Corrosion Failures and Analysis
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Lecture - 34
Erosion Corrosion: Characteristics

Let us start lecture 34 the course is Corrosion Failures and Analysis and we will discuss several aspects of Erosion Corrosion. We have started already discussing erosion corrosion and today, we will talk about some of the characteristics of erosion corrosion as well as factors that favor erosion corrosion.

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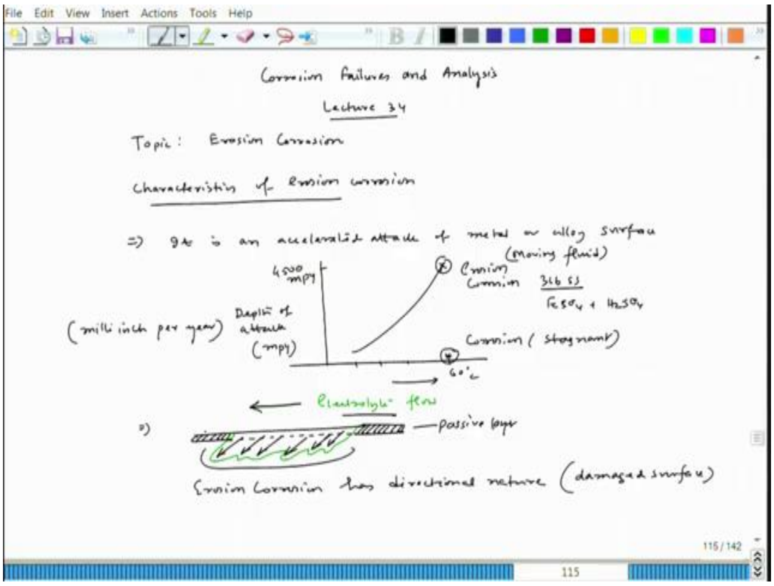

Now, the course is corrosion failures and analysis in lecture 34, topic – erosion corrosion. We have already seen that there are couple of variations in erosion corrosion like one set called cavitation, another set that is fretting corrosion and of course, there is there are several aspects of erosion corrosion due to the flow of fluid inside a pipeline or a system, ok.

So, now, we will talk about characteristics of erosion corrosion. So, these are basically general characteristics, we will separately discuss cavitation as well as fretting but the general characteristics of erosion corrosion if it relates to the flow of fluid one is it is an accelerated attack. In fact, the attack is very unusual it at times and it does not match with the laboratory scale test because in laboratory scale test what we do?

We do mostly you know in a very static condition the corrosion analysis of a material, but when erosion corrosion comes in that erosion factor comes in due to the speed of that particular flow of that particular fluid the damage becomes very aggressive, ok. So, and at the same time erosion corrosion always talks about the increased attack due to the flow and if there is a decrease in attack due to the flow, it does not fall under the erosion corrosion ok.

For example, if we increase the flow sometimes there would be a situation that corrosion reduces; for example, inhibitors. If we add inhibitors the speed of that particular fluid would allow those inhibitors to reach to the intricate corners of the metal surface and it will give preventing action against corrosion, ok. So, that will not fall under erosion corrosion sever.

Similarly, erosion corrosion will not be considered if the flow actually reduces crevice and pitting corrosion. So, that will not come under erosion corrosion whenever there is a increase in attack due to the flow we consider it to be a erosion corrosion. So, this is an in an accelerated attack of the metal surface of metal or alloy surface.

In fact, in that regard as I have mentioned as I mentioned that if we do a stagnant test let us say 316 SS this is the steel if we use a stagnant condition and the medium is let us say the slurry which contains $FeSO_4$ plus H_2SO_4 this is the acid strong acid. So, that case if we see at a 60 degree Celsius temperature and if we see with respect to temperature at 60 degree temperature even the attack would be very small ok on that metal surface 316.

But, if it is moving fluid then this is damage in terms of mpy or depth of attack depth of attack in terms of mpy; mpy is milli inch per year, ok. So, that time that attack goes very high, ok. So, it can go even up to around 450 for 4500 mpy it can reach, ok. So, that is the level of attack due to that erosion factor. Now, in that aspect let me just show you one example of erosion corrosion that happens in a chrome pipe fitting, ok.

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So, let me just share that particular set of images which I have taken. Now, if we check this, so, this is the chrome fitting and we are our concerned portion is this portion ok where the water comes out. Now, if we check that portion that portion is this one. Now, there is a small faucet which is fitted to that pipe fitting and that allows the water to have a very nice smooth flow and the impingement effect is reduced to a great extent.

If we remove that and if the water flow is heavy, then it can impinge on the surface of human body but, if it is there then that reduces that impingement and makes the water flow very smooth. Now, if we take that particular portion out, inside that we have a plastic grid and there is a washer rubber washer also fitted to that and I just opened that and it was almost about say it is to be clean time to time that faucet I opened that and I saw that on top of that plastic grid its a basically there are small small particles.

And, you could see that those particles are quite big and few millimeters, and the particles are red colored and then I try to put little pressure with my finger. And, then saw that those particles are breaking those are flocculated and its not a solid that 1 millimeters or 2 millimeter solid particles. So, inside each one; inside each one if we take that so, inside each one if we take and then press with your finger, it will crumble into pieces and then you will see that small small sand particles.

That is quite natural because its a filter water, but still that sand particles can come in and this particular grid is give put just to trap those sand particles falling out. Now, those sand particles are actually covered with iron rust. It is basically nothing, but red rust which is iron oxide rust and this is inside is basically iron pipe. Now, those rust is forming and those rust is covering that small small tiny sand particles and getting accumulated on top of that grid.

Now, I opened it and then I could see the inside part I took a photograph from after opening I took a photograph like this way I took a photograph, ok and that photograph is given here, fine. Now, you could sense that water is flowing out at a high speed and the sand particles are also circulating around it and the water is actually changing direction, it is coming like this and it is changing direction.

Of course, there will be turbulence and that turbulence as well as those particles they will be moving at a good speed and that will have a kind of micro machining kind of effect on the metal surface and this is oxygenated metal sub because its open to air. So, that would it is a I can say this aerated water and this aeration of water there are oxygen and then those particles are actually scrubbing the surface because of that erosion effect and, due to scrubbing iron oxide is forming, ok.

And, we know that what are the reactions. So, I can write those reaction O 2 plus Fe plus H_2O it forms FeOH whole 2, ok. So, now, I can make it half. So, this is the reaction. In fact, there are two reactions, if we break it half O_2 plus H_2O plus 2e equal to 2 OH minus this is cathodic reaction cathodic and Fe minus 2 e Fe plus 2 and these two react and form this. And, later on we can also get FeOH whole 2 it can further react and then form FeOH whole 3 or it can form Fe_2O_3 H_2O, ok.

So, now this is the red rust this is the ferric oxide hydrated ferric oxide. So, those actually rust and there could be other rust also FeOOH. So, this rust has several variations alpha, gamma, beta. So, these are the variations. So, those can also form, but those are actually iron rust. Now, that is forming because of this chemical electrochemical reaction at the same time we have a scrubbing effect because of those sand particles and turbulence created when the water is changing direction.

And, the turbulence will be high because this is a grid and that grid is actually stopping the water flow making it smooth flow and those grid is allowing those particles to be accumulated on top of it. Now, coming to this location you check this location the kind of erosion effect that can experience that inner part.

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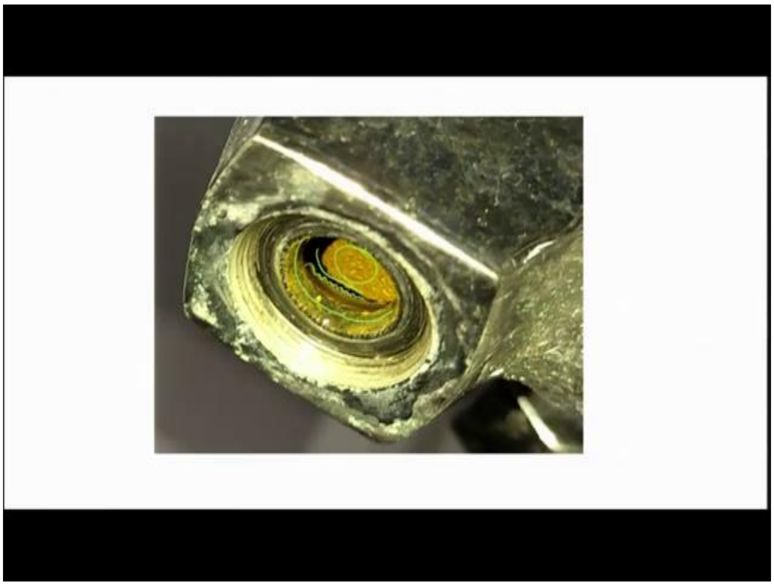

I just go to the next slide, you see I have made it much bigger you see this particular section. So, this particular section; this particular section you see this iron is basically has formed a serrated part the serration as well as this wall this wall as well as the top part they are covered with the thick red rust, ok. So, this rust is basically of course, the corrosion is happening, otherwise those rust would not form. But, those erosion factor due to the sand particles and water flow that is also playing a big role in the corrosion of this rust formation.

So, this is one of the typical erosion corrosion that is experienced. In fact, this rust formation will be much less if we just take this particular sample out put in a stagnant the same type of water for months we will not see much of rust formation because that is a stagnant condition and stagnant condition the corrosion is only the electrochemical factor is coming in no erosion factor.

So, this is one reason that erosion corrosion is highly aggravated corrosion mode or damage mode I would say, fine. So, let me go to where we were. So, now, that means, here also this is also experimental data it shows that because of the movement this is erosion corrosion and here it is only corrosion which is stagnant and this is moving, moving fluid. So, this is one of the characteristics of erosion corrosion.

The second characteristic we can say that whenever there is an erosion corrosion will have a directionality of damage. For example, if we take a condenser pipe not condenser pipe you can say it is a heat exchanger pipe if you take. So, let us say this is the wall of the heat exchanger pipe.

Now, defect starts forming and we have let us say the fluid is or the liquid or the electrolyte is flowing this way; this is a electrolyte flow and the damage takes place like this, fine and let us say this is a kind of surface which has a layer of oxide which is passive layer. So, that means, this was my this dotted line was my initial metal surface and now, the damage has taken place and you could see that this kind of forms is actually having a sort of directionality.

So, you see every time it is in an inclined way where the attack is developing because the fluid flow is actually electrolyte flow is going this way, fine. So, that is a directionality. So, erosion corrosion has directional nature and this is nothing but on the damaged surface, fine. Now, coming to other factors like this can be this erosion corrosion can happen where in an wet condition or in an dry in a dry condition you know.

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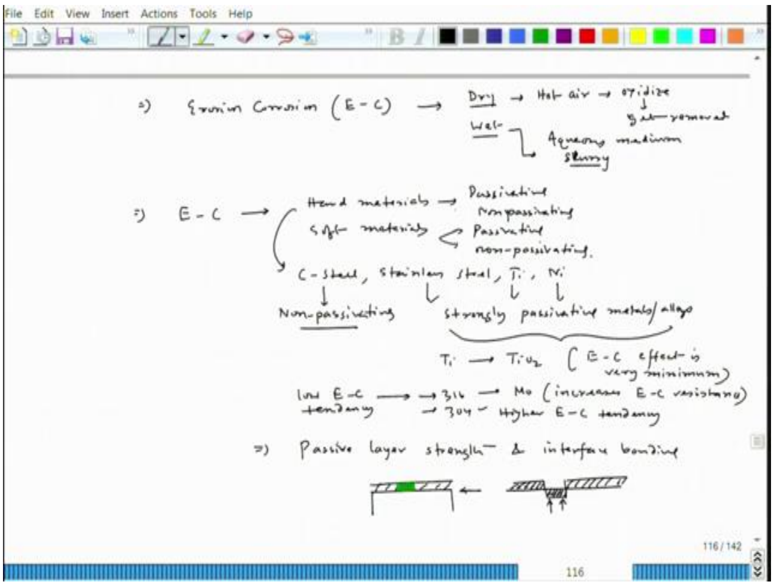

So, the erosion corrosion instead of erosion corrosion I can simply say E-C ok. So, this erosion corrosion can happen in both dry medium or wet medium. So, now, coming to the variation whether we can have it in dry medium; for example, if hot air going hot air is passing through a pipeline. So, then hot air can oxidize the surface and this oxidized surface can get removed. So, the so, this surface can get removed due to the erosion factor and then erosion corrosion or corrosion can take place.

Now, in case of wet of course, whenever there is aqueous medium and this factor would be much more aggressive if it is a slurry; slurry means it is a thicker fluid or thicker liquid which contains lot of dust particles. So, the dust particles could be a small small metal fines or anything else for example, in the example what I showed just now that erosion corrosion of pipe fitting chrome pipe fitting. So, that is basically those tiny sand particles. So, those are actually giving much more aggressive erosion corrosion effect. So, this is the erosion corrosion in wet as well as dry condition.

Now, E-C which is erosion corrosion is if we consider the material aspect. So, there are aspects like hard materials soft materials and in case of hard materials there could be passivating or non-passivating. Here also we can have both passivating as well as non passivating, ok. So, both almost all the materials in the metallic materials they can be susceptible to erosion corrosion. Of course, the degree would be different.

Now, if we talk about hard materials the erosion corrosion effect would be much less compared to soft material. Hard materials example is carbon steel let, then we can have stainless steel, titanium, we can have nickel. So, those cases out of that this one and this one even this one they are strongly passivating metal metals or alloys, nickel based super alloys or titanium alloys those are very strong and hard materials.

Now, carbon steel they may not passivate in a normal situation, but if we have a like stainless steel because stainless steel passivate because of the chromium, but carbon steel does not passivate quick quite easily, but still it can passivated passive it if it finds a suitable environment like the pH high pH medium carbon steel also passivate like rebar in the rebar condition the rebar maintains the passive pH of the order of around 12.5 to 13.

So, in that pH actually carbon steel which is nothing, but a low medium carbon or low carbon steel which passivates, but stainless steel, titanium, nickel even when neutral medium it can passivate. So, those cases so, this is I can term it as a non-passivating. So, non-passivating so, now, out of that if we consider the passivating kind of metal they are depending on the passive layer strength ok, that erosion corrosion factor can be highly felt or it can also be reduced, ok.

So, for example, in case of titanium it has titanium oxide which is a very very adherent strong passive layer. So, that is what in case of titanium we have E-C effect is very minimal very minimum, but stainless steel. Let us say 316 or 304, 30 316 it contains molybdenum; molybdenum increases E-C resistance, fine. Now, 304 so, that means, if we compare between this two and this two, this one will have this one will have higher E-C tendency, but this one would have low E-C tendency; this particular part 316 3 compared if we compare 316 and 304.

Now, in case of passivating metal, the passive layer strength as I have said that passive layer strength would decide. So, the passive layer strength decide strength as well as its bonding character as well as an interface bonding. For example, if we have a metal surface this is my passive layer, this interface which is very important. If interface is porous then that passive layer can get knocked off due to the erosion factor and this is interesting.

For example, if it is a passive metal let us say because of some reason a local point is chipped off because of the erosion effect, now we have this particular zone, small zone this is now this is the passive zone passive layer and this is a small zone which is now exposed to the electrolyte. And, then if it is a strongly passivating metal, then immediately as another passive layer would form ok. And, in the second stage some other places passive layer can be broken ok.

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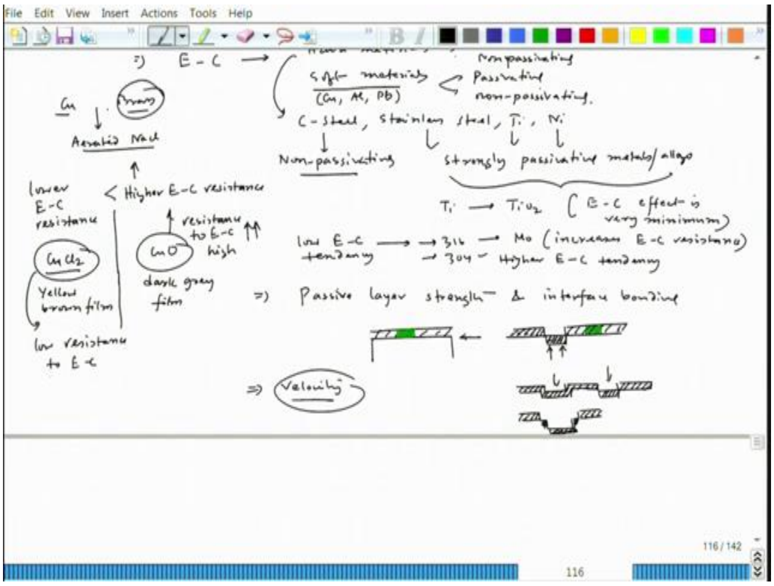

So, like that the second stage we have. So, now, we have passive layer like this. So, now, this particular section is open. So, here also some passive layer would form again, fine.

Now, if this layer again knocks off this layer again locks off, then again there will be another dip here, like this.

So, now, this is the passive layer. So, here we have passive layer, but now this zone will be forming another passive zone like this. So, like that with dissolution keeps on happening due to the formation of passive layer and then breaking of passive layer due to the erosion effect.

So, now the passive layer strength if it is strong then it does not get chipped very easily and that also depends on the velocity. The velocity would be a guiding factor as well as whether its a clean water or its a clean electrolyte or full of and if it is a slurry, the situation would be different, ok.

Now, for example, if it is a slurry and then for example, if it is considered the velocity. So, velocity factor will discuss in a while. We need to give some data how the velocity factor changes the cavitation corrosion sorry, changes the erosion corrosion, fine. So, but velocity is important if it is a high velocity the breaking of those passive layer can be easy.

Now, coming to a soft material that can also be passivating or non-passivating like example is like copper, aluminum, even lead ok. So, those are kind of soft metal ok. So, those soft metal or alloys like brass; brass is little harder than copper because its a solid solution strengthening effect is coming because of the addition of zinc in it.

Now, that could be also passivating or non-passivating type like copper can also passivate aluminum is of course, a passivating strongly passivating metal aluminium oxide forms; lead can also passivate. For example, in a H_2SO_4 medium if it is a dilute H_2SO_4 lead does not it lead immediately passivate, it forms lead sulphate and, but if it is a strong sulfuric acid, then lead sulphate that forms that dissolves in a strong sulphuric acid medium lead sulphate dissolves and that actually it aggravates erosion corrosion.

So, we will talk about that. So, there also we can have a passivating and non-passivating kind of situation and now, soft material the effect of erosion corrosion would be much higher because that erosion factor would be much higher on soft material the material removal can be very fast. But, if it is passivating then material removal in case of soft metal also reduces, for example, aluminum it is a very strongly passivating metal. So, erosion corrosion effect would be much less in case of aluminum.

Now, if we compare let us say in case of copper as well as lead, the two examples we can have the copper and brass let us say these two things and if they are put up in aerated NaCl solution and it is a flowing system and there if the flow happens, this one has a higher E-C resistance compared to this. So, that means, higher E-C resistance and lower E-C resistance.

Interestingly it relates to the passive layer or the oxide that the layer forms due to the reaction with the medium. Now, here we have Cu Cu 2 $CuCl_2$ which is a kind of very dark yellow a black yellow brown film yellow brown film and here we have CO which is a dark grey film, fine.

So, now if we compare the resistance offered by these two films, this one offers much more resistance to erosion corrosion. So, resistance to erosion corrosion would be very high ok I can say high and this one gives a low resistance to E-C. So, that is what this brass would have a higher resistance to erosion corrosion compared to copper.

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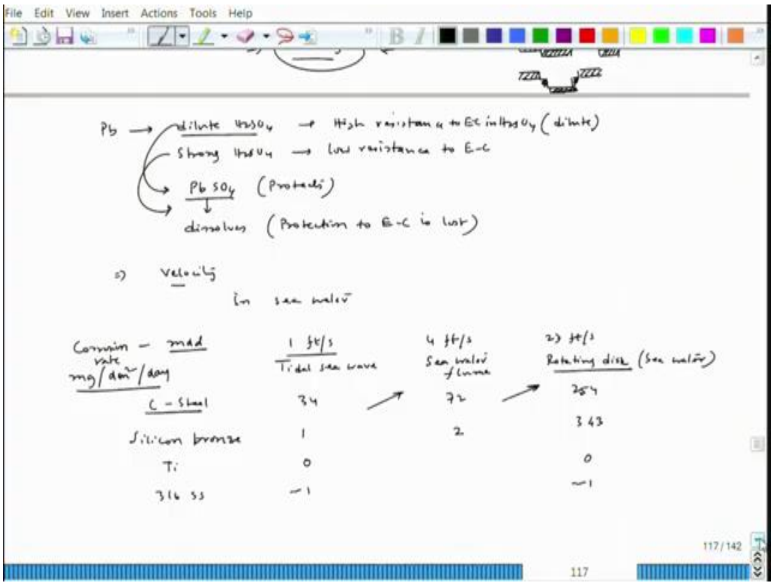

Now, even lead we can have an example lead. This lead if we have dilute let us say dilute lead pipe. So, dilute H_2SO_4 it gives you fantastic resistance high resistance to H_2SO_4 when it is dilute, but if it is strong H_2SO_4, high resistance to of course, E-C in

H_2SO_4 a dilute H_2SO_4. But, if it is a strong H_2SO_4 then it gives you a low resistance. In fact, erosion corrosion would be much faster if it is a strong H_2SO_4 to E-C, fine.

So, now, why it happens? Because in this particular case; in this particular case $PbSO_4$ so, that forms which actually protects, but in this case this one dissolves and protection is lost and remember, this is only in terms of flowing system ok. So, this is one example that depending on the type of metals and type of film we can have different react different sort of protection to erosion corrosion. So, there are other factors as well as characteristics.

Now, as we see that from the characteristics part of it, we have seen that it is a very accelerated attack erosion corrosion and it has a directional nature and other important aspect what I have said that if it reduces corrosion, then it should not be falling under erosion corrosion.

That means, for erosion corrosion is always that factor which is basically aggressive attack of the surface due to erosion plus corrosion effect. And, finally, we talked about the effect of different metals one metal could be soft metal, hard metal and then passive metal non-passive metal. So, those are the factors coming into picture.

Now, we talked about velocity. So, let us see what is the velocity factor that does. So, now, if we talk about velocity now as per the data as you could find it in the book by Fontana and Greene this corrosion engineering they have given the effect of velocity, ok. Now, if the velocity is less, the corrosion erosion corrosion effect is not that big, but once it reaches to certain value it is a sort of critical value the erosion if corrosion effect would be very very high ok.

So, for example, one set of data they have given it is basically in sea water; in sea water ok. So, they have tried to measure the corrosion rate of different metals and alloys and in three condition: when the speed is 1 feet per second, when it is 4 feet per second and when is it is 27 feet per second and in fact, how the how was the where those speeds achieved? So, this is nothing but the tidal wave tidal sea wave; tidal sea wave that is the kind of speed they have achieved. This is in seawater film.

So, there they have achieved this and another one is in sea water they have attached a rotating disk. So, that achieves that speed of around 27 feet per second. So, all are in sea water, ok and there they have found that for example, if we consider carbon steel when the speed is 1 feet per second it is 34 mpy this is in I think it is in mpy, just a minute. I am sorry this corrosion rate is in the corrosion rate is in corrosion rate mdd; mdd means milligram per decimeter square per day.

So, this is the corrosion rate they have observed, this is 34 in a medium where it is moving at a speed of 1 feet per second for carbon steel then it is 72 when the speed becomes 4 feet per second and it becomes 254 when it is 27 for feet per second. So, this is the kind of increase in corrosion rate observed in case of the increase in speed and you could see that till 4 feet its not much of increase, but once it reaches to 27 there is quite a lot of increase.

Now, if we consider silicon bronze so, that time this 1 feet per second the corrosion rate is 1 mdd and then it is 2 mdd when it is 4 feet per second and it becomes quite a jump 350 343 mdd. So, that is the kind of increase in erosion corrosion that happens once the speed increases beyond a critical limit and as we are as I was giving an example of titanium, if you consider titanium it has a very very minimal effect towards erosion corrosion, it is almost 0 and here also it is almost 0, this the entire speed range the titanium gives you the best resistance.

Even stainless steel 316 stainless steel also gives a quite a good resistance to erosion corrosion. So, this is let us say one and it is also one kind of value one can get in that medium in sea water medium. So, this is the effect of velocity. So, it does not happen if it is a small change in velocity, but it happens aggressively when there is a critical speed achieved. So, this is the effect of velocity, fine and interestingly this because of this factor depending on the metal part.

So, you could see there are other mention, there are several metal mention. For example, cupronickel 90 10 copper nickel, 70 30 copper nickel, those kind of metals have also been noted in that table. You can just go to that particular book and see that particular table. So, it actually indicates the velocity has a great effect towards that and remember the increase in velocity might be helpful in reducing corrosion, ok. Its not that all the time velocity would have effect on bad effect on corrosion.

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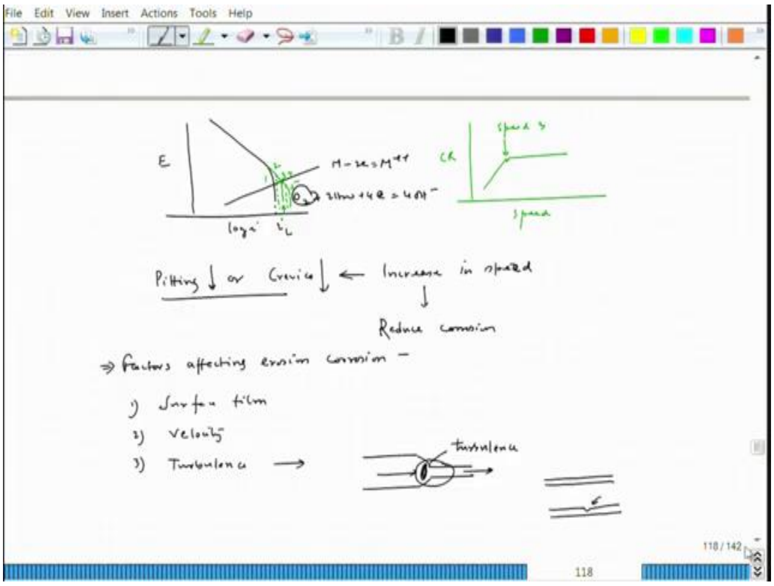

For example, if we recall a mixed potential theory, there if it is if the metal is the metal corrosion is controlled by diffusion mode so, that time this is potential, this is log i which is the plot would be corrosion let us say this is the kind of attack that happens. Let us say this is the metal dissolution part metal minus 2 equal to metal plus 2 the anodic part. So, this is the cathodic part, let us say which is guided by oxygen diffusion.

So, the diffusion of oxygen guides that particular corrosion rate and this is i L limiting current density. Now, if we increase the speed and then check the way this I l changes with the increase in speed i L increases. So, this curve will come in like this, ok. So, these are the kind of different i L. So, now, we have given of 1 2 3 4 5 and you could see that this is 1, this is 2, this is 3, this is 4, this is 5. So, now, till 3 we have effect of the increase in speed.

So, now, if we plot corrosion rate versus speed ok, now it goes like this and then becomes constant because once it crosses this speed i L 3 whatever speed you go for your i L is not the i L part is not cutting that straight line part that steep parallel line with respect to potential axis is not cutting the anodic line of metal dissolution. So, there itself it stop. So, this is basically 0.17 corresponding to speed 3, ok.

So, and beyond that as you increase the speed, the iL is increasing, but it does not affect the dissolution character because the anodic line is not cutting on those concentration polarization part. So, that is what the corrosion rate remains constant. So, this is one effect, but corrosion rate can also reduce due to increase in speed. Those examples are like related to pitting or crevice. So, their increase in speed would reduce. So, these factors would reduce ok, pitting effect and crevice effect would reduce.

Now, increase in speed can also reduce corrosion. Let us say if we add inhibitor and that inhibitor can actually go to the intricate sections of the metal surface and we will have inhibiting effect of the entire surface. So, that factor can also reduce the corrosion. So, its not necessary that all the time increase in speed can increase the corrosion that can reduce the corrosion also.

So, now, this is about speed, now there are other factors like impingement, there would be factors like galvanic effect. So, those factors let me just mention those factors. We have already discussed some of the factors like factors affecting erosion corrosion. So, this one is surface film. We have already seen couple of examples like in case of lead, in case of copper in case of brass that can affect the erosion corrosion.

2nd is velocity we have seen that if we until unless we reach to a critical value it can lead to un till it can it cannot lead to a aggressive erosion corrosion, but once it reaches the critical value velocity value the erosion corrosion would be very fast the rate of erosion corrosion would be very fast. 3rd is of course, turbulence, fine. So, we have talked about velocity and surface film.

Now, if we talk about turbulence the turbulence factor would be felt for example, if we have a large segment pipe and then we have a small pipe which is coming like this. So, if this is the situation large pipe the flow is coming and then through a small pipe if the flow is directed, now in this portion we have lot of turbulence, fine. So, there the erosion corrosion effect would be very fast.

Of course, that factor will be felt around this zone. If we go away from this, then the erosion corrosion factor would be less because after entering into that small pipeline, it will attain laminar flow after a short distance. So, that within the short section where that change in orifice or change in diameter takes place there it happens more, ok. So, that is what this is basically the turbulence effect.

In fact, if we have a pipeline where the pipeline is having a kind of kind of dip in that this is a defect of that pipeline its not smooth.

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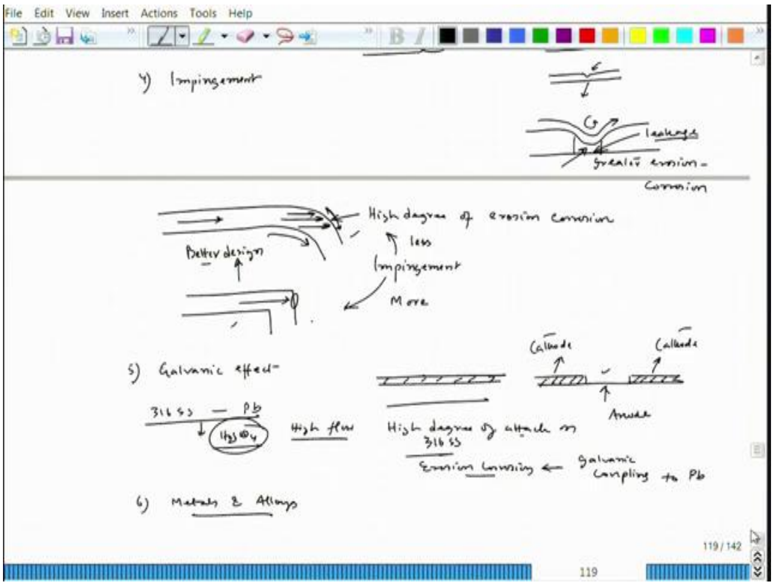

And, if this is my let us say pipe thickness this zone if we draw it in a and zoom it and then see this. So, this is like this ok, now here we have water flow or the fluid flow is going through this and here we have a kind of turbulence, ok. So, this turbulence will have a greater corrosion erosion corrosion here in this portion greater erosion corrosion erosion corrosion.

And, that would actually since in this part we have the lowest thickness so, that particular part can get leaked. So, this part can leak leakage can happen. So, this is one of the situations that can be experienced due to the turbulence factor. Of course, then 4th is impingement. Impingement is also important in the sense for example; if we have a pipe design like this let us say a slurry is moving, we have already explained in previous lecture.

So, that slurry is actually impinging on the this particular surface before it is going because there is a sharp change in direction, ok. So, that change lead to of impingement at this zone and in this zone and this zone can have high degree of; high degree of erosion corrosion, fine.

So, in this portion there could be a possibility of leakage also, ok. So, this is the impingement factor. In fact, this impingement factor can be more if it is like this; if it is like this. This impingement factor here if we compare the impingement factor, in this case it will be more, in this case it will be less. So, here it is much sharper change in velocity and here is a gradual change in sorry, not much sharper change in direction, but here is a gradual change in direction.

So, that is what the impingement would be less in this case, more would this in this case. So, here leakage tendency should be more. So, in fact, that is what erosion corrosion can be controlled to a great extent. If we modify the design without changing the material if we modify for example, this is the typical modification we take care in order to it is done in order to take care this impingement factor as well as erosion corrosion. So, this is a better design, this is a bad design ok.

So, we will talk about this design factor because by simply changing design without changing material or condition we can achieve a great deal of protection towards erosion corrosion in fact, towards many other corrosion problems. So, then finally, of course, we have metal then galvanic effect; galvanic effect is a factor. For example, if we have let us say this is a passive layer fine and this is passive layer is broken somewhere.

Now, this passive layer is broken at this zone. So, this passive layer is intact and this part is broken now this will be anode, this will be cathode, this is also cathode. In fact, that time we have that favorable condition for excessive galvanic attack in that exposed area because those passive layer other areas which is a large area and they are actually substrate for cathodic reaction.

And, in order to supply electrons greater degree of dissolution should take place in that exposed area before the passivity again appears. So, this is one of the typical galvanic effect. In fact, there is a galvanic effect that is mentioned in the book by Fontana and Greene where 316 they have mentioned that 316 which is a very which offers very high degree of resistance to erosion corrosion.

But, if it is connected to lead in the flow condition where acid is kept so, that time it actually leads to high degree of erosion corrosion, but if lead and iron that 316 is connected in a stagnant condition in H_2SO_4 medium it does not that corrosion effect would be less on 316, but when it flow so, this is the effect. So, for example, 316 SS and lead so, at a high and this is whole 4 H_2SO_4. So, this is the acid.

Now, high flow ok so, galvanic effect would lead to high degree of attack on 316 SS and this attack is basically erosion corrosion and that erosion corrosion is enhanced of course, the speed is one factor, the other factor is of course, connected to lead galvanic coupling to lead. So, this is the effect of galvanic situation where two metal contacts are there.

Now, 6th is of course, metals and alloys. As we have seen from the table itself that stainless steel and titanium provides a very good erosion corrosion resistance whereas, carbon steel is poor resistant. Now, recently it has been observed that we have many microstructures in carbon steel itself, ok. On the metals and alloys part the microstructure also plays a big role in combating erosion corrosion which makes the metal soft erosion corrosion rate would be very high.

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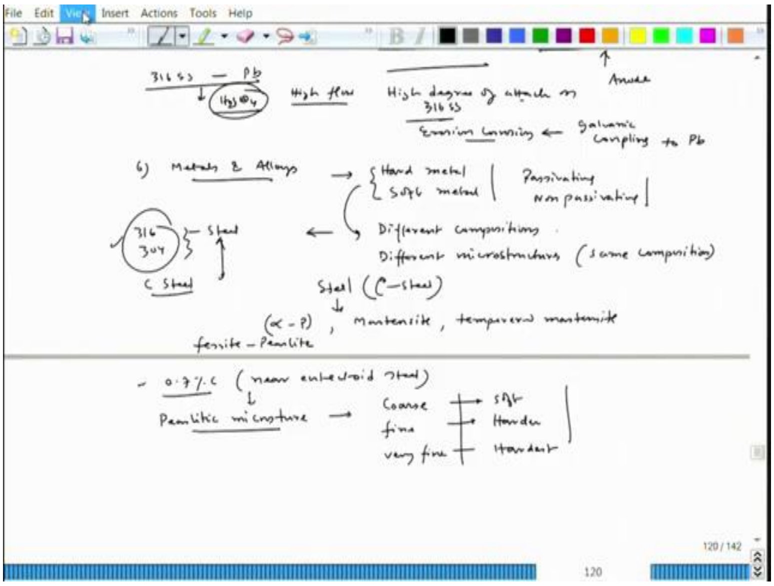

Now, on the metals and alloys, we have talked about hard metal soft metal and then of course, passivating as well as non-passivating kind, fine. When we talk about this hard metal, so, the hard metal and soft metal it can come from different metals different compositions as well as different microstructures in a same composition, fine.

So, if I what do I mean by microstructures in a same composition? Like let us say steel let us say carbon steel – if we talk about carbon steel that can have soft microstructures like ferrite like alpha pearlite combination or ferrite pearlite combination we can have martensite. So, this is ferrite pearlite, this is martensite. There could be tempered martensite like that way you can generate several microstructures in a single composition pearlitic single composition carbon steel.

For example, if we can generate let us say 0.7 percent carbon steel or let us say near eutectoid steel you can generate this is a typical pearlitic microstructure. So, this pearlitic microstructure can be made coarse, fine, very fine and that would lead to a different degrees of hardness. This would be soft compared to all three, this will be harder, this will be hardest and depending on that erosion corrosion rate would also be different, ok.

On that particular composition factor of course, for example, we have given an example like 316 and 304. So, and also let us say carbon steel if we compare this is also steel, this is also steel. So, if we compare between this two segment and this one, these two will have definitely much higher degree of erosion corrosion resistance compared to carbon steel.

So, this is on the factor of composition like different metals can also have a different degree of erosion corrosion like titanium has the best resistance then followed by 316 like that way metals can have depending on the composition or character can have different erosion corrosion resistance, but the microstructures also microstructures also play a big role.

Now, as I have talked here so, on this we have done one small study. So, let us check that particular study results. This paper one can go and check.

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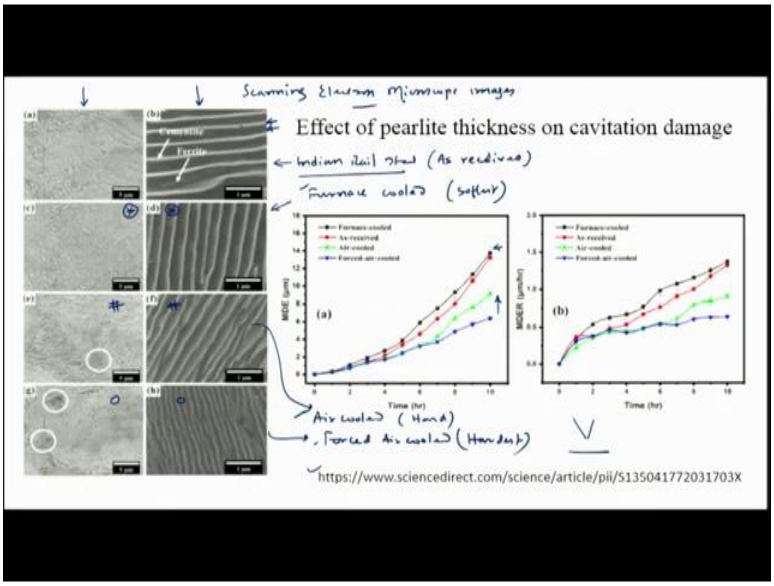

So, this is the paper one can go and check, this is the paper by paper in our lab. Now, this is a typical rail steel ok, the Indian rail steel. So, Indian rail steel, this is as rigid condition and then we have done few modification. Modification is that steel sample was kept in a furnace and we did a furnace cooling, then we did air cooling; that means, after taking it to the of sanitization condition, we kept it outside furnace in the open air and then it cools down that time one structure develops.

And, then in one case we have forced air cool; that means, after taking the sample out we have kept it in front of a moving fan. So, that time it is basically force air cools we have different degrees of fineness of structures, but in all the cases mostly pearlitic ok. So, this is as received as received; that means, the rail is cut into pieces and that microstructure is shown here. So, this is this particular part this one so, this one and this one. So, these two are basically furnace cooled furnace cool.

So, this one and this one they are air cooled and if we consider if we consider this and this. So, this is forced air cooled and you could see the fineness gradually the inter lamellar spacing. So, these are inter lamellar spacings. So, this is the cementite lamellae and this is the ferrite lamellae. So, those spacing is actually coming closer and closer and in case of forced air cool, it is the closest.

And, in fact, if we compare the hardness so, this is if we compare between this and this. So, this is softest, this is hard and this is the hardest, most hard material. Now, we try to see erosion factor this is MDE is basically mean depth erosion and MDER mean depth erosion rate, ok.

So, these are the two factors we try to see as a function of time and this time erosion factor we are actually having a ultrasonicator which is a; which is a pin. This is a pin which creates ultrasonic waves and that falls on a metal surface and that way we try to create damage on that it is a basically a typical cavitation mode and of course, we have seen the cavitation is nothing but erosion corrosion.

So, we could see that when it is forced air cool that gives you the best resistance ok and if we consider the air cooled one; air cooled gives you the next best is a better one and then compared to the furnace cool is giving the poor erosion corrosion resistance or ratio poor cavitation resistance. So, all the cases is basically the erosion factor is involved.

Now, you could see that as the fineness of the pearlite colony inter lamellar spacing is increasing; that means, it becomes more close by those spur like cementite lamellae it gives you the best resistance to cavitation damage or simply erosion damage. So, this is one typical data I have I am just I thought that I should share with you because this actually gives a sense that yes, microstructure plays a big role.

In fact, we have data where one around 0.2 percent carbon steel and 0.4 percent carbon steel both are furnace cooled and that is the composition effect the 0.2 percent carbon steel gives you the poor erosion corrosion resistance whereas, 0.4 percent carbon steel gives you the higher erosion corrosion resistance because 0.4 percent contain more pearlite compared to 0.2 percent carbon steel. So, that is what it becomes much harder and it prevents erosion effect ok. So, that is what that 0.4 percent gives you a better resistance.

In fact, we have also seen with respect to martensitic as well as tempered martensitic we saw that the tempered martensitic steel gives you the best resistance. Now, here all not only hard material is important the hard material as well as its toughness more rather more important is the toughness. More would be the tough; that means, hardness as well as malleability, both are there then it gives you the one of the best situations where erosion corrosion resistance would be extremely good.

So, this is one such example I just thought that let me share the data what I have received and erosion corrosion factor. In fact, if we see this set of microstructure and this set of microstructures they are both are one is at a low magnification and one is at a higher magnification, otherwise there is no difference, fine. So, the left side images are low magnification and right side images are high magnification and all are SEM images, scanning electron microscope images, fine.

So, let me get back to we were. Now, this is the part we were talking about that metals and alloys depending on composition depending on microstructures that they can give a varied degree of erosion corrosion resistance. So, these are the kind of factors general factors that are associated with erosion corrosion. Now, we will in the next class we will talk about cavitation and fretting corrosion. So, then we will end erosion corrosion.

So, till then let me stop here. We will continue discussing two special erosion corrosion modes one is cavitation, one is fretting in our next lecture.

Thank you.