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Environmental Degradation of Materials

Lecture – 40
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So we see that the doping has a distinct effect on oxidation resistance of different metals and we see that in case of zinc oxide if we have lower valance lithium then oxidation resistance will go down or if we have higher valance aluminum the oxidation resistance improves and it would be reverse in case of nickel where lithium leads to improvement in oxidation resistance whereas chromium decreases the oxidation resistance of nickel, or the oxidation resistance power of that nickel oxide on top of nickel. The same thing also relates to iron where iron oxide FEO is P type oxide and they are also if you have more chromium it decreases them if you have a chromium doping it decreases the oxidation resistance, but once it reaches to a certain limit for example 18% instead of having a doped structure we have a chromium oxide layer which actually improves the oxidation resistance, so the doping effect will be effective up to a certain limit and maximum around 5%.

Now in order to improve the oxidation resistance there are few more techniques and most of them are basically alloying related, for example if we have molybdenum or tungsten or niobium in iron then the oxidation resistance improves as well as the creep behavior improves at higher temperature but if we would like, if the oxidation resistance is to be improved and if the iron operates at around 1200 degree Celsius then the alloying is basically done with, there will be a coating which is actually metal then which is basically for example one coating that is M CR aluminum and atrium and here this is either nickel or iron or cobalt, so this coating can give a very good oxidation resistance at 1200 degree Celsius, even sometime boron containing silica glass that can also give a very good oxidation resistance. So this is about oxidation but there is one more corrosion phenomena that is called hot corrosion, so the hot corrosion so it's actually a degradation process rather than corrosion because already if we have oxides and due to the reaction with the ingredients in the environment the oxide layer transforms to a different scale and that scale would be non-protective. For example in case of turbines, gas turbines where we have if we see the gas turbines so ingress there will be air which is coming in and then it will be compressed then mixed with fuel and then they are, this will be ignited and then the temperature reaches around 700 degree Celsius to 1400 degree Celsius this is gas turbine.

Now there that high temperature, the sulfur would be present in the fuel and that sulfur would lead to degradation of that oxide which is forming on the surface and which gives actually protection of the turbine blades and the total turbine structure. Now if we see that if this turbine blade, the gas turbine is operates its operating in the sea environment there we have sodium chloride, so the sodium chloride if we have sodium chloride and then also sulfur in the presence of oxygen as well as H2O there could be a formation of sodium sulfate, so sodium sulfate would be possibility so there could be a product of NA2SO4 + HCL if we balance it then this will be 2, then this would be 3/2 H2 and then this goes to 2HCL. Now this is the reaction that can happen inside the turbine, and this one has two components one is acidic, another one is basic, which is NA2O and SO3, so this is acidic and this is basic. Now if we have oxide MO that can react with acidic part, basic part which is NA2 and it can form M2+, this would become MO2 2- + 2NA+, so we see that the oxide layer is becoming non-productive because it's forming ion and then again this one can react with acidic part it can form M+2+SO2 2- so again we see that ion formation so the oxide is losing its protective nature, so this is actually the hot corrosion effect and this one this plus NACL they can form low temperature eutectic so that would be also not good so this is about, this is basically the hot corrosion which you can see, we can see that it's not a corrosion effect where we don't have any oxidation or reduction process rather it's actually this one converts to a non-protective scale.

Now we discuss corrosion testing and corrosion rate measurement as well as failure analysis, so corrosion testing and failure analysis. Now in order to measure the corrosion rate of a particular metal or alloy we need to know how we would perform the corrosion test but before that we need to know what are the purpose of why do you want to go for corrosion testing for a particular metal or alloy. Now the purpose of corrosion test, one definitely evaluation it will help in evaluation and selection of material response to some corrosive, to the environment, of course we need to know about the corrosion response as well as its corrosion rate in a particular environment so that we can choose that a suitable material, and of course it would be specific for application to corrosion environment as well as application. Then second would be evaluation of new and old metals and alloys to determine the environment, in which environment they would be suitable, so suitability of metals and alloys whether new or old in a particular application, in a particular environment, for example in case of new we need to see its response at the same time for old how long it will offer it in that particular application exposed to the environment that application is, exposed to the environment where it is working. Then we can also think of controlling corrosion of metals and alloys. Then finally we also need to know mechanism of corrosion, how far, this is for research development, so these are the, before these we need to go for corrosion testing.

Now how many ways we can do corrosion testing there could be, corrosion testing actually we need to know what is the rate first thing, the thing that comes into our mind that is the corrosion rate measurement and we can do it in different ways and the rate measurement should be also done in house that means where the material will be subjected to application or operation or we need to also perform some tests in the laboratory for either research and development purpose or the preliminary assessment of the corrosion rate of a new material let's say so that case preliminary assessment will guide us that whether, out of ten materials which material will be suitable for that particular application. So corrosion testing can be divided into four types, so corrosion testing can be divided into four types, so one is laboratory test, in case of laboratory tests definitely as we are, as discussed it's basically a simulated environment in the lab and then we have of course when we perform the test that time the samples size would be small, small sample and of course the small number of and number would also be small.

And then we have pilot plant, pilot plant test or semi work test, and in this case also we can incorporate let's say 2I 2II we can also incorporate field test, so in this case what we need to do here of course that material will be subjected to a small scale operation, and then there of course one would be large number of sample, large number of samples would be considered and that time either that can be exposed to service condition or may not be exposed to service condition, so then we have coupons actually a small, small coupons that can be placed in a rack, in a particular fashion and time to time we can take those samples out and we can see what would be the corrosion response.

Then we have actual plant or actual service test, here of course this is a real condition of course and this samples will be materials will be under subjected to service mode and that means that would be in operation, then for example, one example is the tube let's say you have a iron tube and there's some tube where you have some corrosive which is going through and that time we can place some sample and that sample corrosion rate can be, that sample corrosion rate can be judged in the real condition. Then pilot staff of course and before coming to this plant test we need to perform this two tests, one is laboratory test and the pilot plant test, if we have a large number of options then that these two tests will narrow down those options and then finally we are left with a very few options so out of those option the plant test will decide which material would perform in that service condition better. So these are different test methods, laboratory test, test routes.

Now if we consider how we can perform these two test routes, of course one is exposure test then this can be also broadly categorized into two sections, one is exposure test and second one is electrochemical test. And in case of exposure test this is the simplest one where we have some test space and that test space we exposed to the environment and after a certain timeframe we will take that sample out and see what is the weight loss, so if we see the weight loss is Del W then Del W divided with the area and then the time this would give you, this would give the corrosion rate of that particular material in that particular condition, so exposure test of course we need to follow some standard so one is the conditions for exposure test, specific test methods and those test methods can be found out in different standards either ASTM or NACE, so those test standards are to be used.

And then also we need to know how long can this test standard will tell us how long one material is to be exposed to a particular environment, what would be the sample size, what would be the sample dimension. Then of course we have few conditions let's say we are hanging, let's say the samples are hanging in sub different angles, for example if we send, if we put it in the environment at a particular angle the angle at which it is interacting with the environment that is one critical issue or it could be velocity of that environment, so one is angle, velocity, then of course proper insulation, proper insulation it means let's say we are exposing, let's say the sample is exposed to the environment by hanging from a station so that time this part it should be insulated and if this is basically the from which it is being hand that is a metallic object then there should be, this connection should be properly insulated otherwise there could be galvanic effect here, and here is the sample, this is my sample but if it is and also this one in this part also we have two metal corrosion, so this part should be properly insulated otherwise there would be galvanic effect, so there wrong information will be obtained if we don't insulate, you don't have proper insulation, so this is exposure test.

Now coming to the electrochemical test which is a very important and this will be discussed in little, maybe this will be discussed, and this will be elaborated little more. And if we come to the electrochemical test there are two methods by which we can calculate the corrosion rate, electrochemical methods, electrochemical methods we have two broad categories, two methods available, one is Tafel extrapolation and the second one is linear polarization. Now if we come to the Tafel extrapolation so in this method we need to polarize the sample in a particular solution or the environment to the positive side as well as negative side from the corrosion potential, free corrosion potential and then we need to draw a Tafel slope and where those type of slopes are connecting that point would be the point of interest there we can determine what is the corrosion, current density at that point and we form that we can find out what is the corrosion rate.

Let us see we have already discussed a lot on Tafel equation and the plots, so those plots will be useful let us see how we can find out corrosion rate from Tafel extrapolation, we know that this equations anodic over voltage would be equal to Beta A log IA I0 for anodic reaction and then we have cathodic over voltage which is bitter C log IC which is current density corresponding to cathodic reaction is I0 and this C is actually for the cathodic reaction which is exchange current density of the cathodic reaction on the metal surface and this is negative and this is also negative so both the negative things are considered in this equation.

Now if we plot it so this is potential and this is log I, and I is the current density, now for a particular metallic corrosion let's say the zinc in HCL we have zinc anodic reaction and for zinc we can also consider what is the cathodic reaction for a single electrode system that time this is my EA which is equilibrium, equilibrium potential of that particular single electrode system zinc system, that means this is Zn++ + 2E = Zn this indicates this one, so for this reaction only this is considered and this is my I0 which is anodic current density of Zn++ Zn on zinc surface, and we have hydrogen evolution reaction which is the cathodic reaction we can consider this is my EC which is equilibrium, hydrogen potential and this is my I0 of hydrogen reaction on zinc surface, this is the cathodic polarization and this indicates this, and this one indicates this, so the two lines are drawn from this concept of Tafel equation. And then if we have zinc dipped in HCL, the potential of the zinc will be at this point which is the corrosion potential because it will reach to a new equilibrium state and the corrosion would happen as per this current density which is ICorr. Now the potential after sometime it will, the potential if we measure the zinc electrode potential if we see it will show this potential, now from that potential we have to take to the positive side as well as negative side and we will get a curve, so if we, let us extend this line in dotted fashion, now from this potential if we extend to the positive side taking it to the anodic side and then also a negative side then we will get a curve like this, so this is the nature of the curve and this line actually meets this straight line part, this is the straight line part, this actually if we extend it this line will meet, this line will meet the straight line part and here also if we extend it this line will meet this linear part. Now rest of the actually we will see this, this line only this yellow line only the graph will be this yellow line only and where this two lines are hidden. Now if we, and this is the straight line part, see if we extend this straight line part if we extend this straight line part, I have extended with the red one and this part this straight line part if we extend it so this is the point we would get and this is actually nothing but ICorr.

Now once we know ICorr then we would definitely get the knowledge of the corrosion rate and of course this line indicates zinc or if we consider general purpose, this line indicates metal ion information, and this one indicates hydrogen gas generation which is the cathodic reaction. And once we know this point we can easily calculate what could be the value of ICorr from the graph as well as we can also find out if we know the pH of the solution, solution pH if we know that can also give you, give us the value of this, and from the metal surface if we know what is I0 now we can have a small equation which is EC, if we draw this if we find out what is the equation for this that is basically this one and this can, we can write as EC corrosion, actually this value is ECorr, so ECorr - EC = Beta C log of ICorr / I0 C. Now ICorr is also falling on the line I can put that ICorr in that equation instead of IC at this point and this is my over voltage, cathodic over voltage Beta C we can calculate for that system, I0 if we know we can also find out what is ICorr, so one way if we can have this Tafel slope and find out from the graph or other way around if we find out what is the corrosion potential that time if we know the pH value we can find out what is the ECorr.

Now let us extend this equation EC is also found out from this, this is H+ H2 + RT/F which is 1 faraday x 2.303 log H+ ion concentration in the solution, and then at 25 degree Celsius and 1 atmosphere pressure this value goes to 0 and this would become minus if we consider the pH of the solution, so EC would be equal to - 0.059 into pH so minus log of H+ ion concentration is nothing but the pH, so this is the equation for EC we put this here, so the final equation would become ECorr - which would become + 0.059 pH would be equal to beta C log of ICorr/I0 C or C in this case is actually H + 1/2 H2 or 2H + H2, so this is the equation, from this we can find out what is ICorr and if we know ICorr, we can find out what is the corrosion rate of that metal in the particular solution. And this is a relatively quick method compared to the plant exposure but it actually doesn't give the actual response of the material in the application, in actual application but it is advantageous because immediately it can give you initial idea about the corrosion rate of that metal in that particular solution. Now it has also a certain limitation, for example when we consider, if we consider the limitation of Tafel extrapolation, so if we consider limitation, one is when we consider let's say zinc in HCL, this is zinc in HCL we assume that the entire surface, on the entire surface we have let's say the area is A0, the entire surface we have cathodic as well as anodic reactions, but actually some part of this area would be cathodic side, some part will be the anodic side and let's say that only the half of this part is if we consider statistical uniform distribution of those two reactions on those sections, so if we consider that this is my cathodic side and this is my anodic side, so we have only half part which is getting dissolved because the cathodic part will be protected because of the cathodic reaction that is happening on this part, but the only the anodic side will get corroded so actually it gives, it actually the corrosion rate is actually half of the corrosion rate what we are measuring from this route, because there the assumption is the whole area is active as anode, so we are getting a double corrosion rate than the actual, so that would happen and depending on the area ratio of cathodic and anodic would have less corrosion rate practical create would be less compared to the theoretical experimental rate what we are finding out here from the Tafel extrapolation, other limitation would be, now when we are considering this gaseous reaction as the cathodic reaction then the cracks of this method is getting this linear part in a graph, polarization graph, this is my polarization graph in that part this should be linear, there should be linear part if we don't have this linear part then there is a problem because we cannot extend it and then find it out where we have, because this EC we can find out from the pH so it has to be connected and this straight line should pass through this point, but if it is not straight and linear then we have difficulty because there could be a possibility of concentration over voltage so before reaching to this linear part before that it can bend down and it can become concentration controlled, so in that case this is the linear part see if we extend like this we will not reach to this point, so that gives wrong desert, the another possibility there could be a resistance polarization that might also lead to a problem in getting this linear part.

So these are certain issues with this Tafel extrapolation but most of these limitations can be avoided if we go into the linear polarization side. So the linear polarization let us discuss what could be the linear polarization. Now whenever we come to the linear polarization that is based on the basic principle, the basic principle is as follows. Now if we consider a point which is the potential, let's say this is the potential axis, this is E axis, and this is the current axis I axis, and if we see that the potential of that metal is at this point which has some value let's say is E0, rather let us put E dashed, so this is the potential at this point.

Now if we go towards the positive side from that potential which is basically the new set equilibrium potential and in case of corrosion it is the corrosion potential, now that time if we go to the positive side or negative side, if we go positive side and if we go the negative side with respect to the absolute current density, it's not the log of current density rather absolute current density then we see the graph would be like this, graph would be like this, so that time if we have this graph then we say that there is very small region in this region we have this line is linear, and this is the voltage where this part is linear that is around, here it would be around 10 volt, 10 millivolt, and here it would be around 10 millivolt. So in this region it is linear, okay, and from this linearity the slope can give us the indication of corrosion rate, the slope of this line. And this is actually the basic principle of linear polarization where we have to go to the positive side or polarized anodically as well as cathodically within the narrow band of 10 millivolt or so potential versus current density would be linear within that narrow range of 10 millivolt in the positive side as well as negative side, and the slope of this line which is actually Del E versus Del I would give information about ICorr, so once we know ICorr we can find out what is the corrosion rate of that metal.

Now in order to understand better and how we would get to this linear part, let us find out what is the basic structure, how come we get to this in this particular linear part, and for that we need to use the help of Butler-Volmer equation, and that equation says that this is I = I0 exponential alpha NF RT - exponential - 1 - alpha NF / RT, this is my over voltage the current density which is actually the I applied current density is the difference between IA - IC or other way around so this is for anodic polarization and this is for anodic or it could be IC - IA so this would come in the front, so this is the equation for Butler-Volmer equation and actually the Tafel equation is coming from these two equations the Tafel equation NA = 2.303 RT alpha NF log of IA/ I0 and whereas C would be = 2.303 RT 1 - alpha NF log of IC / I0, now from this beta A is nothing but this part 2.303 RT / alpha NF and whereas beta C is - 2.303 RT / 1 - alpha NF, now here R is the gas constant, T is the temperature in Kelvin, N is the number of electron that is associated for the metal reduction or oxidation, F is 1 Faraday, alpha is a symmetry factor, and these are the Tafel slopes, this is for anodic slope, this is cathodic Tafel slope.

Now we see that if we would like to, if we plot for a single electrode system if we plot what would be the cathodic and anodic polarization with respect to log I, then over voltage if we plot the plot would be like this and this is 0, this is positive which is anodic, this is negative which is cathodic polarization, and this indicates this line which is for cathodic reaction, and this line is for this anodic reaction. Now here we need to consider what would be the plot, the same plot if we would like to draw with respect to current density in absolute scale not the log I and over voltage, what could be the plot if we take it to the absolute potential versus I plot, so if we see this is an of course this is nothing but I0, this current density corresponding to this point, now if we plot this then the plot would become like this, plot would become like this where this is N, near over-voltage positive side and this is over-voltage negative side and this is 0 over voltage, this is I +, this is I -, I + and I - means this is actually the anodic current density, this is cathodic current density, so that means this when we consider this line that time we consider the cathodic current density which is IC, this is my IA, so if we go from 0 over voltage to a positive side my potential over voltage versus current density plot would be like this, and vice versa for the cathodic side this would be like this, so in this case cathodic current density would be the governing factor at a higher over voltage because we have seen in the case while we discussed and this has already been discussed that at higher over voltage, this part the IC part on this side would be negligible and higher over voltage and the cathodic side this anodic current density would be negligible.

Now how would we see, it's fine that we have anodic and cathodic polarization, but how would we find out what is the I0? Now as we know that higher over voltage so over voltage is I applied would be equal to IA - IC if we consider this side, now at a higher over voltage in this case we have seen that this point is negligible so it would be becoming IA but there would be this component also and this is coming from this and this part. So if we individually if we plot IC part, this is IC part, this is my IA part in addition to I0 so IA = I0 exponential alpha NF RT over voltage this is my IA and IC of course, if we add I0 here so this is my IC, so I'm not putting that I0 part I am just keeping it within the bracket so I have taken out, taken this I0 out, so that case the plot would be for IC, the plot would be in this case, plot would be like this, it will finally match with this. And same thing for IA plot would be like this, now we see that at higher over voltage and this is my IC, this is my IA and this part this is I applied, which is the overall current.

Now in this case we find that at higher over voltage IC contribution is less is negligible and that's what this will be only the IA part and higher, cathodic over voltage side the anodic current contribution to the polarization would be negligible and only the IC part will go over the polarization, so our concept of polarization is fulfilled there and these two points if we find out the at these two points this is same as this is let's say I double prime and this is I prime, so I double prime would be equal to I prime, and we see that in this case this line passes through I0 that means the IC line passes through I0, this is my IC line, so IC line is passing through this current density which is I dashed at 0 over voltage this is also 0 over voltage so this would be equal to I0, and same thing if we consider this one that time this IA line is passing through I0 at 0 over voltage, IA line is passing through 0 over voltage at this point so this is equal to I0, so over voltage as well as current density both are fulfilled. And once we see this if we consider this particular part a very small over voltage that time this part is linear, this can also be probed where if we expand this part these two things considering this is to be very small and then we will find out that if we expand exponential part we'll see that this becomes I0 NF over voltage by RT, so if we expand these two things and then we can get to I0 NF beta by RT which is this Part, which is almost, which is linear that means over voltage is linear to the applied current density. So this is happening on a single electrode system but in case of corrosion we have one cathodic, one anodic, so the same process is happening for cathodic side as well as anodic side and that would lead to the concept of linear polarization, so if we would like to plot the cathodic and anodic linear, cathodic and anodic polarization with respect to potential versus current density then we can get to the linear polarization part, so this is my let's say this is my cathodic side, this is my anodic side, and let's say my corrosion potential is this so if we compare the linear electrochemical polarization Tafel extrapolation we got plot like this and this is two linear part, this is Ecorr and this is my ICorr, and this is my cathodic polarization, this is my anodic polarization. So same thing would like to consider here, this is Ecorr, this is potential, potential axis, and this is my current axis. So on this line this is the point now which is Ecorr, which is nothing but this, and if we consider the cathodic polarization it would be having like this, and where we have, these are the two lines and this is my IA, this is my IC for the cathodic reaction.

So actually we are considering M+ H+ = M2+ + 2H2, so this reaction if we consider this is my cathodic reaction, and this is my I0 for hydrogen evolution, and the same way we can also think of anodic side, where this side is nothing but metal dissolution, in the same way as we have discussed in case of single electrode system, now this part is metal deposition and similarly we can find out what is the I0 for this reaction. So this is my I0, now so this we can extend like this, this way we can extend like this. Now this line if we draw a mirror image of this line we can have a plot like this, we can have a plot like this, this line actually the mirror image let me draw it with the yellow color, so if we draw a mirror image of this so then this rates of this cathodic reaction and anodic reaction would be same at Ecorr, so this is the point where anodic reaction rate and cathodic reaction rates are same, where I value for both the reactions are same. Now this point also would pass through this particular junction point between this line and this line, why? Because at this point we see that IA, this is my IA, and this is my IC, because this part is, this is mirror image of this and this is my IC for the cathodic reaction, so IC = IA, and that time what would be and this would be nothing but ICorr since this is the point which is IA = IC= ICorr, the same thing we are plotting with respect to the potential versus I plot rather log I, here we have log I this plot is E versus log I.

Now we see that these two points are meeting at this point and this is my ICorr and where IA equal to, sorry this is my IC, IA= IC=ICorr, now if we consider a small over voltage from this point that means from this point if we go a small positive side so we can have a, let's say off small over voltage which is Del E that part the small triangle is forming where this line and this line both line can be considered as linear, because they're small over voltage. Now if we extend this triangle, so this is my triangle, this is let’s say this is A, B, and C, so this is C, B, A and if I draw a normal from this point to this line we have two triangles and this is basically 90 degree. Now we have two lines, let’s say this slope is S, so we see that two triangles are forming and these are 90 degree after drawing the normal, let's say this point is D.

Now if we consider slope of this line is SA which is nothing but the slope of anodic reaction line, and the slope of the cathodic reaction line which is SC, then we can also find out what is the SC and SA from this dimension, and SC would be equal to this by this and SA would be equal to this by this. Now if we consider the overall current density, over all current is Del I and if we consider this is to be X then we can find out from geometry what would be SC and what would be SA, find out what is SC here so SC would be equal to DE/DI because this is my E potential and this is my I, so DE DI this is for cathodic, it would be equal to Del I - X by this is Del E, because this is my Del E we have seen that this is my Del E, so this is my Del E, so this is equal to Del E divided by Del I by minus X, because this part this by this, then again we have SA would be Del E / Del I or anodic because if we come to this graph we see that this is for the anodic reaction or we can say that this is this entire thing is for M + 2 + 2E M and this is for with respect to this reaction this 4H+ + 2E H2 so this is for reverse reaction, and this is for forward reaction, and in this case this is for this reaction and this side is for this reaction, so this is anodic because this line is indicating the anodic one for a metal dissolution so this would be equal to Del E / X because this is my X and this is my Del E.

Now if we consider this part then we can convert SC = Del E 1 divided by, where this one is 1/SA, so equal to 1 / Del I Del E – 1/SA and we can simplify and we can get Del I/ Del E = 1/SC + 1 /SA. Now once we know this equation we can get to, we can convert this equation with respect to the Tafel slope beta A and beta C and let's see in case of IA =I0 exponential 2.303 beta A, NA Nita A which is over voltage and Beta A we have already seen 2.303 RT / alpha NF, and this is coming from the Butler-Volmer equation what we have seen in the previous just few minutes back.

Now this we can convert into over voltage which is beta A / 2.303 Ln IA/ I0 and at corrosion potential that means if we come to this point, at corrosion potential if we would like to find out what is the slope, at this point what is the slope and that actually passes through this small linear part or if we consider this anodic site that time the slope would be passing through this point which is at Ecorr so nita at a small over voltage this we can write it as E - ECorr would be equal to Beta A 2.303 Ln ICorr/I0 this is nita A. Now if we do the slope at ICorr, then it would be equal to beta A 2.303, ICorr, because I0 is a constant. Now this is nothing but SA, similarly we can find out for Beta C that time Del E/Del I for cathodic reaction, it would be beta C/2.303 ICorr and that time we start with beta C /2.303 Ln ICorr / I0 for hydrogen and this is for metal, so this is for metal.

Now from this and here we are not considering a negative sign because the negative sign is incorporated while considering beta C and nita C, so from that if we do the same process we will get this expression, so this is one expression, this is second expression, now if we put that value of and this is equal to SC and if we have put the value of SC and SA we can get Del I/ Del E would be equal to 2.303 ICorr 1, just a minute, so Del I this would be this, so ICorr 1/beta C or beta A + 1/ beta C and this would become 2.303 ICorr, beta A, beta C and we can write in terms of Del E, Del I would be equal to 1/2.303 ICorr, beta A + beta C / beta A x beta C, so this is the expression or we can use this expression any of this expression we see that whenever we have a small over voltage then we have the slope of that over voltage versus current plot can give you the ICorr value, because this one we know and if we know this then we can get this. And what would be the experimental plot so we are basically plotting from this point onwards, so actually this is my 0 over voltage, so this is my 0 over voltage and if we would like to find out what would be the experimental plot then actually at this point we have to find out what is the difference between this and this, so if we consider the difference between this line and this line, this line and this line then we can, because at a very, we can find out a plot like this, like this, so the plot would be like this and the small over voltage this line we can find out the slope Del E, Del I and from this expression we find out what is ICorr, so this is the concept of measuring corrosion current density from linear polarization and this is the linear polarization curve. So this is overall the view of or the principle of linear polarization and of course this is advantageous over Tafel slope because here we don't go to a very high polarization, if we don't go to a very high polarization what would happen? We don't get any effect from resistance polarization or we cannot get any, we will minimize the effect of concentration polarization because we are operating in a very small over voltage.

Now this linear after this we can briefly discuss what is failure analysis, now this is basically the electrochemical route so we've already, we have discussed cathodic, we have discussed Tafel extrapolation and linear polarization. Now on top of that there are other test methods to find out what would be the corrosion cracking susceptibility of a particular metal and for corrosion cracking we can a method where nache sample, this is a nache sample, we can place it in a solution and we can wrote it that sample in the solution and we can also put stress on that and then find out nache as well as pre cracked, pre cracked sample this is basically the test for corrosion cracking, pre cracked sample if we put it in solution and rotate it and after giving a certain stress we can found out the fatigue crack, the corrosion fatigue susceptibility of the metal and we can get a plot like stress and number of cycle, so we can have a plot like this, now this is for corrosion fatigue, then we can also think of stress corrosion which is basically SS RT slow strain rate test, slow strain rate test and that case we can also determine what would be its susceptibility towards SCC or hydrogen embrittlement, so these mechanical tests are also there in order to find out what could be the corrosion cracking tendency of particular, of a material or metals and alloys in some corrosive environment.

Now we discuss the failure analysis, once we know all the test methods then we can also get into the failure analysis for and, where the corrosion is one of the factors in the failure of engineering materials, and in case of failure material, failure analysis we have to go step by step and this procedure would allow us to find out reasons for failure as well as allow us to think of some protective mechanism and it's actually not the, it's not about the judgment, only the judgment is not sufficient we have to also find out what could be the protective routes. Now the procedure where the corrosion problem is investigated that is actually the failure analysis in case of corrosion failure and it provides solution rather judgment and of course it is, it could be either destructive or nondestructive, now various stages the first stage would be the stages of failure analysis, actually the first stage is getting whatever informations are available in naked-eye that those are to be collected, for example seeing the metal magnified glass can be used and then we can get all the data logbook information, specification of operation, and then we can get to know, we can also observe the operation in some other, in other case where the material is still working then we can collect samples and we can also get the photograph, taking photograph of the failed surface or failed section would be very important issue, then the second stage, this is stage 1, the second stage actually it involves collection of samples. It involves collection of samples, and two samples collection of samples it could be the material which has failed or the rust that is there so that could be collected and those should be collected in a plastic bag and should be protected properly, at the same time let's say material is fractured like this, this is my fracture surface, care should be taken that the fracture surface would be should not be rubbed so that the information should be protected, when we go for microstructure observation of that fracture surface then there should be, the fracture surface should not get damaged so actually this second stage is collection of samples.

Stage three is basically more tests, laboratory test, laboratory tests of those samples microstructure analysis, rust analysis and those can, and after collecting all the information we can have a judgment on why the failure has happened and finally we can find out what are the reasons and then what could be the protective mechanism further, so that we can prevent this failure.

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