Advances in Welding and Joining Technologies
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Lecture – 19
Welding Metallurgy Part III

So, basic solidification mode in welding process can be represented in four different ways; one is that planar that mean the solidification front move in the form as a plan.

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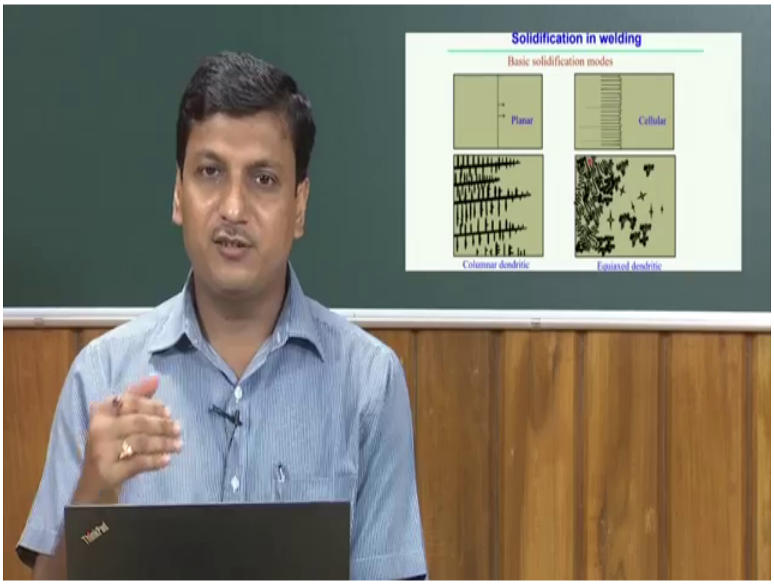

Solidification in welding

Basic solidification modes

A next another mode of the solidification for that can create maybe by breaking the planar interface and it can creates the kind of cellular a structure. And then during the solidification also that there may be the possibility of formation of the another type of solidification mode that is called a columnar dendritic structure that means, the growth happens in such a way that it makes a big column. And their primary and secondary dendritic arms at attached with that columns.

So, this kind of structure also it is obvious from the figure that this structure actually represents a columnar dendritic type structure. And that actually happens during the solidification from that within the liquid metal transform to the solid phase. So, during the transformation, it creates this kind of that means, columnar dendritic structure. Of course, the dendritic structure can be formed in like a equiaxed kind of structure. That means, it is like if you see that from the figure that there is a three arm and the dendrite and secondary dendritic arm spacing accordingly, so that it looks like the equal amount of spacing in all three direction. So, it is a kind of structure or mode is kind of a equiaxed structure microstructure what is almost equally size of the grains throughout the microstructure. So, these are the four different types of solidification mode generally observed in case of welding process.

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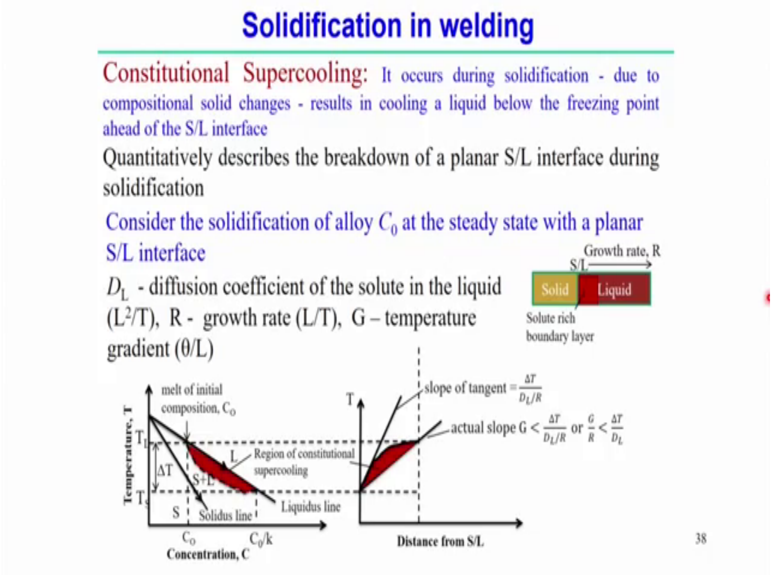

Solidification in welding

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, in much details a solidification in welding process and it is very much specific to that the alloy material specifically solidification of the not pure metal. So, maybe we can say that in case of alloy metal that constitutional supercooling is the one of the important phenomenon that is attached with solidification during the welding process.

So, supercooling we have some idea that from during the solidification that when the liquid molten metal comes around the phase transformation temperature that means, from solid to liquid phase transformation temperature. So, during the transformation and there is a amount of the supercooling observed in the liquid metal.

Of course, it patterns with some conditions that means that before starting of the phase change, the amount the nucleation mechanism involved in the welding process or may be solidification process that actually governed by the what is the amount of the supercooling temperature. (Refer Time: 03:43) the supercooling temperature below the solid to liquid transition temperature.

So, in case of pure metal, it is it can be well-defined from the time versus temperature diagram. And this amount of supercooling depends on the or may be values are the different for the different types of the material. So, normally the amount of the supercooling is mainly promote that the homogeneous nucleation or maybe in case of homo homogenous nucleation for in solidification process is mainly driven by the amount of the supercooling which is entirely different from the heterogeneous nucleation mechanism.

But constitutional supercooling can be defined in such a way that it actually occurs during solidification; and due to the a compositional solid changes which finally, result in the liquid metal below the freezing point temperature and that exist ahead of the solid liquid interface.

Actually, this constitutional supercooling mainly effects or better describe the what is the amount of the supercooling that depends on the whether compositional solid changes specifically for the alloy material. And that amount of the solidification constitutional supercooling during the solidification in case of graphical we can represent here that this region mark by red colour that actually represents the region of the constitutional supercooling or we can say the amount of the supercooling in case of a alloy.

But a this amount of the supercooling generally exist during the solidification process of specific is the alloy metal. But if the mathematical top of parameters that actually govern, or may be linked with the constitutional supercooling is that that is better described by the one is the diffusion coefficients of the solute in the liquid that means, D L that represents the diffusion coefficients. If you see the unit of the diffusion coefficient is the Lenskart part unit time. So, mainly it is a diffusibility represent the diffusibility of the solute in the liquid metal.

Another parameter that actually used to describe the solidification behaviour is specific for the alloy material that is the growth rate, so that is a unit is that length part time or length per unit time that is representation of the growth rate. And then temperature gradient to temperature gradient is the theta by L that means, it is the temperature per unit length.

So, these are the typical parameters that actually involve to represents the constitutional supercooling during the solidification process. Now, we try to explain this a phenomena a graphically that first if you look into this first figure that is a transition of the solid to liquid phase. So, here the growth rate is R; that means, growth rate more it is link the what is the what way that the solid liquid interface is basically moving so that zone between the solid and liquid there is a zone mainly that is called the mushy zone. So, in this zone the liquid and the solid phase coexist, but this depends on the or the in the amount of the supercooling exist within the during the solidification of a specific alloy.

Now, if you see the temperature versus concentration graph, here you can see the solidus line is there and then liquidus line and initial composition having the C 0. So, this material is subjected to some amount of the supercooling so that that constitutional supercooling simply marked by the red colour and that that means, the temperature difference in this case is delta T, so that delta T on the temperature axis it is represented that between the T L and T S that is the amount of the temperature prevent with respect to the initial composition.

And if you see even with respect to on the liquids line the composition a concentration of the alloy material here you can see that C 0 by K that is we represent the C that K equal to ratio of the C is and C 0. So, from here we can this there composition is represented by C 0 by K. Now, this amount of the constitution supercooling, if you project in the right hand side figure, if you see temperature versus distance from solid liquid interface. So, up to what extent from the interface can go that is represented simply just projecting this constitution supercooling on the time versus concentration graph to the time versus distance graph.

Here we can see that the this is the on the this first so lope slope is the actual slope. The actual slope is the temperature gradient represented by the re represent mathematically represented by term G temperature gradient.

And then if we look into the others slope the slope of the tangent at this point here we can see the slope of the tangent can be represented by what is the slope means that change of the temperature; that means, temperature difference with respect to some distance here, but here the distance can be counted maybe in terms of the boundary layer here that is the diffusability or D L diffusion coefficient divided by the growth rate. If you see the dimensionally also so this term delta T and D L by R that actual that also represents the tech slope of the tangent

So, in this case, it is very obvious that definitely the actual slope from the figure also it is very clear the actual slope G is less than equal to the slope of the tangent that point of view we have estimated that during the supercooling what is the temperature difference, and what is the amount of the distance travelled or by the solid liquid interface in terms of the diffusivity and growth rate. So, here if you geometrically or graphically we can see this slope is basically less than that of the estimated slope here.

So, to have the constitutional supercooling, so graphically you can say that this condition G by R less than delta T by D L this condition is satisfying, so that actually that is a mathematical conditions during the solidification so probably having in this case the constitutional supercooling. So, now, we will further look into other condition or maybe we try to explain or physically the what is a mathematical condition for the constitutional supercooling, and how it can be linked with the solidification behaviour during the welding process.

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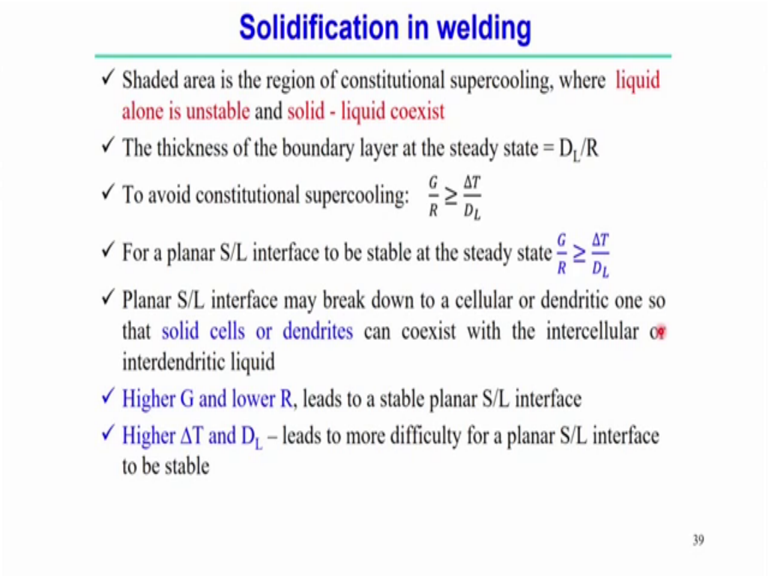

Solidification in welding

- ✓ 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

So, first comments is that that of course, the shaded area that represent the constitutional supercooling. Therefore, that reason is consist of actually a liquid alone is unstable. So, the in that zone basically solid and liquid coexist. Now, to estimate that slope also we assume that the thickness of the boundary layer during the movement of the solid liquid interface at the steady state condition is better described by the D L by R, D L is the diffusivity divided by the growth rate. And that dimensionally it represents the length dimension represent in terms of length D L by R.

Now, to avoid constitutional supercooling, we can put the condition just reverse having the constitutional supercooling. So, having the constitutional supercooling this was the condition G R G by R less than delta T by D L. What to avoid constitutional supercooling it is just G by R, so G greater than equal to delta t by d l this other to have got the constitutional supercooling.

So, this mathematical condition is sometimes help helpful to quantitatively explain the solidification behaviour that what are the driving mechanism whether super constitutional supercooling exist or not based on that type of nucleation whether it is homogenous and heterogeneous nucleation that is better explained by this mathematical conditions.

Now, the constitutional supercooling can also be explained in can also be used to explain whether there is a neat or break down of the solid liquid interface can be stable interface from the planar solid liquid interface that means, planar solid liquid interface is stable if not having the constitutional supercooling that means, just opposite to the condition of the avoiding the constitutional supercooling. So, in that sense G by R greater than equal to delta T by L that actually represents for the stability of the planar solid liquid interface.

Now, in planar solid liquid interface, it is may break also and due to the cellular or maybe in the dendritic, so that solid cell or dendritics actually can coexist with the intercellular spaces or inter dendritic liquid, so that break down of the planar solid liquid interface to other type other solidification mode cellular cellular type or dendritic type that dendritic time that can be explain mathematically here also in terms of this G R delta T and D L of this parameter.

So, higher G and lower R that actually leads to the planar solid liquid interface that mean if you looking to the condition also that G by R this is very high ; that means, there is a there is a existence of the solidification mode in terms of the planar solid liquid interface. Other side higher delta T that means, temperature difference is very high, so that means, degree of supercooling is very high and of course, more amount of the diffusivity D L that actually leads to the more difficulty for a planar solid liquid interface to this stable, so that actually breaks downs the stability of the solid liquid planar interface during the solidification process.

So, here so here you can say mathematically that two things if G by R less than delta T by D L that means, there is a existence of the constitutional supercooling that means, non existence of the planar a solid liquid interface in this case. Other way also if G by R constitution is greater than delta T by a D L that means, there is a existence of the or that is a favourable condition to put the solidification mode in terms of the planar solid liquid interface.

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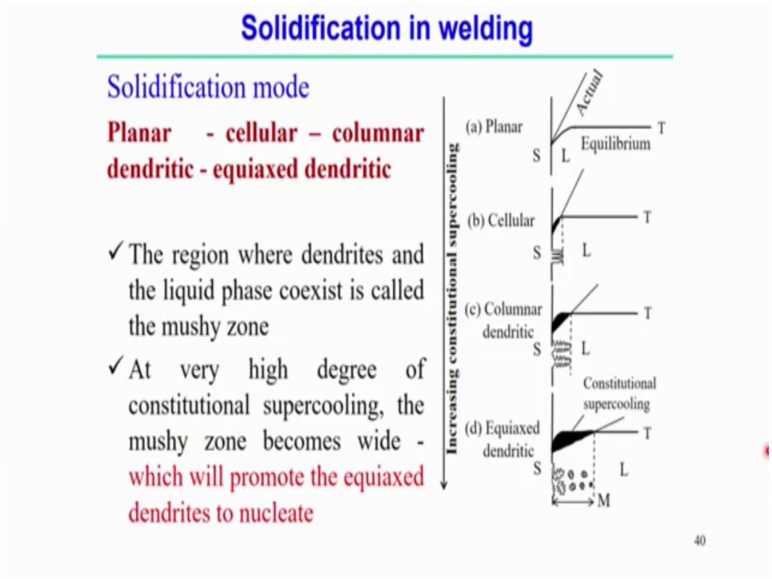

Solidification in welding

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

Now, here you can look into the different type of the solidification mode and structure. So, it is also necessary to mention that although these two parameters G and R. So, G and R these two parameters that means, temperature gradient and growth rate they actually mathematically define the mode of the solidification; at the same time and the also defined the rate of the cooling. That rate of the cooling is decides basically that whether it is fine structure or whether coarse structure exist during the solid produced during the solidification process.

And solidification mode decides what is the type of the whether it is planar or four types of the planar or cellular dendritic, columnar dendritic or equiaxed dendritic kind of structure know. Now, if you see that four different at this mode is better from this figure you can see that there is a four type of solidification mode planer mode cellular columnar dendrites, equiax equixed dendritic, structure.

Now, here you can see that increasing the consti[titional]-constitutional supercooling is transformed the structure from planar so that means, very low amount of the constitutional supercooling promote to the formation of the planar kind of the solid liquid interface. But if the constitutional supercooling is very high maximum in this case they actually promote the structure like equiaxed dendritic structure, it will try to produce.

Now, graphically also you can see that the here the vertical line the solid liquid interface and that is why the equilibrium temperature reach and this is the this represents the actual slope in that curve. So, in the that curve the time and the solid liquid inter the distance versus temperature in that case the actual slope.

So, here if you see that the temperature and actual slope they are not interfering with respect to each other that means, there is a minimum amount of the or we can say there is no super no constitutional supercooling exist, so that promote the planar kind of the solid liquid interface the mode of the solidification is basically planar.

Next, if the certain amount of the increment of the constitutional supercooling, then it cross the slope is less basically and then there is a shaded zone that is marked by the black the shaded zone and that actually produce the cellular kind of the solidification mode cellular cellular mode in this case; that means, there is a small amount of the constitutional supercooling exist if you look into the third that amount of the constitutional supercooling actually increasing and that try to produce the columnar dendritic structure.

And finally, the maximum amount of the supercooling that produce the equiaxed a dendritic a structure. So, depending upon the amount of the constitutional supercooling, the solidification mode basically changes or solidification mode can be decided.

Now, here also other comments that the dendrites and the liquid phase coexist is called physically the mushy zone. So, in that zone where the dendritic formation of the dendrite and the liquid they actually coexist that is the normally called the mushy zone. And that mushy mushy zone is basically in between the temperature between the solidus and liquidus temperature. So, at very high degree of constitutional supercooling, it is very obvious that the mushy zone becomes very wide, so that zone become very wide or at the other way if low degree of the constitution supercooling the there is almost no mushy zone or mushy zone not very wide small.

So, here from that with respect to the point of the few that with the degree of the constitutional supercooling, we can predict at least the what are the type of the solidification mode whether it is planar, cellular, columnar dendritic or equiaxed dendritic structure.

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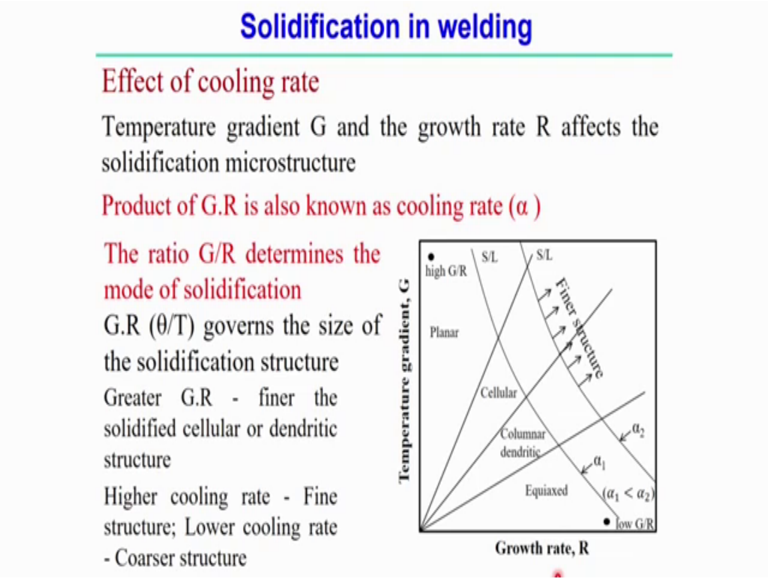

Solidification in welding

Effect of cooling rate

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

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

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

Now, here we can like to mention that the two parameters the temperature gradient G and the growth rate R affects the solidified microstructure, so two different way. So, by combining these two parameters the temperature gradient and growth rate here you can see the product of G into R, this actually known as the cooling rate.

If you eventually check it then that a G is the temperature gradient temperature by length and R is the growth rate, so length by time. So, in that respect the length by time is basically a sorry temperature by time that actually represents the cooling rate. At the same time the ratio G by R actually determines solidification mode that only do you have discussed that depending upon the G by R ratio, we can define the mode of the solidification.

So, this combining this two G R and G by R, if you try to to represent the one axis the x-axis the growth rate R, and temperature gradient is the y-axis it is the G. So, this combining this to you can find out that deferent solidification mode this way that planar, cellular, columnar, dendritic and equiaxed structure.

So, high G by R value that actually promote the kind of the planar structure, but at the same time low G by R they so that actually promote equiaxed structure dendritic solidification mode. But if you see that from the graph also if now we try to incorporate the effect of the cooling rate also, so here this line that represents the rate of the cooling. So, G R and so first line alpha 1 that represents the low cooling rate. And if you see the alpha 2, the second line this is represent of cooling rate on this graph that represents the high cooling rate.

So, if cooling rate is very high, overall microstructure is very fine; if cooling rate is low, the overall microstructure is not the course structure. So, basically higher cooling rate we can expect the fine structure and lower cooling rate we can expect the coarse structure. So, greater G R G into R; that means, get G into R; that means, greater cooling rate that we can find out the very fine solidified cellular kind of dendritic structure.

If you see from this figure also that most of the structure exist discuss that either cellular columnar dendritic, and planar and equiaxed is the more two extreme cases here, but general cellular and columnar dendritic structure exist and it becomes more finer structure if cooling rate is very high; that means, it is beyond that zone the second line corresponds to alpha 2. So, basically alpha 1 equal to one G 1 R 1 or alpha 2 is basically another another value of G into R.

So, from this figure, we can explain also quantitatively that the whether it is fine structure course structure at the same time what is the solidification mode or the what is the solidified structure whether it is very planar, columnar kind of structure, dendritic equiaxed and all these kind of information we can get by analysis of this kind of figure.

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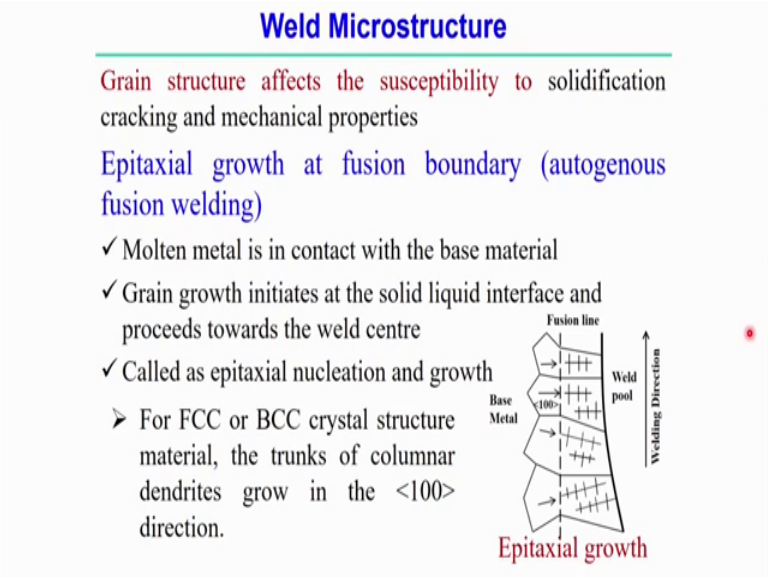

Weld Microstructure

Grain structure affects the susceptibility to solidification cracking and mechanical properties

Epitaxial growth at fusion boundary (autogenous fusion welding)

- ✓ 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.

Now, come after solidification mode, we will try to look into the discussion on the weld microstructure. So, grain structure actually affect the susceptibility of the solidification cracking. So, it is very much linked with the and finally, grain structure also define the mechanical property.

So, it is no it is necessary to link that what is the final microstructure and probably what is the expected mechanical properties or whether there is any solidification cracking may occurs or not that kind of information can be get if we analyse the mechanism of the grain structure or may be weld microstructure formation during the solidification process.

So, one important aspect of the growth in the fusion zone of the welded structure that is called epi epitaxial growth at the fusion boundary; and this actually this epitaxial growth basically happens in case of the autogenous fusion welding process. So, if we use some a filler material that actually destroy the epitaxial growth mechanism may be in that case arm other mechanism can be better to explain the phenomenon of the grain growth.

So, epitaxial growth we can see that molten metal first is in contact with the solid with the base metal then grain growth initiate on that boundary or at the solid liquid interface and it process towards the weld central line. From the figure also it is very saying that very obvious that welding direction is there, and the weld pool from the weld pool the weld pooled, so liquid weld pooled and that interact with the base metal.

So, from that interface the it go happens once particular direction. So, that this type of growth is basically called epitaxial first nucleation and then growth. So, if we see that FCC, BCC crystal structure they have the kind of columnar dendritic structure actually grow in the 1 0 0 direction; So, miller index of this 1 0 0 a direction so that actually observe in case of FCC and BCC material.

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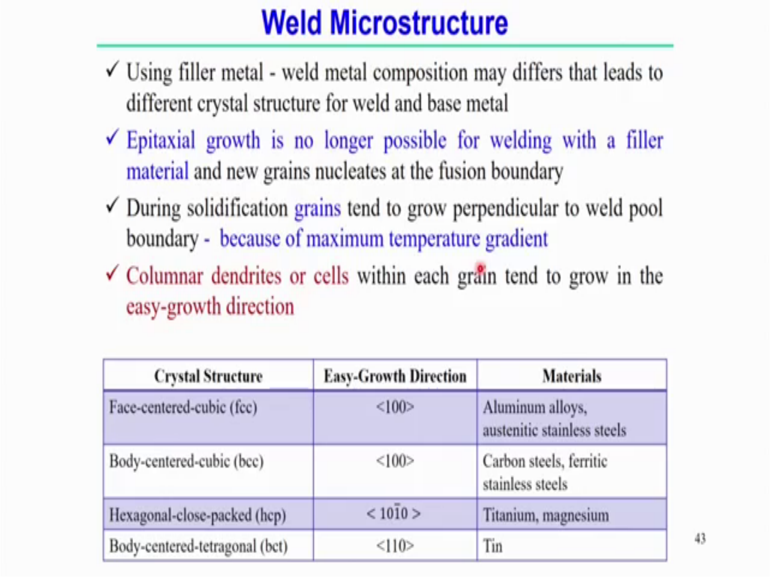

Weld Microstructure

- ✓ 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

Now, to see here that if use the filler material then weld metal composition changes and that actually leads to the different type of the crystal structure for the weld and the base metal. So, that adding the filler material does not does not promote the epitaxial growth. And then a new grains are nucleates basically forms at the fusion boundary when there is a addition of the other alloying elements or maybe can say that with the addition of the filler martial during the welding process.

So, during solidification, the grains tends to grow perpendicular to the weld pooled boundary, but the reason for that there is maximum temperature gradient actually exist along this direction. And then sometimes the columnar dendrites or cellular cells or cellular structure within each grain also grow in the or within grain that try to grow in the easy growth direction so that means, that different type of crystal structure material having the easy growth direction.

For example, the FCC structure the 1 0 0 is the easy growth direction and we can observe specifically for the aluminium alloy and austenitic stainless steel they are having this direction. BCC material also having the easy growth direction is 1 0 0 that is if you look into the one unit cell, the 1 0 0 basically along the one of the edge along the edges

So, the carbon steel ferrite stainless steel this type of materials also having the easy growth direction a for the BCC metal as the along the edge of the unit cell; that means, 1 1 1 0 0 direction than in case of hexagonal close pack also having the easy growth direction and the hexagonal prospect structure titanium and I think magnesium. And body centred tetragonal structure tin also having the easy growth direction is 1 1 0 that means, along the face diagonal of an unit cell.

So, different type of materials may have the easy growth direction. And typically the epitaxial growth nucleation not only growth maybe first nucleation starts and then a growths growth process starts so that epitaxial growth mainly happens probably the pure metal and during the welding process. And that along the normal to the this boundary, because the driving force epitaxial growth specific direction probably the maximum temperature gradient along that direction. But the conclusion from here is that if we add the filler material then the with the epitaxial growth may not be possible in that case.

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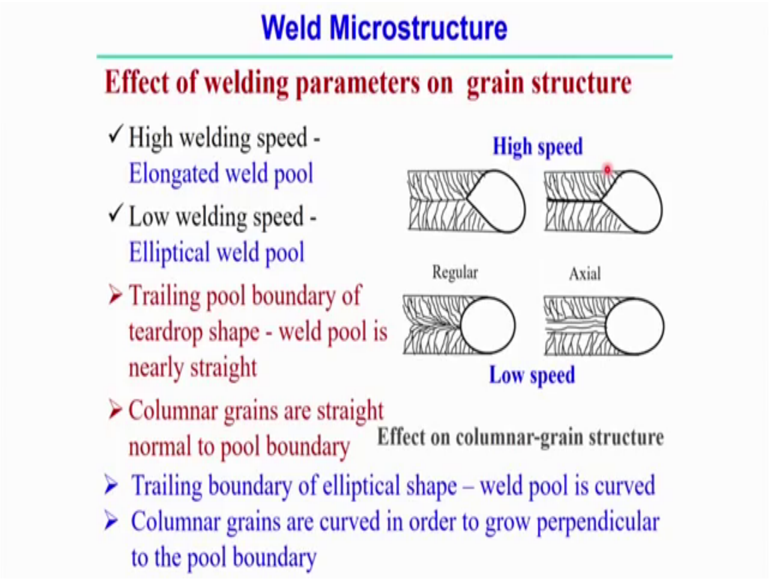

Weld Microstructure

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

Effect on columnar-grain structure

➢ Trailing boundary of elliptical shape – weld pool is curved

➢ Columnar grains are curved in order to grow perpendicular to the pool boundary

Now, what are the effects of the welding parameters on the grain structure just if we try to look into that is the that if you look into the actual weld structure, what type of microstructure we can expect during the welding process at very high speed probably and at very low speed. So, if you see that high welding speed, the typical nature of the weld pooled forms that is elongated weld pooled sometimes teardrops can also form.

So, if you look into the first figure that is a high speed that if it is a elongated weld pool looks like and when the heat sources mop on specific direction during the welding process. So, here the growth of grain actually grow with respect to that weld central line and almost perpendicular to the weld central line. But if it is very high speed that it becomes axial exactly perpendicular to the weld central line and if we gradually reduce the welding speed; that means, very low speed it takes the curvature and with respect to the weld central line. So, and from that weld central lines make a curvature and goes towards the towards the outer periphery of the weld pool.

So, these are the typical grain structure generally observed during the welding process. Now, if in case of low welding speed the welding pool looks like the elliptical form. And trailing pool of the boundary of the teardrop say; that means, it is a very high welding spate the weld pool is nearly weld pool is almost is very nearly straight and the growth also happens perpendicular to that, but columnar grains forms during this things almost the straight normal to the pool boundary.

But in case of low speed, the since the trailing boundary is of elliptical shape, then weld pool is basically make a curvature on make a curved and the columnar grains are also called in order to grow perpendicular to the weld pool boundaries. So, making the initial curved, so that and finally, it makes the final curvature it is still like that almost perpendicular to the weld life. So, these are the typical weld grain structure that actually observed during the welding process.

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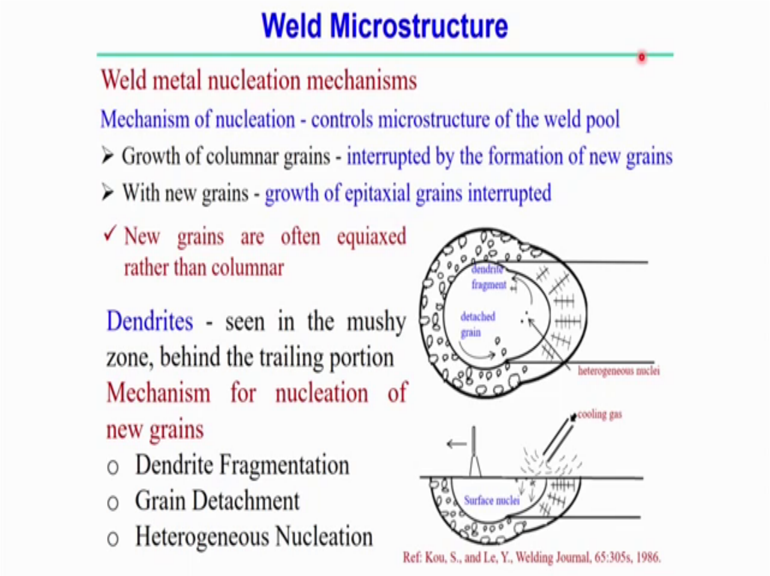

Weld Microstructure

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, we look into that weld metal nucleation mechanism. So, the there is nucleation mechanisms basically the mechanism of nucleation actually controls the microstructure of the weld pool. So, we did some understanding on the nucleation mechanism actually prevents during the welding process. So, two things are there if you see actual welding process that first is the growth of the columnar grains is basically interrupted by the formation of the new grains.

So, new grains foundation of the new grains, they interact the growth of the columnar grain, and we see the growth of the columnar grain is actually the react observe normal in the react side of the weld pool. In the other way, when the new grains form and that actually disturbs the growth of the epitaxial of grains is interrupted, so that disturb the growth of the epitaxial growth of the grains also with the formation of the new grain.

So, these two phenomena counteracting with respect to each other. Then new grains normally are often equiaxed rather than the columnar or kind of the a structure. So, new grains forms here during the welding process most of the time we can find out it is almost the equiaxed structure rather than the columnar kind of the structure. Now, if you see the dendrite in the if you see the dendrite, the mushy zone behind the trailing portion that means, react part of the weld pool and in this case the mechanism of nucleation is basically depends on the several phenomena one thing is the dendritic fragmentation.

So, here if you say that dendritic fragmentation is happens the because on the trailing side on the react side of the weld pool, there is a formation of the dendrites. And the due to the conductive flow of the liquid metal within the weld pool that actually brings the two mechanism that means fragmentation of the dendrite at the same times the partially metals can be detached from the grains. So, these two promotes the formation of the heterogeneous nucleation most of the cases at the trailing side of the weld pool.

So, the mechanism of nucleation during the welding process is better explain one point is that dendritic fragmentation then grain detachment and that actually mainly promote the heterogeneous nucleation process. So, this figure also if you see that dendritic fragmentation grain detachment is very obvious.

So, and that is that travel from one point to another point is due to the only the convection of the molten metal. And here also other way that sometimes the nucleation mechanisms is basically driven by the external gas that on the surface nucleation is mainly promoted using some kind of the cooling gas; So, cooling gas also having effect on the nucleation formation during the welding process.

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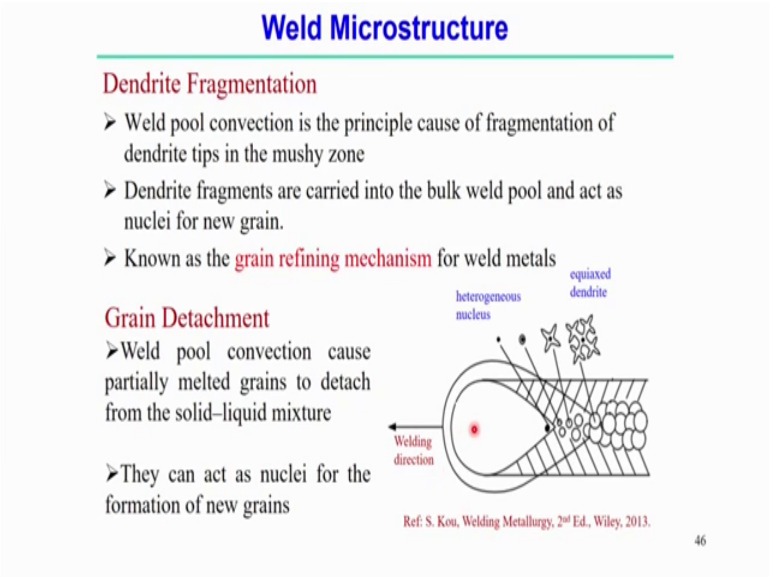

Weld Microstructure

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, if you look into details that dendritic fragmentation in the welding process that weld pool and if it is obvious that weld pool convection is the main reason principle reason to cause the fragmentation of the dendritic tips in the specifically in the mushy zone. And then dendritic fragments are carried out by the bulk weld pool and act as a nuclear for the new grain, so that dendritic fragment dendritic fragments is basically act as a site for the nucleation and then since it act as a site for the nucleation.

So, basically in this case we can expect the heterogeneous nucleation and hetero due to this continuously convective flow the material that always try to promote the heterogeneous nucleation, and the finally, it is a kind of equiaxed structure. So, that is why this dendritic fragmentation mechanism is also known as the grain refining mechanism of the weld metals.

So, another mechanism is that and weld microstructure we can observe that is a grain detachment. Here you can see that again the weld pool convection cause the partially melted grains to detach from the solid liquid interface, and again they can be they can act as a nuclei for the formation of the new grain. So, if you look into the figure that heterogeneous nucleation here starts and the one mechanism for the equiaxed dendritic structure the mushy zone and the from there that promote the heterogeneous nucleation process and with respect to the welding direction.

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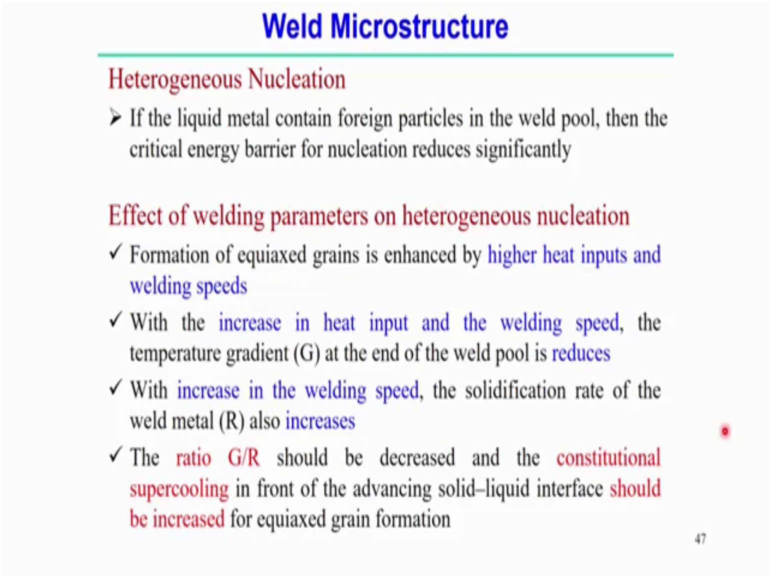

Weld Microstructure

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

So, finally, the heterogeneous nucleation process if the liquid metal content the mainly the heterogenic nucleation process can be explained in that way that if the liquid metal contains from some important particles in the weld pool, then that actually acts as a site for the nucleation. So, in this case, the vary energy barrier the critic or critical energy barrier for the nucleus for the nucleation process is basically less, because some external particles actually start the initial initiates the nucleation process, so that is why we also observed from the solidification theory also that inhomogeneous nucleus and heterogeneous nucleation theoretically almost the size of the critical radius of the nucleus are the same.

But the energy barriers for amount of energy required to form the homogeneous nucleation is more as compared to the heterogeneous nucleation, because heterogeneous nucleation the external particles actually promotes the site of the nucleation. So, barrier requirement is less in this case energy barrier requirement is less.

Now, if you look into that what are the welding parameters that actually affect on the heterogeneous nucleation process. So, first thing is the formation of the equiaxed grains is enhanced by the higher heat input and the welding pool. So, it is observed from the directly the equiaxed grains from the microstructure observe that higher heat input and very high welding speed that actually promotes the equiaxed structure, but with the increase in heat input as well as when increase in the welding speed, the temperature gradient at the end of the weld pool is actually reduces.

So, although there is a heat input is very high, but at the same time the welding speed is also have that promotes or that actually reduces the temperature gradient in the weld pool. Other way with increasing very high welding speed and at the same time the increasing the welding speed also the increases the soli rate of the solidification. So, increment of this one is the by decrement of the G value that means, by decrement by decrement of the temperature gradient and at the same time increment of the solidification rate actually that actually promote lower down of the G by R ratio.

So, G by R ratio should be decrease, so in that sense that G by that actually effect of the G by R ratio. So, we can link with type of the nucleation mechanism with respect to the welding parameters. Welding parameters means here the heat input and welding speed. These are the two parameters.

So, ratio of the G R again can be linked with that constitutional supercooling that means, if ratio of G by R should be decreased that means G by R ratio decrease and that actually and promote the constitutional supercooling in front of the solid liquid interface. So, therefore, should be increased G by R ratio should be increased for the equiaxed grain formation; that means, G by R should if we high value of the G by R ratio that actually promotes the equiaxed and grain formation.

Here you can see the so G by R ratio from here we can see the G by R ratio is very high then it is actually promotes the planar kind of the solid interface or if G by R ratio is low; that means, low value of G by R ratio actually promotes the equiaxed structure. So, in this case, the if you want to find out the low value of the G by R ratio that means, in that case the it promotes the equiaxed grain structure.

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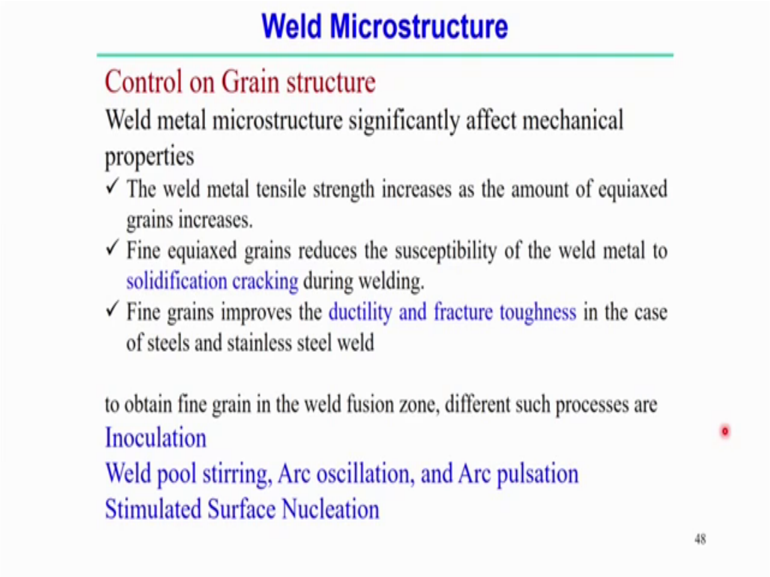

Weld Microstructure

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

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

Now, how to control on the grain structure, so is some over all knowledge about the weld microstructure that actually significantly affect the mechanical properties. So, what may it affect the mechanical properties is that that normally the weld metal tensile strength increases if the amount of the equaxied grain more; that means, within the solidified zone if the amount of the equiaxed grain is more that actually that finally, affect the increment of the weld joint strength.

If equiaxed grains also that means presence of the equiaxed grains and too much in the welded structure that actually reduces the susceptibility of the weld metal for the solidification cracking during the welding process. Also there is another advantage that if fine grains that means, overall grain size is very fine that actually improves the ductility and toughness properties of the weld joint, specifically the steels and specifically the in case of the steels and stainless steels welded process. So, it is always advantageous to produce the equiaxed kind of or fine microstructure in the welded joint that always try to improve the mechanical properties of the weld joint.

But therefore, to find out the very fine weld microstructure then what may be the factors or what way that actually impact of the microstructure during the welding process. So, first thing is the inoculation. Inoculation is that is the inoculating if we add the inoculating agent that promote the kind of heterogeneous nucleation process.

So, if there is a promotion of the heterogeneous nucleation then it is type two from the almost kind equiaxed kind of structure. So, this is one way to promote the equiaxed structure in the weld joint. Next is the weld pool steering action and that means, if it is possible to mechanically staying the steering the weld pool then it is possible to more or less kind of equiaxed kind of structure is possible to produce then arc oscillation so not keeping the arc as a fixed position rather if you try to oxalate the arc that also try to promote the formation of the equiaxed kind of structure.

Arc pulsation instead of using the continuous arc if we use of pulse arc then it also promotes the equiaxed kind of structure. Of course, sometimes the simulated surface nucleation if we some extra heating or extra cooling system using the shielding gas on the surface of the liquid molten pool that also try to promote the formation of the equiaxed structures.

So, these are the different methodologies or techniques that way we can we can produce the equiaxed structure in a solidified weld joint and that is advantageous in terms of the we can expect the very good weld joint properties.

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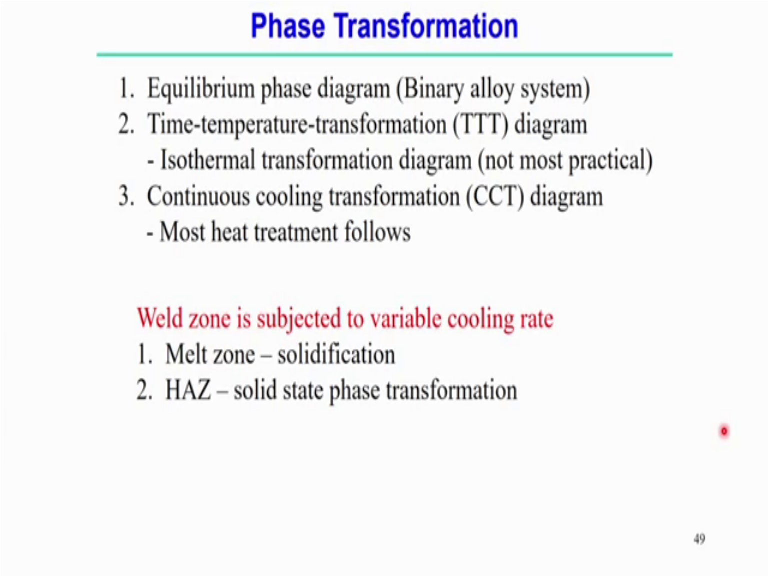

Phase Transformation

1. Equilibrium phase diagram (Binary alloy system)
2. Time-temperature-transformation (TTT) diagram
   - Isothermal transformation diagram (not most practical)
3. Continuous cooling transformation (CCT) diagram
   - Most heat treatment follows

Weld zone is subjected to variable cooling rate

1. Melt zone – solidification
2. HAZ – solid state phase transformation

Now, come to that next other topic that is the phase transformation. So, we will try to look into some overall idea of the phase transformation and it is very specific to the welding process, and very specific to few materials. So, we have some idea about the phase transformation that means, there are three different way we represents the different diagram the phase transformation in case metallic materials. So, first is the equilibrium phase diagram normally we try to represent a binary alloy system. So, two alloy assume that the material is a consists of the two alloy and we can draw the equilibrium phase diagram for this alloys.

So, equilibrium phase diagram is basically drawn as most theoretically the rate of the cooling is almost 0 that means, we try to follow the equilibrium condition of the phase transformation so that means, if that means, there is almost no effect of the time here that that means, we can neglect the effect of the time in this case. But if you look into the other diagram that time temperature transformation diagram, we represents the different phase transformation that phase transformation line with respect to the axis as a one is a temperature axis, another is the time axis.

Similarly, in case of the continuous cooling transformation; that means, that is called the CCT diagram, here also we can plot that the transformation diagram following the constant cooling rate of the constant cooling rate, and here one axis represent the y-axis normally represents the temperature and x-axis represent the time here. So, these are the three different diagram we normally use explain the phase transformation in case of the most a alloy element and we are assuming all these cases we are assuming the it is a binary alloy system.

But the equilibrium phase diagram is mainly to know the what is the phase presents there, but time temperature diagram is the transformation of the phase at constant temperature which is most of the cases not practical because and practically the transformation happens has not have as a constant temperature rather there is a variable temperature that means, the variable temperature can be better represented as a in terms of the cooling rate constant cooling rate so that two represents the transformation using the constant cooling rate that is better represented in the diagram of the CCT diagram.

So, most of the heat treatments actually follows the CCT diagram to find out what is the final microstructure depending up on the what is the cooling rate is followed during the during the process it may be solidification process or it may be welding process.

So, now if you look into the welding process, the it is actually subjected to the any like other practical process subject to the variable cooling rate also variable temperature so, but till you can use the phase transformation diagram CCT diagram or TTT diagram to explain the transformation of the different one phase to another phase with respect to time with respect to temperature with respect to the different fixed cooling rate.

Now, melt zone that means, weld pool molten zone is basically subjected to the solidification, but heat affected zone solidification means here the transports from the solid liquid phase to solid phase, but heat affected zone it is in solid state, but may be solid state, but one phase to another phase transformation may happen that means, it is a solid state phase transformation happens in the heat affected zone.

So, this the typical overlook of the phase transformation we observe in case of the welding process. Now, we have tried to represent the phase diagram because this phase diagram is helpful the composition of the different phases exist within the microstructure.

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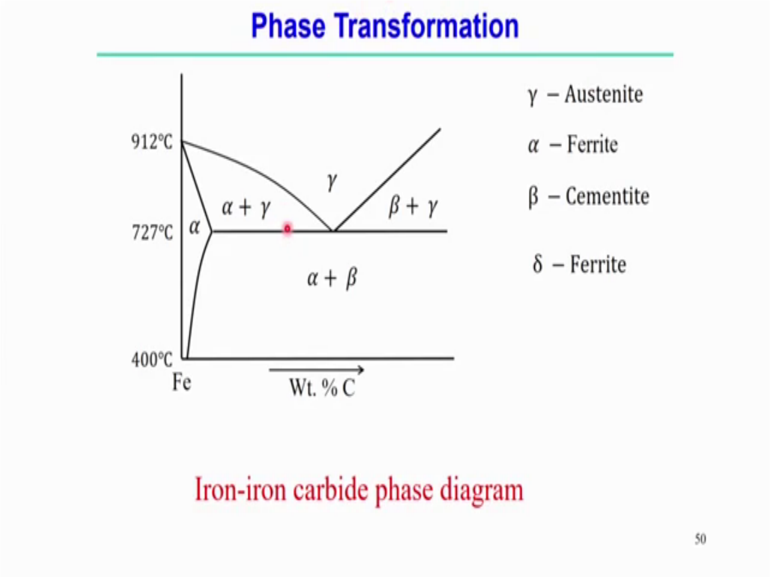

Phase Transformation

γ – Austenite

α – Ferrite

β – Cementite

δ – Ferrite

Iron-iron carbide phase diagram

So, here I just try to represent the iron carbon equilibrium phase diagram here you can see that y-axis represent the temperature the winds are different temperature what is the different phase presents and the y-axis x-axis represent weight percentage of the carbon; that means, it is a binary alloys system here the one component is the iron Fe and another component is the carbon.

So, when Fe and carbon are mixed up to certain comp position and depending upon the temperature different phase presents. For example, there is a phase boundary is represented here also. So, that gamma it is present, but the austenite this is the austenitic phase so that means, who is this iron along with the different percentage of the carbon the constitution austenitic phase at the different range of the temperature.

So, then another phase is the alpha ferrite, so only ferrite or sometimes it is called the alpha ferrite. So, alpha ferrite here you can see the alpha ferrite phase exist it is a very low the percentage of the carbon; basically that carbon is the here the maximum solubility limit of the carbon within this phase produces is I think around point 0.02 percentage of the carbon so that constitutes the one phase depending upon the that phase having the secondary second alloy that means, here is the carbon up to certain percentage and their constitution want single phase alpha phase so that is the alpha phase and this alpha phase is having the some maximum amount of the solubility of the second phase; that means, carbon here.

Next, the other phase the similarly austenite is a single phase structure that means, single phase structure what is it is having the maximum solubility of the certain carbon percentage exist in austenitic structure also. Now, if you look into the other within this phase boundary and this phase mix are exist alpha plus gamma; that means, ferrite it say this zone represent the mixture of the ferrite and austenite.

And here is the beta phase is basically cementite. So, this is the one phase the maximum solubility of the carbon in the cementite phase is the 6.67 percentage of the carbon and their constituency one single phase that is called the cementite.

So, this phase here at this position the here the mix mixture of the two phase exist the beta phase and the gamma phase that means, austenitic plus cementite phase mixer. And here you can say this joint two different phase the ferrite and cementite mixture, but there is no existence of the austenitic phase this at this zone that means, that zone means it is a defined over the certain temperature range.

So, if you know what is specific binary alloy system, this phase diagram will be able to find out from this phase diagram that coexistent of the single phase or mixture of the two different phases over the temperature range, we will get all kind of information from this phase diagram.

But here this phase diagram is can be utilised if you see that with this phase diagram is no longer its equilibrium phase diagram it is no longer related to the time component. So, therefore, rate of the cooling all this things is having no importance here. Here we can constitute the it one phase mixture if you know that one phase mixture, we can using the liberal, we can find out what is the proportionate way the different phases exist within the mixture of the phases, so that kind of information can be where extracted from the phase diagram.

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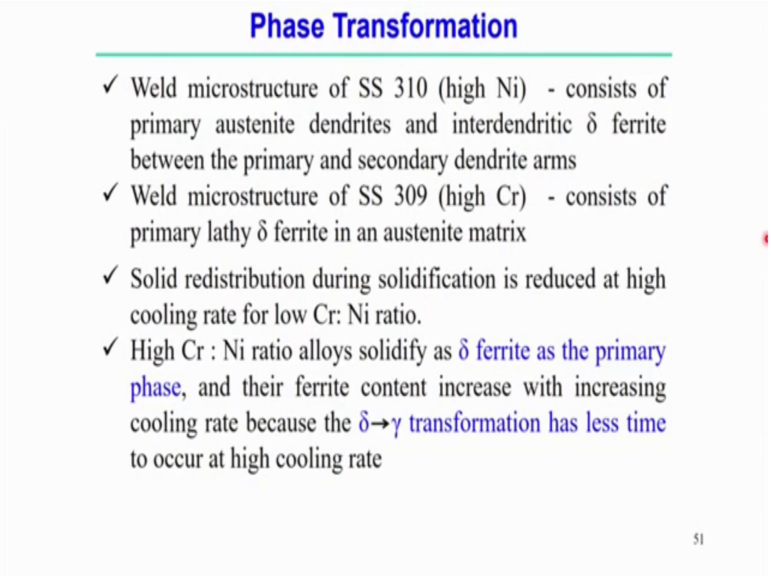

Phase Transformation

- ✓ Weld microstructure of SS 310 (high Ni) - consists of primary austenite dendrites and interdendritic δ ferrite between the primary and secondary dendrite arms
- ✓ Weld microstructure of SS 309 (high Cr) - consists of primary lathy δ ferrite in an austenite matrix
- ✓ Solid redistribution during solidification is reduced at high cooling rate for low Cr: Ni ratio.
- ✓ High Cr : Ni ratio alloys solidify as δ ferrite as the primary phase, and their ferrite content increase with increasing cooling rate because the $\delta \rightarrow \gamma$ transformation has less time to occur at high cooling rate

Anyway if you look into that in the weld structure information of the weld and structure what are the different phase transformation may happen or how it can be predicted in the final structure with respect to the type of the material or composition of the material. For example, first if we look into that stainless steel SS 310 normally the nickel content is high in this type of the stainless steel.

So, this final microstructure consists of the different phases like that primary austenite, dendrites, and intraderi interdendritic delta ferrite between the primary and secondary dendritic arms. So delta ferrite, ferrite structure is also there on the austenite structure austenitic phase and ferrite phase also there, but the delta ferrite mainly exist the in the primary and secondary dendritic arms in that specific and find out the delta ferrite.

So, so this constitute of the two different phases the delta ferrite and austentite phases for their coexistence and making a homogeneous structure. Next, if we look into that the material stainless steel that high chromium SS 309 nine that is chromium quantity is very high in this case as compared to the nickel content.

So, these microstructures consists of the primary function of the primary lathe type delta ferrite in an austenitic matrix, so that means, overall structures the austenitic matrix, so within the austenitic matrix the delta ferrite exist in say type of led, lad type delta ferrite exist within the structure. So, there their microstructure is may be different from the SS 310 although both the cases the phases austenitic phases as well as delta ferrite phases exist, but the distribution of the delta ferrite in the shape and size may be different in this two cases.

So, normally the solid redistribution in during the solidification is basically is reduced; and in presence of the high cooling rate because in the at very high cooling rate probably the transformation of the one phase to another phase chances are or transformation time is very less probably that may be the reason for that redistribution during the redistribution of the different solid constitute or solid phases within the structure is basically reduced at very high cooling rate.

And for this type of material basically high cooling rate at the same time for the low chromium and nickel ratio; when the chromium and nickel ratio is very low in this case the redistribution of the solid phases and be reduced at high cooling rate. But if the chromium and the nickel ratio is very high, so in this case the delta ferri delta ferrite is as the primary phase and the secondary and they are ferrite content actually increases with increasing the cooling rate.

So, delta ferrite if the chromium and nickel ratio is very high, in this case the delta ferri is a primary phases is the delta ferrite and the ferrite content is basically increases with increasing the cooling rate because the transformation from delta ferrite to the austenitic transformation has having the less time to how far is basically high cooling rate.

So, if we say that normal if you look into the like this type different type of the material they are different phase exist within the microstructure, but the phase that formation of the primary phase, secondary phase, it depends on the ratio of the other alloying elements.

So, just this is one example that if nickel and chromium is the main constituent for the stainless steel if the ratio are different in this two cases we can expect the different kind of the microstructure. So, of course, in this case we need to the in depth study different type of the microstructure for other material.

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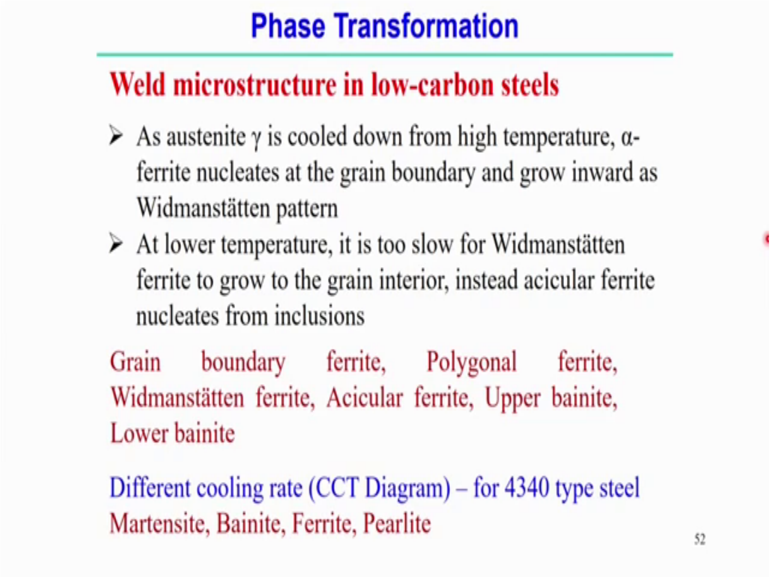

Phase Transformation

Weld microstructure in low-carbon steels

- As austenite γ is cooled down from high temperature, α-ferrite nucleates at the grain boundary and grow inward as Widmanstätten pattern
- At lower temperature, it is too slow for Widmanstätten ferrite to grow to the grain interior, instead acicular ferrite nucleates from inclusions

Grain boundary ferrite, Polygonal ferrite, Widmanstätten ferrite, Acicular ferrite, Upper bainite, Lower bainite

Different cooling rate (CCT Diagram) – for 4340 type steel
Martensite, Bainite, Ferrite, Pearlite

Here, we try to like another example for the weld microstructure in case of the low carbon steel. If we say that in low carbon steel that austenitic phase is cool down from the high temperature and high temperature and it call the alpha ferrite basically nucleus specifically at the grain boundary and basically from the Widmanstatten pattern. So, specific pattern actually it forms when delta when austenitic cool down to the from the high temperature to the low phase all ferrite phase.

So, at low temperature, it is too slow for the Widmanstatten pattern and ferrite structure to grow to the grain interior; So, in that case acicular ferrite nucleus from the inclusions. So, this low carbon steel is basically forms the different type of the structure that that actually that is called the grain boundary ferrite structure, polygonal ferrite structure, Widmanstatten pattern, ferrite structure a acicular of a right upper bainite, lower bainite. So, this type of the different kind of the structure can produced by the weld microstructure or we observed in the weld microstructure of the low carbon steel.

Similarly, if you look into the CCT diagram continues cooling diagram for the four three four type of steel we can find out that at the different range of the cooling rate is if you follow you can find out the different structure. So, it is a high cooling rate probably you can get the martensitic structure for the less of the cooling rate, that bainite structures very low cooling rate they actually we can ferrite and pearlite was some mixture of the ferrite and pearlite. So, all this kind of structure we can expect in low carbon steel.

But this in the CCT diagram in this case is used to define that if you follow the different cooling rate then we can expect the different kind of the structure. Of course, this structure maybe changes the if the composition changes in even in case of the low carbon steel or maybe alloying elements change low carbon steel then probably we can get the other kind of the structure or that the one phase is distributed in different shapes within the other phase that can or that or can produce the different type of the microstructure.

So, all can be depend or explain in terms of the rate of the different cooling different cooling rate so that is why it is very important to estimate during the welding process or it is most of the cases we can find out the rate the link between the rate of the cooling and the typical microstructure. And finally, that microstructure can decides the what is the mechanical properties of the weld joint, but the link between all these three component is not very straightforward or may not be linear always. So, it is a always exist in a non-linear relationship so that relationship is varies depending if there is a change of the alloying elements.

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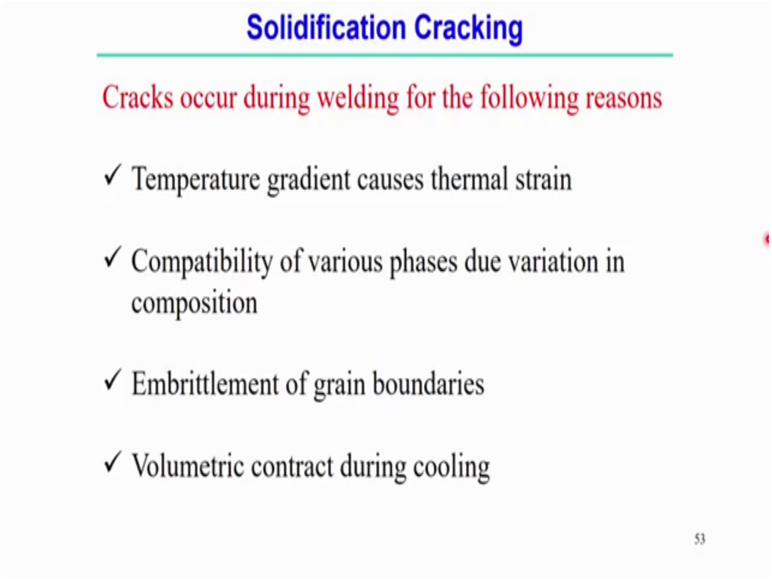

Solidification Cracking

Cracks occur during welding for the following reasons

- ✓ Temperature gradient causes thermal strain
- ✓ Compatibility of various phases due variation in composition
- ✓ Embrittlement of grain boundaries
- ✓ Volumetric contract during cooling

Now, next topic we will try to look into that solidification cracking that is more related to the in the welding process. We see that cracks normally occurs during the welding of the reasons that first is that solid during the solidification process that crack occurs may be due to the temperature gradient. So, if there is existence of the temperature gradient that also brings the thermal strain. And next possible reason for that is the compatibility of the different phases due to variation their compositions.

And third embrittlement of the grain boundary; So, sometimes the grain boundary becomes embrittle that actually induce the kind of the solidification thing and another reason for the volumetric contract during the cooling process. So, different phase having different constitutes.

So, it is not necessary that during the cooling process the there maybe the contraction of the within the there is a change microstructure reduces the changes in the microstructure there may be the contraction in the volume that actually induce may induce some of the cracking phenomenon during solidification process.