Welding Metallurgy
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Lecture – 26
Principles of Solidification in Welding

Welcome to the lecture on principles of solidification in welding. So in this lecture we are going to have some light upon the principles of solidification typically in the welding process because we need to understand that how the certification in welding i*Type equation here* .s different is different from the solidification in normal cases of casting although the solidification mechanism will be same it will be through the process of nucleation and growth.

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Introduction

- Solidification of molten metal occurs by the nucleation of minute grains or crystals which then grow under the influence of crystallographic and thermal conditions that prevail.
- Size and character of the grains are controlled by material composition being cast and the cooling rate.
- In case of fusion welding, partially melted grains provide the necessary nuclei for the growth of crystal to begin. Such a mode of solidification is known as epitaxial solidification.

So solidification of molten metal occurs by the nucleation of minute grains or crystals which then grow under the influence of crystallographic and thermal conditions that prevail. So as you know that you know when in case of welding we talk about in welding the there is a liquid metal you know formation in the you know a fusion zone and then that basically starts solidifying. Now we know that the solidification is basically driven because of the free energy conditions.

So as the temperature comes down then there will be you know certainly in the below the certain temperature the free energy of the solid will be solid-state will be smaller. So during that transformation from liquid to solid there will be change in the free energy that will be decreasing. So that basically the driving force for the transformation to proceed. Now the thing is that now the nucleation has to start.

So we have also studied that the nucleation mechanism is that you know you will have the formation of a grain so the grain will start forming and because of the conditions you know at the equilibrium temperature the solid and liquid state will be you know cancelling each other. So free energy will be same at that point, but when that impression is somewhat smaller then in that case your you know the formation of a nuclei is you know started.

The initially when it is not able to stable you know then it is known as the embryo and if it is able to stabilize the point where the change in free energy becomes 0. So that is the basically limiting point so though so that basically we are looking for that condition and then you are getting a condition which tells that from here onwards any particular addition of the atom you know that will lead to the stabilization of that nuclei.

So then it is known as the nuclei and then further you will have growth. So that is basically you know we have already seen that in that we are having the expression for the volume energy term and we also have the expression for the surface energy term. So that expression is basically differentiated with respect to the r and then you know.

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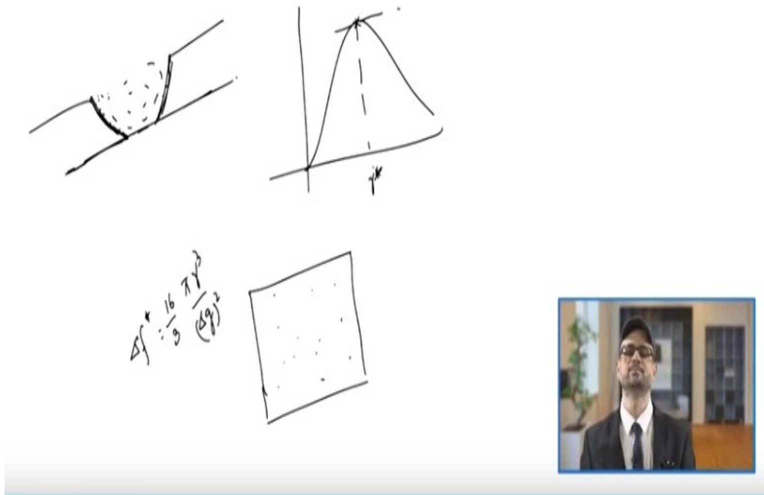

Because that you know you will have a particular kind of change in the free energy. So we are looking for this point where there is you know after that there is a change in the value in the negative direction. So basically we are talking about this r which is known as the critical radius. So that is $-2\gamma/\Delta g$ something like we are getting you know so that becomes the critical radius and from there basically further edition will be talking about the growth.

So you will have nucleation at you know different points and when the probability of these nucleation across all the domains in the you know material in the in the liquid everywhere this probability if it is same that in that case certainly it is a case of homogeneous nucleation. So in those cases we are trying to find the value of the you know the Δf so δ have you know homogeneous is found it has you know certain values which we get that is you know $16/3\ \pi\gamma^3/\Delta g^2$.

So and then you know many a times we take this Δg as $\Delta g\ \Delta t/t_m$. So accordingly you can have these values you know you can find this Δf value. So you know for that critical radius value so this is the concept of homogeneous nucleation where we assume that there is homogeneous you know equal probability of having the nucleation at these different points. However, in welding also in welding in fact the always there will be some nucleation and then for that there will be growth.

We also understood that the growth will be you know so as the crystal grow you will have one preferential direction for the growth according to the crystallographic directions and then also the growth is predominantly in the direction opposite to the direction of heat flow. So accordingly you will have the formation of different types of grains which is there in any you know any case when there will be you know change of you know phase taking place.

So what happens that when you have you know so when you have homogeneous nucleation you will have certain value of the this activation barrier and that barrier need to be overcome and once that is overcome then in that case the nucleation will start. Now in the case of welding what happens that when you are welding you know to two materials two plates. So suppose in this area you are welding so the liquid metal which will be coming here.

So they will be basically melting this so you will have a zone of parent metal which is you know you know melted and partially unmelted. Now that basically resembles to the case of the not the actually the homogenous nucleation because in homogeneous nucleation the nucleation should have occurred any at any point inside. However, there is another kind of nucleation mechanism that is heterogeneous nucleation you know you may have must have the idea where the probability of the nucleation at the preferred points will be higher.

Now in case of welding what happens that these grains which are here they are partially you know melted with all of these heats. Now these are partially melted grains they will be working as the you know heterogeneous nucleating agents. So normally when we talk only about the heterogeneous nucleation in heterogeneous nucleation you know you will have you know normally what we see we assume that you will have the foreign particles.

Especially when we talk about the mould and all in that case we talk about the presence of sand particles at the mould or you may have the inclusions which are there you know inside the melt. So that also you know works I mean serves as the manipulating agents now its job is basically to alter the value of this Δf^*. Because in this case you will have the surface energy term coming into picture and that can be understood you know by the following process. Suppose what happens that suppose you have the inclusion.

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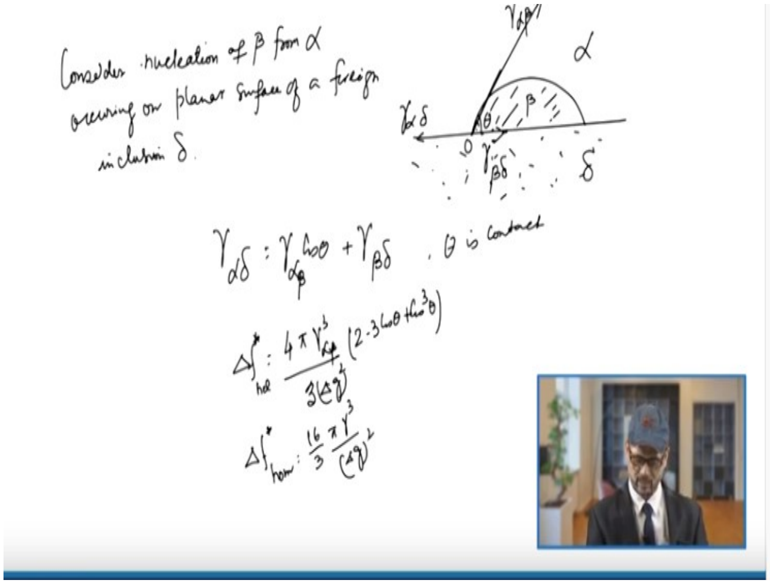

So if you have you know so if you have you know β particle you know which is formed in the form of half shape. So now in this case you just consider this nucleation of this β you know and this is nucleating from the α. So you will have a you know the surface energy term that is $\gamma_{\alpha\beta}$. So we are considering the example of you know nucleation of β from α occurring on planar surface of your foreign inclusion δ.

So basically we are talking about the so you have this is your foreign inclusion you know δ and you know so we are talking about the nucleation of this β you know this β is there. So this is your β and this is nucleating on the planar. So this is nucleating from α so you will have this as the so this is will be your γ you know δ and this will be your γ_{δ}.

So that way now you will have the balancing of the you know equation at this point. Now in this case you will have you know if you look at the these you know γ term in all the directions. So you will have you know γ_{δ} so this will be so you will have here this side. So accordingly if you have the so this will be $\gamma_{\alpha\beta}.\cos\theta$ this is your cosθ and this will be + γ_{δ}.

So theta is basically the contact angle so β particle basically forms in the shape of the half lengths as you see this is forming in the shape of half lengths and we are assuming that you know we are assuming that the surface tension forces basically at this point O they are in equilibrium.

Now when we have you know such system in that case you will have different surface energy terms and what we see that you have a new $\alpha\beta$ interface which is equal to the area of the curved you know surface of the lens that is produced.

Apart from that you have a $\beta\delta$ interface also which is formed which is equal to the circle you know area of circle of the intersection of lens with the planar δ surface. So that is also formed but you have one $\alpha\delta$ interface basically you know that is consumed. So you have 3 surface energy terms 2 is positive and 1 is negative that $\alpha\delta$ is basically consumed and because of the you know nucleation of this β particle.

So you know if you take it has been seen that if you take all these you know surface energy terms into you know account then the Δf^* this comes as you know the $4\pi\ \gamma_{\alpha\beta}/3\Delta g^2$ and then you will have the term. So you know this will be $2\text{-}3\cos\theta + \cos^3\theta$. So this is you know found in the case of you know the heterogeneous nucleation.

Now this is basically heterogeneous and if you go to the our expression for homogeneous you know nucleation in that case it becomes $16/3\ \pi\gamma^3/\Delta g^2$. So basically what we see that if you look at the you know outside the bracket if you leave this term you know outside the bracket.

Then what you see is this is $\Delta f_{heterogeneous}$ will be $1/4^{th}$ of the $\Delta f_{homogeneous}$ because it is $1/4^{th}$ will be $4/3\ \pi\gamma^3/\Delta g^2$. So if you are leaving you know this term now that is your 1/4 of this. Now so neglecting this term now since you know in the case of heterogeneous nucleation you have the extra particle and its presence basically will be altering the mechanism of you know nucleation and further growth in a different manner. Now there may be different cases so if you look at the different cases.

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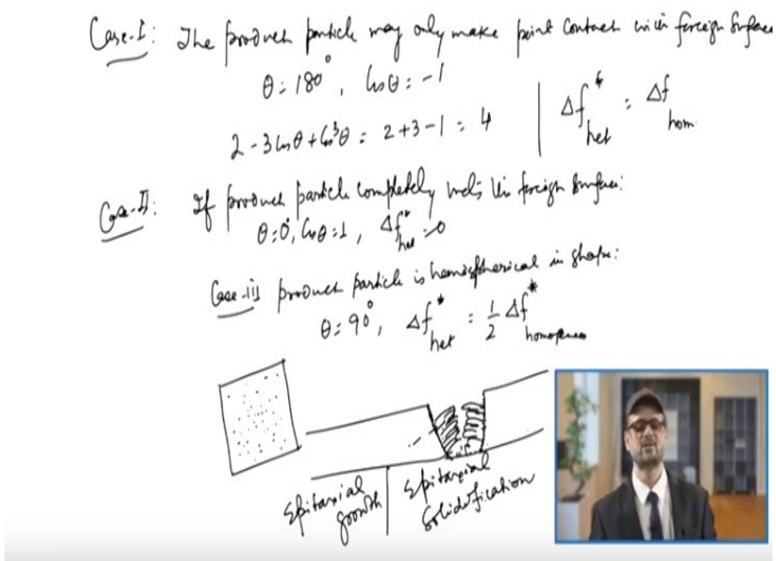

If suppose in the first case if say the product particle may only make point contact with foreign surface. Now depending upon the different values of θ this Δf* heterogeneous and $\Delta f^*_{homogeneous}$ will be changing. So if the product particle is would not be making only point contact now in that case your contact angle theta will be 180^0. Now if you look at the 2 expressions.

So you will have you know the in the case of you know heterogeneous you will have $4\pi\gamma_{\alpha\beta}^3/3\Delta g^2$ are and then 2-3 cosθ + $\cos^3\theta$ so if you put the θ=180^0 so θ=180^0 =-1. So your cosθ will be -1 so your term that is inside the bracket is 2-3cosθ + $\cos^3\theta = 180^0 \cos^3\theta$ so it will be 2 and it will be 3 so 2 + 3 5 and then have -1.

So it is 4 now in the in the case of that the Δf you know heterogeneous that will be multiplied with 4 times. So if you take this term into account and that was the actually the difference between the $\Delta f_{heterogeneous}$ and Δ of homogeneous 4 was the factor. So in that case $\Delta f_{heterogeneous}$ becomes same as $\Delta f_{homogeneous}$. So that becomes the case with the case of the contact angle being 180^0.

Now if you take the second case if the second case is taken in such a manner that your theta is changed. So in that case if product particle completely welds the foreign surface that is you know it is forming a vanishing thin-film on the δ particle. In that case you know theta becomes 0 so if the that is θ becomes 0^0 in that case cosθ will be 1. So your 2-3 cosθ + $\cos^3\theta$ that becomes 1.

So this term when multiplied with the $4\pi\gamma_{\alpha\beta}^{3}/\Delta g^{2}$. So that multiplied with 0 that becomes 0 so $\Delta f^{*}_{heterogeneous}$ it becomes 0. So basically there is no barrier to nucleation so it means if you have a particle which is completely wetting the foreign surface in that case your it is basically very much promoting the heterogeneous nucleation because the activation barrier that becomes 0.

So if you take the next case as case 3 where the product particle is hemispherical in shape. So in such case your theta will be 90^0 and in such cases below theta is 90^0. So you will have this as 0 so you will have this as 2 times so in such case it was 4 times. So now it will be 1/2 times.

So Δ f heterogeneous will be 1/2 of you know $\Delta f_{homogeneous}$ so what is seen that normally you when you have the presence of the foreign you know particles. So that basically is you know assisting the solidification in the way that you have the chance of heterogeneous nucleation and then there will be no further growth depending upon the direction depending upon the other conditions of growth.

Now in the case of welding you know there is chance that you have you know the presence of these sides from where the solidification will start and these chances are as we discussed that when you have you know the welding process going on. Now in this case you know when the liquid metal is melting at these positions.

So basically these positions here they will be partially melting these points and here you will have producers on the surface you will have minute grains which will be now exposed and they will be working as the heterogeneous nucleating agent. Now from here the nucleation will be started and then they will try further to grow.

Now the growth will be certainly as we know that growth will be you know towards the direction of maximum the growth will be towards the direction of opposite to the direction of the heat flows and heat flow is basically going from here. So it will be going like this so you will have the flow of you know so those so the growth will be so initially you will have very large under cooling here and then so you will have some final grains and then ultimately your growth you know occurs like this.

So this way your you know if the growth occurs and you will have the formation of the grains you know going on. So that way you know this growth I mean concept of heterogeneous nucleation can be understood. Now the thing is that it is not the heterogeneous nucleation is not only because the grains are here. Normally heterogeneous nucleation can be at any point and many a times what is done is that you are basically giving some alloying elements or some elements even inside the domains.

So basically at these you know all locations you have the probability of having the conditions in such a manner that your Δf value will be smaller. Now on all these sides normally you will have the chance of nucleation and if the nucleation is occurring at more and more number of sides then you will have the you know the formation of very fine structure. So normally that is in the case of heterogeneous nucleation.

Now in this case you have basically these partially and melted grains which are there which is on that you know solid liquid interface which is formed along the fusion line. Basically your this works as the you know point from where the nucleation is assisted anyway and you have a that works as the point from here the growth starts and this kind of growth is also known as the epitaxial growth.

Or you know the kind of solidification which is because of these unmelted you know grains which are acting as the nucleation sides from where the growth occurs that kind of solidification mechanism is known as the epitaxial solidification. So this is the solidification mechanism in the case of you know welding. Now depending upon that what is the degree of under cooling which is experienced here or how fast the heat is extracted.
So based on that the structure in this locality will be you know determined or will be you know seeing that how will be the structure inside that will be basically depending upon what is the cooling rate and what is the thermal conductivity of the material. Because that will be you know based on that which can be depending upon the degree of under cooling your growth will also

proceed because here this zone is normally smaller and it is always connected with these you know metal on all the sides.

So your heat rate of heat transfer is quite high so your growth occurs and you will have the structure like this. So then also there are other concepts of solidification like we talked about the you know solidification of metals and solidification of alloy they have different mechanism. So for that there are other factors coming into consideration.

Now many times what we do is that to define the you know grains inside this weldpool you can have so many a times what we do is we in the in the filler metal we are giving the alloying elements basically those alloying elements that will go into this zone and these they will be you know dispersed inside this domain. Now these you know if they are there are many elements allowing elements which basically work as the grain refiners.

So that is nothing but their presence will enhance the nucleation centres you know that of the presence of nucleation sides and in turn basically the increase you know the number of grains so they make the grains finer and then finer grains are certainly good for the better mechanical properties to be achieved. So that that again is the concept of the you know my heterogeneous nucleation which we have studied in this case.

Then we will talk about in our coming lectures that what is the solidification mechanism you know when you have the solidification of alloys. Because we must understand that when there is solidification of alloy in that case you know the solute will be coming out so you will have at any point you will have a solid part as well as liquid part inside in between the solidus and liquidus temperature range.

So basically in that you will have the you know the solid part and the liquid part they will be having different solid content and that basically you know establishes a gradient you will have depending upon the you know slope of the solidus or the liquidus line and you will have a different.

You know the difference between the solute you know between the solid and the liquid part and as far as the concentrates of the concentration of the solute is concerned you will have a difference achieved and basically you know that also affects your you know freezing mechanism the type of grain which you are forming.

So the cooling rate which is you know which is experienced which is experienced under any welding process that effects you know the type of structure which you are getting because in those cases depending upon the cooling rate side that you may have the formation of the dendritic structure or you may have the planar structure or so.

So that also can be you know understood if you have a particular you know condition and by looking at the cooling rate you can predict what kind of structure will be there for alloys also because you will have some redistribution of you know atoms taking place in terms of diffusion you know at any temperature or so and what is the you know what is the capability of that or what they what is the degree of diffusion that is possible.

So based on that the structure you know will be also different. So these aspects will be discussed in coming lectures. Thank you very much.