Aqueous Corrosion and its Control
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Lecture – 23
Forms of Corrosion: Intergranular corrosion (Part III)

We shall continue our discussion on Intergranular Corrosion of metals and alloys. We completed two lectures on intergranular corrosion of metals and alloys.

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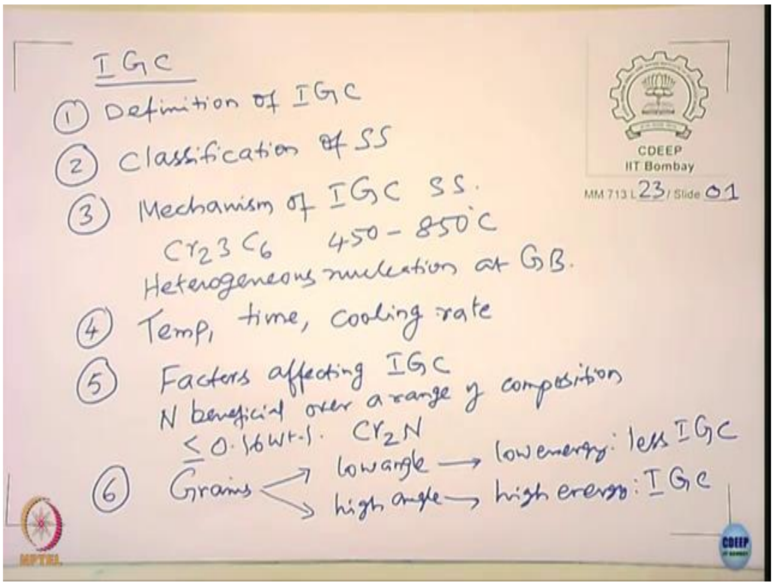

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IGC
① Definition of IGC
② Classification of SS
③ Mechanism of IGC SS.
$Cr_{23}C_6$ 450 – 850°C
Heterogeneous nucleation at GB.
④ Temp, time, cooling rate
⑤ Factors affecting IGC
N beneficial over a range of composition
≤ 0.16 wt.% Cr_2N
⑥ Grains $\to$ low angle $\to$ low energy: less IGC
$\to$ high angle $\to$ high energy: IGC

If I can summarize what we have seen so far, we are I suppose clearer on the definition of intergranular corrosions. I think you people should be very clear that it is happening at the grain boundary selective attack taking place.

Now, we said that among all the metals and alloys stainless steel suffer extensive intergranular corrosion especially when they are being welded, when they are not properly heat treated actually. So, in order to understand the intergranular corrosion of stainless steels I gave very brief introduction to classification of stainless steels and the role of various alloying elements how they affect the corrosion performance, we saw that.

Then we went on to discuss the mechanism or you may call it as a theory of intergranular corrosion of stainless steels. Please notice that the intergranular corrosion mechanism may not be the same for all metals and alloys. So, we focused on what kind of mechanism operating in the intergranular corrosion of stainless steels and very specifically towards the austenitic grade stainless steel.

And, if you recall the major problem is the chromium depletion because of the formation of the chromium carbide and that occurs in the selective temperatures in the range let us say about 450 to about 850°C it occurs. But, more importantly here it is just not the formation of chromium carbide and the depletion of chromium as a result of the formation of the chromium carbide.

But, the chromium carbide formation is heterogeneous nucleation. It forms at the grain boundaries. So, it is heterogeneous nucleation at the grain boundaries and so, the depletion of chromium is center around the grain boundary area. And, so, the stainless steel at that area loses the stainless steel capacity to passivate. So, there is a solid to attack taking place.

The sensitization process we said was dependent on what? Dependent of course, it is it is the chromium carbonate formation, but what are the governing relationship there? The governing relationship there or the temperature, the time, their holding or you are going to cool it the cooling rate if you are going to look at cooling rate it is going to be the cooling rate. These are the essential relationship that happens in the stainless steel.

In a sense I can have a very high carbon containing stainless steel I can still avoid sensitization provided I cool it fast enough to avoid chromium carbonate formation that may not be practical, but in all cases, but you will see later it is possible in some cases with high carbon content I can avoid sensitization. That means, the factors that govern or the kinetics; the kinetics are temperature time cooling rate these are the factors that actually control to what extent the sensitization can happen or if at all it can happen in a given thermal process.

Then we went on to discuss the factors affecting intergranular corrosion from the point of view of the alloy from the point of view of the metallurgy of the stainless steels started looking at it. And, we said that of course, carbon content is a primary one you need to reduce carbon content by no way you can simply increase chromium content and let the carbon content remain the same and avoid the sensitization process which we saw that you know we discussed that in detail.

In addition to carbon content there are other alloying elements can marginally influence the sensitization process some of them are beneficial some of them are detrimental. We saw for example, nitrogen, it is beneficial, chromium is beneficial, tantalum, niobium are all beneficial whereas, nickel is not good. So, you just look at their relationship actually.

But, one thing I forgot to tell there was that the nitrogen is beneficial over a range of constant range of composition somewhere I would say below 0.166 wt.% if I keep adding more nitrogen to stainless steel what could happen? You can also form chromium nitride. You can form Cr_2N that also you see here one hydrogen captures 2 chromium it can happen. But, within the limited extent it is it can be beneficial.

Then we looked at the grains right role of grains. After all the sensitization occurs at the grain boundary area so, the nature of the grain boundaries affects the corrosion. So, we said that the energy of the grain boundary which means you know the energy of the grain boundary related by whether it is going to be low angle or high angle grain boundary. This is got low energy so, less IGC or no IGC you can say, it got a high energy you have IGC occurs.

I do not say high IGC because you know I mean most of the material that you encountered you know alloys and all have high angle grain boundaries only where. So, we did not of course, go in detail about the definition of high angle low angle, but I just say that twin boundaries are supposed to be a low angle grain boundaries.

So, if you have twins in the austenitic stainless steel the twin boundaries will resist the formation of the chromium carbide and so, the sensitization process. In fact, these are important from the point of view of intrassgranular stress corrosion cracking. So, stress corrosion cracking we are not discussed so far.

Stress corrosion cracking can be assisted by the sensitization of the grain boundary because the crack can travel along the grain boundary and make the metal more susceptible to cracking under tensile loading conditions, that part we will see later. Now, we look at the grains and we look at the grains from the point of view of energy of the grains.

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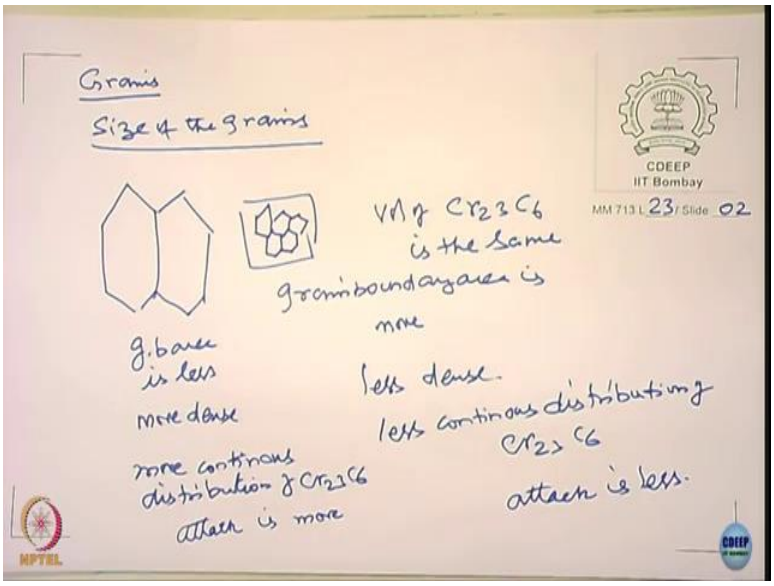

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Grains

Size of the grains

g.b area
is less

more dense

more continous
distribution of $Cr_{23}C_6$
attach is more

V/f of $Cr_{23}C_6$
is the same

grain boundary area is
more

less dense.

less continous distributing
$Cr_{23}C_6$

attach is less.

There one more thing that we need to look at from the grains ah coming continuing the grains is that the size of the grain, you called the grain size of an alloy. Finer the grains a better it is from mechanical properties point of view, it can have high strength and toughness together actually.

So, what would happen? What do you think? Will happen if I reduce the grain size I keep the composition same the carbon content the same, the chromium content the same, even other alloying elements content to the same, but I reduce the grain size. So, what do you think will happen to sensitization?

Student: Increase.

Increase? Why do you think will increase?

Student: Grain boundary is more.

The grain boundaries becomes more it makes yeah one way it makes some sense, but look at other way around. The chromium carbide formation occurs only along the grain boundary. There is a limited carbon right the carbon content is limited. So, you cannot form more chromium carbide than that is allowed in a given alloy that is dictated by the carbon content. So, assume that all the carbon is now converted to chromium carbide.

Now, I have alloy which has got smaller grain size and the larger grain size so, what will happen? Understood or not?

Student: Understood.

The volume fraction of chromium carbide formation does not depend upon the grain size it depends upon what depends upon the carbon content of the alloy. I only say that the volume fraction of chromium carbide formation is the same, but the grain size of the two alloys are different, one has higher one has the lower one.

So, what will happen to sensitization now? So, suppose like that. Now, look at visualize now I wanted to think yeah, but then over a time period you cannot have more carbon I mean carbon content is limited only. If you are going to have infinite source of carbon then probably you will have more sensitization.

Assume that the chromium carbide formation volume of $Cr_{23}C_6$ is the same. Now, I am distributing this chromium carbide over here and over. So, what happens? See if you look at here the overall grain boundary area in this area is more, grain boundary area is less. Am I right? If you calculate the grain boundary area the grain boundary I do not know you guys might have studied this ASTM grain size and so, the grain boundary area and all.

So, if the number of grains are increasing in a given in a given volume, the number of grains are increasing then the volume of grain boundary area or a I would say volume I would say the grain boundary area is more. So, I distribute this chromium carbide here and here the distribution becomes more dense here. So, this could be less continuous, less continuous distribution of chromium carbide here happened more continuous I would say continuous distribution of chromium carbide.

So, you will see that the grain boundaries are so well closely packed with the chromium carbide here it is not packed with the chromium carbide because same chromium carbide has to be distributed over a larger area. So, where is the attack here? Attack is more here, attack is less here. So, lower the grain size is beneficial from the point of view of sensitization.

But, please notice it is not a overriding factor I cannot keep the carbon content at 0.08 and lower the carbon content. I mean I mean keep the carbon content at 0.08 and then lower the grain size yeah, it can have some effect, but it is not going to have overriding affect right please understand that ok, but it does affect the sensitization because of this particular factor. So, the depletion of chromium is more in the grain boundary areas of the larger grains as compared to the depletion of chromium over here.

So, you find the smaller size or better from sensitization point of view as compared to the larger grain size in a in an alloy. I hope you get this idea, right or the still anybody has any problem? Ok.

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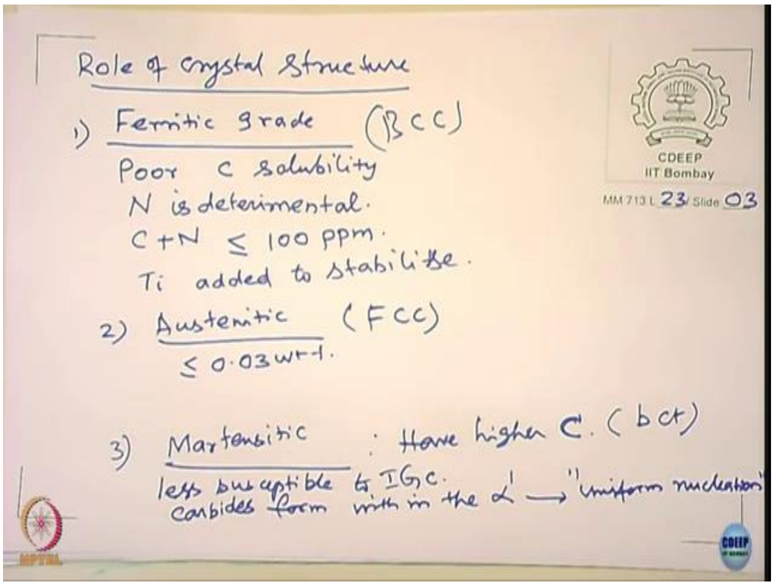

Role of crystal Structure

1) Ferritic grade (BCC)

Poor C solubility

N is deterimental.

C+N $\leq$ 100 ppm.

Ti added to stabilize.

2) Austenitic (FCC)

$\leq$ 0.03 wt%.

3) Martensitic : Have higher C. (bct)

less susceptible to IGC.

carbides form with in the α' → "uniform nucleation"

The next part that I would like to talk about is role of crystal structure. We saw earlier we classified stainless steel as austenitic, ferritic, martensitic, duplex and precipitation hardenable stainless steels. By nature the precipitation hardenable stainless steels do not have very high; carbon content the carbon content is very low. The strength of that stainless steel comes from where? Comes from the alloying elements like aluminum and copper they form precipitates they give rise to strength. So, the carbon content of that is very low.

So, the remaining ones we should look at how these class of stainless steels perform with respect to sensitization. Let us take the ferritic grade. Let us look at the ferritic grade now and see how it performs. If you take an austenitic grade and a ferritic grade which one will suffer more or what is the tolerance of carbon when it comes to ferritic stainless steels suffer more right. So, what is the solubility of carbon in ferrite as compared to austenite?

So, ferrite is dissolves very low amount of carbon. So, it cannot saturate more so, that means, when you are going to heat it is much easier for the carbon to precipitate into chromium carbide in a ferritic stainless steel as compared to the austenitic stainless steels. So, the solubility level of because you know you know is it not? For FCC structure the solubility of carbon is always more as compared to a BCC structure of steel.

So, you find that so, that means, here it is a poor carbon solubility. So, in this case in this case even nitrogen is detrimental. So, we can say that carbon plus nitrogen has to be less than 100 ppm. So, what sometimes people do is they add some titanium some stabilizers titanium is added to stabilize because the modern ferritic stainless steels have very low carbon I mean there is no problem, but even then you can add some titanium becomes easy.

But, there is always a problem in the low carbon varieties. When you weld you can you can pick up carbon from the surrounding suppose you have some grease or something right you weld it the grease gets converted into carbon on when you strike an argon this carbon gets into the material. So, ferritic stainless steels are more problematic compared to the austenitic grade stainless steels.

Austenitic we have discussed very expensively before. Here the carbon content can be less than 0.03 wt.% because the solubility of carbon in the austenite is better as compared to this. Let us take the case of martensitic. Martensitic stainless steels are generally containing higher carbon content. Why need higher carbon content? Yeah.

It forms the martensite and secondly, that is what gives hardness also. So, in order to form martensite you need to have reasonable carbon content without that you cannot form. So, the carbon content of martensitic stainless steels are higher compared to austenitic grade of course, ferritic grade actually, but even then they are less susceptible, have higher carbon in fact, highest carbon in among all the stainless steels.

They are less susceptible to IGC. Can you tell me why? Yeah, the martensitic stainless steels are used in what condition generally or martensitic steels generally what condition do you use it in fully martensitic condition? What do you do that?

You temper it nah? If you do not temper it then what happens? Then becomes so brittle you know the toughness is so bad. So, when you temperate what happen they form what? They form carbides. So, they form carbides. In fact, the martensitic stainless steel also form carbides actually, without that you cannot temper it.

So, when you are going to temperate it can form carbides. It can form chromium carbide, it can form iron carbide, but preferentially it form it forms chromium carbide because the chromium carbide is more stable as compared to the iron carbide.

But, even then I say it is less susceptible to IGC as compared to austenitic grade. Why do I say that? Have you have you heard of tempering martensitic steels forget about stainless steel for the moment, tempering of a martensitic steels, anybody? Have you seen the microstructure of tempered martensite?

No? That is sad then you cannot get an idea about what it is actually, right? What you when you when you take a martensitic steel and you solutionize it take it austenitic region and then quench it you form a martensite and you temperate, how does the carbide form? The carbide forms within the martensite is it, not? What is the martensitic what is the martensitic phase? It is actually it is a BCT right.

Martensite is BCT structure we saw it before and this is the FCC structure and this of course, is a BCT structure this. So, it is distort a lattice. So much of carbon is saturated now, it is not martensite is single phase.

So, when you heat it forms carbide, but how does the carbide form? The carbides form within the martensite. Martensite is given by term called alpha prime, α'. So, you have more or less uniform nucleation. This is not the right term to use, but I will use it.

So, within so, the grain boundary precipitation of chromium carbide is very less here. So, the chromium carbide occurs all through. Now, please understand IGC occurs only when the chromium depletion occurs at the grain boundary area that will happen only when the chromium carbide forms on the grain boundary area if forms everywhere IGC does not occur.

Of course, the chromium carbide formation by itself can bring down the passivity you all we know that right because matrix chromium content comes down, passivity is lost and showed, but the issue here is we are talking about the IGC we are not talking about the overall loss in the passivity.

In fact, the martensitic stainless steels when they temper it they temper optimally so that you do not lose too much of passivation, if you do not temper it, it is brittle. So, they temperate optimally in ordered to have good passivation at the same time good toughness is actually. So, there is optimization process.

So, coming back to the point here the martensitic stainless steels are not prone to IGC primarily because of the fact that the chromium carbides form within the martensite and so, the depletion of chromium at the grain boundary grain boundaries or lath boundaries whatever you can call it acicular boundaries whatever we can call it is less. But of course, we keep on aging for long time they also can undergo intergranular corrosion, but generally they are not prone to intergranular corrosion.

So, please understand the concept of intragranular corrosion in a proper manner actually ok. So, it is not the chromium carbide formation alone is responsible, the chromium carbide formation of the grain boundary and the consequence depletion of chromium, grain boundary is responsible for intergranular corrosion of stainless steels.

Student: Why does chromium carbide precipitate inside martensite?

It is a good question ok, yeah then I think then you have to into the metalized aspect of what is called a nucleation and growth. See martensite when you what is the martensite the martensite consists of a lot of dislocations most of you know about it. That is the reason why it gives you higher hardness, higher strength.

So, when you have lot of dislocations within the martensite when you do annealing or aging process or a tempering process what happens now? The precipitations occur on the dislocations. The dislocations are large in number within the martensite. So, they preferentially precipitate along the dislocation that is why when I say it is uniform nucleation, I do not mean in true sense of it ok.

The true sense means it should not happen at the dislocation also, but because you have lot of dislocations martensite and so, they are very well uniformly distributed in the martensite. So, you have lots of chromium carbide being precipitated there only. So, that is what happens in the case of a martensitic the stainless steels. Any other question?

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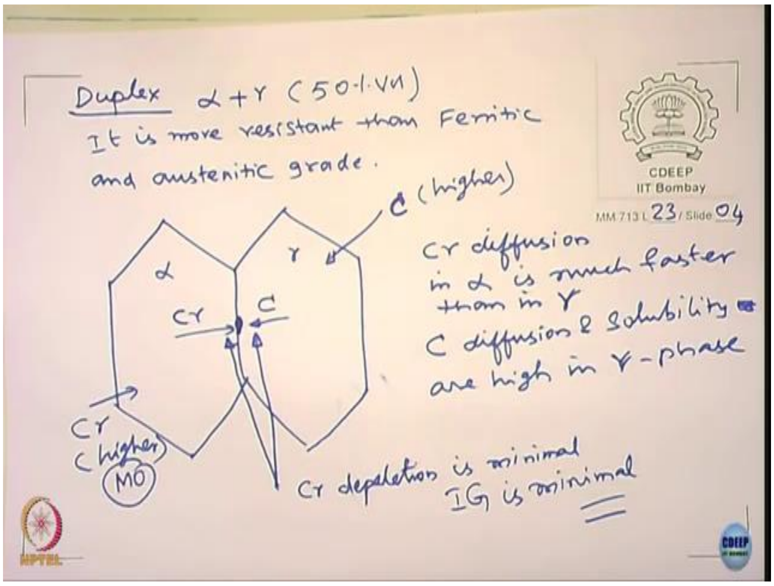

Duplex $\alpha + \gamma$ (50 % vol)

It is more resistant than Ferritic and austenitic grade.

Cr diffusion in α is much faster than in γ

C diffusion & solubility are high in γ-phase

Cr depletion is minimal

IG is minimal

Let us get into the next class of stainless steel duplex stainless steels. The duplex grade when we talk about we say it is a mixture of alpha and gamma, each of them in 50 volume percent each. It is more resistant than ferritic and austenitic grade. It is a very interesting thing actually right. Ferritic stainless steels are more prone to sensitization, austenitic sensitization is also prone to sensitization, but you have two phases in the alloy they are better than both of them actually. And, the reason is not very difficult to understand actually.

Let me draw some diagram. So, this is an alpha phase and this is the gamma phase in a duplex stainless steel. The precipitation of the chromium carbide occurs here the grain boundary. I just take only one precipitate here it occurs here. Very interesting thing happened. Chromium diffusion in alpha is much faster than in gamma. Carbon diffusion and the solubility both are high in gamma phase. Look at how the cooperation takes place.

So, you have here more carbon, is it not? Because the solubility of carbon is more here. If you take if you take alpha phase and the gamma phase in a given alloy, can you guess which would have higher chromium content? Will the alpha or the gamma? Is chromium is what stabilizer is the gamma stabilizer or alpha stabilizer I mean alpha stabilizer.

Alpha. So, it is a chromium is it is got a higher chromium level here is it not? Partitioning taking place in that you will have more chromium it may even have more molybdenum also anyway that is not important for us got it? So, it will have more chromium here and the diffusion of chromium is higher in alpha, higher carbon. Now, what happens now? The carbon diffuses here fast and chromium diffuses fast here.

So, what happens? Now, if it happens now what happens as a consequence chromium depletion is minimal on both the sides because when you have faster diffusion then what happens? Then you do not get a strong concentration gradient, quite fast and there is no need for the chromium in the austenitic side to diffuse because when the carbon goes over here the chromium moves from alpha to form the chromium carbide.

So, that means, the grain boundaries are not going to get depleted so much as it happens in the ferrite or it happens in the austenite. So, that means, what happens? So, minimal. So, IGC is minimal. So, duplex stainless steels are generally more resistance to IGC as compared to austenitic grade and ferritic grade. Of course, martensitic stainless steel it should does not come into picture because they nucleate in the in the grains. Of course, there the corrosion resistance of martensitic stainless steel falls because of the tempering process.

So, this is about the crystal structure you are seeing how they affects the sensitization of the stainless steels. So, this should be known to you. Any questions here?

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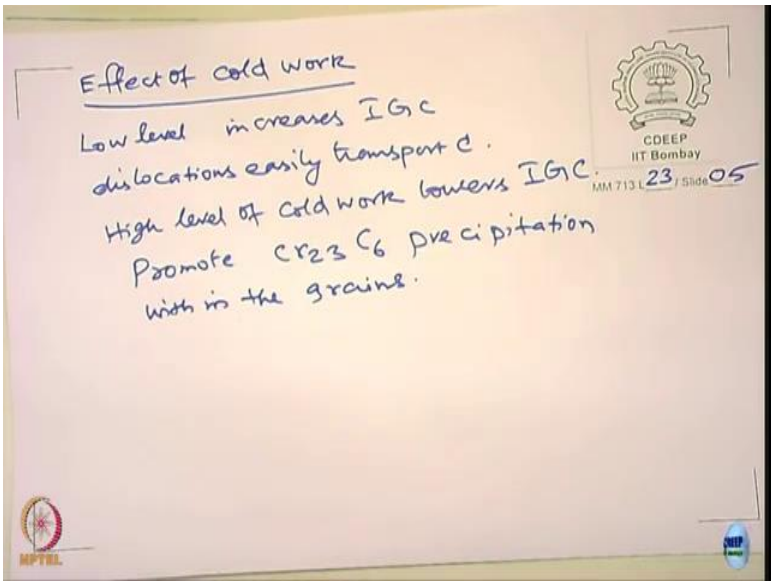

Effect of cold work

Low level increases IGC

dislocations easily transport C.

High level of cold work lowers IGC.

Promote $Cr_{23}C_6$ precipitation

with in the grains.

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So, let us let us move forward, effect of cold work. Effect of cold work when you do a cold working what happens to the material, you have dislocations? Right. So, cold work at the low level increases IGC because dislocations easily transport carbon. High level of cold work lowers IGC. Can anybody guess why at high level IGC is getting reduced? Yeah you have lots of dislocations now. In fact, they get entangled.

So, they because they promote chromium carbide precipitation within the grains. Of course, you see the overall passivation all these will come down you know we are talking. Please again do not try to club everything together, we are only talking about IGC. I am not saying that cold working is better for overall performance of stainless steel no that is not the idea here.

So, this is about the intergranular corrosion, the theory, the factors affecting the intergranular corrosion of stainless steels we have seen so far and any of you have any questions you, please let me know.

Student: How does dislocation facilitate diffusion of carbon, but not chromium?

Yeah, see when you do that when you see what happens is when you do cold work and you anneal it high temperatures the dislocation gets annealed you know they go to the grain boundaries and all. So, the dislocations move and carbon can go along with the dislocations is not it? So, it facilitates the movement of or diffusion of carbon to the grain boundary. So, of course, it is not going to facilitate that much of chromium because see and I mean carbon is so small atom it get entangled with the dislocations.

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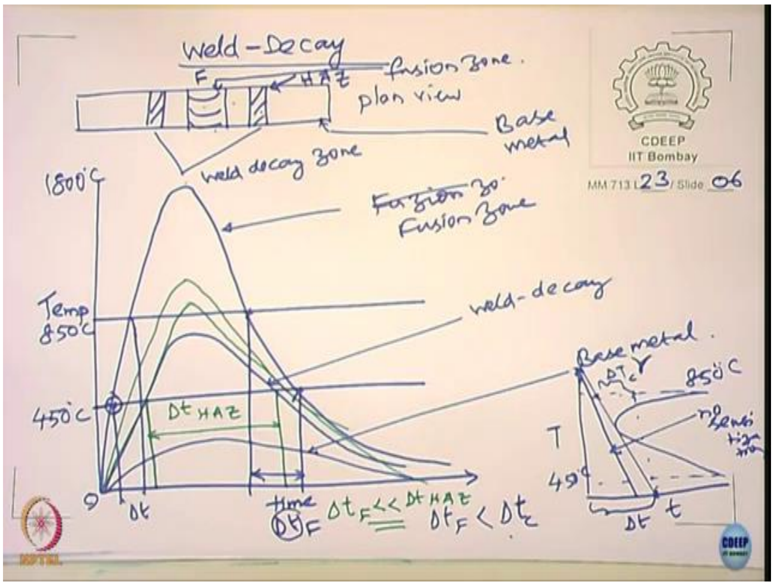

So, let us now go to the main topic of weld decay. This is the real problem in industry. What you have seen is science of that. I am going to show you the one diagram only diagrams photo of the weldment, get back to this here.

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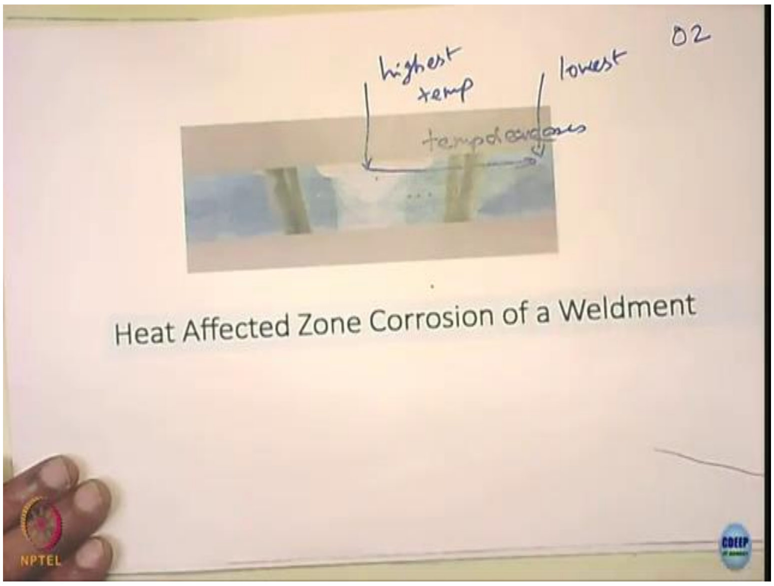

Heat Affected Zone Corrosion of a Weldment

You weld a stainless steel and what is this? This is actually a TIG welding and it is a butt building right it is a butt joint right. What you do in a; what do you do in a TIG welding?

You use like arc and use a filler wire you an arc is stuck between the metal and the electrode. The temperature is so high it melts it melts the electrode either it is a consumer electrode for example, or use a filler wire it melts and then they deposit and they join. That is how you do fusion welding you do that it is a thermal welding here.

So, you have a TIG welding, you have a MIG welding, you have laser welding, you have electron beam welding, you have brazing the several kind of a metal joining techniques they do exist. In all these cases what is common is the joining process is due to the thermal process, they melt and the union between the two pieces they occur. So, stainless steels are being heated now and the molten things join them together.

Now, what is very interesting you look at this diagram here is the highest temperature this is the highest temperatures and here this is the lowest temperatures. The temperature starts decreasing from here to this onwards temperature decreases. Though the maximum temperature is here the sensitization does not occur at the fusion zone, it occurs away from it which is called as a weld decay zone generally, termed as a heat affected zone.

Actually, the heat affected zone is generally categorized as what? That zone where there is no melting takes place, but there is some solid state transformation metallurgical transformation occurs. Over here the so called metallurgical transformation occurs only here, not even here also it happens here. It does not happen here, of course, low temperature nothing happens. Now, we need to understand why it happens here why not here why not here?

Also we need to understand why can it move towards left can move towards right, if so what happens? That means, you need to understand clearly what governs the formation of the weld decay zone that is very important for us to do that. We have seen the science of it we have looked at the interrelation between the metallurgy of the alloy and the time and temperature cycles that you seen that actually. So, with that we try to understand this particular phenomena of weld decay.

Now, let us go back. Sensitization is temperature dependent and time dependent composition dependent. Can I make a statement like that? Ok. So, now let us see why should the weld decay occur at the heat affected zone? Though that is the first discussion that you are going to make it. Let us take a schematic of this. It is a plan view disc.

Now, when you weld, if I keep a thermocouple here or if I keep a series of thermocouples here up to this point, what I can follow? I can follow the temperature rise and fall with respect to the time. Can I do that? So, when I start welding from one end to another end I put a thermocouple there and monitor the temperature with respect to time. If you do this very interesting thing can be observed.

I am going to give you very schematic of the temperature variation with respect to time say at location a say fusion zone and this is the heat affected zone. Let us take the fusion zone the maximum temperature will be at the fusion zone. So, what happens now? The temperature shoots up something like that it goes actually. What is this temperature? It is well above the melting point of the alloy that you are talking about right 1600 beyond that.

Let us take this just take this zone here something like that. This is the fusion zone, this is your weld decay zone and this is your base metal somewhere here. Now, let us identify the weld, let us let us identify the sensitization temperature regime that is between 450 and about 450 to 850 °C.

So, you have between 450 somewhere in the boarder say 600 or 700, it maybe 1800 temperature is quite high temperature. So, between these two temperatures the alloy will form chromium carbide provided what? Provided you give enough? It may be sensitized between 450 to 850 °C this temperature region, provided you give enough time. If time is not sufficient then the guy is not going to give rise to chromium carbon precipitations.

Now, let us look at the heat effected zone. Now, I am going to now look at sensitization I am going to draw a small temperature time sensitization diagram for you because you need to also know this. What is this temperature? Around 850. What is the temperature? 450 °C. If I take it to this temperature and quench it very fast, no sensitization.

Or I put other way around, if I can draw a nice thing, look at this. This is the maximum time that is allowed for the material to cool down. When you hold it in the gamma, this is the- what is this? This is called gamma region. This is the maximum time allowed to cool. If you go beyond that what happens chromium carbide forms.

So, when you take it to this temperature, if you are going to cool it faster than this; that means, less time no problem slower than that you are getting into sensitization. That is, the time that can be held in this temperature in fact, in this region, I am actually speaking it should go from here. If you relook at it this is the time and this is the time, time is it starts from here and goes here. This is the time right.

If you draw in fact, you know more appropriate way of talking about is what? This is the Δt, I hope you get it, is it not? Time taken start from here right up to this temperatures no problem, after this start. So, this is the Δt, critical temperature, critical time required to avoid the sensitization. So, this is Δt here.

Now, look at this look at this curve I have started from here. This is the time it started and time the ends is here this is the time it ends. So, this is the Δt that I have here. Assume that it forms a chromium carbide. Even chromium carbide forms when you raise the temperature above what happens to chromium carbide?

Student: Dissolves.

Dissolves, right? So, it dissolves. So, this time is not counted because when temperature goes up the chromium carbide dissolves. Now, it starts counting from here and then count from here. So, this is the Δt the fusion zone, am I right? Where the material is held in that in the sensitization temperature region, am I right? Is not it? It starts this temperature it ends here because below there is no problem. So, this is the time it has been kept in the temperature region of 450 to 850, right.

If this time, Δt_{fusion} is going to be smaller than $\Delta t_{critical}$, what happens? Yeah.

Yeah if it is within that then there will be no sensitization, agreed? Now, let us take this case of heat affected zone. It starts from here, where does it end? Ends here Δt HAZ.

Now, you look at here. It becomes so obvious for you becomes you will find at least Δt fusion is much smaller than Δt HAZ. Can you make it? You get it from this diagram? Now, what happens in the case of base metal?

Yeah, it does not get into the region at all. So, there is no sensitization. So, the sensitization of the heat affected zone is quite understandable, because the time that heat affected zone resides in the sensitization region is good enough to form what? To form chromium carbide precipitates to get sensitized. So, the heat affected zone is prone to is prone to sensitization. This is the thing that you should be looking at.

What is the significance of this Δt? It only says that when you weld it the fusion zone, it goes through the sensitization region from 450 to 850 for this much time. It may not sensitize. Even it sensitizes assume that if this Δt is much larger assume that this Δt is much larger even then what will happen? Because it goes through higher temperature that will that will get dissolved, the chromium carbide get dissolved.

So, that means, this one anyway has no significance from the point of view of welding right. There is no signification, I am only trying to analyze the thermal cycles during a welding process, but otherwise this one does not have any significance at all because even it gets sensitized for argument sake if you make it they get dissolved in the chromium carbide and you know I mean when the temperature exceeds the solubility of the chromium carbide precipitate.

Student: While you are speaking in case of the in the heat affected zone.

Yeah.

Student: With the temperature 450 °C.

Yeah.

Student: I think Δt from that point to that point that is here to here.

Yeah.

Student: But, in case of fusion zone.

Yeah.

Student: the same weld thermal cycle containing 450 °C at 450 °C at two points.

Yeah.

Student: But in that case they are taking.

It is a good question ok, but I want somebody to answer. Yeah, here look at here look at this I start from here the temperature goes above it is still within the 850. So, what happens the alloy continues to transform, continues to form chromium carbide and till it reaches back here; that means, all this thermal cycle, the alloy is subjected to heating which means chromium carbide will continue to form, right? If it goes above this only what happens? Even there is a chromium carbide forms they will start dissolving.

So, if this assume that this curve goes here, then what happens? I would again will take only the second half of it or put it other way around these portions you see here, see this is the thermal cycle for this, right this is for that.

Now, I can have a series of thermal cycles starting from here to this many of them are in between things, right. Can we can I can you visualize that? What will be the thermal cycle for this? It will be somewhere here only. This guy will go the time is more it is more than this ok, but then the guy has gone up.

So, if I have another thermal cycle this guy again exceeded here right. So, the guy dissolves. If it does not dissolve completely of course, then you can count it also I mean it is not that no hard and fast rule, but that you need to make a calculation and say what happens at all. So, what we are assuming here is that when it goes up the chromium carbide dissolves. Actually dissolution of carbides are much easier than nucleation.

If you look at it generally dissolving is much easier it does not require that that kind of under normally overheating is not required. When you melt it you do not need overheating when you cool it down you need a under cooling because nucleation growth is a problem. But, apart from that you can able to calculate and see what really happens in the in the in the in the thermal cycles actually.

Student: How the when the ∆t f is smaller than delta ∆t c then the sensitization does not occur?

If delta?

Student: ∆t f is smaller than ∆t critical.

Yes.

Student: No, sir but why delta t HAZ it occurs sensitization.

That is what you know you see here the fusion zone it starts from here and ends here. This is the ∆t fusion zone, if that and generally this time is very small. You see what are I am trying to say is that assume that I am going to take 304 of 0.3 percent carbon filler wire, suppose I take hypothetically do you think they do not sensitize? It may sensitize.

Why? The time required to form chromium carbide decreases when the carbon content is increasing. So, when you are increasing the carbon content even the fusion zone also can form chromium carbide, provided the carbon content is very large. But, the carbon content of the fusion zone is almost equal to that of the base metal. So, it requires same amount of time for the formation of chromium carbide.

So, we need to understand from the point of view of again temperature time cycles. So, chromium carbide formation the temperature time required is the same whether it is in the base metal, whether it is in the heat affected zone, whether in the fusion zone, I am not looking at other small variations like I am not looking at all complications arising over nucleation growth and all. Generally, you would say that the time temperature required is same.

If that is about the case then the fusion zone by inherently will have less time in the sensitization region as compared to the heat affected zone because heat affected zone never crosses the solubility region of that actually, does not go up, that is the reason why it is happening at all.

So, what it means to us actually? It means to us that we understand the science of welding in addition to the science of sensitization. What is science of welding? How much heat input I give to the weldment. It all depends upon how much heat I deposit on the weldment, but that decides the cooling rate.

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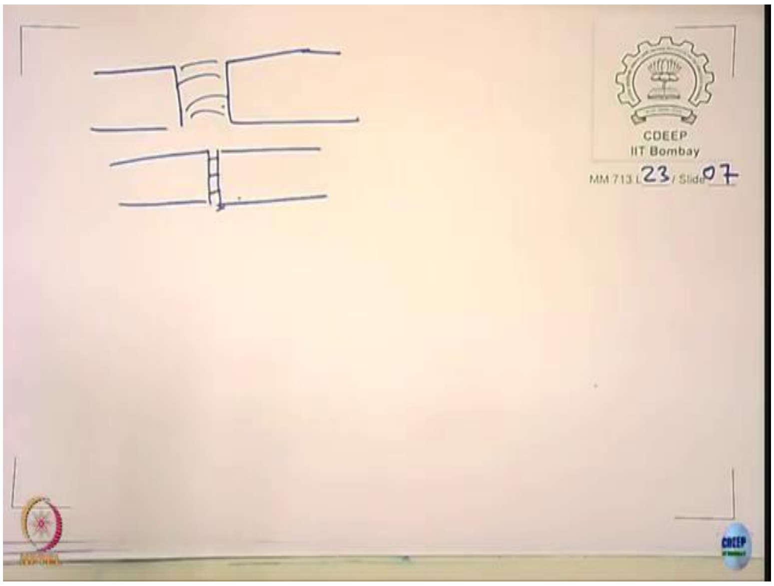

Suppose, I have a weld, somebody welds like this. Somebody welds like this, this is called as a narrow gap welding kind of things, and somebody welds like this. The heat input required to fill here because you are going to deposit small amount of molten metal here, you deposit small amount of molten metal here. The cooling cycle here and here are different. So, the way their sensitizer going to be different, am I right? Similarly, the conductivity of this metal and this is different things will be different.

So, we need to superimpose the sensitization kinetics with respect to the science of the welding process, then only you can able to understand how the weld decay occurs. So, this probably you start very well in the welding course. I do not know how many of you taken the welding course.

There you will go through much rigorous treatment of and the welding and all the things. We will not go through that. I will give you very minimal things to appreciate how the welding processes can affect sensitization weld decay in addition to the alloy chemistry.

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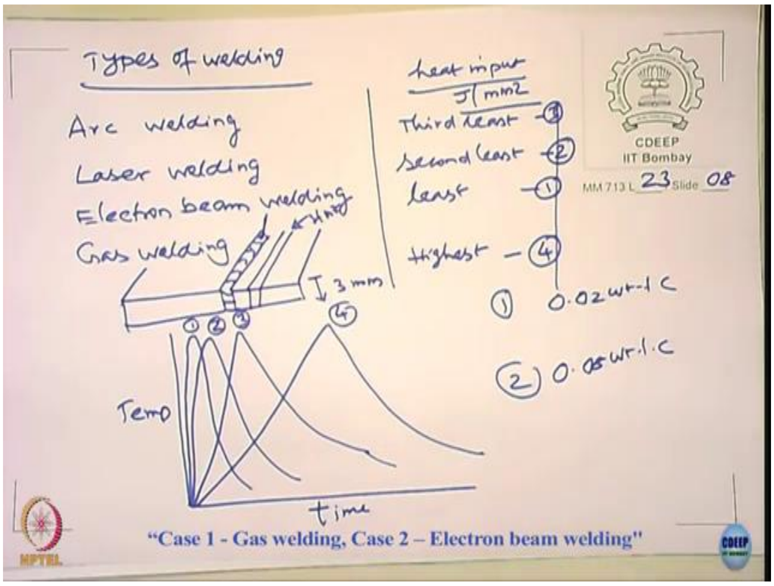

"Case 1 - Gas welding, Case 2 – Electron beam welding"

Now, let us take the cases of types of welding. I am going to now look at types of welding pattern.

Now, we can look at an arc welding; we can look at laser welding; you can look at electron beam welding; you look at the gas welding. How many of you taken a welding course? Ok, for you guys must be very simple, actually it is not that difficult to do that. So, before we get into this let us look at some simple properties of this.

Let us look at the heat input maybe in terms of joules per mm square (J mm^{-2}) or whatever right, is it not? Something like you give it right. Let us look at the heat input required to weld in the case of arc welding, laser welding, electron beam welding, gas welding and how do you consider that which one is highest here in this? Heat input required to weld.

I am not talking about the power of the welding. I am talking about heat input required to weld this much area. So, you should not confuse between these two, right? Is it not? Ok.

So, gas is the highest; which is the least here? Electron beam welding is the least here. It is the second least. This is the third least. It is not the right way of defining I should put number 1 2 3, but anyway I hope you can understand this better actually. So, this have a consequence like this.

So, I want to weld this is a cross-section actually it is a cross section, may be let us say about 3 mm I want to weld and of course, you can draw this also, something like that you can weld. So, I keep welding using many of these techniques. If I take the so called heat affected zone and I measure the thermal cycle, schematic only.

Now, can you map these thermal cycles versus this? Yeah, the first one is the electron beam welding correct, second is the laser, and third is arc and fourth gas welding. Now, we can see that what is the role of the welding technique on sensitization of a stainless steel. Can you or can you not?

Now, I want to let us say I have 0.02 wt.% carbon. I have 0.08 wt.% carbon, 1 and 2. I welded this one I did not get sensitization. I welded this I got sensitization. I welded the first one in one of these techniques. I found it is weld decay sensitized. I use one of these techniques, I welded this even then you do not get sensitized, can it happen?

Student: Yes.

Good. Good answer. If so, you tell me the technique that led to no sensitization, electron beam welding, there you go and I use this still got a welding problem which one of this is a technique?

Student: Gas technique.

Gas technique. So, they are sensitization science. So, you need to understand the sensitization in terms of that it is not an abstract terms. You translate the sensitization kinetics in terms of the welding techniques then you can able to appreciate it and if I want to weld it so, what happens essentially the cooling rate.

Suppose, I use a TIG welding I have 0.05 wt.% carbon I do not want to sensitize. It is a 304 stainless steel; I do not want to sensitize what I should do?

Student: increase welding speed.

Yeah, possible, but yeah of course, I mean this is a good answer I would say when you increase the welding speed what happens now? The Q goes up, but their problem is you need a minimum Q in order to in order to fuse otherwise it will be an improper welding. So, that may not give rise to good welding. Then, what else we can do? I can think of cooling it, if I can think of cooling the system, right? I think of cooling the system, so that the cooling I mean so that the rate of cooling becomes faster.

So, we need to look at it from the point of view of that. There are so many variations that you will get there are people. So, this should be seen in the slide so that you can understand it better.

So, it is not simply that you look at an abstract sense, we need to correlate the process parameters with respect to metallurgy and then see how we can able to control weld decay, so that in practice we can do that same answer that you have been giving.

The people have found TIG welding 0.03 wt.% carbon sometimes they found there is no weld decay and sometime they formed weld decay, why? It is a manual welding, the guy got so tired. He was not welding very fast; he started slowing down the torch. Then what happens? More heat input got sensitizing problem. So, it is just not guarantee you that no sensitization taking place at all.

So, that is how you need to analyze the problems. When you go to industry you know problems are complex, but what gives you the way analyze it, the scientific understanding you find carbon is same. Low carbon, why does it happen? So, you need to understand why things are really happening the way they are happening and how to find a solution to the problems.

I will stop here and meanwhile if you have any questions you please let me know how we can you know clarify those doubts actually.

Thank you very much.