liquid to solid state. Now we will see it is effect on the solidification behavior in case of pure metals and alloys.

Now, we have already understood the fact that in case of pure metals, the solidification had a constant temperature. So, basically what happens when the liquid metal is poured into a cavity?

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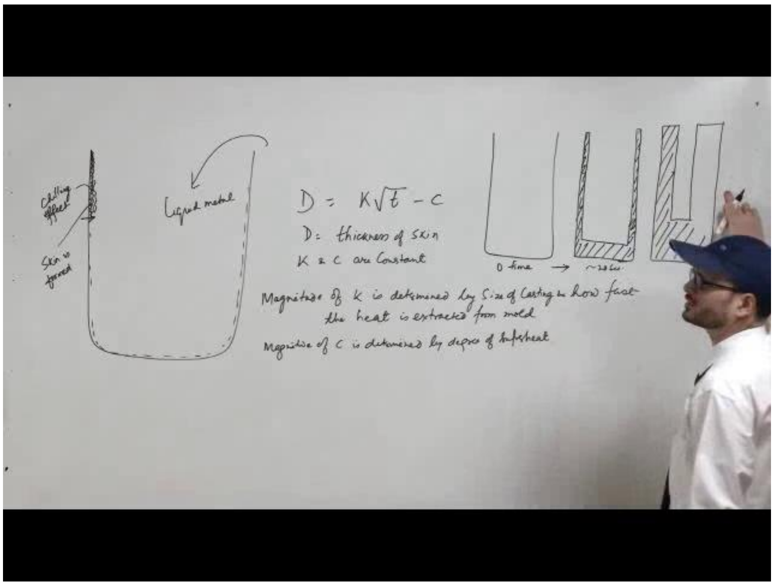

$$D = K\sqrt{t} - C$$

D: thickness of skin

K & C are Constant

Magnitude of K is determined by Size of Casting & how fast the heat is extracted from mold

Magnitude of C is determined by degree of superheat

Suppose you have a cavity, and if the liquid metal is poured, so the liquid metal, and if these surface, is at room temperature. So, certainly as the liquid metal touches these surfaces, or all these surfaces the liquid metal experiences maximum under cooling, and heat transfer from these surfaces is the maximum. So, there will be crystallization of solid particles, solid phases.

Now, since the heat transfer rate is maximum here, and we have also understood that with larger degree of under cooling, the nucleation rate is maximum. So, basically what happens? You have formation of very small nuclei at the surfaces and a skin is formed. So because you have a chilling effect on this point; and due to this chilling effect a skin is formed a skin is formed. So, that is chilling starts next to mode wall and a skin is formed, skin of solid cell or a skin of solid metal is started to form at this point and it further grows.

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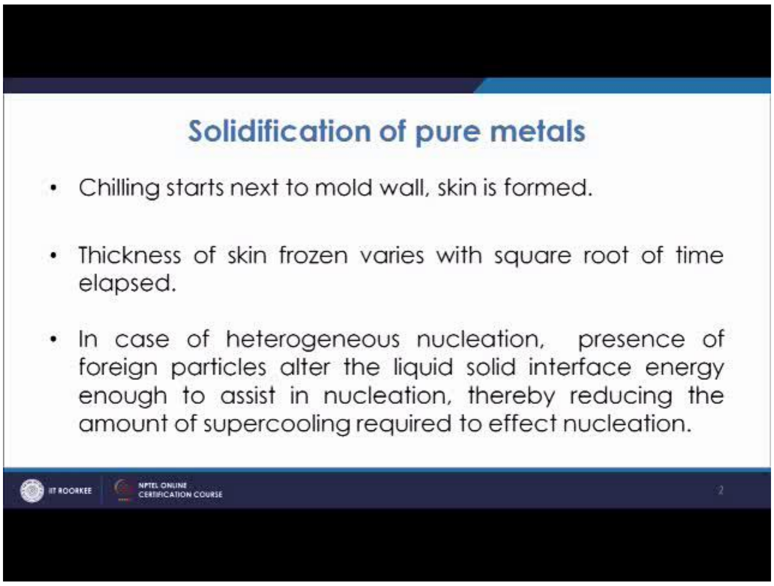

Solidification of pure metals

- Chilling starts next to mold wall, skin is formed.
- Thickness of skin frozen varies with square root of time elapsed.
- In case of heterogeneous nucleation, presence of foreign particles alter the liquid solid interface energy enough to assist in nucleation, thereby reducing the amount of supercooling required to effect nucleation.

Now, thickness of this skin which is frozen varies with square root of time. So, there is an expression which talks about the thickness of the skin formed and that is given as K under root t minus C. So, that is why it is written at the thickness of this skin as it grows with time. So, this thickness D is thickness of the skin and K and c are constants.

Now, the value of K and C being constants, they are governed by certain factors. So, what way they are going to be chased? Now magnitude of K is determined by size of casting, and how fast the heat is extracted from the mold. So, the first constant K, it is magnitude will be determined by the size of casting and how fast the heat is extracted from the mold like what type of mold it is, metal or sand or so. And magnitude of C is determined by degree of super heat. So, these are the 2 constants which come into picture in this particular correlation, which talks about the thickness formed of the solid cell when we are going to cast a particular pure metal and if you look at this, you can very well say that if you have suppose at 0 time, if you have such structure which is poured into; now at further time the solid cell formation will start from both the sides and it will look like this. So, basically this is the solid cell.

Suppose this is at 20 seconds. So, further at 40 seconds it will say the solidified cell may look like this and because the solidification is from the 2 sides, as well as from the bottom. So, this will be the solidified cell at suppose it is a 50 seconds, and further onwards this may be completely solidified. So, this is how the skin thickness goes on increasing in the case of pure metals, and basically it is also known as plane front solidification, where you have a front which is which is having a plane, and that basically advances towards the center of the casting. So, we will also see what way the structure looks likes in case of metals.

Now, in case of heterogeneous nucleation, presence of foreign particles alter the liquid solid interfacial energy, enough to assist in assist in nucleation, thereby reducing the amount of super cooling. Now this was. So, in case of heterogeneous nucleation, the only difference is that due to the presence of certain foreign particles, the free energy requirement changes, the energy requirement changes and the nucleation is more preferred, more favored at preferred sides. So, the degree of under cooling what is required in the case of homogeneous under cooling, that much requirement is not there in case of heterogeneous nucleation. That is the difference in case of heterogeneous nucleation, and that is why you have more nucleation sides in case of heterogeneous nucleation, and whenever we try to have more nucleation points or more nucleuses, then sometimes it is also a common practice, to provide the heterogeneous nucleating agents. Now what happens further; that we will see in our next slide.

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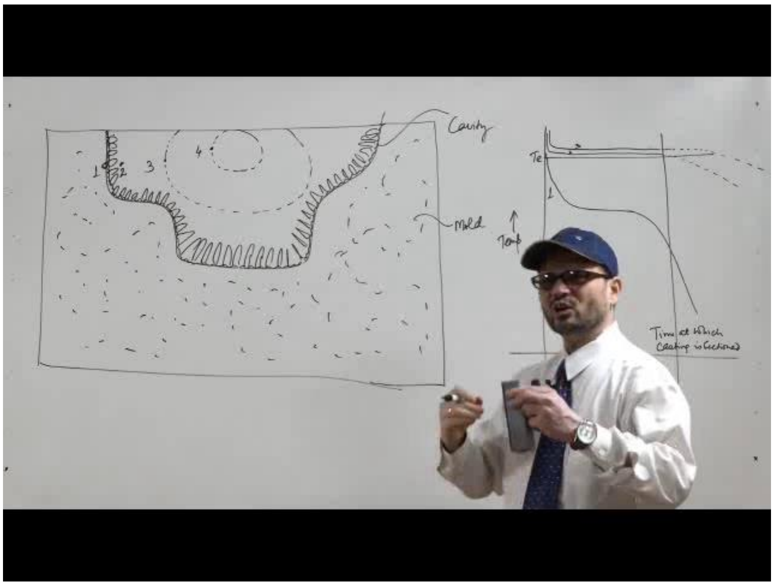

So, what happens that, if suppose you have a cavity of this shape, and it is in a sand mold, this is all sand or any molding material. So, what we see is, this is your cavity; and this is mold. Now once we pour the liquid metal into it, what happens? The liquid metal touches these walls, and the nucleation is starts at this walls. So, all the fine nuclei starts to pour at this walls, and further they grow that will discuss how they grow. So, they grow inwards. So, what we mean to say is, if suppose you have a point here, this is point 1, and you have a point just close to this point, this is point 2, then you have a point suppose a here 3 and one more point is here point 4.

If we try to draw the cooling curve of these points, what has happened here in this case, if we try to draw the cooling curve of the points, and if this is the equilibrium temperature; so, what we see is, we see that it is quickly solidified at point 1. So, this is point 1. Once it touches the wall of the solid due to under cooling, quickly it comes and then it as a thermal rest period, it is somewhat horizontal, and then it goes on like that. If we take the point here, here basically the temperature as just come, and if this is the suppose time at which casting is sectioned. So, at this point, this is yet to solidify. So, this temperature is still there coming and after that is suppose to cross this point temperature.

So, solidification is still has not taken place, but it will come in certain time. Now at this point, if you look at this cooling, this curves of temperature, ISO temperature curves will be like this. Similarly on 4 it will be like this. So, basically these are the ISO temperature lines, they show where the temperature is more. So, for this it will be further, you have these lines and you expect that in future they will sometimes be crossing over this equilibrium temperature line, when the nucleation will take place.

Now, let us see further, how there is the growth and nucleation in case of pure metals.

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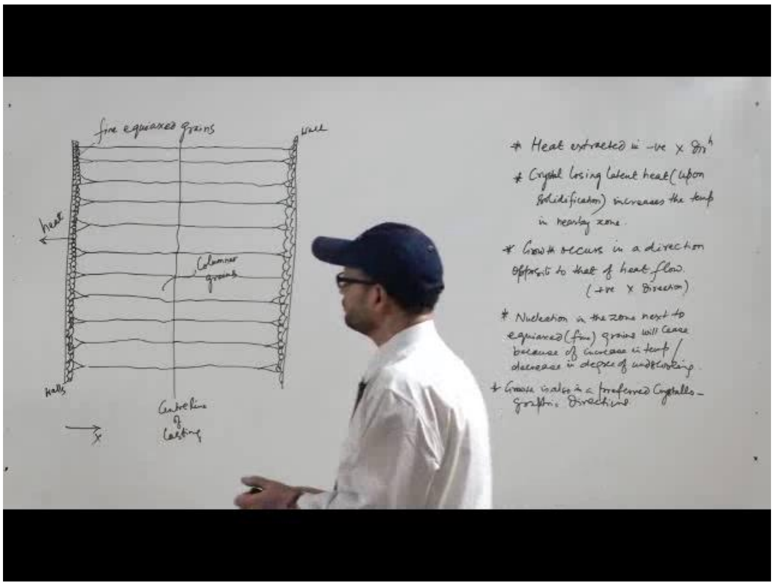

- Heat extracted in -ve x dirn
- Crystal losing latent heat (upon solidification) increases the temp in nearby zone.
- Growth occurs in a direction opposite to that of heat flow. (+ve x Direction)
- Nucleation in the zone next to equiaxed (fine) grains will cease because of increase in temp / decrease in degree of undercooling.
- Growth is also in a preferred crystallographic directions

So, what is happening in case of pure metals that once this is the wall, once the liquid metal is touching to this wall, there is formation of very small grains and these are there is a large number of nucleation because of large under cooling that is experienced when the liquid metal is touching this wall. And these grains are known as Equiaxed grains. So, this is fine equiaxed grains, there is formation of fine equiaxed grains at the mold wall.

Now, what happens that from this mold wall, heat is extracted in this direction. Now because of as we have already discussed that, because of larger degree of under cooling, experienced at the mold wall the nucleation rate is maximum at the mold wall, and you get a fine equiaxed grain structure on the mold wall. Now heat is extracted in the opposite direction, further what happens that, the heat which is extracted because of solidification because of the presence of this surface, but as the solidification is going on; there is also release of latent heat. So, heat extracted in negative x direction, here you have negative x direction the heat is extracted from the mold wall.

Now, what happens? When this crystal is getting solidified it usage it is latent heat? So, the crystal losing latent heat upon solidification increases the temperature in nearby reason, nearby zone. What is happening is that suppose this crystal as solidified, it as lost certain of it is latent heat, this latent heat released will flow in all the directions, it will flow in this direction as well as in this direction. Once it goes into this direction, it is basically immediately increasing the temperature of the adjacent liquid.

Now, once the temperature of the adjacent liquid is increased, the degree of under cooling experienced for this liquid part is becoming less, and that is why nucleation is stopped; the nucleation which was expressed the rate of nucleation which was there because of large under cooling at the zone close to the wall has been decreased because of the increase in temperature in a reason just near this solid cell formed and because of that the nucleation ceases, and because the there is increase in temperature, in that basically increase the temperature zone growth becomes predominant.

Next is the growth also is there, growth occurs in a direction opposite to that of heat flow. So, what happens? Since your heat flow direction is in the negative x direction. So, it will go into positive x direction, one is that there will be growth, nucleation will be ceased. Nucleation in the zone next to equiaxed, fine equiaxed grains, we will cease because of increase in temperature, or decrease in degree of under cooling.

Now, since this growth becomes predominant here. From here there will be the growth of these particular grains which are formed in the direction towards the center of the casting. Growth is also in preferred crystallographic directions. So, basically growth will certainly like to take place in certain preferred crystallographic directions as well as growth is also in a direction opposite to the direction of heat flow. So, what happens after that, the growth starts taking place. This is center of the casting centerline of casting.

So, what happens? After this you have the formation of columnar grains, these grains which are be formed because of the growth of these grains, because nucleation as a stopped, because of the conditions which we have discussed earlier, because of the decreased value of under cooling, then there is formation of the grains and the growth of grains like this and they are known as columnar grains. So, these grains are known as columnar grains. And from this side also similar thing happens. So, this is also wall. So, similar thing will happen this side also, and ultimately you have the structure becomes like this.

Now, what we see is, you have wall on both the sides, you have formation of fine equiaxed grains on the mold wall, and these columnar grains extend up to the center of the casting. And if there is a wall on the bottom also, there will be formation of the equiaxed grain at the bottom of the wall also, as well as from the side also. So, what we see is this is the typical characteristic of the type of grains which are formed in case of pure metals. In case of pure metals, that there is plane front solidification, this front advances uniformly and goes till the center of the casting, and this is basically a typical characteristic of pure metals. So, what we see is next to the fine equiaxed grains on the wall, a zone of columnar grains is formed.

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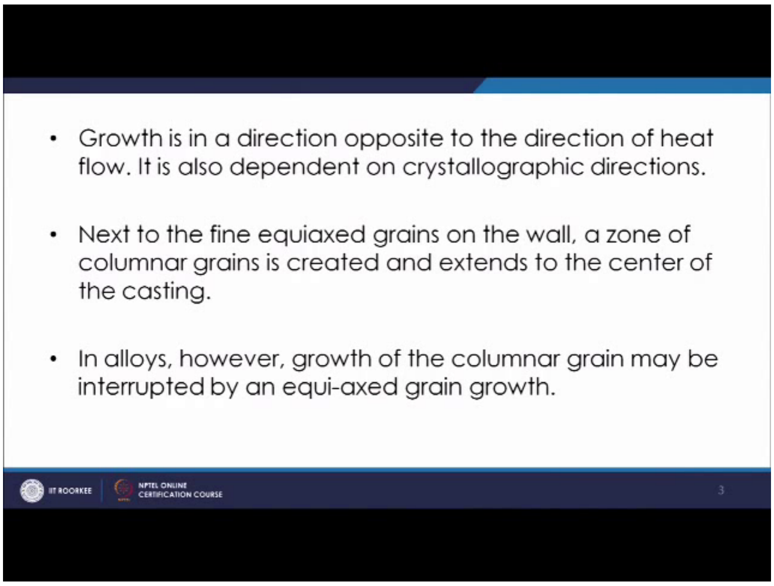

- Growth is in a direction opposite to the direction of heat flow. It is also dependent on crystallographic directions.
- Next to the fine equiaxed grains on the wall, a zone of columnar grains is created and extends to the center of the casting.
- In alloys, however, growth of the columnar grain may be interrupted by an equi-axed grain growth.

Now what we see is in this, we may think of having this is structure, what happens? That the growth they may try to grow in all the directions, but being this as the predominant directions, mostly the growth in other directions is pieced off, they are basically neutralized, and the predominant direction of the growth of the crystal is in this direction, from here that is positive x direction, from here it is negative x direction. So, this way you see that how these grains are there in case of pure metals. Now what happens in case of alloys? In case of alloys, the growths of columnar grains are interrupted by equiaxed grain growth that we are going to discuss when we talk about the freezing of alloys.

Now, we will discuss about the freezing of alloys. Now what happens in case of alloys? As we know in case of alloys, the freezing is over a range of temperature, freezing does not happen at a particular temperature. So, there is no plane front solidification. In case of metals, the solidification is at a particular temperature and slowly this front to moves in towards the center of the casting.

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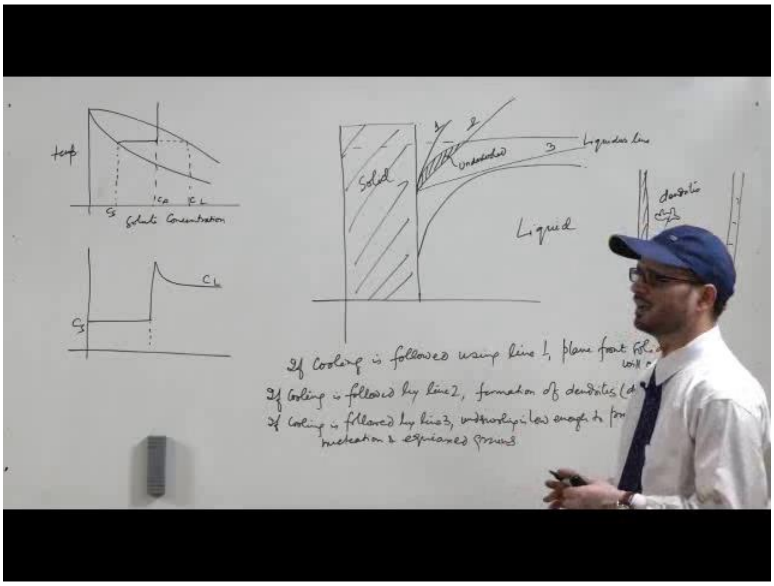

If Cooling is followed using line 1, plane front Sol. will

If Cooling is followed by line 2, formation of dendrites (d

If Cooling is followed by line 3, undercooling is low enough to for
nucleation & equiaxed grains

Whereas in case of alloys, if you look at the freezing is over a range of temperature. So, suppose you have a magnitude alloy, where this is the solute concentration, and this is the temperature.

Now, what happens when the temperature comes down? When it comes to this temperature, suppose at this temperature the concentration of this solid will be this, and concentration of the liquid will be this. So, basically if it is a composition this is concentration of solid, this is C A, and this is concentration of the liquid. Now what happens in this case, that when the solid will start precipitating from the liquid, the solid which is going away, it as lower solute concentration; whereas, the liquid which is away it as a higher solute concentration. So, basically because of that, a concentration gradient is developed. So, in such systems the precipitating solid differs in composition from liquid, due to which a concentration gradient is set up in the liquid. So, what you see is, here you have less C S at this point, this is C S, and this is C L this is the point A.

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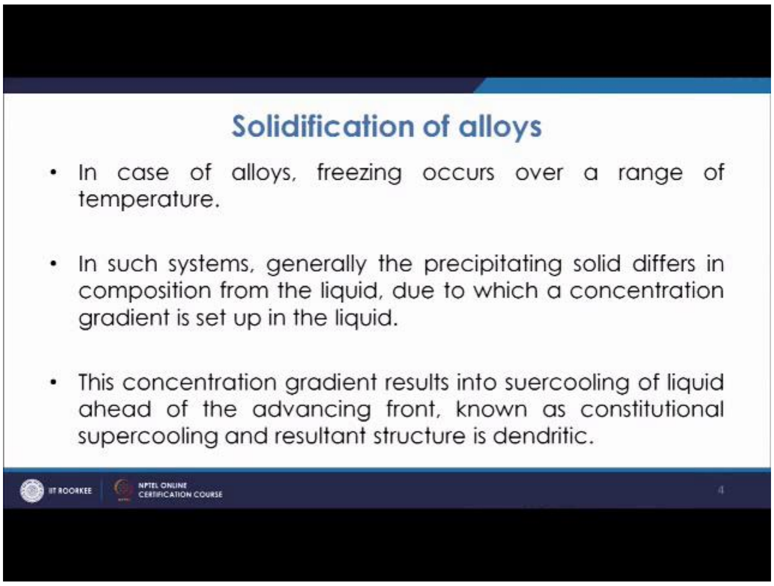

Solidification of alloys

- In case of alloys, freezing occurs over a range of temperature.
- In such systems, generally the precipitating solid differs in composition from the liquid, due to which a concentration gradient is set up in the liquid.
- This concentration gradient results into suercooling of liquid ahead of the advancing front, known as constitutional supercooling and resultant structure is dendritic.

Now, what happens, the concentration of the solute in the solid is less, and that is why in the immediate vicinity there will be large concentration of the solute, and further in the zone it will basically neutralize. So, there will be a concentration gradient set up. This is the set up of the concentration gradient. Now because of this what happens? So, you have, so what we see is, now because of this concentration gradient, you will have the Liquidus line behaving like this is the point. So, this much portion is solidified, this is the portion which is solidified, and your Liquidus line behaves like. So, earlier it was like this, but because of the concentration gradient, this liquidus line as shown to behave like this. Now once your liquidus line changes, your nucleation will occur according to this line.

Now, what happens? If suppose this is your now new liquidus line, which is generated because of the changing composition; now for this, if suppose you have a cooling rate, if cooling is followed using line one, if suppose your cooling rate is maintained like this, if you are providing a cooling rate, which is represented by this line A1 in that case your plane solidify plane front solidification will occur.

But what happens getting this rate of solidification, rate of cooling is not only it is possible? So, if suppose you are providing a cooling like this. So, if cooling is followed by line 2. Now if cooling is followed by line 2, then what may happen? You can experience a zone which is under cooled. Although this zone is liquid, this is a liquid zone, this is a solid zone, but in the liquid zone itself away from the solid, you have a zone which is already under cooled, and once you have under cooled zone there will be nucleation started in a portion, which is in the liquid itself. Basically in ideal case, what happens in case of metals? Your nucleation only has to a start at this point or it as to grow from here, but in this case what happens, because of this concentration gradient and because of the existing cooling mechanism, your certain area becomes under cooled and that will result into formation of nucleus, or formation of solid phases in the zone somewhere.

So, what happens? So, suppose some part as solidified, but in the zone somewhere something as formed. Now this will try to since it is in isolated mass in the liquid, there is no preferred direction of heat flow at that particular point. So, it will grow in all the directions, having certain preferred direction and normally it looks like a dendrite structure. So, it is a tree like a structure, or dendrites. So, they will basically we known as dendrites.

Now, what happens? These dendrites are basically formed at a place which is a still liquid. And if these dendrites are formed all along the points, in that case there may be certain zones which are trapped, some freed or liquid zone may be trapped inside the branches of the dendrites, or in the arms of the dendrites, and they that zone may be prone to having shrinkage defects. So, in this case you get a dendritic type of a structure. So, as we see in that case you have equiaxed zone followed by columnarous structure, you have a columnar dendritic structure in this case. It will grow certainly in this direction, but you have a dendritic type of a structure in this case. So, we have a dendritic structure, and further what we can see is further if your nucleation suppose. So, if the nucleus heating rate is like this. So, when under cooling is further more. In the case of 3, the under cooling is further I mean it is quite low enough, so that promotes random nucleation and equiaxed gains at the center.

So, basically typically in the case of alloys, what happens? In the near zones you have a dendritic, columnar dendritic structure, but in the middle, in the middle portion where the cooling rote is rate is still slow, you will have again equiaxed dendritic type of structure because of the random nucleation. So, what we can see is, if we try to find; now if the cooling is followed by line 2, you have formation of dendrites, dendritic structure. If cooling is followed by line 3, under cooling is low enough to promote random nucleation and equiaxed grains. So, what will be the resultant micro structure that we can see further.

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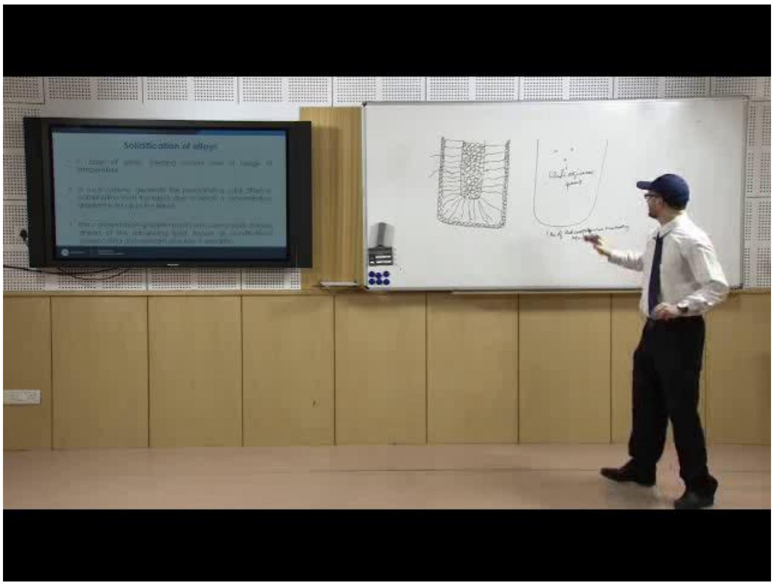

So, what we see is in case of alloys, initially you have formation of equiaxed grains on the mold walls, and further you have the growth of columnar grains, and in the middle portion, you have further equiaxed grains. And you have columnar grains from the both the sides. So, what we see is, in case of alloys you get these are the columnar dendritic structures, you have equiaxed grains and this is also equiaxed dendritic structure, typically this is the micro structure for an alloy. Whereas, if you use of heterogeneous nucleating agents, will all give you whole equiaxed structure, whole equiaxed grains.

So, because the homogeneous nucleating agents, will serve as nucleation centers at different points, and if the nucleation centers are more, they will (Refer Time: 37:09) the growth of individual grains. So, you will have more and more grains and they will be giving you the equiaxed type of grains. So, this is how you get the different type of grains, in case of metals and alloys.

Thank you.