Strengthening
&
Corrosion in Metals

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Content

- ✓ Strengthening Mechanisms in Metals
- ✓ Corrosion in metals
- ✓ Corrosion types & prevention

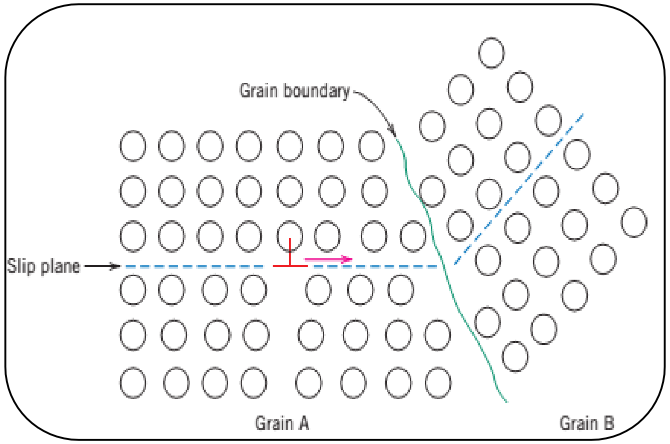
Strengthening Mechanism in Metals

- The ability of a metal to **plastically deform** depends on the ability of **dislocations** to **move**.
- Thus restricting or **hindering dislocation** motion makes a material **harder and stronger**.
- Some mechanism to strengthen metals are as follows:
  - ✓ Grain size reduction
  - ✓ Solid-solution strengthening
  - ✓ Strain hardening

Grain size reduction

- Grain boundary acts as a barrier for dislocations for two reasons:-
  - ✓ **Mis-orientation** : Difficult for a dislocation to pass into another grain, especially if it is more misaligned.
  - ✓ **Atomic disorder** Near/within a grain boundary region leads to discontinuity of slip planes from one grain into the other.

- A **fine-grained** material (one that has small grains) is **harder** and **stronger** than **coarse grained**, due to **greater** total **grain boundary area** to restrict dislocation motion.



Hall-Petch relation showing dependence of Yield strength (σ_y) on average grain diameter (d) as

$$\boxed{\sigma_y = \sigma_o + k_y d^{-1/2}}$$

$where, \sigma_o$ & k_y are constant for particular material

Heat treatment after plastic deformation and changing the rate of solidification are the ways to alter grain size.

Reference: W.D Callister, 7 Ed.

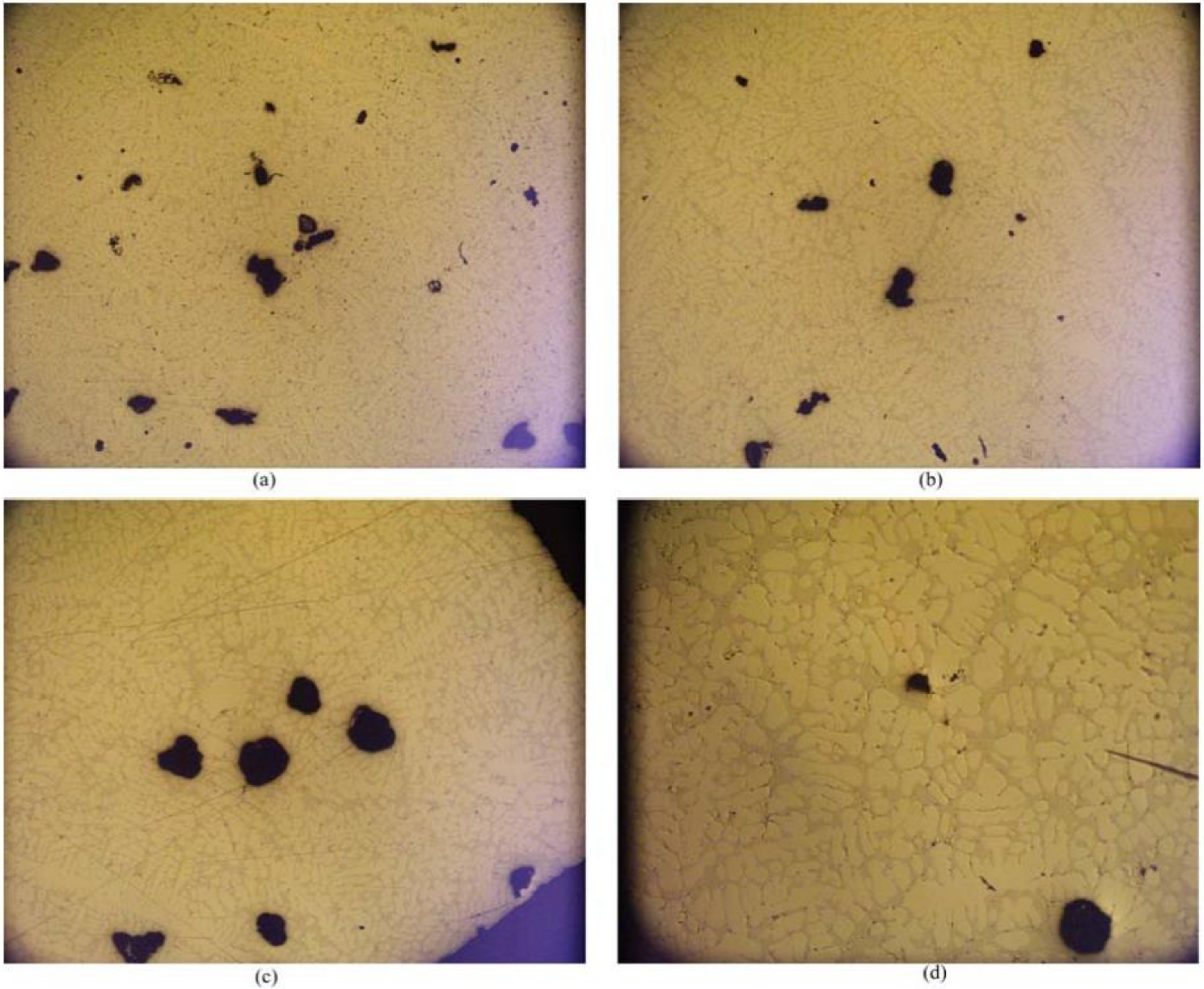
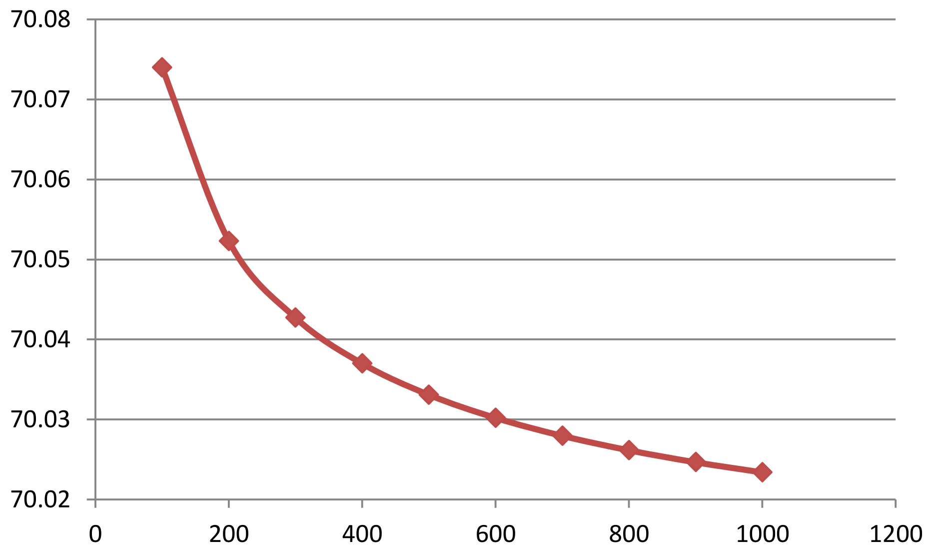


Figure 1: 50x Photomicrographs of A356 Samples with Solidification Rates (a) 6.2°C/sec, (b) 3.8°C/sec, (c) 2.0°C/sec and (d) 0.2°C/sec

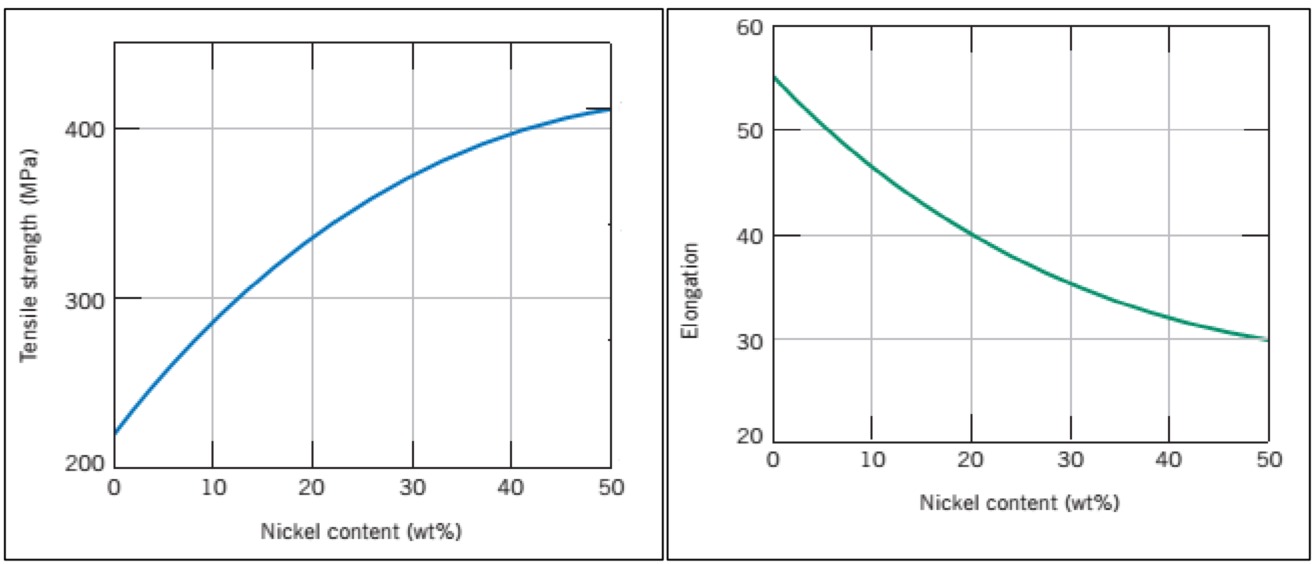
Hall–Petch constants		
Material	σ_o [MPa]	k [MPa $m^{1/2}$]
Copper	25	0.11
Titanium	80	0.40
Mild steel	70	0.74
Ni_3Al	300	1.70



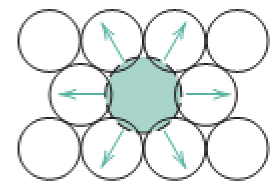
Change of Strength with Grain Diameter in Mild Steel

Solid Solution Strengthening

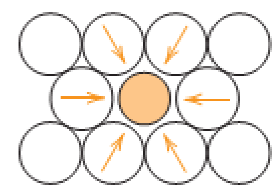
- Pure metals are almost always softer than their alloys.
- Adding another element that goes into interstitial or substitutional positions in a solution increases strength.
- The impurity atoms cause lattice strain which can "anchor" dislocations.
- Thus, Alloys are stronger than pure metals.



Effect: *Nickel added as an alloy in Copper*



Compressive Strain imposed on host atoms by larger impurity atom



Tensile strain imposed on host atoms by smaller impurity atom.

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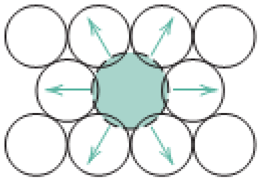
Reference: W.D Callister, 7 Ed.

Strain hardening

- Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed.
- It is also called as **Work hardening / Cold working** because temperature at which deformation takes place is lower than melting temperature.

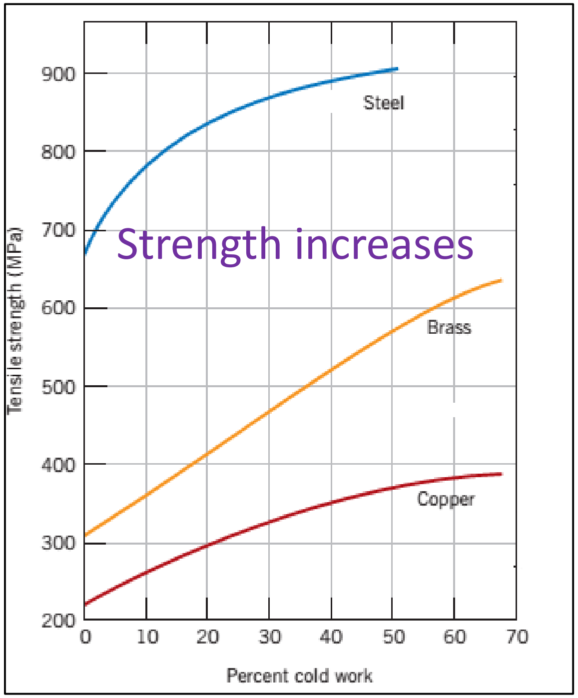
$$\% \, Cold \; working = \left(\frac{A_o - A_d}{A_o}\right) \text{x } 100$$

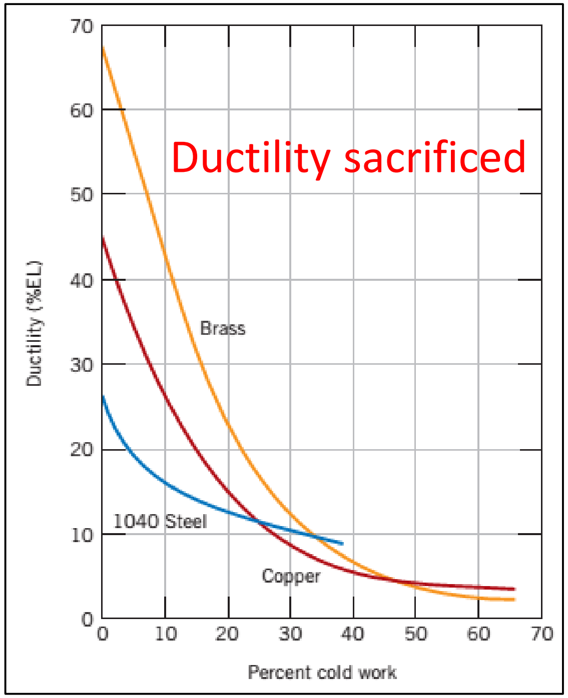
A_o = Original area
A_d = Deformed area



Strain imposed on nearby atoms

The effects of strain hardening may be removed by annealing heat treatment (slow heating & slow cooling).





Reference: W.D Callister, 7 Ed.

Summary of Strengthening mechanisms

- **Refining grain boundaries** - Serve as barriers to dislocation motion; thus refining the grain size of a polycrystalline material renders it harder and stronger.
- **Solid - solution strengthening** - Results from lattice strain interactions between impurity atoms and dislocations.
- **Strain hardening** - Enhancement of strength with increased plastic deformation.

Precipitation/Age hardening

- Technique used to increase the yield strength of **malleable materials** like Al-Cu alloys, stainless steels, etc.
- Based on changes in solid solubility with temperature to produce fine particles of an impurity phase, which blocks the movement of dislocations in a crystal's lattice.
- Alloys must be kept at elevated temperature for ***hours*** to allow precipitation to take place. This time delay is called **aging.**

Corrosion of Metals

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Corrosion

- **Corrosion** is defined as the **destructive** and **deteriorative loss** of a metal which is **electrochemical** in nature and ordinarily **begins** at the **surface**.
- The material loss takes place either by
  - ✓ Dissolution
  - ✓ Formation of scale or a film (*oxidation*)
- It is estimated that approximately 5% of an industrialized nation's income is spent on:-
  - ✓ Corrosion prevention
  - ✓ Maintenance or replacement of products lost or contaminated

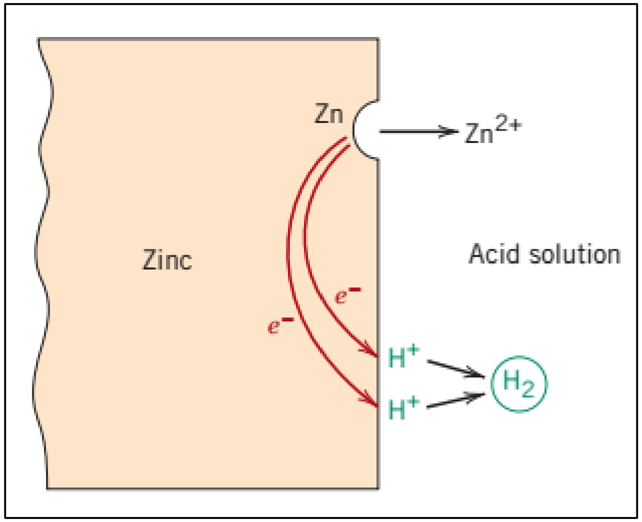
Electrochemical Reaction

- **Oxidation** (anodic) **reaction**: Metals have free electrons which they give-up.
- **Reduction** (cathodic) **reaction**: Electrons transferred to another chemical species.

Oxidation reaction $$Zn \longrightarrow Zn^{2+} + 2e^-$$

Reduction reaction $$2H^+ + 2e^- \longrightarrow H_2\,(\text{gas})$$

$$Zn + 2H^+ \longrightarrow Zn^{2+} + H_2\,(\text{gas})$$



Corrosion of Zinc in an acid solution

Reference: W.D Callister, 7 Ed.

When does the oxidation of the material provide a protective layer?

Pilling - Bedworth ratio, $PB = \dfrac{\text{Volume of the oxide formed}}{\text{Volume of metal consumed in the oxidation}}$

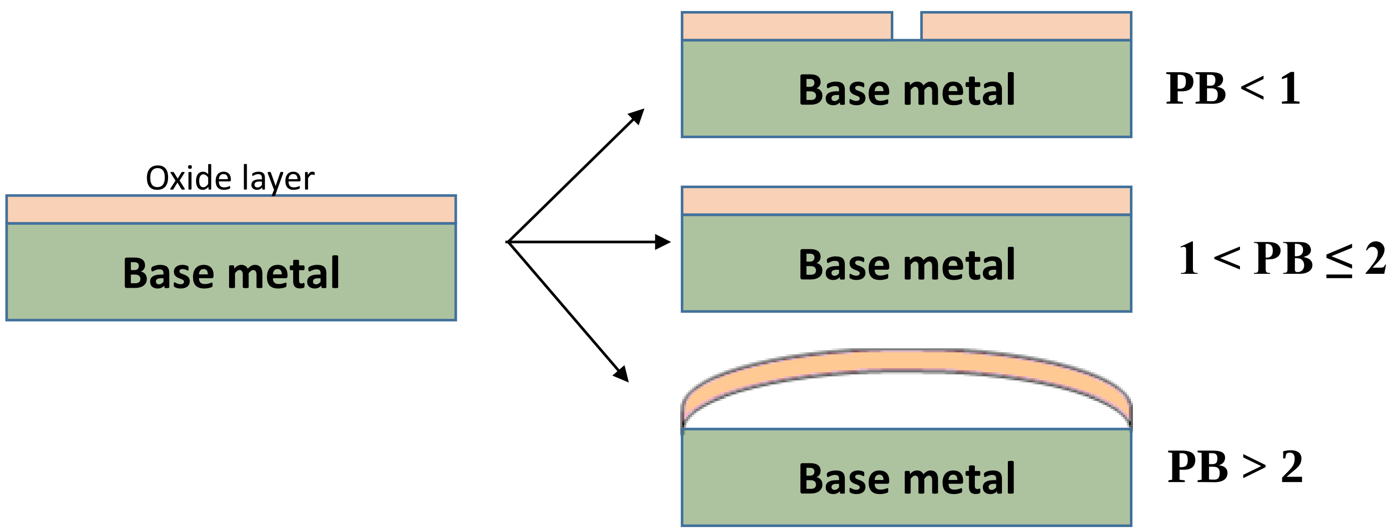
For good oxidation resistance the oxide should be adherent to the surface.

PB < 1 : Tensile stresses in oxide film → brittle oxide cracks & thus **un-protective**.

1 < PB ≤ 2 : Compressive stresses in oxide film → uniformly over metal surface, thus **protective**.

PB > 2 : High compressive stresses in oxide film → oxide cracks & flakes off, **un-protective.**

Oxide	PB Ratio
K_2O	0.41
Na_2O	0.58
MgO	0.79
Al_2O_3	**1.38**
NiO	1.60
Cu_2O	1.71
Cr_2O_3	**2.00**
Fe_2O_3	2.16



Galvanic Series

Ranks the **reactivity** of metals in **sea water**

Susceptibility to corrosion reduces

Increasingly inert (cathodic)

Platinum
Gold
Graphite
Titanium
Silver
316 Stainless steel (passive)
304 Stainless steel (passive)
Inconel (80Ni–13Cr–7Fe) (passive)
Nickel (passive)
Monel (70Ni–30Cu)
Copper–nickel alloys
Bronzes (Cu–Sn alloys)
Copper
Brasses (Cu–Zn alloys)
Inconel (active)
Nickel (active)
Tin
Lead
316 Stainless steel (active)
304 Stainless steel (active)
Cast iron
Iron and steel
Aluminum alloys
Cadmium
Commercially pure aluminum
Zinc
Magnesium and magnesium alloys

Increasingly active (anodic)

Susceptibility to corrosion increases

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Reference: W.D Callister, 7 Ed.

Forms of Corrosion

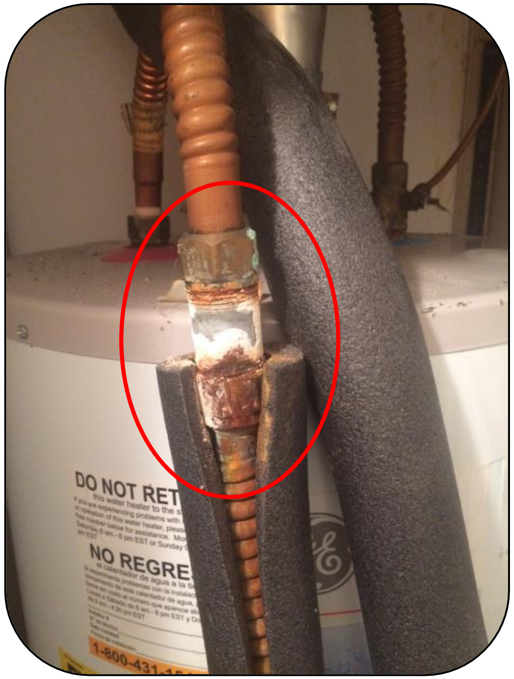
1. Uniform Attack

- Most common form of corrosion.
- Oxidation and reduction reactions occur randomly over the surface.
- Maximum metal loss by this form.

Uniform Attack

2. Galvanic Corrosion

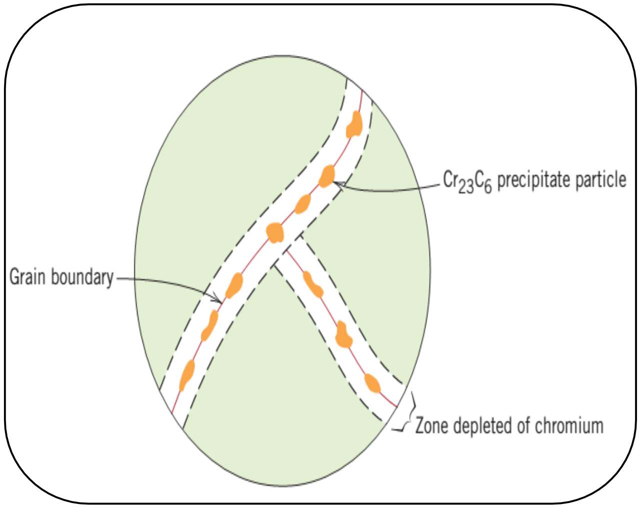
- Occurs when two metals or alloys of different compositions are electrically coupled in presence of an electrolyte.
- Less noble/more reactive metal will get corroded.
- **Example**: Steel corrosion in domestic water heater having Cu - steel junction.
- Avoid either coupling of dissimilar metals or choose relatively close metals from galvanic series.
- Use large anode area.
- Electrically insulate dissimilar metals.



Galvanic corrosion of steel in Water heater

3. Intergranular Corrosion

- Occur along grain boundaries in some stainless steel operating at temperature 500 - 800°C for long time.
- Heat causes formation of chromium carbide ($Cr_{23}C_6$) particles along grain boundary while depleted region gets corroded.
- Hence, reduce carbon content below 0.03% & add Titanium or Niobium which form carbide to protect Chromium.

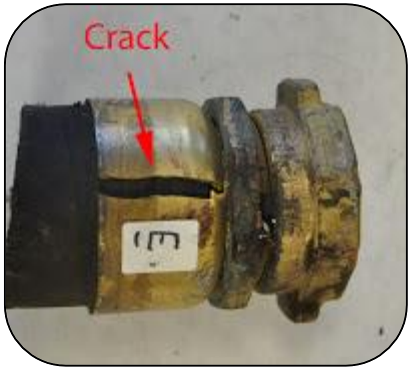


Corrosion in stainless steel

Reference: W.D Callister, 7 Ed.

4. Stress Corrosion

- Stress & corrosion phenomenon occur simultaneously



Crack in Brass pipe under ammonia pressure

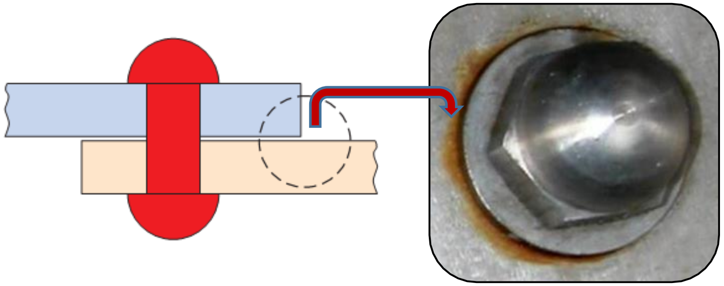
5. Erosion–Corrosion

- Combined effect of chemical attack & mechanical wear due to fluid motion.
- Example : Propellers, turbine blades, valves, and pumps ,i.e., where there is an abrupt change in fluid speed or direction.

Wear & corrosion of propeller blades

6. Crevice corrosion

- Localized corrosion.
- Occur due to concentration difference of fluid/ions between two region of same metal piece.



Crevice corrosion

7. Pitting corrosion

- Localized corrosion attack - Small pits & holes forms.
- Initiated usually by scratch on surface and then grow downwards (due to gravity).

Pitting corrosion – wash basin

Reference : http://sassda.co.za//

Corrosion Resistance

Aerated Water:

High resistance – **Lead Alloy**, Steel Alloy, **Titanium Alloy**, Nickel Alloy, **Copper Alloy**

Medium resistance – Aluminium Alloy

Low resistance - Carbon steels

Strong Acids:

High resistance – **Lead Alloy**, **Titanium alloy**, Stainless Steel

Medium – Aluminium Alloy

Strong Alkali:

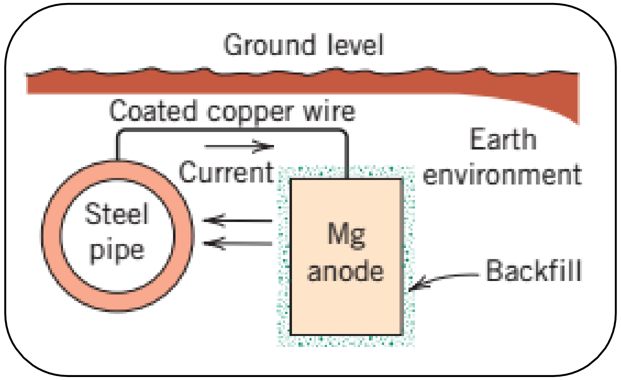
High resistance – Nickel Alloys, Steels, **Titanium Alloy**

Medium – **Copper Alloys**, Zinc Alloys

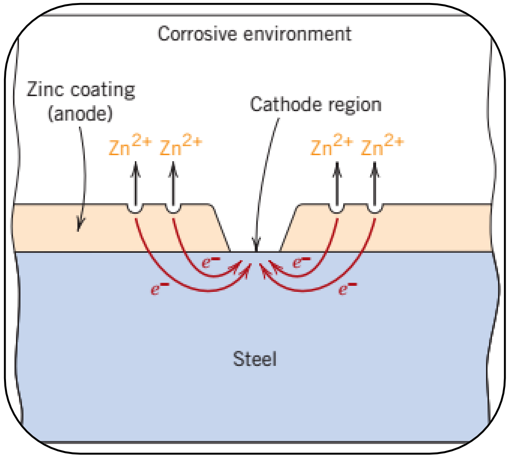
UV - all alloys

Corrosion Prevention

1. Using metals which form a protective oxide layer.
2. Adding inhibitors, for example - Amines & hydrazines removes oxygen.
3. Reducing Temperature – decreases corrosion rate.
4. Painting
5. Cathodic Protection
   - ✓ The metal to be protected is connected to another more reactive metal, which gives up its electrons and gets oxidized (sacrificial anode).
   - ✓ Mg & Zn(galvanizing) are commonly used.



Magnesium sacrificial anode



Galvanic protection of steel

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Reference: W.D Callister, 7 Ed.

In the **next lecture**, we will learn:

- ✓ Ceramic Materials
- ✓ Classification & their properties

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