# Texture in Materials

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## Module - 07
## Texture evolution during solidification
## Lecture - 40
## Solidification Texture in FCC, BCC, and HCP Structures

Good afternoon everyone and today we will be continuing with the module seven which is texture evolution during solidification and this is the last lecture of this module 7 that is lecture number 40, Solidification Texture in FCC, BCC and BCP structure.

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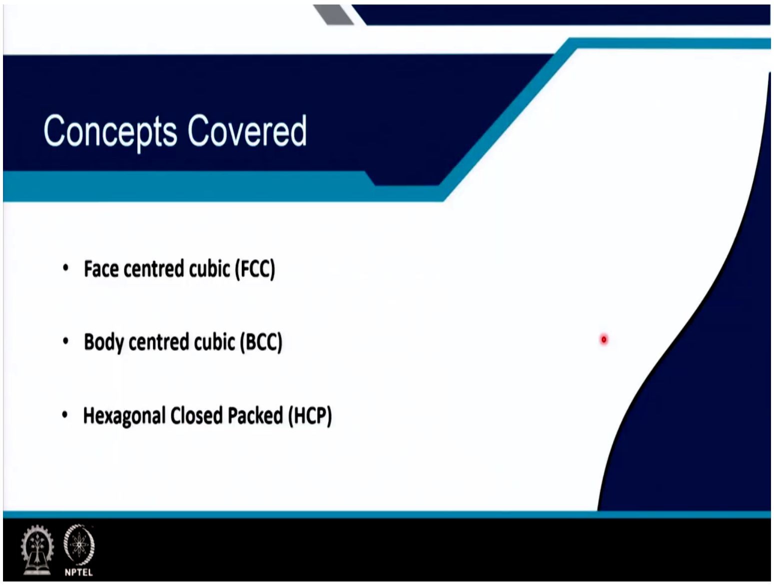


In this lecture we will cover the Solidification of various Face centered cubic, Body centered cubic, Hexagonal closed packed materials along with some other tetragonal or orthorhombic structures. And we will see that how in real life scenario this solidification takes place and how different kinds of actually textures get developed right. So, let us start with this lecture.

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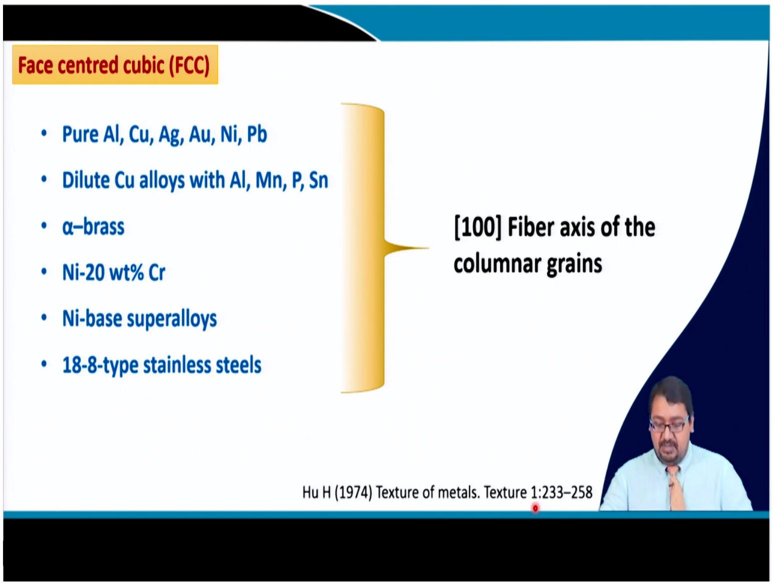


So, you see when we are talking about Face centered cubic material and based on the concepts that we developed during the last two lecture that for pure metals and for even binary alloys the example of brass was given. We showed that how the texture can develop during a positive thermal gradient and how under cooling effects during negative thermal gradient and you know constitutional super cooling effects in case of binary alloys for positive thermal gradient too.

So, in case of positive thermal gradients, pure aluminium, copper and you see silver and gold, nickel and lead, all produces 100 fiber texture along the columnar grains. Even in case of dilute copper alloys containing a small amount of aluminium, manganese, phosphor or tin, we can observe that during a positive temperature gradient 100 Fiber texture is obtained along the columnar axis of the grain growth.

Now, in case of alpha brass also and this was the example we took in the last lecture class where we see that dilute concentration of zinc in copper may lead to you know have super cooling and then it can avoid the 100 Fiber axis formation, but with the positive temperature gradient one can have 100 Fiber axis along the columnar grain.

So, in various alloys like nickel with 20 percent weight percent chromium which is an important alloy for aerospace application and an high temperature alloy, nickel based super alloys. All, even the 18-8- type you know stainless steel or different 304 l LN type stainless steel, they all lead to you know the formation of 100 type fiber axis along the columnar grain. And this you can see that this is given in more detail in HUS work of the time 19-74.

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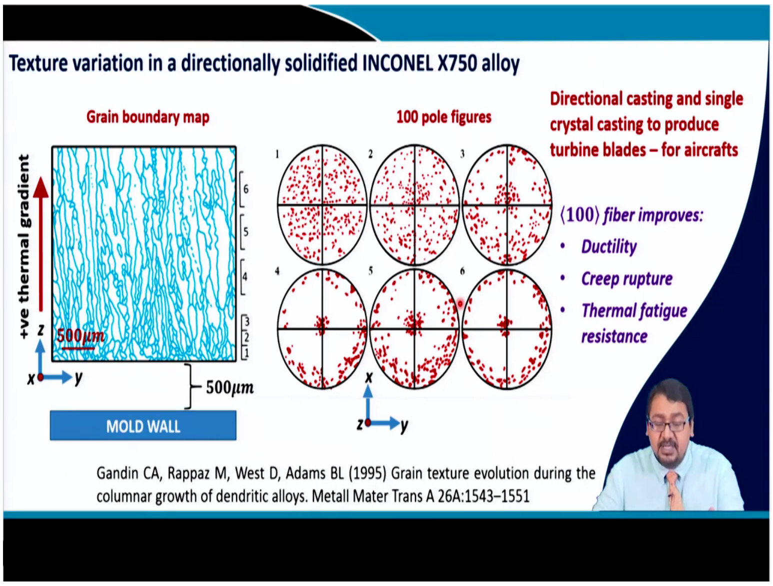


Now if we look closely into Face entered cubic alloy that is INCONEL for example, in this case X 750 alloy and this is a paper taken from Gandin ET AL, you can see that if there is a mold wall in this side and the molten metal is poured in it and the molten metal starts to solidify near to the mold wall and its you know that near to the mold wall which is it is the you know chill zone and then the columnar grain growth starts to take place.

So, if you look into the microstructures near to the mold wall look into the texture of this microstructure, we see that in this position say this position 1, we obtain nearly random kind of you know texture. So, because of the you know chilling or the colder temperature of the mold wall, a negative temperature gradient and large nucleation occurs near the mold wall leading to formation of a dendritic kind of growth or a large amount of nucleation is better to explain that and leading to you know formation of you know large nucleation and then random texture in this nucleation.

So, once we are going away from this mold wall what happens that the texture corresponding to the weaker texture; that means, a random texture, starts to slowly you know rearrange into a certain type of texture and we are looking into the 100 pole figure in this case and if we look into this position the second position just a little away from the mold wall we can see that there is a slight increase in the concentration of the 100 poles near to the center and also towards the side sides.

But you see it is not clear at this moment, but when we go to this position 3 quite away from the mold wall, now even though in this position also the texture is not very prominent and it seems to be near random. Still we see that there is a large concentration of the 100 poles at the center and along the sides. So, because of this we understand that because of the symmetry of the Face centered cubic material, if the 100 axis forms at the center then at 90 degrees also the another 100 axis will develop right.

Because now 100 axises are 90 degree away in the x, y and z direction. So, 100010 and 001 are at 90 degree away. So, you can see that the texture forms due to the corresponding you know crystal symmetry of the FCC. Now once we go at this position four which is quite away from the chill zone and now very specific sorry, very specific you know columnar growth could be observed in the microstructure you can see; that means, in this region a positive temperature gradient definitely has come into play.

And under the this situation this columnar grain growth is taking place. So, in this situation we can see that the concentration of the 100 poles becomes very strong at the center of the pole figure, e while we are looking at this pole figure I have to mention here that when we are looking here the x axis is in front and the z axis is the direction where the columnar grain is growing; whereas, while we are looking in the pole figure here, we should remember that we are looking into the texture when along the z direction.

So, in this case the z direction which is vertical in case of the microstructure shown here is basically coming out of this slide that is perpendicular. So, perpendicular to the slide. So, perpendicular to the plane of this paper. So, when we are looking into the texture, we are looking at the texture of the z direction which is present here, as per my pointer, you see it is present here, here, here, and here and the x axis is vertical and the y axis is horizontal in all these cases.

So, we are looking at the fiber axis that is the z axis right z axis is the fiber axis is the direction at which the columnar grain is growing. So, along the fiber axis, when we are seeing the texture, we are seeing a large concentration of 100 poles along this z axis. So, once we see that this z axis has a large concentration of 100 pole this means directional solidification is taking place in case of this INCONEL X750 alloy as the positive thermal gradient acts into the you know solidification mechanism and columnar grown grain growth takes place.

So, as we are going from 4 to 5 section and the 6 section the concentration of the 100 pole basically increases, and it becomes the you know the spread decreases and so, you can see here that strong texture of 100 pole at the center and along the circumference could be observed. So, such kind of directional casting or single crystal casting, more a for specific you know, modern casting methods can are used to produce turbine blades of such high, temperature high strength material for aircrafts and aerospace applications.

On the other hand you see that 100 texture is favorable in these cases because it has been seen that under this condition under the condition of 100 texture the INCONEL X750 has shown a higher ductility, a higher creep rupture rest creep rupture capability and a higher thermal fatigue resistance at the working temperature.

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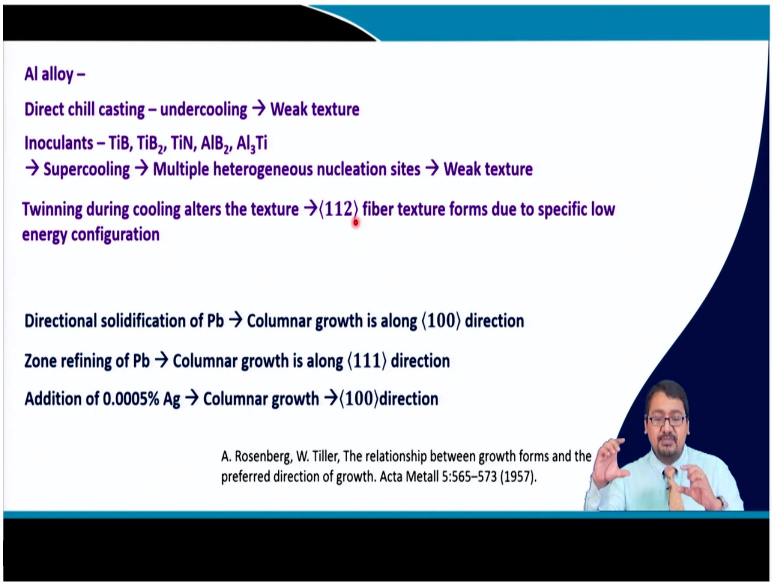


So, apart from this, if we look at different FCC material aluminium or aluminium alloys, in this case one can have directual casting of aluminium alloys and we have seen this in the last to last lecture of the solidification. And this leads to under cooling and production of weak texture.

However, if such a thing cannot be if such a weak texture is required and cannot be obtained inoculants such as TiB, TiB 2, TiN, AIB 2, AI 3 TI can be used so, that you know nucleation can take place at the liquid interface where there is you know even though there is a positive temperature gradient if there could be; there could be a super cooled zone that could be developed by adding this inoculants and multiple heterogeneous nucleation may lead to weaker texture.

On the other hand, one can you know alter the chemical composition of Aluminum and so, that Aluminum alloys can lead to twinning formation after solidification while it cools down a twinning in the structure leads to the formation of 112 type of fiber texture formation because of its specific low energy configuration.

On the other hand there are other examples for example, lead. Lead when its directly when it is given a directional solidification then columnar growth naturally takes place and 100 you know texture fiber develops along the columnar growth.

But in case of zone refining technique, a zone refining is a technique to make the material more purer and purer, and the material for example, a rod is heated so that it melted in a certain position and it then cools one once the you know the heater the heater is moved from one end to the another refining that material to a larger extent.

So, when zone refining of lead is done and one can see that columnar growth of 111 texture fiber is obtained along the columnar axis. And this is little different from what it is obtained from directional solidification technique and there are research papers on it by Rosenberg Et Al in 1957 and it was observed that addition of very small amount of silver that is 0.0005 percent of silver, the columnar growth during the zone refining comes back to the 100 direction along the columnar axis.

So, these are various experiments and you know research being done on the columnar growth during the positive temperature gradient in various alloys.

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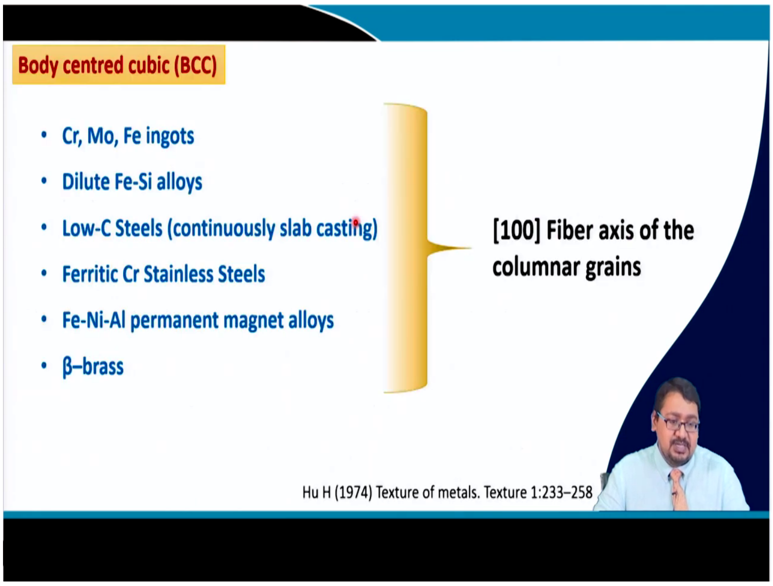


In case of body centered cubic material, you see that Chromium, Molybdenum, Iron, Ingots they all solidify during the positive temperature gradient with 100 fiber axis along the columnar grain growth. Even the dilute Fe-Si alloys which are used for electrical steels also grow along the 100 fiber axis.

Now, low carbon steel by continuous slab casting method and you see Ferritic Chromium Stainless Steel which is of you know BCC Ferritic Steel are also you know grows during the positive thermal gradient with 100 texture fiber along the columnar axis now Fe-Ni-Al permanent magnet even beta brass they have the same 100 texture fiber along this axis.

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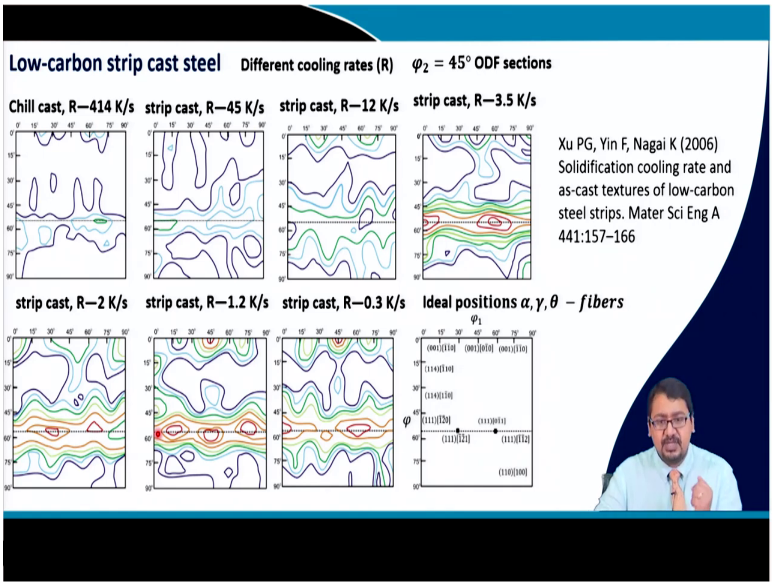


Now, if we look into an example of a low carbon strip till this is taken from X u E t A l and we see that if we change the you know cooling rates from, from a very high cooling rate to the very low cooling rate and we understand that very high cooling rates occurs near the surface of the mold where there is a direct chilling.

So, you know lots of nucleation will take place and this moment and we can see if we look into this you know phi to equal to 45 degree ODF section, if we look into the phi 2 equal to 45 degree ODF section for a cooling rate of 414 kelvin per second, you see that there is a very weak texture formation.

And why we are looking into the phi 2 equal to 45 degree section in BCC, usually phi 2 equal to 0 and 45 degree ODF section in BCC gives almost all the information of the textual components and the you know fibers that forms in BCC.

And we have talked about this a little in few classes earlier and you can see here I have given the ideal position of the you know various components and the fibers that can form during the you know during.

In case of BCC material, and you can see the ideal position of alpha, gamma and theta fiber and I will explain this fiber is basically the gamma fiber right and this fiber has you see the plane 111 is you know constant. On the other hand this particular fiber you see is the alpha fiber and this fiber this particular fiber is known as the theta fiber. So, there are mainly three fibers theta alpha and gamma fiber in case of BCC material.

And as we from we decrease the cooling rate from the chill cast region to the strip cast region where columnar growth starts to occur, that is just near to the mold and then you see that what happens just little away from the mold basically then what happens that during the strip casting slowly the gamma fiber starts to develop.

And when the cooling rate is decreased further to 12 kelvin per second, the gamma fiber further you know develops more if the cooling rate is further reduced to 3.5 kelvin per second you can see quite an amount of strong gamma fiber starts to form right.

Now, for the even you can we can also absorb the formation of the theta fiber. As the cooling rate is decreased to 2 kelvin, 1.2 kelvin, 0.3 kelvin we keep on seeing that the gamma fiber strongly develops along with the theta fiber. So, depending upon the cooling rate, the formation of certain components of the texture happens and certain components of the texture basically diminishes right..

On the other hand as the cooling rate is reduced, we can see prominent strong texture formation of in this case as we are seeing we are seeing mainly gamma fiber and less stronger theta fiber formation.

On the other hand as the cooling rate is very high, that is a negative thermal gradient definitely has taken place and leading to lot of nucleation. This leads to formation of a weaker texture right. So, large nucleation in this case produces weaker texture and growth of grains columnar growth due to positive temperature gradient leads to a formation of a strong gamma and less stronger theta for component sorry fiber.

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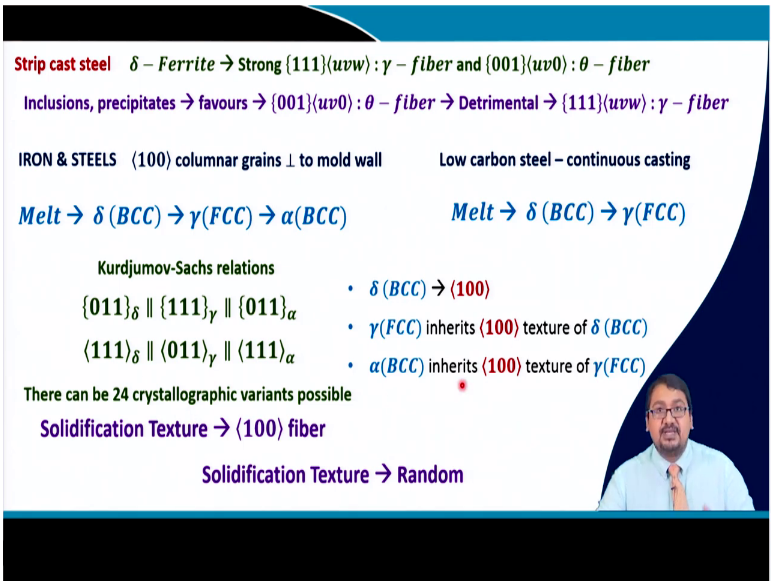


Now, in short we can say that in case of strip cast steel, delta ferrite you know strong 111 u v w, that is the gamma fiber forms and 001 uv 0 theta fibers develop. Now the presence of inclusions precipitates; however, the favors the formation of the you know 001 u v w type theta fiber and this is detrimental for the formation of 111 u v w gamma fiber.

So, you see what I meant to say here is that, in case of body centered cubic material, the formation of gamma fiber is always beneficial in terms of its property, particularly anisotropy of this material. Now, if the material does not have much inclusion and precipitates, strong gamma fiber will form.

However, you can see that there is always a formation of theta fiber even if the cooling rate is decreased to a large extent. This theta fiber can be avoided if the inclusions and the precipitates are as less as possible because inclusions and precipitates favors the formation of this 001 u v w theta fiber.

In case of iron and steel the 100 columnar grain basically grow perpendicular to the mold wall and iron and steel we are talking about the BCC material right, Body Centered Cubic meter. So, once the delta when this liquid solidifies, it solidifies into delta ferrite.

So, the melt when its solidifies its solidifies into delta which is a body centered cubic which has a body centered cubic structure and when it further cools down, if you look into the phase diagram of iron and steel you can see that when it cools down it goes to the gamma austenite and the gamma austenite has a face centered cubic structure.

When it further cools down it becomes alpha ferrite again and alpha ferrite has a body centered cubic structure. So, the melt first forms delta ferrite and then gamma austenite and then alpha ferrite while it solidifies and further cools down. Now while it does so, it follows a certain rule and we will talk about those rules that is the rules of the phase transformation and that we will talk in more detail in the next class that is in the phase transformation that we will see.

Now in case of this delta 2 gamma austenite to alpha ferrite, Kurdjumov Sachs relation will be usually followed. Now, in case of the Kurdjumov Sachs relations I can describe in most softly or most logically like the closest pack planes of the delta ferrite becomes the closest pack plane of the gamma austenite and then the closest pack plane of the alpha ferrite.

Whereas, the closest pack direction of the delta ferrite will become the closest pack direction of gamma austenite and will be becoming the closest pack direction of the alpha ferrite while it is cooled. So, the 011 is the closest pack direction in case of BCC, that is for the delta ferrite. And it becomes parallel to the 111 of the gamma ferrite, which is the closest pack direction in case of FCC and further cooling down it against become 011 of the alpha ferrite which is a BCC again.

So, this is about the plane on the other hand 111 of the delta ferrite is the closest pack direction in cooling down it becomes 011 of the gamma austenite the closest packed direction in case of FCC and then for the cooling it again becomes 111 of the alpha ferrite which is the closest pack direction in case of BCC. So, such kind of transformation if takes place from the delta ferrite which has initially 100 columnar grain growth perpendicular to the mold wall, then what could happen..

You see that as per the symmetry of the cubic crystal there are 24 possible ways this you know Kurdjumov Sachs transformation may take place and such could such transformation will take place because you see there are 24you know symmetric operation that can be done in case of cubic crystals. So, there are 24 crystallographic variants possible.

Does this mean that the solidification texture becomes random? It never happens that with such transformation the solidification texture becomes random. What it happens that as because the solidification has taken place in a certain direction and the certain 100 columnar grain has growth and then further cooling down there is some kind of stress that forms because of the thermal expansion coefficient of this material right.

So, you see that when the material basically cools down there is a stress associated with the thermal expansion coefficient of this material during cooling because the material actually volumetrically it reduces and such stress state associates it to a tensile state stress state at certain direction, a compressive stress state another at another certain direction, such that that only one variant is basically following the Kurdjumov Sachs relationship leading to the formation of 100 fiber texture when delta ferrite converts into gamma austenite, it becomes from BCC to FCC, still the 100 columnar grain of the gamma Austenites remain perpendicular to the mold wall.

And then when it converts to the alpha BCC then also the 100 of the gamma austenite converts into 100 of the alpha BCC leading to the formation of the 100 texture fiber perpendicular to the mold wall, that is along the columnar grain growth.

So, the solidification texture remains 100 fiber texture only. In case of low carbon steel where the melt produces delta ferrite to gamma austenite and the delta ferrite has the 100 fiber texture FCC inherits the 100 texture of the delta ferrite and in case of this iron and steel which finally, forms an alpha ferrite as I said the alpha ferrite inherits the texture of the gamma FCC.

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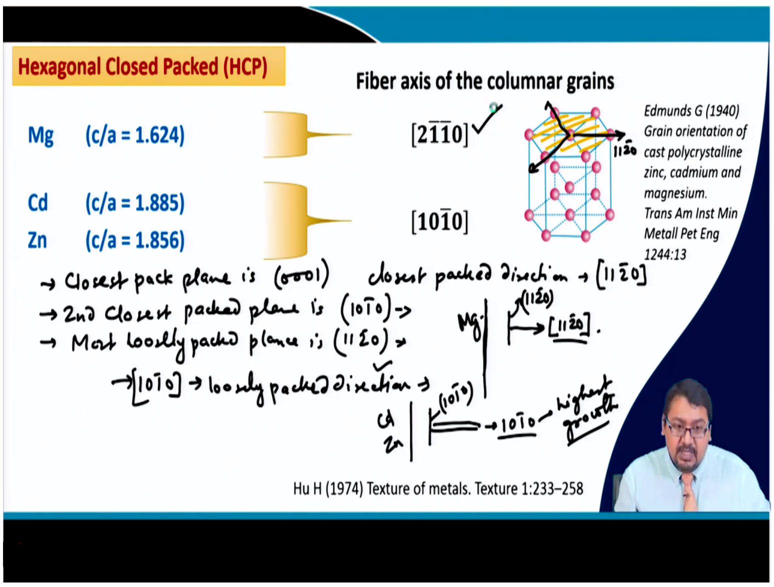

So, in case of Hexagonal closed packed material the growth of the fiber axis along the columnar grain is found out to be 112 bar 0, in case of magnesium, which has a c by a ratio of 1.624 very close to the c by a ratio of for case of ideal hexagonal close packed material which is 1.633.

In case of cadmium and zinc which has a c by a ratio of greater than 1.8, that is for cadmium 1.885, in case of zinc 1.856. The columnar grain growth occurs along the 101 bar 0 axis and this was shown by Edmund in 1940s.

Now if we look into the hexagonal close pack structure hexagonal close packed crystal structure, we see that it looks something like this and the atoms are present at these positions. It is well known that in hexagonal closed pack structure with c by a ratio greater than the ideal c by a ratio or near to the ideal c by a ratio. The Bessel plane is the most closest packed plane.

So, if I write this down, let me take a pen and let me write this down that the closest pack plane is always the Bessel plane which is 0001 right. This is basically this particular plane right. Now the closest packed direction is usually, for all the cases 112 bar 0 or 21 bar 1 bar 0 and there are like this you know 3 possible directions right.

So, all these are closest pack directions. So, the closest pack direction is 112 bar 0 or 1 bar 0 or 11 sorry 1 2 bar 1 0. So, these are the closest pack direction the family of directions of 112 bar 0. So, if we look closely the second closest pack plane is 101 bar 0 type plane right or the family of this plane. Now in case of the most loosely packed plane is either the pyramidal plane or among these three this is 112 bar 0.

Now in case of magnesium, say for suppose when the atoms is in the liquid state and it starts to solidify, the atoms are in a very high vibrational energy in the liquid state and that is why the liquid state the atom cannot be in a crystalline structure. So, it cannot maintain this crystallinity structure of the crystal of the you know hexagonal close packed structure. So, its it has a high vibrational energy.

So, as the temperature is reducing and it is coming closer to the freezing temperature what is happening? The vibrational energy of the atom is reducing and the vibrational energy of the atom is reducing, reducing, reducing towards certain extent that it goes to a plane which can sustain the highest vibrational energy maintaining the crystalline structure.

And in case of magnesium, this is happening a for the that is why the plane at which the atom is going and sitting is the 112 bar 0 plane which is actually perpendicular plane to the you know that is the parallel plane to the mold wall. So, if this is a mold wall and then in case of magnesium, the plane parallel to the mold wall is the 112 bar 0 plane because is the most loosely packed plane among this three planes right. 100 sorry 011 001 and 101 bar 0 right and 112 bar 0.

So, the direction at which the columnar grain growth takes place is basically 112 bar 0. When the c by a ratio is higher, then the 101 bar 0 plane also is quite loosely packed of course, it is less loosely packed than the 112 bar 0 ones, but the advantage that in this case what happens that if the growth occurs along 101 bar 0 direction because this is a very loosely packed direction, there is a large growth if the growth is taking place along the 1010 direction.

So, the combination of the loosely packed plane that is this is the case of magnesium and this is the case of cadmium and zinc that a combination of 101 bar 0 plane and the growth along 101 bar 0 direction which gives the highest growth suffices because it saves the minimum energy it may get the minimum energy configuration.

So, in case of magnesium, the loosely packed prismatic plane is more favorable therefore, the growth of the columnar grain is along 112 bar 0. Whereas in case of zinc and cadmium where the most loosely packed direction is becoming more favorable. So, the growth is along the 101 bar 0 direction.

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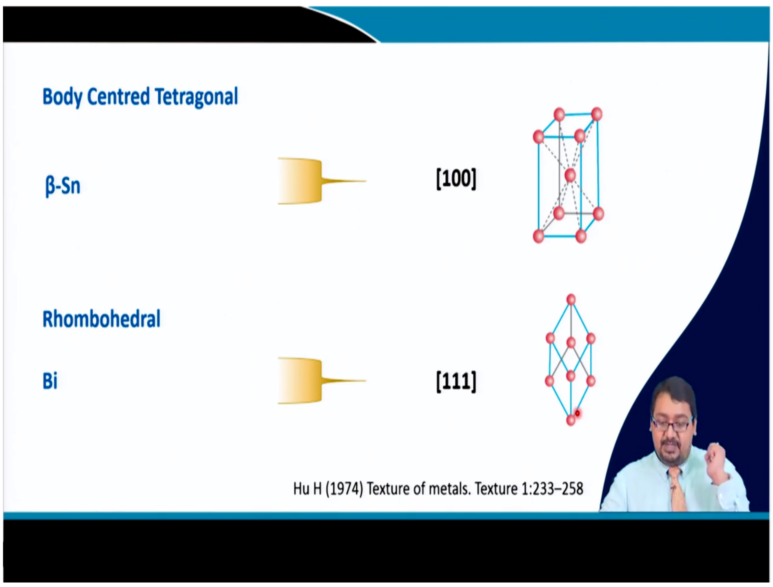

If we look into other materials like Body Centered Tetragonal material, we are talking about beta tin and this tin is having a body centered tetragonal structure something like this, and you see the growth preference of this beta during a positive temperature gradient and is along you know this axis the z axis.

So, we have say for example, x axis which is say 001, y axis which is 010, and z axis which is 100, the growth axis is preferable always along the 1, 100 axis which is this z axis because of the tetragonal structure the this z axis is much greater than the x and y axis. So, the lattice spacing of the z axis is much higher and therefore, it will go to that axis to have the growth.

On the other hand in case of Rhombohedral Materials like Bismuth for example, the it has a Rhombohedral structure like this and the growth preference always occurs along the 111 axis parallel to the columnar grain.

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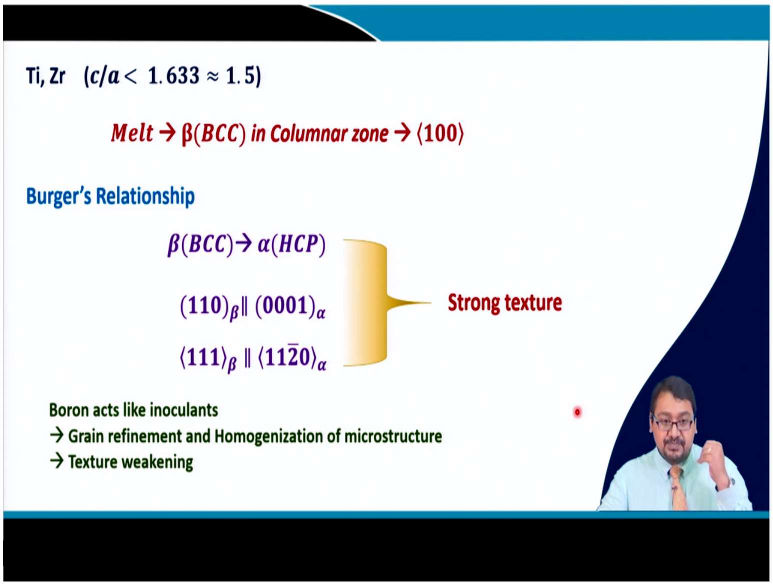


So, if we look into hexagonal close packed material further like for example, Titanium or Zirconium and this case the c by a ratio is along around 1.5 which is much lower than the c by a ratio of 1.633. Now in both the cases of titanium and zirconium the melt solidifies not directly into hexagonal close packed structure, but it solidifies into a beta structure which is basically a body centered cubic material.

If the temperature gradient is maintained positive, then this body centered cubic material titanium or zirconium will have a columnar grain growth along the columnar zone or the columnar axis will be 100.

Now, while it cools it will follow the phase transformation relationship that we will learn in the next class and this relationship is basically the burgers relationship which states that the beta of BCC when it transforms into alpha HCP of a titanium or zirconium, the closest packed plane of the beta will transforms into the coolest packed plane of the alpha HCP and the closest packed direction of the beta BCC will be transformed parallel to the closest pack direction of the alpha HCP.

So, following this burgers relationship when the cooling of the solidified structure from the BCC to the HCP occurs in both in case of titanium and zirconium the 110 of the BCC which was the closest pack planes converts and becomes parallel to the 001 of the alpha phase which is HCP.

And the 111 direction which is the closest packed direction of the BCC remains parallel to the 112 bar 0 direction of the alpha HCP which is the closest pack direction and thus the you know the relationship maintains and then a strong texture of alpha HCP basically develops.

Now, it has been reported that inoculants in titanium such as and zirconium such as boron are added. So, that such a strong texture could be avoided in certain cases where the there is a requirement of isotropic material properties. So, boron is added, this leads to grain refinement grain refinement gives higher strength to the material and microstructure becomes more homogeneous and texture becomes weakens.

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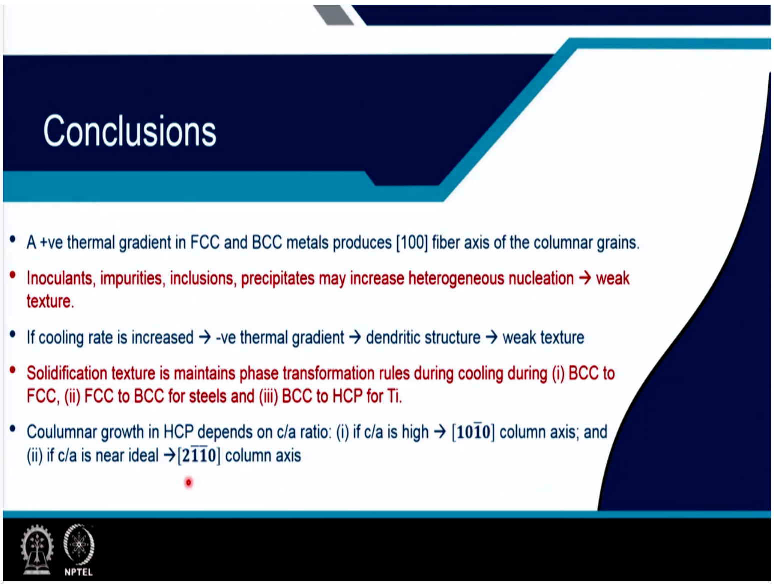


So, in this lecture we learned that a positive thermal gradient in both in case of Face Centered Cubic material and Body Centered Cubic material produces 100 fiber type texture parallel to the columnar growth the presence of inoculants impurities inclusions precipitates may increase heterogeneous nucleation and it may weaken the texture.

Third, if the cooling rate is increased to a higher extent like it happens in near to the mold wall, the temperature gradient remains negative and thus a dendritic structure and weak structure may form. There is a lot of nucleation and small small nucleation nucleated grains will develop the grain size may be very small in this case.

Solidification texture is maintained during the phase transformation. When the phase transformation occurred during cooling from you know BCC to FCC, FCC to BCC or even BCC to HCP Hexagonal Close Packed condition and therefore, strong texture remain the texture does not become random in any of these cases.

Columnar growth in HCP depends upon the c by a ratio. So, if the c by a ratio is high the columnar grain growth occurs along 101 bar 0. So, it prefers the loses packed distance direction as the growth on the other hand when the c by a ratio is lower then the columnar growth is along 112 bar 0. So, it prefers the loosest packed plane for the atom to get settled.

Thank you very much.