Corrosion of Metals

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Course structure
Learning modules
1. Introduction to corrosion
2. Corrosion rate
3. Uniform corrosion
4. Galvanic corrosion
5. Crevice corrosion
6. Pitting corrosion
7. Intergranular corrosion
8. Stress corrosion cracking
9. Dealloying
10. Review
Module 1: Introduction
Module learning objectives
By the end of this module learners will be able to:

1. Describe the three possible behaviors of a metal in an aqueous (water based) solution
2. List the four requirements of an corrosion cell
3. Describe the anode and cathode reactions that occur in a corrosion cell
4. Describe the three forms of anode and cathode electrical contact
5. List four factors that influence the corrosion performance of a metal component
Metal behavior in an environment

**Immune**
- No reaction
- No corrosion

**Active**
- Metal dissolves
- Form non-protective corrosion products
- Corrosion products do not interfere with further corrosion

**Passive**
- Protective film formed
- Passive layer
- Slows reaction rate
- Corrosion resistance depends on integrity of passive layer
- Metal can become active if layer broken or dissolves
Several forms of corrosion

1. Uniform
2. Localized
   a. Galvanic
   b. Pitting
   c. Crevice
   d. Intergranular
   e. Stress corrosion cracking
   f. Dealloying

Other forms of corrosion
   Å Combination of corrosion and other degradation mechanisms
Corrosion and electrochemistry

Electrochemical reaction between one or more materials and environment

- Results in deterioration of the material

Course focus

- Corrosion of metals
- Aqueous environments (water based liquids)

- Electrochemical reaction
- Electrochemical cell
- Anode & cathode reactions
- Factors affecting corrosion
**Electrochemical reaction**

Chemical changes of metal and environment

Electrical charges flowing from metal to environment

Loss of electrons called oxidation

Gaining electrons called reduction

Electron (e^-) Becomes + charged ion

Corroding metal atom

Environment atom
**Oxidation reaction – lose electrons**

M $\rightarrow$ $M^{n+}$ + ne$^-$

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

Al $\rightarrow$ Al$^{3+}$ + 3e$^-$
**Electrochemical cell**

Electrical current flow as a result of transfer of electrons

- **Corrosion**
- **Oxidation reactions**

1. Conductive fluid in contact with anode and cathode
2. Contains corrosive species that reacts with anode to form metal ions
3. Provides ionic current path for metal ions created at anode

- **Electrical contact**
- **Reduction reactions**

**Diagram:**
- Anode
- Cathode
- Electrolyte
- Metal ions
**Reduction reactions at cathode**

6 possible reduction reactions

\[ 2H^+ + 2e^- \rightarrow H_2 \text{ (gas)} \]  
Hydrogen ion reduction in acid

\[ 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \]  
Water reduction in neutral or alkaline solutions

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]  
Oxygen reduction in aerated acid

\[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \]  
Oxygen reduction in aerated neutral and alkaline solutions

\[ Fe^{3+} + e^- \rightarrow Fe^{2+} \]  
Metal ion reduction

\[ Cu^{2+} + 2e^- \rightarrow Cu \]  
Metal deposition
Two paths for current

There are reduction reactions that result in formation of negative ions
- Ions move from cathode towards anode along ionic current path
- Current flow same as shown here

Electronic path (electrons)

Ionic current path (metal ions)

Current flow
Electrical contact in an electrochemical cell

Single piece of metal

Two metals in contact

Two metals not in direct contact but joined electrically
Preventing formation of electrochemical cells

Eliminate one of the four components

1. Anode
2. Cathode
3. Electrical contact
4. Electrolyte
Anode and cathode reactions

$\text{Zn} + 2\text{H}^+ \rightarrow \text{Zn}^{2+} + \text{H}_2 \text{ (gas)}$

$\text{Zn} \rightarrow \text{Zn}^{2+} + 2e^-$

$2\text{H}^+ + 2e^- \rightarrow \text{H}_2 \text{ (gas)}$
Corrosion products
Some corrosion reactions result in formation of corrosion product on metal surface.

Corrosion in water
- OH⁻ react with Mn⁺ from anode reaction
- Produce solid product

Corrosion of steel in water
- Fe²⁺ + 2OH⁻ → Fe(OH)₂
- 2Fe(OH)₂ + ½O₂ + H₂O → 2Fe(OH)₃
- Ferric hydroxide most common form of rust
Corrosion in many acids results in formation of corrosion product. Metal ions react with negative ions in acid.

\[ \text{Zn} + 2\text{HCl} \rightarrow \text{ZnCl}_2 + \text{H}_2 \text{ (gas)} \]

\[ \text{Zn} + \text{H}_2\text{SO}_4 \rightarrow \text{ZnSO}_4 + \text{H}_2 \text{ (gas)} \]

\[ \text{Fe} + 2\text{HCl} \rightarrow \text{FeCl}_2 + \text{H}_2 \text{ (gas)} \]
Anode

Solid Zinc

Hydrochloric acid (H⁺ and Cl⁻)

Cathode

Zn → Zn²⁺ + 2e⁻

Zn²⁺ + 2Cl⁻ → ZnCl₂

2H⁺ + 2e⁻ → H₂
Factors for corrosion performance of a metal component

1. Material
2. Environment
3. Stress
4. Geometry of item

Click each topic for more information

Click Next after reviewing each topic
Material
Corrosion performance of any metal depends on
  • Composition
  • Microstructure

Different metals have different inherent corrosion behaviors

Microscopic variations in composition can reduce corrosion resistance

Microstructure features
  • Grain size
  • Precipitates on grain boundaries
  • Non-metallic inclusions within grains
Environments vary with respect to factors that influence corrosion such as

- Moisture, temperature, chemical make-up, and pH

Corrosiveness depends on specific chemistry of environment and metal of concern

Understanding the environment is required to better understand the criteria for materials selection or corrosion prevention measures.
Other environment factors

Velocity of solution

Fluid flow through pipe

Agitation of fluid
State of stress

Mechanical stresses on a metal component or joint

Susceptibility to stress corrosion cracking increases as tensile stresses increase

Possible sources of stress
  - External
  - Residual stress that result from manufacturing processes
  - Differential thermal expansion
**Item geometry**

- Gaps between components
- Stress concentrators
- Features that retain liquid
Corrosion references – general

References – specific metals

End of module