Welding Metallurgy
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Lecture - 29
Microsegregation and Banding

Welcome to the lecture on Microsegregation and Banding. So the last lecture we talked about the constitutional supercooling and we talked that how you know when you have the temperature gradient line. So it has to have a slope which will ensure the planar front to move you know so that there is no constitutional supercooling whereas if the gradient line temperature gradient line is such that you have a reason of supercooling.

In that case there may be chances and there will be formation of dendritic grains so and again that depends upon what is the degree of supercooling. So we talked that you know the ratio G/R so that has to be you know so it has to be correlated with some value you know accordingly and that is $\Delta T/D_L$ so ΔT is basically the freezing range and then you have the D_L that is the coefficient of diffusion value in the liquid.

So basically it talks about those conditions and we also saw that when you have you know the different conditions then how you have initially you know planar mode of solidification then you have cellular mode of solidification then you know you have the columnar dendritic mode of solidification and then further you go to the equiaxed dendritic because you know when the reason becomes too large.

And it is not possible it becomes a remote possibility for the you know columnar dendrites to go till the whole region which is super cool. In that case there will be chances of the formation of equiaxed type of dendritic grains. So you know there are ways to avoid certainly based on the, you know, temperature gradient you know which you can put in you can say that you can avoid the formation of the dendritic structures.

But typically it does not happen because having that you know gradient is practically not possible. So you are bound to get that dendritic type of structure. However certainly you can control you know the arm width or the you know the dendritic arm spacing. So by certain external factors and that is you know maybe the cooling rate or so.

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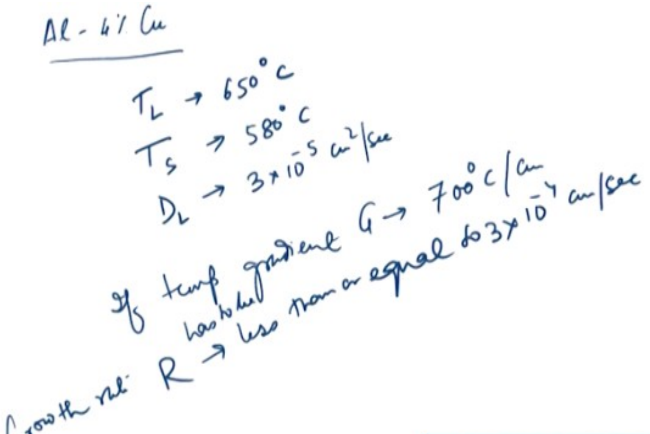


Al - 4% Cu

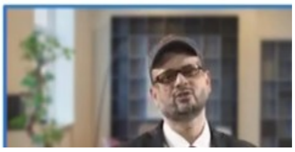
$T_L \rightarrow 650^\circ C$

$T_S \rightarrow 580^\circ C$

$D_L \rightarrow 3\times10^{-5}$ cm²/sec

If temp gradient $G \rightarrow 700^\circ C$/cm

Growth rate $R \rightarrow$ has to be less than or equal to 3×10^{-4} cm/sec



So you know we had seen you know for example suppose if you look at you know the conditions like say if you have if you go for you know an example of aluminum 4% copper for this. Now for this as we have seen that your slope of the tangent on that liquidus line that was $\Delta T/D_L/R$ and basically that you know G that is your temperature gradient. So it is value has to be you know more than or so or less than depending upon the conditions will vary.

So for suppose if you take the aluminum 4% copper and its values if you take so for them the T_L you know that that value is supposed to 650 ^{0}C and agreed and T_S is say 580 ^{0}C and your D_L is diffusional coefficient in the liquid. It is 3×10^{-5} you know cm^2/sec. Suppose that is the case now in this case if your temperature gradient so if suppose the temperature gradient G if temperature gradient you know G and this its value is suppose say 700 ^{0}C/cm.

So as we know that you know G/R value so has to be higher so your R value so you can have the value of ΔT so you know ΔT will be something like 70 and divided by D_L so that is how this value comes. Now so if you get you know the value now if you calculate the R that is your growth rate so we have the expression like G/R so growth rate that is R that has to be you know < or = so this has to be < or =3 $\times10^{-4}$ cm/sec.

In order to have the, you know, planar mode of solidification and if the growth rate is higher than this in that case the plane mode of solidification will break and that you will be likely to get cellular or dendratic type of you know solidification structure. So this we have seen you know in our earlier lectures. Now the thing is that as we know that when you have the arms being formed. Now these arms are basically certainly not good in the sense that you have the chance of the liquid being trapped in the dendritic arms.

And that will be certainly prone to the defects or prone to the chemical inhomogeneities as the situation may be again that will be depending upon again the different cases which we have discussed that whether you have the how your diffusion is there in solid and liquid stages like diffusion metal. There may be diffusion in total solid and a liquid case or there may be you know incomplete diffusion in solid and incomplete diffusion in liquid or so.

So we have discussed about these cases the thing is that the liquid which is trapped you know inside these you know inter-dendritic arms or so. Now they again have to solidify now in those cases there they are assumed to move in a you know planar manner, they are in a very small domain. So there the question of the you know segregation comes into picture.

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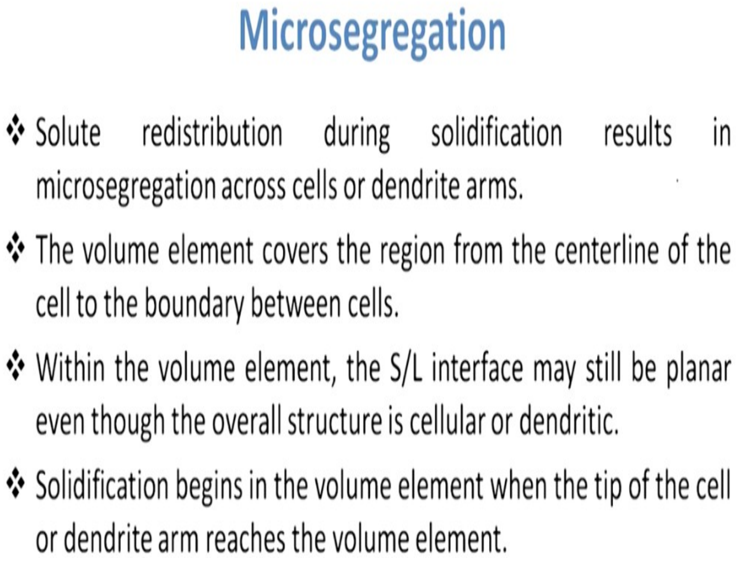

Microsegregation

- Solute redistribution during solidification results in microsegregation across cells or dendrite arms.
- The volume element covers the region from the centerline of the cell to the boundary between cells.
- Within the volume element, the S/L interface may still be planar even though the overall structure is cellular or dendritic.
- Solidification begins in the volume element when the tip of the cell or dendrite arm reaches the volume element.

So the solute redistribution during the solidification results in microsegregation across cells or the dendritic arms. So you know that is basically the you know the result of the microsegregation because they will be resulting across the cells or the you know dendritic arms. So if you talk about the you know the arms so how it looks like.

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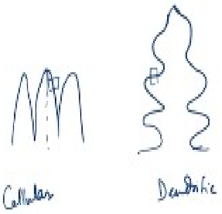
K<1

→ No segregation if diffusion is complete in liquid & solid

$D_L t \gg l^2$

$D_s t \gg l^2$



You see you have the you know the dendritic or cellular type of solidification say you have you have a cellular type of structure or you may have the you know dendritic arms. So it will be going like this so you know it goes like this. So this is your cellular type of solidification and this is your dendritic. Now in this you have basically you will have the liquid which is trapped in between these arms so you will have the liquid here.

Similarly, you may have the liquid trapped in this case so this case again you will have you know so here this is the liquid element that is volume element which is considered or you know that will be so this is your centerline so this is your volume element. So that is how you know you have the small you know volume element there you have the full volume of the liquid where you will have the experience of undercooling.

And then you have you know the formation of dendrites, but then again here also you have the liquid and there also the solidification has to proceed and again because of the conditions you will have you know in these cases also you will have the effect of microsegregation. So the volume element covers the region from the centerline of the cell you know or the dendritic arms you can say and you know to the boundary between the cells.

So this way these volume elements are defined. Now it within the volume element the solid liquid interface may still be planar so in that case although we see that the all structure is you know the cellular or dendritic, but within that volume element which is small volume element in that the interface may still be you know planar depending upon the different conditions again you know how that condition is existing.

So based on that there may be even the you know still the you know planar type of solidification that may you know proceed in these cases. Now for these you know it depends upon the you know again the different cases and if your cases may be that there may be no you know microsegregation, no segregation when you have you know the diffusion is you know completing both solid and liquid.

So based on that basically you will have different condition so suppose you have we talked about a ratio of the case where K is < 1 so equilibrium partition ratio. If you take that to be <1 and your because in that case the slope is you know <1 certainly slope is negative. Now in these cases you know you will have no segregation if you have complete diffusion you know when diffusion is complete in both solid and liquid.

So no segregation if diffusion is complete in liquid and solid so that way this will be the condition when there will be you know you know diffusion there will be complete diffusion in liquid as well as in the solid and for that we have already discussed that for that the condition has to be satisfied. In that case your diffusion coefficient multiplied by time it has to be you know quite larger than the distance over which the diffusion has to take place.

So for that the condition will be $D_L \times t$ has to be quite larger than you know L^2 similarly $D_S \times t$ and that has also to be quite larger than L^2. So this is you know the case when you have the you know case where there is a complete diffusion in the solid as well as in the liquid and in that case you know microsegregation profiles will be like. So for these cases what will happen that you have you know for k <= 1 values you will have you know this C_0 value will be there altogether that will be constant.

Similarly, even for K>1 value also you know across the profile you will have no segregation and the concentration will be you know same. So if you are taking for the you know C_0 concentration. Now second case is that now the segregation will be worst so if you take about the another case where you have the you know in solid case you have no diffusion so no solid diffusion and you have complete liquid diffusion.

In those cases, the segregation you know that will be affected so that that will be worst in those cases.

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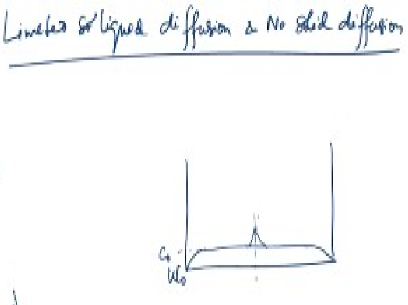

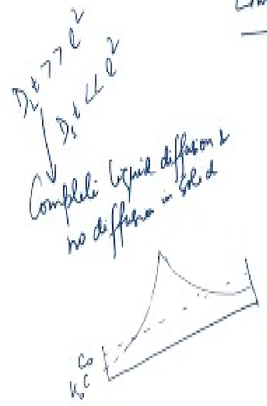

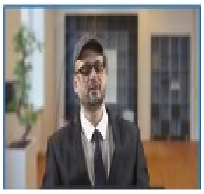

So if you talk about the case when you have you know limited you know liquid diffusion and you have no solid diffusion and no solid diffusion. So if that is the case now in this cases you know so you will have now if you talk about this case that is limited liquid diffusion and no solid diffusion. In that case what happens that your this segregation profile for the case you know for <1 you will have you know it will start from KC_0 and then it will move like this.

And then it will be from both this side you will have such profile so this will be your C_0. So this will be the case of initial transients as you have seen in such cases, but as we have seen in the in earlier cases now towards the middle portion you will have such kind of you know case. So this is the case for no solid diffusion and limited liquid if it was in the liquid also you do not have full diffusion so towards the end you have you know reach of in the higher you know of the value more than C_0 it goes, but so in this case the it is intermediate.

However, if you take the case of complete liquid diffusion and you will take suppose no diffusion in solid. So you know in these cases you know this will be case when for this the condition will be you have complete liquid diffusion so $D_L \times t$ has > L^2 whereas no diffusion in solid so you will have Ds ×t is quite less than L^2. So in these cases the situation is very much severe.

And here you know as you see in these cases what happens if your this is your C_0 value so we start from C_0 KC_0 and then you know what happens that it will move and then it goes to a very high value. So this way your profile moves like in the case of limited you know this will be the case when you have the complete liquid diffusion whereas there is no solid diffusion. So in those cases as you see that your concentration will be too high and then it will be going like this.

So your segregation condition will be worst you know in these cases when you have complete diffusion in the liquid and there is no diffusion in the solid as it appears in these cases. So if you take the example of you know the aluminum copper alloys or aluminum alloys.

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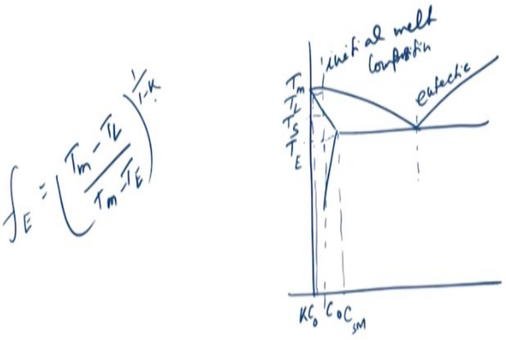
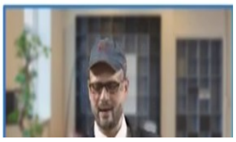


$$f_E = \left(\frac{T_m - T_L}{T_m - T_E}\right)^{\frac{1}{1-k}}$$



Now in this case as we know that in that case you see the eutectic you know composition also. So for taking a eutectic phase diagram if you know if you look at so you have this is the eutectic composition now this is your, you know, eutectic point. Now if you see you know if you take any composition suppose here in such cases now what is happening that if you take this as the initial melt composition that is your C_0.

So this is you know C_0 and as you see that it will be touching here. So this will be your for the you know so the solid part which is coming out so certainly this will be KC_0 depending upon the value of K that that point will be you know case KC_0 and then it will move through that. So this is your eutectic point here this will be if you take this point this is your T_E similarly this point where it is touching this is the solidus line so this is T_s and this temperature will be T_L and this will be T_m.

So if you look at you know this point now this is your C_{SM} so you know what we see in this cases again what we see that the solid composition will be moving from KC_0 to C_{SM} so this way this solid this line is moving. So solid composition as the temperature is you know dropped so the solid composition will certainly be moving along this line. So it will be moving from KC_0 so its concentration will be moving from KC_0 to C_{SM}.

And you know that will be maximum when your this eutectic temperature is this that is T_E so that way this you know eutectic at this point this comes as a C_M and also you know the composition becomes C therefore. So then after that it will be formed as the solid eutectic you know after this point. So the fraction of the eutectic which can be formed you know that can be calculated as indicated earlier so that can be you know formed.

So that will be the you know we are taking this as the complete diffusion in the liquid and no solid diffusion. So you can have the you know for example if you try to find it will be $(\frac{T_m - T_L}{T_m - T_E})^{\frac{1}{1-K}}$. So this way you can have the fraction of eutectic which can be formed in such cases. Now we will talk about you know another phenomena which occurs that is banding.

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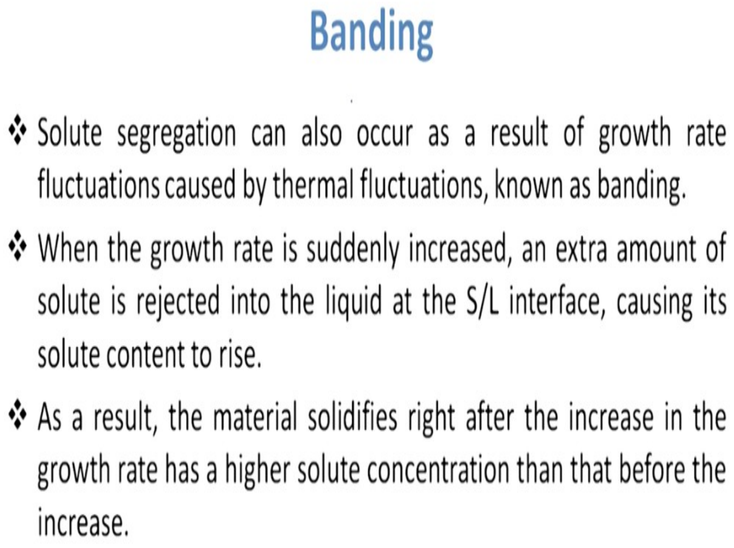

Banding

- Solute segregation can also occur as a result of growth rate fluctuations caused by thermal fluctuations, known as banding.
- When the growth rate is suddenly increased, an extra amount of solute is rejected into the liquid at the S/L interface, causing its solute content to rise.
- As a result, the material solidifies right after the increase in the growth rate has a higher solute concentration than that before the increase.

Now what happens that the solute segregation it can also occur as a result of growth rate fluctuations caused by thermal fluctuations and then in that case you know it is known as banding because we have seen that the in that expression where we have got G/R and then on the other side you have $\Delta T/D_L$. So in those cases you know R is you know the growth rate that is that becomes important even for the solute segregation.

So when it is occurring because of the result of growth rate fluctuation in that case it is known as the banding. So what happens that you may have a case where you know you suddenly the growth rate is increased. So if the growth rate is increased then the extra amount of solute you know will be rejected into the liquid because as the growth rate is increased. So the solid which is lower in concentration of solute so certainly it will be rejecting the you know solute at a larger rate.

So it will be you know larger amount and so what will happen that you know so it will be rejected into the liquid at the solid liquid interface and so the solute content you know you will be rising. Now as a result the material solidifies right after the increase in the growth rate. So if there will be further material you know solidification you know after the increase in the growth rate.

So it will have a higher solute concentration then that which has you know occurred before, you know, so you can see that there will be you know the difference you know.

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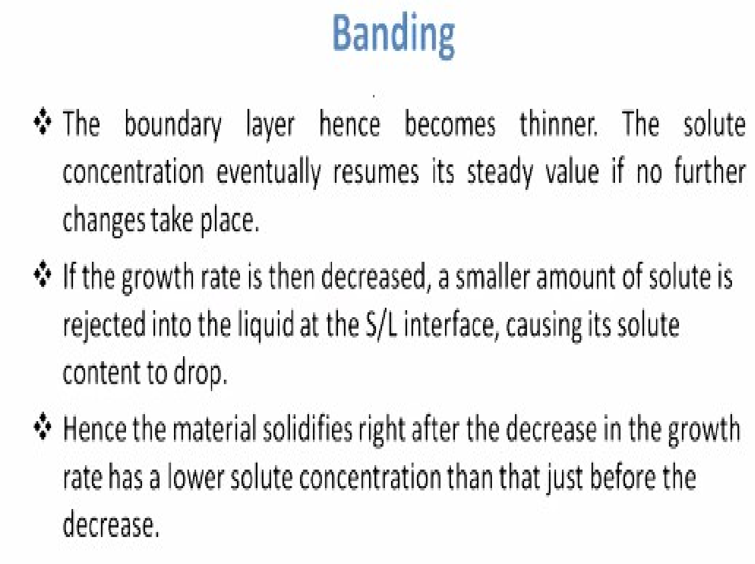

Banding

- The boundary layer hence becomes thinner. The solute concentration eventually resumes its steady value if no further changes take place.
- If the growth rate is then decreased, a smaller amount of solute is rejected into the liquid at the S/L interface, causing its solute content to drop.
- Hence the material solidifies right after the decrease in the growth rate has a lower solute concentration than that just before the decrease.

That difference can be seen you know in the term that the boundary layer will be becoming thinner in those cases. So because the growth rate has increased and if you know the solute concentration eventually resume will be if so if and if there is no further change taking place then again the solute concentration will be eventually taking you know it you know a steady value from there onwards.

And then if suppose it is further decreased so if suppose it may increase from one value to the second value and from the second value again so you will have the decrease in the growth rate. So you will have the solute rich band, solute rich band which is formed when the growth rate is formed and growth rate is increased. Similarly, when there is further decrease in the growth rate so you have the solute depleted you know band formation in such cases.

And eventually I mean that is what is the effect of the you know increase or decrease you know in the case of banding when your there is increase or decrease in the growth rate that is how it affects. So that can be understood.

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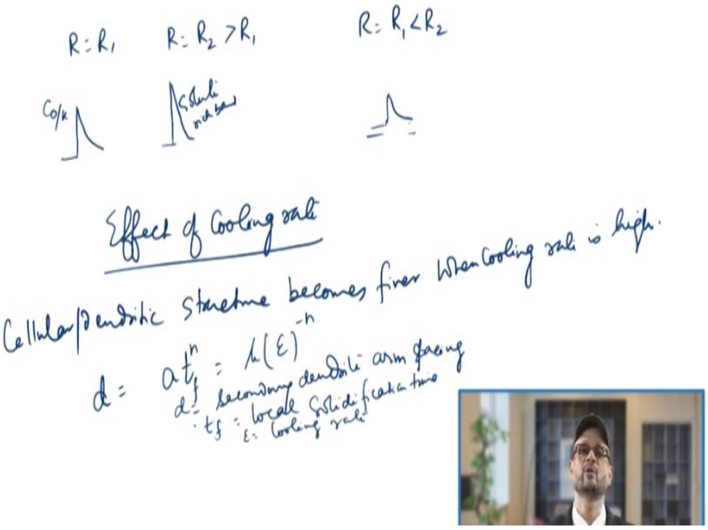

Effect of Cooling rate

Cellular/Dendritic Structure becomes finer when cooling rate is high.

$$d = a t_f^n = b(\varepsilon)^{-n}$$

d: secondary dendritic arm spacing
t_f: locale Solidification time
ε: Cooling rate

Suppose if you look at you know the pictorial representation of these banding so that you can understand suppose your when your growth rate is R_1 now in that case your if you look at the solute concentration profile now that you know that it moves from C_0 to C_0/K so that way it moves and then it goes like that. Now suppose you from R_1 it is increased to R_2 which is $> R_1$.

So in that case you will have a solute rich band ahead so your you know the that profile it will be looking like it will go from here and then it will be coming down so you will have a solute rich band. So that you will have you know and this will become thinner because it goes above so it becomes thinner in those cases and as you see when it is further decreased from R_2 to R_1 now in that case you know again it will be you know it will be smaller.

So it is coming like this so that way you will have the solute rich band and also you will have the solute you know depleted band formation in the case of the increase or decrease of the growth rate. There is a also affect you know of you know on the cellular or dendritic structure whether it will be finer or coarser so there is effect of cooling rate also. So if you talk about the effect of cooling rate.

So when your cooling rate will be higher in that case your solidification time will be shorter. So now when the solidification time is shorter in that case your cellular or dendritic you know so cellular or dendritic structure will become finer. So cellular or dendritic structure becomes finer when cooling rate is high. So basically that can be understood by looking at the dendritic arms spacing.

And there has been expression for you know the secondary dendrite arm spacing d and d basically is taken to be you know it is calculated as $a \times t_f^n$ or it is also written as $a \times \varepsilon^{-n}$. So the d is the secondary you know dendrite arm spacing and if you see the other time that is t_f it is the you know the local solidification time.

$\varepsilon$is the cooling rate so you know ε is the cooling rate and A and B are the proportionality constants. So you know from here you can see that your if the you know t_f is less in that case your dendritic secondly dendritic arm spacing will be smaller. similarly cooling rate becoming higher this value will be smaller. So that is basically you know this is the you know formula for finding the dendritic you know arm spacing.

And you know it has been seen that as you know increase the cooling rate then the arm spacing that will be becoming narrower and narrower so that is the effect of you know increasing the cooling rate so increasing this value or you know decreasing the time of solidification in such cases. So that is how you know you have to more and more analyze these situations you can have the study of these terminologies.

And you can have you know a concept that how you know this dendritic arm spacing will be varying by the change of either the cooling rate or the solidification time. So we discussed about these issues in this lecture we will be talking about other issues related to the solidification or epitaxial solidification and non epitaxial growth in our coming lectures. Thank you very much.