Welding Metallurgy

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Lecture - 30
Grain Structure during Solidification in Welding

Welcome to the lecture on Grain Structure during Solidification in Welding. So we will talk about you know after the solidification starts in welding then what way the grain growth takes place and we have already discussed about you know this phenomenon which primarily takes place in welding that is epitaxial solidification or epitaxial growth. So we will have the idea about the epitaxial growth as well as the non epitaxial growth and also you know how that nucleation starts. So about these things we will have the discussion in this lecture.

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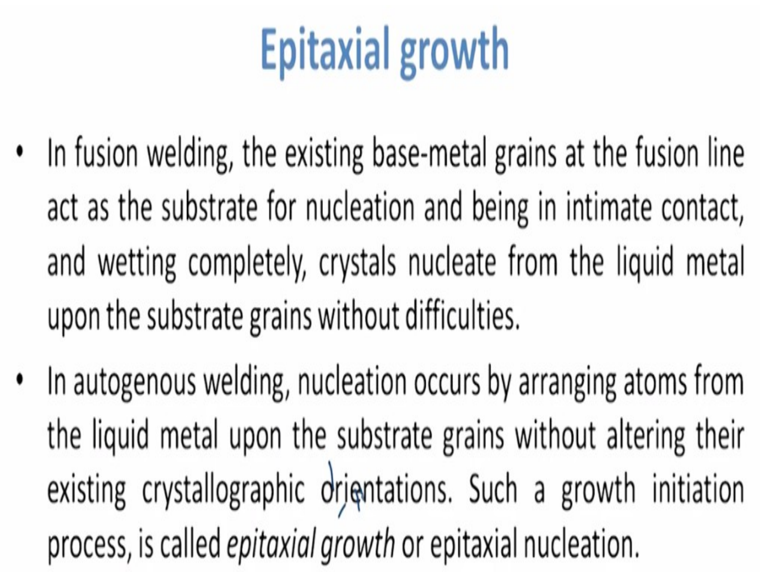

So in fusion welding the existing base metal grains at the fusion line act as a substrate for nucleation and being in intimate contact and wetting completely crystals nucleate from the liquid metal upon the substrate grains without difficulties. So as we have seen in the case of you know nucleation so we understood that nucleation is normally of two types. So you have the homogeneous nucleation and you have heterogeneous nucleation.

So as we have seen that in the case of heterogeneous nucleation again the particle to nucleate you know from the substrate there are few things which are you know coming into picture. The one is the surface energy terms another is the contact angle and based on that we already have seen that you have the, you know, activation energy formula that was there. So the energy barrier that has to be overcome.

So that basically can be computed with the help of the formula and there it was 4 and gamma cube and then you have a term of $T_m^2/3$ of ΔH and ΔT^2. So and then in the bracket term we had $2-3\cos\theta+\cos^2\theta$. So in that basically we had seen that depending upon the θ value this barrier for the nucleation which has some value in relation to what is required in the case of homogeneous nucleation.

So you know that factor can be computed for different value of θ and when your θ is 0 that is there is complete wetting in that case the term inside that is $2-3\cos\theta+\cos^2\theta$ so that term becomes 0 so your energy barrier becomes 0. So you do not have any difficulty in nucleation. So that in how now in those cases what will happen that you will have a growth and typically what you see in welding that if you have the similar material which is present.

And which act as the nucleation sites then the further and further the growth takes place. So that is the in the case of you know epitaxial type of solidification or epitaxial growth. So that is how it is defined in such cases.

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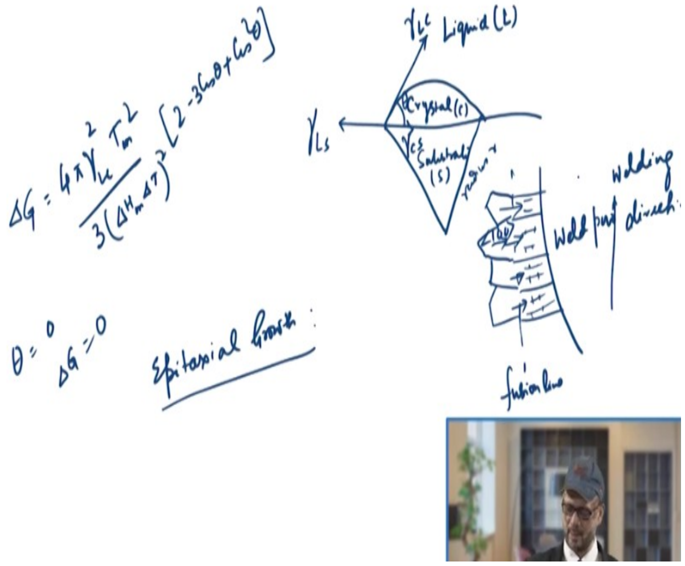

So we have already seen that when we saw that we have a substrate suppose you have a substrate here so and for the crystal which is you know here so this is suppose crystal which is to nucleate. So this is C and this is your substrate so that is denoted by S and you know this is liquid so this is L. So you know we have already seen that if this theta is the contact angle so you will have you know surface tension term gamma L_C you know this value and then you will have you know gamma C_S so this will be here.

And similarly you will have the gamma L_S and we have already seen that so this will be the radius r in this case. Now we have seen that if you talk about the energy barrier which is to be computed so for the crystal to nucleate so that is actually $\frac{4\pi\gamma^2 T_m^2}{3(\Delta H_m \Delta T)^2}[2-3\cos\theta+\cos^2\theta]$.

So that is what was the equation I mean expression for the energy barrier for the nucleation. Now as we see when there will be you know mostly in case of autogenous welding when you do there is no filler and when there will be complete wetting characteristics. So in those cases you know when it becomes θ as equal to 0. So this term will become 0 so your ΔG becomes 0.

So you know so when the metal in the weld pool is in intimate contact with the substrate grains so then it will be the case where there will be no barrier to the nucleation and there will be nucleation without much of the difficulties. So what happens that now in these cases when your there is no difficulty for the grains to nucleate so what will happen that the nucleation is occurring.

Now in these cases the nucleation will be occurring by the arrangement of atoms from the liquid metal you know upon the substrate grains without altering basically their you know crystallographic orientations and that is what is you know such that such process is known as the epitaxial you know growth. So this epitaxial growth is you know normally we have given this referring to the example of the autogenous type of welding process.

So in these cases you know the growth mechanism that will be known as the epitaxial growth or the nucleation also which is occurring you know the pre-existing grains which are there and working as a nucleation sites so that will be basically the epitaxial nucleation. So normally it will depend upon you know if you have a material so you will have a preferred crystallographic direction in which the growth will occur.

And it will be looking like you suppose this is your you know weld pool so suppose this is your welding direction and if this is the weld pool so what will happen that you will have a fusion line will be there. So this becomes your fusion line and be on that fusion line you may have the grains. So you will have the, you know, grains here and then these so you have different type of grains like that it was you know there.

Now these grains basically will be growing and they will be growing in these direction. So what has been seen the for FCC or body centered cubic structures. Now in these cases you will have the growing of the grains in this fashion it will be you know moving. So these are the for FCC or BCC the preferred directions of growth are basically a 100. So they are basically the way they are moving it is basically <100> direction.

So we know that this is the preferred direction of growth in the case of FCC or even you know BCC crystal structure. So the trunks of the columnar dendrites will be growing in that direction and going towards this weld pool and go up to this the center line. So without changing their directions basically these grains grow. So that is your you know epitaxial growth in the welding.

And that is what is you know written that in autogenous welding basically nucleation will occur by arranging atoms from the liquid metal upon the substrate grains without altering their existing crystallographic orientations and that is known as the epitaxial growth or such kind of nucleation will be known as the epitaxial type of nucleation.

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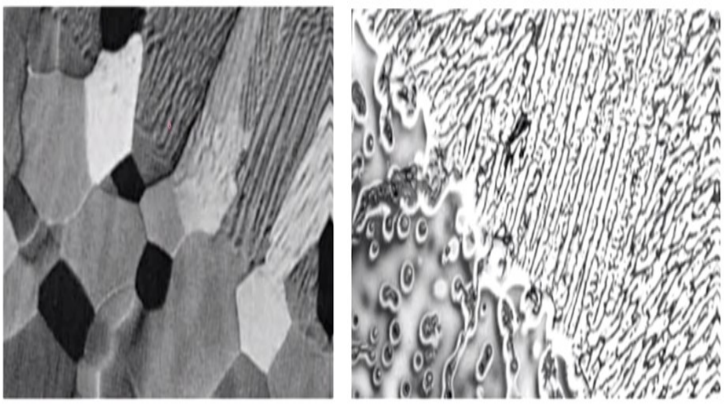

Epitaxial growth near fusion boundary

So this can be understood by referring to these micro structures and here you can see this is for the electron beam welding of the alloy. So this is for the you know C103 alloy and now it has it is seen that you have the you know how you see that this dotted line this is your fusion line and what you see that this is the epitaxial growth you know from the fusion line going into it.

Now similar is the case when we go for the aluminum copper if you look at the aluminum copper alloy. Now in these cases this is Al-4.5%Cu alloy and here also you see that they are growing in you know one particular direction so that is your preferred direction of growth in such cases. Now this is about the epitaxial growth however there may be you know the non epitaxial growth also.

When you use the you know fillers in those cases you will have the chance of non epitaxial growth at the fusion boundary.

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Non-epitaxial growth at fusion boundary

- When welding with a filler metal (or joining two different materials), the weld metal composition is different from the base metal composition, and the weld metal crystal structure can differ from the base metal crystal structure.
- When this occurs, epitaxial growth is no longer possible and new grains will have to nucleate at the fusion boundary.
- The fusion boundary exhibits random misorientations between base metal grains and weld metal grains as a result of heterogeneous nucleation at the pool boundary.

So you know in this cases when you are doing the welding with a filler metal or we are joining two different materials then the weld metal composition will be certainly different from the base metal composition because there are two different materials being welded or similar material being welded, but you have a filler material which is of different composition, different material.

So in those cases you know the weld metal crystal structure can differ from the base metal crystal structure and in these cases you know when this occurs the epitaxial growth is no longer possible and new grains will have to nucleate at the fusion boundary. So in those cases you do not have you know the complete wetting characteristics being satisfied. So you will have the nucleation of the new grains.

And so new grains will be nucleated at you know the fusion boundaries and from there you will have the, you know, further growth of the grains. So the fusion boundary will be exhibiting it exhibits random misorientation between base metal grains and weld metal grains. So because you know they are not of the same materials so you will have the you know there will be certainly some misorientation between you know these grains.

And so you know in these cases you will have the chances of heterogeneous nucleation you know occurring and by that process basically the growth will be taking place. So normally when we talk about the you know the grain structure near the fusion line you know in those cases.

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Competitive growth

- Away from the fusion line, the grain structure is dominated by a different mechanism known as competitive growth.
- Grains tend to grow in the direction perpendicular to pool boundary. However, columnar dendrites or cells within each grain tend to grow in the easy-growth direction.
- Hence, grains with their easy-growth direction essentially perpendicular to the pool boundary will grow more easily than less favorably oriented grains. This mechanism of competitive growth dominates the grain structure of the bulk weld metal.

So away from the fusion line, the grain structure will be dominated by the different mechanism that will be known as the competitive growth because what we see that you will have two directions of growth one is your crystallographic direction and another so that is your easy growth direction and you know you have two way one in crystallographic direction another is the growth direction in which the growth will be maximum because that will be depending upon the direction of heat flow.

So the grains will tend to grow in the direction perpendicular to the pool boundary. So however columnar dendrites or cells with each grain tend to grow in the easy growth direction. So normally you have certainly because you have one is your perpendicular to the pool boundary another is you know in the easy growth direction. So the grains with the easy grow direction essentially perpendicular to the pool boundary will grow more easily than less favorably oriented grains.

So basically you have you know two conditions of growth and in that case you know wherever the grains which have their easy growth direction which is perpendicular to the pool boundary that will so if these two conditions are met in that case the growth will be more easily then basically where it is not you know meeting this condition and when it is so only along that you know those grains which have this condition satisfied they will be growing.

And this mechanism is basically known as the you know competitive growth so this is known as the mechanism of a competitive growth you know in such cases. So basically we need to know the easy growth directions and if you talk about you know the easy growth directions so you have for different type of crystals you have different easy growth directions.

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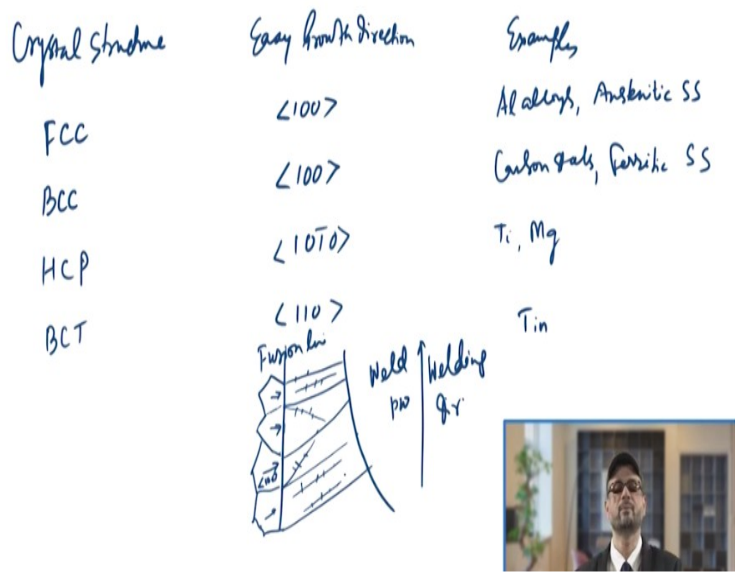

So if you talk about the you know crystal structure and if you look at the easy growth direction. So that basically you must have the idea when you study these material science in engineering. So if you talk about the face centered cubic structure FCC now for them the easy growth direction is <100>. Similarly, for the BCC you know crystal crystals having BCC structure again you have the easy growth direction as <100>.

Then for FCC we know that the you have typical examples will be you know like you have aluminum alloys or you have austenitic stainless steel. So similarly for BCC you have carbon steels and you have ferritic stainless steel so these are the you know BCC having BCC crystal structure. Similarly, you may have the hexagonal close-packed structure and it has the direction of <10$\bar{1}$0> and then we know that for such you know materials like titanium or magnesium they come under these type of crystal structure.

And they have the value <10$\bar{1}$0> this is the easy growth direction and similarly you have the body centered tetragonal. So now in these cases you have the direction as <110> and the example is Tin. So this way you know easy growth directions are there for you know for the different type of materials with different crystal structure and you know the concept of the you know perpendicular phase because that will basically give you the idea of maximum temperature gradient or maximum heat transfer.

And then when it is matching with when so all those grains which are having you know the easy growth direction and then they are perpendicular. So your grains with the easy growth direction essentially perpendicular to the pool boundary they will grow more easily. So others growth will be pitched up because they will try to grow in their easy growth direction, but then that is not basically you know having any perpendicular direction to the primary heat flow direction.

So they will be pitched off and you will have you know the pinching off certain grains and then growing primarily you know columnar of some grains which have the that orientation. So if you try to look at the you know competitive grain growth direction so how you can see you know that if suppose you have this is the suppose weld pool and this is being the welding direction.

So what will happen now assume that this is your, you know, fusion line so in those cases now what will happen that you have the you know different you know grains which are there. So now they will be shown like you know you have such grains is there. Now what may happen that you know if so this will grow in this fashion or that may grow so and this will grow in this fashion so this is your <100> so you know and from here it will grow like this.

So this being <100>. So you know perpendicular to this pool boundary basically your growth will take place so your growth is going like this similarly you know this will be moving like and then so and some maybe you know pitched off like this. So there may be some going like that but ultimately the growth becomes you know like this. So this is the example of you know the competitive you know growth mechanism in the case of welding.

So then we will talk about you know the effect of the welding parameters and if you talk about the effect of the welding parameters like the especially the welding speed. So if you choose high speed and if you choose the low speed in that cases the you know along with the orientation of the grains also they will be changing. So you may have the low speed and you have the high speed.

So when you know you have a low speed then the weld pool shape is basically elliptic and we have understood, we have already discussed about it that when you are you know changing this speed then at higher speed it becomes in the form of tear shape and accordingly the grain orientations also grain structure changes.

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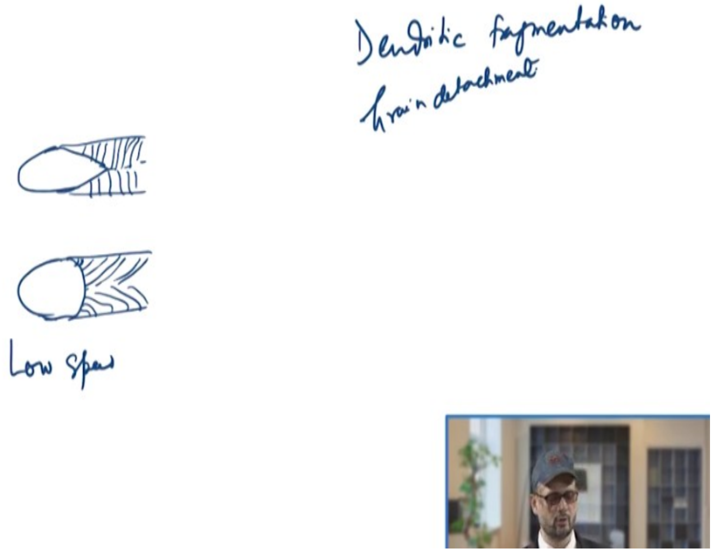

So when you have the low speed now in those cases your you know the grains which you get they will be having this is the you know pool looks like and that way your grains will be you know shown. So you know in the middle it will be moving like this so this way your grains will be looking like. So this is how you know grains will look in the case of low speed and at high welding speed you will have the you know tear-shaped you know pool.

So you will have so this way the pool shape will become and in that case your range will be straighter so that way. So you know columnar grains are essentially straight you know when the high speed is higher and you know here it is curved you know to grow perpendicular to the boundary. So that is the effect of welding parameters you know so by looking at the structure you can have the field that how the speed variation will be you know changing the you know grain structure.

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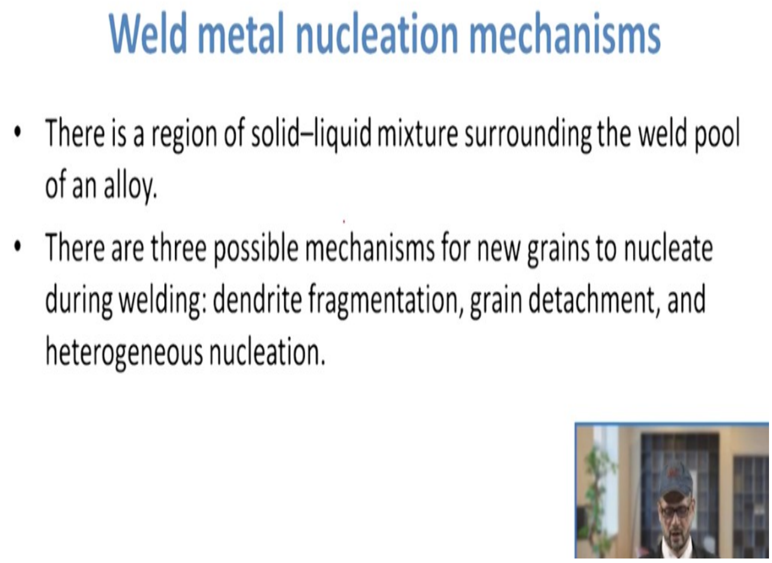

Next thing which is important to be understood is the weld metal nucleation mechanism and there is typically you have you know you have certain as we know that there is region of solid liquid mixture in the case of welding. So I mean when we talk about alloy. So as we know that when we talk about alloy so you have a region of you know mushy zone. Now these mushy zone have the solid as well as the liquid region.

Now these regions so now there are basically three possible mechanisms of the new grains to nucleate during the welding and these three mechanisms are said to be the dendritic fragmentation, grain detachment, and the heterogeneous nucleation. So what happens that when there will be convection will be dominating so what may happen that in the you know weld pool you know convection so if there is a weld pool convection.

So that may lead to the fragmentation of the dendrites and you know basically they will be towards the tip of dendrites and it is in the mushy zone. So those dendrite fragments they actually work as the nucleation points, they will be acting as the new nuclei to form the grains. So basically they are like the heterogeneous nucleation sites which occurred in the case of you know welding.

And this is you know frequently this is a basically said to be a grain refining you know mechanism for the weld metal. Similarly, the second point is so one is your dendritic fragmentation then you have the grain detachment also is being experienced. So what will happen that during in the case of the weld pool convection the partially melted grains they will be detaching themselves from the solid liquid mixture.

And then they will be again working as these you know as the nucleation points. So that way they also work as the heterogeneous nucleation sites and then you know many a times you have the heterogeneous nucleation. So that is by the addition of or by because of the presence of heterogeneous you know nucleation nucleating elements or you may have you know many a times you have the foreign particles which are present in the weld pool.

And these foreign particles which are present in the weld pool they act as the nucleation sites. So they also work as the place from where the nucleation and you know starts. So these are the 3 ways for you know the nucleation to occur in the case of weld pool. So this is you know this has to be understood you know so once we understood that you know you have solidification taking place.

Solidification will be because of the thermal gradient then we will be next we will be talking about you know what are the consequences of these thermal gradients, what are the distinct zones in those you know weldments so we will have more and more idea about the other aspects because of this temperature you know in the weldments. So that is about you know this grain structure and their trades during the welding process. Thank you very much.