Advances in Welding and Joining Technologies
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Lecture – 18
Welding Metallurgy Part II

A distortion involvement also a consequence of the residual stresses developed during the welding process. But the main reason for the distortion in the weldment structure is mainly the solidification shrinkage, any thermal contraction and of course, metallurgical changes also happens during the welding process.

And if there is any boundary constants all this actually influence the distortion in the final weld joint structure. So, the reasons for the distortion involvement is very similar to the reasons for the generation of the residual stress in welding, so that is why always we usually used to say the distortion residual stress in weld your structure they are linked with respect to each other.

Now, how we can measure or how we can quantify the distortion in a weld joint. So, if you looking to try to do some butt join configuration, then main straightforward way to measure the specifically the angular distortion during the welding, so angular distortion can be measure even for the welding of the very thick plate or maybe welding of the very thin plate.

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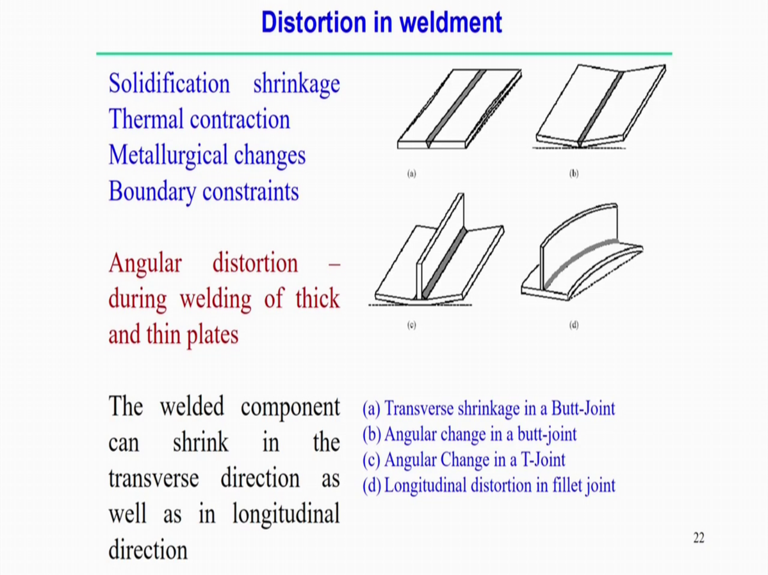

Distortion in weldment

Solidification shrinkage
Thermal contraction
Metallurgical changes
Boundary constraints

Angular distortion – during welding of thick and thin plates

The welded component can shrink in the transverse direction as well as in longitudinal direction

(a) Transverse shrinkage in a Butt-Joint
(b) Angular change in a butt-joint
(c) Angular Change in a T-Joint
(d) Longitudinal distortion in fillet joint

So, figure shows that first figure the transverse shrinkage in a butt joint configuration that transverse shrinkage if we it can be a concave or convex type of buckling also occur within the welded structure depending upon the types of materials. And if you look into that because the angular change in a butt joint, so simply assuming the along the longitudinal direction the plate is very straight and there is only the angular distortion and that we can measure it.

Or angular change in the T-joint may also happens during the in valid structure and longitudinal direction in a fillet joint also, it bends or buckling may happens corresponds to the kind of convex kind of structure.

So, depending upon the whether the distortion is with can happen in a concave type of convex type or maybe step forward simply angular distortion or all can be measured instead for using problem we can use it simple quadrant measuring machine or some laser scanning system with respect to some reference point, we can measure the distortion.

But what is the reason for this generation of the distortion the welded component basically can shrink in the different direction depending upon the weld nature of the type of the weld joint. And that means both transverse as well as longitudinal direction the deformation may also happens or buckling may also happens and accordingly we can classify the different types of the distortion in a welded structure.

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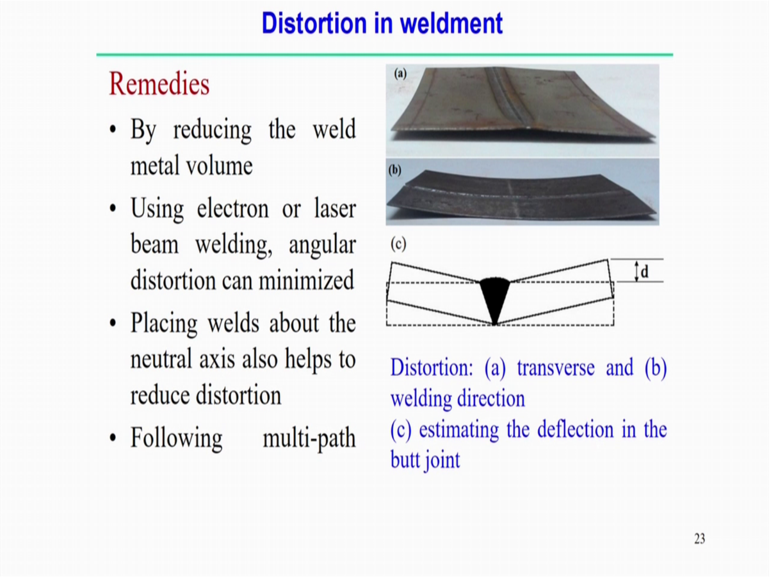

Distortion in weldment

Remedies

- By reducing the weld metal volume
- Using electron or laser beam welding, angular distortion can minimized
- Placing welds about the neutral axis also helps to reduce distortion
- Following multi-path

Distortion: (a) transverse and (b) welding direction
(c) estimating the deflection in the butt joint

23

Here if you see that right hand side the figure indicates the actual the joining of the titanium alloy using the plasma micro welding process. And here only the thickness of the plate is 0.5 milli (Refer Time: 03:40) that that means, it can be considered as a joining of very thin sheet. So, in this case, we can see that the deformation is a concave convex type depending upon which on the whether we are looking in the along the transverse direction or whether we will look into the in the longitudinal or welding direction.

So, in this case, it is wise to measure the distortion not in terms of the angular distortion, but more accurate measurement of the distortion can be done if we look at the several points on this weld. And then if we try to measure the different point probably we can we can measure the distribution of the distortion at the stood out the whole structure. What is a simplified way we can measure only on the angular distortion, so with respect to the initial position and after the butt welding what is the what is the distortion of the plate happens and that can be measured in terms of the d as shown in the figure.

So, this is the way to measure the distortion, but what way we can reduce the distortion because this amount of the distortion is a very serious problem in the welding process, and this actually creates the dimensional accuracy when two different components we are try to joint this. So, there are several way to reduce this amount of the distortion. One is the by reducing the weld metal volume, so that means, melting volume of the material. If it is less amount, then probably we can reduce the distortion.

Of course, in this case the less amount volume less amount of the molten cool volume, but at the same time it should attend the full depth of penetration. In case of by using electron or laser beam welding the may be the solution because in this case the weld pool volume is relatively small as compared to the other gas or arc welding processes. So, therefore, laser welding or electron beam welding is one solution to minimize the angular distortion or other kind of the distortion in welding process.

Placing welds about the neutral axis if you when you try to do kind of T-joint kind of this thing. So, there is a the hole of the weld pool metals not this not uniform throughout the depth of penetration structure it varies from maximum to the minimum point. So, with respect to that type of cross section if it is possible to place the equilibrate amount of the weld pool volume with respect to the neutral axis, then probably in that case that the amount of the distortion can be reduced. And of course, one very large structure or may be in a very complicated that following the multipath or multi pass welding process the distortion can be controlled.

So, multipath means if you use a laser scanning using the laser welding throughout the structure and following some specific pattern of the weld scanning of the laser on the surface, and the path are can be different. So, designing the path probably we can reduce the amount of the distortion or sometimes in case of multipath welding not placing the or supplying the molten material within the weld pool volume not only on the single pass if you it can be filled by using the several passes probably in this case the amount of the distortion can be reduced.

And this multi pass welding process mainly happens very high thick metal. So, these are the very straight forward way to reduce the distortion of the different welded structure.

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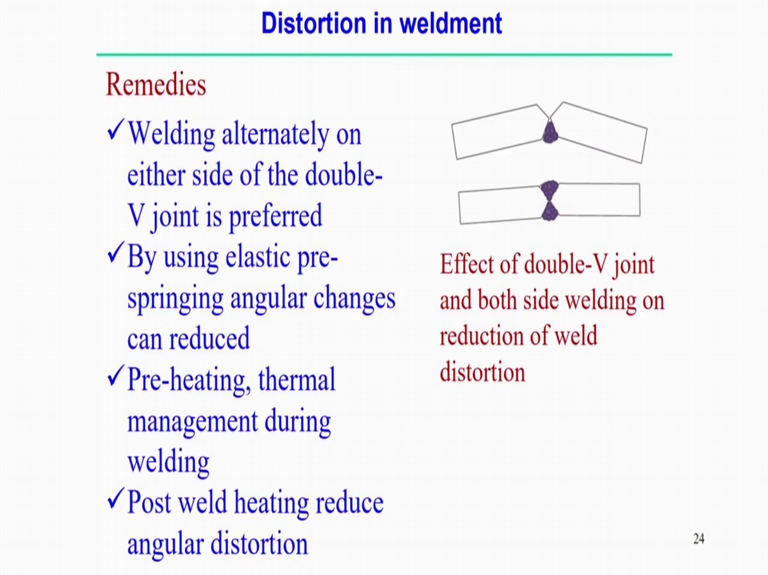

Distortion in weldment

Remedies

- ✓ Welding alternately on either side of the double-V joint is preferred
- ✓ By using elastic pre-springing angular changes can reduced
- ✓ Pre-heating, thermal management during welding
- ✓ Post weld heating reduce angular distortion

Effect of double-V joint and both side welding on reduction of weld distortion

Now, another the other type of methodology also exits to reduce the amount of the distortion. If you simply look into this figure, the presence of only single V that means, one sided and welding of this thing can definitely most of the cases it will produce try to some angular distortion. Specifically the angular distortion is mainly happens when the thickness of the plate is relatively high. And in this case if the similar kind of V similar kind of weld pool volume can be placed in the both sides of the plate, then it will try to neutralize the amount of the angular distortion or it can be reduced the amount of the angular distortion, and it is very obvious from this the figure.

So, therefore, welding alternatively on the either side of the double V joint is preferred to reduce the distortion. And another mechanical way to that by using the elastic pre-springing before the welding can also helps to reduce the angular joint that means, simply that before welding some angular intentionally you give some angular distortion.

And if you do the welding joint, so that after welding it can you try to neutralize the pre-existing angular dispersion of the weld joint, so that is a one way to reduce the distortion. Definitely preheating sometimes the preheating of the material before welding can also reduced that can also try to can also reduce the distortion.

Thermal management during welding that means, heat is possible to control the thermal cycle; that means, time temperature cycle during the welding process that also influence the distortion level of the weld joint.

And of course, post weld heat treatment or post weld heating also sometimes reduce the angular distortion, so that means it is a very straight forward way using some mechanical means for example, pre-training or pre-springing angular changes can reduce the distortion. But at the same time the distortion also affected by the some metallurgical changes and that metallurgical changes is very much influenced by the thermal cycle in the welding process. Thermal cycle mean the time versus temperature cycle.

So, by proper control of this time versus temperature cycle or you can say the thermal management of the during the welding process that helps to reduce the amount of the distortion apart from that the pre-preheating or post-heating also helps to reduce the distortion level simply by changing by the microstructure of the welded joints. So, these are the typical methods for reducing the distortion level in a welded structure.

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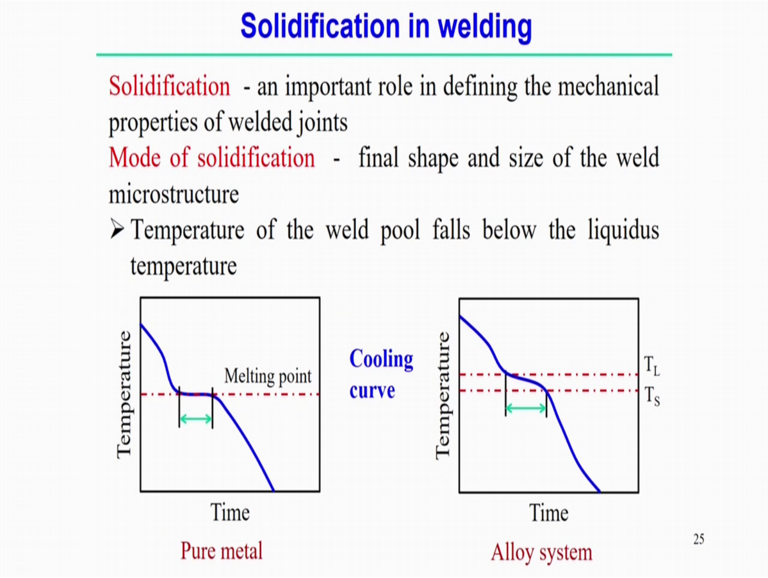

Solidification in welding

Solidification - an important role in defining the mechanical properties of welded joints

Mode of solidification - final shape and size of the weld microstructure

- Temperature of the weld pool falls below the liquidus temperature

Temperature

Melting point

Time

Pure metal

Cooling curve

Temperature

T_L

T_S

Time

Alloy system

Now, we come to that point that one is significant or important part that is a welding a solidification in welding process. So, definitely the molten pool with when come in contact with the some cooling medium and most of the cases is the open atmosphere and that or it is also sometimes under the shielding gas or maybe in sometimes it can be done so close chamber also.

So, anyway some kind of cooling medium exist, so the molten pool casually solidify and come back to the ambient temperature or maybe come back to the service temperature. So, that during the cooling period the what is the thermal cycle, time temperature cycle, and what is the rate of cooling that is very much significant or important in the solidification process of the welding in any welding process; So, because the solidified structure is actually decides the mechanical properties of the weld joint. So, it is very much necessary to understand the solidification behavior in welding process.

Now, there are several solidification theory, but our focusing only in specific to the welding process. Here if you see the mode of the solidification that what is the final shape and size of the welded microstructure that can be same that mode of the solid that depends on the mod of the solidification. So, therefore, temperature the solidification happens the temperature of the weld pool comes from superheating temperature to the phase transformation temperature, basically solid state phase transfer from liquid to solid phase; transformation temperature and then gradually cooling from that solidification temperature to the ambient temperature. So, throughout this process there may be the several phase transformation may occurs; and specifically that phase transformation not only the liquid to solid phase, but in case of alloy there is a solid state phase transformation may also occur.

Now, if you look into that typical the time temperature curve in solidification process, if you look into the specific pure metal, we know the basic elementary curve for the time versus temperature. So, first curve is a first figure is shows that in case of the pure metal used when you try to follow the cooling from the some superheated temperature, and then when it comes to the melting point temperature, there is some time lag maybe some time is required to change the face without changing the temperature so that that the melting at the melting point of the specific pure metal.

So, specifically in case of the pure metal there is a single point melt there is a single melting point temperature. So, that means, the from liquid molten pool to the solid material may happens over single temperature, but over a lapse of time. So, that lapse of time is basically the release the basically latent heat by changing the phase from liquid to solid phase. So, that graph clearly shows that there is a phase change over time and from liquid to solid and gradually the solid state there is a constantly decrement of the times. So, this is a typical solidification curve in can in any in case of the pure metal.

But if you look into that cooling curve of the alloy system, so in this case specifically the alloy system or it is easy to explain the alloy system if we consider binary alloy. So, in this case, the time versus temperature if you so if you see that it starts from the superlative temperature and one that is a liquids temperature and there is a two define temperature over which the solidification happens that means, from between the liquidus temperature to the solidus temperature.

So, between these two is normally call the mushy zone. So, the mixing of the solid and liquid phase exist between these two temperature solidus temperature and liquidus temperature.

So, like pure metal the phase transformer from liquid phase to the solid phase does not happen of on a single point temperature whether heat happens over a range of the temperature. So, within this range of the temperature of course, the phase change happens from liquid to solid phase. And this are the typical cooling curve or time temperature cycle in case of alloy in case of alloy material alloy system. So, with this basic understanding of the cooling curve, we will try to explain the solidification behavior of the in case of the welding process.

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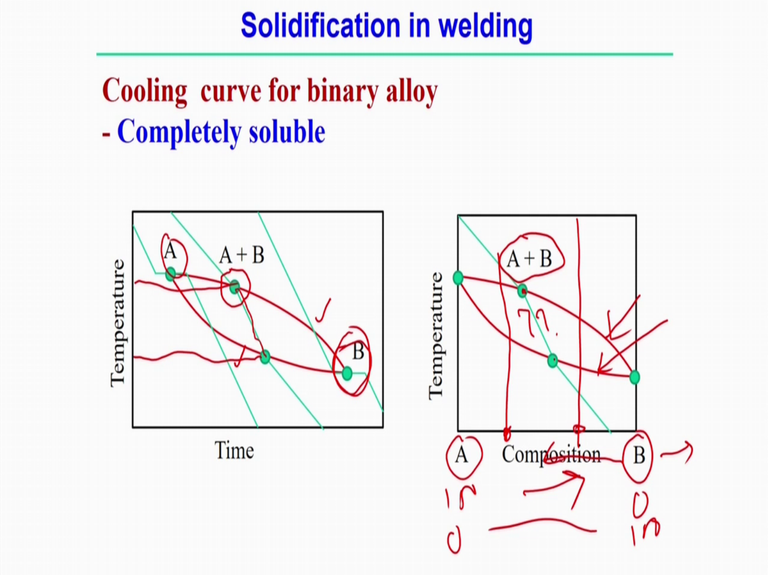

Solidification in welding

Cooling curve for binary alloy

- Completely soluble

Now, more intuitively if we look into that cooling curve of an binary alloy. So, we assume that it is a binary alloy, there is a two their soluble completely soluble with respect to the each other. Now, if you start the temperature verses time here we can we can draw this two curve.

So, we can say that first curve one part that convex part is the basically the liquidus temperature; and concave part is basically the solidus temperature that means, within this there is a change of the phase from the it starts from the liquid phase and then comes to the solid phase. But here there are two alloy sorry two components are there is a specific alloys system.

So, in this case, if you look into at point A, point A is a single point. So, that single point actually indicates the melting point of the of the component A, so that means, of the component A means here it indicates that the it is a pure metal. So, on this pure metal, it follows the simply cooling curve like that that at this point the if the it is a 100 percent composition of the single component, then here if we see that the phase that happens over a range phase that happens once in one constant temperature and then after this it come after cooling it comes to the ambient temperature.

But similarly if you look into the point B also here you can see that at point B, it is also a pure metal for the different metal. So, here the melting point a different as compared to the metal A. So, here we can see that phase change also happens over a range of the time, but at constant temperature. So, it is follows a similar kind of the similar kind of the cooling curve like the pure metal A.

Now, if the alloy system consists of the material A and B at the mixing of this thing. So, it becomes alloy. So, the in this case the phase change starts at point at this point so that that actually exactly on the liquidus line. So, here at this point, it just starts from the changes of the phase from liquid phase to the solid phase.

So, the change of the phase happens over a range of temperature, and here corresponds to this is the solidus temperature; and here it is the corresponds to the liquidus temperature. So, it starts from the liquidus temperatures and comes to the solidus temperature and that phase change happens with this range of the temperature because it is a an alloy systems. So, binary alloy system it is a is consists of the component A and B. And that in that way we can represents that different cooling curve if there is a change of the composition.

So, here basically the pure 100 percent A composition, here at this point 100 percent B, so both the cases we can consider as a pure metal, but in between. Any stage this is the certain percentage of the A and certain percentage of B they constitutes some alloy system and that alloy system actually change the phase from solid phase to a liquid phase to solid phase and that actually happens over a range of the temperature. So, this is a time versus representation of the typical temperature versus time.

But if you look into that temperature verses composition here we can see that x-axis is actually represents the composition. So, here A at this point it is a basically exactly 100 percent A that means, we can say it is a pure metal at point A. Similarly, at B hundred percent composition in 100 percent B that means, it is a pure metal b, but in between there is a mixture of A and B certain percentage of A and certain percentage of B exits.

So, at any point we can define the this is the if it draw any vertical line so that actually represents the composition that consists of A plus B and any professional may be different at the different point. So, it is start from 100 percent A gradually if you moves towards the x direct towards the positive direction, so towards the B.

Then here percentage of A actually decrease and gradually here the here the A is the 100 percent and here at this point A is basically 0 percent. Similarly, if you move in other direction B is 100 percent, and here B is the 9 percent. So, in that we try to represent the composition along the x-axis of an of an alloy system.

So, this alloy system and if you are intermediate point at any point it is a alloy system consists of A plus B. So, here the this point starter solidification and it is solidify it is a completely becomes the completely solidified. So, in between there is a mixture of the solid phase and the liquid phase actually co exits that the two different line.

So, this line is basically represents the liquidus temperature line and this line curve specially represents the solidus temperature plane. So, this is the simplified way we can represent the cooling curve of an alloy system. Now, we looking further analysis of that now that basic understanding of the solidification in welding process so how it happens the in case of the solidification process.

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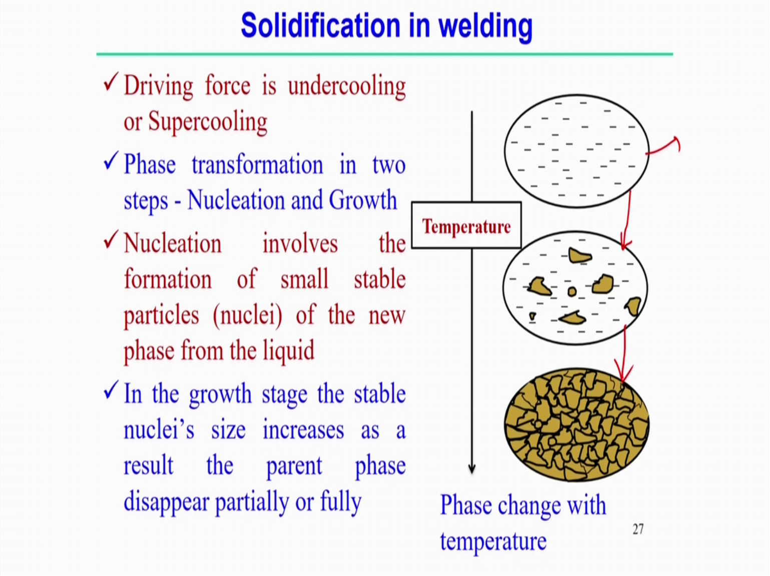

Solidification in welding

- ✓ Driving force is undercooling or Supercooling
- ✓ Phase transformation in two steps - Nucleation and Growth
- ✓ Nucleation involves the formation of small stable particles (nuclei) of the new phase from the liquid
- ✓ In the growth stage the stable nuclei's size increases as a result the parent phase disappear partially or fully

Phase change with temperature

So, in this case mainly the driving forces is in the solidification of the will just try to look into the solidification of the pure metal. So, here the driving forces is mainly the under cooling or super cooling. We will come back to that analysis of the under cooling and the super cooling.

So, in this case, the solidification mainly happens in the two phase first is the nucleation and that means, phase transformation may happens in this two phase the nucleation and then subsequent growth. And nucleation basically involved that the formation of the small stable particles that is called nuclei of the new phase from the liquid.

So, if you look into that picture, so suppose this is the liquid metal. So, when this liquid metal exactly comes from super heated temperature to the liquidus temperature. So, then there is a start of the formation of the small nuclear a small particle and that particle and the liquid metal actually coexist. And after certain when it close the solidus temperature, then the consists of the all other solid particles, but that afterwards the solid particles may also grow and it will try to consume the completely replaced by the liquid phase molten metal.

So, in the growth stage basically the stable nuclear size is mainly increases as a result of the parent phase and that gradually that parent phase basically liquid phase gradually disappear. So, initially partiality this happen gradually completely disappeared. So, this is a simply phase change occurs with respect to temperature and that also we can find out in the solidification process.

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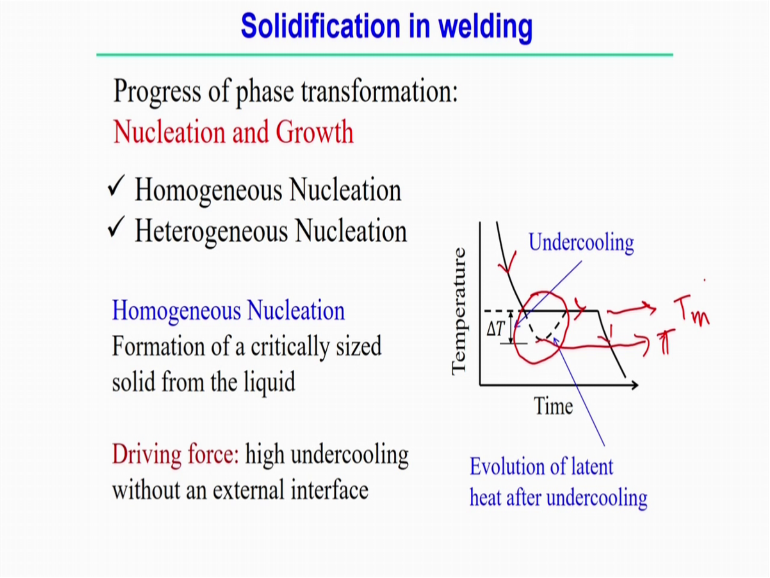

Solidification in welding

Progress of phase transformation:
Nucleation and Growth

- ✓ Homogeneous Nucleation
- ✓ Heterogeneous Nucleation

Homogeneous Nucleation
Formation of a critically sized solid from the liquid

Driving force: high undercooling without an external interface

Now, progress of the phase transformation so that means, liquid phase to the solid phase transformation is consist of the two components; first is the nucleation and the growth process. So, nucleation process there may be the two types of the nucleation process, one is the homogeneous nucleation another is the heterogeneous nucleation.

And both this cases there are some driving forces that actually promote the homogeneous nucleation or whether it is promoting the heterogeneous nucleation. So, we will try to find out what are the driving motive for the these two types of the nucleation that we generally observed in the in general the solidification process in specific to the welding.

So, homogeneous nucleation it starts with the formation of the critical critically size solid from the liquid. Now, the driving force for the homogeneous nucleation is basically the under cooling, high amount of the under cooling without any external interface. So, if you purely the basic elements elemental part of the homogeneous nucleation is simply it is driven by the presence of the under cooling, but how it happens under cooling.

So, if you look into this curve during the cooling process, it say the this line indicates the actually the melting point or that means, that temperature actually decides the transformation from the solid phase to liquid phase or vice versa liquid phase to solid phase. But during the cooling process this before change of the phase, the metal may subjected to locally let say amount of the under cooling, so that is the with respect to that melting point this is the amount of the under cooling that represented by the delta T that is a below the phase change temperature.

Now, once this achieve some under cooling and it starts the nucleation process, and then after starting of the nucleation process; and then it is exactly come back to the equilibrium temperature that means the temperature that decides the phase change between solid and liquid.

So, this the equilibrium temperature and then its change of phase and finally, then evaluation of the latent heat is basically starts after the under cooling under cooling of the system. So, then it is starts this point reach locally achieve some amount of the under cooling and then release a latent heat. And then finally, it follow the cooling to the gradually after changing of the phase it gradually cool to the and then temperature by releasing the specific heat in this case.

So, this under cooling is the main driving forces and that under cooling is specifically responsible for the homogeneous nucleation process that nucleation actually happens throughout the throughout the structure at a time. But of course, this under cooling actually reach or achieved in a very local position within the pool of the molten within the pool of the liquid metal at which points there is a under cooling several point can be under cooling locally some among this some amount of achieving this under cooling, and that once it achieve the under cooling it starts the nucleation process. So, these type of nucleation process is mainly known as the homogeneous nucleation process.

Of course, there is another nucleation process. So, in this homogeneous nucleation process, probably there is no role of the external surface. So, presence of external surface that is may be adjacent to the liquid metal or may be some interface with the liquid metal that actually sometime that also actually acts as a cites to create the nucleation process.

But if you try to theoretically look into the homogeneous nucleation process, so here the driving force of the homogeneous nucleation process is only the under cooling, so the degree of under cooling is more. So, tendency of (Refer Time: 28:20) formation of observe nucleus homogeneous nucleation will be more. So, in this case homogeneous nucleation, the role of the external surface is no, no more there.

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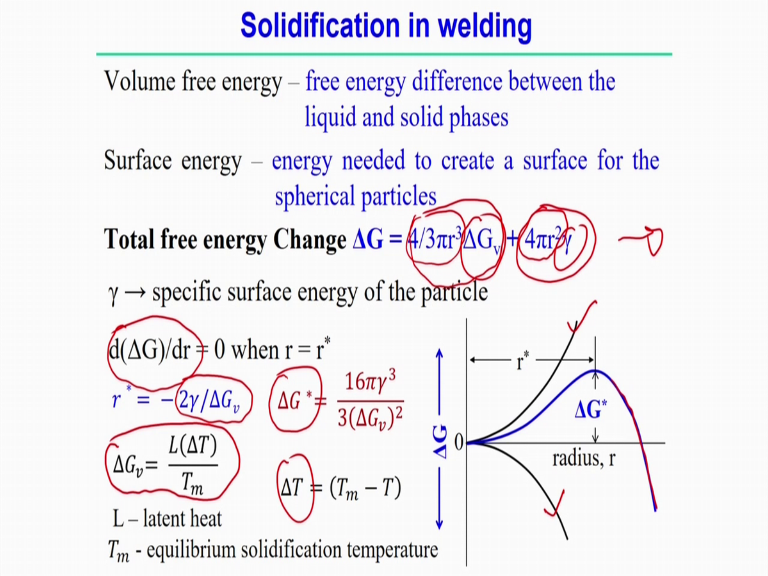

Solidification in welding

Volume free energy – free energy difference between the liquid and solid phases

Surface energy – energy needed to create a surface for the spherical particles

Total free energy Change $\Delta G = 4/3\pi r^3 \Delta G_v + 4\pi r^2 \gamma$

$\gamma \rightarrow$ specific surface energy of the particle

$d(\Delta G)/dr = 0$ when $r = r^*$

$r^* = -2\gamma/\Delta G_v$

$\Delta G^* = \frac{16\pi\gamma^3}{3(\Delta G_v)^2}$

$\Delta G_v = \frac{L(\Delta T)}{T_m}$

$\Delta T = (T_m - T)$

L – latent heat

T_m - equilibrium solidification temperature

Now, if you took look into in little bit among the theoretical aspects of this nucleation process probably then it will be more beneficial to understand the solidification process in welding. So, we try to ping this two things. So, for your understand the solidification in the simple way we understand that this simply change of the phase from liquid phase to solid phase that they happen one single point temperature or that may happens over a range of the temperature whether it is pure metal or whether it is some alloy system.

Now, if you define the volume free energy that is the free energy difference between the liquid and solid presence, because during the solid during the solidification process there is a change of the liquid to liquid to the solid phase. So, during this change of the phase some amount of the volume, some amount of volumetric energy is required to change from liquid to solid, so that is the that is that is can be define as volume free energy.

But another surface energy that is also energy needed to create a surface from the spherical particle if you assume some spherical size of the nucleus as a sphere. So, the for the spherical particle what is the amount of the surface energy is needed to create surface to create a basically energy needed to create a surface.

So; that means, total free energy change in this process is consist of the two components, one is that over the volume over the surface, so that is over the volume the first component 4 by 3 pi r cube that represents the volume of a spherical particle and delta g B is the volume free energy change of the free energy is required to change from solid to liquid phase and that with per unit volume, so that means, volume free energy this is the first component, is the second component the surface energy. So, 4 pi r square is the area of the surface for a sphere or spherical particle and gamma is basically the specific surface energy of that particle, so that delta G represents the total free energy change during the nucleation process probably.

Now, this free energy change can be represented graphically that if you look into the graph also here you can see that one component that this one that actually representation of the volume free energy. Change during the during this change of the phase from solid to liquid to solid phase. So, it is a negative we consider the because we just this actually represent, but the difference the liquid and the solid amount of the energy needed the difference between the liquid and solid phases. So, it is a negative quantity and other is a second component that is a surface energy to create a surface of a spherical particle.

So, this is growing positively that is the amount of changing this thing. Now, overall total free energy change can be represented like this that means, initially total amount of the free energy is actually balancing between the surface energy and volume energy. So, balancing these two is initially growing and it reach some of maximum point and then again amount of the energy actually reduces and finally it reach to the negative value.

Now, from the theoretical from this typical nature of the energy total energy free energy change during the nucleation process, we can find out that this optimum point is the amount of the optimum energy that this amount of the optimum energy is the maximum amount of the energy is required to form a stable nucleus, so that optimum point of the optimum energy level actually decides what may be the size of the nucleus, so that it can sustained that this critical energy simply estimated by the derivative first derivative of free energy total free energy change making is 0. And then from this, we can find out that size of the nucleus in this case the critical size is basically the can be represented at in terms of the specific surface energy and the volume free energy.

So, that r square equals to minus twice lambda by delta G v, so that is the ratio of the surface energy by the volume free energy, so that means, these two types of the energy actually decides what may be the critical size of the nucleus, so that that nucleus can grow further, but what is the total maximum amount of the energy or optimum amount of the free energy change that is also related to that is surface energy and the volume free energy in this in this cases.

Now, critical size of the nucleus is a some negative sign is there that means, it is a depending on the sign convection what we can consider the is the delta delta G v. So, because of that the because of that sign convention the negative sign is there, but we can consider the magnitude of this size of the critical nucleus is the ratio of this two types of the ratio of this specific surface energy and the volume free energy to change volume free energy related to change from the liquid to the free energy difference between the liquid to the solid phase.

Now, this amount of the optimum amount of the energy or is also represented in terms of these two components that volume free energy and the specific surface energy, but if we see that volume free energy can also be represented in term also depends on the latent heat and the degree of under cooling that means, the temperature difference between the equilibrium solidification temperature, so that means, equilibrium solidification temperature we can assume at is a phase change temperature single phase temperature and it is a latent amount of the latent heat.

All this actually decides the as a decides the amount of the free energy difference between the liquid and solid liquid and the solid phase for a specific material. Therefore, delta T can also be represented by the temperature the phase change temperature and T is a temperature in between.

For example, here it is can be represented the equivalent solidification temperature and T can be an intermediate temperature T, so that the T m minus T is basically represents the amount of the amount of the super cooling here. So, our l is the latent heat. So, this is the typical calculation of the size of the or amount of the energy required to start the nucleation process or the stable nuclear to start the stable nucleation process what is the energy barrier probably required in case of the homogenous nucleation process. These are the typical expression of the size of the nucleus, and what is the optimum amount of the free energy change is required to start the nucleation process or stable nucleation process.

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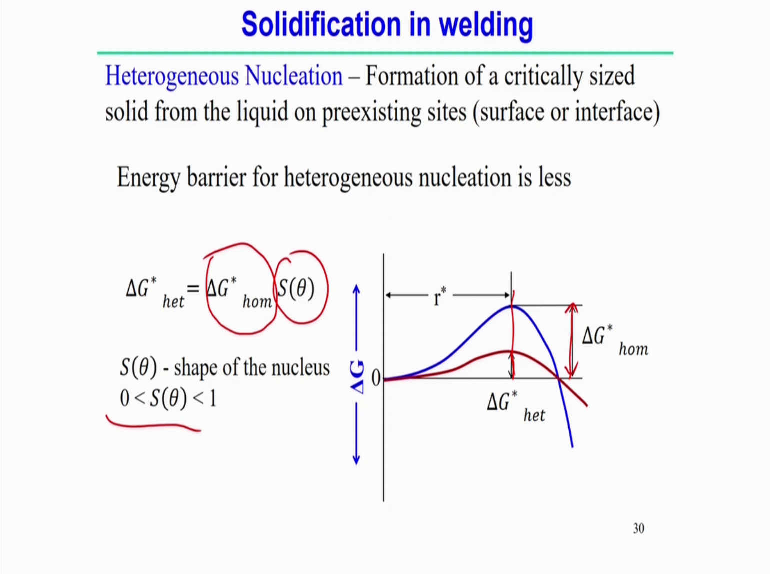

Solidification in welding

Heterogeneous Nucleation – Formation of a critically sized solid from the liquid on preexisting sites (surface or interface)

Energy barrier for heterogeneous nucleation is less

$$\Delta G^*_{het} = \Delta G^*_{hom} S(\theta)$$

$S(\theta)$ - shape of the nucleus

$0 < S(\theta) < 1$

Now, heterogeneous nucleation also to some extent that it is also formation of the critically sized solid from the liquid, liquid, but that formation of the critically sized nucleation nucleus happens from the preexisting sites or either the preexisting site of presence of the any surface it surface of the in presence of the interface the heterogeneous nucleation start.

So, driving force or maybe here the driving force maybe the difference in case of heterogeneous welding process, but the in case of heterogeneous nucleation process any kind of inclusion presence in the liquid metal or any interface or any surface they actually thought they actually initiate the at this point there is initiation of the nucleation happens in case of the heterogeneous nucleation a process.

So, if we simply representation that what is the amount of the optimum amount of the energy required in case of the heterogeneous nucleation process that is the homo amount of the energy optimum energy required for the homogeneous nucleation process into some factor that S is a as a function of theta, so that factor is actually intuitively depend on the size shape of the nucleus because when the heterogeneous nucleation happens based on the nucleation theory over the interface. The surface tension between this interface of surface and the liquid metal can be different as compared to the only the surface tension of the completely solid metal when it is the solid metal exist within the liquid molten pool that happens in case of the homogeneous nucleation process.

So, that is why depending upon that S theta is a shape of the shape of the nucleus and of course, this as a function of the shape of the nucleus and this S theta can vary from 0 to 1 in between 0 to 1. So, if we typically plot the total free energy change in case of homogenous nucleation process and in case of heterogeneous nucleation process, we can find out the difference here. Here you can see that amount of the heterogeneous nucleation process the barrier to start the nucleation process is less in case of the heterogeneous in case of heterogeneous nucleation as compared to the homogenous nucleation process.

So, this amount total amount is the amount to critical amount of the energy required for the to start the homogenous nucleation process, and this is only the small amount that start the nucleation process in case of heterogeneous nucleation. But critical size of the nucleus both the cases is the same because that the critical size of the nucleus is intuitively depend on the volume free energy and the surface specific surface energy of the of the material of the particle basically, so that is why it is the critical size of a nucleus is independent of the shape of the nucleus.

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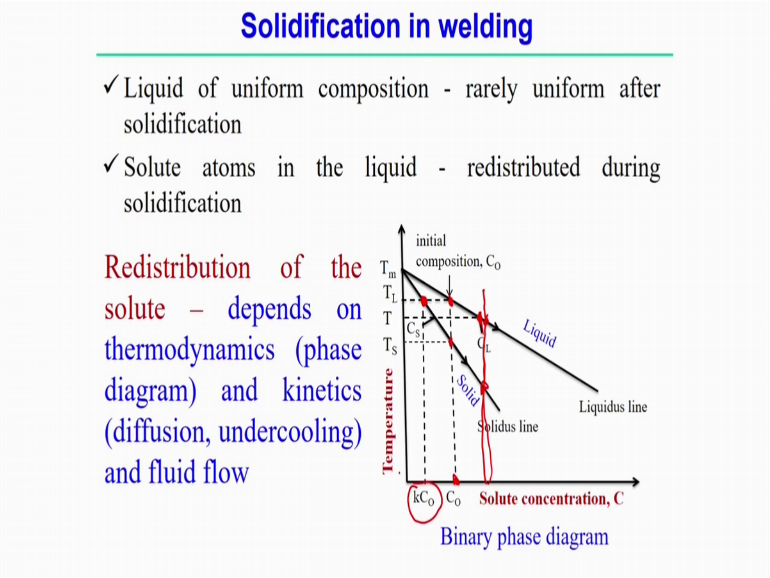

Solidification in welding

- ✓ Liquid of uniform composition - rarely uniform after solidification
- ✓ Solute atoms in the liquid - redistributed during solidification

Redistribution of the solute – depends on thermodynamics (phase diagram) and kinetics (diffusion, undercooling) and fluid flow

Binary phase diagram

Now, we will try to look into that solidification in case of the binary alloy system; So, here the liquid of the uniform composition really uniform after the solidification, because we assume the liquid of the uniform composition. But after the solidification, it may not be the uniform and solute atoms in the liquid the redistribution solute atoms in the liquid that also happens the redistribution of the solute atoms during the solidification process.

So, redistribution of the solid atom in the solidification process in specific to binary alloying that actually depends on the thermodynamics that means, phase diagram and kinetics. Kinetics means the diffusion under cooling and in any material flow. Of course, under cooling this are the kinetics and that fluid flow all these are the influencing factor for redistribution of the solute atoms in case of the binary alloying system.

Now, if you look into one typical phase diagram binary phase diagram, here if you see that there is a liquidus line and we representing the liquidus and solidus line as a straight line. So, and if you pick up any initial composition of the solutes, the sorry x-axis represents the solute concentration and y-axis represents the temperature; So, at any solute concentrations, if you assume the initial solute concentration at this point C 0. So, at this point, if you draw one vertical line, so this points corresponds to that liquidus temperature, and this point corresponds to that solidus temperature.

Similarly, if you consider the concentration at different the liquidus and solidus temperature can be different depending upon the liquidus line and the solidus line, and for a the different composition. So, with this composition the liquidus line here equal to T L and solid solidus temperature is basically it represents by the T S; And at any temperature in between the solidus and liquidus because between the solidus and liquidus temperature, there may be the solid content and the liquid content.

So, at any temp any temperature, in the case of the initial concentration initial composition of the binary alloy is the C 0. So, in between temperature, so this represents the liquid content so that means, with respect to the any temperature line if you draw one horizontal line, so that actually cross the liquidus temperature and solidus temperature. So, that liquidus temperature this point correspond to that this actually represents the liquid content and the which that at that point corresponds to the liquid solidus line that actually represents the solid content so that means, we can say that although initial composition of the metal is concentration C 0.

So, in between the liquidus and solidus temperature that should that consists of the liquid content and solid content, so that can be this among the solid content and liquid content can be evaluated simply using by using the simply the proportional way we can usually find out what is the amount of the liquid composition what is the amount of the solid concentration on a specific temperature.

So, here also we can see that C 0 that will this C 0 composition correspond to the liquidus line when it cross the liquidus line sorry liquidus, it cross the liquidus line at that corresponding point. If you draw one temperature line the basically liquidus temperature, so which point it is it cross that solidus line this composition is corresponds to the K into C 0. So, definitely here case would be the less than 1 that means, less than 1 means the there liquid content for this case in this case is basically less than C 0.

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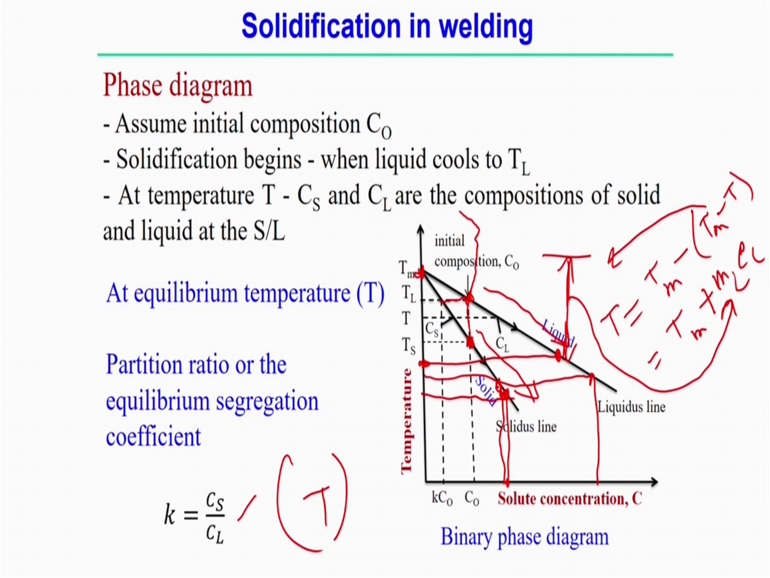

Solidification in welding

Phase diagram

- Assume initial composition C_O
- Solidification begins - when liquid cools to T_L
- At temperature T - C_S and C_L are the compositions of solid and liquid at the S/L

At equilibrium temperature (T)

Partition ratio or the equilibrium segregation coefficient

$k = \frac{C_S}{C_L} / (T)$

Binary phase diagram

Now, if we further discuss on the phase diagram, so we assume the initial composition C 0, and the solidification starts when the liquid cools towns to the T l temp cools to the T l. So, solidification starts because at this composition solidification when it cools to the T l, the solidification sorry it when it comes to the some superheating temperature and it when it comes at this point the T L point exactly the solidification starts and gradually it solidify it comes to the solidus line then we can say the solidification complete that means, in the solidus line it is a the phase is completely solid phase.

But the concentration in its composition of the concentration is exactly at the same amount C 0, it is a simply following this vertical line it start from the solidification starts at this point and gradually it reach this point that completes the solidification.

So, we can analyze by using the lever rule in between the solidus and liquidus temperature, we can find out the composition that means, liquid content and the solid content from this binary phase diagram. Now, what is the typical point that, so at any temperature T the C S and C S represents the solid content and C L represents the composition of the liquid and basically the here the coexisting of the liquid and the solid phase here.

Now, at equilibrium temperature T, the partition ratio or the equilibrium segregation coefficients between these two that k can be represented small k can be represented by the ratio of the C S by the C L, it is a simply a composition of the solid composition and the liquid composition, but this composites is corresponds to at equilibrium temperature T. So, equilibrium temperature changes T this value of the k may be may change if the equilibrium solidification temperature changes.

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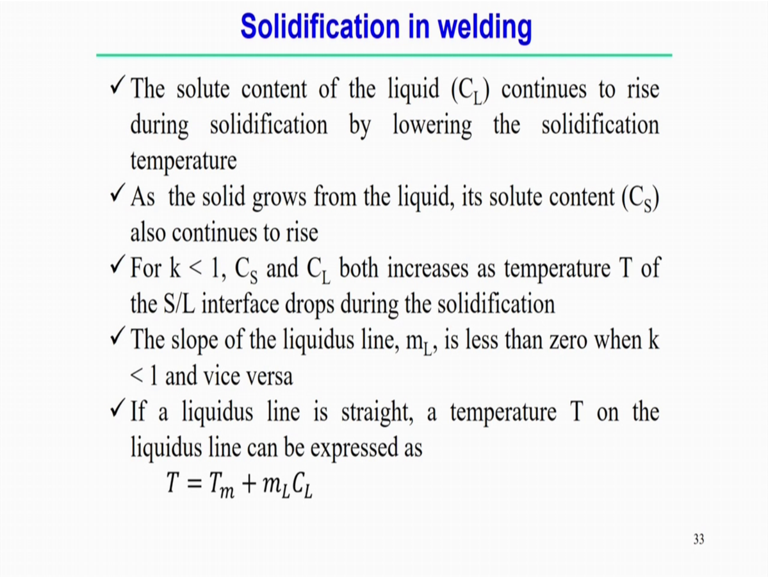

Solidification in welding

- ✓ The solute content of the liquid (C_L) continues to rise during solidification by lowering the solidification temperature
- ✓ As the solid grows from the liquid, its solute content (C_S) also continues to rise
- ✓ For k < 1, C_S and C_L both increases as temperature T of the S/L interface drops during the solidification
- ✓ The slope of the liquidus line, m_L, is less than zero when k < 1 and vice versa
- ✓ If a liquidus line is straight, a temperature T on the liquidus line can be expressed as

$$T = T_m + m_L C_L$$

So, from this information phase diagram, we can further analyze the this phase diagram. In case of binary alloy that solute content of the liquid continues to rise during the solidification by lowering the solidification temperature. So, solute content by lowering the solidification temperature it will move along this by lowering the solidification temperature.

So, at this point the definitely the solute content is more if solidification temperature is less. Second point at the solid grows from the liquid its solute content also continuous to rise; definitely as the solid grows from the liquid. So, when the it starts from the liquid phase and continuously go towards the solid phase the concentration of the solid phase actually increases. If k less than 1, then C S and C L both increases as temperature T of the solid liquid interface drops during the solidification.

So, when the solidification temperature actually drops both the C S and corresponding C L liquid content and the solid content actually both are increases if that if there is a there is a decrement of the temperature T. The slope of the liquidus line m L is less than the 0, when k is less than 1 and vice versa. The slope definitely here we can see this diagram the slope is basically less than zero that slope is basically negative in this case; and k when k is less than 1, definitely when k is less than 1, the slope is basically is negative and of course vice versa also correct.

If the liquidus line is straight, then temperature T on liquidus line can be expressed as this way, so that if you see the if you we can see that a liquid liquidus line is straight the any temperature T on the liquidus line that can be express at this. So, if you see here the liquidus line is liquidus line is basically straight, so at any point the temperature is can be T can be that melting point temperature minus the difference between the T m and T between that is temperature.

So, T m minus T, so that T m minus T the increment can be represented by the slope m L and the slope act corresponds to the C L. So, m into C L and this slope is negative. So, T m can be represented by the T at any point can be represented by the T m negative slope, and the amount of the liquid content on that on that on the specific point.

So, so at this at this specific point what is the slope this actually represents the T m, this actually represents this also mathematically says that this is also equal to that slope into that li content C l so this amount so which is equivalent to that this amount, so that way that liquidus line is straight not the curve. Here then a temperature T on the liquidus line can be expressed like this.

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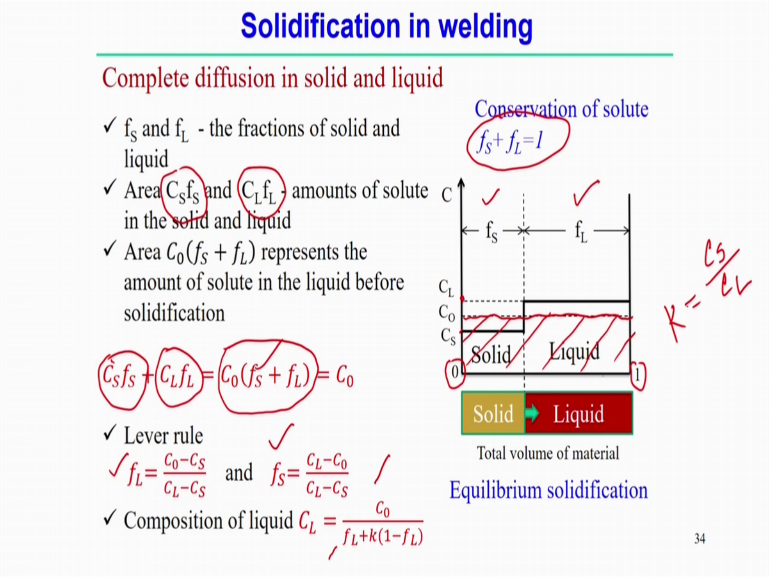

Solidification in welding

Complete diffusion in solid and liquid

- ✓ f_S and f_L - the fractions of solid and liquid
- ✓ Area C_Sf_S and C_Lf_L - amounts of solute in the solid and liquid
- ✓ Area $C_0(f_S + f_L)$ represents the amount of solute in the liquid before solidification

$$C_Sf_S + C_Lf_L = C_0(f_S + f_L) = C_0$$

- ✓ Lever rule

$$f_L = \frac{C_0 - C_S}{C_L - C_S} \quad \text{and} \quad f_S = \frac{C_L - C_0}{C_L - C_S}$$

- ✓ Composition of liquid $C_L = \frac{C_0}{f_L + k(1 - f_L)}$

Conservation of solute

$f_S + f_L = 1$

Total volume of material

Equilibrium solidification

So, this understanding of the binary phase diagram during the solidification process. And here we will try to look into other aspects that complete solidification in welding process that complete diffusion in solid and a liquid state. Here you can see you can see that we assume that the material the complete diffusion in the solid and liquid the composition we choose in such a that there is a complete diffusion in the solid and liquid state, so that means if f S and f L actually represents the fraction of the solid and the liquid state then if the according to conservation of the solute this should be 1, f S plus f l should be respect to 1.

And if you look into that figure represent to that the fraction solid fraction and liquid fraction is starts from 0; and gradually increasing to 1. And there is a transformation that happens during the that solid is a solid goes from the liquid phase. And that means, from liquid to solid phase and in that direction the solid phase is gradually consuming the liquid phase, so that total volume total faction should be 1.

Now, graphically you can see that at any point, so this is a solid faction some part and some part is a liquid fraction. So, this is a liquid fraction, and this is a solid fraction and seizure is the initial composition of the initial composition of the of the solute. Now, here at any point, here the C L liquid content this point representation the C L, and this is the solid content that means, concentration of the liquid phase and concentration of the solid phase here in this case.

Now, f f S into C S and C L into f L basically represent the amount of the solute in the solid and liquid phase. So, that total area with respect to C 0, if you see the total area with respect to C 0 is basically f S into f L into C 0 the area represents and which is corresponds to the amounts of the solute in the solid phase and amount of the solute in the liquid phase, so that means, it is equal to the area occupied by the solid phase last area occupied by the liquid phase. So, that total content should be equal to the with respect to the C 0.

So, f S plus f l is simply 1 according to the solute conservation and that means, it is equal to C 0. So, from the situation, we can easily find out by applying the lever rule what is a solid liquid fraction and what is a solid fraction in this case. And of course, composition of the liquid also can be represented C L, C 0 in terms of the k also because k actually represents the ratio of the C S by C L that mean liquid solid content and the liquid content of this.

So, in terms of the k, so here we can find out the C L equal to in terms of the C 0 fraction of the liquid k in terms of k and as well as the in terms of the fraction the liquid we can we can write on this things. So, that is in this way we can represent the changes the fraction of the solid and liquid during the transformation from the solid phase and liquid phase specific to the in case of the binary alloy system.

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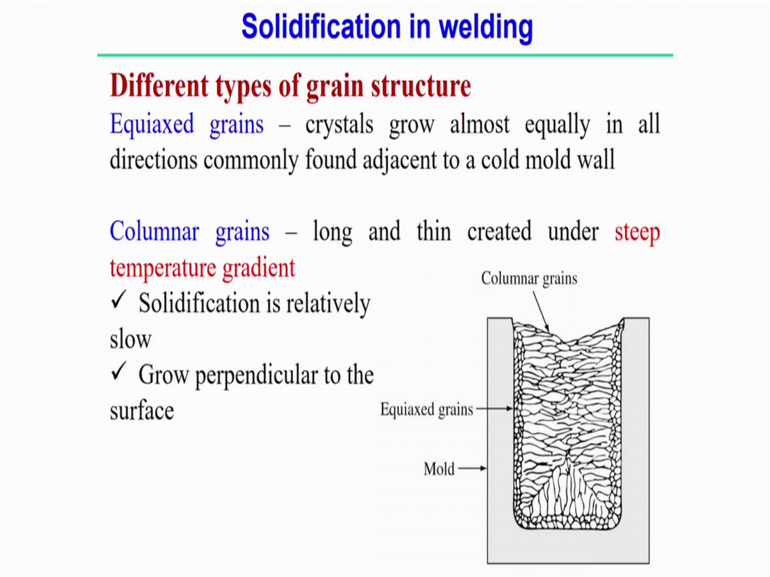

Solidification in welding

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

Now, if you look into that the during this solidification process, the different types of the grain structure we can expect normally one is that equiaxed kind of grains that in this case equiaxed kind of grain if you see that equiaxed grain the if you pool a consider the pool of the molten pool within the container then the surface actually acts as a heterogeneous nucleation process.

So, around the surface we can find out the almost equal size of the grains. So, crystal growth almost equally and all the directions and that is the commonly found out in the adjacent to the cold metal walls. So, around the cold wall this there is a formation of the equiaxed grain structure.

Similarly, you can find out the columnar grain structure it is basically long and very thin created under the steep temperature gradient. So, temperature gradient high temperature gradient is oriented on specific direction that actually driving force make a columnar type of the grains. So, definitely columnar type of the grains is relatively slow as compared to the equiaxed type of grains because equiaxed type of grains more or less actually happened throughout the whole throughout the surface is almost at the same time.

And another point is the columnar grain actually grow perpendicular to the surface. And entirely it depends on the differently this columnar types of the grain it depends on the directed temperature gradient or high amount of the temperature gradient, it would specific direction; So, this easily form kind of grain structure normally option in the solidification process.

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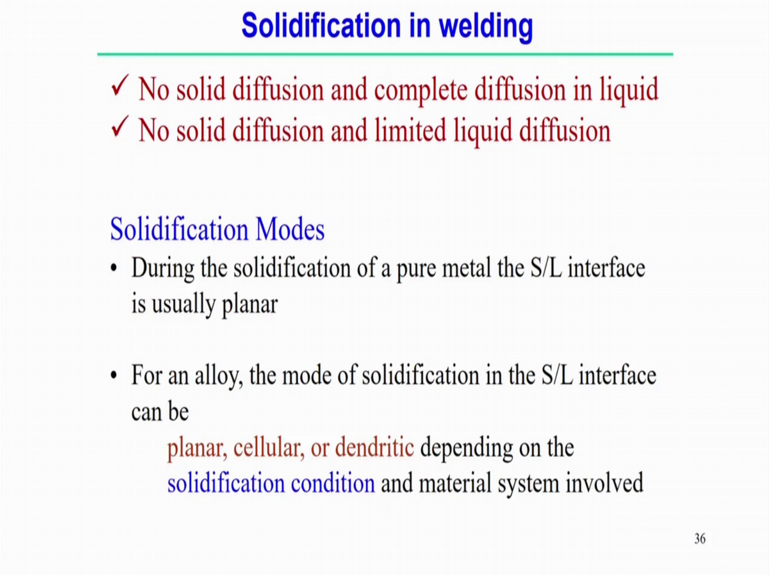

Solidification in welding

✓ No solid diffusion and complete diffusion in liquid
✓ No solid diffusion and limited liquid diffusion

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

Here we can find out that other type of binary alloy system, but here no solidification and complete diffusion in liquid we generally observed and one cases that no solid diffusion and limited diffusion also observe. So, in that case the behavior of the solidification becomes more complicated. So, here these two types of the solidification behavior is it is beyond our scope.

Now, if you look into the what are the different types of solidification modes. So, during the solidification of pure metal the solid liquid interface is usually planar type thing. So, there is a front moves in say making like a plane, so that is a one type of a mo mode, but normally for an alloy system the mode of the solidification in the solid liquid interface can be the planar type of it can be cellular, it can be dendritic type of the mode depending on the solidification condition and the material system involved. So, we will try to look into the different types of solidification mode generally observed this thing.

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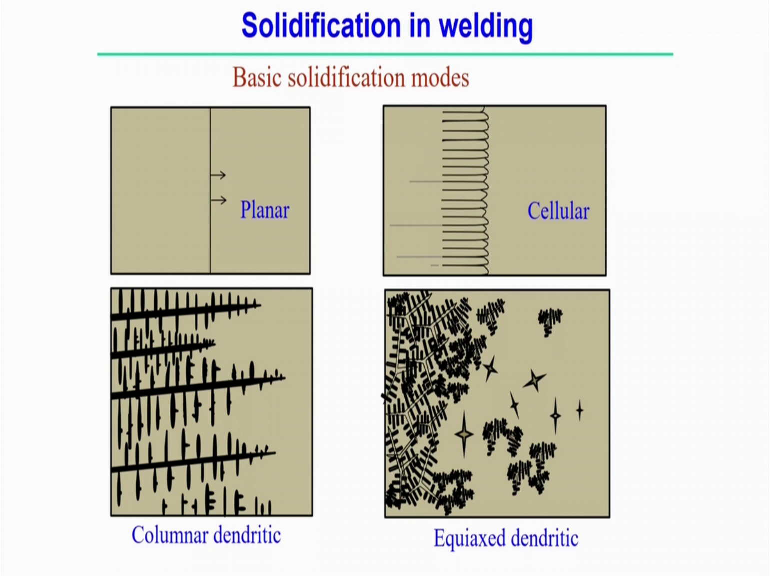

Solidification in welding

Basic solidification modes

Planar

Cellular

Columnar dendritic

Equiaxed dendritic

So, first one is planar mode so that solidification front exactly moves making a plane and gradually moves. Cellular there is a breaking of the planar mode and it is make a kind of structure like loops like a sale kind of structure. So, this is a cellular type of solidification modes. Another thought is a columnar dendritic structure. So, is a growth is a kind of columnar one direct one direction, but the dendrite dendrites forms is a primary dendritic secondary dendritic are cannot see form.

So, this is the typical columnar dendritic type of structure may also solidification mode can also be observed another is a equiaxed dendrite. So, of course, there is a dendritic structure exist within the one ben, but there are several position almost equal size of the grains exist with each within the each grain there may be the development of the columnar type of the dendritic structure sorry may be the dendritic structure observe within the equiaxed structure.

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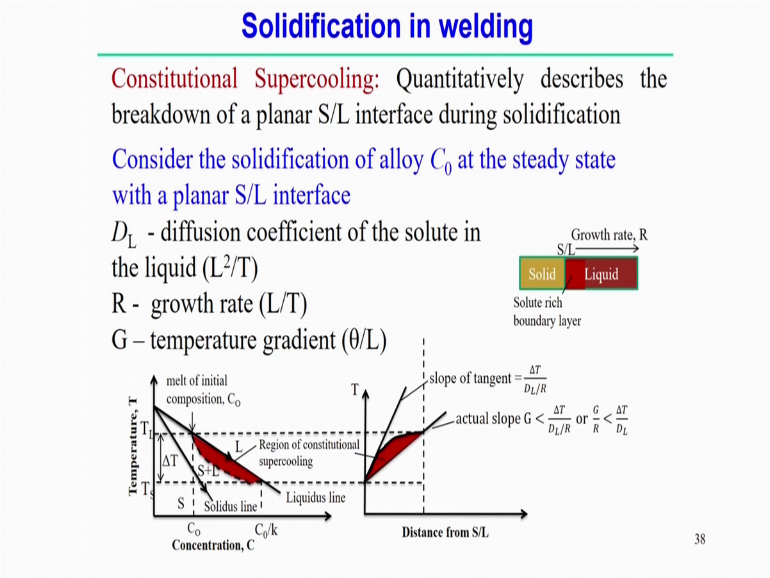

Solidification in welding

Constitutional Supercooling: 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)

So, these are the typical solidification modes in normally observed, but if you look into that here solidification and welding, but to analyze this thing that little bit a quantitative analysis of the solidification we can look into that constitutional supercooling.