Weldability of Metals
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Lecture - 39
Weldability of Austenitic Stainless Steels - II

Hello, I welcome you all in this presentation related with the weldability of metals and we are talking about the weldability of austenitic stainless steel. In the previous presentation we have seen that the phases being developed in the weld metal to a great extent influenced by the composition like what is the percentage of the elements leading to the particular value of the nickel equivalent or the chromium equivalent.

And the fractions of these nickel or the values of the nickel equivalent and the chromium equivalents determine the kind of the phases which will be formed.

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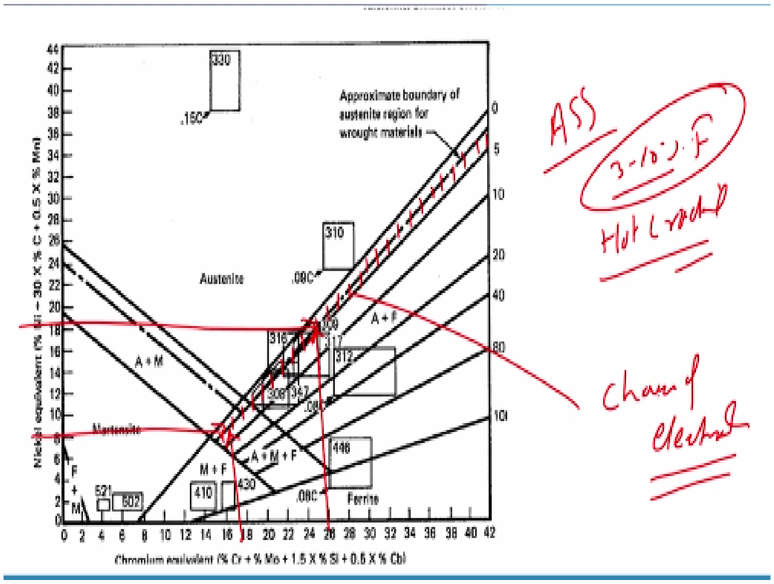

So it is important during the welding of the austenitic stainless steel that it is having enough 3–10% of the ferrite so that the hot cracking or the solidification cracking tendency of the weld metal can be reduced. And therefore it is important that the composition of the weld metal is adjusted in such a way that it is along this kind of the line.

And which can be realized through the proper adjustment of the chromium and nickel equivalent of the weld metal for the different grades of the steel. So this makes us the choice of the electrode suitable in such a way that it leads to the development of the 3–10% of the ferrite. However, the low ferrite content will promote the cracking and too high percentage of the ferrite will reduce the corrosion resistance.

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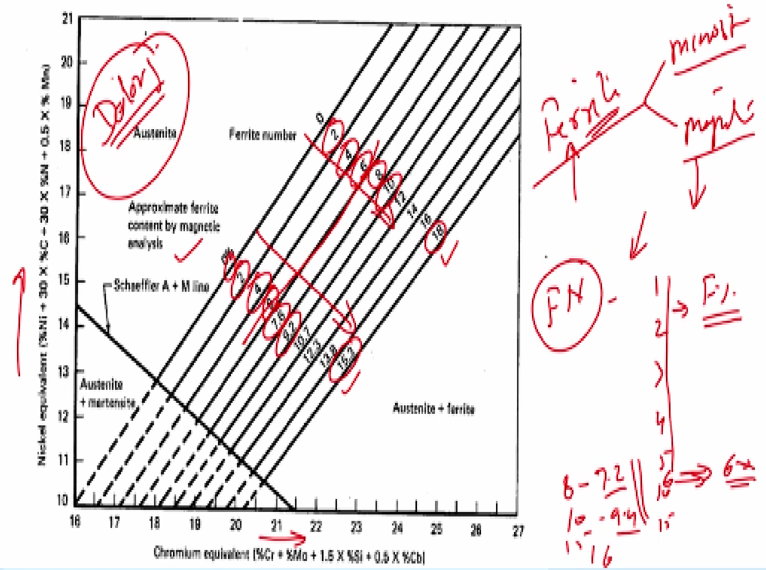

More precisely the amount of the ferrite being formed, ferrite can be identified using the microstructural approach or using the magnetic property approach. So it is easier like the weldment has been developed it is easier to measure the magnetic characteristics of the weld metal according to the percentage of the ferrite which is present and that is converted and that is represented in terms of the ferrite number.

Ferrite number is just an arbitrary number which is given like 1, 2, 3, 4, 5 to 10, 15 like this. So for low ferrite numbers, this number actually corresponds to the ferrite percentage present in the weld metal. Actually, these numbers are like qualitative number indicating the magnetic property of the weld metal which corresponds to the ferrite percentage.

But these numbers beyond means for higher value of the ferrite number it does not correspond to the ferrite percentage directly. Like say up to ferrite number 6, the value will be, for ferrite number 6 the ferrite percentage will also be 6%. But for the higher values like 8, 10, 15, 16 the values may be slightly less like 7.2 or 9.4. So the values are lower than the or the percentage of the ferrite is lesser than the ferrite numbers, that is for higher value of the ferrite numbers.

So based on the chromium equivalent and the nickel equivalent, only one more diagram has been developed. This is called Delong diagram. So using this we can identify precisely the kind of the ferrite. These numbers are indicating the ferrite number and this is indicating the ferrite percentage. So approximate ferrite content by the magnetic property analysis and these are the ferrite number.

So what it is showing that the ferrite percentage and the ferrite number is 2 both the sides. Ferrite percentage and ferrite number is 4 and it is 6 and then we will see ferrite number is 8 and ferrite percentage is 7.6. Ferrite number is 10 and ferrite percentage is 9.2. Likewise for ferrite number 18 and the ferrite percentage is 15.

So for the lower percentage, for the lower ferrite numbers it shows the ferrite percentage as identified through the magnetic property analysis. So the Delong diagram is one which helps in estimating the ferrite percentage precisely using the nickel and the chromium equivalents.

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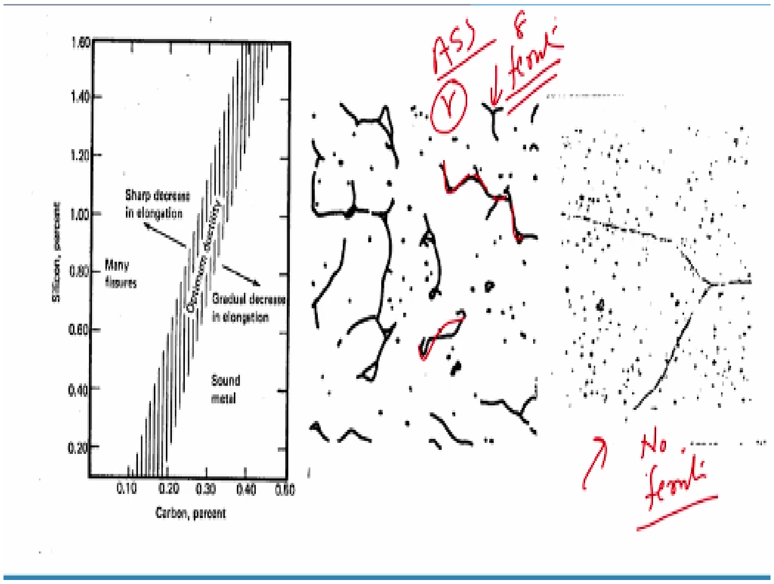

So how to identify if there is a presence of ferrite. So this is the typical austenitic stainless steel weld metal which is showing the austenite in the matrix and the ferrite. These worm shaped constituents are corresponding to the delta ferrite and this is the microstructure where there is no delta ferrite. So this is how can we understand when there is a presence of ferrite and there is no ferrite which is present.

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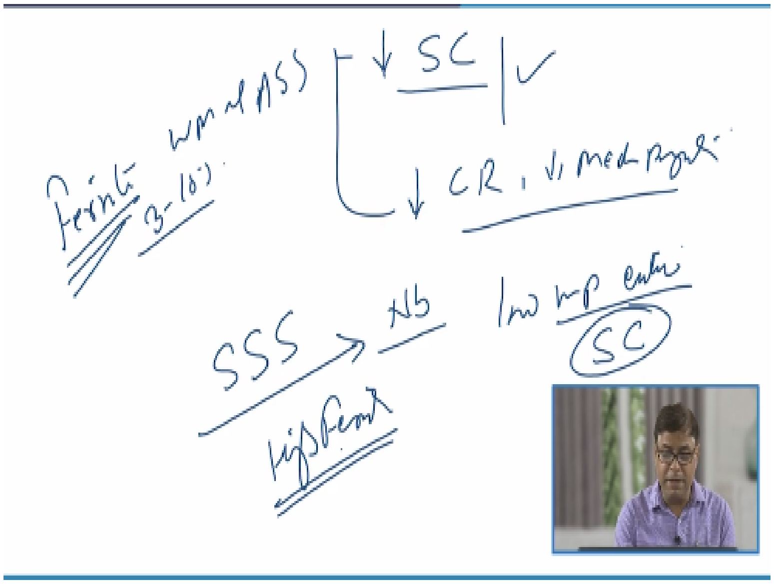

So as far as the importance of the ferrite is concerned ferrite is important in the weld metal of the austenitic stainless steel on two counts primarily one it reduces in appropriate amount like 3–5%, 8% or 10% like it reduces the solidification cracking tendency but at the same time a higher percentage also reduces the corrosion resistance and sometimes reduces the mechanical properties as well.

So that is why we need to strike a balance between the control of the solidification cracking and the kind of the deterioration in mechanical properties is taking place and so these are the two contradicting responses or you can say these are the two opposite responses. One side, control of the solidification cracking is being facilitated through the ferrite.

On the other hand the corrosion resistance and the mechanical properties are being diluted. Apart from this sometimes the stabilized austenitic stainless steels having the niobium especially it forms the low melting point eutectics in the weld metal and which promotes the solidification cracking significantly and that is why we may need very high the ferrite number to deal with these problems of the solidification cracking tendency.

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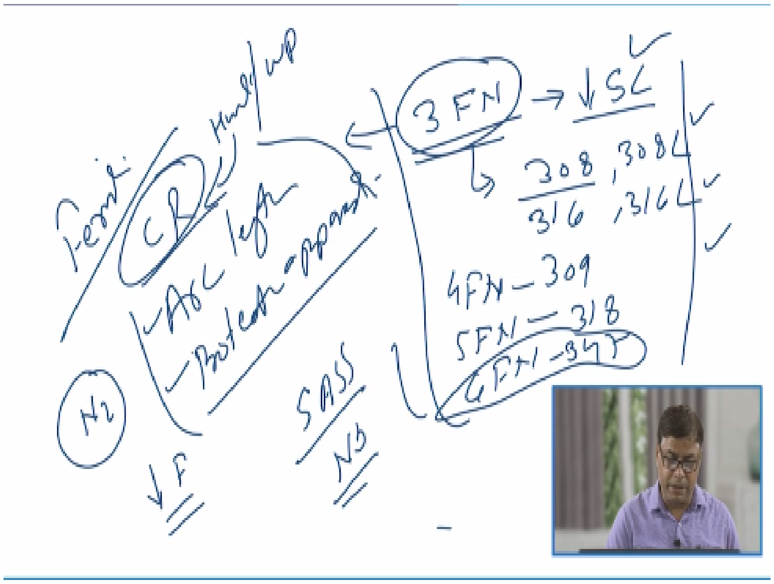

Here is some data related with this which shows the kind of the ferrite number which is found okay to control, which is found good enough to control the solidification cracking in normal austenitic stainless steel is ferrite number 3, 3 FN is good enough to control the solidification cracking and this kind of the ferrite number is offered by the number of the electrodes of the 308, 308 L grade and then 316 and 316 L grade electrode.

Then 4 ferrite number weld metal is produced by 309 electrode or the filler. Then 5 ferrite number is offered by 318 grade of the electrode. And 6 ferrite number is offered by 347 filler metal. So there are different grades of the electrodes which offer the different ferrite number. For most of the grades, 3 FN is good enough to control.

But for like stabilized austenitic stainless steels having the niobium forming the low melting point, we may require higher ferrite numbers to control the solidification cracking tendency in the austenitic stainless steel weldment. So how much the ferrite will be produced? As I have said, that depends upon the certain factors which includes the cooling rate, the kind of the welding conditions in terms of the arc length and the kind of the weld protection approach or the effectiveness of the shielding.

So higher cooling rates will be suppressing the ferrite formation. On the other hand these two arc length will be affecting the effectiveness of the shielding or the possibility of the atmospheric gases like nitrogen and oxygen in the weld metal. So if the arc length is more protection is poor, more nitrogen will be getting into the weld metal. That will be reducing the ferrite formation tendency.

So apart from the composition aspects, the heat input which is being given by the particular welding process that will be affecting the cooling rate. At the same time that will also be affecting the kind of the protection being provided to the weld metal during the welding.

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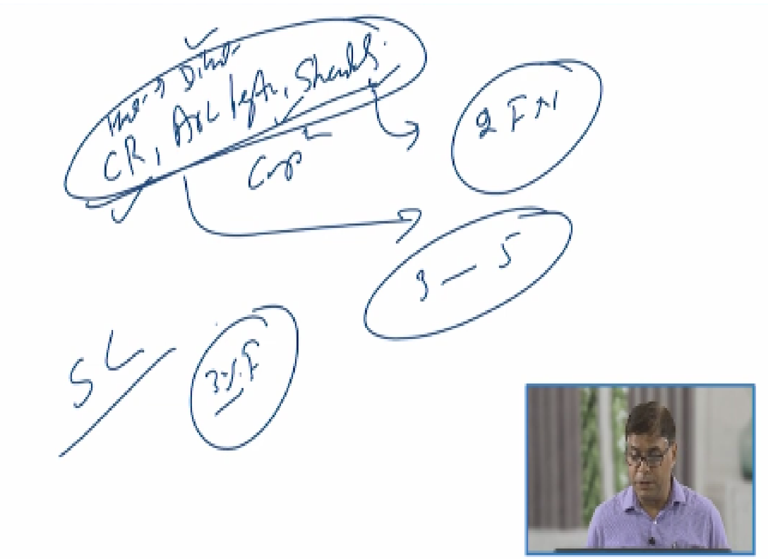

So due to the cooling rate, arc length and the shielding related aspects even when the composition is controlled these are the variable aspects. So it can lead to the, cooling rate is being influenced by the H net which is going to affect the dilution as well. So these variations can lead to the variation of the 2 ferrite number in the weld metal. Like in one case it may be 3, in another case it may be 5.

So there can be large variation in ferrite number so especially in those conditions where there is a huge possibility for solidification cracking we must control the dilution, cooling rate, arc length and protection in such a way that such large variation in ferrite number can be avoided so that we have the required amount of the delta ferrite in the weld metal in order to avoid the cracking tendency of the weld metal. So the control of the process parameters becomes crucial in those cases.

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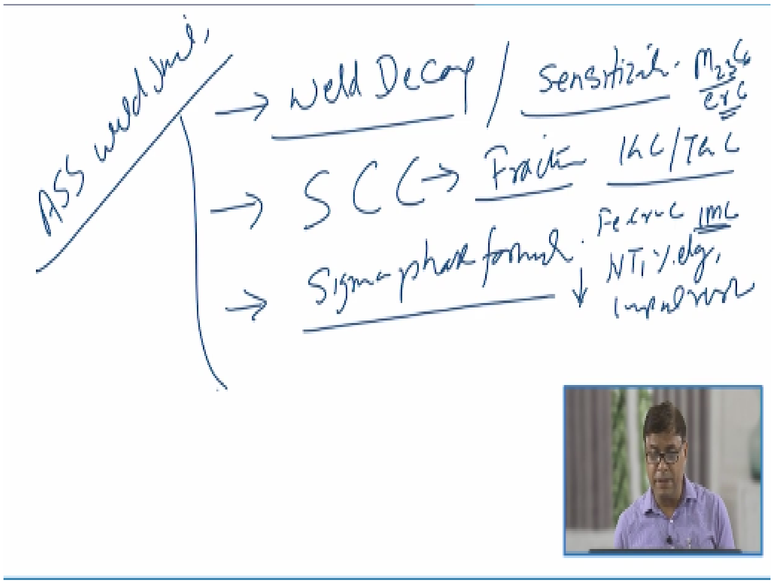

Now as far as the behavior of the ASS weld joint is concerned which will be reflecting in form of the, the way by which the performance is given by the austenitic stainless steel weldment; so there are 3 problematic zone as far as the austenitic stainless steel weldment is concerned. One is called weld decay. This is also known as the sensitization problem of the austenitic stainless steel weldment. The second is the stress corrosion cracking.

And the third is the sigma phase formation. So stress corrosion cracking will be leading to the fracture due to the growth through either intragranular or through the transgranular crack propagation. Sigma phase formation will be reducing the notch toughness, will be reducing the percentage elongation, will be reducing the impact resistance because of the formation of the iron, chromium, carbon, intermetallic or phase formation which is hard and brittle.

So on the other hand weld decay is primarily caused by the formation of the carbides in form of M 23C 6 the chromium carbide like CrC. So we will be talking in detail about these issues and these aspects related with the weldment.

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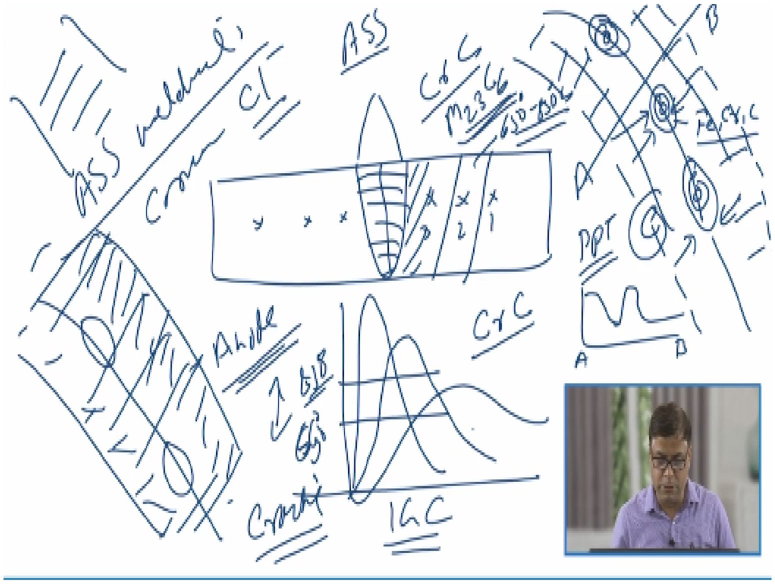

So when a weld ASS weldment is exposed for the higher temperature or the stainless steel during the welding of course is exposed to the higher temperature or the weld joint itself is exposed to the higher temperature for longer time then it leads to the various issues. So we will be initially talking about the kind of the problem which is encountered during the welding of the ASS that is about the weld decay.

Like when we apply the suitable heat source for fusion of the faying surfaces, the weld metal is produced and the zones near the fusion boundary also are heated to the higher temperature and so these temperatures like 0.12 and 3 they will be experiencing the different weld thermal cycles. The 0.3 will be experiencing this kind of thermal cycle where heating and cooling rates both are high.

On the other hand points which are slightly away from the fusion boundary, they will be experiencing lower heating rate and lower cooling rates but longer retention at higher temperature that is especially temperature in the band of 650 to the 850 degree centigrade. So longer retention in this temperature band especially during the cooling leads to the formation of the chromium carbide.

So this chromium carbide formation especially takes place with the precipitation of the carbon at the grain boundary. So once the carbon precipitates which is having the higher, so the chromium is having the higher affinity to the carbon so it forms its chromium carbide or there may be some percentage of the iron, chromium and carbon. So such kind of the carbides are found at the grain boundary.

So wherever these formed near those regions a zone is formed where the region where chromium initially was in solid solution form this region experiences deficiency and depletion due to the reason that the chromium from these regions have diffused the grain boundary to form these chromium carbides.

And that is why when we perform such kind of the analysis across the grain boundary, what we notice that on variation from A to B at the grain boundary the region at the A the chromium is high but as we approach to the grain deficient zone, the chromium deficient zone the chromium is less and suddenly at the grain boundary it may be more then again it is less. So both the sides of the grain boundary chromium deficient zone is formed.

Like this is the grain boundary. Here we have got the chromium carbide formation. So around both the sides of the grain boundary, chromium deficient zone is formed and this chromium deficient zone acts as anode. So there is a region where chromium is deficient or chromium is less and there are other zones where chromium is more. So the region where chromium is less that acts as anode and other zones start to act as cathode.

So when such kind of the weldment is exposed to the corrosive environment like having the chlorides then the grain boundary zone where chromium was, the area near the grain boundary where the chromium was deficient this experiences the localized selective attack and this kind of the attack primarily takes place both the sides of the grain boundary.

This is how the grains are eaten out, grain boundaries are eaten out and you will see that grains have got separated. Grains boundary has been vanished because of the corrosion. So the grains get separated and when this process means the localized attack or localized corrosion along the grain boundary continues this eventually leads to the failure of the weld joint through the cracking.

And since this kind of corrosion is taking place primarily along the grain boundary that is why it is called intergranular corrosion and the primary reason behind this is the formation of the chromium carbide or M23C6 type of the carbides along the grain boundary and this kind of formation primarily takes place when it gets sufficient time during the slow cooling in the band of 650–850 degree centigrade.

If the cooling rate is fast then time is not much in the zones near the fusion boundary. So such kind of the carbide formation does not take place. While the regions which are away from again such of the temperature is not realized means sensitization temperature is not realized or exposure to the sensitization temperature is very limited.

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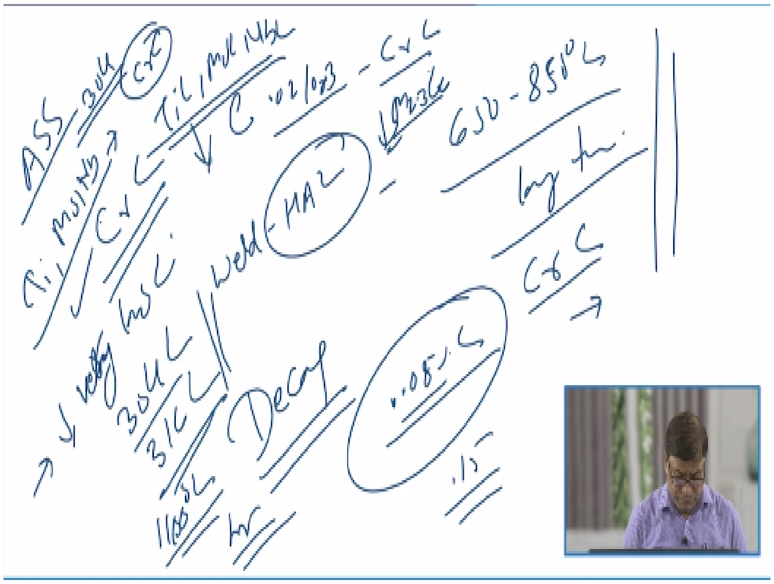

So when a region of the weld heat affected zone where the exposure in the band of 650–850 degree centigrade takes place for longer time such kind of the carbide formation takes place and leads to the deficiency of the chromium along the grain boundaries or near the grain boundaries that promotes the localized attack and this kind of the corrosion due to the chromium carbide formation is known as weld decay.

And especially this kind of the problem is being caused due to the formation of the carbon. So if stainless steel is having the low carbon, very low carbon like 0.02, 0.03, then tendency to form chromium carbide or M23C 6 type of the carbides will be reduced. So if the austenitic stainless steel is having the carbon up to 0.8% then the chromium carbide formation tendency is very limited.

But in those austenitic stainless steel where carbon is more like 0.15 then this kind of tendency will be more and in very less time chromium carbide formation will be facilitated and that in turn will be reducing the corrosion resistance very rapidly. So one best way to control the weld decay is that reduce the means select the austenitic stainless steel with a very low carbon content like 304L, 316L will be having very low carbon content.

Another option is that such kind of the weld joints can be heated to the like 1100 degree centigrade for 1 hour so that all chromium carbide which was formed will get dissolved and will form the homogenous solid solution and will eliminate the or will reduce the problem related with the heterogeneity in distribution of the chromium. So the associated problem will also be reduced.

And there is a third approach where in simple austenitic stainless steel like 304 if we add certain type of the stabilizing elements like titanium, molybdenum and niobium, these elements have the greater affinity to the carbon than the chromium. So instead of formation of, when these elements are present in steel, instead of formation of the chromium carbide, the formation of the TiC, MoC, or NbC is facilitated.

And that in turn helps to avoid the formation of the chromium carbide. So the depletion or deficiency near the grain boundaries does not take place and the corrosion resistance is maintained. So these are the 3 approaches in order to reduce the problem of the weld decay go for the low carbon content, do the annealing above the high temperature so that all chromium carbide can be dissolved or add few stabilizing elements so that the chromium carbide formation can be avoided and instead of that some other types of the carbides are formed.

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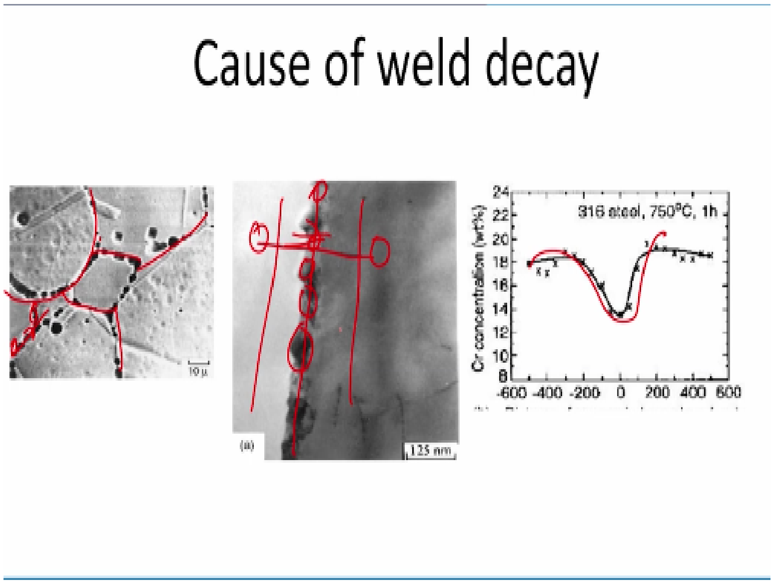

Cause of weld decay

And to see this just to appreciate this I can show here some of the micrographs. Here what it shows that this is the grain boundary and where the chromium carbide precipitation has taken place. So these are the different zones which are showing the kind of the precipitation along the grain boundary has taken place.

And along the grain boundary, this is the grain boundary where these precipitates have been formed and if we perform the analysis of the chromium percentage variation, then we will see that both the sides the chromium is more but on moving towards the grain boundary there is a deficiency of the chromium in certain zones where chromium carbide has not been formed.

So there are two possibilities, one either grain boundary itself is depleted because of the localized formation of the chromium carbide here and there or the region both the sides of the grain boundary can also be depleted.

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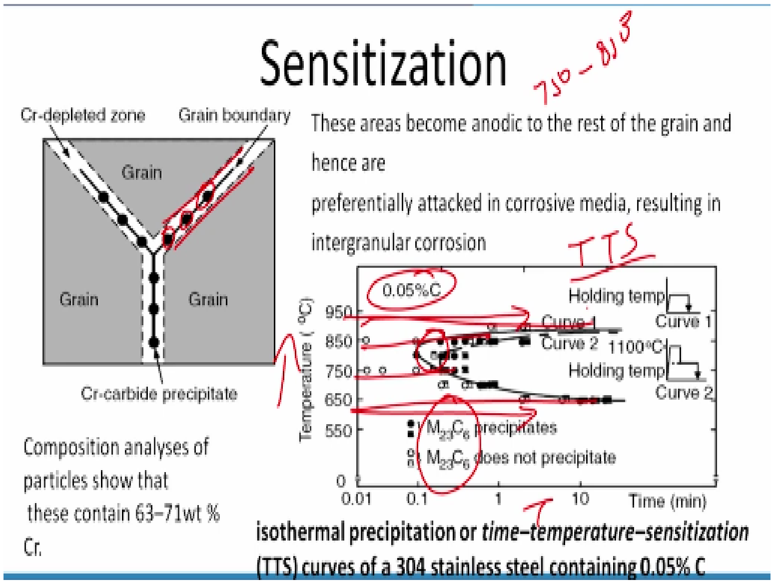

Sensitization

750 - 813

These areas become anodic to the rest of the grain and hence are preferentially attacked in corrosive media, resulting in intergranular corrosion

Composition analyses of particles show that these contain 63–71wt % Cr.

TTS

isothermal precipitation or *time–temperature–sensitization* (TTS) curves of a 304 stainless steel containing 0.05% C

And this heterogeneity in the chromium composition distribution is considered as a reason behind the sensitization or the weld decay. So here this is how it is shown. This is the schematic explanation, chromium carbides are being formed and both the sides a region is formed where the chromium is depleted and that becomes the sensitive for the chromium carbide formation.

So now if you see here, for the very low carbon content, this is like the temperature and the time. This is called TTS, temperature, time, sensitization diagram. So maximum sensitization takes place over a certain range of temperature. Here it takes minimum time for chromium carbide formation or M23C6 kind of the precipitate formation. Before and after that other than these compositions means at higher temperature and at a lower temperature it takes the longer time.

So the most sensitive temperature zone is a 750 to the 850 degree centigrade. However, sensitization can occur in this band of the temperature. So it is 650 to the 850 is the normal kind of the temperature band in which it takes place.

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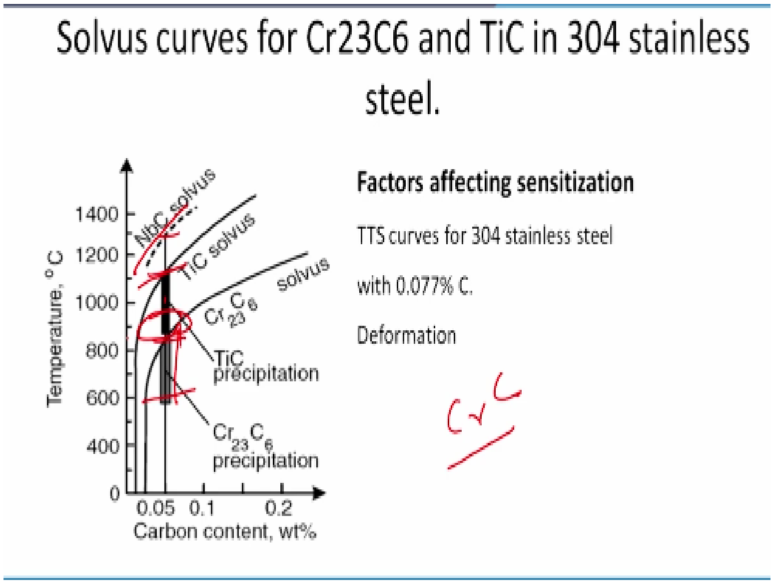

Solvus curves for Cr23C6 and TiC in 304 stainless steel.

Factors affecting sensitization

TTS curves for 304 stainless steel

with 0.077% C.

Deformation

CrC

This is another aspect like as I have said this is the temperature range in which the chromium carbide is formed at further higher temperature the titanium carbide is formed. At further higher temperature the NbC is formed. So these are basically solvus lines. Above this temperature the chromium carbide gets dissolved. Above this temperature titanium carbide gets dissolved. And above this temperature niobium carbide gets dissolved.

So if the chromium carbide has been formed then we have to heat above this temperature so that it can be completely dissolved and homogenous solid solution of the chromium in the iron can be realized.

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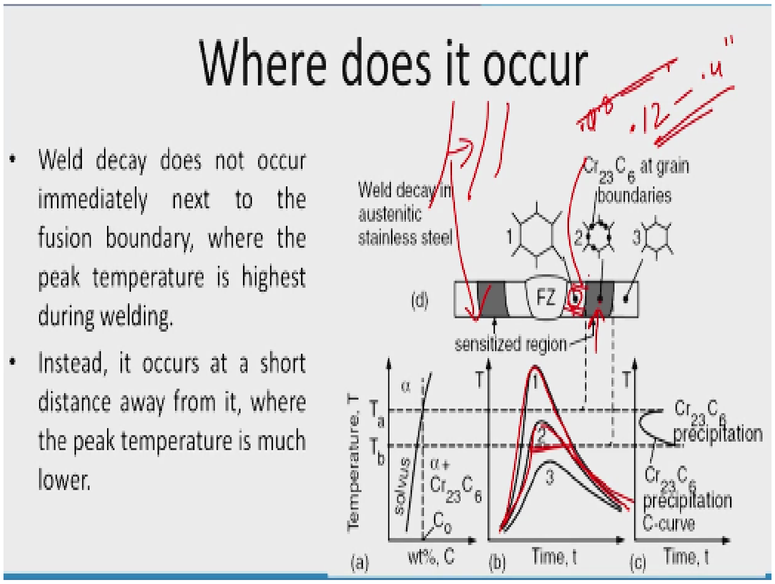

Where does it occur

- Weld decay does not occur immediately next to the fusion boundary, where the peak temperature is highest during welding.
- Instead, it occurs at a short distance away from it, where the peak temperature is much lower.

There is one more diagram. This was the explanation I have already explained like the zone next to the fusion boundary experiences very high heating rate and cooling rate and thereafter there is a zone away from that which experiences the lower heating and the lower cooling rate so the exposure in the sensitization temperature zone is for longer period at some distance away from the fusion boundary.

This distance may vary from like say 0.12 to 0.4 inch. So depending upon the kind of the heat input, thickness of the sheet, the kind of the metal, so this sensitization occurs at some distance, not very next to the fusion boundary because next to the fusion boundary the heating rates and cooling rates are very high and the time available for precipitation in the sensitization temperature is very narrow, very low.

And that is why the chromium carbide precipitation does not take place next to the fusion boundary but it occurs at some distance away from the fusion boundary. Likewise, the another issue is the stress corrosion cracking. Stress corrosion cracking occurs in the austenitic stainless steel weldment.

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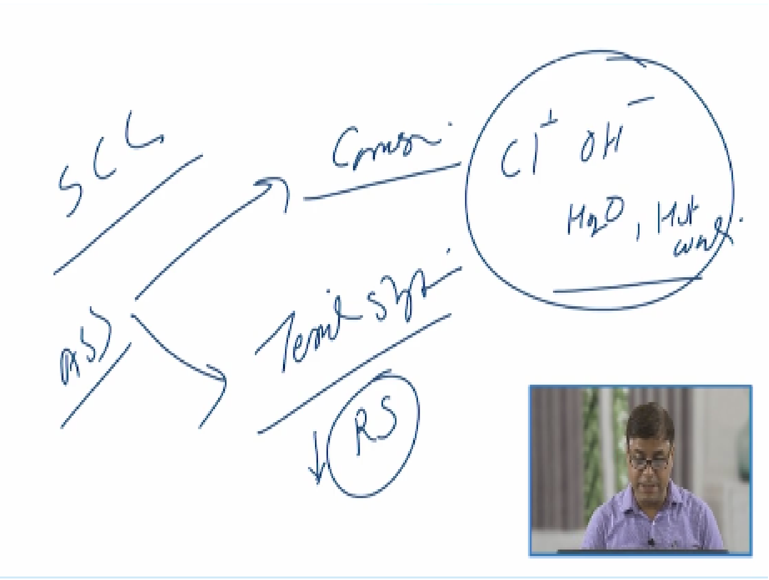

Especially when the joint is exposed in the suitable sensitive environment like chloride ions, hydroxyl ions or the steam or the hot water and the tensile stresses are present and the weld metal or the metal of the ASS weld joint is sensitive to the corrosion in presence of the tensile stress the transgranular as well as the intragranular cracking takes place very rapidly and leads to the premature failure.

So idea here is to reduce such kind of the fractures is to relieve the residual stresses. Through the preheating, we can relieve the residual stresses then we can do the annealing so that the homogenous solid solution of the chromium can be formed and all these carbides which are being formed can be eliminated or if possible then avoid such kind of the environments for which the weldment is sensitive to the corrosion.

Now I will summarize this presentation. In this presentation we have talked about the kind of the phases which are being formed in the weld metal and at high temperature how the performance of the austenitic weld joint is affected and what is the mechanism of the weld thermal cycle and because of which the weld decay is taking place. Thank you for your attention.