Texture in Materials

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Module - 07
Texture evolution during solidification
Lecture - 38
Introduction to Solidification Texture

Good afternoon everyone and today, in our course Texture and Materials, we will be starting module 7 and we have finished the part of the course which shows the various ways to observe texture and the tools that are used to measure them. We have went to very high details to understand various kinds of texture measurement techniques and then, we have also gone through the analysis techniques.

On the other hand, we have known the mathematical formulation of the texture analysis pertaining to pole figures, inverse pole figures and orientation distribution function and orientation matrices and we have related between them. Today, we will be starting with the second part of the course which basically relates that texture information, how we can use it in metallurgical processes like solidification, phase transformation, deformation behavior and recrystallization techniques.

So, we I will give you practical information relating it to the fundamentals of the subjects of this solidification, phase transformation, deformation and annealing. In case of with various examples like face centered cubic material, body centered cubic material and hexagonal close packed materials to and we will try to understand how texture influences during this processes and their properties. So, this is today, module number 7 that is Texture evolution during solidification and this is lecture number 38, Introduction to Solidification Texture.

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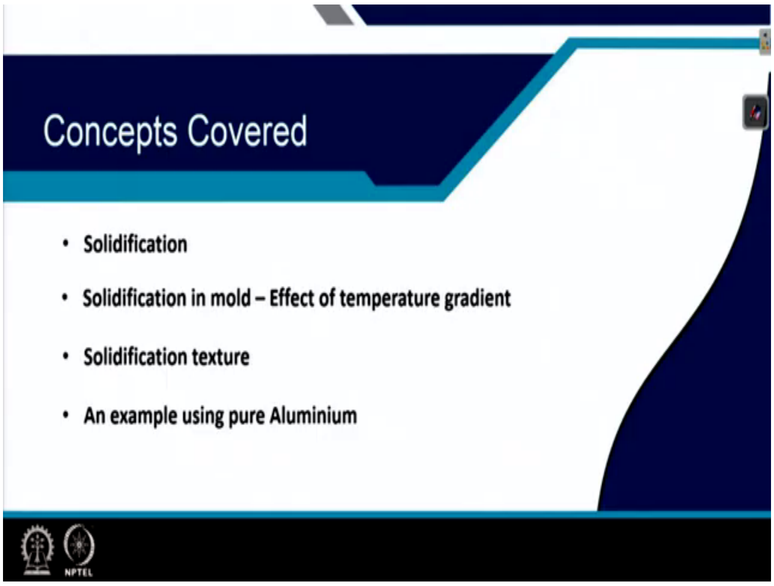

The concepts that will be covered in this lecture are solidification processes relating it to the texture. Solidification of the mold that is the effect of temperature gradient; that means, that while we pour us liquid metal into the cold mold, then three zones that forms that is chill zone, columnar zone and the interior equiaxed zone; the how the growth of the grains occurs and relating it to the texture.

So, the third concept that will be covered is solidification texture. And the finally, we will give you an example of pure aluminium which how the texture will develop under two different conditions.

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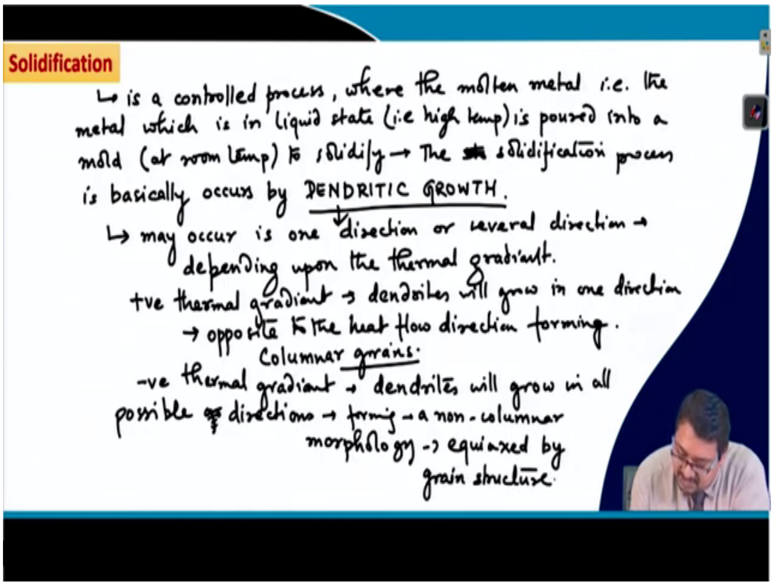

Solidification is a controlled process right, where the molten metal that is the metal which is in liquid state that is high temperature is poured into a mold. The mold surface may be at room temperature; mold at room temperature you know to solidify.

Now, the solidification process is basically occurs by dendritic growth right. So, while this dendritic growth may occur this dendritic growth may occur in one direction or several direction depending upon the thermal gradient and we will talk about this in the later slides in quite detail.

So, if the thermal gradient is positive, then dendrites will grow in one direction which is basically opposite to the heat flow direction forming you know columnar grains right. Now, in case of you know a negative thermal gradient, the dendrites will grow in all possible directions, sorry directions forming a non-columnar morphology or equiaxed type grain structure right.

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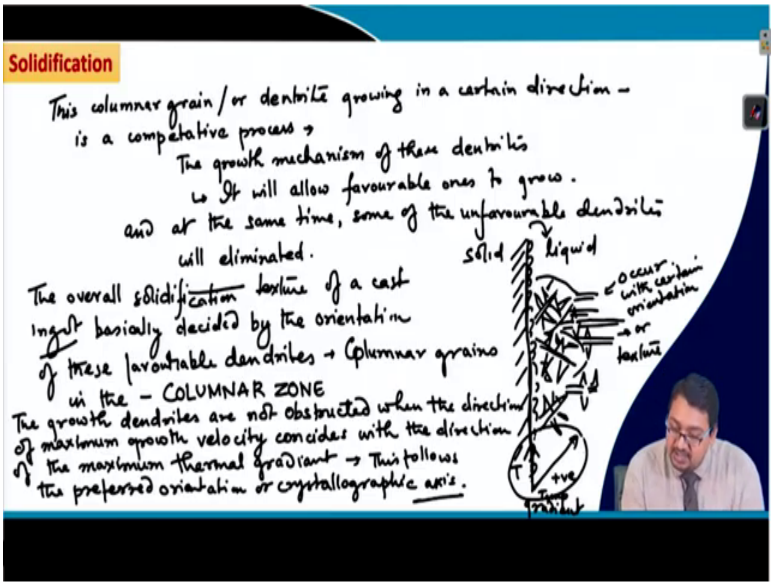

This columnar grain or dendrite growing in a certain direction you know is a competitive process. So, the growth mechanism of these dendrites will be such that it will allow favourable ones to grow and at the same time, some of the unfavourable dendrites will be eliminated. So, the overall solidification texture of a cast ingot basically is decided by the orientation of these favourable dendrites which are basically becoming columnar grains in the you know mainly the columnar zone.

So, if we look into the solidification process and let us say that this is a wall and this is an interface between the solid and the liquid phase. Now say for example, this is the mold wall and the liquid has been poured into it and because the temperature of this mold wall is very small, then suddenly there will be a lot of you know nucleation and so, there will be a lot of small small grain that will form and depending upon the orientation of this grains, the preferable planes will get you know further you know growth.

So, the dendrites may grow in different direction and in each direction, there could be various other dendrites that will be growing something like that right. Now, the formation of this kind of dendritic structure right will occur; but finally, the ones which will be favourable will only survive in this.

For example, if we have a positive temperature gradient; say for example, if this is the vertical is the T and this is the temperature gradient and inside the liquid is this if this temperature gradient is positive, then what will happen? That the dendrites, those will the growth of the dendrites will that will survive finally, will be mostly like this and there will be few dendrites which will be falling like this.

So, you see that the dendrites which may occur in all possible direction initially because of the certain chill zone and lots of nucleation and the effect of the initial orientation in the you know solidified nucleated chill zone area and because also of the very low temperature of the mold.

Finally, when come under a stable circumstances that is in the positive temperature gradient that out of all the dendrites, only those dendrites which grows which are able to grow perpendicular to the mold wall or perpendicular to the wall of the solidified and the liquid state survives. This particular growth will occur with certain you know orientation; specific orientation or texture right.

So, the growth dendrites are not obstructed, when the direction of maximum growth velocity coincides with the direction of the maximum thermal gradient and this follows the preferred orientation or crystallographic axis right. That means, that the one columnar grain growth will occur using that crystallographic axis or on that crystallographic plane in which that the one which will be most loosely packed; that means, which will grow the most fastest right.

So, the one that will be closely packed will be moving very slowly or growing very slowly; whereas, the ones which will having the most loosely packed will be growing faster. Moreover, it will occur in the direction which is you know opposite to the direction of the thermal gradient right. So, opposite to the direction of the heat flow and towards the maximum thermal gradient that is in the positive temperature gradient.

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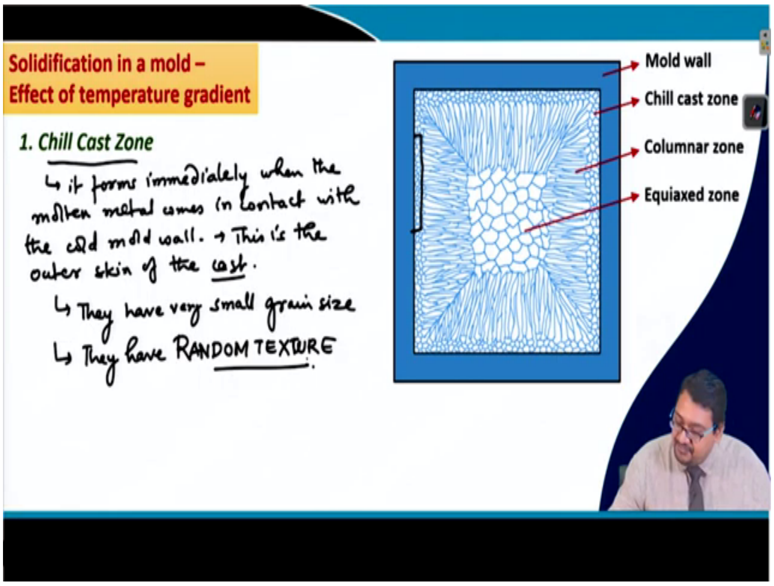

So, solidification occurs usually in a kind of a mold structure, in which the molten metal is poured on a mold which is shown here right; the blue colored mold in which the molten metal is poured.

The mold wall are basically at room temperature and therefore, when the very high temperature molten metal comes in contact with the mold wall, it gets chilled immediately and lots of nucleation takes place and then, small-small grains starts to develop because of a large amount of nucleation in the near to the mold wall and this is known as the Chill cast zone.

On the other hand, as the after the chill cast zone, columnar zone starts to develop. The columnar zone basically is that area, where the thermal gradient is positive. So, the dendrites actually grow in one direction, at the direction of the maximum thermal gradient that is opposite to the direction of the heat flow and therefore, elongated columnar grains could be observed. And finally, at the center at the interior, an equiaxed zone, where the positive temperature gradient does not exist.

So, if I write that the let me take the pen. So, there are three zones; chill cast zone, columnar zone and equiaxed zone and if we look into this chill cast zone; that is only this area, then what we will find? That it forms immediately right when the molten metal comes in contact with the cold mold wall and this is the outer scale right of the cast right.

So, they have very small grain size as you can see in the pictorial representation and they have random texture usually ok; because they nucleate in a larger amount because of a rapid solidification at the at this position.

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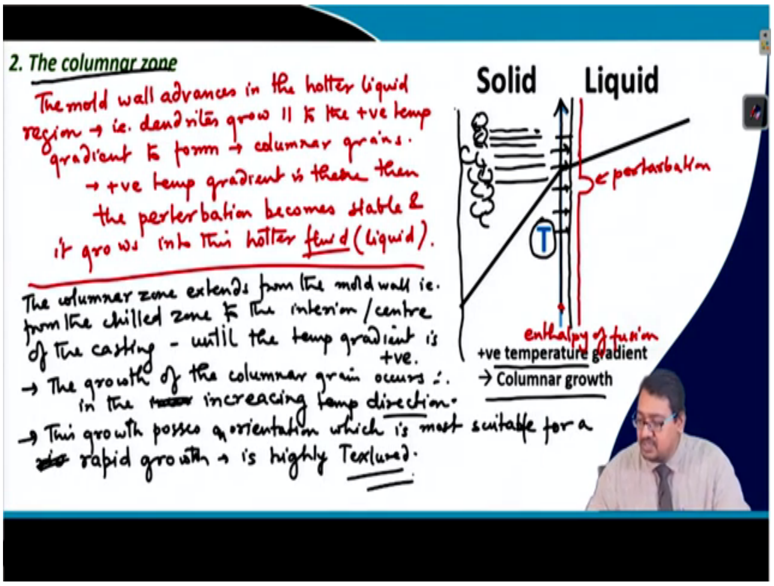

Now, if we go to the next slide, we will see what is the columnar zone? The columnar zone is a zone, where there is a positive temperature gradient and if we look into the solid liquid interface and let us say that this is the solid liquid interface and if we look into the temperature profile and if the temperature profile is going up like this, then so T is the temperature here.

So, in the solid, in front of the solid liquid interface, if the temperature gradient is positive, of course, if this is the mold wall, then the temperature where the metal has been solidified will be less and away from the mold wall, it will be high.

And in the liquid solid liquid interface, if the temperature gradient in the liquid is also positive that is the positive temperature gradient, then in case as I said, columnar growth takes place. Now, you see that in this case, let us say here there is a lot of nucleation because of the presence of the mold wall chill zone and then say for example, columnar grain growth has occurred something like this.

Now, if we look into this interface of the solid liquid interface, then you will see that as the temperature reduces, keeping the positive temperature gradient, the mold wall basically you know increases in this direction right; increases in this direction.

Now, let us change the color of my pen. Now, if we look the mold wall basically moves ahead forming a perturbation something like this. So, if this is something a perturbation like this right. So, the dendritic growth which is you know parallel to the maximum positive temperature gradient, if it occurs; then at the solid liquid interface, it will be you know there will be a enthalpy of fusion right.

In the solid liquid interface and then, the you know the mold wall advances as a whole into the hotter region right. So, the mold wall basically advances as a whole into the hotter region that is the hotter liquid region as its cool down slowly to form a columnar grain structure right.

So, let me write it down that in this case, the mold wall advances in the hotter liquid region right. That is the dendrites grow parallel to the positive temperature gradient to form columnar grains. So, if the positive temperature gradient is there, then the perturbation becomes stable and it grows right into this hotter than the solid fluid right. Now, fluid or liquid right.

Now, this indicates that the liquid and the solid phase interface is you know stable and smooth. So, let me change the color of the pen a little bit; let me take it black. And so, the columnar zone extends from the mold wall that is from the chilled zone to the you know interior or center of the casting, until the temperature gradient is positive right.

The growth of the columnar grain occurs therefore, in the increasing sorry increasing temperature direction right, positive temperature gradient. So, this growth poses possesses a orientation an orientation sorry an orientation which is most suitable for a rapid growth right; sorry for a rapid growth.

Now, as I said that the rapid growth can only take place in the direction which is the most loosely packed direction and therefore, the this kind of columnar grain structure is highly you know textured. So, this is the normal scenario of the you know solidification, where the solidification texture is basically related to the columnar zone which is a highly textured region.

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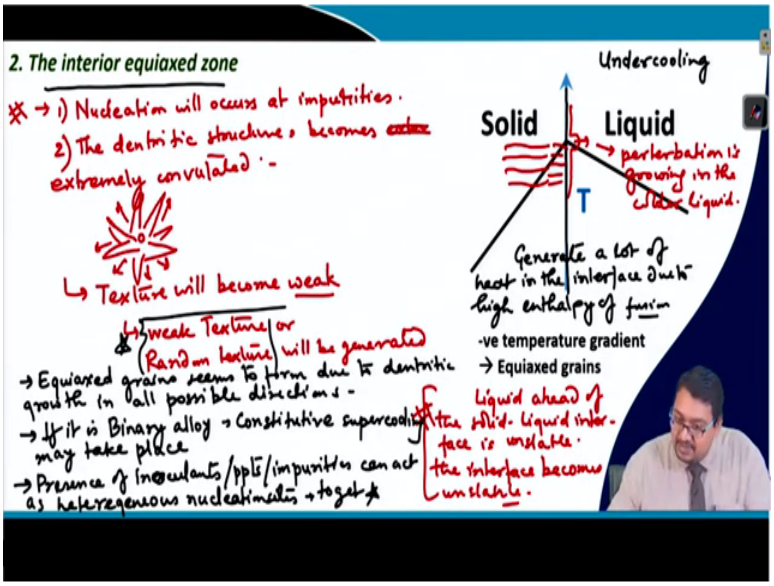

Now, as I said that as we go in the interior of the zone, the thermal gradient does not remain positive and then, because of this ,the dendritic growth may not occur in a certain direction; but it may occur in all possible direction leading to a formation of an equiaxed kind of grain morphology. If we because we see the grains, we cut the grains, we cut the metal cast metal from the inside and c 1 surface and that surface will look as if it has an equiaxed grain morphology.

So, this is the case from the interior of the microstructure which so shows you know equiaxed grains as observed in the earlier slides and this is a situation, where you see that there is a positive temperature gradient in the solid state right and this is the solid liquid interface and the liquid is in the negative temperature gradient. So, the liquid is under a situation which is known as you know under cooling.

So, the solid, in the solid-liquid interface has a higher temperature than the liquid in front of the solid liquid interface. So, under such situation, what will happen? Under such situation, you see the first thing is that because of the enthalpy of fusion in the solid liquid interface, the temperature of the interface will become very high.

So, it will if I say generate a lot of heat in the interface due to high enthalpy of fusion right. So, what things that happens? In this case, let me change the color of this pen for clarity; in this case, if you see as the metal basically let say that it has columnar grains up to here and when this metal tries to grow further and there is a perturbation, the perturbation will not remain stable because as it goes out, the temperature is basically lower than from where it is coming from.

So, as the liquid basically cools down, the perturbation may occur in all possible direction because there is no you know positive thermal gradient. So, the perturbation is basically growing you know the perturbation is growing in the colder liquid right; it is growing in the colder liquid. So, there are two things that may happen. The first thing is that because the liquid ahead of the solid liquid interface is unstable; the interface becomes unstable right.

And when such a thing happens, when the interface becomes unstable, then what happens? Then, what happens? That there could be two things; the first thing is that if there are impurities present, then nucleation will occur and loss will occur at these impurities under this situation.

And second, it may happen that the you know the dendritic structure becomes extremely sorry convoluted; that means, that formation of dendrites from the nucleated grains in all possible direction right and therefore, you know what will happen? The texture will become weak right.

So, you see that even though each of this dendritic growth may have preferred texture formation; but the texture as the dendrites are growing in all possible direction because of the absence of a positive temperature gradient, the texture will become extremely weak.

So, either weak texture or random texture will be generated right. So, under this situation, what happens? Equiaxed grains seems to form due to dendritic growth in all possible directions. Second thing is that if it is binary alloy, then constitutive super cooling may take place right. Third, presence of inoculants or precipitates you know or impurities can act as heterogeneous nucleation sites to get you know weak or random texture.

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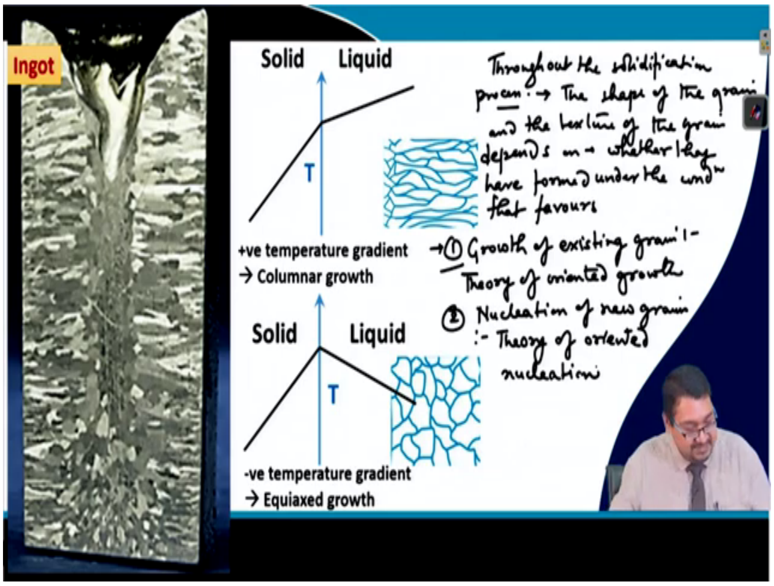

So, if we look into the solidification process and this is a picture of an aluminium ingot which is solidified into a square mold and you see this ingot, at if we look into this position, this position, it has the chill zone and then, one can observe after some time after some distance, columnar growth is occurring right; columnar growth is occurring and then, here is the you see the interior you know equiaxed zone, you can see the grains are almost in an equiaxed state.

So, as in the columnar zone, there is a positive temperature gradient, this kind of microstructure feature will form. In case of you know the interior equiaxed zone because of the formation of dendritic structure in all the direction, this kind of equiaxed growth will be observed. So, throughout the solidification process, let me write it down.

So, throughout the solidification process, the shape of the grain and the texture of the grains basically depends on whether they have found under the condition that favours you know one, that is growth of existing grains known as theory of oriented growth right. Second, nucleation of new grains which is known as theory of oriented nucleation ok.

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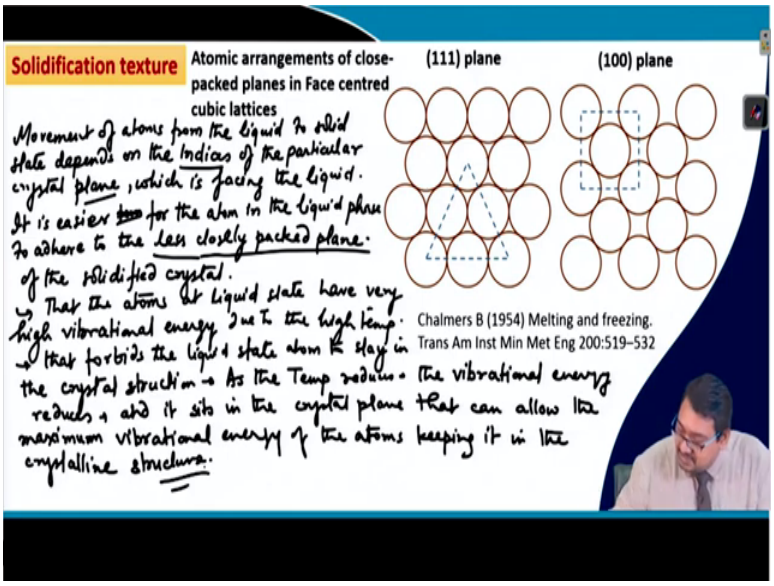

So, a solidification texture basically depends upon the you know the crystal structure of that material which is being solidified. Now, if we look into this example of a cubic structured material, so here is an example of a face centered cubic material. Let me take the pointer ok. So, the face centered cubic material and we have shown two planes; one is the 111 plane and another is the 100 plane.

This is been taken from the paper by Chalmers of 1954. So, the two planes; the 111 plane is the closest packed plane in case of the FCC material and its structure something looks like this. In case of the 100 plane, this is the most loosely packed plane in the FCC material and the structure basically looks like this.

So, it has a very open structure; whereas, this one is having a very close structure. Now, if the molten metal atom is trying to join a structure, which structure it will basically join? If we look into this you know mechanism in a logical manner, the molten metal, the crystal structure is not maintained. So, as the temperature of the metal is increased, the atomic vibration increases.

So, as the atomic vibration increases and it increases to a level, where the metal basically becomes molten; that means, it could not maintain the crystal structure. That means, the vibrational energy of the of the atoms because of the temperature attributed to the temperature has increased to the level that it cannot be kept in that close packed structure, then the metal loses its crystallinity and goes to the molten state right.

And in the solidification process, what happens that molten metal basically you know the temperature of the molten metal is reduced and during that time, what happens that the molten metals vibrational energy is reduced bit by bit as the temperature is reducing.

So, the molten metal which could not sit in any crystal structure as the vibrational energy will reduce and reduce and reduce to a certain extent, then at a certain vibrational energy, the smallest reduction, it may get fit to the one crystal structure or in the crystal plane which is the most loosely packed right.

So, during the dendritic growth or the columnar growth, what will happen? The vibrational energy of the atoms will reduce, reduce, reduce and go to the most loosely packed plane that is the 100 plane and will be able to sit on it, keeping its very high vibrational energy still, but lower than that of the molten atom molten metal atom right.

Now, when it sits on the 100 plane, it is the most loosely packed. So, the 100 direction which is perpendicular to this plane is also the most loosely packed direction. So, its growth will be faster right. So, if any grain, any atom sits on the closed pack plane on the 111 plane also because by losing a lot of vibrational energy, it won't survive because the normal to the 111 plane, which is the 111 direction is also the close packed direction and closer than the 100 direction.

So, the growth of 111 direction by putting say 3 atoms will be much lower than the growth of 100 direction by putting equally 3 atoms. So, the 100 plane and the direction will survive and therefore, most of the cases, the you know in the columnar zone the 100 texture basically forms parallel to the growth of the grains. Now, if we look into it and let me write it down for you.

So, you see what I am saying is that the movement of atom from the liquid to solid state depends upon solid state depends on the indices means the Miller indices of the particular you know crystal structure, crystal plane rather right, which is facing the liquid right. Now, what I was saying that it is easier for sorry for the atom in the liquid phase to you know adhere to the less the most least closely packed structure right; it is just ok.

So, it should adheres to the less closely packed basically plane right; the most least closely packed plane of the solidified crystal right. Now, we should remember that the atoms at liquid state have very high vibrational energy due to or pertaining to the high temperature and that forbids the liquid you know state sorry liquid state atom to stay in the you know crystal structure, to stay in its you know crystal structure solidified state. That is why it is in the molten state right.

So, as the temperature reduces; the vibrational energy reduces and it sits in the you know the crystal plane that can allow the maximum vibrational energy of the atom, keeping it in the crystalline structure right.

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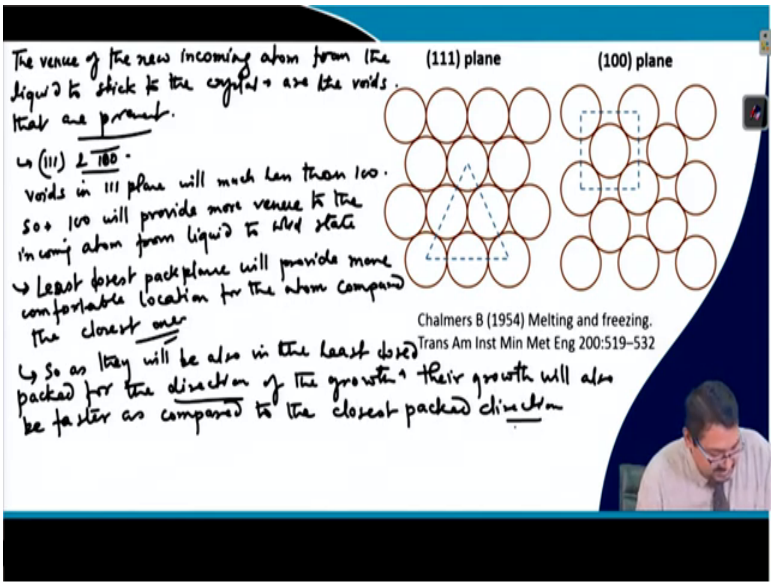

So, let me take another slide. So, the venue of the new incoming atom from the liquid to stick to the you know the solid crystal are the you know the voids, are into the voids that are present there. So, as I said that if we have two planes; 111 and 110, the voids in sorry 100 the voids in the 111 plane will be much less than 100.

So, 100 will provide more venue to the incoming atom from liquid to solid state right. Now, this shows that less means the least the least closest, sorry closest packed plane will provide more comfortable location for the atom compared to the closest one right.

So, as the atom is sitting on the least close packed plane, so they will be also in the least closed packed for the direction right of the growth. So, their growth will also be faster as compared to the closest packed direction.

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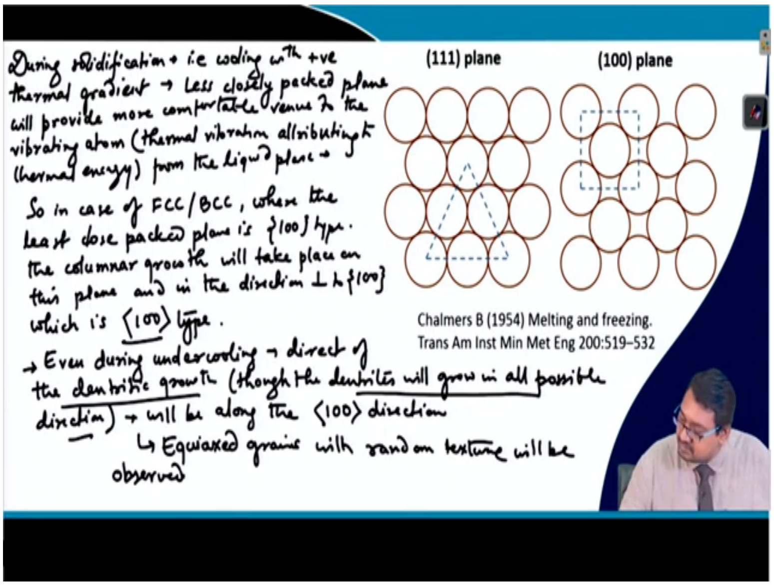

So, what we can conclude here is that during solidification, that is cooling with positive you know thermal gradient less closely packed plane will provide more comfortable venue to the vibrating atom, thermal vibration attributing to thermal energy from the liquid phase.

So, the closest packed planes the least, so in case of FCC or BCC, where the least close packed plane is you know 100 type the columnar growth; growth will take place on this plane and in the direction perpendicular to 100 which is 100 type family right.

Even during undercooling, direction of the dendritic growth, though the dendrites will grow in all possible direction the growth of the dendrites will be along the 11; 100 direction as because the dendrites will grow in all possible direction, equiaxed grains with random texture will be observed.

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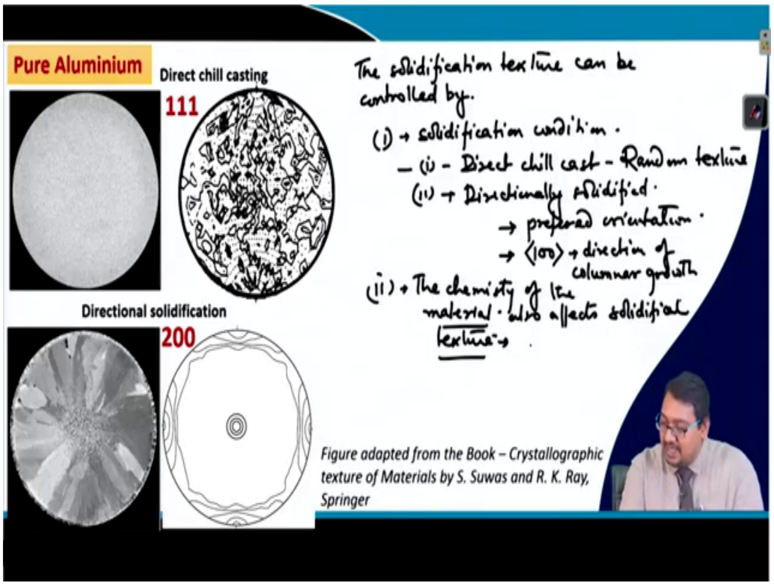

Now, if we take the example of pure aluminium and this figure, I have adopted it from the book of Crystallographic texture of materials by Suwas and Ray, it is a book from Springer, you can see that under if a pure aluminium is taken and it is direct chilled, casting is taken place and then the microstructure that evolves, let me take the pointer is looks something like this right.

So, it has equiaxed grains and very small microstructure that has present and the if we look into the pole figure, if you look it into any pole figure; here the 111 pole figure has been shown, there is no specific intensity of the texture component present. The texture component is present randomly over the whole pole figure. So, this kind of direct chill casting of pure aluminium led to the formation of random texture because of the growth of the dendrites in all possible direction, due to a negative thermal gradient.

On the other hand, if directional solidification occurred in pure aluminium and if we look into the you know we have this chill cast zone and this columnar grains and the interior equation and if we look into this you know columnar grain portion of this microstructure, we can see that we are looking into the 100 or the 200 pole figure and if we look into that direction which is the least close pack direction, what will happen?

We will see that strong texture component have formed, if this is the center is the direction of the growth of the columnar grains and you can see strong 100 texture has developed. On the other hand, you can see that because of the symmetry, one can see that the 100 poles are also present at 90 degree to this you know the point, where the pointer is there.

And therefore, strong 100 planes strong 100 planes or poles could be observed which shows that the texture developed on the least close packed plane and the columnar grain growth also occurred in the direction normal to that plane. So, the solidification texture can be controlled by first one and if it is a you know single phase you know pure metal.

So, it can be controlled by solidification condition; that is one, if it is direct chill cast, it will have random texture; second, it if it is directionally solidified, then it will have preferred orientation. In case of FCC aluminium, the preferred orientation of the direction of columnar growth will be 100.

The second thing is that the chemistry of the material also affects solidification texture and one can alter the texture during directional solidification also and make it random because of the presence of alloying elements and we will look into that in the next lecture class.

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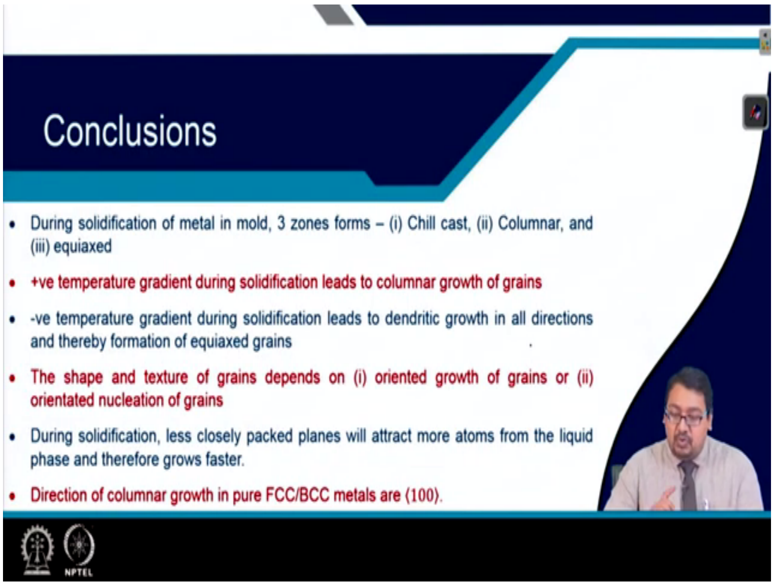

So, what we have concluded from this lecture class today? We found out that during solidification of the mold of the metal in the mold three zones formed that is chill cast zone, columnar zone and equiaxed zone. Positive temperature gradient during solidification, leads to columnar growth of grains right.

The negative temperature gradient during solidification leads to dendritic growth in all the direction. Thereby, if we cut the sample in a particular plane to see the microstructure, the 2D microstructure will show an equiaxed grain formation. The shape of the grain and the texture of the grains depend upon two things, the mechanism of the formation of those microstructure; the first one is the theory of oriented growth of grains or the and the second one is the theory of oriented nucleation of grains.

So, during solidification, less closely packed planes will attract more atoms from the liquid phase and therefore, they will also grow faster because the least close packed planes perpendicular directions are also the comparatively the near to the low close packed directions. Finally, the direction of the columnar growth in case of FCC, BCC material that is cubic materials are basically 100 family of direction.

Thank you very much.