Corrosion Failures and Analysis
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Lecture - 39
Stress corrosion cracking: Mechanism (Part 1)

Let us start lecture 39 and the course is Corrosion Failures and Analysis. We will continue our discussion on Stress corrosion cracking.

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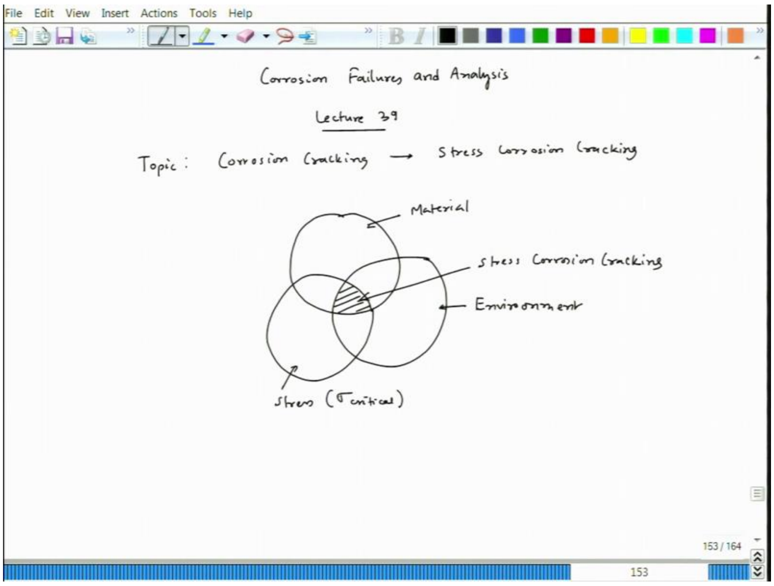

The course is corrosion failures and analysis, lecture 39. We can say corrosion cracking or crack assisted corrosion failure, within that we are discussing about stress corrosion cracking. So, if you recall that we have discussed a couple of characteristics of stress corrosion cracking and among that we found that all materials do not show SCC susceptibility in the same way in a particular solution.

At the same time same material has will also not show the same susceptibility in different mediums and then we also found out that there should be a critical stress intensity factor or K1 SCC must be reached before the material starts showing SCC susceptibility in a particular corrosive media.

So, that means, it is very clear that material is one aspect, ok. So, whether it shows susceptibility or not depends on in a particular medium depends on as compositions, its purity. Now, another part is the environment factor which for example, in aluminium lithium alloy may not show susceptibility in simple 3.5 percent NaCl solution, but it can show severe SCC susceptibility in a solution containing sodium chloride, chromic oxide as well as potassium by a dichromate. So, those are the situations which are coming due to environment factor.

Now, another factor is stress if stress intensity factor has to reach a critical value to show stress corrosion cracking, then definitely there should be a critical stress which should be exceeded before it starts exhibiting stress corrosion cracking.

So, that means, it is very clear that if we try to draw a circle like this and three circles like this see one circle corresponds to let us say environment, another corresponds to material and the last one is corresponding to stress and here stress means sigma critical which has to exceed.

Now, in case of if you see all those circles you could see that this is the common zone and in fact, when we have combination of these three major aspects then only we get to see SCC. So, this is the zone where we could see stress corrosion cracking. Now, in order to find out the SCC behaviour we have to take material, environment and stress all three in combination. Now, in and how could we do it?

For example, in case of let us say in galvanic corrosion or in case of dealloying or in case of erosion corrosion. So, they are all; all those places we have some test methods, ok. So, like galvanic corrosion we can see that one part is not corroding one part is corroding.

In case of erosion corrosion we could see that one section is having influence from the turbulence factor or impingement factor those factor we could see clearly from the mark point of view or even dealloying case we could see that perforation on the surface. So, we have we could see that yes, there is a manifestation.

Now, in SCC until and unless failures happens we do not see any manifestation. In fact, it is very silently happening. So, on one fine moment it will happen it will the crack will grow at a very high speed and then catastrophic failure would happen.

So, now, in order to understand; that means, it becomes a kind of a serious aspect to the integrity of a structure. So, that is what one has to find ways to find out SCC susceptibility. So, in order to find that ways to find out SCC susceptibility one has to do test. So, that is what in case of SCC the test processes are very important.

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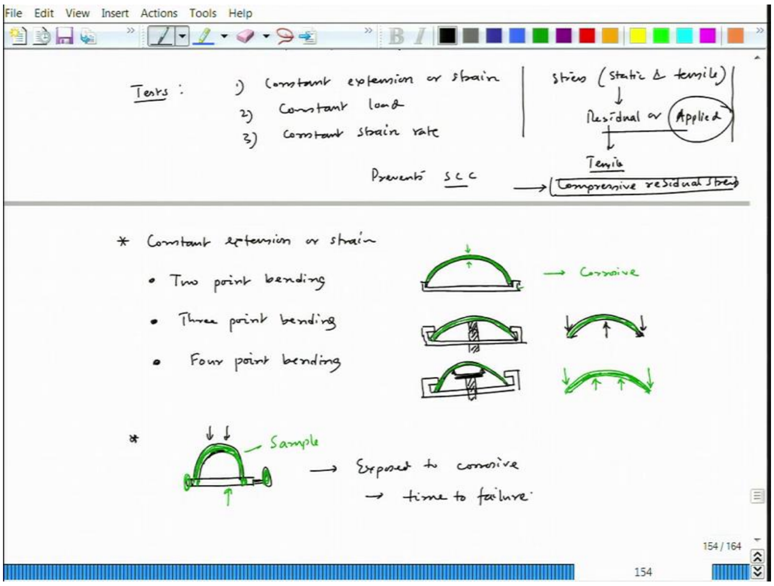

So, in order to find the test processes one can do several test. So, different test major tests are like 1 is constant extension or strain; 2nd is constant load and 3rd is constant strain rate. Within this regime of experiments one can choose particular test method to find out SCC susceptibility of a material.

Now, one part is SCC susceptibility of a material different solutions, another part is different materials in a same solution or another part is the effect of load on the material for SCC. For example, a material shows SCC susceptibility in a particular solution. Now, one has to find out what could be that critical load which would be needed for exhibiting or manifestation of SCC.

So, out of that so, every case we can have different ways to load a specimen because in case of SCC we need stress which should be static and tensile. In this aspect this stress could be either residual or applied and when we talk about residual it has to be tensile because when we have compressive residual, this compressive residual stress in fact, it does not lead to SCC it actually prevents SCC.

So, we can say this is SCC prevent SCC how when we have this compressive stress is actually acting opposite to tensile action tensile stress that is what it actually prevents fracture tendency of that material. Now, that is why many materials are short pinned to introduce residual compressive stress in the material which actually prevents stress corrosion cracking.

In fact, this compressive stress also prevents corrosion fatigue. In corrosion fatigue we have a tensile component when that alternate stress is happening. So, the tensile component intensity of the tensile component can be reduced by this short pinned compressive stress. So, this is one that is what these conditions are to be maintained.

Now, in order to maintain that condition and here mostly all those tests test we actually giving applied stress. Now, how can we have those applied stress? One is let us say those how do we have those arrangements. For example, if we consider constant extension or strain, one can use this kind of arrangement. So, like two point bending, how one can do this? One can use a fixture like this and the sample could be plate kind of thing or a circular cross-section.

Now, then you bend the sample like this; this is the sample part and you can meant you have see the stress can be maintained within the elastic zone and then this entire fixture is to be placed in corrosive. So, that is what this fixture should be corrosion resistor in that corrosive and only the corrosion effect will come on this material and then one can wait for the time when first crack appears because when you bend it this particular part will experience tensile loading this particular part will experience compressive loading.

So, now one can wait till the first crack happens and that is the time to failure for the for that particular material. So, that way one can compare two materials in a same solution or the same material can be compared in two solutions just by looking at the time to appearance of that particular first crack on this surface. So, that is what regular inspection or even it can fracture there. So, this is two point.

Then, there could be; there could be three point bending. So, three point bending is like one can have a fixture like this, fixture like this and then we have a screw here, ok which will push this sample from bottom and then the sample can be fixed like this.

And, this particular thing can extend up to this which can be screwed and then this after holding this material between two fixtures end fixtures, and then one can push that particular screwed object which will push the centre part upward. And, that is way it will basically a three point bending.

So, where the sample is loaded like this. So, this is the sample you have fixture like this; this is the loading and this is another loading. So, this is three point bending, fine and this is the sample. So, now similarly one can use four point bending, so, where loading would be like this.

So, in the schematic how do we have the load one can have similar fixture like this. This is the sample. Now, one can have a pin here, a pin here and this is fixed to screwed arrangement like this. So, now, this plate, this entire block can be pushed up. So, now, the loading is like this. So, it is basically loading is this two ends we are fixing, now we are loading like this. So, this is four point loading. So, one can use that one also.

So, like that way several ways to have this constant extension method. So, there could be u there could be ways like u shaped samples. So, one can have a rod fixture like this and then here there is a tightening arrangement and now this is a holding part, sample can be bend like an u separate object. So, this is the sample this is the sample and it is hold with a screw and this end also screw and this is the fixture where the sample is fixed.

So, this is the sample and this is the fixture which holds that sample and then it is exposed to corrosive and we wait for we start looking at this surface at this portions and then try to see time to time what is where is the point of crack generation and once we get that first crack then we note down that particular time to failure and then we compare that time to failure with for the different materials in a same solution or different same material in different solutions.

So, that way it is a quick ways to determine SCC susceptibility just by looking at the track appearance and the time to crack appearance and this method is very simple as we could see that and this here you can use a plate, you can use a rod and you do not need a very complicated machine arrangements and then one has to see again time to failure, fine.

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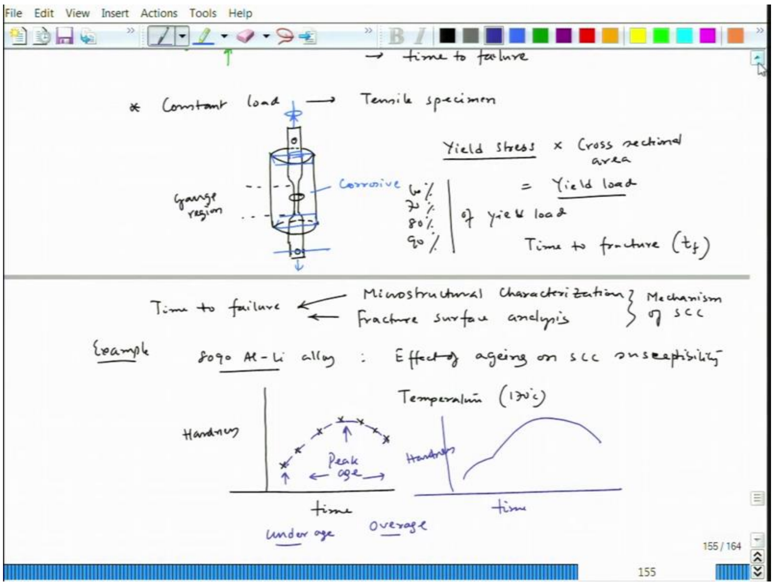

Now, in case of there is one sort of arrangement which is actually nothing but constant load and in a constant load where you can use a tensile specimen and for example, one can use a dog bones type of specimen. So, this is the specimen, we have two holes here to hold the specimen.

And, now, one can use cylindrical the cylindrical glass apparatus both ends opening and then one can put rubber gaskets, rubber cork. And, that rubber cork will have a small hole of the size of this particular tensile specimen and then that tensile specimen will be pushed through that and those holes where it will come out from that particular rubber gasket.

And, so, that particular hole should be tight enough so that the liquid should not spill out and inside that you put corrosive. And, now you load it and while loading and loading can be done it is a very simple process. For example, you have this apartment this particular arrangement and now, this is connected to a loading part and this is fixed let us say this end you have fixed it.

So, the top part we can load by giving a weight on top of a platform and then that platform will give the load on top of the sample and this load would be decided on the basis of yield stress of that material. Now, if the material has got a yield stress which can be found out by doing simple mechanical testing and after that we multiply with cross sectional area of the gauge portion. So, this is the gauge portion.

So, in that gauge region we have to find out what is the area there and then we found out what is the yield load and that yield load is nothing, but the load at which the permanent deformation starts of that particular engineering material or the steel let us say if it is a steel or titanium alloy or copper alloy or aluminium alloys.

Now, once we find out that yield load we can decide the load because the load has to be less than the yield stress and that load could be 80 percent, 90 percent, 70 percent, 60 percent different loads of so percent of yield load and then we leave it there. And, we have to wait for the fracture to happen and when fracture happens that time we note down. So, time to fracture which is same as time to failure. So, that time is noted down.

Now, if we need to perform SCC, you know the SCC susceptibility, qualitative knowledge of SCC susceptibility of two materials in the same solution definitely this time to failure which has a higher time to failure definitely that material is resistant against the SCC. And, why we are keeping less than the yield load because we know that this load is below yield point and that is what it cannot deform at that load and that is what if it deforms if it fails and should not fail at that particular load.

For example, in air if we put 60 percent of the yield load of a material, it will never fail. It will have a elastic extension, but it will not fail. But, if we put that same material in corrosive because the corrosive action is coming into play, it can fail and it actually does fail and that time to failure becomes our qualitative measure of different SCC susceptibility of same material in a different solution or say different materials in the same solution. So, it is a kind of comparative finding.

But, in addition to that comparative finding if we try to combine so, this is time to failure is one failure and if we combine microstructural characterization if we combine fracture surface analysis, then we definitely would be able to know the mechanism of SCC, ok.

So, now let me just show one such example in case of 8090 aluminium – lithium alloy ok. So, we wanted to find out the effect of ageing on SCC susceptibility of this alloy now this alloy just like 2000 series aluminium – copper alloy this alloy also is a precipitation hardening alloy.

Now, whenever a precipitation hardening alloy is there now once you solutionize and then take it to a little higher temperature than room temperature you hold it there you would see the hardness profile like this hardness and time. So, now this is at a particular temperature let us say around 170 degree Celsius which is more than room temperature after solutionization let me tell you this is; that means, all the things all the elements are taken into solution and then you quench it and then take it to that temperature.

So hardness variation would be with as a function of time, if you calculate you will see the hardness variation would be like this, ok. So, this is the kind of hardness variation typical hardness variation one can think of. So, this hardness variation could have different characters like this is hardness, this is time for holding at that particular temperature.

So, hardness can be like this hardness variation like this in case of copper aluminium – copper system this is the typical hardness variation one can think of which is first one is GP zone formation and then theta prime, theta double prime theta double prime, then theta prime and then finally, theta which is the equilibrium precipitated that forms.

So, now this particular part this region this is called peak age, this is called underage below peak age is basically underage and then beyond the peak age we call it overage. Now, we wanted to study what is the SSC susceptibility of underage, peak age and overage of that same material.

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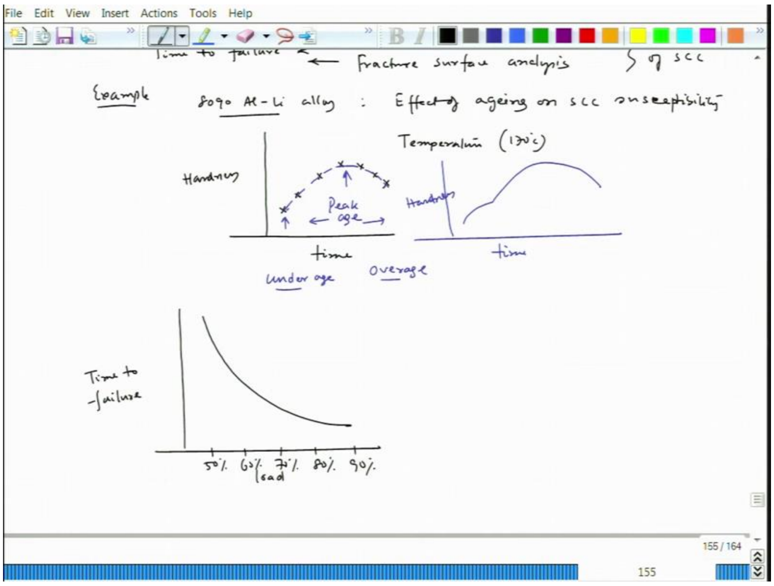

Now, that study gave us and we did it through via this constant load method, at different load we find found out the time to failure in a solution and that time to failure plot looks like this. So, this is percentage this is time to failure and this is load and load is let us say this is 50 percent, this is 60 percent, this is 70 percent, 80 percent and then 90 percent.

Since it is below yield point, so, we do not expect deformation. So, you can also roughly assume that this is basically the percentage of yield stress of that material. And, then we found out that as the load decreases time to failure increases and the plot would like look like this, ok.

And, then we found out that we try to find out for different materials peak age, underage and overage we just compared that this kind of graph. This graph can be generated for all the materials at different loads and we just compared and I am just showing you that data.

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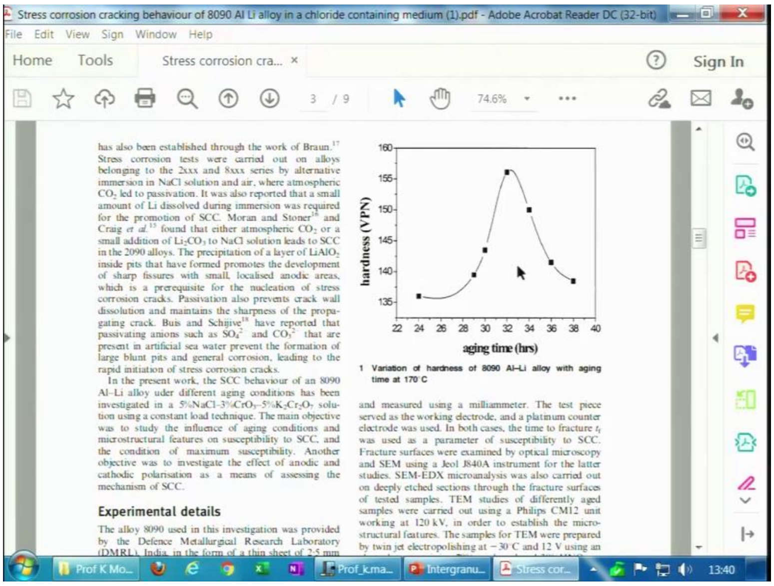

If you see this particular graph this is a typical aging curve of that material at 170 degree Celsius. So, this is the peak age condition, the cursor if you see that cursor is the peak age, below that it is underage and above that time is basically the overage condition.

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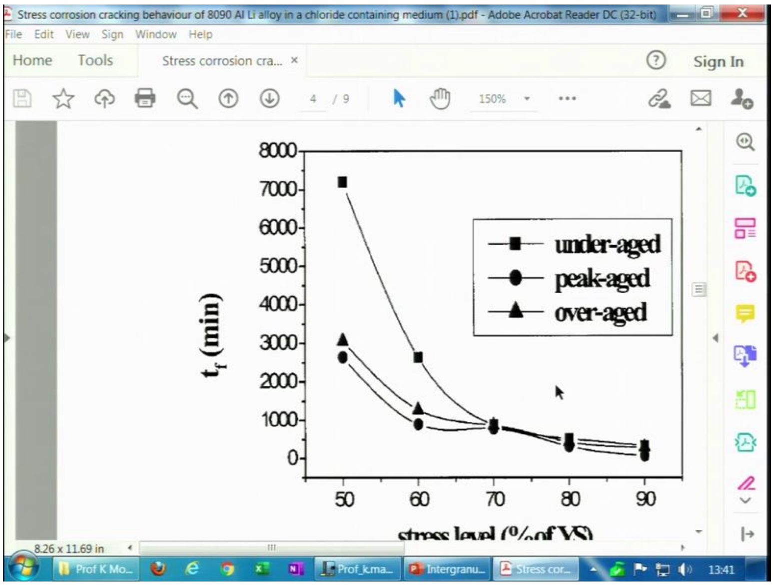

And, then we studied this particular plot if you see that underage has got the highest SCC resistance below 70 percent of yield stress; that means, below 70 percent yield stress beyond a 70 percent all the materials behave similarly, but below say 70 percent, we could see a huge difference between underage and peak age.

Whereas peak age and overage they are actually almost of the same level, though overage has got a little higher SCC resistance rather than peak age. Why we could say that? Because the time to failure all the time this particular thing, this square solid circle is basically the time to failure data at different stress values for that particular alloy and for the peak age it has the minimum value; that means, it has the highest susceptibility against highest susceptibility to SCC.

And, underage has got the highest time to failure at the same load that means, it has got a highest susceptible highest resistance to SCC susceptibility. So, this way we can compare that which material is better which material is not. In this case in the at least same alloy, but different conditions, different microstructures and we could get such kind of behaviour.

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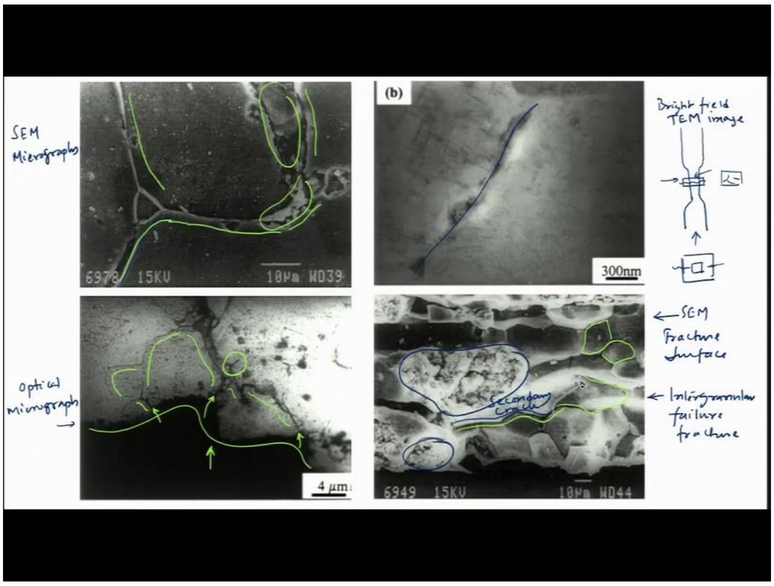

Now, let us look at other aspects to that. So, this is stress corrosion is taking place because the corrosion action is coming into play. The same material has been tested in air and no fracture happens even if you wait for 6 months. So, in fact, say fracture will not happen because the deformation is not there and if you leave that particular load it will come back because it is in the elastic zone, you say 70 percent of load if you consider.

So, now, why it is happening? If you want to understand, so, time to failure gives me a qualitative assessment that who which has higher susceptibility to SCC or which has not. Now, in order to find out the reasons behind that why the SCC is initiated so, in order to know that we have to look at the microstructure part.

So, here four such microstructure of the same alloy has been shown. Now, this is the optical microstructure this is the optical microstructure micrograph you can say. So, this optical micrograph is taken. So, if you see this particular tensile specimen. So, now, it has failed from here.

Now, the cross-section has been looked at, the cross-section gives you the fracture surface; that means, if you fail, so, cross-section would look like this. So, this is the cross-section, fine. So, that means, you are looking at from this direction or you can just look at from side direction which will tell me the surface appearance here the surface appearance here.

And, if you see the surface appearance it is interesting feature now optical microscope. So, this is the fracture surface. So, this is the fracture surface ok if you look at from this direction you should be able to see the fracture modes, but if we take this sample from here a small piece is cut small piece is cut from here ok and then we have polish because it is a plate specimen that particular alloy is a plate 3millimetre plate we took and now, that plate the surface part we can polish, we can etch.

And, after etching we could see that these are the grain boundary. Grain boundary is clearly visible here now. So, these are the grain boundary if we see my a trace of that green line so, these are the grain boundary even this is the grain boundary these are the grain boundary, ok.

Now, interesting part is so, this is another set of grain boundary the corrosion actually progressed through the grain boundary. So, if you see that corrosion progress points are basically through the grain boundary, here also through the grain boundary, here also through the grain boundary.

So, that means, grain boundary is getting attacked. So, now, we try to find out why the grain boundary is getting attacked and in bandwidth dissolution is taking place we saw that this is the TEM picture bright field TEM image. TEM is basically Transmission Electron Microscopic image and we could see along the grain boundary there are a precipitates, ok.

So, these precipitates are actually dissolving and then we had to find out whether that precipitate dissolution can give me a mark, then we did SEM. So, this is the SEM or Scanning Electron Microscopic image and there we could found we could find out that these are the grain boundary.

So, these are the grain boundary and along the grain boundary you could see that the dissolution front has gone in and how do we did we make sure that it is dissolution because if you could see those white patterns these white patterns these white patterns are nothing but the corrosion products, ok. So, that corrosion products after dissolution that corrosion product is forming and those corrosion product is actually having a trace along the grain boundary.

So, it is not only grain boundary also, though it is majorly grain boundary, but you could see some of the dissolution front which is going inside the grain. For example, this is one location where the dissolution front has also gone inside the grain ok. So, that is also possible.

Now, once we found those informations that yes grain boundary has got a precipitate stress and it is also dissolving. So, we could see that the precipitates are dissolving and now that is what the dissolution front is going like this. Now, we have a stress acting to that and then we looked at the fracture surface. So, this is SEM fracture surface.

This is SEM fracture surface, we could see interesting feature like these are the kind of grain facets these are the grain facets, fantastic grain facets are formed, ok. So, these are as if like and in fact, you could see that the crack is following the this is the one crack path which is following between two grains the interface along the interfaces between two grains; so, that means, along the grain boundary.

And, along the grain when it is following, this is one of the secondary crack you can say secondary crack. So, this is the crack movement, is it not? So, now, when the cracks are happening and then that crack is actually tearing apart those grains along the grain boundaries that is what this nice grain facets are looked at can be seen and it is a typical inter granular failure or fracture. Why? Because it the fracture front is going along the grain boundary.

And, also we could see corrosion products. So, this is a corrosion product. So, this is a corrosion product ok. So, those products are also forming. Now, when the fracture happens so, for example, this is a interface this is the part where corrosion is taking place. So, corrosion is going like this, at some point of time the loading could be beyond the fracture stress and then final part the centre part of it will have a normal mechanical failure.

So, but before that we have those signatures that signatures that corrosion deposits that is the signature that yes, corrosion is taking place, that inter granular corrosion pattern yes it also gives the significance that corrosion is taking place. At the same time failure can only happen like this when the stress is active. So, that means, it is a typical case of stress corrosion and also it is an intra granular mode, but then we also looked at some of the other fracture surface.

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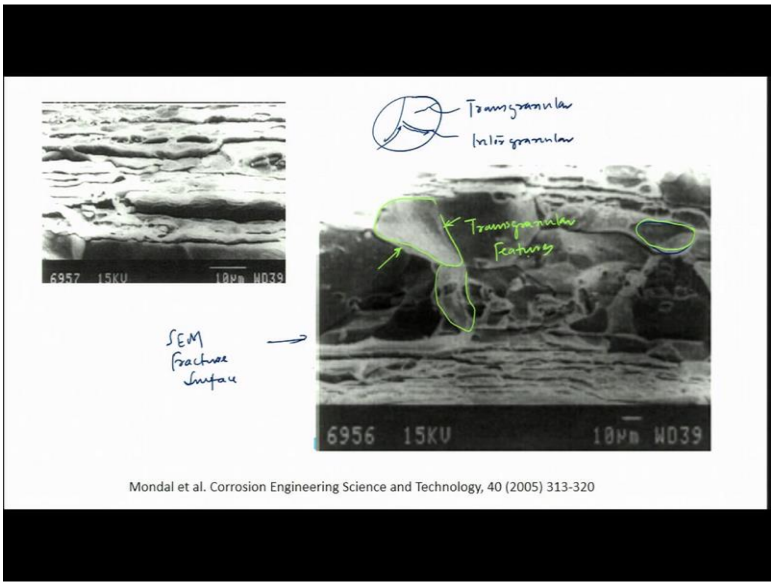

And, interestingly we could see one such fracture surface like this. This is also SEM fracture surface, SEM fracture surface. We could see that yes, there are also some facets. So, like this is a facets, these are the typical facets. But, there are other regions like this region if you could carefully see so, these are not looking like a facet.

In fact, these are also looking like a kind of slip points slip the material got slipped not like pulled apart from the grain boundary. So, these are the typical trans granular feature. So, that means, we could see that majorly it is intra granular, but there are also trans granular features.

So, we can say this is a kind of mixed mode of fracture which involves both inter granular as well as trans granular failure. And, that way we could conclude that yes, which material or the same material which aged one has got a highest resistance to stress corrosion cracking that is a qualitative understanding, then we could understand what is the mechanism for the stress corrosion cracking.

The mechanism is solute dissolution or the precipitate dissolution along the grain boundary and then stress is acting there and then stress takes the material away and the failures happens and the failure happens through inter granular majorly inter granular, but there are also trans granular features.

And, here trans granular means if this is a grain if this is a grain, this is a grain structures, if the crack path follows this path so, then it is a inter granular and if crack path follows through the grain then it is a trans granular. So, this is trans granular and this is inter granular. So, these many information's can be obtained from the simple constant load test. So, I just wanted to share this information.

So, we will talk about another interesting test method which is the I would say the one of the complete test methods to decide stress corrosion susceptibility of a material because you get too many information's which could be extremely useful. So, till then let me stop here we will continue our discussion on stress corrosion cracking, rather we will talk about mechanisms of stress corrosion cracking after this lecture.

So, in the second next lecture we will talk about initial we will start with slow strain rate test machine which is test actually because that test gives us much more information about stress corrosion susceptibility of a material, and then we go for mechanism analysis of different mechanism that are active for stress corrosion cracking of a material. So, till then thank you.