Texture in Materials
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Module - 07
Texture evolution during solidification
Lecture - 39
Solidification Texture in Alloys

Good afternoon everyone. And we are doing module number 7 of the course Texture in Materials. So, this module is Texture evolution during solidification. In the earlier lecture, we have tried to understand the Solidification Texture evolution in pure metals. And today, we will be focusing on Solidification Texture evolution of Alloys; mainly, we will consider binary alloys.

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Concepts Covered

- Solidification of Binary alloys
- Steady state solidification
- Constitutional supercooling

So, the concepts that will be covered in this lecture are solidification of binary alloys; steady state solidification mostly and then, constitutional supercooling.

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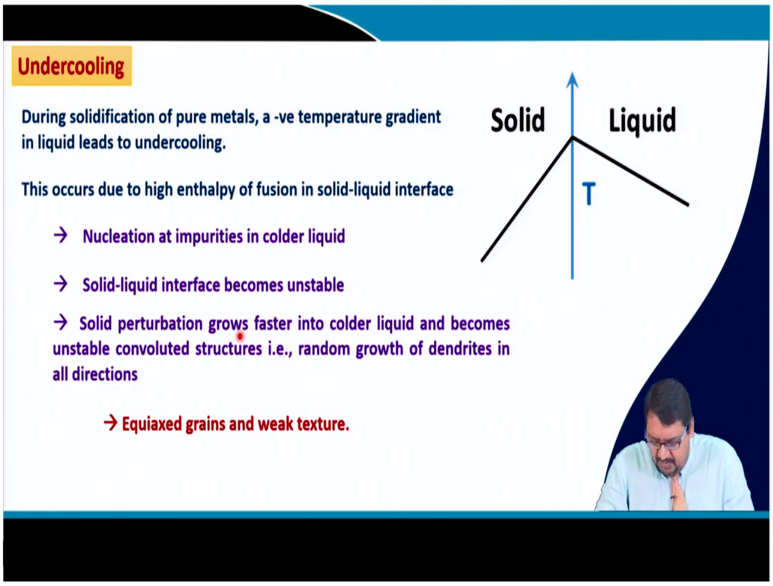

Undercooling

During solidification of pure metals, a -ve temperature gradient in liquid leads to undercooling.

This occurs due to high enthalpy of fusion in solid-liquid interface

→ Nucleation at impurities in colder liquid

→ Solid-liquid interface becomes unstable

→ Solid perturbation grows faster into colder liquid and becomes unstable convoluted structures i.e., random growth of dendrites in all directions

→ Equiaxed grains and weak texture.

So, in the last lecture, what we saw that during the solidification in case of pure metals, initially there could be a positive temperature gradient. But gradually, may be at the center of the mold, when the temperature gradient does not remain positive. That means, it becomes negative and this may happen due to you know the enthalpy of fusion at the solid liquid interface, if it is it be if it becomes very high.

So, under such situation, what happens that the nucleation could take place in the impurities in the colder liquid zone ahead; this is one thing. The second thing is that that the solid liquid interface, if this is the solid liquid interface and this solid liquid interface does not remain stable. And so, the solid perturbation grows much faster into the colder liquid and this becomes highly unstable and convoluted structures starts to develop.

So, random growths of dendrites could be observed in all possible direction leading to you know when we observe the sample on a certain plane, if we cut the sample in a certain plane. We will observe equiaxed kinds of microstructure with if we look into texture, we will find that the texture is also not very you know strong. It is a weak texture of condition, sometimes very weak.

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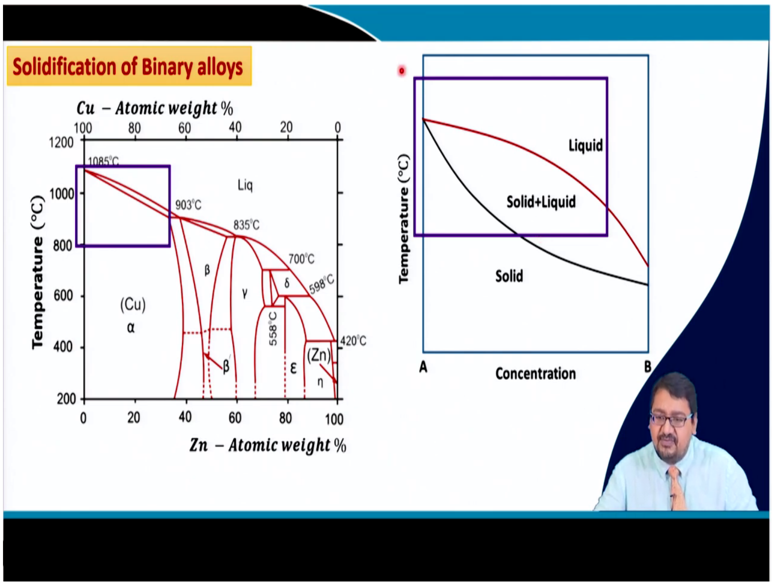

Solidification of Binary alloys

So, in this lecture, we will talk about solidification of binary alloys. And we are taking example of the alloy which is having only two elements. So, it is a binary alloy. One should understand that the majority of the metallic elements that are used in industrial and any purpose for are not pure metals, they are mainly alloys.

So, many elements are actually incorporated in a certain metal to produce alloy to you know to control the microstructure character; character of that material, to control the texture of that material and to obtain the desirable mechanical properties or electrical magnetic whatever properties is required.

So, if we look into this phase diagram of the binary alloy, in this case as I said that we will take a binary alloy for example, like copper zinc binary alloy and this is you know the normal brass that we see. We can see that in this phase diagram, this side is 100 percent copper and this side is 100 percent zinc right.

And if we look into this portion of the curve, we will find out that this is atomic per weight percentage of copper and this is atomic weight percentage of sorry this is atomic weight percentage of zinc; this is 100 percent zinc and this is 100 percent copper, atomic weight percent of copper.

So, if we look into this part of this you know phase diagram, you will see that it has a simple binary kind of phase diagram; where, we have the liquidus line, the solidus line and if we you know magnify this one, we are magnifying it here and you can see that this red colour line, I have shown is the liquidus line and this black colour line that I have shown is the solidus line. So, here, it is liquid; here, it is solid plus liquid interface and here, it is solid.

So, in the phase diagram, if we look that there is a liquidus line, which is known as the liquidus you know phase boundary between the liquid and the solid plus liquid interface and there is a solidus phase boundary that is the solidus line which is basically the interface between the solid and the solid and liquid phase.

So, here all the phase fields, solid, solid plus liquid and the liquid is in complete equilibrium. So, phase diagrams are actually shows the composition solid, solid plus liquid and liquid which is in complete equilibrium right. So, if we look into a smaller part of this, this small you know binary phase diagram.

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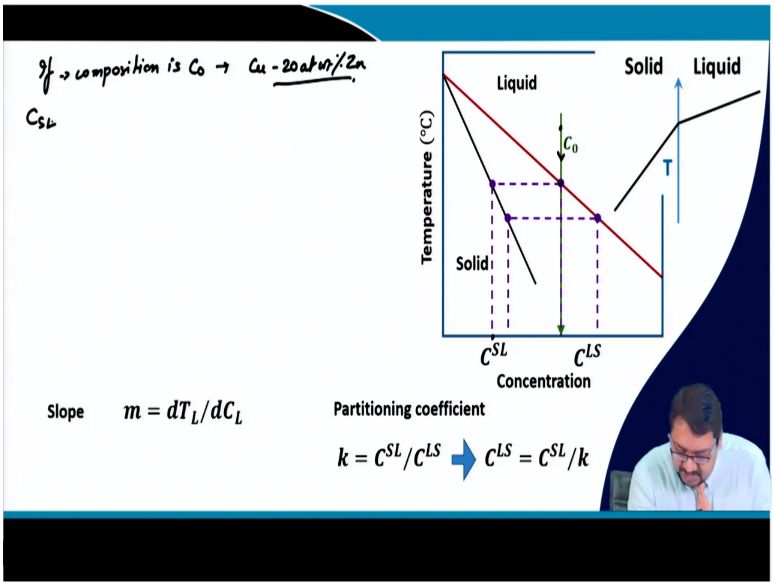

If → composition is C_0 → $\underline{Cu - 20 at wt \% Zn}$

C_{SL}

Slope $m = dT_L/dC_L$

Partitioning coefficient

$k = C^{SL}/C^{LS} \Rightarrow C^{LS} = C^{SL}/k$

So, if we say that if our composition of the alloy is C 0 and it is you know solidifying. So, let us say that it is alloy with say if our composition, if composition is C 0. And say it is a copper 20 atomic weight percent zinc alloy. Say, hypothetically it is.

So, when it is you know when its temperature is reducing and say that it is somewhere in a positive temperature gradient and that is what I have shown it here that we are in the positive temperature gradient regime and when the temperature is slowly slowly reducing.

At this point, the composition C 0 is equal to the composition of the you know solid-liquid interface. So, you see and the composition here for this C 0 is this much right that is C SL. So, what is C SL? C SL is the equilibrium composition of the solute in the solid in front of the you know solid-liquid interface right, where it is just solidify.

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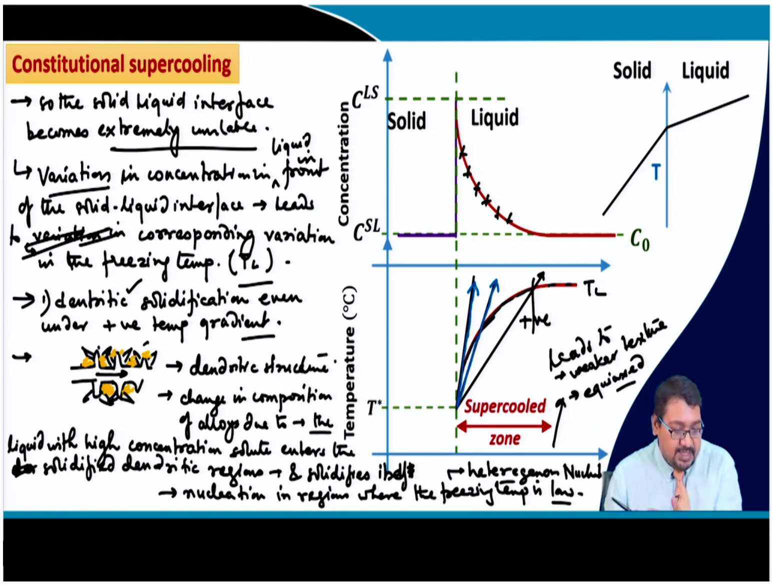

Constitutional supercooling

→ so the solid liquid interface becomes extremely unstable.

↳ Variation in concentration in liquid in front of the solid-liquid interface → leads to ~~variation~~ in corresponding variation in the freezing temp. (T_L).

→ 1) dentritic solidification even under +ve temp gradient.

→ dendritic structure.

→ change in composition of alloys due to → the liquid with high concentration solute enters the ~~der~~ solidified dendritic regions → & solidifies itself

→ nucleation in regions where the freezing temp is low.

→ heteregenon Nuclea

leads to → weaker texture → equiaxed

So, if I write what is C SL, then C SL, if the temperature gradient is increased, so if it is increased to this much or if you further increase to this much. The increase in a temperature gradient should be such that the actual temperature gradient becomes greater than the temperature you know gradient of the liquidus line as the concentration is changing.

So, to get the you know no constitutional supercooling; that means, to get a stable solid-liquid interface and a kind of a columnar grain structure. Now, what is the condition of no constitutional supercooling? So, that is the condition of the no constitutional supercooling that if we increase the temperature gradient from here to here so that there is no super cooled zone.

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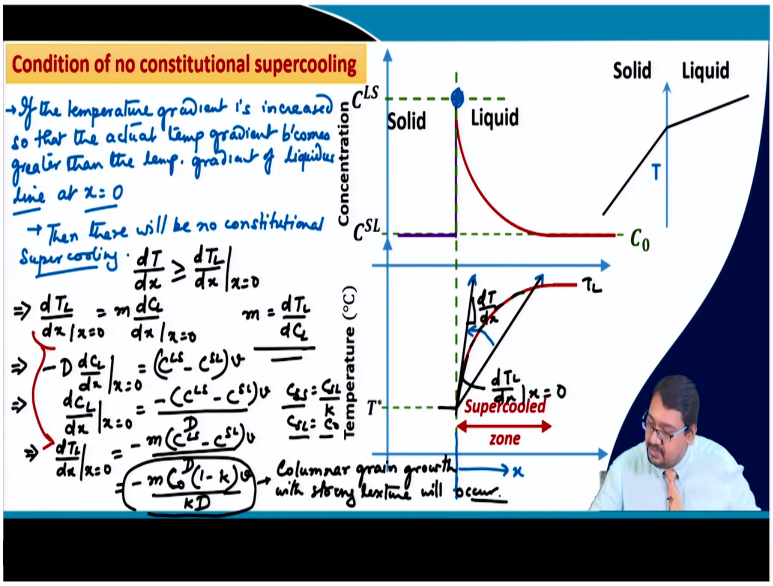

Condition of no constitutional supercooling

→ If the temperature gradient is increased so that the actual temp gradient b'comes greater than the temp. gradient of liquidus line at $x = 0$

→ Then there will be no constitutional supercooling. $\frac{dT}{dx} \geq \left.\frac{dT_L}{dx}\right|_{x=0}$

$\Rightarrow \left.\frac{dT_L}{dx}\right|_{x=0} = m \left.\frac{dC_L}{dx}\right|_{x=0}$ $\quad m = \frac{dT_L}{dC_L}$

$\Rightarrow -D\left.\frac{dC_L}{dx}\right|_{x=0} = (C^{LS} - C^{SL})v$

$\Rightarrow \left.\frac{dC_L}{dx}\right|_{x=0} = \frac{-(C^{LS} - C^{SL})v}{D}$ $\quad C_{LS} = \frac{C_{SL}}{k}$ $\quad C_{SL} = C_0$

$\Rightarrow \left.\frac{dT_L}{dx}\right|_{x=0} = -\frac{m(C^{LS} - C^{SL})v}{D} = \boxed{-\frac{mC_0(1-k)v}{kD}}$ → Columnar grain growth with strong texture will occur.

So, if we write it down, this one, if the temperature gradient is increased as I said. So, that the actual temperature gradient becomes greater than the temperature gradient of liquidus line due to the change in the concentration of the solute in the liquid right at x equal to 0.

So, at this position, just at the position of the interface; that means, this composition. Now, then, there will be no constitutional supercooling right. So, the condition of the no constitutional supercooling is that let me take the black colored pen so that it is visible quite nicely is that d T by d x right.

This slope d T by d x; d T by d x should be greater or equal to at least than the d T L by d x at x equal to 0; that means, this line has to be tangential to this particular curve for T L that is d T L by d x at x equal to 0 right. Now, we know that d T L by d x at x equal to 0 is equal to you know m times d C L by d x at x equal to 0 because we know that m is equal to d T L by d C L right. And m is basically the slope of the liquidus line considering that it is a straight line right.

Now, if we solve this further, what will happen? We also know that minus of D d C L by d x at x equal to 0 equal to C LS minus C SL. C SL is basically C 0 in this case times v right. And then, if we write this equation like in terms of d C L by d x equal to x equal to 0, then, this becomes equal to you see minus of bracket C LS minus C SL times v by D right.

So, if we take this particular equation, this equation and write it down here in. Then we can say that this implies that d T L by d x at x equal to 0 becomes equal to minus of m times C LS minus C SL by v by D right. And then, we can write that yes we know that C LS equal to C SL by k and C SL is equal to C 0, then, we can write this equation in terms of minus of m C 0, 1 minus k by k times D and v right. So, this becomes the final equation, if we substitute the C LS in terms of C SL by k and C SL which is equal to C 0 in our case, at this temperature right; at the steady state condition.

So, the condition of no constitutional supercooling would be this that if d T by d x is at least greater and greater than or equal to this value minus of m C 0, 1 minus k times v divided by k D, then there will be no constitutional supercooling and columnar grain growth will occur with you know strong texture, favourable texture for a larger growth will occur ok.

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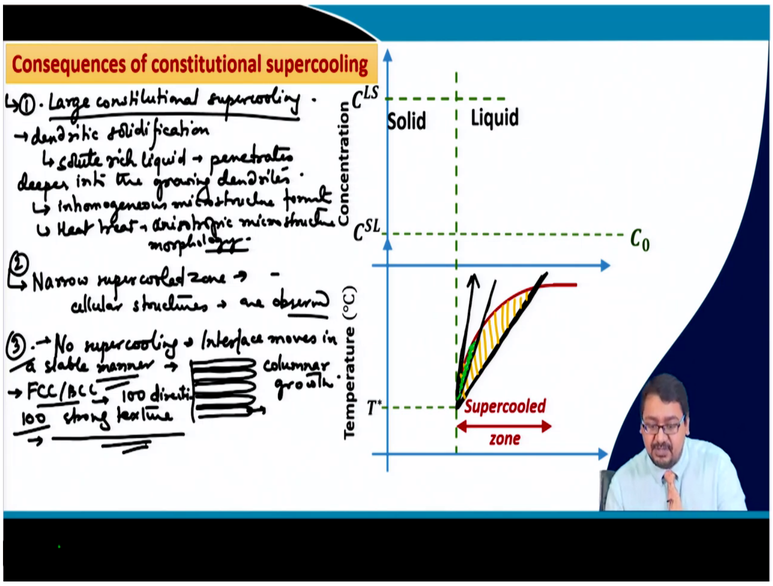

Consequences of constitutional supercooling

↳① . Large constitutional supercooling .
→ dendritic solidification
↳ solute rich liquid → penetrates deeper into the growing dendrites .
↳ inhomogeneous microstructure formed
↳ Heat treat → anisotropic microstructure morphology .

②
↳ Narrow supercooled zone → -
cellular structures → are observed

③ . → No supercooling → Interface moves in a stable manner → columnar growth .
→ FCC/BCC → 100 direction
100 strong texture
→

Now, if we look into the consequences of this constitutional supercooling, the observation shows that there are three conditions. The first condition is large constitutional supercooling which is supercooled zone maybe ok, which shows that dendritic you know solidification and this is we are talking about this one. So, let me take this; so, a large amount of constitutional supercooling right. So, dendritic solidification, solute as I said solute you know solute rich liquid you know penetrates deeper into the growing dendrites right. So, we see in homogeneous microstructure formation.

Secondly, you see we can all if we heat treat the material, then we obtain you know totally anisotropic you know microstructure morphology right. And if you see that if the positive temperature gradient is increased to this much and there is only say very narrow you know supercooled zone.

So, second case narrow supercooled zone, then usually you know cellular structures are observed. And in the final case, when there is no constitutional supercooling, then you see no sorry no supercooling, then interface moves in a stable manner right. And so, solute rich liquid does not penetrate into you know because it is not now not dendritic solidification, it is like a columnar growth right; something like that into the liquid and the interface remains stable right something like this.

And what happens is that because of this columnar growth. So if we say in case of FCC and BCC material, the 1 0 0 direction right will grow faster because this is the most loosely packed plane and the loosely packed direction.

So, it will grow fast. So, there will be a strong texture and that will be 1 0 0 texture right. So, similarly as I have told in case of under cooling also, that the sorry in case of single phase material also that the growth of closely packed direction will occur very fast.

So, in case that in in FCC and BCC, there is a growth of or on a plane or the growth direction is the closely packed direction say it is 1 1 0 or 1 1 1, then the number of atoms that are required to have a same amount of growth at that as that of the one with 1 0 0 growth direction will be much higher in case of 1 1 0 and 1 1 1.

So, the growth along 1 1 1 and 1 1 0s will be suppressed or the growth along any other direction will be suppressed and the growth with respect to 1 0 0 will remain or will prevail leading to the formation of this 1 0 0 strong texture. In case when the constitutional supercooling is totally can be avoided by increasing the you know positive temperature gradient much higher than the T L right at that is d T L by d x at x equal to 0.

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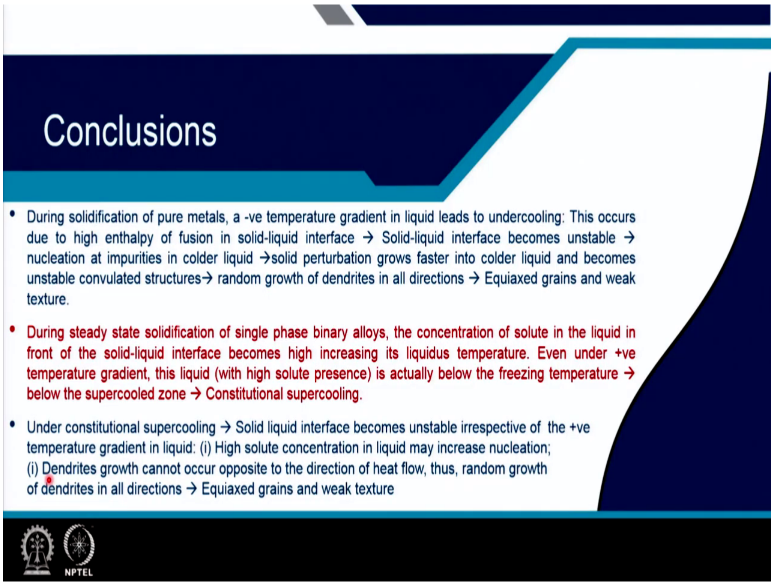

Conclusions

- During solidification of pure metals, a -ve temperature gradient in liquid leads to undercooling: This occurs due to high enthalpy of fusion in solid-liquid interface → Solid-liquid interface becomes unstable → nucleation at impurities in colder liquid →solid perturbation grows faster into colder liquid and becomes unstable convulated structures→ random growth of dendrites in all directions → Equiaxed grains and weak texture.
- During steady state solidification of single phase binary alloys, the concentration of solute in the liquid in front of the solid-liquid interface becomes high increasing its liquidus temperature. Even under +ve temperature gradient, this liquid (with high solute presence) is actually below the freezing temperature → below the supercooled zone → Constitutional supercooling.
- Under constitutional supercooling → Solid liquid interface becomes unstable irrespective of the +ve temperature gradient in liquid: (i) High solute concentration in liquid may increase nucleation; (i) Dendrites growth cannot occur opposite to the direction of heat flow, thus, random growth of dendrites in all directions → Equiaxed grains and weak texture

So, what we can conclude from this lecture class today is that; during solidification of pure metals, a negative temperature gradient in the liquid leads to under cooling and this occurs due to high enthalpy of fusion in the solid-liquid interface. So, the solid-liquid interface becomes extremely unstable and you see it grows very faster in the colder liquid.

Moreover, what happens that there is nucleation of means heterogeneous nucleation in the colder liquid because of the presence of impurities or inoculations or whatever or inclusions; but we are talking about pure material, so there could be impurities in this case.

So, solid perturbation grows very faster in the cold liquid and becomes unstable convoluted structure. So, dendrites starts to form in all possible directions, leading to you know if you if we see the microstructure on a certain plane, even perpendicular to the growth direction in a plane parallel to the growth direction I am sorry.

So, we will see equiaxed grains, if we look into the texture, we will see that there is no specific texture in this case. Now, the second point that we understand that during steady state solidification of us, you know single phase binary alloys means two elements binary single phase alloy. The concentration of solute in the liquid in front of the solid liquid interface becomes very high.

And this increases the liquidus temperature more than that of the positive temperature gradients temperature right and therefore, the liquid is actually below the freezing temperature because of the high solute present and this makes the liquid in front of the you know liquid solid-liquid interface in a supercooled zone situation and this is known as constitutional supercooling.

So, under constitutional supercooling solid liquid interface becomes very you know unstable irrespective of the positive temperature gradient. So, high solute concentration of liquid may increase nucleation. Secondly, dendritic growth occurs. The third point is under constitutional supercooling, solid-liquid interface becomes unstable irrespective of the positive temperature gradient in the liquid.

So, first thing that occurs is that because of the high solute concentration in the liquid ahead of the solid liquid interface and even if there is a positive temperature gradient. There could be increase in the nucleation in the liquid in front of the solid liquid interface. The second thing is that the dendrite grows growth cannot occur in the you know opposite to the heat flow direction that is towards the positive temperature gradient because of the difference in the you know concentration of the of solid in the liquid right, leading towards leading to this supercooled zone.

So, you know dendrite occurs in different direction leading to a random growth of dendrites right and not only that, while the dendrites are growing in all the direction, the high concentration liquid flows into these dendrites deeper into this dendrites to solidify and therefore, we observe equiaxed grains and weak texture.

Thank you.