Mathematical Modeling of Manufacturing Processes
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Lecture - 24
Solidification in Welding 2

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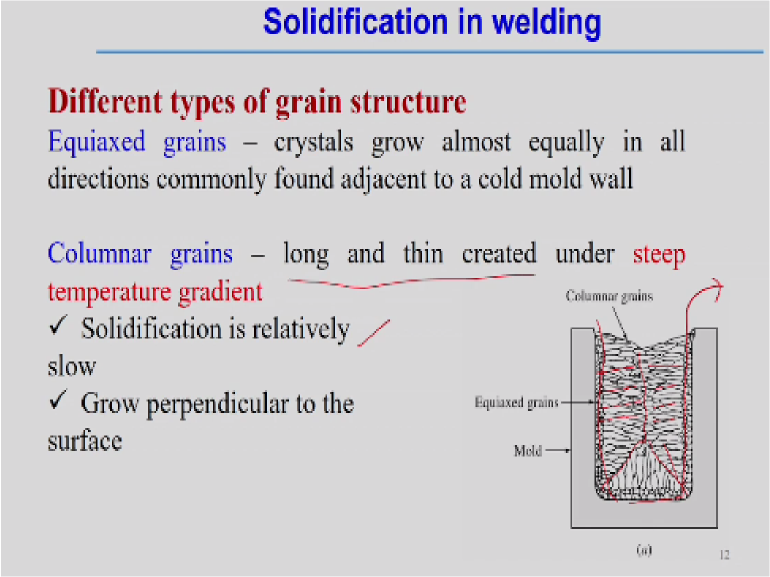

Solidification in welding

Different types of grain structure

Equiaxed grains – crystals grow almost equally in all directions commonly found adjacent to a cold mold wall

Columnar grains – long and thin created under steep temperature gradient

- ✓ Solidification is relatively slow
- ✓ Grow perpendicular to the surface

So now we will discuss about the solidified structure in specific to the different fusion welding process. If you see normally during solidification we can expect this kind of structure if we assume that mold as the solid liquid interface in a specific welding situation then normally we can find out the equiaxed grain structure normally found at the boundary and from there, there is a growth of the columnar kind of the structure towards the center.

Specifically, the columnar kind of structure normally we can find out it forms in which direction the steepest temperature gradient actually exist. So in the equiaxed grain that actually at the zone where the equiaxed grains normally forms that zone is normally is very less. If you see near about the boundary you can find out that equiaxed kind of grain structure, but that (()) (01:26) is very small zone.

And equiaxed we can define that almost equal grow almost equal in all directions adjacent to the mold surface. So once the equiaxed grain structure adjust with the mold surface then after that it follows by the kind of the columnar kind of the grains. So it is a characterized by the long and thin grains it moves the growth actually happens particular direction and which direction we assume there is a highest temperature gradient actually exist in the direction.

So in this case it is relatively slow process so basically columnar grains formation is relatively slow as compared to the equiaxed grain type of structure and the second part is that it grow perpendicular to the surface. If you see that in this structure that all grow perpendicular to the surface and of course (()) (02:19) it grows from the other side and we can get some interference between this part.

So similarly we can get the interference between this also and we can get similar way we can interfere in particular. So this is the typical kind of the 2 different types of the grain structure equiaxed to columnar kind of the grain normally we found out in case of fusion welded structure.

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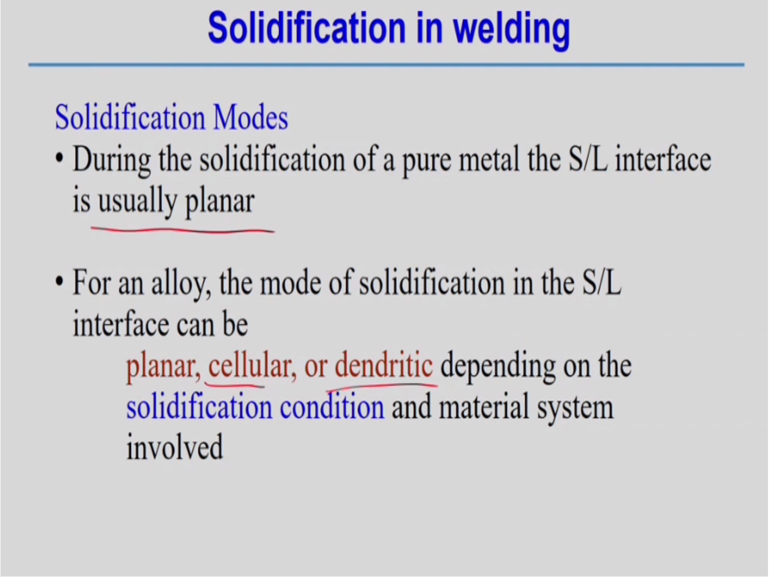

Solidification in welding

Solidification Modes

- During the solidification of a pure metal the S/L interface is usually planar
- For an alloy, the mode of solidification in the S/L interface can be
  planar, cellular, or dendritic depending on the solidification condition and material system involved

Now we will try to look into what are the different solidification mode actually the solidification mode to some extent decides the solidified structure and depending upon the composition of the material and of course the solidification conditions the undercooling exist or growth rate as well as the temperature gradient exist based on that different modes of solidification we can found out specific to the fusion welding process.

One is that kind of planar growth that means the solidification front actually moves like a plane and they are normally observed in case of pure metal of course apart from this condition in case of pure metal the solidification growth planar mode of solidification may also observes in case of other alloy system, but subjected to typical kind of conditions exist that we will try to find out that condition what condition we can found there is a planar growth.

And what condition we can say there maybe something other that means apart from the planar mode of the solidification the other mode of the solidification can be cellular, dendritic or mixture of between cellular and dendritic kind of this things. So it completely depends on the solidification condition, but solidification condition rather we can say that it depends completely what is the parametric value of the solidification parameters or what way we can define it is a cooling rate, growth rate all matter here to decide the mode of the solidification.

But we will try to look into this mode of the solidification and by measuring to very simple parameters that is called the G and R parameters.

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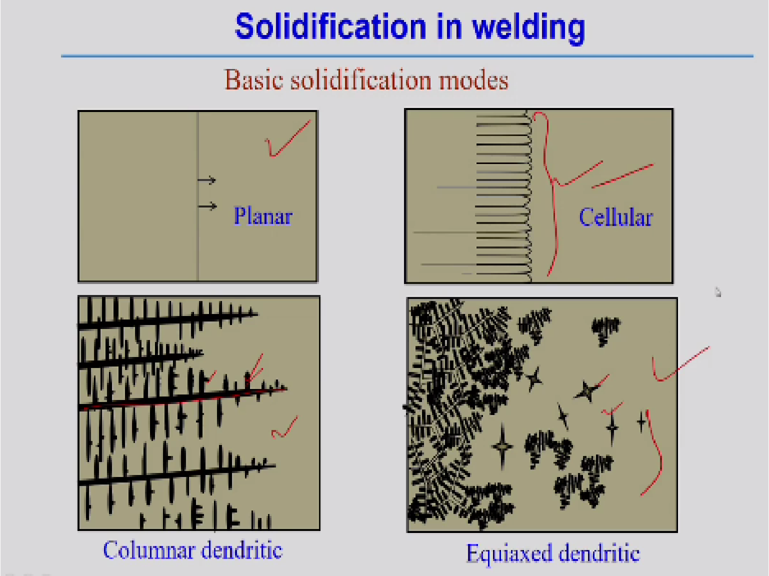

Solidification in welding

Basic solidification modes

But before that we can look that how looks like the modes of the solidification. We can see the first figure it is a planar mode it moves the front like a plane and then we can say the kind of cellular mode in this cases we can see the structure is something kind of cell structure and we gradually moves in this way and moves in a particular direction that means solid liquid in the mixing of the liquid and solid zone.

And solid part is gradually solidify from the liquid part and the front looks like this kind of cellular structure this is called the cellular mode of the solidification and then another basic normally we found out that is called kind of the dendritic structure. A dendritic structure and if we say the columnar dendritic structure so it is a long column kind of structure. The first solidification starts along a particular direction specific to which direction the highest temperature gradient exist.

And it is subjected to associated with the secondary and primary dendritic arms so this is primary dendritic arm and the secondary dendritic arm so it looks this type of typical structure the mode of solidification we can say the columnar dendritic structure we can form. So that here we can see this is the solidified part and remaining part we can say it is a liquid phase.

So within the liquid phase how it convert to the solid phase in the different geometry formation for example it can be planar, it can be cellular or it can be columnar dendritic it depends on the typical solidification conditions of course other modes of the solidification can be equiaxed kind of dendritic structure. Here we can see that almost equal kind of all directions growth is more or less same.

And the shape is kind of dendritic kind of structure. So it is different from the columnar dendritic structure it is rather we can say they are kind of equiaxed kind of dendritic structure that kind of structure also we can found out during the solidification. So now we look into this modes of the solidification how we can explain this mode of the solidification from looking into some certain parameter relevant to the welding process.

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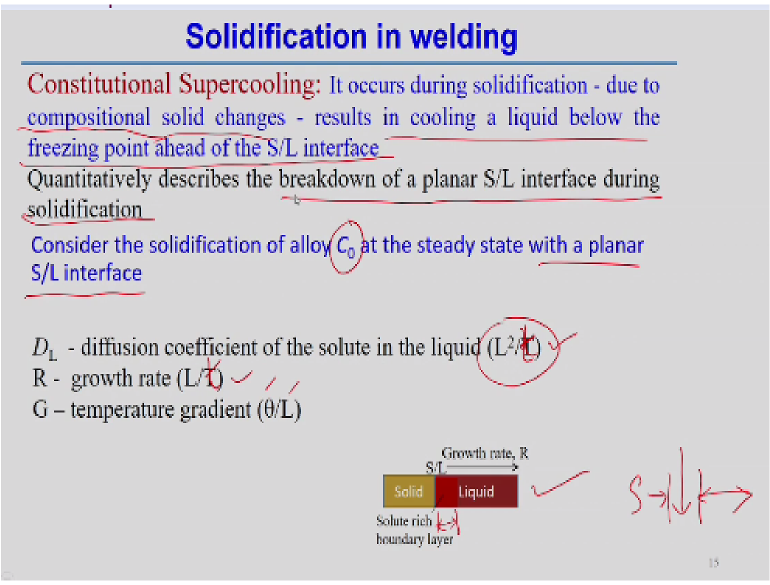

Solidification in welding

Constitutional Supercooling: It occurs during solidification - due to compositional solid changes - results in cooling a liquid below the freezing point ahead of the S/L interface

Quantitatively describes the breakdown of a planar S/L interface during solidification

Consider the solidification of alloy C_0 at the steady state with a planar S/L interface

D_L - diffusion coefficient of the solute in the liquid (L^2/T)
R - growth rate (L/T)
G – temperature gradient (θ/L)

Now we start with that so we will try to explain this solidification behavior by assuming the constitutional supercooling theory which is based on the thermodynamic normally during the solidification process, but we need to understand what is the supercooling maybe exist in this thing we observe during the solidification process. So we have already mentioned that there is a degree of undercoiling actually exist during the solidification process.

And that maybe subjected to kind of pure metal. So degree of undercooling normally happens it is due to the compositional actually the supercooling normally happens in here due to the compositional solid changes that means most of the cases in the localized area due to the heat extraction or maybe absorption of the heat to convert the phase from one phase to another phase specifically from liquid phase to solid phase at the time during the solid phase.

There is a release of the latent heat. So that latent heat actually it may not be rate of absorption of the latent heat may not be the same at particular position. So there maybe it is a very localized position there maybe the possibility that the cooling liquid can be freeze below ahead of the solid liquid interface and that can be below the melting point temperature. So that means locally you can say there exist some sort of undercooling exist.

So that depends on the nature of the material and normally in case of alloy system this normally happens between the solidus and liquidus temperature of a particular material. So then actually the solidification normally happens some equilibrium temperature in between the solidus and liquidus temperature this undercooling or supercooling behavior normally is associated with during the solidification.

And based on that we can explain on this or we can relate this mathematical parameter in terms of the solidification behavior. So we assume that first using the constitutional supercooling theory we try to find out what maybe the conditions that breakdown of the solid liquid interface during the solidification we try to establish that things. So before that we assume start with that solidification of an alloy having that composition=C0 or we can say the solute concentration is C0 in that alloy and at steady state with planar solid liquid interface.

So we assume that steady state planar solid liquid interface exist having an alloy where solute concentration is C0. Now what way we can explain the solidification normally happens. So actually there is a growth rate that means according to the growth rate the solid liquid interface will move then gradually if you look into this figure it starts from solid phase at intermediate point suppose at this point there is a solid liquid interface.

It move and then this side it is completely liquid phase, but the intermediate zone we can say the solute rich boundary layer and we can assume that zone is basically liquid and solid phase coexist in that zone, but our interest to know the growth rate we define what way the solid liquid interface actually moves based on that parameter is defined by the growth rate. So of course apart from that we assume that diffusion coefficient of the solid and the liquid.

And if you see the diffusion coefficient of the solute how it dissolve in the liquid based on that in L square the dimension is basically length square/ I think this should be time length square/time and growth rate we can see the growth rate means simply what way we can move what is the rate through which the solid liquid interface actually moves we can say dimension with that growth rate is basically the length/ time it should be actually length/time.

So that means it is equivalent to the velocity the unit is like that. And temperature gradient we assume the temperature gradient exist because of that there is a movement of the solid liquid interface or we can say there is a temperature gradient may exist between this at the boundary layer that it corresponds to the temperature change with respect to length or distance that indicates the temperature gradient.

So we define all this parameters, but in this case of course diffusion coefficient depends on the type of the material and diffusivity of this particular material and at different phases so it depends on that parameter, but we can utilize this coefficient to link with the solidification behavior here.

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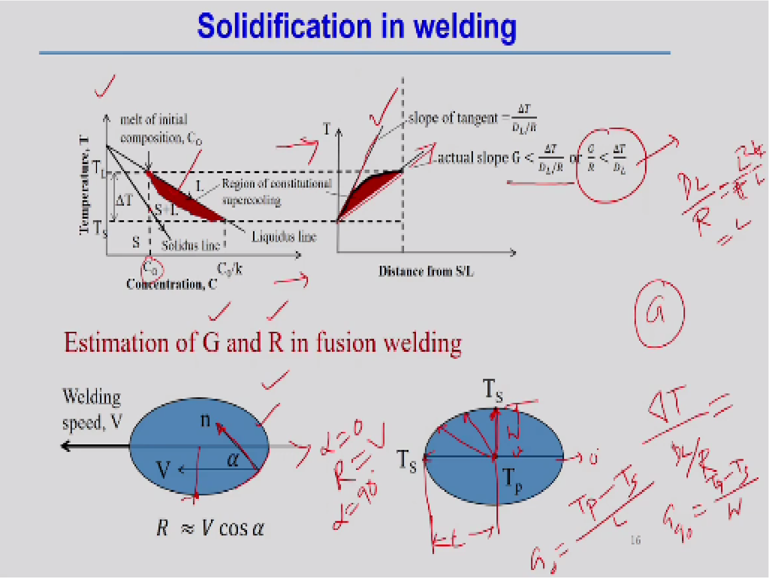

Solidification in welding

Estimation of G and R in fusion welding

$R \approx V\cos\alpha$

Now we look into that this graph we already explained this thing that solid concentration we assume the initial concentration=C0 and solidus line liquidus line and we assume there is a temperature difference we see the delta T temperature difference and we assume this zone is basically we assume that mark by red color is the region of the constitutional supercooling that means in this case the freezing even happens lower than the in this cases in between solidus and liquidus temperature in these case.

Of course in case of pure metal that is a below the melting point temperature, but here in between solidus and liquidus temperature. So then this zone actually represents the supercooling region constitutional supercooling part and this correspond to concentration x axis and y axis represent the temperature and for this C0 concentration the solute concentration this corresponds to the melt of the initial composition C0/

The melt of the initial composion C0 means it is just above the liquidus temperature and this liquidus temperature and of course I think this corresponds to the solidus temperature and suppose there is a difference between these two is the delta T. Now we try to link with this all this parameters here and we can look into the right hand side graph figure which corresponds to the temperature versus the distance from the solid liquid interface.

So distance from the solid liquid interface and we can find out that the actual slope is this one which is represented that slope is represented by G temperature gradient temperature gradient how we define the temperature gradient difference the temperature that y axis/distance. Distance we measure along the x axis so that slope actually represents the actual temperature gradient.

And G basically and on other way we can because there is a presence of the constitutional supercooling so from here we can see that because dissipation we can look into the what is the initial slope by initial point what is the slope and that slope we can measure using the other parameters. For example, here you can see that this suppose the constitutional supercooling exist because of temperature difference delta T and supercooling.

So then this delta T, but what is the distance we should consider such that we can estimate again the other way what is the temperature gradient that is the representation of the slope here. So here delta T and we see that DL/R. DL/R actually it represents the thickness of the boundary layer at steady state situation. So that means it corresponds to that here the boundary layer thickness it corresponds to we can say there diffusion coefficient/actually growth rate that represents the other way the temperature gradient corresponds to that.

So DL/R the unit of DL/R is basically L square/T and R is the L/T so it corresponds to the t means small t that represents the time and then it corresponds to the L. So it is basically the unit of the length so then DL/R actually represents that unit of length and its finally represents the other way we estimate the temperature gradient, but this temperature gradient we are estimating from that point of view how the solute actually based on the diffusion mechanism here.

And that diffusion mechanism solid to conversation from liquid phase to solid phase and accordingly we will consider the diffusion coefficient and this is happening under the certain temperature difference that temperature difference is the constitutional corresponds to the constitutional supercooling. So then if we compare definitely geometry we can see that this slope is less than that of the this slope.

So that we put the one slope is less than that of the slope and if you look into that then we get this kind of relation. So the planar I think in this case if we looking into the constitutional supercooling theory and we want to sustain that mode of the solidification it is a planar then from the geometrically we can find out that existence of certain amount of the temperature difference due to constitutional supercooling then we can reach this kind of relation.

Let us see how what way we can explain use this relation to explain the different solidification behavior. So first thing is that estimation of G and R. G is the growth rate sorry G is the temperature gradient and R is the growth rate, but in practically in fusion welding process how we can measure G and R. So suppose we assume that one kind of steady state welding process and welding process particular velocity V.

Then at particular point of time this is the formation of the weld pool. Now what is the growth rate corresponds to at any point what is the growth rate we can estimate thus using this assumption R=V*cos alpha. So V is the velocity vector and alpha is the angle between this normal that means we can say the direction of the rate of the growth and with respect to the velocity vector.

So we can see when we use this relation R=V cos alpha so along this central line the growth rate will be the maximum because in this case alpha=0 then R= is the V. So in steady state welding process that basically the rate of the solidification is equal to the welding velocity, but it varies from maximum, but at this point the transverse direction in this point in this cases alpha=maximum alpha=90 degree.

So in this case the growth rate is actually 0. So there is a variation depending upon the geometric shape of the weld pool the variation of the growth rate and that vary from the central line welding central line to the transverse this point transverse point the maximum from 0 to 1. So maximum can be= velocity of the welding speed. So this way we can estimate we just simply estimate if you know the location at any particular point we can estimate what is the growth rate so this is why what way we can estimate the growth rate.

Now we estimate the temperature gradient. So temperature gradient in welding process we can see normally at the center point the temperature reaches the maximum. So we can say the peak temperature Tp and of course this gradient also at different direction the gradient will be different depending upon this. So at the boundary we can assume that solidus temperature we assume that single temperature solidus temperature and divided by the distance.

It maybe this distance we can say that corresponds to the temperature gradient at suppose this is zero degree G0=the distance between these two. Suppose this is L so that is the temperature gradient and G0 similarly G90 also that means in other directions this 90 it can be Tp-Ts, but suppose this=W so it can be estimate like that Tp-Ts/W. So average temperature gradient in any particular direction we can measure by just simply tracking the temperature at the different position.

So definitely the gradient depends on what is the value of L or what is the value of W based on that we can estimate the temperature gradient. So it is a simple if you have all the data with respect to in a steady state welding process we can easily estimate what is the growth rate and what is the temperature gradient in a particular direction and we can utilize this data to find out the different solidification mode using this relation just we predicted.

So what conclusion can be made from this kind of relation how we can utilize this things. So basically we are trying to relate the solidification mode with this parameter GR and DLR.

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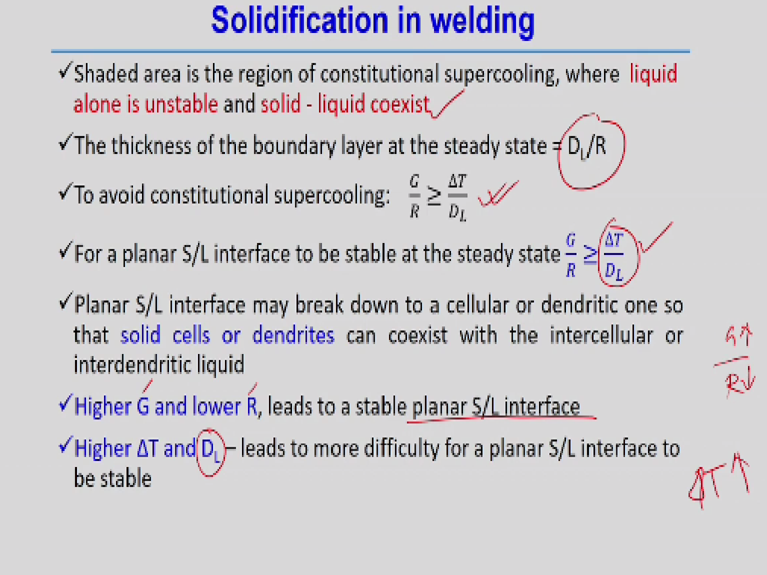

Solidification in welding

- ✓Shaded area is the region of constitutional supercooling, where liquid alone is unstable and solid - liquid coexist
- ✓The thickness of the boundary layer at the steady state = D_L/R
- ✓To avoid constitutional supercooling: $\frac{G}{R} \geq \frac{\Delta T}{D_L}$
- ✓For a planar S/L interface to be stable at the steady state $\frac{G}{R} \geq \frac{\Delta T}{D_L}$
- ✓Planar S/L interface may break down to a cellular or dendritic one so that solid cells or dendrites can coexist with the intercellular or interdendritic liquid
- ✓Higher G and lower R, leads to a stable planar S/L interface
- ✓Higher ΔT and D_L – leads to more difficulty for a planar S/L interface to be stable

$\frac{G\uparrow}{R\downarrow}$

$\Delta T\uparrow$

So basically the shaded zone we have represented that it corresponds to the region of constitutional supercooling where liquid alone is unstable, but in that point the liquid and solid coexist. So we assuming that coexistence of this thing and of course thickness of the boundary layer at the steady state situation can be measure just we explain DL/R and to avoid constitutional supercooling because we just use the other equation to avoid the constitutional supercooling this should be the condition so G/R should be>= delta T/DL.

But here we can find out the condition is like that G/R<delta T/DL, but definitely their existence of certain amount of the constitutional supercooling, but here if you try to avoid this things we need to put this condition it is opposite of that and for planar solid liquid interface

to be stable at steady state if stability of the planar solid liquid interface there is a mode of solidification as a planar then this condition should satisfy.

So definitely planar solid liquid interface of course it can break and can form kind of the cellular or dendritic and that solid cells or dendritic can coexist with the intercellular or the interdendritic liquid. So with definitely even it is from the cellular kind of the solidification front or dendritic so there also existence of the solid and liquid phase. So in this case higher G and lower R So G/R.

So higher G and lower R both promote the ratio should be very high. So if that G increasing order and R also decreasing order that promotes to the more stable planar solid liquid interface so that leads to the stable solid liquid interface. Other way also higher delta T just opposite the other side delta T that means high amount of the degree of supercooling may exist.

And of course diffusion coefficient DLC depends on that particular alloy system that basically delta T higher that actually leads to more difficulty for the solid liquid interface to be stable. So that high amount of the supercooling existence of such high amount of the supercooling do not promote the planar solid liquid interface movement rather it promotes the instability in the planar mode.

And then it creates kind of other kind of the structure other kind of structure means maybe cellular or dendritic equiaxed dendritic kind of structure it can promote. So that means from this condition we can make conclusion and of course if we measure this parameter then we can predict some kind of the solidification (()) (25:22) welding process.

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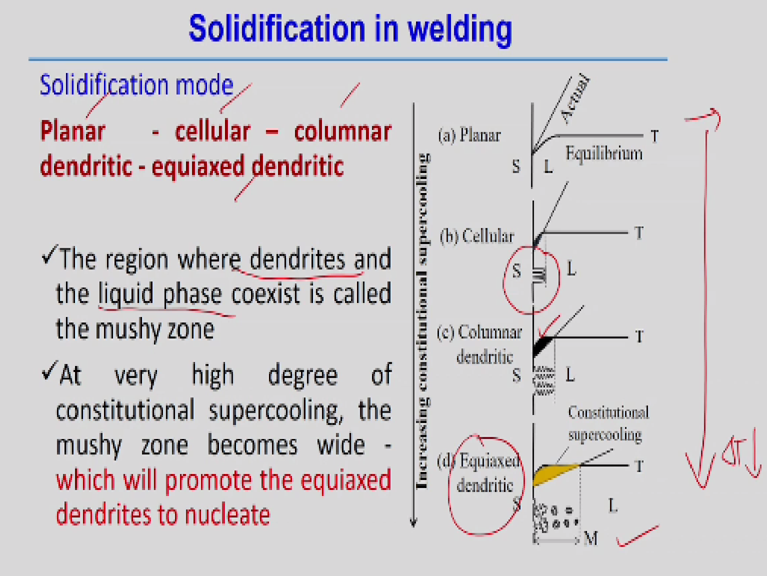

Solidification in welding

Solidification mode

Planar - cellular - columnar dendritic - equiaxed dendritic

- ✓The region where dendrites and the liquid phase coexist is called the mushy zone
- ✓At very high degree of constitutional supercooling, the mushy zone becomes wide - which will promote the equiaxed dendrites to nucleate

So it will be more easy to understand in this case if you see that there is increasing amount of the supercooling. So along this direction is if delta T is increasing what will happen planar will existing if almost no amount of the supercooling in this case the planar structure is more. So that means in that cases delta T should be very low value and in that case the planar kind of structure exist planar mode of the solidification actually exist.

Now gradually increasing the delta T little more amount you can expect this cellular kind of the structure even delta T is more you can represent this delta T this thing that zone is indicates that supercooling amount is more gradual increasing is a columnar dendritic and finally it is a very high it can promote the equiaxed kind of dendritic structure. So of course if it is possible to create high amount of the delta T supercooling.

Then constitutional supercooling then actually it promotes the kind of equiaxed kind of the dendrites that maybe beneficial in certain during the welding process. So solidification mode we can say that it can be planer, cellular, columnar, dendritic or equiaxed depending upon what is the amount of constitutional supercooling actually exist during the process. So based on that we can say that this kind of structure is expected.

Of course if constitutional supercooling amount are different at different positions so we can get one structure can be mixture of the different kind of the structure planar, cellular, columnar, dendritic kind of this structures.

So definitely the region where the dendrites and the liquid phase actually the dendrites and the liquid phase exist that is normally called in between the solidus and liquidus temperature that is normally called the mushy zone, but at very high degree of constitutional supercooling mushy zone becomes wide basically the high degree of constitutional supercooling the mushy zone becomes wide or in other way if we see that there is a huge difference in the solidus and liquidus temperature is more.

The difference between the solidus and liquidus temperature is more (()) (27:36) alloy system in that cases may be there is a possibility of increasing the constitutional supercooling mode and in other way constitutional supercooling mode means it promotes kind of equiaxed kind of the dendritic structures.

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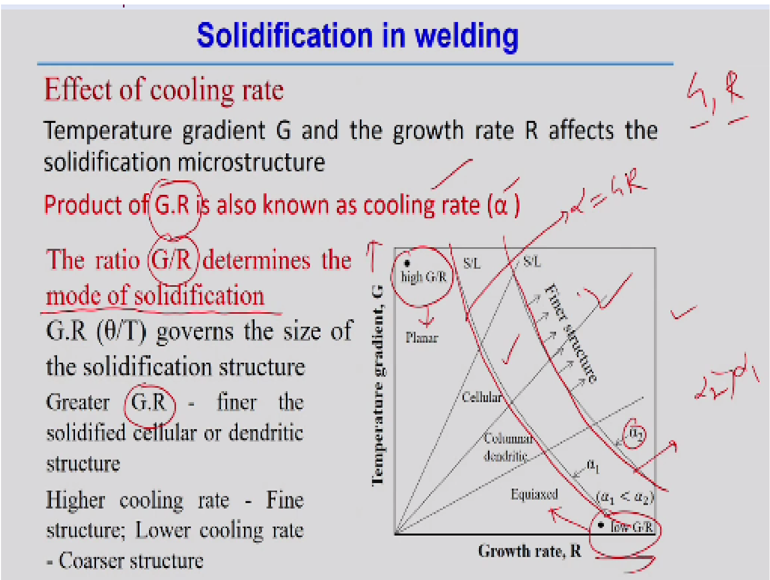

Solidification in welding

Effect of cooling rate

Temperature gradient G and the growth rate R affects the solidification microstructure

G, R

Product of G.R is also known as cooling rate (α)

$\alpha = GR$

The ratio G/R determines the mode of solidification

G.R (θ/T) governs the size of the solidification structure

Greater G.R - finer the solidified cellular or dendritic structure

Higher cooling rate - Fine structure; Lower cooling rate - Coarser structure

$\alpha_2 > \alpha_1$

We can more clearly say the other way represents the different solidified structure just look into this parameter G and R parameter that means growth rate and temperate gradient if you see the temperature gradient G and growth rate affect the solidification of microstructure also, but what way if you multiply product of G*R. Product of G*R if you look into the dimension that it represents the cooling rate.

We can say it is say suppose alpha and of course other way also G/R ratio already we have discussed based on the constitutional supercooling theory. Here we can see the G/R also determines the mode of solidification that we have already seen that how G/R decides the mode of the solidification and of course the solidification or other way cooling rate G*R represents actually cooling rate.

So high cooling rate means we can expect the fine microstructure, low cooling rate we can expect the coarse kind of structure. Now if we look into that if this is the graph growth rate and this corresponds to the temperature gradient. So this side indicates low G/R and this side it indicates the high value of G/R. So high value of G/R planar kind of structure and low value of G/R is basically promotes the kind of equiaxed dendritic kind of structure.

At the same time this represents G this represents the alpha that is=G*R. So in this case the rate of the cooling is low as compared to the other super impose line that it corresponds to the alpha 2. See in this case the rate of cooling rate=alpha 2> alpha 1. So here we can expect the fine microstructure here we can expect the coarse microstructure. So in a particular alloy system we have this kind of diagram GR in terms of only G and R.

Then we can decide what kind of solidification mode exist and as well as the solidification structure whether it is a very fine structure or whether it maybe the coarse structure.

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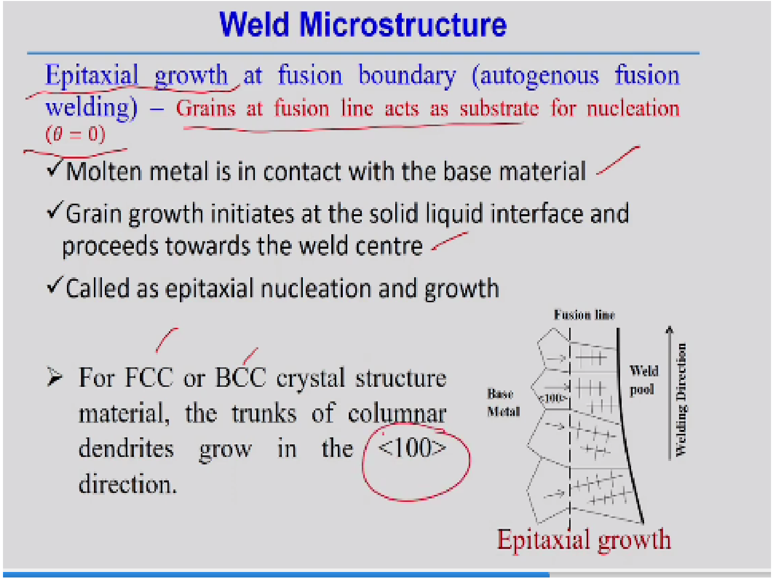

Weld Microstructure

Epitaxial growth at fusion boundary (autogenous fusion welding) – Grains at fusion line acts as substrate for nucleation ($\theta = 0$)

- ✓Molten metal is in contact with the base material
- ✓Grain growth initiates at the solid liquid interface and proceeds towards the weld centre
- ✓Called as epitaxial nucleation and growth

➢ For FCC or BCC crystal structure material, the trunks of columnar dendrites grow in the <100> direction.

There is in weld microstructure are normally it is observed specifically for the autogenous fusion welding processes. In that case we observe kind of epitaxial growth nucleation as well as growth normally happens start with the solid liquid interface because it comes from the this theory that grains at the fusion line acts as a substrate for nucleation. So in this case a situation arises is like that liquid part completes wets the solid grains.

In that case correspond to the nucleation theory of that theta=0 if we look into the heterogeneous nucleation theory in that case which represents as a function of theta. So in that case if theta become 0 then that means the liquid phase completely wet the solid grain boundary and that corresponds theoretically there is no energy barrier is required to start the nucleation process.

So that type of nucleation process actually is called epitaxial nucleation as well as the growth and of course the conditions for the epitaxial growth is the metal molten contact with the base metal first. Growth initiates at the solid liquid interface and proceeds towards the weld central line. So it starts from the interface and towards the weld central line it moves if we look into the figure.

It is called the epitaxial nucleation as well as the growth and definitely this kind of nucleation growth is more suitable in case of autogenous fusion welding process that means if there is no addition of the filler material. Normally BCC FCC crystal structure materials the columnar dendrites grow is basically 100 easy growth direction that basically 100 direction.

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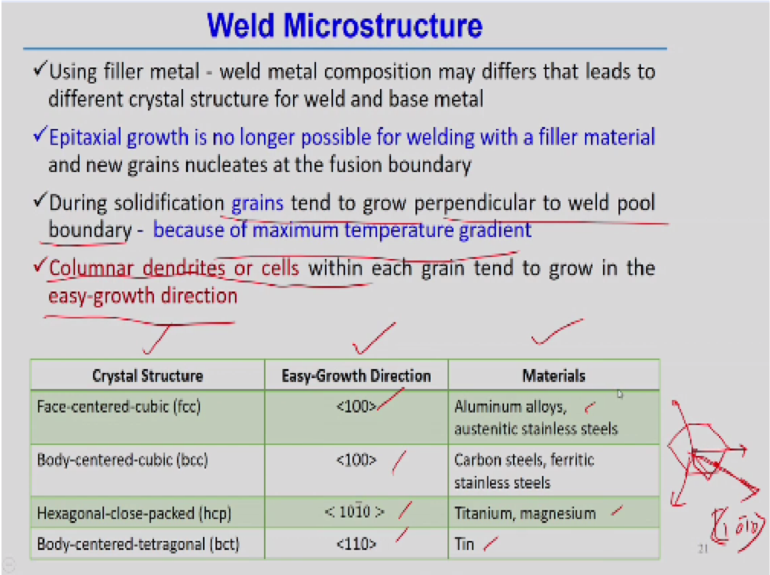

Weld Microstructure

- ✓Using filler metal - weld metal composition may differs that leads to different crystal structure for weld and base metal
- ✓Epitaxial growth is no longer possible for welding with a filler material and new grains nucleates at the fusion boundary
- ✓During solidification grains tend to grow perpendicular to weld pool boundary - because of maximum temperature gradient
- ✓Columnar dendrites or cells within each grain tend to grow in the easy-growth direction

Crystal Structure	Easy-Growth Direction	Materials
Face-centered-cubic (fcc)	<100>	Aluminum alloys, austenitic stainless steels
Body-centered-cubic (bcc)	<100>	Carbon steels, ferritic stainless steels
Hexagonal-close-packed (hcp)	< $10\bar{1}0$ >	Titanium, magnesium
Body-centered-tetragonal (bct)	<110>	Tin

But if we use the filler material then weld metal composition can differ and it breaks leads to the different crystal structure of the weld and base metal and using the filler material this is not possible to follow kind of epitaxial growth because the new grains actually nucleate at the fusion boundary. So practically the epitaxial growth actually normally exist. It is a very narrow domain most of the cases, but in this case during solidification grains overall perpendicular to the weld pool boundary.

So it always try to move the perpendicular the weld pool boundary because the maximum temperature gradient actually exist in the direction. So columnar dendrite or the cells within each grains tend to grow in the columnar dendritic actually it always tend to grow in a particular grain in the easy growth direction. We can see the easy growth direction corresponding crystal structure and what type of materials actually follow the easy growth direction.

If we see the FCC material 100 of course bcc 100 hexagonal close packed we can say that 10-10 that thing in the hexagonal close packed if we see probably it is this direction and probably the 1001 is basically this direction the middle point of this triangle. So that corresponds to I think 1010. So titanium magnesium we follow the hcp this is the easy growth direction and bct structure we can say the 110 Tin we can find out this kind of structure.

So epitaxial growth normally happens the columnar dendrite or cells actually normally happens in case of easy growth direction we can find out all this direction.

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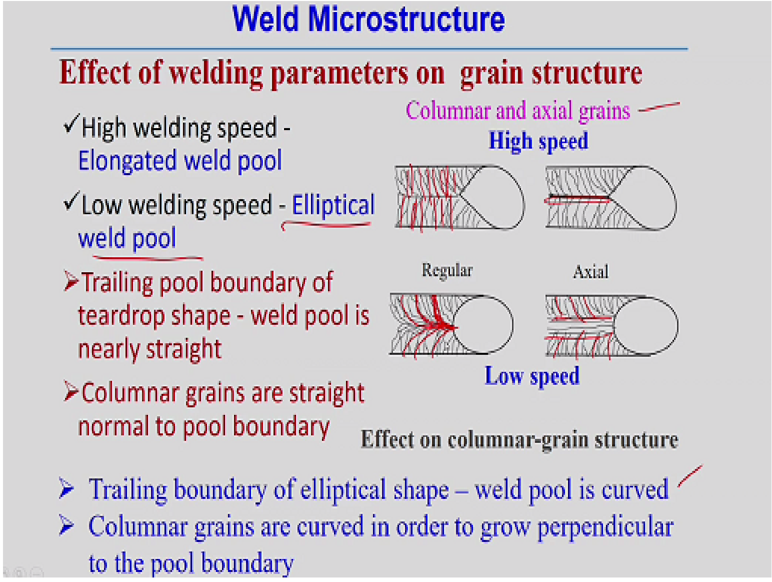

Weld Microstructure

Effect of welding parameters on grain structure

- ✓High welding speed - Elongated weld pool
- ✓Low welding speed - Elliptical weld pool
- ➢Trailing pool boundary of teardrop shape - weld pool is nearly straight
- ➢Columnar grains are straight normal to pool boundary

- ➢ Trailing boundary of elliptical shape – weld pool is curved
- ➢ Columnar grains are curved in order to grow perpendicular to the pool boundary

Now effects of the welding parameters in the grain structure overall effect of this thing we can say that normally find out the columnar kind of structure and axial grain we can find with in a welded structure. So here we can see the two things are possible with the very high speed at the very high speed the weld pool profile is different from the low speed. Low speed we can say the more elliptical weld pool we can found out low elliptical weld pool in case of very low speed.

More kind of regular kind of structure we can found out, but if it is a very high speed you can expect the kind of teardrop at the end and maybe we can say the elongated kind of structure we can found out if it is a speed is very high. So depending upon the speed the columnar structure grain columnar grain structure normally we found out that it grow more or less perpendicular to this direction.

And of course here it is a very narrow zone we can find out the axial grains also at the interface, but if it very low speed it start from the boundary perpendicular to that and comes to this, this is a typical structure columnar structure we can found out both the side and of course in case of low speed it is possible relatively high zone that we can get kind of axial structure in between and remaining structure is something like that towards this thing.

If we can say the trailing pool boundary of the teardrop say weld pool is almost nearly straight so that is why we are getting the solidified structure is something perpendicular towards the center kind of things, but columnar grains are straight normal to pool boundary in this case if speed is very high almost it becomes straight structure in case of high speed. If it is elliptical then it is curved it is not very straight rather the columnar structure is not follow kind of straight path rather it kind of curve.

And of course columnar curve in the order to grow perpendicular to the pool boundary so that it follow this kind of structure. In other cases we can see the kind of here this part we can expect the kind of axial grain specifically that axial grain will be more in case of low speed as compared to the high speed.

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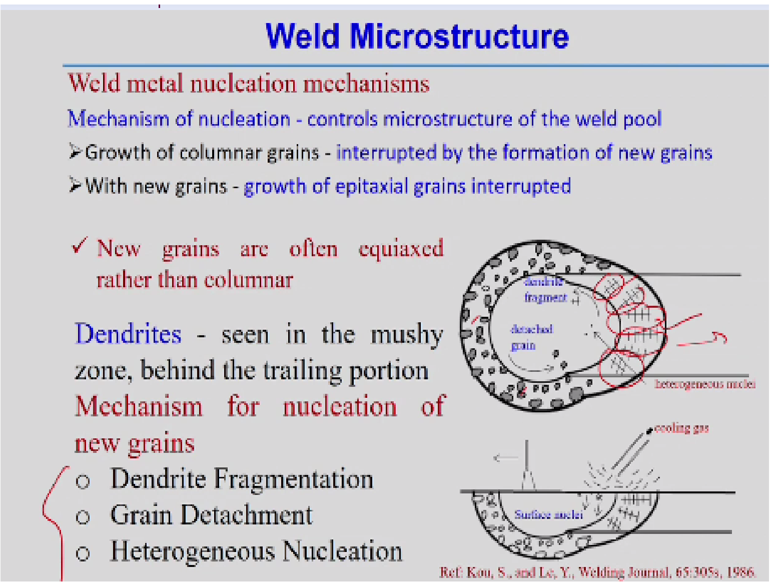

Weld Microstructure

Weld metal nucleation mechanisms

Mechanism of nucleation - controls microstructure of the weld pool

- Growth of columnar grains - interrupted by the formation of new grains
- With new grains - growth of epitaxial grains interrupted

✓ New grains are often equiaxed rather than columnar

Dendrites - seen in the mushy zone, behind the trailing portion

Mechanism for nucleation of new grains

- Dendrite Fragmentation
- Grain Detachment
- Heterogeneous Nucleation

Ref: Kou, S., and Le, Y., Welding Journal, 65:305s, 1986.

Now typical weld microstructure how looks like weld microstructure what weld metal or what maybe the nucleation mechanism (()) (36:26) to some extent it can be possible to predict the weld microstructure. So mechanism of nucleation actually controls the microstructure so we will try to look into what are the different mechanism of nucleation exist in case of weld pool or how the growth actually happens.

So since in a (()) (36:43) stir welding process there is a continues movement of the weld pool so there is a temperature gradient in the front part of the arc is different as compared to the rare part of the arc. At the same time rare part sometimes is subjected to some kind of cooling gas. So we can find out some kind of the columnar kind of structure at the columnar growth, columnar dendritic growth at the rare part.

But the turbulence or disturbance is more in the front part. So in this cases there is a formation of the new grains occurs or we can say the growth of the columnar grains is interrupted by the formation of new grains. Again the new grains also if there is a formation of the new grains it actually stops the growth of the epitaxial grains so that means we can see interrupted of the epitaxial growth of the grain is interrupted by the formation of the new grains.

So here little bit complex microstructure formation in case of weld pool, but overall if we look into that the new grains are often equiaxed form the new grains, but new grains are normally equiaxed kind of structure rather than the columnar structure. Columnar structure only you can expect at the back side as compared to the front side, but dendrites are seen mushy zone behind the trailing part.

If you see the dendritic we form at the trailing part rather than in the front part. While mechanism for the nucleation of the new grains we can say the new grains forms so what are the mechanism for the formation of the new grains is basically 3 parts. One is the dendritic form and their fragmentation of the dendrites grain detachment and of course heterogeneous nucleation normally happens in case of fusion welding process.

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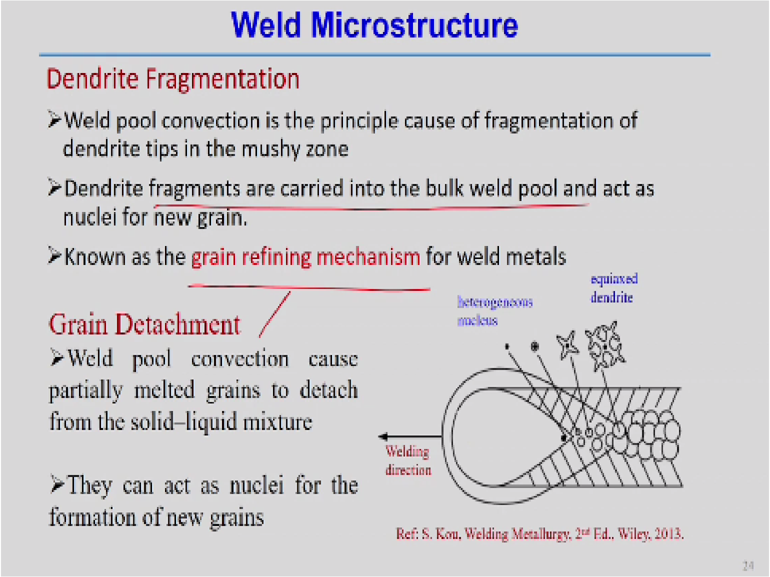

Weld Microstructure

Dendrite Fragmentation

- Weld pool convection is the principle cause of fragmentation of dendrite tips in the mushy zone
- Dendrite fragments are carried into the bulk weld pool and act as nuclei for new grain.
- Known as the grain refining mechanism for weld metals

Grain Detachment

- Weld pool convection cause partially melted grains to detach from the solid–liquid mixture
- They can act as nuclei for the formation of new grains

Ref: S. Kou, Welding Metallurgy, 2nd Ed., Wiley, 2013.

So dendritic fragmentation is mainly happens at the weld pool that means the convective flow of the liquid metal during in the weld pool that actually promotes the fragmentation of the dendrites and also carried out at the different part depending upon the motion of the liquid molten pool during the welding process. So dendritic fragments are normally carried out by the bulk weld pool and that dendritic fragment actually acts for the nucleation of a new grain.

So then it is known as grain refining mechanism for weld metals and of course we can say that other mechanism is the grain detachment. So grain detachment in this case part of the grains actually detach because of the convective flow of the liquid metal and that from the solid liquid mixture and that actually that detached part of the grains actually start or initiate the nucleation process.

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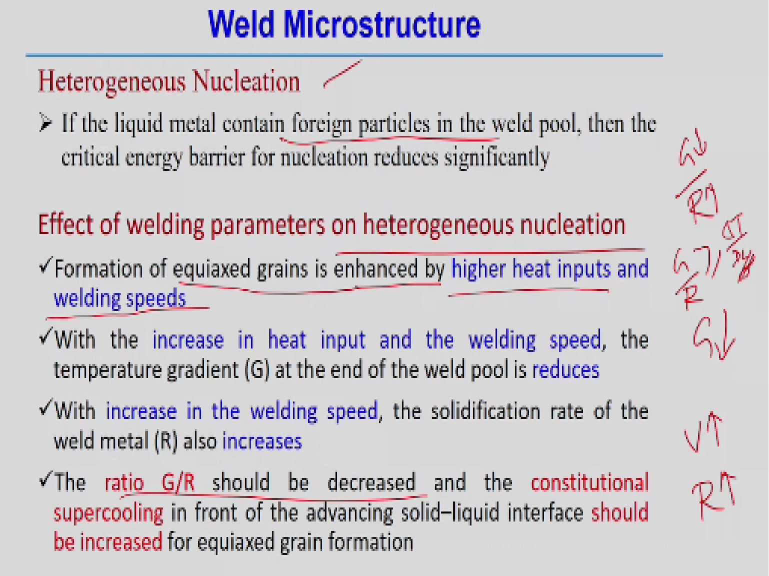

Weld Microstructure

Heterogeneous Nucleation ✓

- ➢ If the liquid metal contain foreign particles in the weld pool, then the critical energy barrier for nucleation reduces significantly

Effect of welding parameters on heterogeneous nucleation

- ✓Formation of equiaxed grains is enhanced by higher heat inputs and welding speeds
- ✓With the increase in heat input and the welding speed, the temperature gradient (G) at the end of the weld pool is reduces
- ✓With increase in the welding speed, the solidification rate of the weld metal (R) also increases
- ✓The ratio G/R should be decreased and the constitutional supercooling in front of the advancing solid–liquid interface should be increased for equiaxed grain formation

$G\downarrow / R\uparrow$

$G\uparrow / R$ ΔT

$G\downarrow$

$V\uparrow$

$R\uparrow$

In that way it modify the nucleation process. In general, the heterogeneous nucleation process also happens in the fusion welding process and that foreign particles weld pool and we know that foreign particles exist in that actually start the heterogeneous nucleation process and of course in this case is the barrier for the nucleation, barrier for the heterogeneous nucleation the energy when you start the nucleus is less than that as compared to the homogeneous nucleation process.

So these are the mechanism for the new grain formation this 3 mechanism we can say we can discuss, but further if we look what are the overall if we look into what are the effect of the welding parameters on heterogeneous nucleation process. First formation of the equiaxed it is more preferable to form the equiaxed grains because that actually improves the mechanical properties.

But what are the conditions for the equiaxed grains during formation is basically enhanced definitely we can find out that high welding inputs and welding speed because high increasing the heat input and welding speed increasing the welding speed both actually promotes reduce the G. If you want the temperature gradient want to link with the welding process parameters for example in terms of higher heat input the heat input is very high.

And if you use the very high welding speed both actually promotes the reduction of the G value because increasing the welding speed the solidification rate of the weld metal are also increases. So in other way if we increase the welding speed then the rate of the solidification also the solidification rate also increases. So R also increase in this case. So G/R if G decreases and R increases.

So in that cases G/R ratio actually decreases so when G/R ratio decreases so in that cases the constitutional supercooling in front of the advancing solid liquid interface actually should be increased and when a constitutional supercooling actually increasing then that actually promotes the equiaxed kind of structure. So we can say that G/R delta T/DL I think we can look back that condition G/R>= delta T/DL we can look into that.

So G/R high value promotes the planar mode of the solidification so G/R in the lower side promotes the formation of the high amount of the constitutional supercooling and high amount of the constitutional actually promotes the equiaxed kind of the grain formation. So all this parameters are linked when we can explain different phenomena in the welding process.

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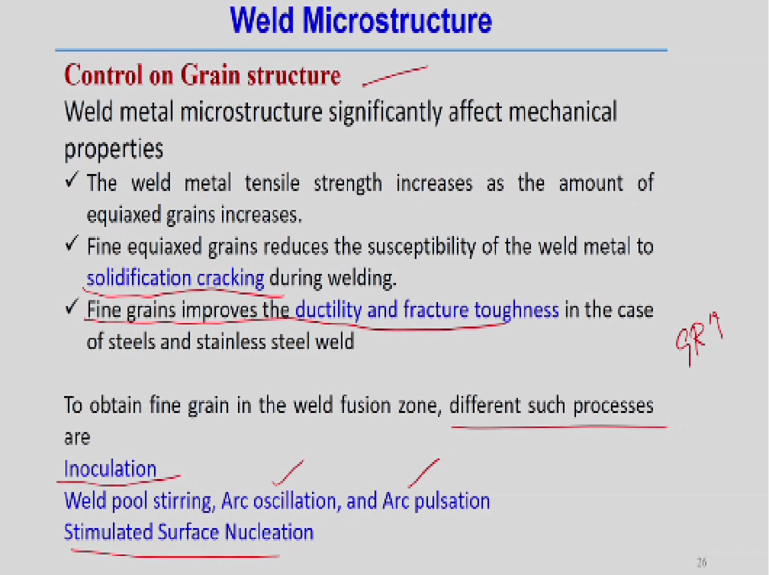

Weld Microstructure

Control on Grain structure

Weld metal microstructure significantly affect mechanical properties

- ✓ The weld metal tensile strength increases as the amount of equiaxed grains increases.
- ✓ Fine equiaxed grains reduces the susceptibility of the weld metal to solidification cracking during welding.
- ✓ Fine grains improves the ductility and fracture toughness in the case of steels and stainless steel weld

GR↑

To obtain fine grain in the weld fusion zone, different such processes are

Inoculation

Weld pool stirring, Arc oscillation, and Arc pulsation

Stimulated Surface Nucleation

But if we look into the control on the grain structure during the solidification process because if we modify the weld structure that actually finally impact on the mechanical properties of a weld joint. So therefore weld metals tensile strength increases as the amount of the equiaxed can increased. So equiaxed there is a formation of the more equiaxed kind of grains in the welded structure that tensile strength of welded structure actually increases.

So that promotes the very good tensile properties of course fine equiaxed grains are the other way also reduces the susceptibility of the weld metal to the solidification. So solidification cracking can be reduced if we promote the kind of equiaxed kind of structure during the solidification of course and fine grains. Fine grain structure improves the ductility and the fracture toughness in case of the steel central analysis.

So fine grains is sometimes useful it improves the ductility also and fracture toughness. So some mechanical properties can be improved fine structure as compared to the coarse structure. So that in terms of the fine structure it promotes G/R is in the higher side. So to obtain the fine grain in the weld fusion zone. So sometimes to promote kind of equiaxed kind of structure in the weld fusion zone some nucleating agent we promotes the more heterogeneous nucleation process.

And that can be done using some kind of nucleating agent, strain, weld pool stirring during the process by using some kind of ultrasound system then arc oscillation of the arc that actually define the structure the equiaxed kind of structure arc pulsation as compared to the continuous arc and stimulated surface nucleation of course all this influence the equiaxed kind of structure.

So that kind of additional system we can add to the welding system to improve the solidification behavior of the welded structure and that improvement of the solidification structure normally we understand to promote the formation of equiaxed kind of structure.

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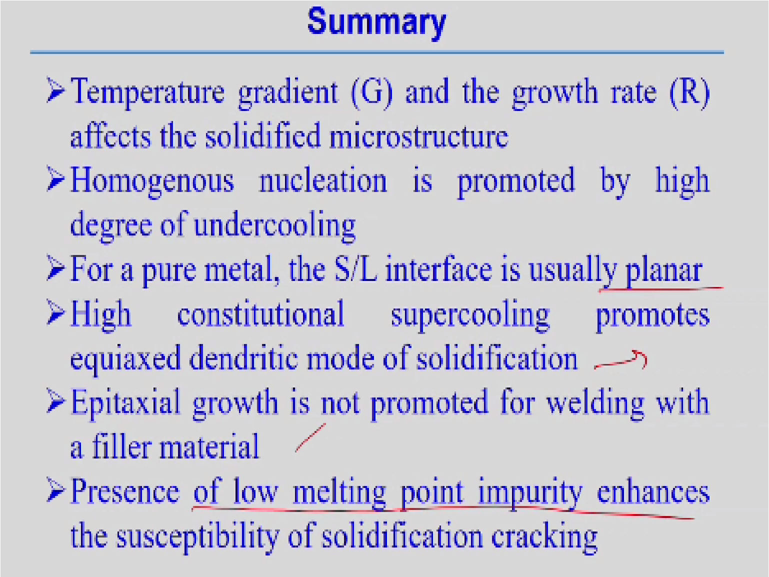

Summary

- Temperature gradient (G) and the growth rate (R) affects the solidified microstructure
- Homogenous nucleation is promoted by high degree of undercooling
- For a pure metal, the S/L interface is usually planar
- High constitutional supercooling promotes equiaxed dendritic mode of solidification
- Epitaxial growth is not promoted for welding with a filler material
- Presence of low melting point impurity enhances the susceptibility of solidification cracking

So in summary we can say of solidification that temperature gradient and growth rate are two important parameters and based on this two important parameters we can explain the different kind of the solidification mode or we can explain the solidified structure by using simply by estimating G and R value. Homogeneous nucleation is mainly promoted by the high degree of undercooling or heterogeneous nucleation is the degree of undercooling is not a matter.

Pure metal the mode of the solidification normally we found out the usually planar. So pure metal we can find out the solid liquid interface moves in a planar front and high constitutional supercooling normally promotes the kind of equiaxed dendritic structure and that is more desirable in case of welded structure. Epitaxial growth is not promoted by the application of the kind of the filler metal during the welding process.

So therefore epitaxial growth we can expect in case of autogenous fusion welding process. Presence of low melting point temperature are low melting point impurity in the welded structure that actually promotes the suspectibility of solidification cracking. So that we have to be very careful using the analyzing the solidification behavior in their presence of the low melting point impurity in the alloy system or that may observe during the welding process. So thank you very much for your kind attention.