Basics of Corrosion

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Topics to be Discussed ..

- Corrosion's Definition
- Corrosion Mechanism
- Corrosion & Environment
- Engineering Materials
- Forms of Corrosion
- Corrosion Control
- Open Discussion

Corrosion Definition

What is corrosion ?!

The deterioration of a metal or its properties because of a reaction with its environment (NACE).

Corrosion Affect You !

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Corrosion Costs !

Direct Costs …	Indirect Costs …
Excessive Maintenance	Safety
Replacement	Water
Loss of production / downtime	Consumer Confidence
Product contamination	Toxic Releases
Accidents	Structural Collapse
Capital costs	Appearance

Direct Losses > 300 $ Billion / Year in U.S.

$ 300 Billion = $ 300,000,000,000

3 % of Gross National Product of the U.S.

Corrosion Cost & Preventive Strategies in U.S., Sep 2001, FHWA

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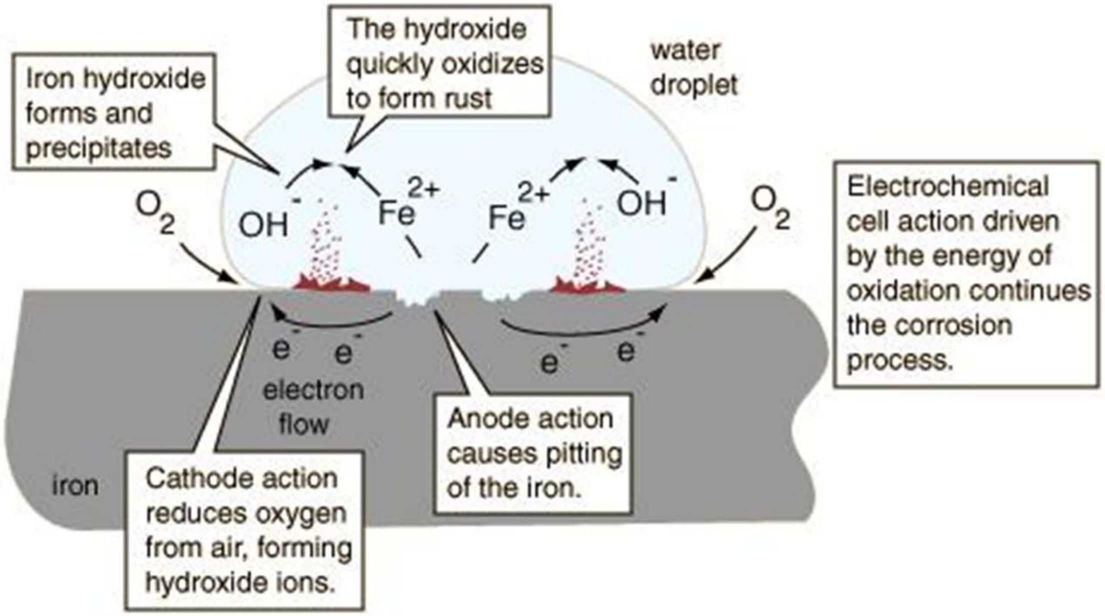
Corrosion Mechanism

Anode = Oxidation = Corrosion



Item	Function
Anode (Metal)	Oxidation: Fe to Fe^{+2}
Cathode (Metal)	Reduction: O_2 to OH^-
Water Droplet	Electrolyte

Galvanic Cell – Spontaneous

Corrosion Reactions

Anodic Reactions:

Generic:	M^0	$\longrightarrow$	$M^{n+} + n\,e^-$
Iron:	Fe	$\longrightarrow$	$Fe^{++} + 2\,e^-$
	Fe	$\longrightarrow$	$Fe^{+++} + 3\,e^-$
	Fe^{++}	$\longrightarrow$	$Fe^{+++} + e^-$
Aluminum:	Al	$\longrightarrow$	$Al^{+++} + 3\,e^-$

All anodic reactions make the metal more positive and produce electrons

Cathodic Reactions:

Generic: $R^+ + e^- \longrightarrow R^0$

- Hydrogen Reduction

$$2H^+ + 2e^- \longrightarrow H_2$$

- Oxygen Reduction

$$2\,H_2O + O_2 + 4e^- \longrightarrow 4\,(OH)^-$$

$$O_2 + 4\,H^+ + 4e^- \longrightarrow 2\,H_2O$$

All cathodic reactions make the metal more negative and consume electrons

Corrosion Reactions

4 Requirements .....

- Area that give up electrons

- Area that receives or consume electrons

Anode

Cathode

Electrolyte

Metallic Path

- Area that transport ions

- Area that transport electrons

Corrosion can be controlled by controlling one of the 4 requirements

Where is the Anode ?!

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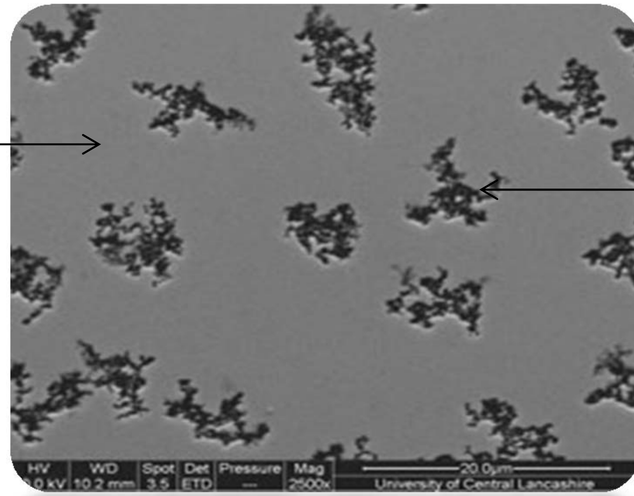

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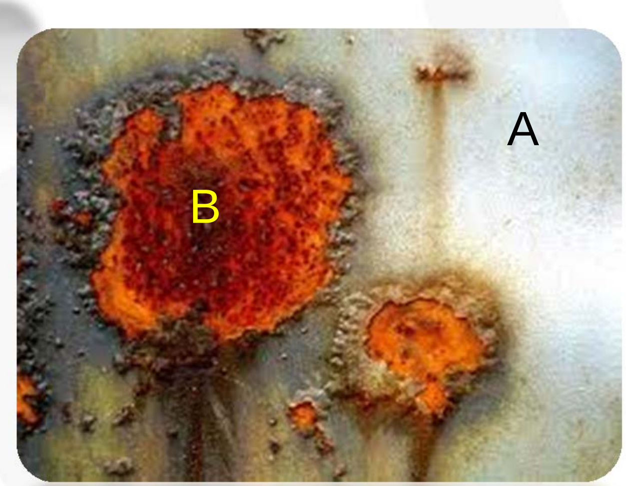
Corrosion Doctors



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Corrosion Potential

Facts

- Energy naturally flows from sites with high energy to sites with low energy.
- Thermodynamics can predict if corrosion will happen under specific conditions.
- Kinetics can predict the rate of corrosion reactions.
- A corrosion potential is made by comparing a metal site's voltage to a reference electrode's potential.
- Applying thermodynamics (Nernest Equation) & kinetics (Farady's law) will determine the corrosion rates.

RCS ROHRBACK COSASCO SYSTEMS

Metal Samples®

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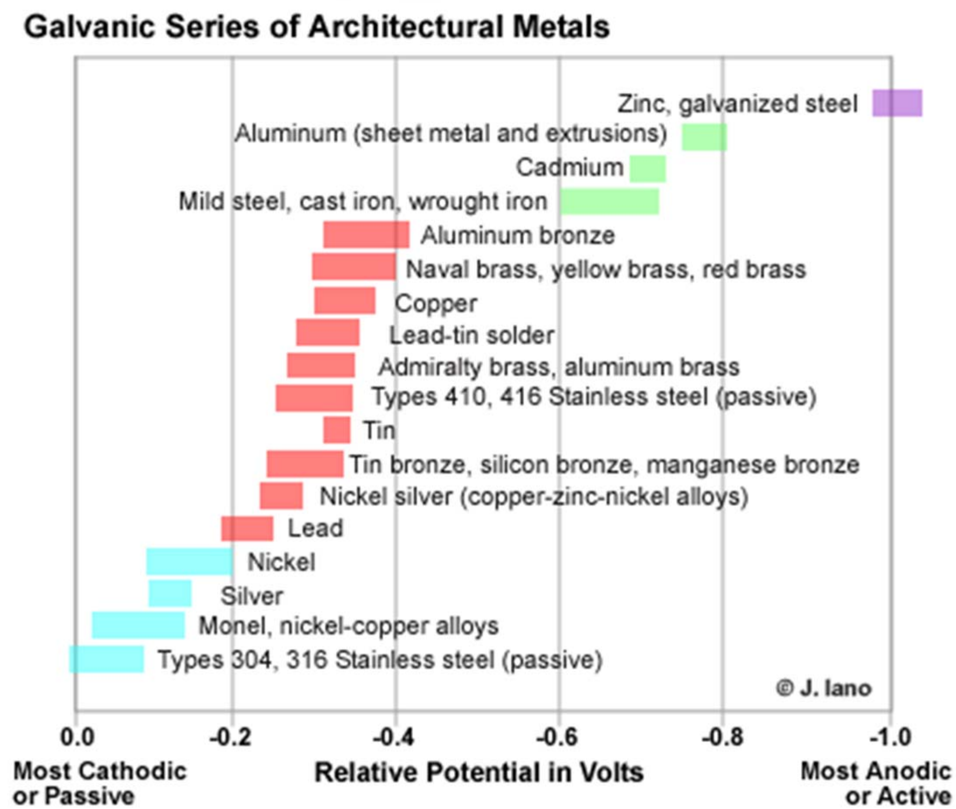
Galvanic Series

Table 1- The Galvanic Series of Metals

Cathodic — Least Active, High Potential

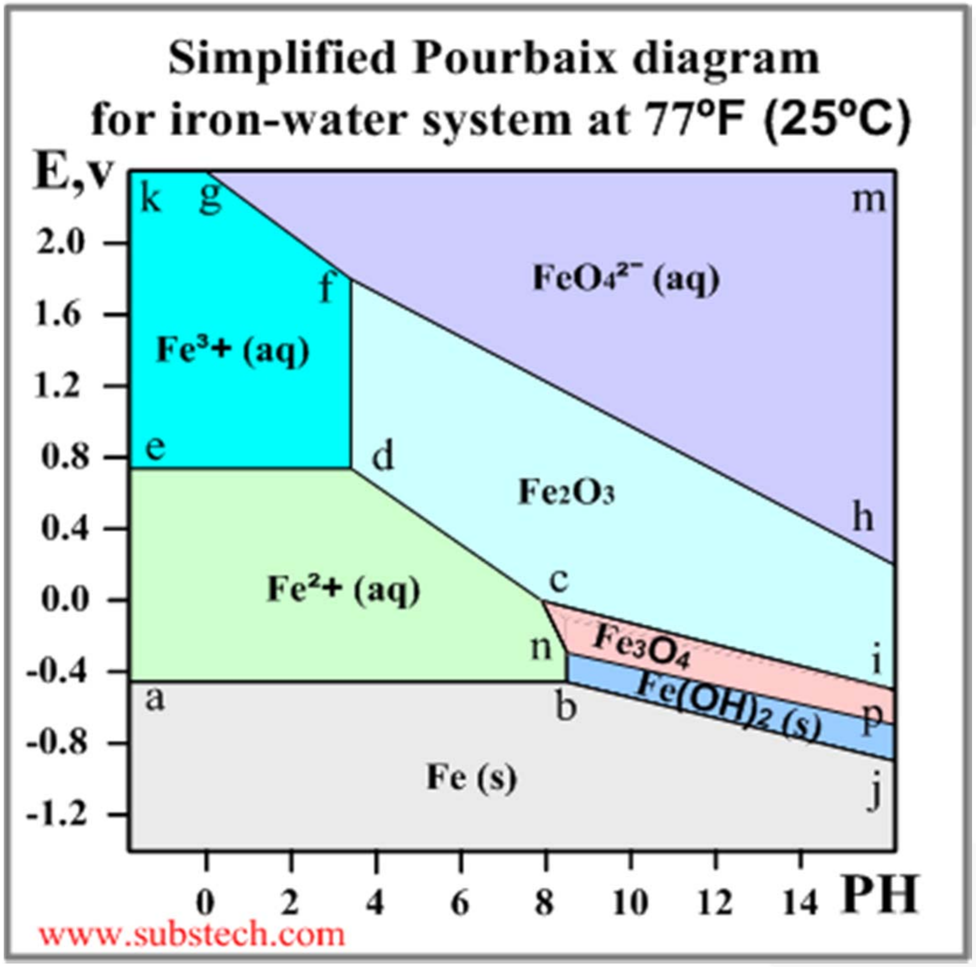
- Platinum
- Gold
- Carbon (graphite)
- Titanium
- Type 316 or 304 stainless steel (passive)
- Monel metal (70% nickel, 30% copper)
- Silver
- Nickel
- Lead
- Bronze, Copper, Brass
- Tin
- Lead/Tin solder
- Type 316 or 304 stainless steel (active)
- Cast Iron/Mild Steel
- Cadmium
- Aluminium
- Zinc
- Magnesium

Anodic — Most Active, Low Potential



Different for different environment

Pourbaix Diagrams



Benefits ….

- ➢ It is available for each metal
- ➢ Predicting stability of substances
- ➢ Consider potential & pH
- ➢ Predicts corrosion products
- ➢ Predicts stability of metal
- ➢ Evaluate effects of pH

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Passivity

What is Passivity ?!

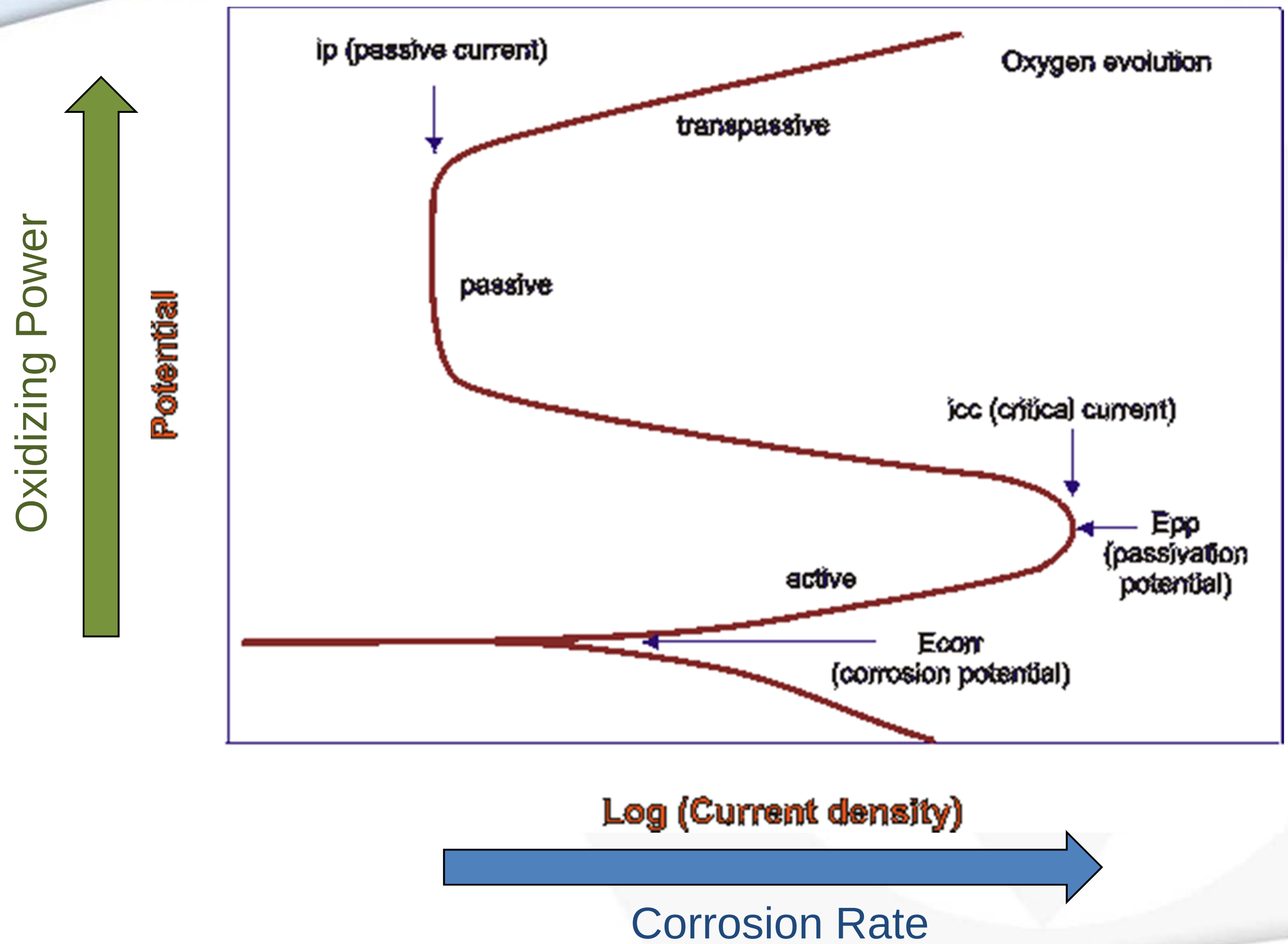
A relatively inactive state in which the metal displays a more noble behavior than thermodynamic conditions predict or simply defined as Formation of passive films of reaction products

Occur Naturally
- Stainless Steel
- Nickel Alloys
- Titanium

Formed Chemically or Electrochemically
- Corrosion Inhibitors
- Applied Current

→ **No Corrosion**

Passivity


Oxidizing Power
Potential
ip (passive current)
Oxygen evolution
transpassive
passive
icc (critical current)
Epp
(passivation
potential)
active
Ecorr
(corrosion potential)
Log (Current density)
Corrosion Rate

Environment

Major Types of Corrosive Environments

- Atmospheric
- Underground
- Liquid (Submerged)
- High Temperature

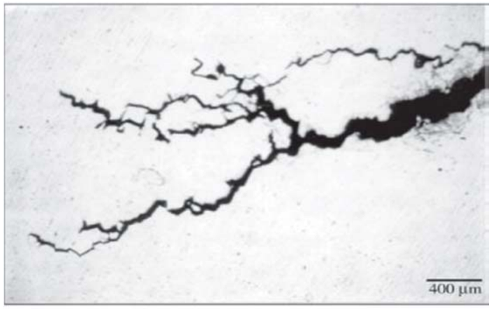
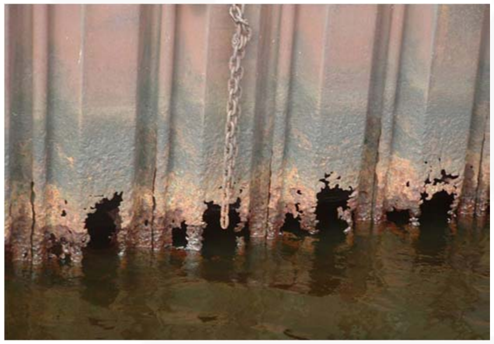


Figure 10. LME cracking of austenitic stainless steel by molten Zn.



Atmospheric Environment

Industrial Atmospheres	• Corrosive gases (SO_2,Nox, CO) • Solids & Soot
Marine Atmospheres	• Sea Salts (NaCl, MgCl2) • High Rltv. Humidity
Rural Atmospheres	• Dusts & corrosive gases (NH_3) • Temperature
Indoor Atmospheres	• Can be controlled • Some aggressive conditions

Can you give an example for each case? Let us do it !

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Underground Environment

Factors affect the corrosion underground …

- Physical Soil Characteristics (grain size & distru, Moisture retention)
- Chemical Soil Characteristics (pH, Water soluble salts, alkalinity)
- Moisture Content (1-100% is possible)
- Electrical Resistivity (ohm.cm, reciprocal of conductivity)
- Aeration (more oxygen)
- Bacteria (*Aerobic* – less problems, *Anaerobic* – more aggressive such as SRB)

Acidic pH → **More aeration** → **High conductivity** → **More bacteria** → **More Moisture** → Corrosion

Liquid Environment

Factors affect the corrosion in liquids …

- Physical configuration (surface smoothness, etc.)
- Chemical make-up (Dissolved solids, dissolved gases)
- Flow rate (new surfaces, destroying protective film)
- Temperature & pressure (more diffusion & dissolved gasses)
- Biological Organisms (Microbiological Influenced Corrosion – MIC)

Qurayyah Case ?!!

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High Temperature Corrosion

High Temperature Oxidation	High temperature Reduction
Oxidizing Atmosphere	Reducing Atmosphere
e- are lost	
Oxygen not necessary	In presence of reducing gases
Oxygen + Sulfur increases the rate (Sulfidation)	H_2, CO, CO_2

Factors should be in materials have oxide films:

- Physical Stability & low volatility (don't melt – don't boil)
- Maintenance of good mechanical integrity (don't crack)
- Slow growth kinetics (don't allow rapid corrosion)

Engineering Materials

Metals

Ceramics

Concrete

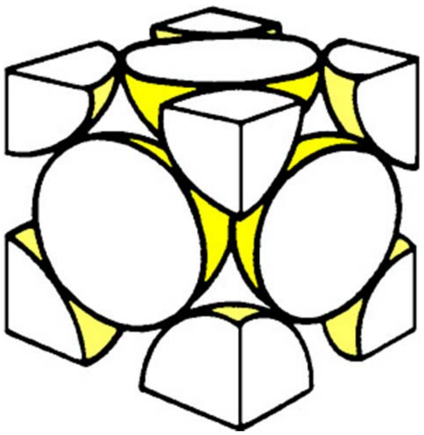
Elastomers

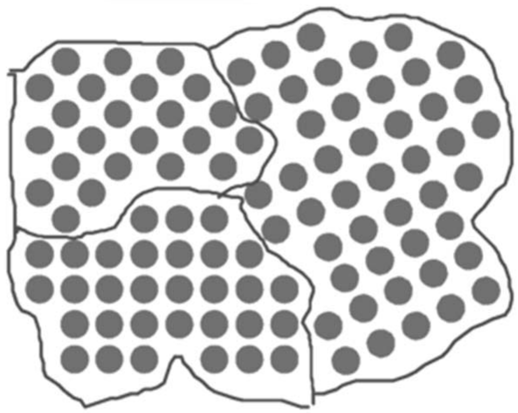
Plastics

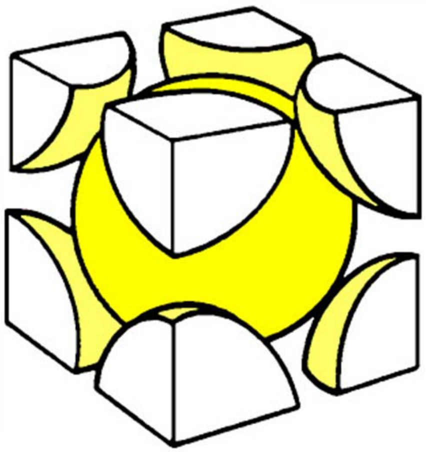
Metals Metallurgy Concepts

Crystalline Structure:

- Repeating pattern of atoms called Unit Cells (Crystals = Grains)
- In each grain the crystal structure is fairly uniform (0.025 – 0.25 mm)
- Grain boundaries is area of disorder (less purity – Imperfection)







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Metals Metallurgy Concepts

Alloys:

- Mixture of two or more metals, 2 types: Solid Solution, Multiphase
- Solidification by slow cooling produces large grains
- Solidification by fast cooling produces large grains

Solid Solution Alloys

- Two solid metals
- Properties related to mixture
- Uniform structure
- Brass

Multiphase Alloys

- Insolubility of metals
- Properties depends on phases
- Phase diagrams show phase changes
- Cast Iron

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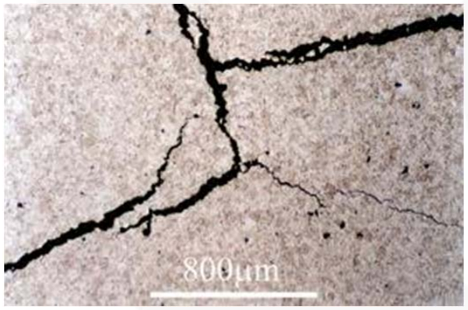
Metallurgy Cells

Quenching Problems:

- Stresses may be produced during quenching which will produce corrosion cells
- Non-uniform structures may produce corrosion cells caused by non-uniform cooling rates
- Some of the problems can be corrected by heat treatment after quenching.



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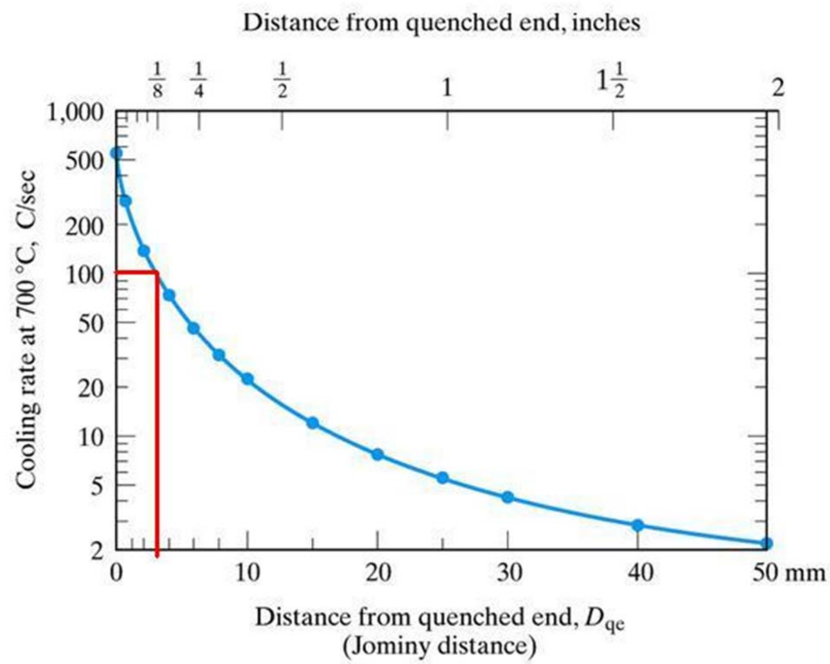
Metallurgy Cells

Causes of Metallurgy Cells:

- Stressed areas
- Imperfections & impurities
- Alloy additions
- Unequal Cooling rates
- welding

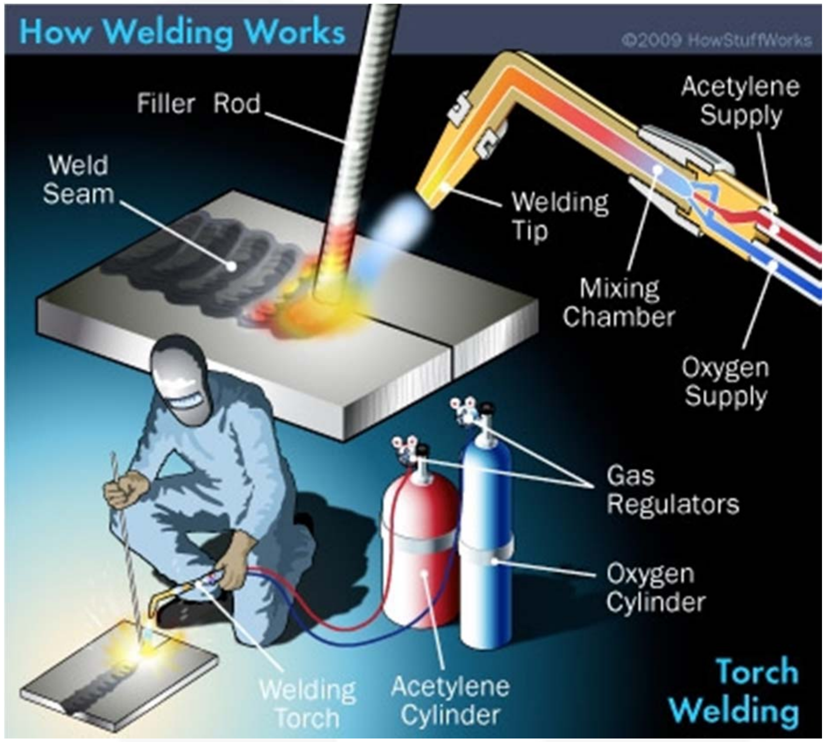


The cooling rate for the Jominy bar varies along its length. This curve applies to virtually all carbon and low-alloy steels.

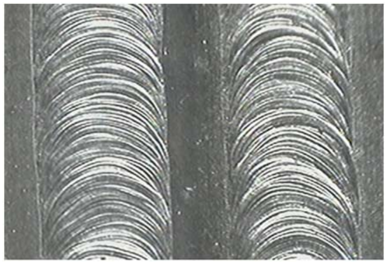
Welding

Welding Benefits:

- Low cost solution
- High strength
- High corrosion resistance
- Wide range of materials (Filler Rod)
- Some materials are unweldable



How you can avoid corrosion due to welding & cutting?



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Carbon & Low Allow Steel (CS)

- Inexpensive & available materials
- Wide range of properties
- Weldable
- Commonly 0.2% Carbon
- Tensile strength range 40 – 200 ksi (275-1,400 Mpa)
- Few % of alloying elements (Cr, Ni, Cu, Mo, P, V)
- Similar corrosion resistance & some additions improve it

Cast Iron (CI)

- Higher Carbon content 2 – 4%, in the form of graphite
- Low cost of castings
- Relatively brittle
- Has six types

Gray CI	Malleable CI	White CI	Ductile CI	High Silicon CI	Alloy CI
• Carbon as Flakes • Brittle	• Carbon as rosettes • Less brittle than gray	• Carbon as Iron carbide • Hard & brittle • Not weldable	• Carbon as spheroids • Ductile	• Highly corrosion resistant • Used as anodes in CP • Si > 14%	• Ni resistant – pumps & turbines • Ni hard – erosion resistant

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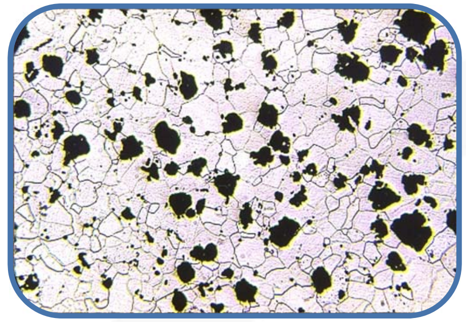
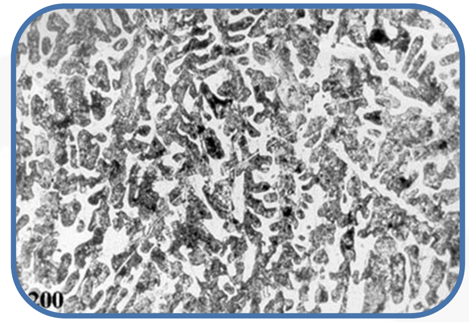
Cast Iron (CI)

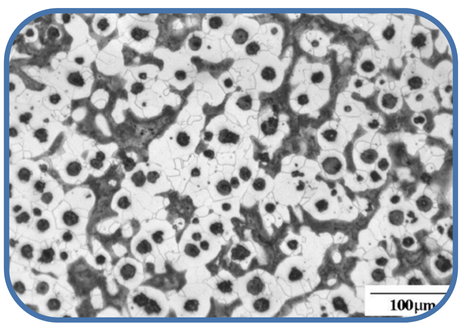
Gray CI



Malleable CI



White CI



Ductile CI

High Silicon CI

Alloy CI

Cast Iron (CI)

Cast Iron Corrosion

- Atmospheric corrosion is slower than Carbon steel
- De-alloying corrosion is possible & also graphitization

Brittle Failure

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Copper Alloys

Copper Alloy Benefits

- Good corrosion resistance
- High heat & electrical conductivity
- Good mechanical properties – ductility
- Can form passive films in aqueous environments
- Wide range of alloys in a variety of applications

Brass: copper-zinc alloys

Bronze: copper-tin alloys

Principle : Always use UNS & ASTM numbers for alloys, No common names

Copper Alloys

99% Cu *C11000 Copper*	90% Cu, 10% Zn *C22000 Commercial Bronze*	Cu, Sn, Pb, Zn *C23000 Red Brass*
70% Cu, 30% Zn *C26000 Cartrige Brass*	60% Cu, 40% Zn *C28000 Muntz Metal*	Cu, Zn, Pb, Fe *C38500 Architectural Bronze*
Cu, Zn, Si *C65500 Silicon Bronze*	Cu, Zn = Ni *C74500 Nickel Silver*	Cu, Ni *C70600 Copper Nickel*

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Copper Alloys

Technical Points

- Copper corrodes in the presence of oxidants such as Nitric acid, hydrogen peroxide .. etc.
- Copper alloys are generally subject to erosion-corrosion in high velocity flow conditions.
- Poor resistance to CO_2, acids, chlorides, sulfides and ammonia compounds.
- Patina: a thin protective layer of corrosion products.

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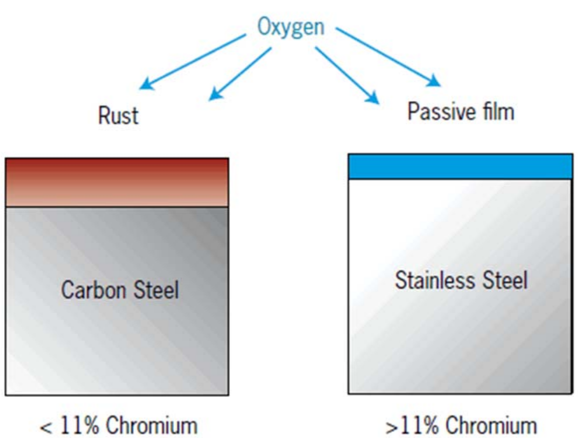
Stainless Steel

Stainless Steel Benefits

- Highly corrosion resistant in specific environments
- Forms passive films of chromium oxide
- Corrosion resistance depends on passive film stability
- Alloying elements increases passive film stability (Mo, Ni)
- Wide range of alloys in a many applications (families & groups)



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Stainless Steel Groups

Martensitic SS

- AISI 400 series
- 12-17% Cr
- Moderate corrosion resistance
- Weldable
- Used for valves, cutlery

Magnetic

Ferritic SS

- AISI 400 series
- 12-30% Cr
- Better corrosion resistance
- Resistance to Cl stress cracking
- Difficult to weld
- Used for furnace parts, exhaust systems

Magnetic

Austenitic SS

- AISI 200 & 300
- 17-25% Cr + 9-10% Ni
- 200 use Mn partially of Ni %
- High corrosion resistance (Ni)
- Mo addition is good for Sea water
- Weldable

Nonmagnetic

Duplex SS

- 20-30% Cr + 3-10% Ni + 1-5% Mo
- High corrosion resistance
- Resistance to Cl stress cracking
- Good ductility & high strength
- Used for marine tanks, heat exchangers

Magnetic

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Nickel Alloys

Nickel Alloys

- Highly corrosion resistant
- Corrosion resistance depends on alloy & environment
- Resistant to alkaline environments
- Highly resistant to pitting & crevice corrosion
- Must be carefully selected & specified
- Not universally immune

Aluminum Alloys

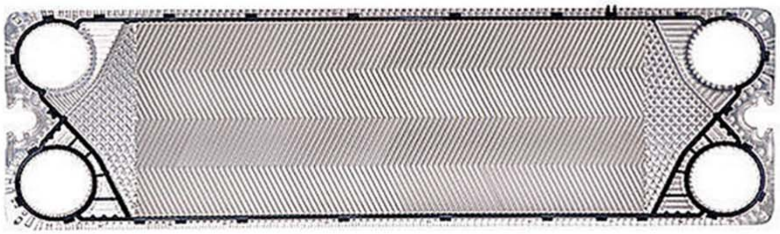
Aluminum Alloys

- Used for low weight applications
- Reactive metal (Amphoteric metal)
- Corrosion resistance due to passive film (Al_2O_3)
- Exfoliation problems
- Stable in neutral solutions & oxidizing acids (why?!)
- Unstable in acids, alkaline & Cl solutions.

Titanium & Its Alloys

Titanium & Its Alloys

- Reactive metal
- High Corrosion resistance due to passive film (TiO_2)
- Low weight, high strength, high strength to weight ratio
- Difficult to form & fabricate
- Very stable & resistant to chloride, chlorine & sea water.



Forms of Corrosion

Forms of Corrosion

There are 16 types of Corrosion !!!

Corrosion Types	
General Corrosion	Corrosion Fatigue
Pitting Corrosion (Localized)	Erosion corrosion
Crevice Corrosion (Localized)	Impingement Corrosion
Filiform Corrosion (Localized)	Cavitation Corrosion
Galvanic Corrosion	Intergranular Corrosion
Stress Corrosion Cracking (Environ)	Dealloying Corrosion
Hydrogen Induced Cracking (Environ)	Fretting Corrosion
Liquid Metal embrittlement (Environ)	High-temperature Corrosion

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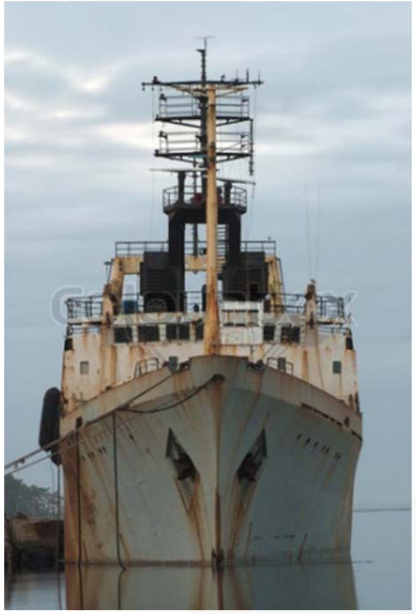
Forms of Corrosion

Principle:

More than one form of corrosion can, and usually dose, occur within a system, even on a single alloy at different points



General Corrosion

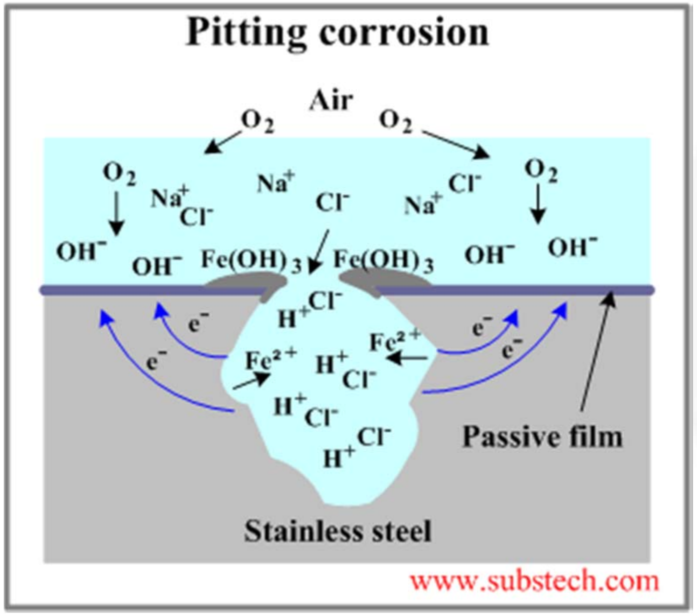
- It is a corrosion that proceeds more or less uniformity over the entire exposed surface.
- It is forming anodic & cathodic sites

General corrosion - Structural steel I-beam support

Pitting Corrosion

- It is a form of localized corrosion appears as deep narrow attack & rapid penetration.
- Interior is anodic, exterior is cathodic.

QCCPP Story ?!



Pitting Corrosion

Performance of Metals & Alloys

- Aluminum alloys (Halides)
- Stainless Steel (Chlorides)
- Copper alloys (NH_3, Hot O_2 water, Soft water, Sulfides, oxidizing acids)
- Carbon Steel

What are the solutions ?!

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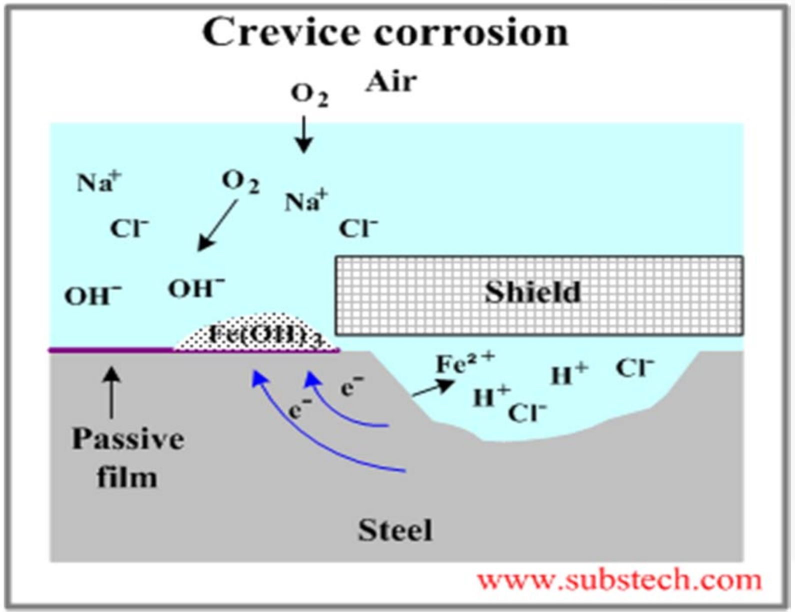
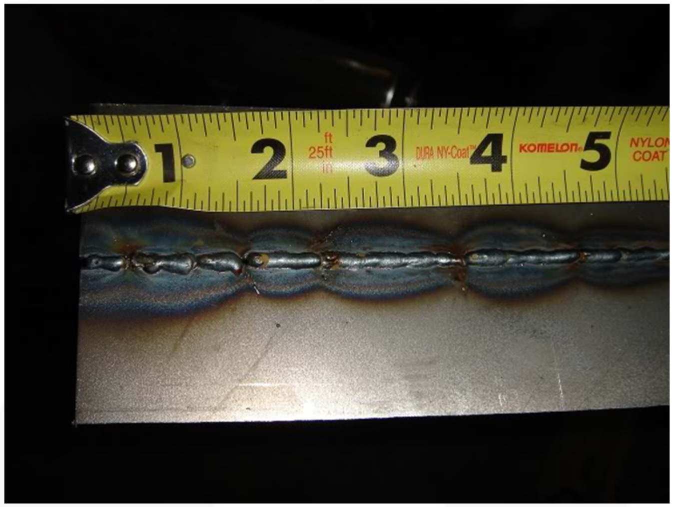
Crevice Corrosion

- It is a localized attack that occurs in areas where access to surrounding environment is restricted
- Crevices: Metal-to-Metal, Metal-to-nonmetal, deposits of depris or corrosion products
- Anodic sites will be concentrated in the crevice.



Crevice Corrosion

- Crevice corrosion is initiating *under deposit attack*.
- Most metals could face this problem
- Materials selection is very important
- Eliminate crevices during design
- Cathodic protection reduces its effects
- Avoid skip welds & provide drainage.
- Use seal joints



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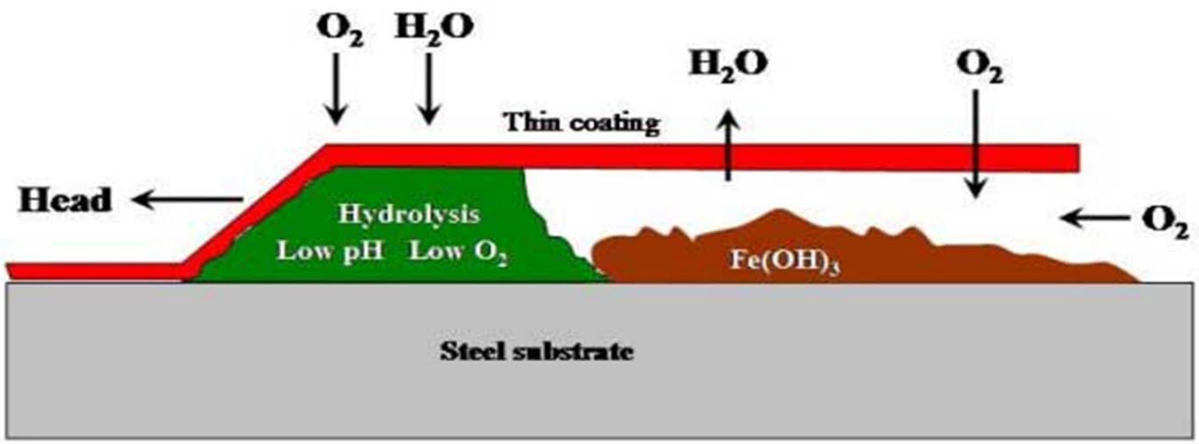
Filiform Corrosion

- It is a special localized corrosion occurring beneath a metallic or organic coating (*Corrosion Under coating*)
- Driven by potential difference between head of attack and area behind (*oxygen concentration cell*)
- Associated with surface contamination (*coating quality & selectivity*).



Cross sectional view of a corrosion filament on a steel substrate

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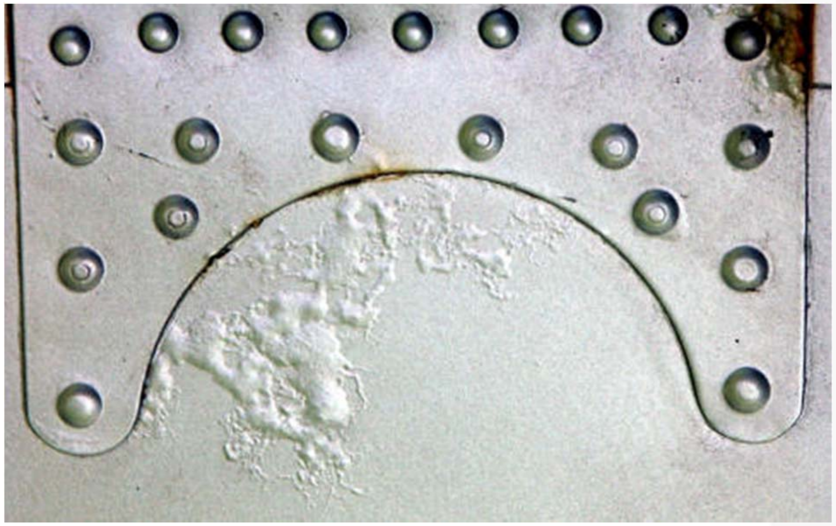
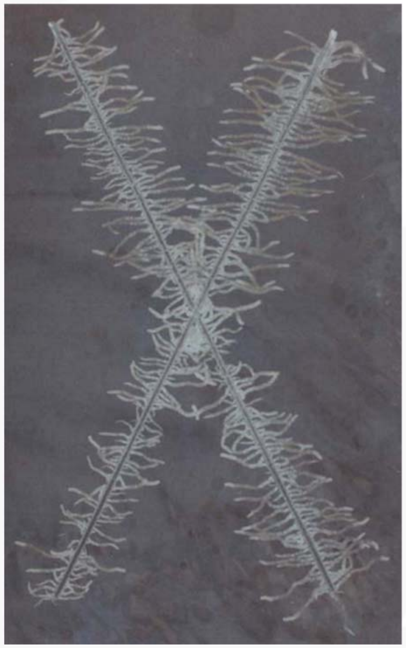
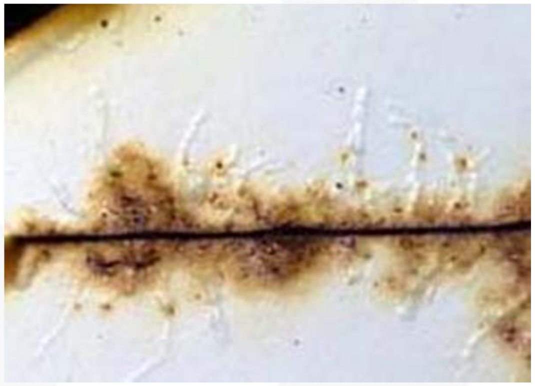
Filiform Corrosion

Solutions

- Proper surface preparation (ex. Sand blasting)
- Clean & dry surfaces for coatings

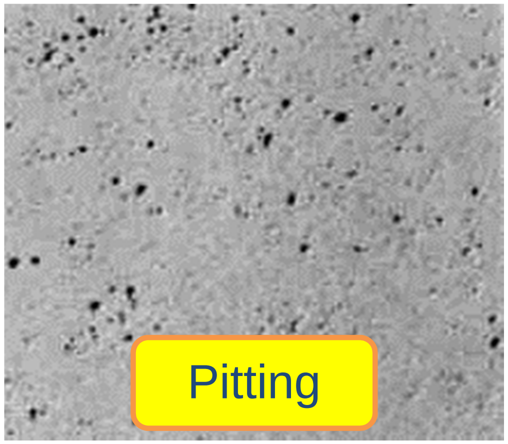


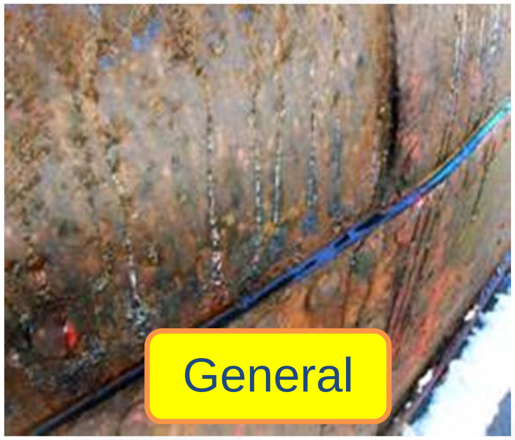




Which corrosion is that?

1- General Corrosion	2- Pitting Corrosion
3- Crevice corrosion	4- Filiform Corrosion





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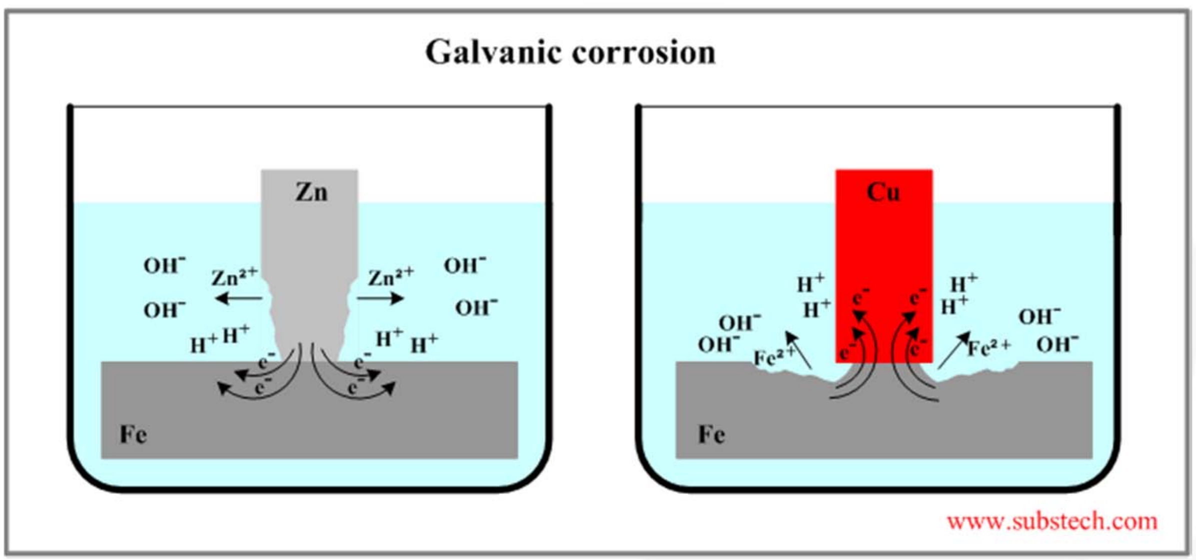
Galvanic Corrosion

- It is a classical electrochemical cell.
- Corrosion accelerated by the potential differences between metals when they are in electrical contact and exposed to electrolyte (*Atmosphere or immersion*).



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Galvanic Corrosion

Anode Effects

- Corrosion accelerated
- Different forms of attack

Cathode Effects

- Corrosion reduced
- Hydrogen effects

Affected by …

- Nature of the Environment
- Potential difference (metals)
- Resistivity of electrolyte

Why ?!

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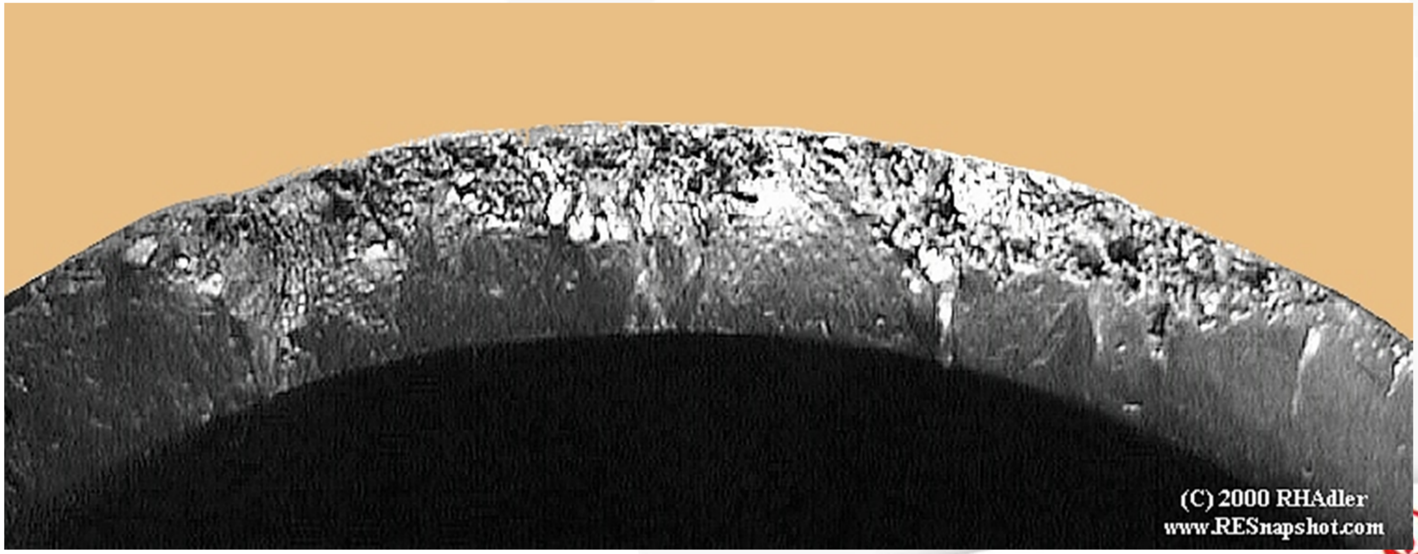
Corrosion Fatigue

- It is a fatigue in a corrosive environment. It is the mechanical degradation of a material under the joint action of corrosion and cyclic loading. Nearly all engineering structures experience some form of alternating stress, and are exposed to harmful environments during their service life.



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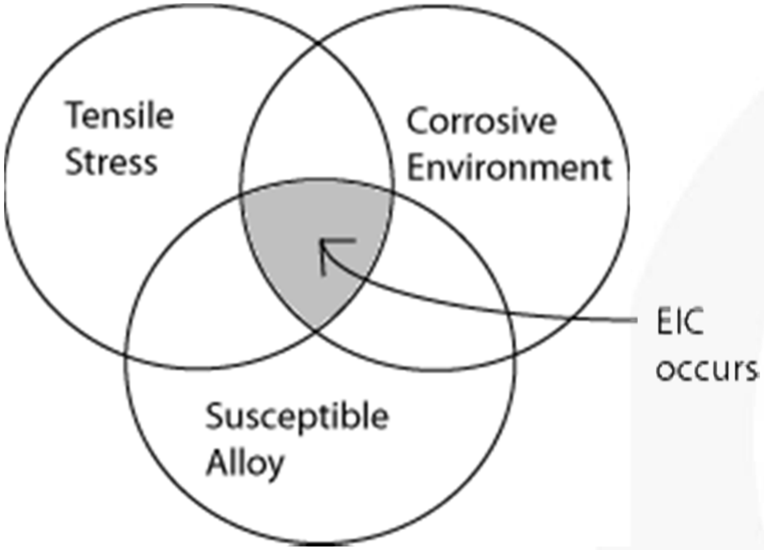
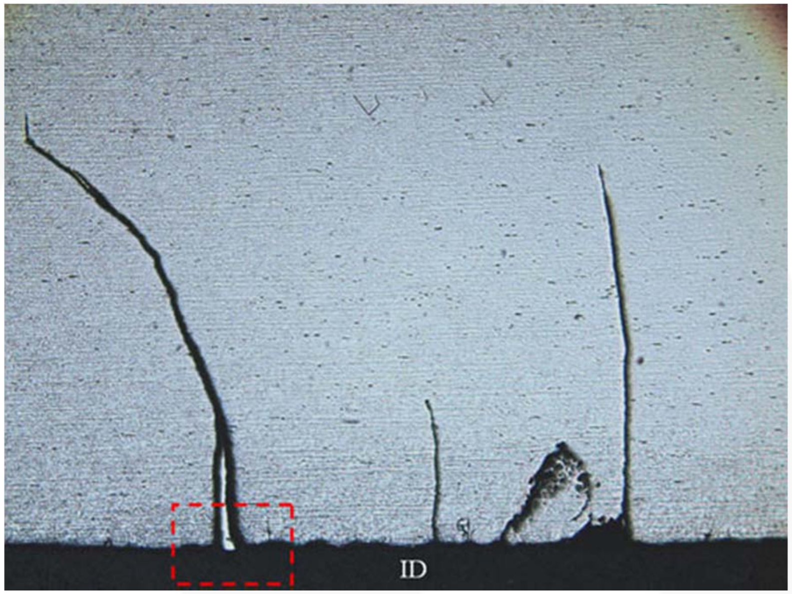
Corrosion Fatigue





Erosion Corrosion

- **Erosion corrosion** is a degradation of material surface due to mechanical action, often by impinging liquid, abrasion by a slurry, particles suspended in fast flowing liquid or gas, bubbles or droplets, cavitation, etc.

Called in some cases: Flow assisted corrosion

It is the most common case for Cupper tube failure

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Erosion Corrosion

Brass pump

Brass tube

Erosion Corrosion

The recommended maximum velocity for water in a copper tube system is 5 - 8 feet per second (1.5 – 2.4 m/s) for cold water systems,

&

4 - 5 fps (1.2 – 1.5 m/s) for hot water systems <u>< 140º F</u>, and 2-3 fps (0.61 – 0.91 m/s) for hot water systems with a temperature greater than <u>140º F</u>.

Erosion Corrosion damages even noble metals … as Titanium, Monel, Stainless Steel

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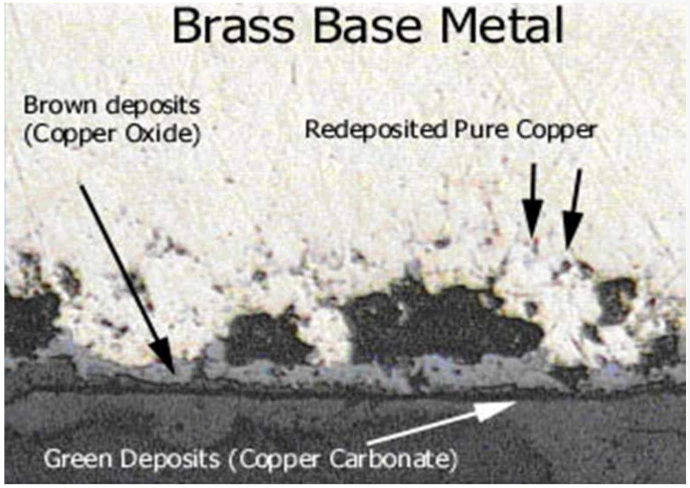
De-Alloying Corrosion

Called also: **Selective leaching**

- It is selective removal of one element from an alloy by corrosion processes. A common example is the dezincification of unstabilized brass, whereby a weakened, porous copper structure is produced.



Dezincification

Graphitization

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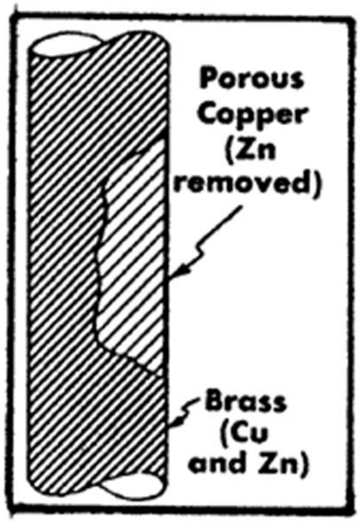
De-Alloying Corrosion

- Active metal selectively removed (corroded)
- Less active metal is residue
- It is known in brass, copper-zinc alloys (*dezincification*)
- Bronze is subjected to the selective removal of tin (*destanification*)
- Aluminum bronze is subjected to *dealuminification*
- Cast Iron is subjected to *graphitization*



Methods of Corrosion Control

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Corrosion Science

Call Mohammed, Asaad, Ahmed … don’t be late

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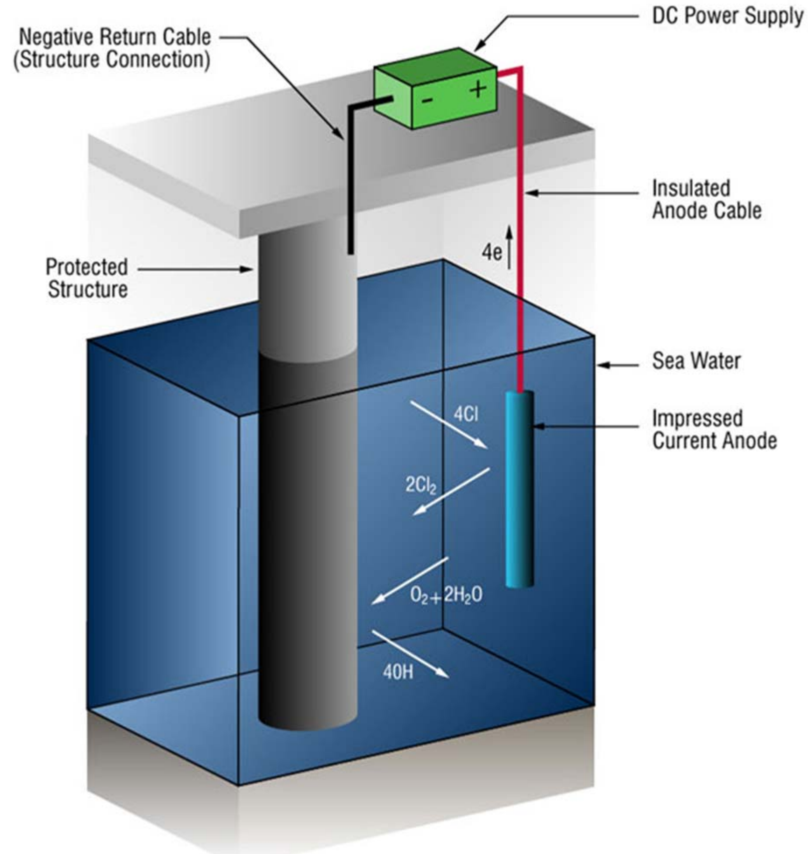
Methods of Corrosion Control

- Design Parameters
- Materials Selection
- Modification of Environment
- Chemical Solutions
- Cathodic Protection
- Protective Coating



Design Parameters

- Materials Selection during design
- Understanding process parameters (chemistry, T, P, velocity ..)
- Construction Parameters (welding)
- Dissimilar Metals
- Avoid crevices (skip welds)
- Geometry for drain (avoid stagnancy & accumulation)
- Using coating materials for some parts

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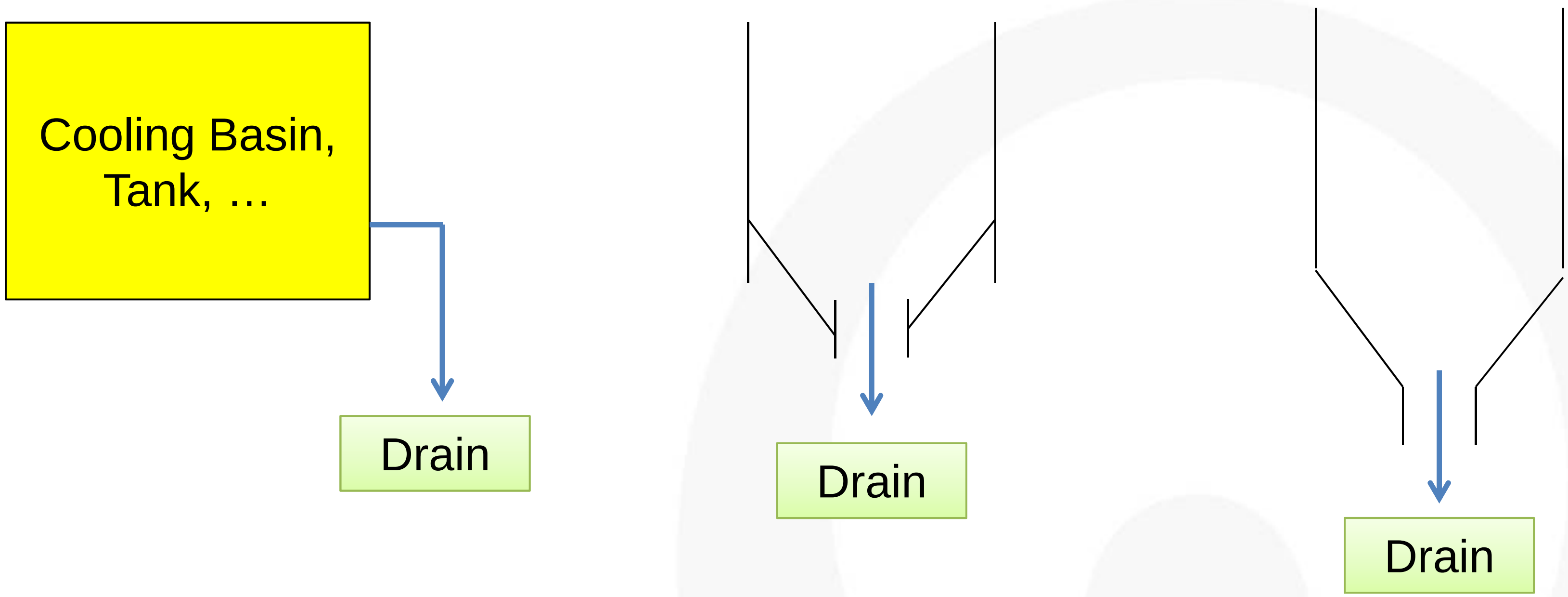
Design Parameters



What is the best design ?!

Cathodic Protection

Chemical Solutions

- Corrosion Inhibitors
- Dispersants
- Biocides
- Coating Materials

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Thank You

Questions ?!