Non - Metallic Materials
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Module - 11
Corrosion and degradation of non - metallic materials
Lecture - 55
Fundamentals of corrosion, corrosion of materials

Welcome to my course Non-Metallic Materials and today we are in module number 11 Corrosion and degradation of non-metallic materials. And this is lecture number 55, where I will be discussing the Fundamentals of corrosion, and corrosion of materials.

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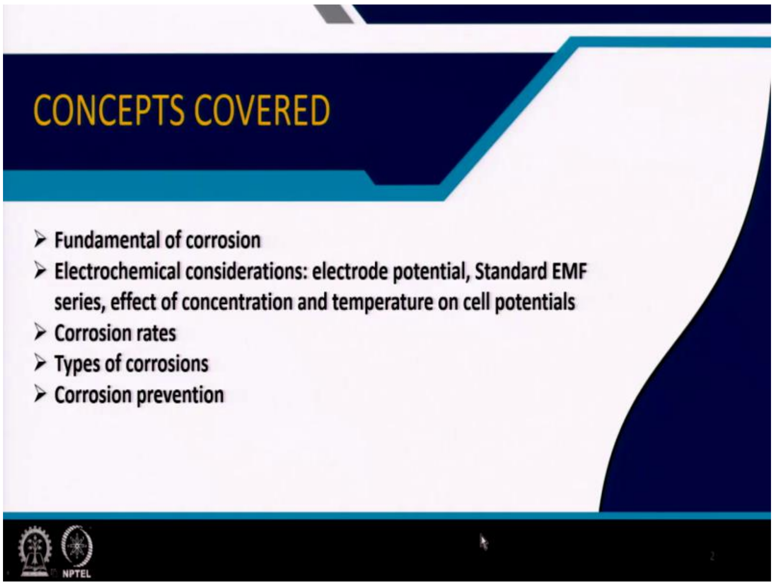

CONCEPTS COVERED

- Fundamental of corrosion
- Electrochemical considerations: electrode potential, Standard EMF series, effect of concentration and temperature on cell potentials
- Corrosion rates
- Types of corrosions
- Corrosion prevention

Initially I will introduce the fundamental concept of corrosion; mostly we will be talking about the corrosion in metal. And in the next lecture, we will briefly introduce the corrosion or degradation behavior of ceramics, polymers and related materials.

So, this lecture is mostly devoted on various metal corrosion. So, electrochemical consideration will be taken care of, electrode potential will be introduced standard EMF series; then effect of concentration and temperature on cell potential that will be discussed. Then corrosion rates will be described, types of various corrosion pertinent to mostly metal that will be introduced and finally, how the corrosion can be prevented will be talked about.

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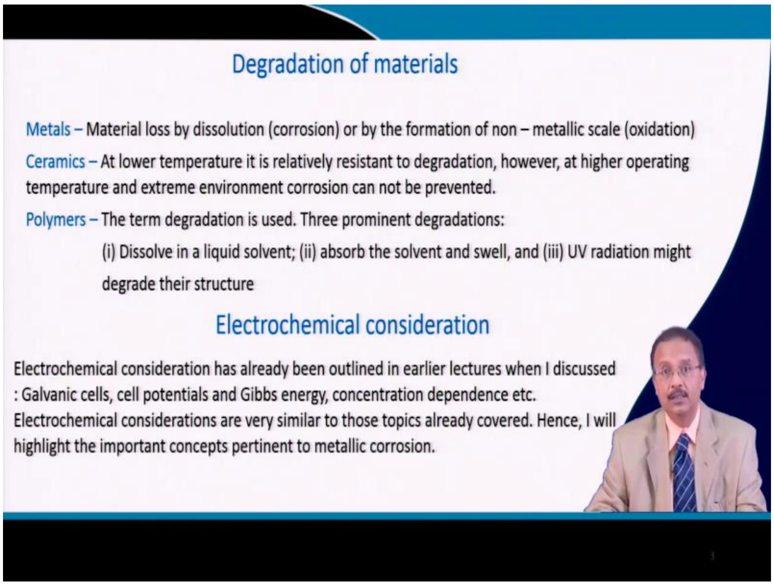

Degradation of materials

Metals – Material loss by dissolution (corrosion) or by the formation of non – metallic scale (oxidation)

Ceramics – At lower temperature it is relatively resistant to degradation, however, at higher operating temperature and extreme environment corrosion can not be prevented.

Polymers – The term degradation is used. Three prominent degradations:

(i) Dissolve in a liquid solvent; (ii) absorb the solvent and swell, and (iii) UV radiation might degrade their structure

Electrochemical consideration

Electrochemical consideration has already been outlined in earlier lectures when I discussed : Galvanic cells, cell potentials and Gibbs energy, concentration dependence etc. Electrochemical considerations are very similar to those topics already covered. Hence, I will highlight the important concepts pertinent to metallic corrosion.

The topic you will find it ah similarity already is there, when I talked about electrochemistry principles; then many of the concept what I will be describing today, you will find that is relevant to what you already know. So, in case of metal, materials loss by dissolution, we call it say corrosion; or by the formation of a non metallic scale, which is termed as oxidation, both will be talked about in this lecture and the following lecture.

In case of ceramic at low temperature, it is relatively resistant to degradation; but at high operating temperature, in particularly extreme environment, the corrosion cannot be prevented, otherwise they are corrosion free materials. In case of polymer, usually the term degradation is more appropriate. So, we will talk about three prominent degradation in the next lecture.

First one is dissolve in a liquid solvent, then second one absorb the solvent and swell and third one is UV radiation related degradation; these three things will be discussed in the next lecture. So, first let us take this electrochemical consideration. And as I told that this has already been outlined in earlier lectures when I discussed the galvanic cell, cell potential, Gibbs energy, concentration dependence, and etcetera.

So, electrochemical consideration are very similar to this those topics already covered. So, only the important outcome, important things will be highlighted in this particular lecture, which is relevant to the corrosion of metal.

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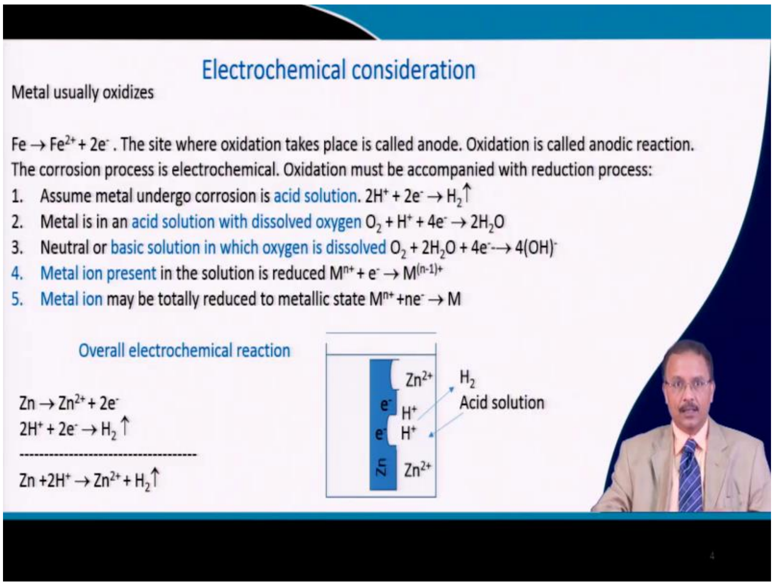

Electrochemical consideration

Metal usually oxidizes

$Fe \rightarrow Fe^{2+} + 2e^-$. The site where oxidation takes place is called anode. Oxidation is called anodic reaction. The corrosion process is electrochemical. Oxidation must be accompanied with reduction process:

1. Assume metal undergo corrosion is acid solution. $2H^+ + 2e^- \rightarrow H_2\uparrow$
2. Metal is in an acid solution with dissolved oxygen $O_2 + H^+ + 4e^- \rightarrow 2H_2O$
3. Neutral or basic solution in which oxygen is dissolved $O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$
4. Metal ion present in the solution is reduced $M^{n+} + e^- \rightarrow M^{(n-1)+}$
5. Metal ion may be totally reduced to metallic state $M^{n+} + ne^- \rightarrow M$

Overall electrochemical reaction

$Zn \rightarrow Zn^{2+} + 2e^-$
$2H^+ + 2e^- \rightarrow H_2\uparrow$

$Zn + 2H^+ \rightarrow Zn^{2+} + H_2\uparrow$

Now, metal usually as you know that they oxidizes; I can site an example, if you take the example of iron, then it oxidizes from metallic state to plus 2 state and it generates this electron. So, the site where this oxidation takes place usually we call it as an anode. And oxidation basically called as anodic reaction. So, the corrosion process in metal that is electrochemical in nature. And this oxidation is also accompanied by the reduction process.

Now, the question is that, how this reduction takes place? So, if you assume that the metal undergo corrosion in an acid solution; then acid solution will have H plus ion, that will take up this electron which is coming out from the metal to form hydrogen gas. If the metal is in acid solution which is having dissolved oxygen in it; then this reaction takes place oxygen, H plus ion, and the electron that forms water molecule.

The third criteria could be that, it is a neutral or basic solution, where oxygen is dissolved. So, here this oxygen H_2O molecule and the electron that will form hydroxyl ion. It is also possible that the metal is present in the solution, which is reduced eventually. So, M plus is reduced to metallic M. And either two of them, either it can be a metallic M or it can reduce its balance. So, if it is M^n plus, it is M^n minus 1.

So, both type of reduction is possible. So, in case of zinc which corrodes quite easily, I can write the half-cell reaction for oxidation and in an acidic solution, the reduction reaction. So, basically zinc corrodes like this. So, here is an example that in acidic solution, if you dip zinc; then it will eventually corrode and hydrogen gas will be generated as a reaction product.

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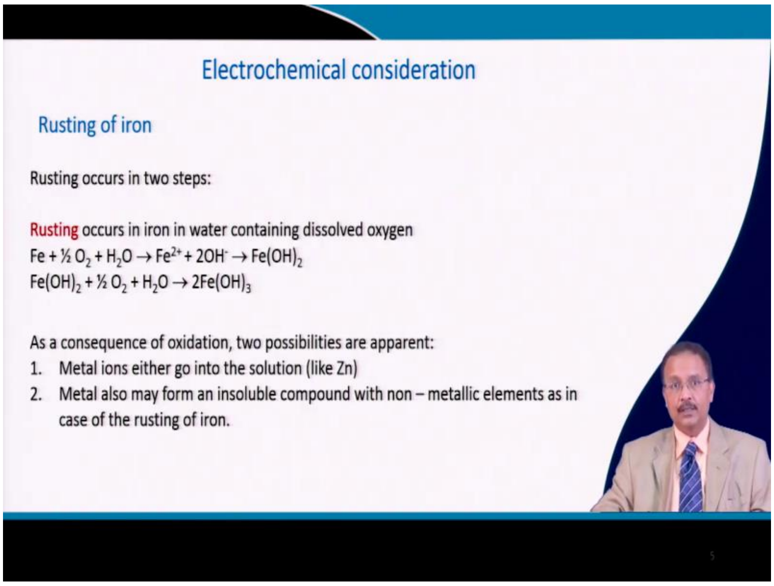

Electrochemical consideration

Rusting of iron

Rusting occurs in two steps:

Rusting occurs in iron in water containing dissolved oxygen

$Fe + ½\,O_2 + H_2O \rightarrow Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$

$Fe(OH)_2 + ½\,O_2 + H_2O \rightarrow 2Fe(OH)_3$

As a consequence of oxidation, two possibilities are apparent:

1. Metal ions either go into the solution (like Zn)
2. Metal also may form an insoluble compound with non – metallic elements as in case of the rusting of iron.

Rusting of iron is another example. So, rusting actually occurs in two different step. In the first step iron is oxidized Fe 2 plus and eventually it forms iron hydroxide. And then iron hydroxide that reacts with dissolved oxygen and H_2 O or could be oxygen from the ambient, moist ambient. And eventually it forms iron hydroxide $Fe(OH)_3$.

So, oxidation as you can see two possibilities are there, either metal ions they go into the solution, like that we observe in case of zinc. Or the metal ions can form an insoluble compound with non metallic elements as in case of the rusting of iron, which I just described.

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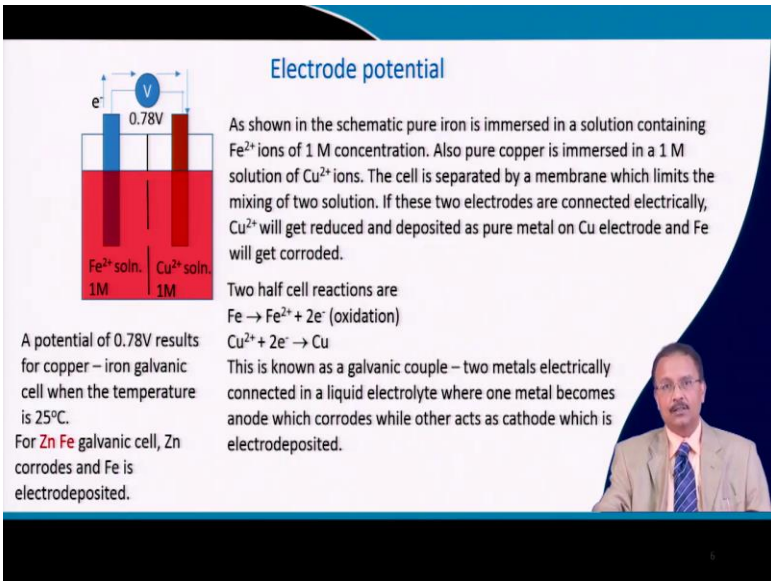

Electrode potential

As shown in the schematic pure iron is immersed in a solution containing Fe^{2+} ions of 1 M concentration. Also pure copper is immersed in a 1 M solution of Cu^{2+} ions. The cell is separated by a membrane which limits the mixing of two solution. If these two electrodes are connected electrically, Cu^{2+} will get reduced and deposited as pure metal on Cu electrode and Fe will get corroded.

Two half cell reactions are

$Fe \rightarrow Fe^{2+} + 2e^-$ (oxidation)

$Cu^{2+} + 2e^- \rightarrow Cu$

This is known as a galvanic couple – two metals electrically connected in a liquid electrolyte where one metal becomes anode which corrodes while other acts as cathode which is electrodeposited.

A potential of 0.78V results for copper – iron galvanic cell when the temperature is 25°C.

For Zn Fe galvanic cell, Zn corrodes and Fe is electrodeposited.

Now, look at this schematic here; pure iron it is immersed in a solution, which contains iron salt and the concentration of the salt is 1 mole. And also in the other half you have copper, which is also immersed in 1 mole solution of copper ions. And the cell that is separated by a membrane, which basically limits the mixing of this two solution.

Now, if this two couple is connected electrically and if you have a voltmeter here; then you will see that the copper will get reduced and this copper ion will get reduced and eventually it will deposit on this copper electrode and iron will get corrode. So, one can write the half equations for oxidation and for the reduction to get this metallic copper.

So, this kind of situation is called a galvanic couple, two metals which are electrically connected in a liquid electrolyte, where one metal becomes anode and corrode and other one acts as a cathode, which is basically electro deposited. This is also the principle of electro deposition. So, a very specific voltage about 0.78 volt this results out of this reaction or copper and iron galvanic cell at room temperature.

Now, if you consider a zinc iron galvanic cell, then zinc corrodes and iron is electro deposited. So, depending on the type of this two couple; one will get oxidized, and other will get reduced. So, it is not that always iron will corrode. In the later case, as you can see zinc corrodes and iron is electro deposited.

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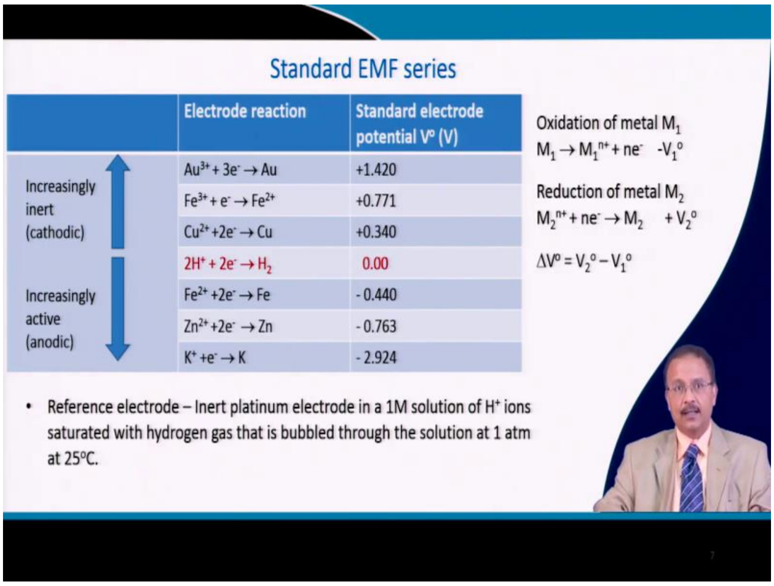

Standard EMF series

	Electrode reaction	Standard electrode potential V° (V)
Increasingly inert (cathodic) ↑	$Au^{3+} + 3e^- \rightarrow Au$	+1.420
	$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.771
	$Cu^{2+} + 2e^- \rightarrow Cu$	+0.340
Increasingly active (anodic) ↓	$2H^+ + 2e^- \rightarrow H_2$	0.00
	$Fe^{2+} + 2e^- \rightarrow Fe$	- 0.440
	$Zn^{2+} + 2e^- \rightarrow Zn$	- 0.763
	$K^+ + e^- \rightarrow K$	- 2.924

Oxidation of metal M_1

$M_1 \rightarrow M_1^{n+} + ne^- \quad -V_1^o$

Reduction of metal M_2

$M_2^{n+} + ne^- \rightarrow M_2 \quad +V_2^o$

$\Delta V^o = V_2^o - V_1^o$

- Reference electrode – Inert platinum electrode in a 1M solution of H^+ ions saturated with hydrogen gas that is bubbled through the solution at 1 atm at 25°C.

Now, this is related to the standard EMF series. So, you can see the oxidation of metal that is basically given by this half-cell. And the voltage is taken as negative. So, this is I have denoted as negative V 1 0. For the reduction of the metal, this kind of reaction takes place and pure metal is electro deposited and the standard electrode potential in this case is taken positive.

So, the voltage difference is nothing, but V 2 minus V 1; that already we have described when we talked about Daniel cell you have seen it, zinc and copper we get a voltage out of it. So, depending on that, you can have an EMF, standard EMF series and this reaction the reduction of H plus ion to hydrogen gas that is called a reference point. And the voltage is taken as 0 at a particular temperature, which is typically 25 degree Celsius and 1 atmospheric pressure.

So, you can make easily a hydrogen reference cell, where inside a 1 molar solution of H plus hydrogen ion, hydrogen gas is bubbled on a platinum electrode and this reference is taken as 0. So, whatever is upper than that; so they are increasingly inert and whatever is below this reference series, that is increasingly active and act as anode.

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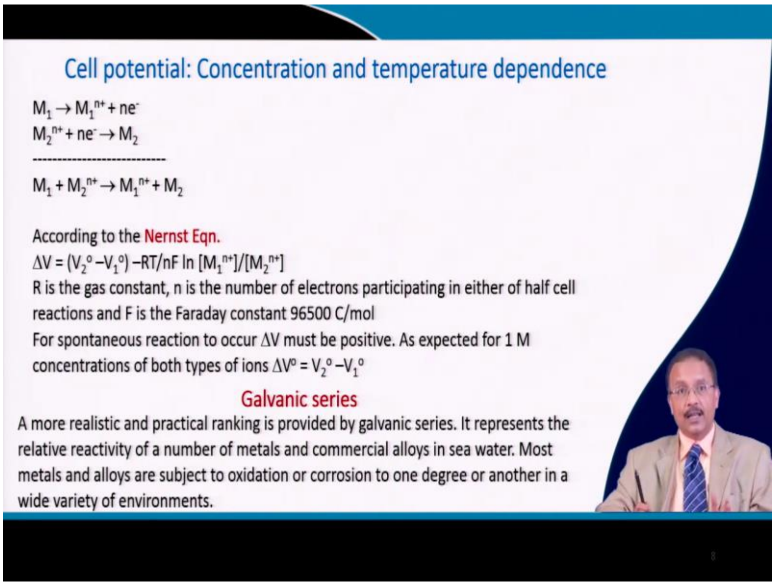

Cell potential: Concentration and temperature dependence

$M_1 \rightarrow M_1^{n+} + ne^-$
$M_2^{n+} + ne^- \rightarrow M_2$

$M_1 + M_2^{n+} \rightarrow M_1^{n+} + M_2$

According to the Nernst Eqn.
$\Delta V = (V_2^o - V_1^o) - RT/nF \ln [M_1^{n+}]/[M_2^{n+}]$
R is the gas constant, n is the number of electrons participating in either of half cell reactions and F is the Faraday constant 96500 C/mol
For spontaneous reaction to occur ΔV must be positive. As expected for 1 M concentrations of both types of ions $\Delta V^o = V_2^o - V_1^o$

Galvanic series

A more realistic and practical ranking is provided by galvanic series. It represents the relative reactivity of a number of metals and commercial alloys in sea water. Most metals and alloys are subject to oxidation or corrosion to one degree or another in a wide variety of environments.

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So, the half-cell reaction already I talked about for oxidation and for reduction. And this is your actual relation, actual reaction; this is a full cell reaction. So, if I apply the Nernst equation, which already I have described; then the generated voltage depends on the standard electrode potential minus this term, which is concentration potential R T by n F l n of the product concentration divided by the reactant concentration.

So, R here is the gas constant, n is the number of electrons participating in either of the half cell reaction and F is a Faraday constant, which typical is having a value of 96500. So, for spontaneous reaction to occur, the del V value must be positive. So, as expected for 1 molar concentration for both types of ion; if it is 1 molar standard case, then del V 0 is nothing, but the standard electrode potential V_2^0 minus V_1^0.

So, a more realistic kind of practical ranking that is provided in terms of the galvanic series. So, it eventually represents the relative reactivity of the number of metal and metal alloys and electrolyte is typically sea water is considered. So, most metal and alloys they are subjected to oxidation or corrosion; the degree may vary depending on the where it is placed in the galvanic series. And a wide variety of environment can be chosen for this purpose.

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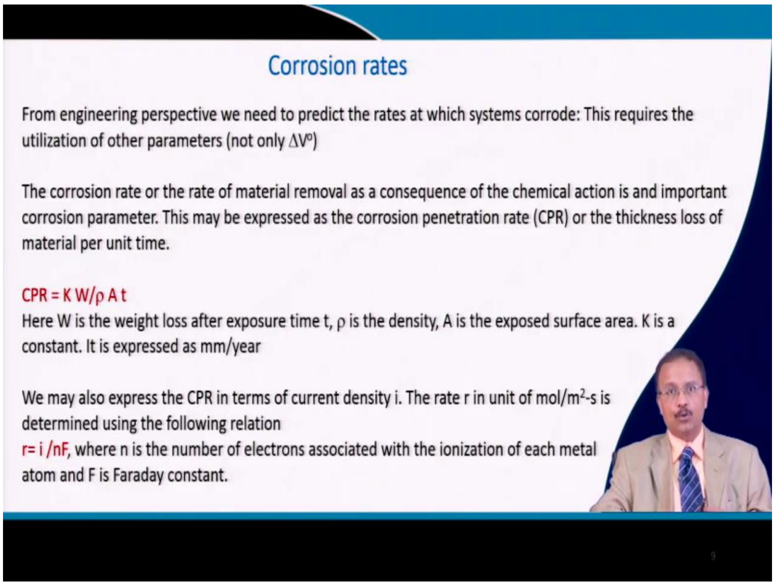

Corrosion rates

From engineering perspective we need to predict the rates at which systems corrode: This requires the utilization of other parameters (not only ΔV^o)

The corrosion rate or the rate of material removal as a consequence of the chemical action is and important corrosion parameter. This may be expressed as the corrosion penetration rate (CPR) or the thickness loss of material per unit time.

$CPR = K\,W/\rho\,A\,t$

Here W is the weight loss after exposure time t, ρ is the density, A is the exposed surface area. K is a constant. It is expressed as mm/year

We may also express the CPR in terms of current density i. The rate r in unit of mol/m^2-s is determined using the following relation

$r= i\,/nF$, where n is the number of electrons associated with the ionization of each metal atom and F is Faraday constant.

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So, from engineering point of view, we need to predict the rate at which the system corrodes. So, this requires the utilization of other parameters. So, not only del V 0 is sufficient. So, the corrosion rate or the rate of material removal as a consequence of the said chemical actions that is important corrosion parameter. So, this actually may be expressed by corrosion penetration rate, which is abbreviated as CPR or the thickness loss of the material per unit time.

So, this corrosion penetration rate that is defined as a constant K and then W is the weight loss after it is exposed in that environment at a time t; rho is the density, and A is the exposed surface area. So, this is usually defined as millimeter per year. We can also express the corrosion penetration rate in terms of current density i. So, note that i is a current density. So, current per unit area and the rate unit is r.

So, r is your current density divided by number of electron and Faraday constant. And its dimension is mole per meter square per second and this is also used to define the corrosion penetration rate.

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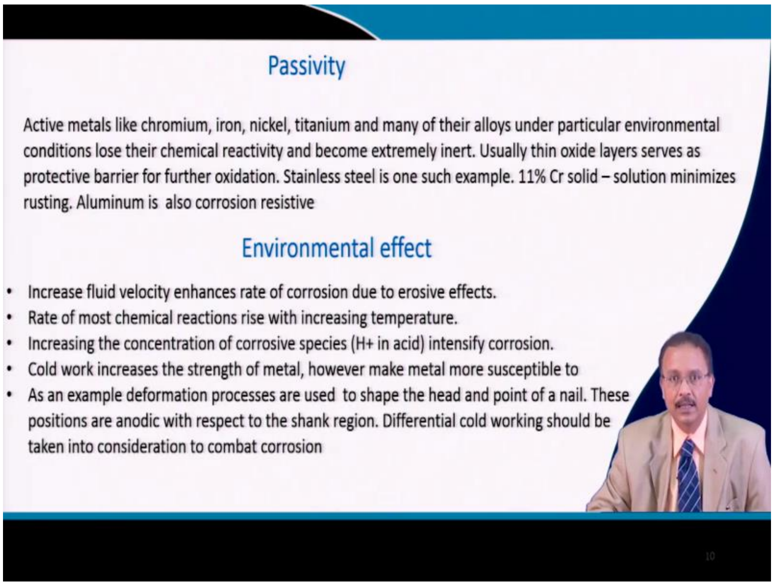

Passivity

Active metals like chromium, iron, nickel, titanium and many of their alloys under particular environmental conditions lose their chemical reactivity and become extremely inert. Usually thin oxide layers serves as protective barrier for further oxidation. Stainless steel is one such example. 11% Cr solid – solution minimizes rusting. Aluminum is also corrosion resistive

Environmental effect

- Increase fluid velocity enhances rate of corrosion due to erosive effects.
- Rate of most chemical reactions rise with increasing temperature.
- Increasing the concentration of corrosive species (H+ in acid) intensify corrosion.
- Cold work increases the strength of metal, however make metal more susceptible to
- As an example deformation processes are used to shape the head and point of a nail. These positions are anodic with respect to the shank region. Differential cold working should be taken into consideration to combat corrosion

Active material like chromium or iron or nickel, titanium and many other alloys under particular environment condition, they lose their chemical reactivity and become extremely inert.

So, this is due to the fact, a very thin oxide layer that serves as a protective layer for further oxidation of this material. Stainless steel is one example; as you know in stainless steel about 11 percent of chromium that is made as a solid solution that minimizes rusting. Also aluminum is quite corrosion resistive material. So, environment has a strong effect on corrosion; usually the increase of fluid velocity, which is corrosive in nature that enhances the corrosion rate and this is called erosion.

So, material is lost because of this increased fluid velocity. So, rate of the most chemical reaction rise with the increasing temperature. So, increasing the concentration of the corrosive species; particularly if H plus iron is there in the acid, that also increases the corrosion. So, as an example of the deformation process are used to shape; for example, the head point of a nail and this is anodic in nature, so as compared to the shank.

So, different cold working also will have to be taken into consideration. So, if you do the processing of the metal, particularly cold working or doing some kind of special shape forming. So, those area are prone to corrosion.

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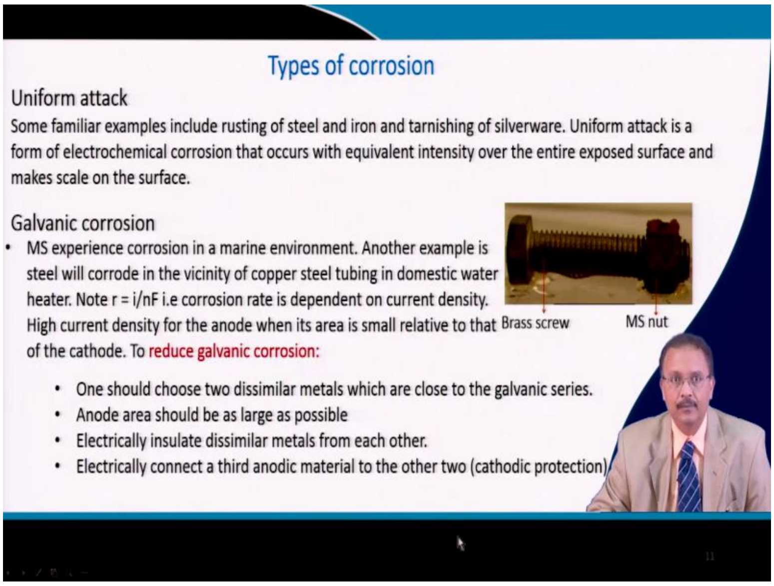

Types of corrosion

Uniform attack

Some familiar examples include rusting of steel and iron and tarnishing of silverware. Uniform attack is a form of electrochemical corrosion that occurs with equivalent intensity over the entire exposed surface and makes scale on the surface.

Galvanic corrosion

- MS experience corrosion in a marine environment. Another example is steel will corrode in the vicinity of copper steel tubing in domestic water heater. Note r = i/nF i.e corrosion rate is dependent on current density. High current density for the anode when its area is small relative to that of the cathode. To reduce galvanic corrosion:
  - One should choose two dissimilar metals which are close to the galvanic series.
  - Anode area should be as large as possible
  - Electrically insulate dissimilar metals from each other.
  - Electrically connect a third anodic material to the other two (cathodic protection)

So, corrosion could be of uniform attack. So, the familiar example of rusting of steel and iron and tarnishing of your silverware; particularly if sulphur is there in the ambient, it forms silver sulphide and it forms a black color of layer on the shining glittering silver surface.

So, it is a uniform attack. So, attack that form the electrochemical corrosion that occurs with equivalent intensity over the entire exposed surface. So, it forms a scale. Next is the galvanic corrosion. So, MS tell that corrosion is quite; it is quite common in marine environment. Another example is steel will corrode in the vicinity of copper steel tubing in a domestic water heater.

So, here as I mentioned, the rate corrosion penetration rate is i by n F. So, the corrosion rate is dependent on current density. So, high current density of the anode will be more when its area is more exposed. So, to reduce the galvanic corrosion what I will do; I will reduce the area of the anode material, so that it reduce the galvanic corrosion. So, one should choose two dissimilar metal which are close to the galvanic series, so that the corrosion is minimized.

As I said the anodic area should be as large as possible, so that the I by a is small; so corrosion penetration rate is lowered. Eelectrically you can insulate the dissimilar metal from each other or electrically connect a third anodic material to the other one. And we will discuss that is called cathodic protection.

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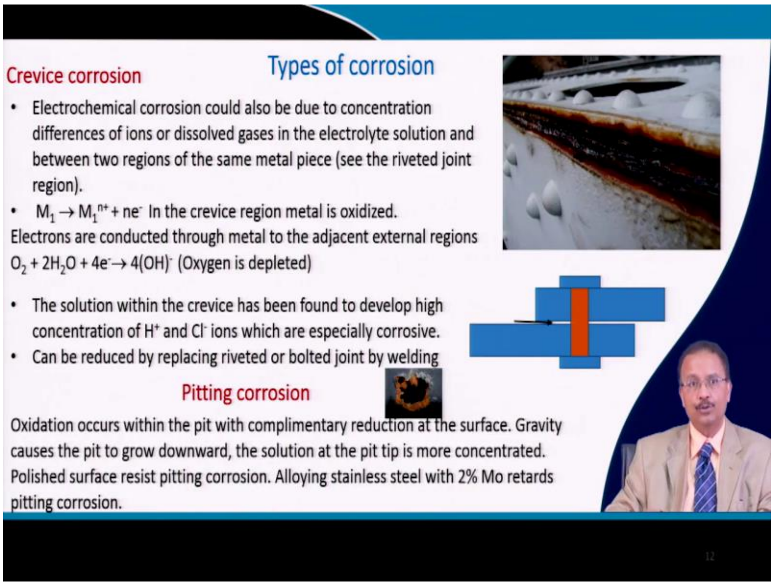

Types of corrosion

Crevice corrosion

- Electrochemical corrosion could also be due to concentration differences of ions or dissolved gases in the electrolyte solution and between two regions of the same metal piece (see the riveted joint region).
- $M_1 \rightarrow M_1^{n+} + ne^-$ In the crevice region metal is oxidized.

Electrons are conducted through metal to the adjacent external regions

$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$ (Oxygen is depleted)

- The solution within the crevice has been found to develop high concentration of H^+ and Cl^- ions which are especially corrosive.
- Can be reduced by replacing riveted or bolted joint by welding

Pitting corrosion

Oxidation occurs within the pit with complimentary reduction at the surface. Gravity causes the pit to grow downward, the solution at the pit tip is more concentrated. Polished surface resist pitting corrosion. Alloying stainless steel with 2% Mo retards pitting corrosion.

Crevice corrosion is also electrochemical corrosion that could be due to the concentration difference of the dissolved ion or dissolved gases in the electrolyte solution, which is snag stagnant between two regions. And it is particularly occur in the riveted, riveted joint like this. So, there is a small area as you can see. So, here the electrolyte becomes stagnant and here it give rise to the crevice corrosion.

So, initially the metal is oxide oxidized by this known reaction. So, electrons are conducted to metal to the adjacent external region and there the oxygen is there. So, oxygen is getting reduced and eventually the oxygen is depleted.

So, the solution within the crevice is therefore, develop a high concentration of H plus and chloride ion, which are especially very corrosive. And this can be reduced by replacing the riveted joint with welding; riveted or bolting joint can be replaced by welding to get rid of this kind of corrosion.

Another typical corrosion is the pitting corrosion. So, here oxidation occurs within the pit with a complementary reduction at the surface. So, gravity causes the pit to grow downwards. So, this is a small hole type of thing. The solution at the pit tip is more concentrated and usually the polished surface can resist the pitting corrosion. Alloying the stainless steel with say 2 percent molybdenum also get rid of the pitting corrosion of this type.

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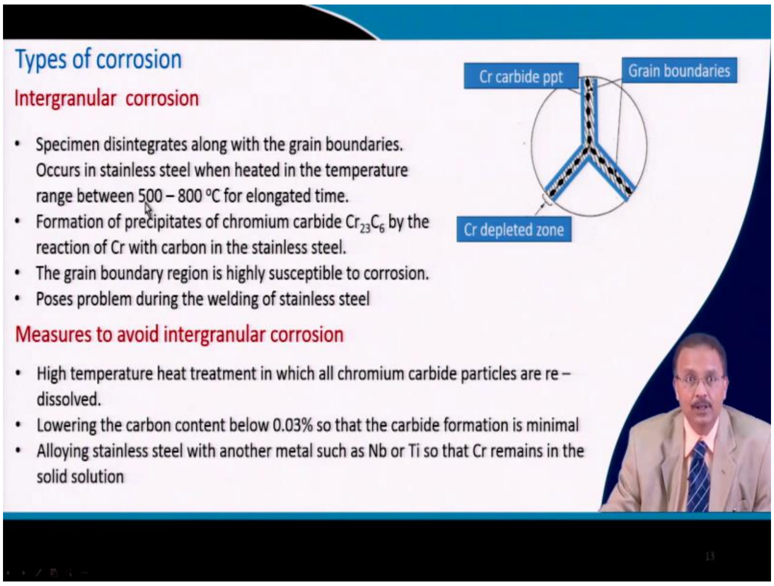

Types of corrosion

Intergranular corrosion

Cr carbide ppt

Grain boundaries

Cr depleted zone

- Specimen disintegrates along with the grain boundaries. Occurs in stainless steel when heated in the temperature range between 500 – 800 °C for elongated time.
- Formation of precipitates of chromium carbide $Cr_{23}C_6$ by the reaction of Cr with carbon in the stainless steel.
- The grain boundary region is highly susceptible to corrosion.
- Poses problem during the welding of stainless steel

Measures to avoid intergranular corrosion

- High temperature heat treatment in which all chromium carbide particles are re – dissolved.
- Lowering the carbon content below 0.03% so that the carbide formation is minimal
- Alloying stainless steel with another metal such as Nb or Ti so that Cr remains in the solid solution

Inter granular corrosion is also operative particularly in case of stainless steel. So, here the particular material that degrades along with the grain boundary. So, when the stainless steel is heated at a temperature in the range of 500 to 800 degree Celsius for prolonged time; then it occurs the chromium within the steel, they form chromium carbide and then in the steel carbon is there. So, chromium carbide is formed and then they are precipitated along with the grain boundary.

So, this grain boundary region is highly susceptible to the corrosion and this poses the problem particularly when the steel structure is welding. So, the temperature is raised up to this level. So, then chromium inside the stainless steel reacts with carbon and then the weak the grain boundary to have this inter granular corrosion. So, as obvious to get rid of this high temperature heat treated, heat treating can be done.

So, that this chromium carbide particles they are re-dissolved. One can lower the carbon content below 0.03 percent, so that the carbide formation is also minimal. Or one can alloy the steel with some other material like niobium or titanium, so that the chromium remains in the solid solution and it does not react with the carbon in the steel.

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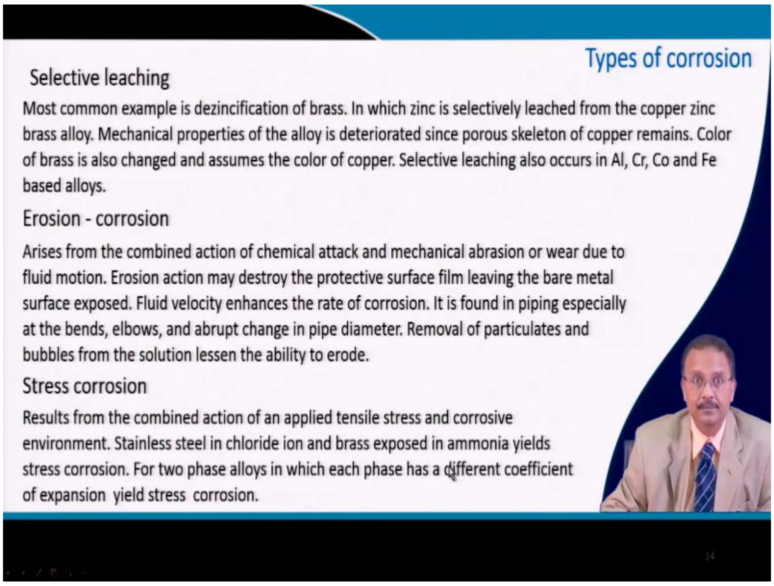

Types of corrosion

Selective leaching

Most common example is dezincification of brass. In which zinc is selectively leached from the copper zinc brass alloy. Mechanical properties of the alloy is deteriorated since porous skeleton of copper remains. Color of brass is also changed and assumes the color of copper. Selective leaching also occurs in Al, Cr, Co and Fe based alloys.

Erosion - corrosion

Arises from the combined action of chemical attack and mechanical abrasion or wear due to fluid motion. Erosion action may destroy the protective surface film leaving the bare metal surface exposed. Fluid velocity enhances the rate of corrosion. It is found in piping especially at the bends, elbows, and abrupt change in pipe diameter. Removal of particulates and bubbles from the solution lessen the ability to erode.

Stress corrosion

Results from the combined action of an applied tensile stress and corrosive environment. Stainless steel in chloride ion and brass exposed in ammonia yields stress corrosion. For two phase alloys in which each phase has a different coefficient of expansion yield stress corrosion.

Selective leaching is very common for the alloy material; in brass is one example you know that copper and zinc alloy is there. So, selectively zinc is highly oxidizing material, so selectively it gets leached out. So, mechanical property is grossly deteriorated; because zinc is out from the structure and the resultant structure of copper they are porous in nature.

So, the color also changes from yellowish color, it changes to red reddish color due to the copper. So, selective leaching is also quite prominent for aluminum, chromium, cobalt, iron base alloy, it is also quite common. Erosion-corrosion already I have talked about. It arises from the combined action of chemical attack and mechanical abrasion, where due to the fluid motion.

An erosion action may be destroy the protective surface film leaving the bare metal surface exposed. And that thereby it is corrosive, environment will corrode the metal. Stress corrosion that result from the combined action of an applied stress and corrosive environment. And stainless steel in chloride solution or brass exposed to ammonia that yields to this type of stress corrosion.

For any two phase alloy in which each phase is having different coefficient of expansion, that also yield stress corrosion type of behavior.

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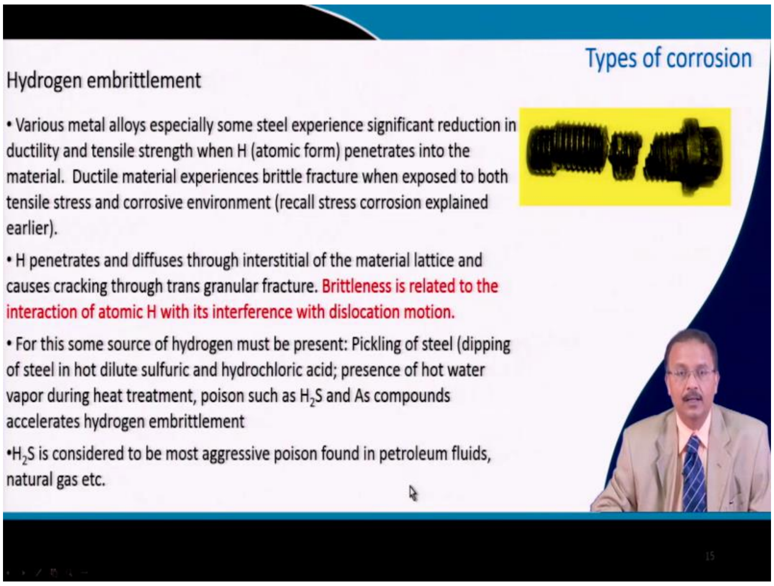

Types of corrosion

Hydrogen embrittlement

- Various metal alloys especially some steel experience significant reduction in ductility and tensile strength when H (atomic form) penetrates into the material. Ductile material experiences brittle fracture when exposed to both tensile stress and corrosive environment (recall stress corrosion explained earlier).
- H penetrates and diffuses through interstitial of the material lattice and causes cracking through trans granular fracture. Brittleness is related to the interaction of atomic H with its interference with dislocation motion.
- For this some source of hydrogen must be present: Pickling of steel (dipping of steel in hot dilute sulfuric and hydrochloric acid; presence of hot water vapor during heat treatment, poison such as H_2S and As compounds accelerates hydrogen embrittlement
- H_2S is considered to be most aggressive poison found in petroleum fluids, natural gas etc.

Another corrosive effect is hydrogen embrittlement. And various metal alloys especially some kind of steel experience significant reduction of the ductility and tensile strength when molecular form of hydrogen that penetrates into the material. So, the ductile material experience a brittle nature of brittle kind of fracture, when exposed to both tensile stress and a corrosive environment; it is something similar to the stress corrosion, which already I have explained earlier.

So, this is due to hydrogen penetrates through the interstitial of the material and causes cracking through the trans, mostly trans granular fracture. And it is proposed that this brittleness is related to the interaction of the atomic hydrogen and it interferes with the dislocation motion and therefore, I turned it to a brittle kind of behavior. So, some source of hydrogen must be present.

So, one example is the pickling of the steel. So, you know that steel is dipped into a hot sulfuric acid or hydrochloric acid; presence of hot vapor during heat treatment or if the poisonous material like H_2S and arsenic compounds are there, so these things will accelerate the hydrogen embrittlement. So, out of that H_2S is considered to be very aggressive poison, especially found in the petroleum fluid and natural gas.

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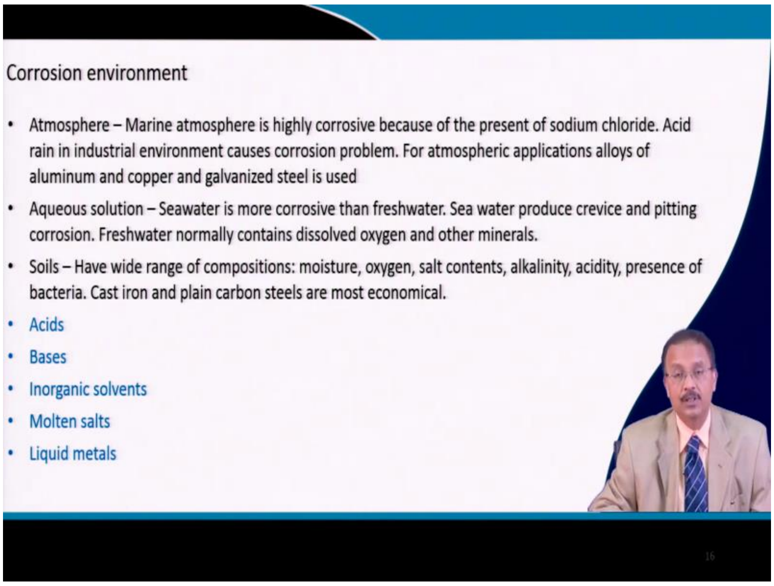

Corrosion environment

- Atmosphere – Marine atmosphere is highly corrosive because of the present of sodium chloride. Acid rain in industrial environment causes corrosion problem. For atmospheric applications alloys of aluminum and copper and galvanized steel is used
- Aqueous solution – Seawater is more corrosive than freshwater. Sea water produce crevice and pitting corrosion. Freshwater normally contains dissolved oxygen and other minerals.
- Soils – Have wide range of compositions: moisture, oxygen, salt contents, alkalinity, acidity, presence of bacteria. Cast iron and plain carbon steels are most economical.
- Acids
- Bases
- Inorganic solvents
- Molten salts
- Liquid metals

Corrosion environment is also important, particularly marine atmosphere is highly corrosive because of the presence of sodium chloride. Acid rain is another example in the industrial environment that creates this corrosion problem. So, for this type of application, usually atmosphere ambient dopamine ambient condition, condition usually alloys of aluminum, copper or galvanized steel that is. Aqueous solution also could be corrosive, sea water is more corrosive than fresh water.

Sea water produces the crevice corrosion and also pitting corrosion. And fresh water normally they contains dissolved oxygen along with the other minerals which also can be; because of this reduction nature, it can also corrode the metal. Soils could also be corrosive. So, it is having a wide range of composition, moisture content, oxygen content, salt content, alkyl alkalinity and acidity, presence of bacteria.

So, all these things can expedite the corrosion. So, usually cast iron and plain carbon steel are most economical to get rid of this environmental effect. Other than that different acid, base, inorganic solvents, molten salts, and liquid metals they also expedite the corrosion.

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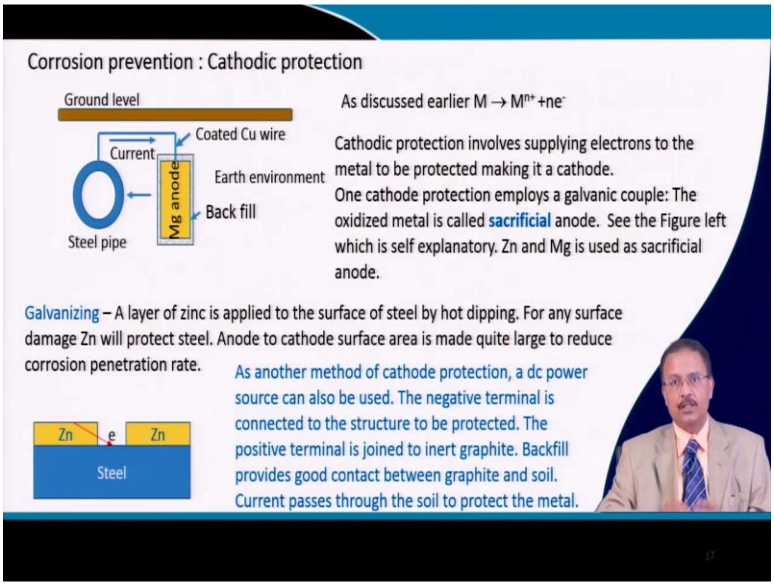

Corrosion prevention : Cathodic protection

As discussed earlier M → $M^{n+} + ne^-$

Cathodic protection involves supplying electrons to the metal to be protected making it a cathode. One cathode protection employs a galvanic couple: The oxidized metal is called **sacrificial** anode. See the Figure left which is self explanatory. Zn and Mg is used as sacrificial anode.

Galvanizing – A layer of zinc is applied to the surface of steel by hot dipping. For any surface damage Zn will protect steel. Anode to cathode surface area is made quite large to reduce corrosion penetration rate.

As another method of cathode protection, a dc power source can also be used. The negative terminal is connected to the structure to be protected. The positive terminal is joined to inert graphite. Backfill provides good contact between graphite and soil. Current passes through the soil to protect the metal.

So, cathodic protection is one good way to get rid of the corrosion and it is a very simple way. So, if you have a steel pipe here and which is prone to corrode; then cathodic protection involves supplying something which can supply electron to the metal and protect it. So, you will have to make it as a cathode. So, one of the cathode protection underground, it uses a sacrificial anode in the form of magnesium.

So, this magnesium or zinc that is used as sacrificial anode, so eventually it supplies electron to the steel pipe. So, it does not get corroded, it acts as a cathodic material and this thing it corrodes. And this is one way to get rid of the, it is one form of protection. Galvanization is another way.

So, a layer of zinc is applied to the surface of steel by hot dipping. So, for any surface damage, you know that the zinc will protect the steel. Anode to cathode surface area is made quite large to reduce the corrosion penetration rate whatever I talked about earlier.

So, as another method of cathode protection, one can apply a simple DC source one can use it; the negative terminal is usually connected to the structure that to be protected. The positive terminal is joined to an inert graphite, which is dipped into the soil with a backfill. So, the backfill it provides a good contact between graphite and soil. And current passes through the soil to protect the metal body.

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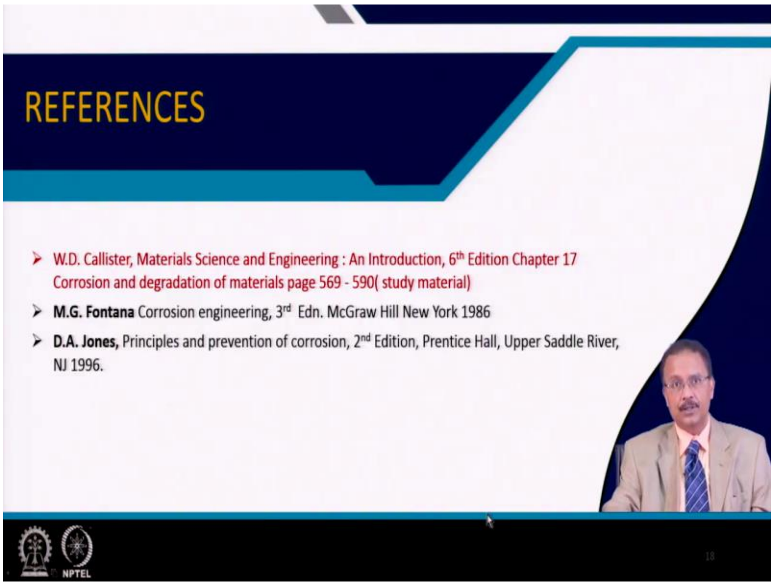

REFERENCES

- W.D. Callister, Materials Science and Engineering : An Introduction, 6th Edition Chapter 17 Corrosion and degradation of materials page 569 - 590(study material)
- **M.G. Fontana** Corrosion engineering, 3rd Edn. McGraw Hill New York 1986
- **D.A. Jones,** Principles and prevention of corrosion, 2nd Edition, Prentice Hall, Upper Saddle River, NJ 1996.

So, the study material is the book by Callister, chapter 17, corrosion and degradation of material and apart from that, the book by M G Fontana and D A Jones are also quite effective to know this principles.

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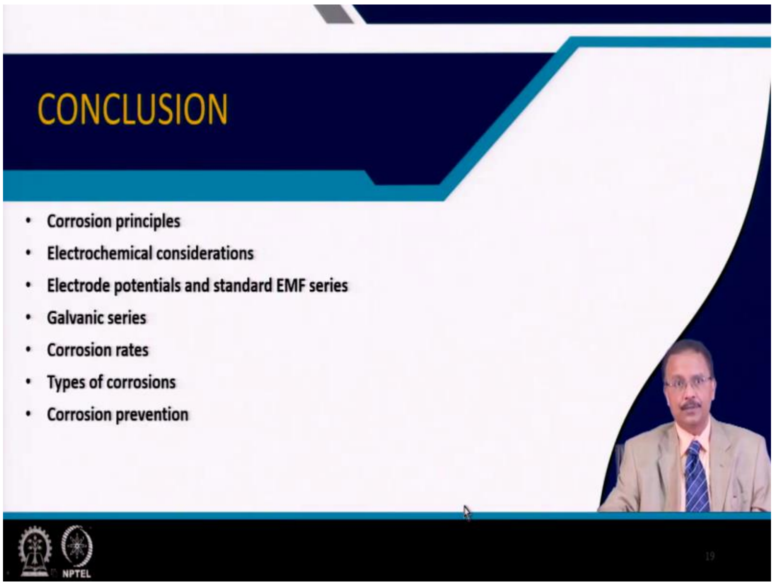

CONCLUSION

- Corrosion principles
- Electrochemical considerations
- Electrode potentials and standard EMF series
- Galvanic series
- Corrosion rates
- Types of corrosions
- Corrosion prevention

So, in this particular lecture, we talked about corrosion principles; then electrochemical considerations; then electro potentials and standard EMF series; then we introduced the galvanic series concept; then corrosion rate was described. Then types of corrosion, there are total eight types of corrosion we have briefly introduced and then finally, corrosion prevention in terms of this cathodic protection that was introduced.

Thank you for your attention.