Joining Technologies of Commercial Importance
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Lecture – 37
Solidification cracking and their control

Hello, I welcome you all in this presentation. This presentation is based on the solidification cracking and its control. You know that this type of cracking is observed mainly in the weld metal and specially in case of the base metal having the wider solidification temperature range or the impurities are involved too much in the base metal leading to the wider solidification temperature range or inappropriate selection of the base metal is made leading to the wider solidification range. So, these are the some.

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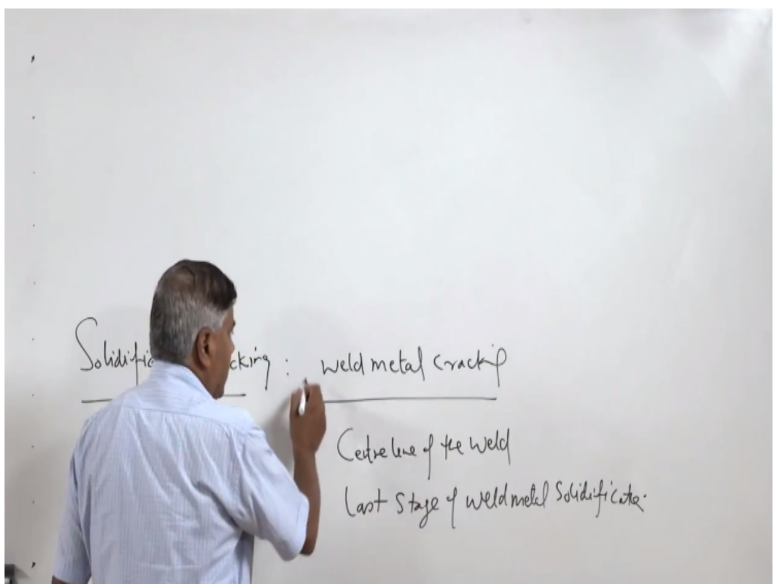

In all these cases, the common factor is the solidification temperature range which is observed, if it is very wide then it promotes the solidification cracking and it can occur not necessarily only in the aluminum alloys but also in the stainless steel. It is observed especially when the silicates of low melting point are present in the stainless steel or impurities like sulfur and phosphorus are present in the larger quantity.

So all those factor which are promoting to the wider solidification temperature range increasing the residual distresses. They will be causing the solidification cracking. So, solidification cracking is basically the weld metal cracking and that invariably it occurs at the center line of the weld, it occur at the last stage of the weld solidification. So last stage of the weld metal solidification.

So we will try to understand these are the common things occurs at the center line of the weld, it occurs in the weld metal and invariably occurs at the last stage of the solidification of the weld metal.

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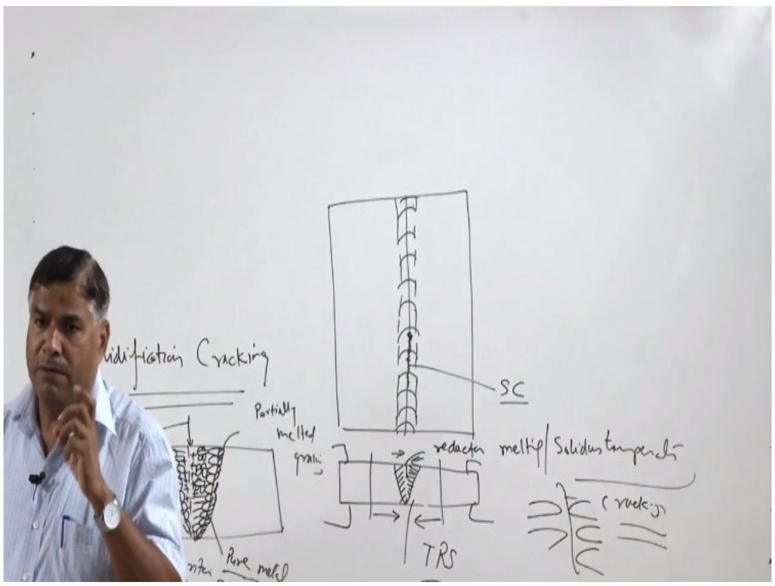

So now we will first the mechanism or the way by which it happens like say this is the plate welded, this is the center line and the weld made along the center line is like this, so if the solidification temperature range is really very wide for this metal, which may be either auto-genius or the filler is added resulting in the wider solidification temperature range in both the cases, we can find the crack running all along the weld.

So maybe crack may run like this all along the weld. This is called solidification crack. So how does it happen and how does it is start, we know that the whenever the two plates to be welded like this when they are fused with the application of the heat like this, so one fusion boundary is there and along the fusion boundary we will be having the partially melted grains, so solidification starts basically from the fusion boundary.

In epitaxial solidification typically it starts with the planar solidification which is almost pure metal most of the time, then it will have the cellular structure like this, so solidification proceeds by consuming the liquid metal and impurities or alloying elements are rejected into the weld metal. So after the cellular structure we have the dendrites like this. The dendrites also grow by consuming the liquid metal and rejecting the alloying elements and impurities in the weld metal.

So this is how things will be growing from both the sides so similarly the planer, other side also cellular and then dendritic like this and at the end what we have equiaxed dendritic at the centre, so finally things left for rejection at the centre, so finely actually the solid liquid front proceeds from the fusion boundary towards the center line and towards the center of the weld, so whatever is the molten metal left at the center.

This has a large amount of, like impurities which were rejected in course of the solidification or the alloying elements. So impurities like sulfur, phosphorus, lead or alloying elements like copper, silicon, manganese etc., so there is a continuous change in composition of the liquid weld metal during the solidification of the weld metal and what we have at the end is enriched with the alloying elements or the impurities.

So we know that as the alloying concentration increases as the impurity concentration increases in any metal it is melting point decreases so high concentration of the alloying elements and impurities results in the reduction in the melting point or the solidus temperature. Solidus temperature is the temperature at which it will be solidifying, so this reduction leads to the situation where entire-weld metal has already got solidified.

But it is still there is liquid metal which is present along at the centre of the weld so the base metal which was heated to the different temperature values during the welding and the weld metal which was brought to the molten estate in course of the cooling regime of the weld thermal cycling, all these things starts shrinking and shrinking under the restraint conditions results in the residual stresses.

So shrinkage in the head affected zone and shrinkage in the weld metal all these results in the setting of the tensile residual stresses and tensile residual stresses, all these residual stresses will be localized in the centre where we have the liquid metals, since the liquid metal actually cannot support these residual recesses so it gets separated. So this separation ultimately happens in form of separation of the equax or the dendrites at the centre.

And it leaves a gap between these two especially at the center line which in turn appears in form of the solidification cracking or solidification crack. So if we see this occurs in the very last stage of the solidification and especially when the impurity concentration is high or lot of alloying elements are left at the centre and this typically happens when the alloying elements are present in the large quantity or present in the very small quantity.

Then are this kind of the cracking is a invariably observed so for a particular kind of composition of the aluminum or of any metal where the low melting point liquid metal is formed in very limited quantity, then only the solidification cracking occurs, if the low melting point liquid metal is formed a large quantity then all the separation of due to the tensile residual stresses is filled in by the presence of the liquid metal present in the large quantity.

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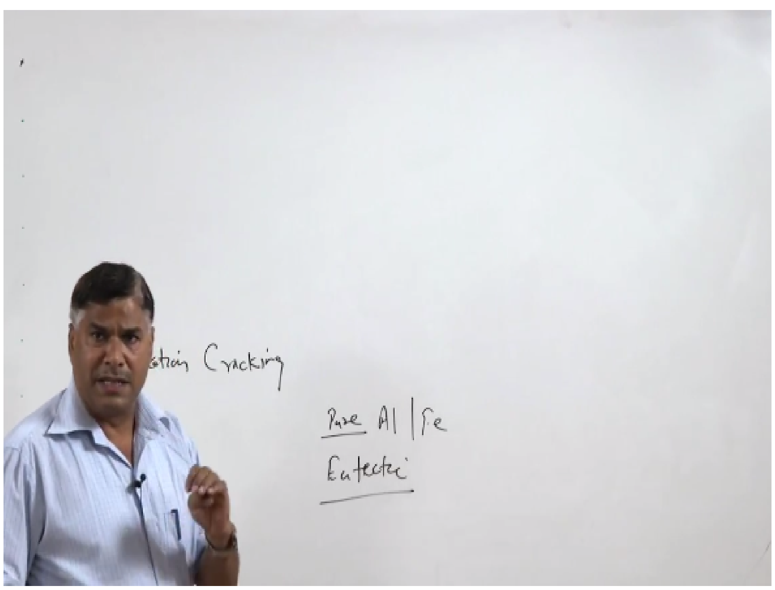

So in the two situations when either the metal is pure than the entire solidification will be taking place at one temperature and there will be no rejection of the impurities or the low alloying element in case of the pure aluminum or the pure iron, similarly in case of the eutectic system also melt and solidify at one temperature so they will also be solidifying or melting at one temperature. So there is nothing like a rejection or rejection of the impurities and the alloying element.

So especially in the cases where the amount of the liquid metal being formed at the last stage of the solidification is very limited. So this limited quantity of the liquid metal is found insufficient for healing the cracks which are being developed due to the tensile residual stresses at the center line of the weld and this in turn leads to the development of crack.

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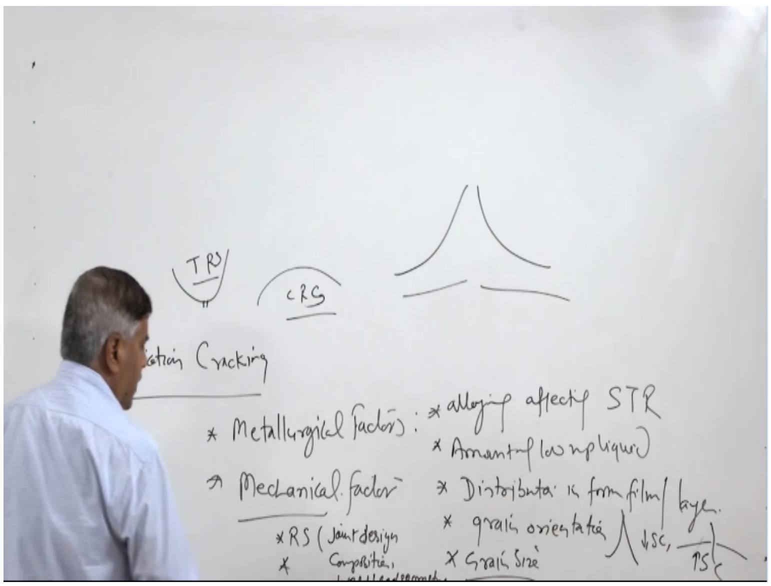

So this is what is called typical solidification cracking and so there are a few contributors for the solidification cracking and these contributors can be categorized in two broad groups one is the metallurgical factors and another is we can say the mechanical factors. Among the metallurgical factors, the first one is the factors alloying affecting the solidification temperature range. So presence of the certain alloying elements increases solidification temperature insignificantly.

And they in turn leads to the increase in the solidification cracking then the amount of the low melting point, the liquid metal so if the amount of the liquid metal is either absent or its very negligible then there is no solidification cracking or if its amount is very large. Then again no solidification cracking is observed for a very little quality of the low melting point liquid metal present the center line of the weld.

This particularly increases the cracking tendency to the maximum level. Next is the distribution how the low melting point liquid metal gets distributed, if the low melting point liquid metal foams the film. Then it becomes most crack sensitive and if it forms the spherical inclusions or it forms the ball shape and it is present in very localized form then it reduces the cracking tendencies.

So distribution in form of films or layers this promotes the cracking maximum and like iron sulphide foams the films of the iron sulphide and distributes along the grain boundary that promotes the cracking significantly. Then the grain orientation during the solidification are the grains can grow perpendicular like this or they can grow in curved columnar foam.

So the columnar grains having the high, steep abetting angle they promote the cracking tendency due to the increased low melting point alloying, due to the increased tendency of the segregation of the alloying elements or impurities along the weld center line, so the grain orientation is one of the factors. So the curved grains they lower the solidification cracking while the abutting high steep the grains growing perpendicular to the fusion boundary.

And the abutting at a high angle at the centre these promote the concentration of the alloying element at the center line and so they promote the solidification cracking. Further the grain size of the whatever is being formed, so final grains in turn results in the large then boundary area reduces the concentration of the low melting point liquid as compared to the course grains. Course grains promotes the cracking, solidification cracking tendency as compared to the fine grains.

So another is the mechanical factor, under the mechanical factor we have like the factors which are related with the residual stresses. So residual stresses, so all those factors which promote the tensile residual stresses, they will be increasing the cracking tendency while other factors, so the factors which promote the residual stresses like the joint design, determining the volume of the weld metal.

Then composition of the filler, liked yield strength of the weld metal, composition of the filler determining the yield strength of the filler metal, higher is the yield strength, greater will be the residual stresses as compared to the low strength. Filler metal similarly the bead, weld bead geometry, concave beads and convex beads. These are the 2 types of the beads which can be developed.

So the convex bead promotes the compressive residual stresses and while the concave bead promotes the tensile residual stresses, so tensile residual stresses will be promoting more cracking tendency at the centre line as compared to the another one. Likewise, another factor is the restraint, higher is the restraint during the wedding, greater will be the residual stresses.

Apart from that are the composition, now composition of the base metal or the filler metal which is being, so all these factors will be discussing at the length to show how these factors affect the solidification cracking and these factors itself will give us idea about what can be done in order to avoid or in order to reduce the solidification cracking tendency.

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For this will be going through the certain diagrams, so typical diagram which it shows that crack running all along the centre line of the weld this is the typical diagram showing the solidification cracking and it is the inter dendritic, whenever the fracture surface or the cracked mouth is opened, then we will see that the separation is there between the dendrites and there is typical morphology of the fracture surface on separation shows the presence of the dendrites.

Because this kind of the separation happens when the gap is not filled in by other liquid metal especially when it is amount is a very limited.

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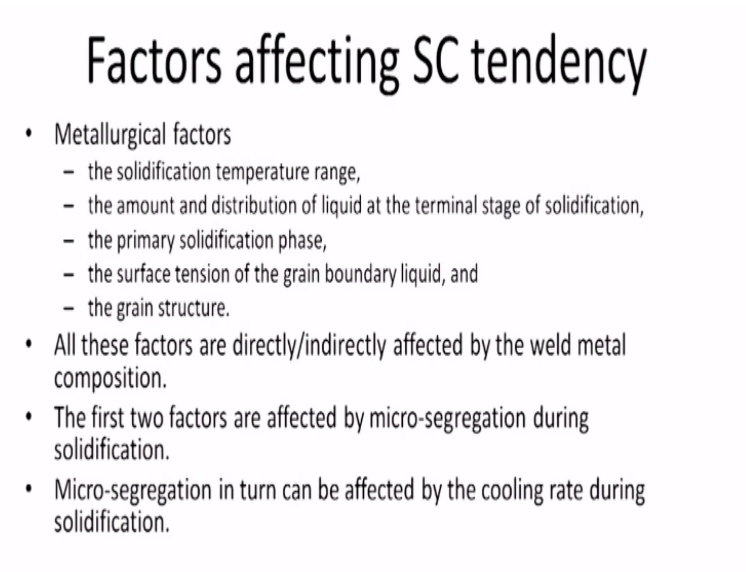

So the factors as I have explained. There are 2 categories of the factors that if it is solidification cracking one is metallurgical factor and most of these metallurgical factor will be actually influenced by the segregation tendency, so solidification temperature range if the alloying elements are more less so that will determine the solidification temperature range because as the solidification proceeds, more alloying elements are rejected.

So that in turn will be are affecting determining the gap between the liquidus and the solidus, amount and distribution of the liquid metal in the last stage of the solidification, like if the amount is very less or amount is very large in both the cases solidification cracking will not be happening but if the amount of the low melting point liquid metal left for the last stage of solidification is in between.

Then it will promote the cracking to the maximum level and similarly the distribution if it is present in form of the film then it promotes the cracking as compared to the case when the liquid metal is present in form of the like balls. So primary solidification phase, especially in case of the steels, if the solidification starts with the austenite.

Then it promotes the cracking because in presence of the sulphur and phosphorus these increase the solidification temperature range significantly while in case when those steels, when the steels solidify with the delta ferrite as a primary phase, means on the solidification first of all the delta ferrite is formed. Then in that case the impurities are absorbed by the delta ferrite because these act as a sink for the Sulphur.

And phosphorus having the much larger solubility for the sulphur and phosphorus that is why the formation of the delta ferrite as a primary phase reduces the cracking tendency as compared to the case when the austenite is the primary phase in case of the steels or stainless steel. Then, the surface tension, if the surface tension is less than it will form films and the films and layers of the low melting point things will be promoting the solidification cracking as compared to the high surface tension or the liquid metal which will be forming the balls.

And it will be present in very localized manner. Then the finer grain structure and the columnar curved grains reduce the solidification cracking tendency because these increase the distribution of the low melting point phases and it lowers the solidification cracking tendency so all these factors are either directly or indirectly affected by the weld metal composition and since in course of the solidification.

There is a continuous rejection of the alloying elements that is why there is a continuous change in composition of the weld metal and this is why macro segregation also results in sometimes the form results in the solidification cracking due to the rejection of the alloying element. So micro segregation affects the completion of the weld metal and micro segregation is actually influenced by the cooling rate.

If the cooling it is very high than we do not, means liquid metal does not get much time for the rejection of the alloying elements and in that case we get much more homogeneity and uniformity in composition as compared to the case when lot of time is available for rejection especially under the low cooling rate conditions, so the micro segregation tendency will be much higher under the low cooling rate conditions and which will promote the solidification cracking.

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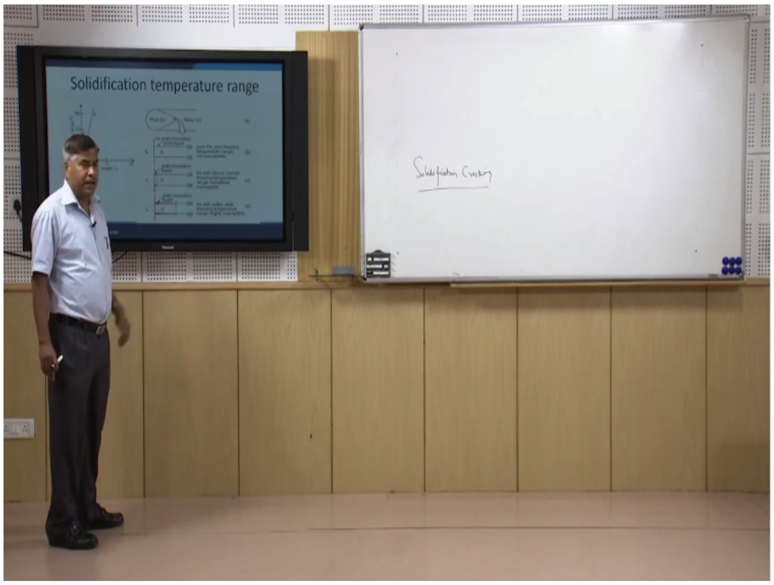

So, the factors that will be affecting will be solidification temperature range, so if we see here are the weight percentage of the different alloying elements like silicon, carbon, phosphorus, sulphur and boron and how do these aliments affect the solidification temperature range especially in case of the iron, so freezing temperature range 100, 100, 200, 300.

So if we see here very little addition of the sulphur results in the maximum increase in solidification temperature range of about 150 and the boron similarly the addition of the boron increases the solidification temperature range by 100 degrees centigrade and the addition of the phosphorus about 3% results in the increase in solidification temperature range or the freezing range by more than 300 degree centigrade.

Similarly, carbon also increase the solidification temperature range of freezing range and silicon, however, the affect of the silicon is less as compared to that of carbon, boron, phosphorus and sulphur. So, now you will see that when the system is pure, there is no range, so there is no grain boundary liquid metal and the when elements like only silicon are present the range is very narrow.

So very little amount of the liquid metal will be presented the grain boundary, but when the sulphur, phosphorus or the boron, when these are present in the large quantity there will be resulting large freezing range or solidification temperature range and this in turn will be leading to the presence of the large amount of the liquid metal at the grain boundary. So, this thin layer of the iron sulphide, actually sulphur will be reacting with the iron and forming the iron sulphide in form of thin film along the grain boundary.

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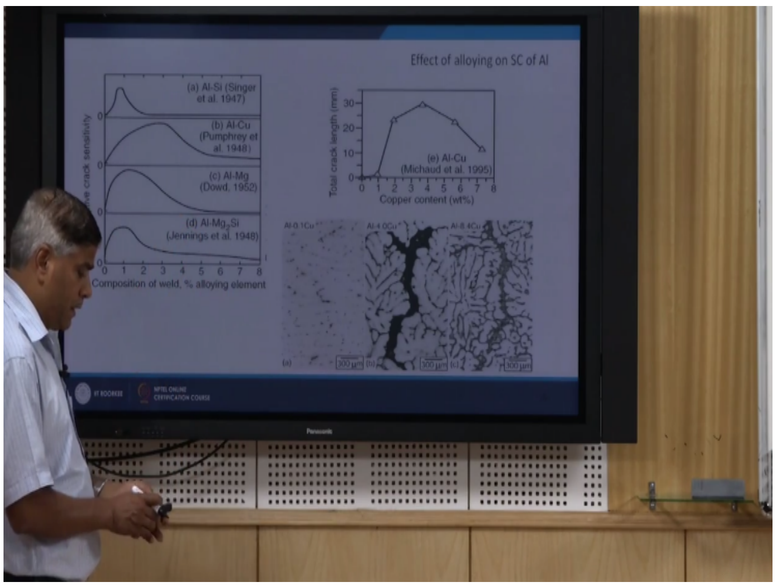

So now coming to the aluminium, as I have told that very less amount of the sulphur, a very less amount of the liquid metal does not cause the solidification cracking, similarly very large amount of the liquid metals does not cause the cracking that is what we can see here the aluminium with 0.1% copperhead having very limited quantity of the liquid metal which is not sufficient to promote the cracks while.

Similarly, in case when the very large quantity of the liquid metal is present with the aluminium, 8.4% of the copper than also whatever cracks are formed they will be filled in by the low melting point the liquid metal present in the large quantity. But when the case is in between like aluminium 4% copper having the limited quantity of the liquid metal. So this will promote the cracking.

And the cracking is occurring to such an extent that the developing cracks cannot be filled in by the limited quantity of the liquid metal which is present, that is why solidification cracking tendency or crack length is very limited up to 1% and crack length further reduces with the copper content more than 6 or 7% and the crack length is maximum for about 4%. So, the same trend, we can see for the other aluminium alloys like for their crack sensitivity for the solidification cracking as a function of the different alloying elements.

What we can see here silicon with about 1% results in the maxim cracking tendency, cracking tendency is less with very limited quantity of the silicon as well as higher quality of the silicon. Similarly, the copper for about 4% it results in the maximum cracking tendency for 1% of the magnesium, it results in maxim cracking tendency and higher concentration of the magnesium, copper, silicon this cracking tendency keeps on decreasing.

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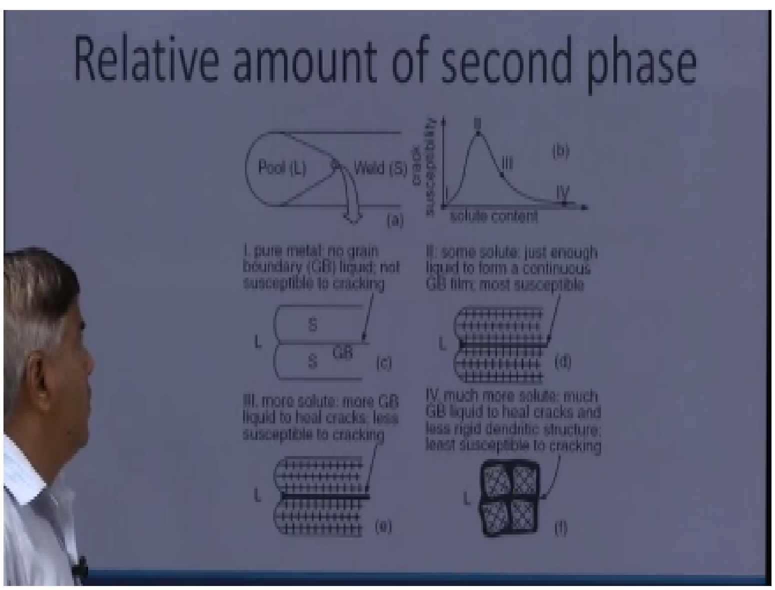

So now coming to the relative amount of the phases, when the related amount is very less, like there is no liquid metal present at the grain boundary, so cracking tendency is very limited but when very thin layer is present the cracking tendency is maximum because it just gets separated and then separated crack is not filled in by the limited quantity of the liquid metal on the other and when more solute is where the increased amount of the low melting point phases.

It reduces the cracking tendency because whatever crack is being developed it will be filled in by the already existing low melting point metal and when it is present in the large amount, then the cracking tendency is further reduced. So, for very less amount of the liquid metal and for a very large amount of the liquid metal, cracking tendency is very negligible while the cracking tendency is found maximum when it is present in very limited quantity but is forming the thin network along the grain boundary.

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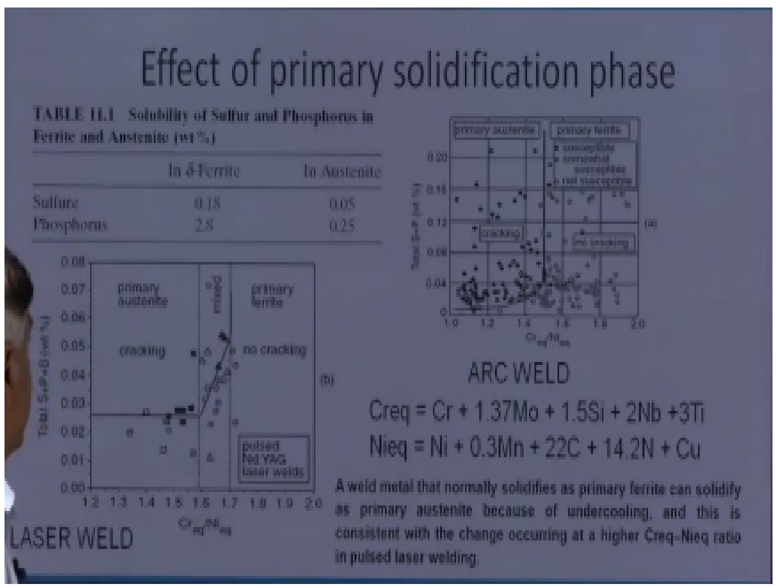

Now coming to the primary solidification phase, primary solidification phase, especially this is true in case of the stainless steel. When stainless steel can solidify either as austenite as a primary phase or the ferrite. When the ferrite is formed as a primary phase, we find that there is no cracking tendency, primary phase formation if when primary phase is ferrite, the cracking tendency is negligible or no cracking tendency.

But when the primary phase is austenite it results in the maxim cracking tendency. So whether there will be a primary phase ferrite or the austenite that is governed by the under cooling expediency during the welding and even for the given chromium, nickel equivalent ratio chromium and the nickel ratio, what we can see, this happens like for the laser welded joints.

The chromium to the nickel equivalent ratio more than 1.7 results in the primary ferrite phase formation while less than 1.6 chromium nickel equivalent ratio results in the primary austenite phase formation. This ratio is found between 1.4 to the 1.6 in case of the arc welded joints, so conditions are developed in such a way that our primary phase is ferrite so that it can reduce the cracking tendency.

While formation of the primary ferrite lowers the cracking tendency that is what we can see from this diagram that ferrite has higher solubility for the sulphur and that is 0.18 and 2.8 as compared to the austenite. Solubility of these impurities for austenite is very negligible so the ferrite acts as a sink for these impurities and therefore it absorbs all these impurities and the lower the cracking tendency. That is what we have seen.

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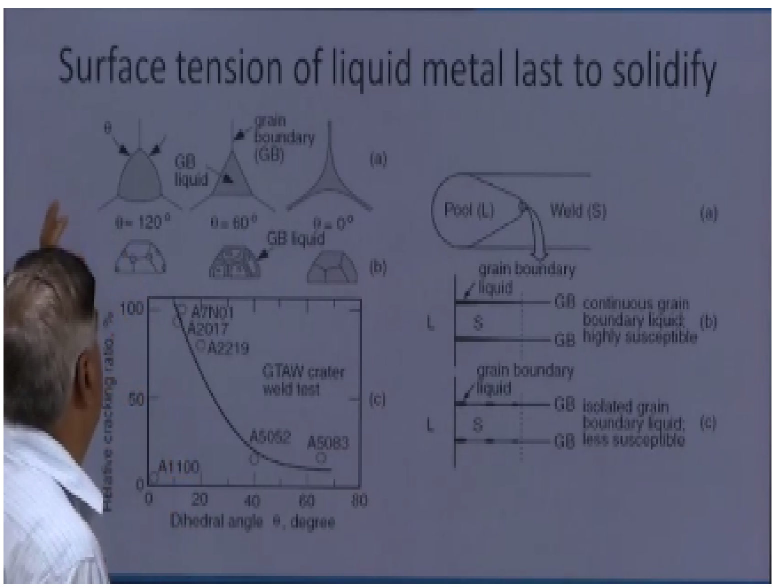

So the surface tension also affects the surface tension of the liquid metal last to solidify also determines the cracking tendency in one away when it is of and this is measured in terms of the dihedral angle. When dihedral angle is very less, then we will see the cracking tendency, the dihedral angle is 0, then we will see that the liquid metal forms continuous film along the grain boundary.

And the cracking tendency is very high when the dihedral angle is high, then it forms like in nodule or the globular or ball shape, so this kind of structure will be reducing the cracking tendency as compared to the case when it forms thin-film. So this is what can be seen schematically here when the low melting point liquid forms continuous grain boundary of film then it results in the maxim cracking tendency.

While in case when it forms the balls or discrete nodules here and there, then it reduces the cracking tendency. So especially like the addition of the magnesium in the steels forms of magnesium sulphide instead of the iron sulphide and magnesium sulphide is present in form of the nodules or the balls and further it has a higher melting point. So as compared to the iron sulphide, so it reduces the solidification temperature range and whatever nodules are there.

They are present in the form of the balls not in form of the network and therefore it reduces the magnesium edition, reduces the cracking tendency.

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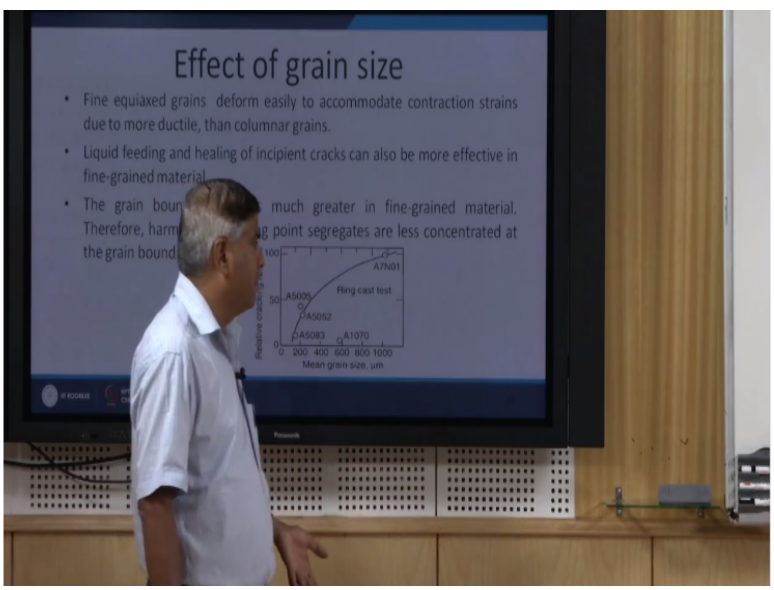

Similarly, the grain size concept when the grains are fine, then cracking tendency is less because of low melting point thing are well distributed and the concentration of the low melting point things is less, low melting point metal along the grain boundaries less, when the grains are course there will be fewer grains, so fewer grains will have the higher concentration of the low melting point liquid metal along the grain boundary which in turn will promote the cracking tendency.

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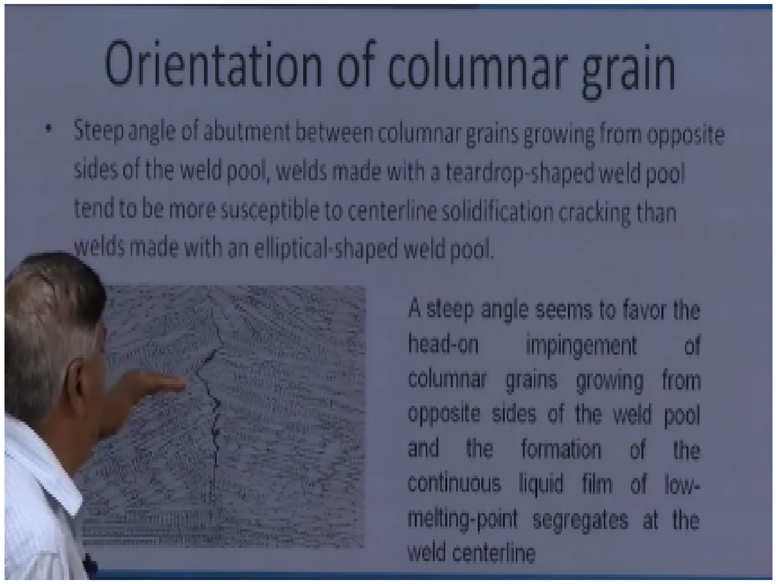

Similarly, when the grains having the high abutting angle they meet at the centre so this will because in the localization of all impurities, low melting point things at the grain boundary and that is why it will be promoting that cracking tendency as compared the case when the grains grow in curved columnar manner which will be leading to the very scattered distribution of the low melting point liquid metal along the weld centre line.

So it will be reducing the cracking tendency.

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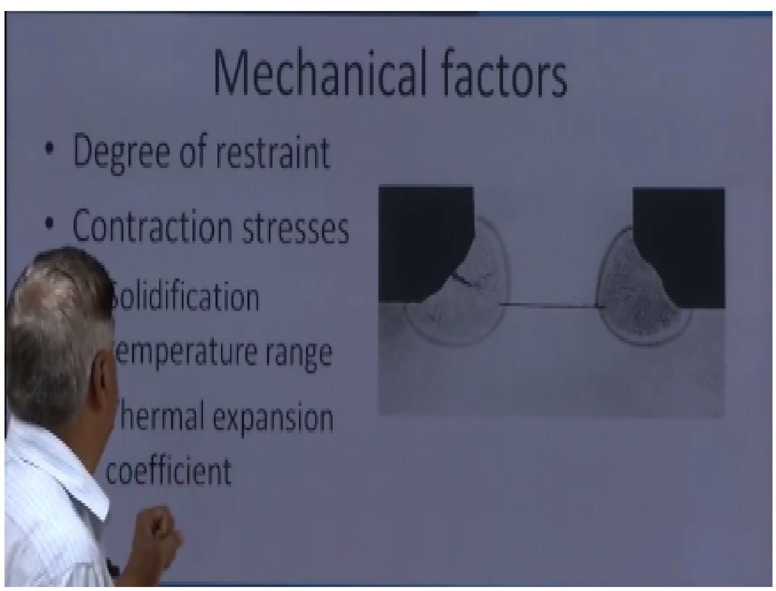

So, among the mechanical factors there are two types of mechanical factor, one is degree of restraint, higher is the degree of restraint greater will be residual stresses and the contraction stresses. So, higher is the solidification and temperature range, greater will be the contraction stresses which will be set in, higher is the expansion co-efficient, greater will be residual magnitude which will be set in.

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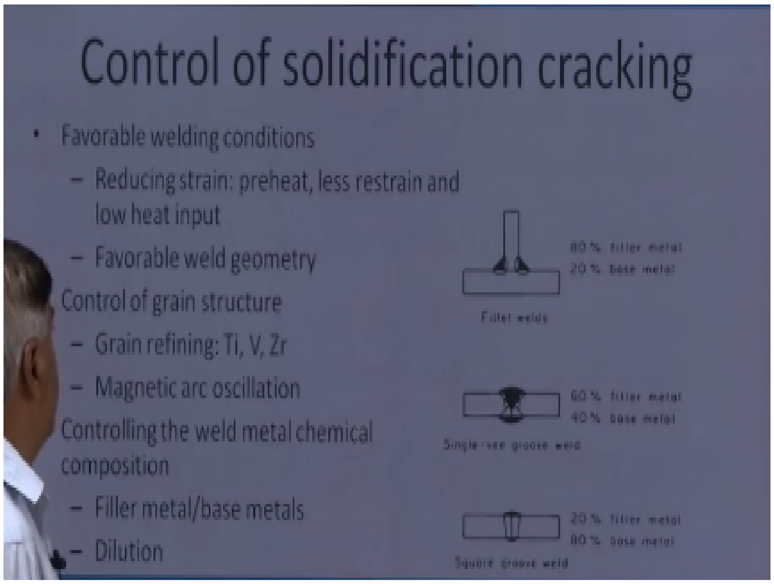

Apart from the other factors, these also affect the solidification cracking tendency, so reducing the restraint, increasing the preheat and reducing the heat input, these factors in totality will be reducing the residual stresses magnitude, so they will reduce the solidification cracking. Favorable weld geometry, it is better to have the convex bead geometry as compared to the concave so that the cracking tendency can be reduced as I have explained.

Having the finer grain structure either through the inoculation by adding the titanium, vanadium zirconium or through the magnetic arc oscillations grains can be refined, so the distribution of the low melting point things can be improved and the cracking tendency can be reduced. Then the controlling the weld metal composition as I have said, filler metal composition is selected in such a way that the solidification temperature range is reduced.

So the cracking tendency can be reduced and similarly dilution also considering the composition of the weld metal the dilution needs to be controlled as per the requirement. For example, use of the filler in case of the grove weld, when the filler is used, it is contribution is just 20% and the base metal contributes to the 80%.

While in case of the filler weld, 80% of the filler metal and 20% of the base metal forms the weld metal, while in case of the groove welds, 60% of the filler metal and 40% of the base metal. So, these approximate contributions to the in mind while identifying the composition of the weld metal or selecting the filler metal in such a way that the solidification temperature range of the weld metal can be reduced in order to reduce the solidification cracking tendency.

So now I will summarize this presentation. In this presentation, we have talked about the mechanism leading to the solidification cracking and the different factors that will affecting to the solidification cracking tendency as well as also I have talked about the methods which can be used for reducing the solidification cracking tendency. Thank you for your attention.