**Corrosion Failures and Analysis**
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**Lecture - 38**
**Environmental cracking or stress assisted corrosion failures**

Let us start lecture 38. The course is Corrosion Failures and Analysis. We have talked about corrosion problems or failures due to some of the forms that happen on metal surface or the alloy surface like uniform corrosion, galvanic corrosion, and pitting, we talked about crevice, we talked about dealloying, and even we talked about effect of alternating this vibration as well as corrosion. So, it comes under erosion corrosion.

So, where we also talked about cavitation damage, as well as flooding damage. Now, here we talk about some sort of failures of a material which happens due to combine action of stress as well as corrosion. So, that is popularly known as corrosion cracking or environmental cracking or stress assisted corrosion cracking.

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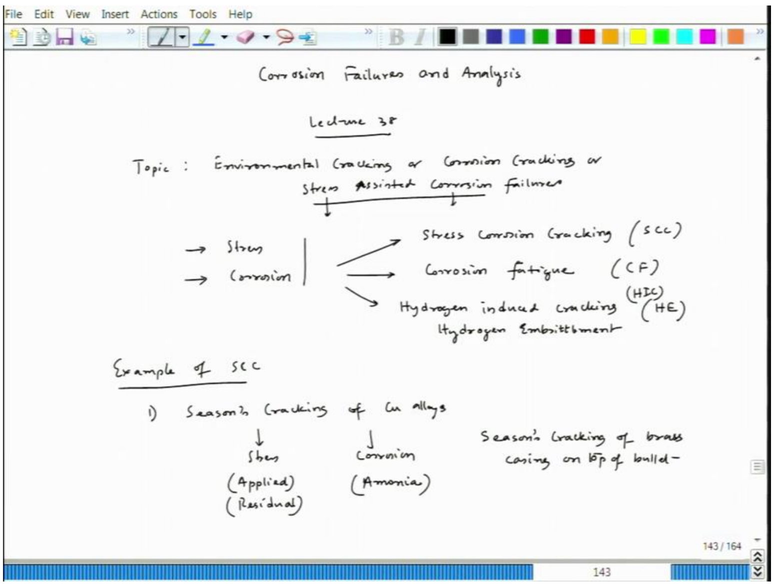


So, now the course is Corrosion Failures and Analysis, lecture 38 and topic Environmental Cracking or Corrosion Cracking or Stress Assisted Corrosion Cracking Corrosion Failure; corrosion failures. Now, here the stress assisted corrosion failures when we talk about that the corrosion can start the process of failure and then stress comes into picture or the stress starts the deformation part and then corrosion comes into picture or they can combined both stress as well as corrosion and then failures happens.

In fact, when such kind of failures happen so, the material cracks into two pieces. In fact, there could be accidents, serious accidents and there could be loss of lives. So, an interesting part is it is very difficult to predict sometimes that what time that material will fail, because in the lab the design stress what has been found out is based on in air, ok.

So, now what would happen when that particular material is exposed to an environment where corrosion comes into picture, but the material works on the basis of design stress? Many a times what happens the design stress plus that corrosion effect that is coming into picture the that particular combination can lead to catastrophic failure. And that can happen in a very short time. So, that is what this by particular kind particular failure is extremely important for the integrity of a structure.

Now, when we talk about stress assisted corrosion failures or environmental crackings or corrosion cracking are definitely it involves stress as well as corrosion, fine. Now, when we have this depending on the nature of stress as well as nature of corrosion product rather, we can distribute we can distinguish three kind of variations in this kind of stress as a state corrosion failures. The variations are one is stress corrosion cracking, then another one is corrosion fatigue, the another one is hydrogen induced cracking or hydrogen embrittlement.

Now, if we look at all these three cases, now kind of accidents that have happened before ok and also it can happen; it can happen in future also because of the stress corrosion, corrosion fatigue and hydrogen induced cracking. Now, in case of corrosion stress corrosion cracking one example of and this is known as SCC, this is known as SCF, and this is hydrogen embrittlement ok, this is or hydrogen induced cracking which is HIC, right. So, those short names you can we can use.

Now, example of SCC: So, one such example is season cracking of copper alloys. And if we talk about season cracking of copper alloys, then it is basically the stress is definitely which can be applied or it can be residual. And the corrosion part, this is a typical problem associated with ammonia. Now, when we talk about a specific such situation one example is season cracking of brass casing on top of bullet.

Now before, early days when this brass cased bullet was used those ammunitions were kept in a stable ok where horses stay. So, that stable because in the winter season they are kept there and when they are kept in that wind during winter season in the stable what happens? After that particular brass cased bullets are taken out people saw that where the brass is crimped around the bullet.

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For example, if the this is the bullet end the brass casing is actually crimped around this portion. So, around the portion so, that brass casing is crimped, around that point sharp crack has been noticed. And if somebody fires that particular cracked bullet definitely it will lead to calamity because it can also lead to lot of splinters and then that can kill the person who is firing. Now, what exactly happens there?

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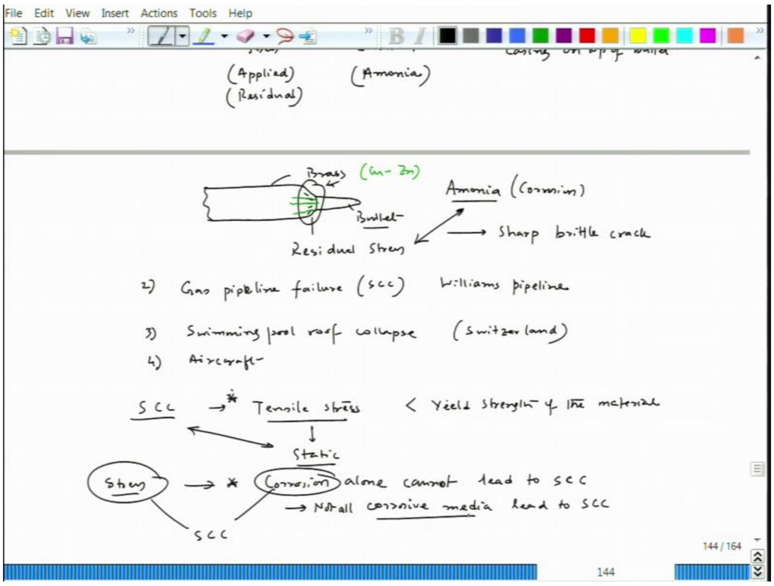


So, if this is my brass casing and this is the bullet part, ok so this is the brass part and here it is crimped. This is the where it is held together the bullet part. So, this is the bullet part, fine. Now, this is brass med casing. Now around this zone sharp crack forms, ok. So, these are the cracks happens in that crimped portion.

Now, this is very general observation and the brass is copper-zinc alloy. And later on it was found out the ammonia is generated because of the manures that are left by the horses. So, that ammonia reacts with copper and leads to a serious corrosion related dissolution and in this crimped portion we have already residual stress.

So, here we have residual stress and now, it combines with ammonia; that means, the corrosion part and it leads to sharp brittle cracks around this circle zone. And, this is a typical form of stress corrosion cracking. Now, this is one example.

So, there are other several examples. So, if you want to know those examples you go to Google and then search. For example, one is gas pipeline failure and which is SCC related failure and this happened, this is a catastrophic rupture that happened and that happened in William’s Pipeline near Washington, ok.

So, that happens and this is a typical example of SCC. And what happened? Because of that burst many people were taken off from that zone even when school was removed. So, those kind of serious calamity, serious difficulty can arise because of this kind of failure. And, here also corrosion as well as stress both played a role.

Again, another example is in Switzerland swimming pool a roof collapsed. So, this happens in Switzerland, and what happens? This particular roof was supported by stainless steel rods and those stainless steel rod had this corrosion cracking and that is what the entire roof collapsed. And, it actually worked for 13; only 13 years and that is it and so, the entire thing collapsed and there were loss of life, ok.

So, these are the kind of examples. And then there are several other examples aircraft also can get through this SCC, ship structures can go through SCC. So, those kind of situations would be very damaging to the entire structure as well as it involves loss of economy, loss of cost you know it involves cost as well as it involves sometimes loss of life.

And, moreover the another important aspect is once something is failed now to make it to in order to make it you again need to have a capital investment. So, those all those factors are actually negative when we have SCC. This is one such situation where stress corrosion cracking happens.

Now, in case of stress corrosion cracking all the time there were SCC, so, it involves tensile stress. And interestingly, when we talk about this tensile stress the value that value is less than yield strength of the metal. So now, you understand that if we are testing in air at yield strength at yield point or yield stress the material will start deforming permanently.

But, now when we have tensile stress which is let us say design stress of a particular structure that if that is below the tensile strength below the yield strength still the material can fail in SCC mode. And, here the tensile stress what we are applying is not variable, it is or it is not alternating, it is static. This is very important, SCC is associated with a static tensile stress and that should be below yield strength of the material ok. So, this is one typical characteristic of SCC.

Now, if we try to see other characteristics of SCC. Now here this is one, this is let us say one characteristic, second characteristics if we try to look at; corrosion alone cannot lead to SCC. In fact, if we extend this particular information or characteristics in fact, this not all corrosive media lead to SCC, ok. Now, you must have stress factor. So, one has to have stress and that too static tensile stress then only it would lead to; so, this corrosion and static tensile stress that would lead to SCC.

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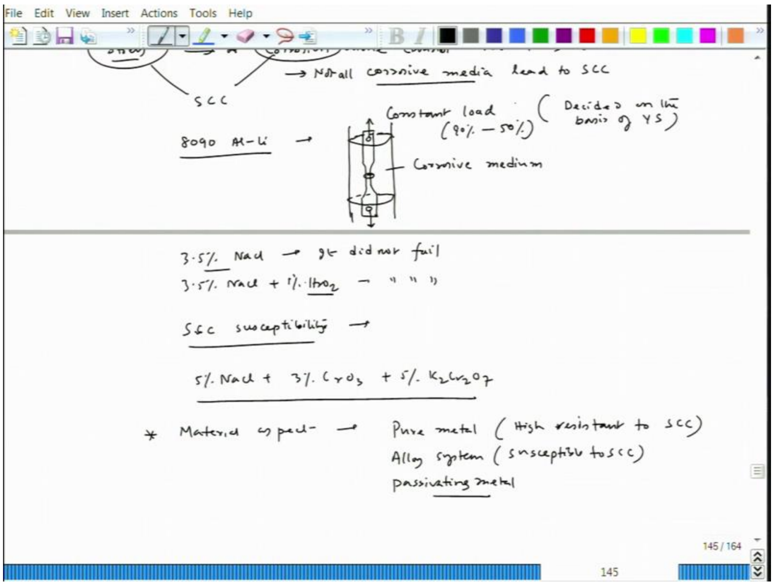


Now, coming to this corrosive media, now we have done some test let if we look at 8090 aluminium-lithium alloy and there that material was tested for stress corrosion cracking behaviour; and now, that time what we did? We made our tensile specimen. So, this is the kind of tensile specimen we have made.

And, now we have given an extension ok, as a kind of load constant load, constant load was applied and this entire assembly was kept in a corrosive media and this was pulled. So, actually if we try to see the actual design of that cell, so it was like this, ok. And inside that we have corrosive medium, fine.

Now, this constant load is decided on the basis of yield strength ok. So, you if you consider yield strength. So, we can shortly write yield strength. So, on the basis of yield strength; that means, once you decide the yield strength you can find out yield load by looking at the gauge diameter. Sorry, if it is a circular then gauge diameter, if it is a rectangular then also you can find out the actual area and find out what is the load required for yielding.

So, that is yield load. And on that basis of yield load one can calculate; what is the load we should choose so that the stress always remain below yield strength. So, that is what the constant load we took around 90 percent to 90 percent to around 50 percent different ranges we have chosen, that kind of load. And we left it in different medium in order to find out whether it gives rise to failure or not or crack or not.

Now, initially we tried with 3.5 percent NaCl, it did not fail. Only some small pits have generated, but otherwise material where was very resistant to that kind of corrosive attack and it is constantly having that particular load; tensile load. Now, we tried with 3.5 percent NaCl plus 1 percent $H_2O_2$ which is hydrogen peroxide which gives a highly oxidizing situation, then also it did not fail.

Then even we have tried with sodium dichromate as well as sodium chloride there also it did not fail. Actually we waited for at least about let say 20-30 days, it still did not fail. In fact, one samples we waited for 3 months, no action there. So now, in order to do that comparative analysis or the SCC behaviour of a material we call it SCC susceptibility of a material. So, this particular term will come SCC susceptibility.

SCC susceptibility of a material in a lab scale we need to quickly break the sample and see what how it behaves in corrosive media when the stress is active. Now, if we wait for 3 months 4 months, even somebody has to wait for maybe a couple of years to get a crack in a sample in a particular medium.

Now for example air; air if it is a having if it is having moisture still it is corrosive, but in that corrosive environment if the load is below yield load the failure may not happen, ok. So, if it may not happen even after 10 years. So, like that kind of time frame you have to need to find out what is the level of SCC susceptibility in that, that is why in the lab scale when you do the test, the crack must appear quickly.

So, that is what we chose finally, one particular solution which is 5 percent NaCl plus 3 percent $CrO_3$ and plus 5 percent $K_2Cr_2O_7$ potassium dichromate. Now, this particular solution we started getting quick cracking, and that is allowed to understand the SCC behaviour of that material. I will show you some of the pictures, then you will see that how the SCC behaviour was studied there.

Now, it is very clear that it is also depended on corrosion medium, not all media will lead to SCC in a particular material. And same way on the material aspect if we try to find out; material aspect not all metals and alloys would lead to a same level of SCC in a particular medium.

For example, if we consider pure metal; so they are generally highly resistant to SCC. In case of alloy system, so they are susceptible to SCC. In fact, if we take if you take a passivating metal, so they are susceptible within a specific voltage range. We will talk about that.

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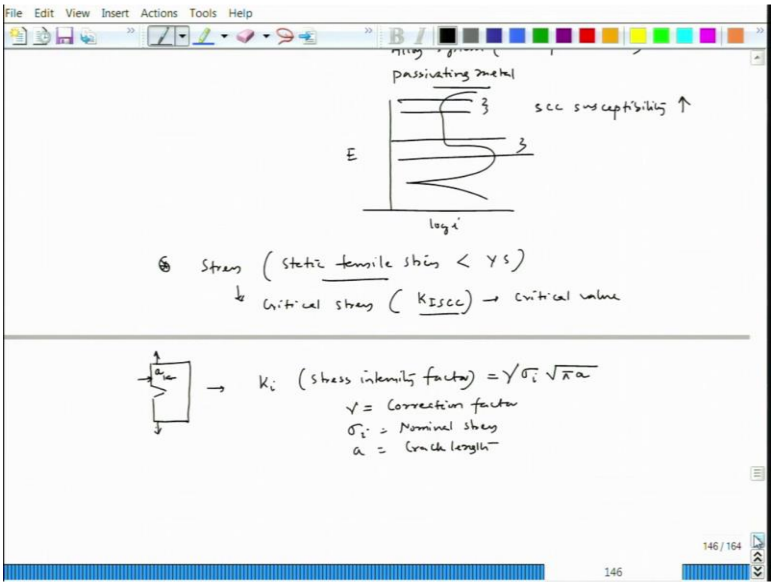


In fact, if we see the passivating metal, let us say the passivating metal shows active passive behaviour let us say this is potential this is log i, now the behaviour could be like this, like this. Now, it has been always noticed that this zone, this is the zone. So, this is zone, this is another zone where the transformation from active to passive or passive to trans passive happens, then only that particular material is seriously susceptible to SCC.

So, these are actually two zones where SCC susceptibility increases the major thing is that time the material surface is half exposed half covered. So, those kind of situation happens we will talk about that in greater details. Now, material also different material has different SCC susceptibility in the in a same medium at the same time different medium on a same material could have different SCC susceptibility. So, that is another character of SCC that is to be kept in mind.

Now, when we talk about other character that stress as we have said in case of one example what we have cited that seasons cracking of brass casing over bullet due to the action of ammonia, there we do not have any external loading. The why that load part came in or stress part came in? It is basically the residual stress; when you crimp it that time the stress is in stress is going into the material and that is getting stored.

In fact, if we anneal that casing after crimping, so that particular material will not show same susceptibility rather it will show resistance to SCC susceptibility or season cracking; resistance to season cracking. Season cracking is actually SCC of copper based alloys in ammonia solution.

Now, coming to other characteristics, when you talk about stress as it is very clear it should be a static, tensile stress and that should be below yield stress of a material, but at the same time this also relates to a kind of critical stress or in terms of fracture because since it is crackings we have to talk about in terms of fracture mechanics.

So, in terms of fracture mechanics, if we talk about the fracture toughness, so K1C if we talk about so, in case of SCC we talk about K1 SCC. So, this value when it drops to a critical value below that critical value SCC does not happen, ok.

So, that pine kind of information for example, if we talk about that fracture toughness in a material, when we talk about fracture toughness and the simple fashion. Let us say if this is a material and there is a crack like this and this is the crack length and we are talking about surface crack, this is length; this is the length of the crack and this way we are giving the tensile stress.

So, then we can write K i which is basically called stress intensity factor. So, that will be related to some constant, then sigma i which is called nominal applied stress and then root over pi a, ok. So now, here this is correction factor, now sigma i is basically nominal stress, a is crack length, ok. So, now failure happens when the stress density factor reaches a critical factor.

$$K_i(stress\ intensity\ factor) = \gamma\sigma_i\sqrt{\pi a}$$

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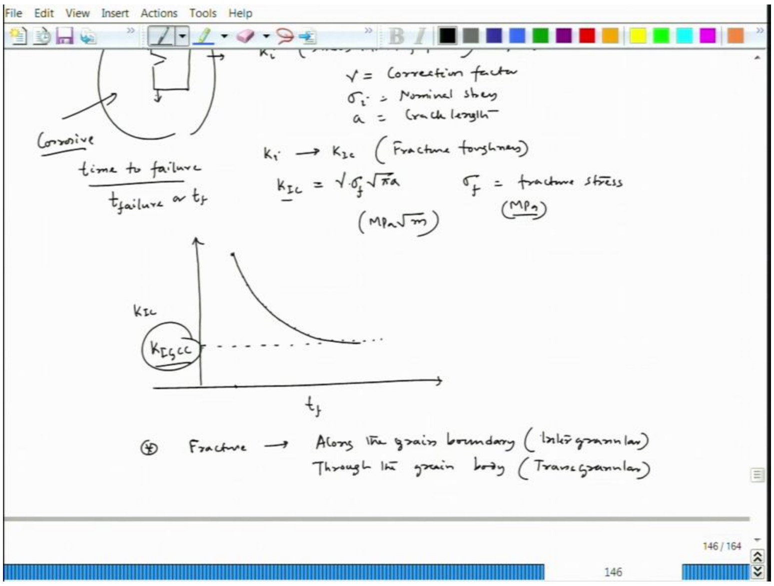


So, that Ki reaches a critical factor K and 1 c, so that is nothing but the fracture toughness. And that fracture toughness can be written as where sigma f is nothing but the fracture stress ok. So, now in fracture toughness its unit is MPa root over meter and this one is fracture stress which is MPa. This is the unit of a K1c and this one is the unit of fracture stress.

Now, if we try to find out this fracture stress have the fracture toughness in a corrosive. Now, we can have a plot like this. So, this is K1c we are plotting. Now, let us say we have a crack specimen in the corrosive we have, so this is around that we have a corrosive. So now, that corrosive will lead to a final cracking of the specimen and then we note down the time; time to failure.

Remember, this time to failure is extremely important parameter to decide the susceptibility of a material to SCC. Now, that is what it is called tf or tfailure or tf. So now, tf I can plot and if the K1c is very high definitely the fracture will happen quickly. So, if this is the K1c the fracture time will be less. As you are reducing the K1c, so this one will decrease, decrease and then finally it will reach a plateau, ok.

So, that value corresponding value so, now if you join those particular values and then this plateau value this becomes K1 SCC. So, now below this fracture toughness value will not have an any stress corrosion cracking of a particular material. So, this is one way to find out this value. So that means, you need to do a large number of experiments in a particular solution or corrosive. So, this is another characteristic of SCC.

Now, if we talk about other character of SCC, now since it is a in say it is a fracture. So now, it is a fracture finally, so this fracture can be along the grain boundary so that time we call it inter granular, another fracture can happen through the grain body so that time we call it transgranular. Now, both the type can be possible in case of SCC.

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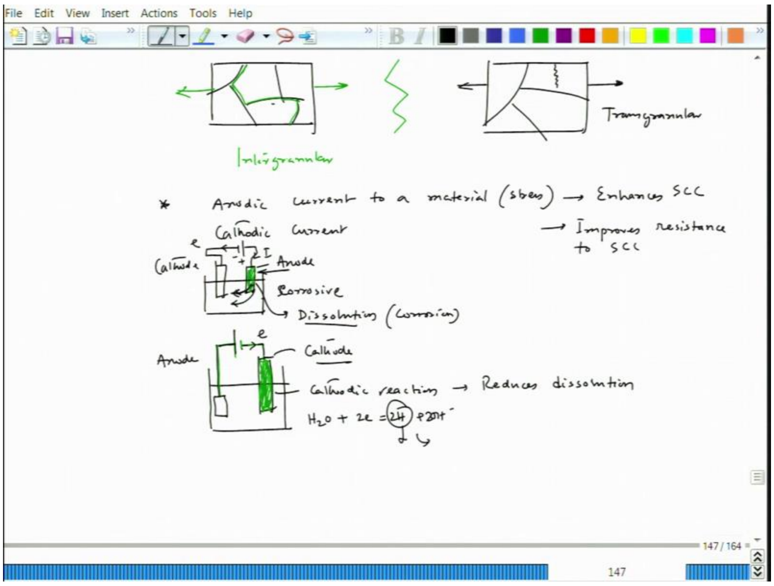

For example, if we talk about semantically if we would like to see let us say we have a these are the grains; these are the grains and let us say the crack is propagating, the crack might go like this. So, if we try to locate the crack propagation and if this is the load and this is exposed to a corrosive medium, now crack will move like this.

So, that is what that time the crack would be zigzag. So, that time we call it since it is propagating through the along the grain boundary we call it is inter granular. Now, if it is this is inter granular. Now, if it is transgranular, then same way we can see a grain body grain structure. So, this is let us say the grain structure of a material.

Now, crack if this is the stress direction, now the crack can go through the grain body not along the grain boundary. So, that time it is called transgranular, fine. So, now this there are we I will I shall show you some pictures of intergranular and transgranular cracks in our next lecture, ok.

Now, other characteristics if we try to find out then this is interesting part is. If we apply anodic current to a material under stress; and whenever I am talking about stress remember it is a tensile static stress because we are talking about characteristics of stress corrosion cracking. So, that is what let me go back let me put it here.

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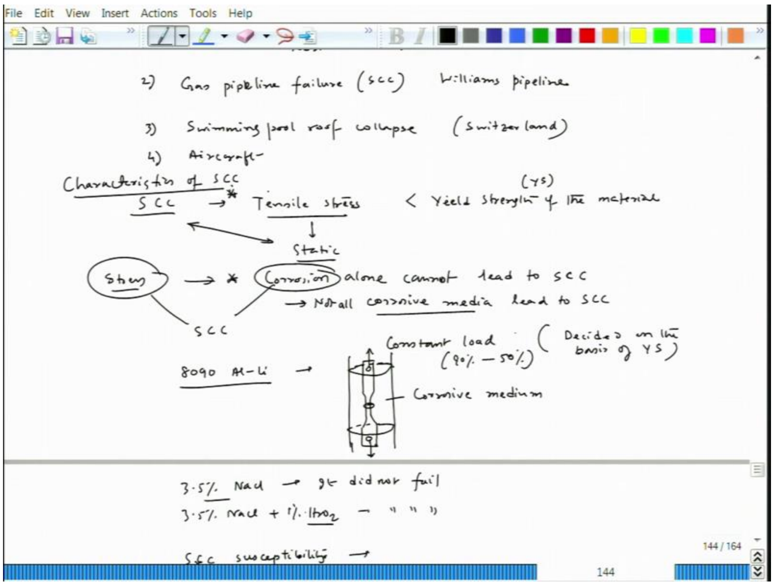


So, we started the characteristics here. So, it is we can say it that characteristics SCC so now, we started with this. Now, when we talk about anodic current to the material which is under static tensile load below yield strength that enhances SCC. Now, if we apply cathodic current, same way it actually improves stress corrosion resistance to SCC.

Now, it is very logical in the sense that when you are sending anodic current means if we try to look at the cell any cell so, this is a plate, this is another plate and we have connected it to let us say this is positive terminal is connected it to this. This is negative terminal; so that means, this is positive, this is negative. So, electron will go this way and this is in a medium, this is let us say corrosive. So, that time this is anode, this is cathode, this is anode.

Now, if we send current here I; so, that means, this current has to leave this surface to go to the other metal surface other electrode surface in order to keep the circuit completed. Now, when this current moves out whenever current moves out that is the place where dissolution happens. So, these are the place that means, this body will go for dissolution which is corrosion since anode corrodes.

So, now we are actually when we send anodic current we are actually enhancing the dissolution character of that particular material. So, that is what cathodic anodic current sending anodic current would lead to enhance the SCC.

But, when we talk about cathodic currents let us say so, this is the material where we sent; this is the material where we sent anodic current. Now, the same material we are changing the polarity let us change the polarity. So now, this material which is green colour, this material is now connected to negative terminal and positive terminal is connected to some other material ok. So now, this is now anode, this is cathode.

Now, if it is connected to cathode, so that means, electron will come to this side. Now, once electron comes that electron needs to be consumed by some cathodic reaction. So, here cathodic reaction take place and if cathodic reaction happens, then definitely it reduces dissolution.

So, if it is reduces dissolution of that metal definitely that corrosion related effect to the SCC we are reducing, because stress we are not changing only thing is the corrosion part we are reducing. So of course, it will automatically give resistance to SCC. So, this is another character that is actually observed when we talk about SCC.

Now, these are some of the characters of SCC. Now, we will take it up in our next lecture where we will talk about how to do SCC characterization. For example, this time to failure as I have said that time to failure is one of the important parameters to decide SCC behaviour of a material.

For example, in a same solution you want to study which one has a higher SCC susceptibility, the best way to do is doing a mechanical test in that solution or the tensile test in that solution and then see which one is actually cracking early. So, that definitely that indicates that the material which is cracking early has higher SCC susceptibility.

But, though it is look it looks simple, but it is not it is there are several experiments to find out that time to failure. In addition to the time to failure we have to find out other parameters like the reduction of stress. Whenever there is a stress assisted cracking definitely there would be a reduction in the stress where the crack happens, there will be reduction of yield strength, there would be reduction of UTS or Ultimate Tensile Stress. In fact, there will be reduction of total elongation, the material would become brittle; more and more brittle.

For example, one such example if we talk about this cathode when the material becomes cathode there is a chance of hydrogen embrittlement, because if the cathodic reaction is hydrogen water reduction. So, this is 2H OH minus 2 OH minus. So, this 2H if it is not combined this 2 hydrogen atom is not combined if they stay as a in the form of atoms and that can be possible if we have arsenic.

So, arsenic is considered as a hydrogen poison which does not allow that combination reaction to make hydrogen gas. So, those hydrogen are very tiny atoms and that can diffuses into the material and that would lead to (Refer Time: 37:07) of the atoms between the; those (Refer Time: 37:11) of atoms of a metal ok. So, that would induce of a kind of embrittlement into the material or this atomic hydrogen can react with some of the elements present in that material.

For example, zirconium alloy; zirconium has the possibility of forming hydrides and those hydrides are brittle. So, since those hydrides are brittle so, the material becomes embrittled. So, that way that material can fail early if we do not look at that part if.

So, let us say this cathodic current we send we think that that material is protected, but that does not happen. So, those hydride forming elements can form hydrides at the crack tip and since the hydride is very brittle the crack will grow at a very very fast rate and that material can go under a catastrophic failure. So, those are the kind of stuff we have to look at and then try to understand that how to assess SCC susceptibility of a material. So till then, we will stop here we will continue our discussion in our next lecture.

Thank you.