Joining Technologies of Commercial Importance
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Lecture - 31
Solidification of Weld Metal

Hello. I welcome you all in this presentation. This presentation is based on the solidification of the weld metal. Which is primarily related with the fusion welding process and this presentation is also associated with the subject joining technologies for the metals. So, today we will be talking about the weld metal solidification.

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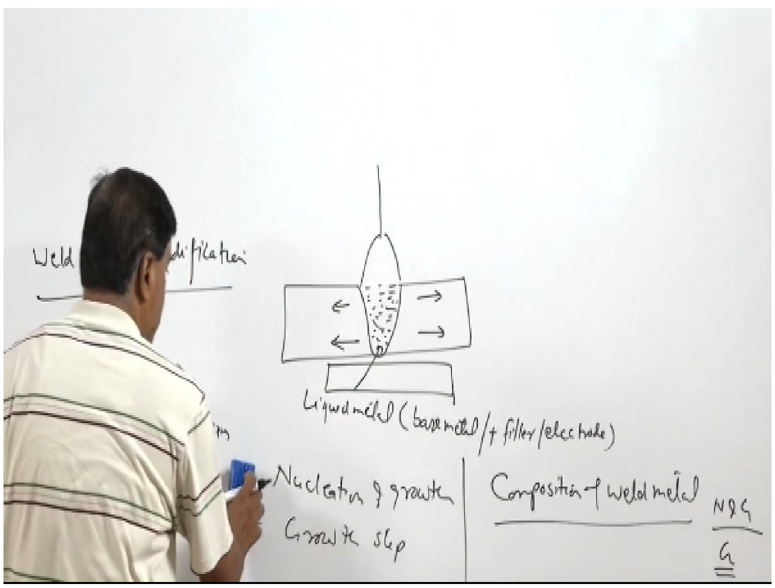

We know that in fusion welding processes when the base metal is joined the fusion of the edges of the plate is achieved so the molten metal, the weld metal which may be either composed of just the base metal or may be the filler metal is coming also from the either electrode or additionally from the outside. So, this portion of the liquid metal either from the base metal fusion or plus it may be from the filler or electrode.

In case of the consumable electrode, consumable arc welding processes. So, with the application to it, things are brought to the molten state and due to the thermal conductivity of the base metal heat is lost gradually to the base metal, to the backing plate and then to the ambient condition. So, the heat loses result in the transformation of the liquid weld metal to the solid state and this is achieved through the solidification of the weld metal.

Solidification of the weld metal is found to be different from what is typically observed in case of the casting processes. So, in which way it is different, in which way it is same that is what we will be talking about here. So, solidification mechanism in welds can be of the two types one is the Nucleation and growth steps or directly the growth step. So, here in the first case the nucleants will be formed or nucleation will take place first.

And there after the molten metal consumed by the growth of those nucleants to form the degrees of the different sizes. So, more the number of nucleants are found finer will be the grains and more numbers of the grains will be formed in a given volume of the weld metal. While in case of the growth under the condition when just growth is involved during the solidification.

The partially melted grains of the base metal consume the liquid metal or atoms of the liquid metal deposit over the partially melted grains directly so just the growth step is involved. Under what condition these two kinds of mechanisms are observed. So it depends primarily on the composition of the weld metal. So, whether there will be a nucleation and growth mechanism only for the solidification.

Or just growth mechanism for the completion of the solidification of the weld metals it depends upon the composition of the weld metal. So, the conditions when the weld metal. So, the conditions when the weld metal composition is completely different from the base metal. Like the cast iron is welded using the Nickel filler so once side we have the BCC crystal structure another side we have FCC crystal structure.

So, when we have completely different the weld metal then the base metal then the nucleation and growth mechanism is involved for completion of the solidification while when the both base and weld metal composition are either they are same or similar with the marginal difference, minor difference does not affect the things much as far as mechanism of the solidification is concerned.

And in that case just the growth mechanism is involved for the completion of the solidification. So now we will see that how it works and what happens in these two cases.

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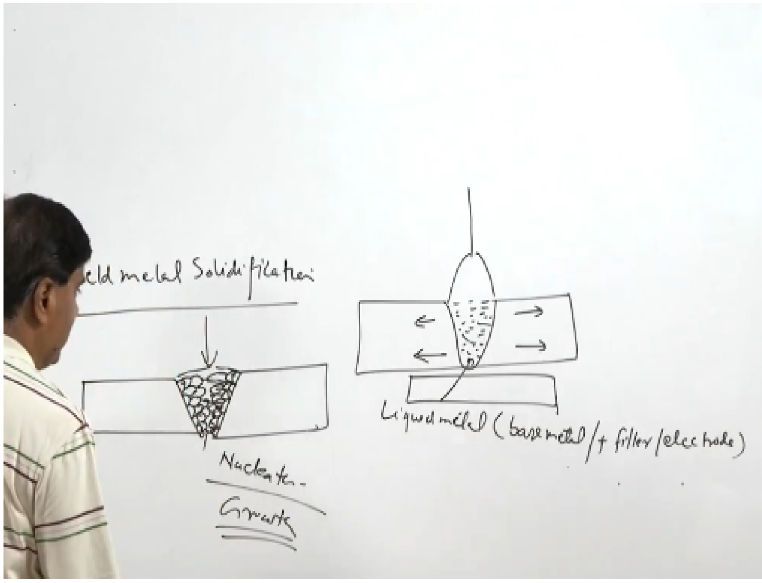

For example, say this is the faying surfaces of the base metal and here the completely different weld metal is obtained so in that case the first nucleation takes place at the fusion boundary and then these nucleants will be consuming the remaining liquid metal in course of the solidification due to the transfer of the heat or heat loses to the base metal as well as to the environment. So, here next to the fusion boundary first the nucleation is observed.

And thereafter once the nucleants are formed the growth step takes place and then during the growth only most of the liquid metal is consumed during the solidification process and they change from the liquid state to the solid state takes place. This is what happens typically in case when the nucleation and growth mechanisms are involved and when completely different base metal and the filler metal composition exists and when the 2 are same then what we will see?

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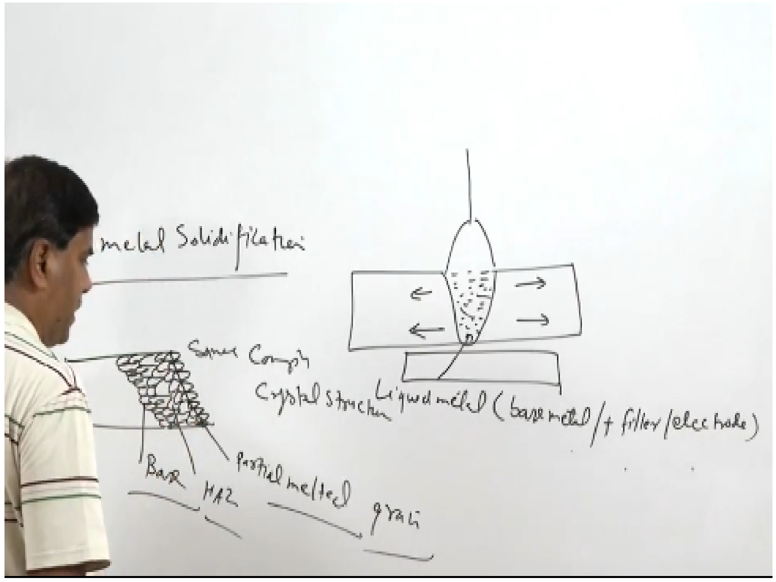

Like say this side we have the fusion boundary so when we fuse the things it will have typically the curve surface and at the fusion surface we will have partially melted grains like this. Next to that we will have heat effect zone which will have somewhat coarse grain structure like this and then with the finer structure as we approach towards the base metal. So, far away from the fusion boundary there will be no effect of the heat so that we can define as a base.

Then next to that which is coarse that will be defined as heat effected zone and then next to the fusion boundary there will be partially melted grain and these partially melted grain actually are of the same composition and same crystal structure and because of this as the heat loss takes place the atoms from the liquid metal directly start to deposit over the partially melted grains and then grains starts to grow.

So, the growth of such grains, partially melted grains is primarily takes place in course of the solidification when the composition of the filler and the base metal is same crystal structure of the base and the filler are of the weld metal which will be produced are same. So, in that case we will have just the growth mechanism involved in solidification of the base metal. But there is a continuous change also in the grain structure which is observed typically in casting what we get?

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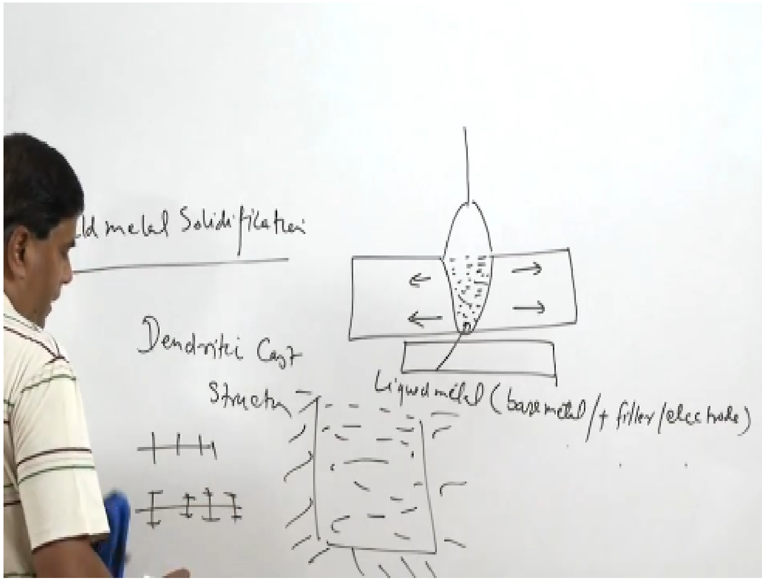

We get the dendritic cast structure. Like if this is the mould may be metallic or sand and when the liquid metal is allowed to solidify it mostly forms the dendritic structure. So dendritic structure schematically is shown like this one primary arm, secondary arm, may be tertiary arms also like this. All these are representative of the dendritic structure and the typical caste structure is the dendritic in nature.

In weld also the dendritic structure is observed but in addition to the dendritic structure we will be able to see the other types of the grain structure also. So, this is what we have seen that the weld metal can solidify through the nucleation or growth mechanism in case when the composition of the weld metal and the base metal are completely different and in case when the 2 are same then it is just the growth mechanism which is involved.

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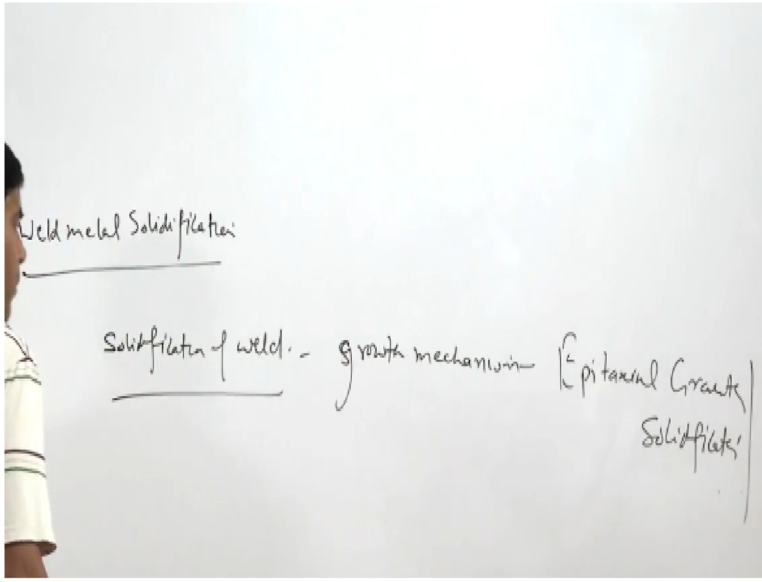

So, this typical solidification of weld which is based on just the growth mechanism is called epitaxial growth or epitaxial solidification which is primarily based on the growth. The mechanism only which in other case typical or the nucleation and growth mechanisms are involved. Now, we will see that what are the different types of the grain structures

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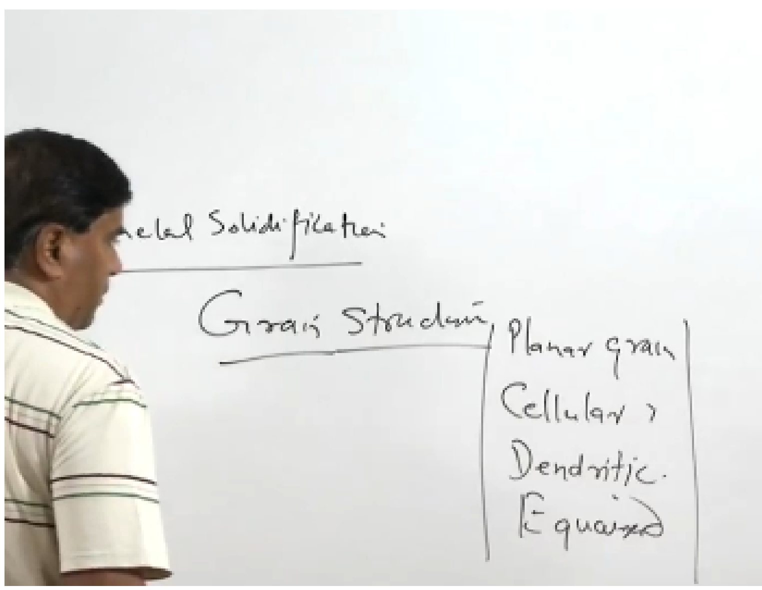

which are developed in the welding? So, grain structures which are observed in any typical weld metal it consists of the plainer grains, cellular grains, dendritic grains, and equant grains. And these four type of the grain structures are normally observed in typically conventional weld metal which is solidifying through the either the growth mechanism only or through the nucleation and the growth mechanism.

So, what are the conditions which will lead to the different types of the grain structures in the weld metal and what are the factors that govern this, the formation of the different types of grains structures. So there are basically the two factors

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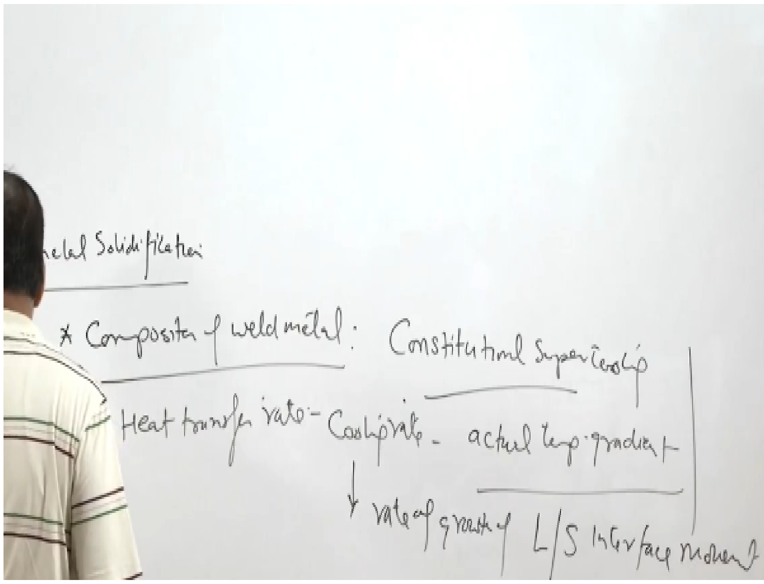

One is composition of the weld metal which is solidifying. This is one and this composition basically affects the constitutional super cooling aspect related with the solidification. And another is the heat transfer rate away from the weld metal so basically this is about the weld metal. So, basically this is about the cooling rate experienced by the weld metal and it actually affects the actual temperature gradient in the weld metal.

So, these are the 2 main factors that will be determining the kind of structures which will be formed and the cooling rate determines the rate at which rate of growth of solid, liquid interface movement. So basically rate of movement of solid liquid interface, the rate at which the grains grow during the solidification. So, these factors will actually be determining the kind of the grain structure which is formed one is the cooling rate experienced by the weld metal.

Which in turn will be governing the actual temperature gradient at the solid liquid interface and also that will be governing the rate at which the solid, liquid interface will be moving or the growing. And another one is the composition that will be governing the constitution cooling rate aspect. So to understand this

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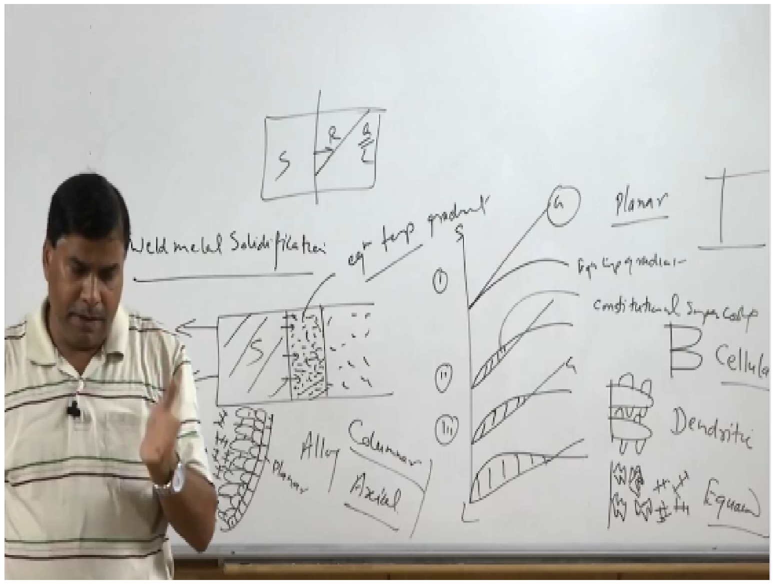

what we need to see this is say typical case, this is the portion which has already solidified, solid state. Heat is being extracted in this direction and this is the liquid metal which is here to solidify. So, in typical case what happens that if it is an alloy so solidification starts with the formation of the pure metal or the metal with a minimum concentration of the alloying element and one having the higher liquidus temperature.

So, this is the portion of the solid which will be formed by consuming the liquid metal and rejecting the excess alloying element or excess elements which are beyond the solubility limit in the solid state. So, basically in the region next to the solid liquid interface will be enriched with the alloying element. So, this is the region which will have the greater concentration of the alloying element.

It will be enriched with the different alloying element so this region very next to the interface will have the higher concentration of the alloying element as compared to those away from the solid, liquid interface. And because of this we will see that equilibrium temperature gradient in this region is found different from what is there for the remaining portion due to this compositional difference or enrichment of the alloying element in the vicinity of the solid liquid interface.

So, equilibrium temperature gradient is found different and it will depend upon at what rate the enrichment is taking place at what rate. Alloying elements are getting diffused within the liquid metal. So, if we will see this the typical say at solid liquid interface this is solid liquid interface and what we will have? The actual temperature gradient as per the cooling conditions is this. And then equilibrium temperature gradient may be high this.

Or for another condition this is one case for another case for the same actual temperature gradient you may have equilibrium temperature gradient like this and for third case equilibrium temperature for the same actual temperature gradient? So, this equilibrium temperature gradient is termed as G and equilibrium temperature gradient is this which is in increasing in terms of the concentration we can say. So, actual temperature gradient and more like this. So, this is what we can see.

So, here equilibrium temperature gradient is below the actual temperature gradient. This condition results in the case when the equilibrium temperature gradient is below the actual temperature gradient then this condition leads to the development of the plainer grains. And as soon as this condition is bypassed means we will have the equilibrium temperature gradient higher than the actual temperature gradient.

Then it results in the formation of the zone having the effects of the constitutional super cooling. And in this case constitutional super cooling zone is very limited it is somewhat wider and further wider so as the extent of constitutional super cooling increases in this case the solid liquid interface which was completely plain then and the case when the constitutional super cooling just starts it breaks the plain interphase.

And it results in the cellular grain structure or the plain interface is broken and cells starts to grow. So here the plain interface is disturbed and cells starts to grow and then further increasing constitutional super cooling results in the formation of the dendritic structure like this. So, increasing constitutional super cooling will be resulting in the first cellular and then further increasing constitutional super cooling will be resulting in the dendritic structure

And thereafter it will be causing the here equiaxed grain structure like this. So, all these fine these are typically represented like this. So, equiaxed grain structure. So, this is cellular grain structure, dendritic grain structure, and equiaxed grain structure technically. So, if we will see all these grains actually be growing if we take a typical weld metal where we have the liquid metal here and the heat is being extracted away from the fusion boundary in the base metal.

Then what we will have first due to the heat extraction the grains will be growing perpendicular to the fusion boundary and opposite with the direction of the heat flow. So, basically they will be growing perpendicular to the fusion boundary and opposite to the direction of the heat flow. So, here first of all its forms the cleaner grain structure next to the fusion boundary. Initially, we will have the plainer grains and thereafter we will have the cellular grains like this.

Width of these zones will be governed by the composition as well as the cooling conditions experienced by the weld metal during the solidification and thereafter we will have dendritic structure like this having the dendrites and in between at the same time normally we have the equiaxed grain structure and the similar kind of thing is repeated from both the sides. Since the plainer grain structure, planer, dendritic and cellular both these are columnar in the form.

Like they grow perpendicular to the fusion boundary. So, the grains which grow perpendicular to the fusion boundary they will be termed as columnar grain. And those which grow along the weld metal they are termed as axial grains. So, I will come to the columnar, axial grains slightly later so as far as these four types of the grains are concerned what we will have first the plainer grains then cellular, then dendritic and the equiaxed weld metal at the center.

And these are further related with the other parameters and they are shown schematically. The condition under which the four types of the grain structures are observed one important parameter is the G that is the actual temperature gradient and another parameter is the rate at which solid liquid metal interface will be moving. So, if this is the solid liquid interphase solid this side, liquid this side.

So, at what speed it is moving and what is the temperature gradient these two factors significantly govern temperature gradient is simple that what is the liquidus temperature and what is the solidus temperature and what is the gap between the two. And how fast it is moving and due to the concentration of the –due to the enrichment of the alloying elements how far reduction in the liquidus temperature is taking place.

So, these things will be governing the value of the G and R. So, the G and R values are basically used to relate the way by which the different types of the grains are formed. So, if we see here the typical diagram which is used to relate with the types of grain structure being formed here R the growth rate.

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And here G the actual temperature gradient in the y axis and the two R shown schematically. So, for the different combinations of the G and R values will be having the different grain structures like this. So, when the value of G is high and R is low we basically have the plainer grain structure and then for somewhat lower value of the G and higher value of R we have cellular then dendritic.

And then finally for the low value of G and higher value of R we have equiaxed grain structure. In addition to this, what we can show we can have one additional line like this. This is corresponding to the low cooling rate and this is corresponding to the high cooling rate. So, what it will have, what kind of effect it will have? Say for high C R, high cooling rate condition? So, when the cooling rate is high then cellular grains are fine.

And when the cooling rate is really low then in that case the cellular grains will be wider. When the cooling rate is high the dendritic grains will be fine like this and when the cooling rate is low then it will result very coarse, widely spaced arms like so because the dendritic arm spacing is used to define the size of the grains. And similarly here very big coarse equiaxed structure is obtained when the cooling rate is low.

And when the cooling rate is high we will have very fine equiaxed grain structure. Similarly, here big plain front is observed and here we may have finer the plain front, the solid liquid interface where the cooling rate is high. And since the temperature gradient is about degree centigrade per unite length and the cooling rate is also and growth rate is in mm per second say. So, the product of the G into R results in degree centigrade per second.

Basically this reflects through the cooling rate. So, product of the G and R reflects through the cooling conditions or the cooling rate. So, product of the G and R reflects through the cooling conditions or the cooling rate. So, all these things have been summarized in form of –so this diagram basically shows that how the actual temperature gradient and the growth rate effects the grain structure of the weld metal.

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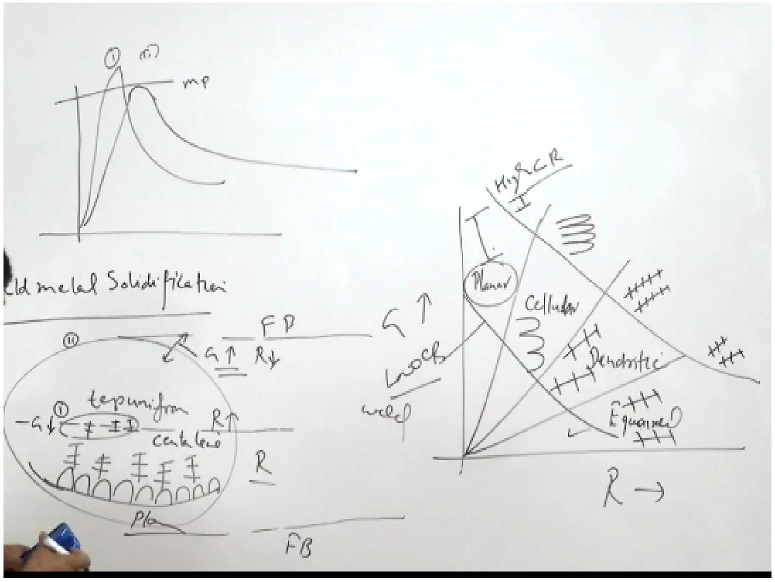

So, if we see any grain structure, then will have like say the typical weld pool like this her this is the fusion boundary. This is the weld portion. This is the fusion boundary and this is center line of the weld. So, at the center line of the weld the temperature is uniform or temperature all though peak but it is uniform. Well at the fusion boundary there is a sharp temperature gradient so G is actually high at the fusion boundary while the G is low because of uniformity in temperature.

So, the temperature gradient at the center is low so G value is low at the center while G value is high at the fusion boundary. On the other hand, the growth rate R since the center experiences the maximum cooling rate if we will see the weld thermal cycle for the point 1 and for the point 2, two is at the fusion boundary and point 1 at the center then we will see the center will have much higher cooling rate conditions as compared to that for the fusion boundary.

So, the fusion boundary the cooling rate conditions this is for 1 this for 2 both will have say may be center will have much higher temperature as compared to the fusion boundary. So, here we may have it like this. So, this is the melting point. So, at the center the temperature is above the melting point and the cooling rate conditions experienced are much higher. So the high cooling rate results in the higher growth rate also.

So, R value is high at the center and R value is low at the fusion boundary. So, the combination of the high value of G and low value of R, at the fusion boundary results in the high value of G and low value of R results in the plainer grain structure while at the center the low value of G and high value of R results in the equiaxed grain structure. So, it is very common that the fusion boundary invariably shows the plainer grain structure.

While the center will be having the equiaxed grain structure. That is why we see the continuous variation at the boundary we have plainer then we have cells like this and then we have the dendrites like this and then equiaxed at the center so that is why there is a continuous change in the grain structure from the fusion boundary to the center of the weld. In addition to this typical four type of the grain structures.

Which are observed in the weld metal additionally depending upon the heat input and the welding speed the two types of the grains are also observed based on the general orientation of the grains in the weld metal and these are termed as -

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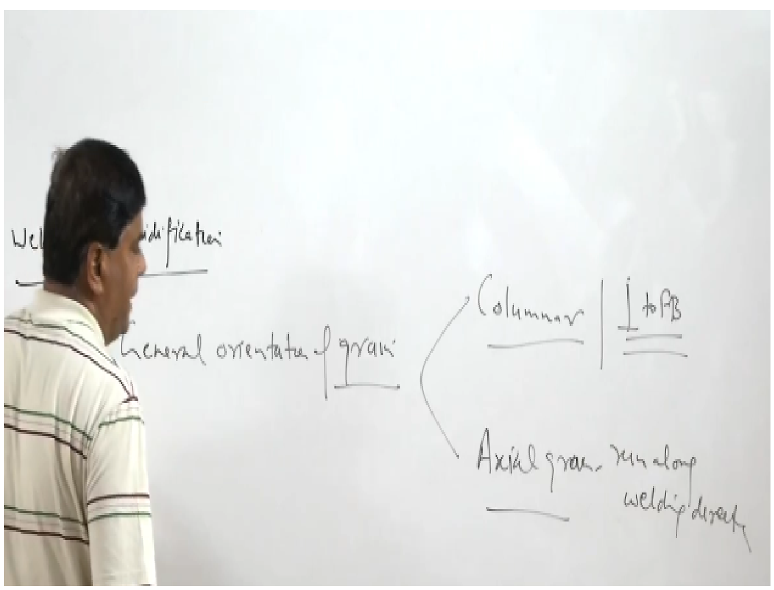

So, based on the general orientation of the grains in the weld we may have the columnar grains like all cellular, dendritic structures were the columnar ones and the axial grains. Axial grains these runs along welding direction while these are perpendicular to the fusion boundary. So the columnar grains basically perpendicular to the fusion boundary while the axial grains will be running along the length of the weld.

And these two are found to be the function of the shape of the weld pool, heat input and shape of the weld pool is actually effected by the heat input and the speed of the welding.

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So, if we will see we know that like say this is the base metal and if you are going very slowly then the pool is circular in nature and if we go slightly faster than it will be oval shape. And if it is too fast then half of the portion will be like say semicircular and the remaining will be the tier drop shape so here the edges are straight. So, very low speed, medium speed and the high speed. So, very low speed we will see as the pool will move.

We will have the grains like this which will be conversing at the center when it is oval shape what we will have the grains are conversing like this the pool is really very wide then in case of oval shape it results in the card grains meeting at the center like this. Because our pool is curve so during the solidification when the pool is also moving what we will see the boundary is also moving.

So the growth will be occurring perpendicular to the grains and in this case it will have all the grains will be growing like this because heat is transferred away and the grains will be going perpendicular to the fusion boundary. But when it is straight in case of the straight fusion boundary it will be resulting in, the pool is straight then all these grains will be meeting at the center.

So, curved columnar or very straight one so in one case the grains will be meeting like this at the different point while in another case they will be meeting at the common points. So, the curved grains meet at the different points and when they are straight they all will be meeting at the center so it is more preferred to have the curve columnar grains rather than those which go exactly in perpendicular to the fusion boundary and meeting at the center.

Because this kind of growth observed at high speed of the welding the grains coming from both the sides are abutting at the center results in the higher concentration of alloying elements at center. When we have the curved columnar grains then all these alloying elements will be distributed over the different locations. So they will not be segregating along the center line because segregation of these alloying elements at the center promotes the solidification cracking.

So, we want to avoid this. So, this is how we can say the columnar grains may be curved type or the straight ones under the different conditions these are found and when the pool is really very

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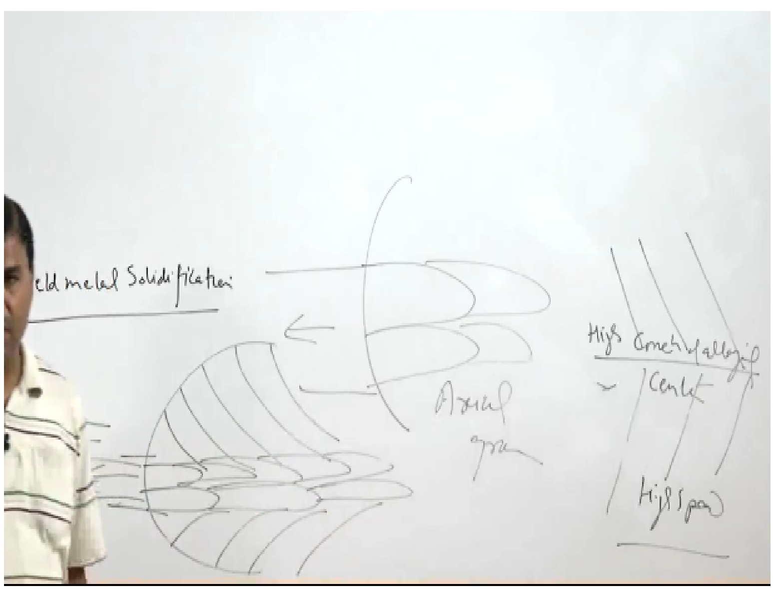

wide like this then apart from the curved columnar grains we see that some of the grains actually starts growing since this pool, this portion also starts extracting means already welded portion also starts extracting heat away from the pool so it results in the growth of the grains along the direction of the welding itself. So, this kind of the grains which are growing exactly perpendicular along the welding direction while other grains will be coming like this.

So these are curved columnar grains and few are axial grains. So, the axial grains are formed when the pool is very wide and already welded portion extract lot of heat so some of the grains start to grow in the direction of the welding. So, this in turn results in the axial grains. Actually, axial grains weaken the material as compared to the columnar grains. So, it is always preferred to have the columnar grains first.

And even in the columnar grains we try to avoid the cellular and the dendritic structures by replacing them with equiaxed grain structure because equiaxed grain structure results in the best combination of the mechanical properties as compared to the columnar cellular structures. So, now here I will summarize this presentation. In this presentation I have talked about the different mechanism which are involved in solidification of the weld metals.

What are the factors govern the grain structure of the weld metal and why the grain structures vary from the fusion boundary to the weld metal and on the bases of the general orientation of the grains how can we define them? What are the factors that affect the grain structures in the weld metal? Thank you for your attention.