CORROSION OF METALS AND ITS PREVENTION

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WHAT IS CORROSION ?

Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals. The most widely used metal is iron (usually as steel) and the following discussion is mainly related to its corrosion.

The Consequences of Corrosion:

The consequences of corrosion are many and varied and the effects of these on the safe, reliable and efficient operation of equipment or structures are often more serious than the simple loss of a mass of metal. Failures of various kinds and the need for expensive replacements may occur even though the amount of metal destroyed is quite small. Some of the major harmful effects of corrosion can be summarized as follows:

1. Reduction of metal thickness, leading to loss of mechanical strength and structural failure or breakdown. When the metal is lost in localized zones so as to give a cracklike structure, very considerable weakening may result from quite a small amount of metal loss.
2. Hazards or injuries to people arising from structural failure or breakdown (e.g. bridges, cars, aircraft).
3. Loss of time in availability of profile-making industrial equipment.
4. Reduced value of goods due to deterioration of appearance.
5. Contamination of fluids in vessels and pipes (e.g. beer goes cloudy when small quantities of heavy metals are released by corrosion).
6. Perforation of vessels and pipes allowing escape of their contents and possible harm to the surroundings. For example a leaky domestic radiator can cause expensive damage to carpets and decorations, while corrosive sea water may enter the boilers of a power station if the condenser tubes perforate.
7. Loss of technically important surface properties of a metallic component. These could include frictional and bearing properties, ease of fluid flow over a pipe surface, electrical conductivity of contacts, surface reflectivity or heat transfer across a surface.
8. Mechanical damage to valves, pumps, etc, or blockage of pipes by solid corrosion products.
9. Added complexity and expense of equipment, which needs to be designed to withstand a certain amount of corrosion, and to allow corroded components to be conveniently replaced.

Chemistry of Corrosion:

Common structural metals are obtained from their ores or naturally occurring compounds by the expenditure of large amounts of energy. These metals can therefore be regarded as being in a metastable state and will tend to lose their energy by reverting to compounds more or less similar to their original states. Since most metallic compounds, and especially corrosion products, have little mechanical strength a severely corroded piece of metal is quite useless for its original purpose.

Virtually all corrosion reactions are electrochemical in nature; at anodic sites on the surface the iron goes into solution as ferrous ions, this constituting the anodic reaction. As iron atoms undergo oxidation to ions they release electrons whose negative charge would quickly build up in the metal and prevent further anodic reaction, or corrosion. Thus this dissolution will only continue if the electrons released can pass to a site on the metal surface where a cathodic reaction is possible. At a cathodic site the electrons react with some reducible component of the electrolyte and are themselves removed from the metal. The rates of the anodic and cathodic reactions must be equivalent according to Faraday's Laws, being determined by the total flow of electrons from anodes to cathodes, which is called the "corrosion current", I_{corr}. Since the corrosion current must also flow through the electrolyte by ionic conduction the conductivity of the electrolyte will influence the way in which corrosion cells operate. The corroding piece of metal is described as a "mixed electrode" since simultaneous anodic and cathodic reactions are proceeding on its surface. The mixed electrode is a complete electrochemical cell on one metal surface.

The most common and important electrochemical reactions in the corrosion of iron are thus

Anodic reaction (corrosion)
$$Fe \rightarrow Fe^{2+} + 2e^- \tag{1}$$

Cathodic reactions (simplified)
$$2H^+ + 2e^- \rightarrow H_2 \tag{2a}$$
or
$$H_2O + \tfrac{1}{2} O_2 + 2e^- \rightarrow 2OH^- \tag{2b}$$

Reaction 2a is most common in acids and in the pH range $6.5 - 8.5$ the most important reaction is oxygen reduction 2b. In this latter case corrosion is usually accompanied by the formation of solid corrosion debris from the reaction between the anodic and cathodic products.

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \text{ , iron (II) hydroxide}$$
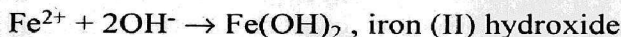
Pure iron (II) hydroxide is white but the material initially produced by corrosion is normally a greenish colour due to partial oxidation in air.

$$Fe(OH)_2 + H_2O + \tfrac{1}{2} O_2 \rightarrow Fe(OH)_3 \text{ , hydrated iron (III) oxide}$$
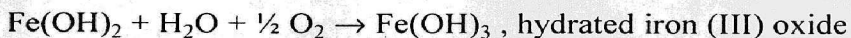
Further hydration and oxidation reactions can occur and the reddish rust that eventually forms is a complex mixture whose exact constitution will depend on other trace

elements, which are present. Because the rust is precipitated as a result of secondary reactions it is porous and absorbent and tends to act as a sort of harmful poultice, which encourages further corrosion. For other metals or different environments different types of anodic and cathodic reactions may occur. If solid corrosion products are produced directly on the surface as the first result of anodic oxidation these may provide a highly protective surface film, which retards further corrosion, the surface is then said to be "passive". An example of such a process would be the production of an oxide film on iron in water, a reaction which is encouraged by oxidizing conditions or elevated temperatures.
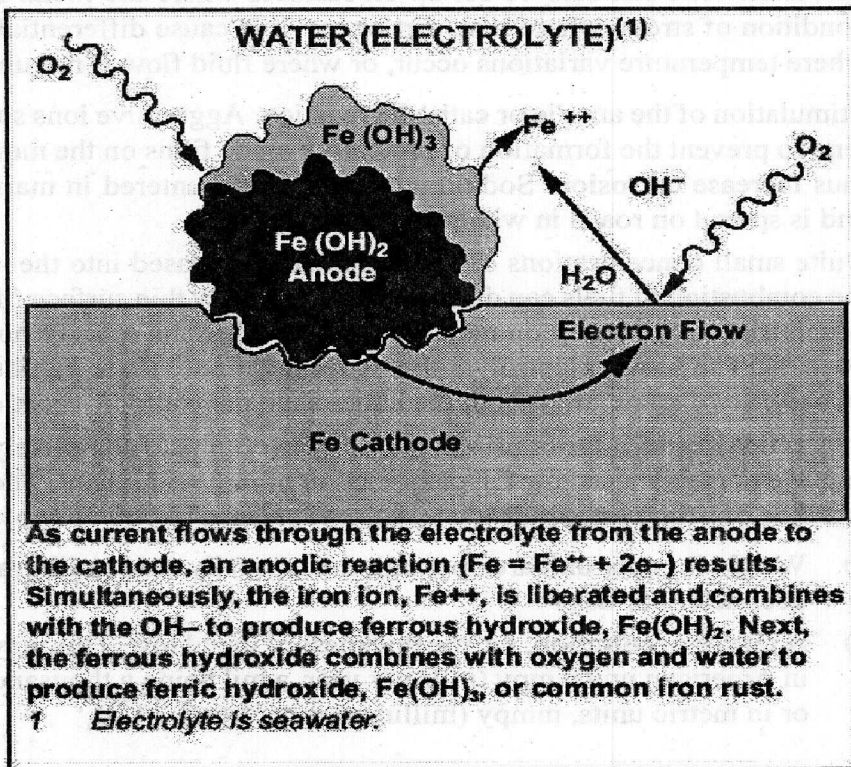
$$Fe + 3H_2O \rightarrow Fe_2O_3 + 6H^+ + 6e^-$$

As current flows through the electrolyte from the anode to the cathode, an anodic reaction (Fe = Fe^{++} + 2e–) results. Simultaneously, the iron ion, Fe++, is liberated and combines with the OH– to produce ferrous hydroxide, Fe(OH)$_2$. Next, the ferrous hydroxide combines with oxygen and water to produce ferric hydroxide, Fe(OH)$_3$, or common iron rust.
1   Electrolyte is seawater.

Fig.1 : *Showing classic corrosion cell, and corrosion reactions taking place.*

Factors that Control the Corrosion Rate:

Certain factors can tend to accelerate the action of a corrosion cell.

These include:

a) Establishment of well-defined locations on the surface for the anodic and cathodic reactions. This concentrates the damage on small areas where it may have more serious effects, this being described as "local cell action". Such effects can occur when metals of differing electrochemical properties are placed in contact, giving a "galvanic couple". Galvanic effects may be predicted by means of a study of

the Galvanic Series, which is a list of metals and alloys placed in order of their potentials in the corrosive environment, such as seawater. Metals having a more positive (noble) potential will tend to extract electrons from a metal, which is in a more negative (base) position in the series and hence accelerate its corrosion when in contact with it. The Galvanic Series should not be confused with the Electrochemical Series, which lists the potentials only of pure metals in equilibrium with standard solutions of their ions.

Galvanic effects can occur on metallic surfaces, which contain more than one phase, so that "local cells" are set up on the heterogeneous surface. Localized corrosion cells can also be set up on surfaces where the metal is in a varying condition of stress, where rust, dirt or crevices cause differential access of air, where temperature variations occur, or where fluid flow is not uniform.

b) Stimulation of the anodic or cathodic reaction. Aggressive ions such as chloride tend to prevent the formation of protective oxide films on the metal surface and thus increase corrosion. Sodium chloride is encountered in marine conditions and is spread on roads in winter for de-icing.

Quite small concentrations of sulphur dioxide released into the atmosphere by the combustion of fuels can dissolve in the invisibly thin surface film of moisture which is usually present on metallic surfaces when the relative humidity is over 60-70%. The acidic electrolyte that is formed under these conditions seems to be capable of stimulating both the anodic and the cathodic reactions.

In practical terms it is not usually possible to eliminate completely all corrosion damage to metals used for the construction of industrial plant. The rate at which attack is of prime importance is usually expressed in one of two ways:

1) Weight loss per unit area per unit time, usually mdd (milligrams per square decimeter per day)

2) A rate of penetration, i.e. the thickness of metal lost. This may be expressed in American units, mpy (mils per year, a mil being a thousandth of an inch) or in metric units, mmpy (millimetres per year).

Taking as an example the corrosion of heat exchanger tubes in industrial cooling water a typical corrosion rate in untreated water would be 40-50 mpy (210-260 mdd); the use of a corrosion inhibitor could reduce this to less than 5 mpy (26 mdd). The mild steel tubing used in heat exchangers is a maximum of 200 thousandths of an inch thick, thus with corrosion rates of 40-50 mpy in untreated water, severe problems might be expected within four or five years. If suitable water treatment with corrosion inhibitors is used a life of at least twenty years might be expected. This, of course, is ignoring the fact that at some time before the metal corrodes away the tubing may have thinned to a point where its required mechanical strength is not attained. When designing equipment for a certain service life engineers often add a "corrosion allowance" to the metal thickness, permitting a certain amount of thinning before serious weakening occurs. In a cooling water system the factors influencing the rate of attack are:

(a)	**The condition of the metal surface**	
	Corrosion debris and other deposits	Corrosion under the deposits, with a possibility of pitting(severe attack in small spots)
(b)	**The nature of the environment**	
	pH	In the range of 4-10 corrosion rate is fairly independent of pH, but it increases rapidly when the pH falls below 4.
	Oxygen content	Increase in oxygen concentration usually gives an increase in corrosion rate.
	Flow rate	Increased water flow increased oxygen access to the surface and removes protective surface films, so usually increases corrosion, but can sometimes improve access for corrosion inhibiting reactants.
	Water type	Very important, in general low corrosion rates are found with scale-forming (hard) waters. Aggressive ions, which accelerate corrosion, are Cl^-, SO_4^{2-} but quite complex interactions may occur between the various dissolved species in natural waters.

CORROSION PREVENTION

By retarding either the anodic or cathodic reactions the rate of corrosion can be reduced. This can be achieved in several ways:

Conditioning the Metal

This can be sub-divided into two main groups:

(a) Coating the metal, in order to interpose a corrosion resistant coating between metal and environment. The coating may consist of:

     i) Another metal, e.g. zinc or tin coatings on steel,

     ii) A protective coating derived from the metal itself, e.g. aluminium oxide on "anodised" aluminium,

     iii) Organic coatings, such as resins, plastics, paints, enamel, oils and greases.

     The action of protective coatings is often more complex than simply providing a barrier between metal and environment. Paints may contain a corrosion inhibitor (see Section 2): zinc coating in iron or steel confers cathodic protection (see Section 3).

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(b) Alloying the metal to produce a more corrosion resistant alloy, e.g. stainless steel, in which ordinary steel is alloyed with chromium and nickel. Stainless steel is protected by an invisibly thin, naturally formed film of chromium sesquioxide Cr_2O_3.

Conditioning the Corrosive Environment

(a) Removal of Oxygen: By the removal of oxygen from water systems in the pH range 6.5-8.5 one of the components required for corrosion would be absent. The removal of oxygen could be achieved by the use of strong reducing agents e.g. sulphite. However, for open evaporative cooling systems this approach to corrosion prevention is not practical since fresh oxygen from the atmosphere will have continual access.

(b) Corrosion Inhibitors: A corrosion inhibitor is a chemical additive, which, when added to a corrosive aqueous environment, reduces the rate of metal wastage. It can function in one of the following ways:

   i) Anodic inhibitors – as the name implies an anodic inhibitor interferes with the anodic process.

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{1}$$

If an anodic inhibitor is not present at a concentration level sufficient to block off all the anodic sites, localized attack such as pitting corrosion can become a serious problem due to the oxidizing nature of the inhibitor, which raises the metal potential and encourages the anodic reaction (equation 1). Anodic inhibitors are thus classified as "dangerous inhibitors". Other examples of anodic inhibitors include orthophosphate, nitrite, ferricyanide and silicates.

   ii) Cathodic inhibitors – the major cathodic reaction in cooling systems is the reduction of oxygen.

$$H_2O + \tfrac{1}{2} O_2 + 2e^- \rightarrow 2OH^- \tag{2b}$$

There are other cathodic reactions and additives that suppress these reactions called cathodic inhibitors. They function by reducing the available area for the cathodic reaction. This is often achieved by precipitating an insoluble species onto the cathodic sites. Zinc ions are used as cathodic inhibitors because of the precipitation of $Zn(OH)_2$ at cathodic sites as a consequence of the localized high pH. (See reaction 2(b). Cathodic inhibitors are classed as safe because they do not cause localized corrosion.

   iii) Adsorption type corrosion inhibitors – many organic inhibitors work by an adsorption mechanism. The resultant film of chemisorbed inhibitor is then responsible for protection either by physically blocking the surface from the corrosion environment or by retarding the electrochemical processes. The main functional groups capable of forming chemisorbed bonds with metal surfaces are amino ($-NH_2$), carboxyl ($-COOH$), and phosphonate ($-PO_3H_2$) although other functional groups or atoms can form co-ordinate bonds with metal surfaces.

iv) Mixed inhibitors – because of the danger of pitting when using anodic inhibitors alone, it became common practice to incorporate a cathodic inhibitor into formulated performance was obtained by a combination of inhibitors than from the sum of the individual performances. This observation is generally referred to a 'synergism' and demonstrates the synergistic action, which exists between zinc and chromate ions.

Electrochemical Control

Since corrosion is an electrochemical process its progress may be studied by measuring the changes, which occur in metal potential with time or with applied electrical currents. Conversely, the rate of corrosion reactions may be controlled, by passing anodic or cathodic currents into the metal. If, for example, electrons are passed into the metal and reach the metal/electrolyte interface (a cathodic current) the anodic reaction will be stifled while the cathodic reaction rate increases. This process is called cathodic protection and can only be applied if there is a suitable conducting medium such as earth or water through which a current can flow to the metal to be protected. In most soils or natural waters corrosion of steel is prevented if the potential of the metal surface is lowered by 300 or 400 mV. Cathodic protection may be achieved by using a DC power supply (impressed current) or by obtaining electrons from the anodic dissolution of a metal low in the galvanic series such as aluminum, zinc or magnesium (sacrificial anodes). Similar protection is obtained when steel is coated with a layer of zinc. Even at scratches or cut edges where some bare metal is exposed the zinc is able to pass protective current through the thin layer of surface moisture. In certain chemical environments it is sometimes possible to achieve anodic protection, by passing a current, which takes electrons out of the metal and raises its potential. Initially this stimulates anodic corrosion, but in favourable circumstances this will be followed by the formation of a protective oxidized passive surface film.

EIGHT FORMS OF CORROSION

The classification of different forms of corrosion can be done on the basis of appearance of corroded metal. Each form can be identified by mere visual observation. In most cases the naked eye is sufficient, but sometimes magnification is helpful or required. In order to solve a corrosion problem, valuable information can often be obtained through careful observation of the corroded test specimens or failed equipment. Examination 'before' cleaning is particularly desirable.

Some of the eight forms of corrosion are unique, but all of them are more or less interrelated. The eight forms are:

1. Uniform corrosion, or general attack
2. Galvanic, or two metal corrosion
3. Crevice corrosion
4. Pitting
5. Intergranular corrosion
6. Selective leaching, or parting
7. Erosion corrosion
8. Stress corrosion

The above listing is arbitrary but covers practically all corrosion failures and problems. The forms are not listed in any particular order of importance. Below, these eight forms of corrosion are discussed in terms of their characteristics, examples, pictorials, mechanisms, relevant standards/testing methods and preventive measures

Uniform corrosion, or general attack :

Uniform corrosion or uniform attack is the most common form of corrosion. It is normally characterized by a chemical or electrochemical reaction that proceeds uniformly over the entire exposed surface or over a large area. The eventual failing occurs due to thinning of metal/alloy. E.g., a piece of zinc or steel immersed in dilute sulphuric acid will normally dissolve at a uniform rate over its entire surface.

However, uniform corrosion is relatively easily measured and predicted, making disastrous failures relatively rare. In many cases, it is objectionable only from an appearance standpoint. As corrosion occurs uniformly over the entire surface of the metal component, it can be practically controlled by cathodic protection, use of coatings or paints, or simply by specifying a corrosion allowance. In other cases uniform corrosion adds color and appeal to a surface. Two classics in this respect are the patina created by naturally tarnishing copper roofs and the rust hues produced on weathering steels.

The breakdown of protective coating systems on structures often leads to this form of corrosion. Dulling of a bright or polished surface, etching by acid cleaners, or oxidation (discoloration) of steel are examples of surface corrosion. Corrosion resistant alloys and stainless steels can become tarnished or oxidized in corrosive environments. Surface corrosion can indicate a breakdown in the protective coating system, however, and should be examined closely for more advanced attack. If surface corrosion is permitted to continue, the surface may become rough and surface corrosion can lead to more serious types of corrosion. An example of uniform corrosion damage on a rocket assisted artillery projectile is shown here.

Uniform attack, or general overall corrosion, represents the greatest destruction of metal on a tonnage basis. This form of corrosion, however, is not of very great concern from technical standpoint, because the life of equipment can be accurately estimated using relatively simple tests. Mere immersion of specimens in the solution involved is often sufficient.
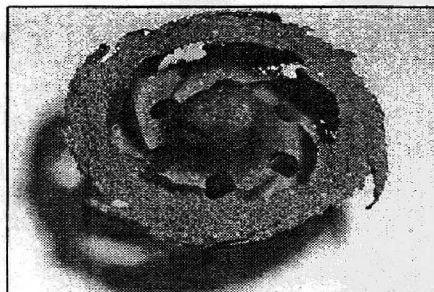
Fig. 2 : *Example of uniform attack in Pump Impeller in cleanup system*

Relevant standards:

- G1-03 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.
- G3-89 (2004) Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing.
- G4-01 Standard Guide for Conducting Corrosion Tests in Field Applications.
- G5-94 (2004) Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements.
- G15-07 Standard Terminology Relating to Corrosion and Corrosion Testing.
- G16-95 (2004) Standard Guide for Applying Statistics to Analysis of Corrosion Data.
- G31-72 (2004) Standard Practice for Laboratory Immersion Corrosion Testing of Metals.
- G102-89 (2004) e1 Standard Practice for Calculation of Corrosion Rates and RelatedInformation from Electrochemical Measurements.
- G135-95 (2007) Standard Guide for Computerized Exchange of Corrosion Data for Metals.

Preventive Measures:

i) Proper materials, including coatings
ii) Inhibitors
iii) Cathodic protection.

Galvanic, or two metal corrosion:

In engineering structures, a variety of different metals and alloys are used and these are often in contact (or otherwise electrical connected). Electrical contact or coupling of dissimilar metals sometimes causes increased corrosion, which is frequently termed galvanic corrosion. The driving force for current and corrosion is the potential developed between two metals. There are two general rules of galvanic corrosion:

a) When dissimilar metals are connected, the most active or anodic metal is more rapidly corroded, while the more noble or cathodic metal tends to be protected.
b) As the potential difference increases, galvanic corrosion increases.

Examples: Coupling aluminum and iron pipe together usually results in very rapid corrosion of aluminum pipe section. A frequent source of galvanic corrosion is in heat exchangers where the tubing is often made of copper, while the remainder of exchanger is made of steel.

The general tendency for galvanic corrosion to occur may be ascertained using galvanic series. The series is shown in table 1, which is a based on potential measurements and galvanic corrosion tests in unpolluted seawater.

Table 1
GALVANIC SERIES
In Flowing Seawater

Alloy		Voltage Range of Alloy vs. Reference Electrode*
Magnesium	**Anodic or**	-1.60 to -1.63
Zinc	**Active End**	-0.98 to -1.03
Aluminum Alloys		-0.70 to -0.90
Cadmium		-0.70 to -0.76
Cast Irons		-0.60 to -0.72
Steel		-0.60 to -0.70
Aluminum Bronze		-0.30 to -0.40
Red Brass, Yellow Brass, Naval Brass		-0.30 to -0.40
Copper		-0.28 to -0.36
Lead-Tin Solder (50/50)		-0.26 to -0.35
Admiralty Brass		-0.25 to -0.34
Manganese Bronze		-0.25 to -0.33
Silicon Bronze		-0.24 to -0.27
400 Series Stainless Steels**		-0.20 to -0.35
90-10 Copper-Nickel		-0.21 to -0.28
Lead		-0.19 to -0.25
70-30 Copper-Nickel		-0.13 to -0.22
17-4 PH Stainless Steel †		-0.10 to -0.20
Silver		-0.09 to -0.14
Monel		-0.04 to -0.14
300 Series Stainless Steels ** †		-0.00 to -0.15
Titanium and Titanium Alloys †		+0.06 to -0.05
Inconel 625 †		+0.10 to -0.04
Hastelloy C-276 †		+0.10 to -0.04
Platinum †	**Cathodic or**	+0.25 to +0.18
Graphite	**Noble End**	+0.30 to +0.20

* These numbers refer to a Saturated Calomel Electrode.
** In low-velocity or poorly aerated water, or inside crevices, these alloys may start to corrode and exhibit potentials near -0.5 V.
† When covered with slime films of marine bacteria, these alloys may exhibit potentials from +0.3 to +0.4 V.
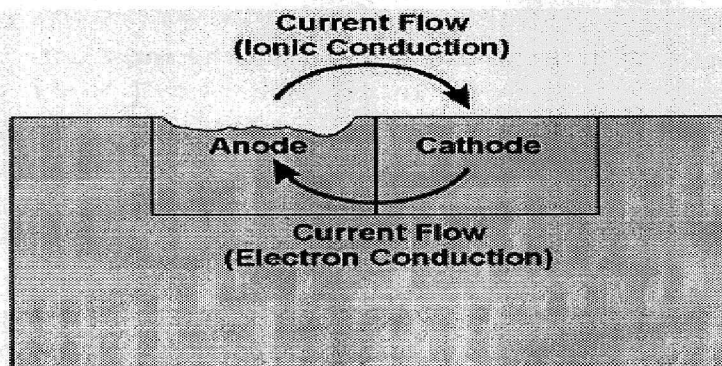
Figu. 3 : *Phenomenon of galvanic corrosion*

Relevant Standards:

- G71-81 (2003) Standard Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes
- G82-98 (2003) Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance
- G116-99 (2004) Standard Practice for Conducting Wire-on-Bolt Test for Atmospheric Galvanic Corrosion

Preventive Measures:

i) Avoid the use of dissimilar metals wherever possible. If this is not practical, metals close together in the galvanic series, can be used.

ii) Avoid and unfavorable area ratio whenever possible. Under no circumstances should a small anode be connected to a large cathode.

iii) If dissimilar metals are used, insulate these electrically from one another.

iv) If it is necessary to use dissimilar metals, and these cannot be insulated, then the more anodic part should be designed for easy replacement or should be constructed of thick materials to absorb longer the effects of corrosion.

Crevice corrosion:

This is an intensive localized form of corrosion, which frequently occurs within crevices, and other shielded areas on metal surfaces exposed to corrosive environment. The solution within the crevice becomes highly concentrated and acidic. This type of attack is usually associated with small volumes of stagnant solution caused by holes, gasket surfaces, lap joints, surface deposits, and crevices under bolt and rivet heads. Hence, this form of corrosion is called crevice corrosion or sometimes, deposit or gasket corrosion.

Contact between metal and nonmetallic surfaces can cause crevice corrosion as in the case of a gasket. Wood, plastics, rubber, glass, concrete, asbestos, wax, and fabrics are examples of materials that can cause this type of corrosion.

Example: A sheet of 18-8 stainless steel can be cut by placing a stretched rubber band around it and then immersing in seawater. Crevice attack begins and progresses in the area where the metal and rubber are in contact.

Relevant Standards:

- G48-03 Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution
- G78-01 (2007) Standard Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments
- G1-03 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
- G15-07 Standard Terminology Relating to Corrosion and Corrosion Testing

Preventive Measures:

  i)   Using welded butt joints instead of riveted or bolted joints.
  ii) Closing crevices in existing lap joints by continuous welding, soldering.
  iii) Designing vessels for complete drainage.
  iv) Inspecting equipment and removing deposits frequently.
  v)   Removing solids in suspension early in the process.
  vi) Removing wet packing materials during long shutdowns.
  vii) Using "solid", nonabsorbent gaskets, such as Teflon, wherever possible.
  viii) Providing uniform environments.
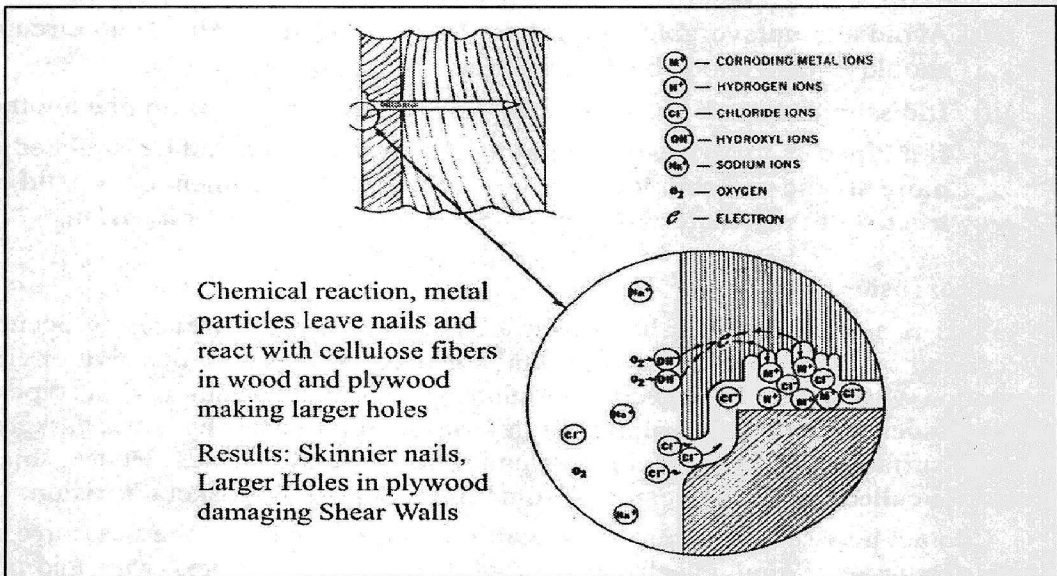
Fig. 4 : *Schematic of conditions possible after crevice corrosion has progressed*

Pitting :

Pitting corrosion is a localized form of corrosion by which cavities or "holes" are produced in the material. Pitting is considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict and design against. Corrosion products often cover the pits. A small, narrow pit with minimal overall metal loss can lead to the failure of an entire engineering system. Pitting corrosion, which, for example, is almost a common denominator of all types of localized corrosion attack, *may assume different shapes* as shown in figure 4.

Pitting corrosion is most aggressive in solutions containing chloride, bromide or hypochlorite ions. Iodides and fluorides are much less harmful. The presence of sulfides and H_2S enhances pitting corrosion, and systematically impairs the resistance criteria for this type of attack.

The stainless steels are particularly sensitive to pitting corrosion, but other metals, such as passive iron, chromium, cobalt, aluminum, copper and their alloys are also prone to this form of corrosion.

Very often, in non-passivatable metals, a "tubercular" surface morphology is observed, beneath which pits develop.

Contrary to crevice corrosion, the cause of pitting is not always completely local in nature. Thus, although alterations or intrinsic defects at the metal-solution interface (e.g. inclusions emerging through the passive film in stainless steels) often represent nuclei for local dissolution, all such potential nuclei are not attacked. The stabilization and development of these nuclei always show a random nature. Galvanic coupling is then established between the discontinuous zones, which form small anodes where metal dissolution occurs, and the remainder of the surface where the cathodic reaction takes place.

Mechanism: It is stated that pits begin by the breakdown of passivity at favored nuclei on the metal surface. The breakdown is followed by the formation of electrolytic cell. The anode of this cell is a minute area of active metal, and the cathode is a considerable area of passive metal. The large potential difference characteristic of this passive-active cell (for example, approximately 0.5 V for 300-series stainless steel) accounts for considerable flow of currents with rapid corrosion at the small anode. The corrosion resistant passive metal surrounding the anode, and the activating property of corrosion products within the pit, account for the tendency of corrosion to penetrate the metal rather than spread along the surface.

Once pits are initiated, they may continue to grow by a self, or autocatalytic, process; that is, the corrosion processes within a pit produce a condition that are both stimulating and necessary for the continuing activity of the pit.
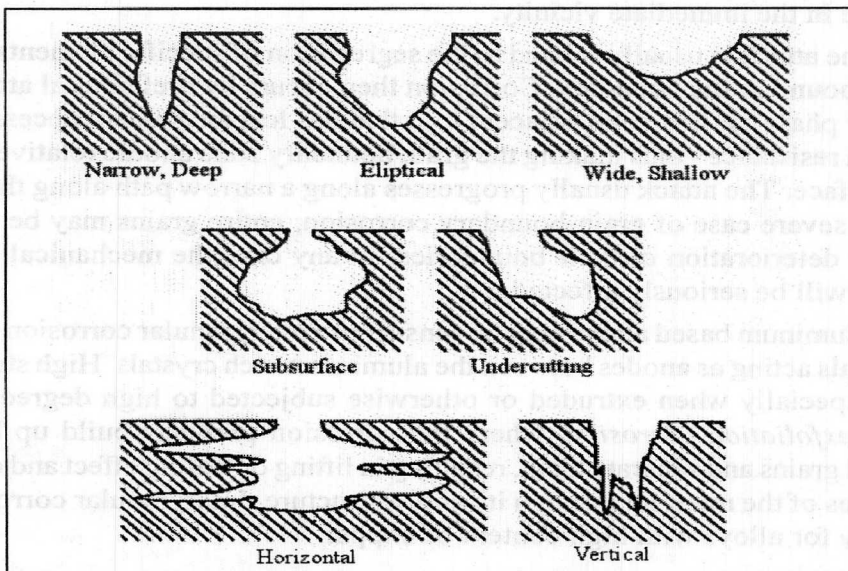

Fig. 5 : Different shapes, which a pit may assume

Relevant Standards:

- G46-94 (2005) Standard Guide for Examination and Evaluation of Pitting Corrosion
- G48-03 Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution   .
- G150-99 (2004) Standard Test Method for Electrochemical Critical Pitting Temperature Testing of Stainless Steels
- G1-03 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens

Preventive Measures:

i) Proper selection of materials with known resistance to the service environment
ii) Control pH, chloride concentration and temperature
iii) Cathodic protection and/or Anodic Protection
iv) Use higher alloys (ASTM G48) for increased resistance to pitting corrosion

Intergranular corrosion:

The microstructure of metals and alloys is made up of grains, separated by grain boundaries. Intergranular corrosion is localized attack along the grain boundaries, or immediately adjacent to grain boundaries, while the bulk of the grains remain largely unaffected. This form of corrosion is usually associated with chemical segregation effects (impurities have a tendency to be enriched at grain boundaries) or specific phases precipitated on the grain boundaries. Such precipitation can produce zones of reduced corrosion resistance in the immediate vicinity.

The attack is usually related to the segregation of specific elements or the formation of a compound in the boundary. Corrosion then occurs by preferential attack on the grain-boundary phase, or in a zone adjacent to it that has lost an element necessary for adequate corrosion resistance - thus making the grain boundary zone anodic relative to the remainder of the surface. The attack usually progresses along a narrow path along the grain boundary and, in a severe case of grain-boundary corrosion, entire grains may be dislodged due to complete deterioration of their boundaries. In any case the mechanical properties of the structure will be seriously affected.

Aluminum based alloys may be sensitive to intergranular corrosion if there are layers of materials acting as anodes between the aluminium-rich crystals. High strength aluminium alloys, especially when extruded or otherwise subjected to high degree of working, can undergo *exfoliation corrosion*, where the corrosion products build up between the flat, elongated grains and separate them, resulting in lifting or leafing effect and often propagating from edges of the material through its entire structure. Intergranular corrosion is a concern especially for alloys with high content of copper.

Example: A classic example is the sensitization of *stainless steels or weld decay*. Chromium-rich grain boundary precipitates lead to a local depletion of Cr immediately adjacent to

these precipitates, leaving these areas vulnerable to corrosive attack in certain electrolytes. Reheating a welded component during multi-pass welding is a common cause of this problem. In austenitic stainless steels, titanium or niobium can react with carbon to form carbides in the heat-affected zone (HAZ) causing a specific type of intergranular corrosion known as *knife-line attack*. These carbides build up next to the weld bead where they cannot diffuse due to rapid cooling of the weld metal. The problem of knife-line attack can be corrected by reheating the welded metal to allow diffusion to occur.

Many aluminum base alloys are susceptible to intergranular corrosion on account of either phases anodic to aluminum being present along grain boundaries or due to depleted zones of copper adjacent to grain boundaries in copper-containing alloys. Alloys that have been extruded or otherwise worked heavily, with a microstructure of elongated, flattened grains, are particularly prone to this damage.

Mechanism: Intergranular corrosion takes place when the corrosion rate of the grain-boundary areas of an alloy exceeds that of the great interiors. This difference in corrosion rate is generally the result of differences in composition between the grain boundary and the interior.

The difference in corrosion rate may be caused by a number of reactions. A phase may precipitate at the grain boundary and deplete the matrix of an element that its corrosion resistance. A grain-boundary phase may be more reactive than the matrix. Various solute atoms may segregate to the grain boundaries and locally accelerate corrosion. The metallurgical changes that lead to intergranular corrosion are not always observable in the microstructure; therefore corrosion tests may sometimes be the most sensitive indication of metallurgical changes.
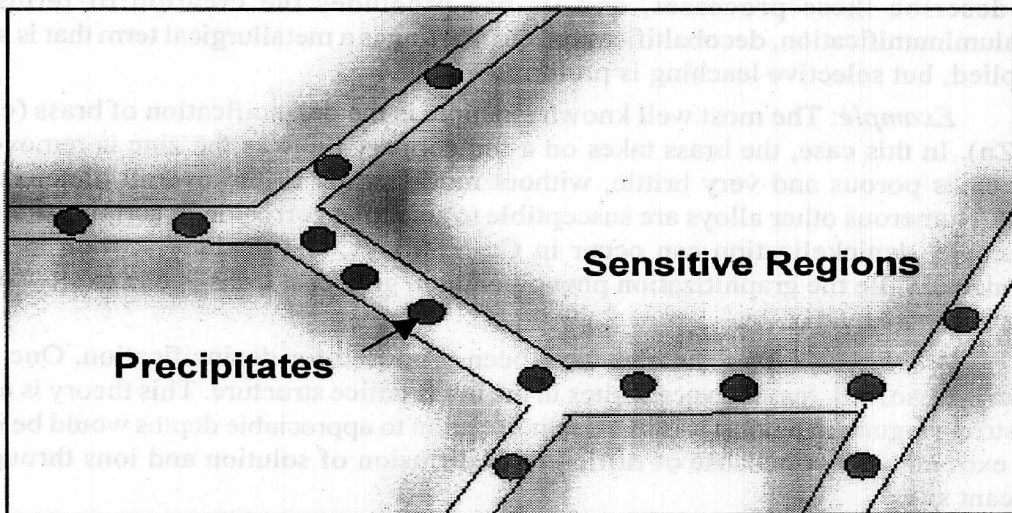
Fig. 6 : *Diagrammatic representation of a grain boundary in sensitized type 304 stainless steel*

Relevant Standards:

- G28-02 Standard Test Methods of Detecting Susceptibility to Intergranular Corrosion in Wrought, Nickel-Rich, Chromium-Bearing Alloys

- G67-04 Standard Test Method for Determining the Susceptibility to Intergranular Corrosion of 5XXX Series Aluminum Alloys by Mass Loss After Exposure to Nitric Acid (NAMLT Test)

- G110-92(2003)e1 Standard Practice for Evaluating Intergranular Corrosion Resistance of Heat Treatable Aluminum Alloys by Immersion in Sodium Chloride + Hydrogen Peroxide Solution

Preventive Measures:

Following methods are used to control intergranular corrosion in austenitic stainless steels.

i) Employing high temperature solution heat treatment, commonly termed 'quench-annealing' or 'solution quenching'.

ii) Adding strong carbide forming elements (Nb, Ti etc)

iii) Lowering the carbon content to below 0.03%.

Selective leaching, or parting:

Selective leaching is the removal of one element from a solid alloy by corrosion processes. The most common example is the selective removal of zinc in brass alloys (dezincification). Similar processes occur in other alloy systems in which aluminum; iron, cobalt, chromium, and other elements are removed. Selective leaching is the general term to describe these processes, and its use precludes the creation of terms such as dealuminumification, decobaltification, etc. Parting is a metallurgical term that is sometimes applied, but selective leaching is preferred.

Example: The most well known example is the dezincification of brass (e.g. 70Cu - 30Zn). In this case, the brass takes on a red coppery tinge as the zinc is removed. It also becomes porous and very brittle, without modification to the overall dimensions of the part. Numerous other alloys are susceptible to selective corrosion in certain conditions. For example, denickelization can occur in Cu-Ni alloys, and dealuminization in aluminium bronzes, while the graphitization phenomenon in gray cast irons is due to slow dissolution of the ferrite matrix.

Mechanism: Two theories have been proposed for dezincification. One states that zinc is dissolved, leaving vacant sites in the brass lattice structure. This theory is not proven. A strong argument against it is that dezincification to appreciable depths would be impossible or extremely slow because of difficulty of diffusion of solution and ions through a small vacant sites.

The commonly accepted mechanism consist of three steps, as follows:

a. The brass dissolves,

b. The zinc ion stay in solution, and

c. The copper corrodes slowly in pure water by the cathodic ion reduction of H_2O into hydrogen gas and hydroxide ions. For this reason dezincification can proceed in the absence of oxygen. Oxygen also enters into the cathodic reaction and hence increase the rate of attack when it is present. Analysis of dezincified areas show 90 to 95% of copper with some of it present as copper oxide. The amount of copper oxide is related to oxygen content of the environment. The porous nature of the deposit permits easy contact between the solution and the brass.
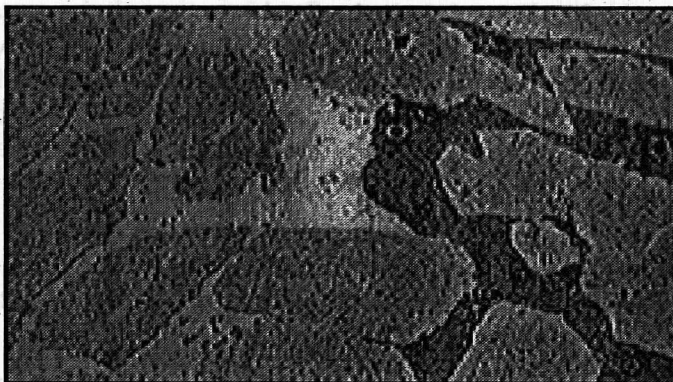
Fig. 7 : shows micrographic appearance of a dezincification of brass

Preventive Measures:

    i) Choosing an alloy that is less prone, such as a copper-rich cupro-nickel.

    ii) Brasses with lower zinc contents or containing elements such as tin (1%) and/or small quantities of arsenic, antimony, or phosphorus have much greater resistance

Erosion corrosion:

Erosion-corrosion is caused by the relative movement between a corrosive fluid and a metal surface. The mechanical aspect of the movement is important and friction and wear phenomena can be involved. This process leads to the formation of grooves, valleys, wavy surfaces, holes, etc., with a characteristic directional appearance (comet tails, horseshoe marks, etc.

Erosion-corrosion is most prevalent in soft alloys (i.e. copper, aluminum and lead alloys). Alloys which form a surface film in a corrosive environment commonly show a limiting velocity above which corrosion rapidly accelerates. With the exception of cavitation, flow induced corrosion problems are generally termed erosion-corrosion, encompassing flow enhanced dissolution and impingement attack. The fluid can be aqueous or gaseous, single or multiphase.

Turbulence phenomena can destroy protective films and cause very high corrosion rates in materials otherwise highly resistant under static conditions. In the laminar flow regime, the fluid flow rate has a variable effect depending on the material concerned.

In two-phase liquids (containing suspended solid particles or gas bubbles), the impact of the particles can damage or even eliminate the protective layers or passive films that are normally stable in the absence of particles, and the local corrosion rate is then markedly accelerated. This phenomenon is called abrasion-corrosion.

Cavitation-corrosion is particular form of erosion caused by the "implosion" of gas bubbles on a metal surface. It is often associated with sudden variations in pressure related to the hydrodynamic parameters of the fluid (e.g. hydraulic turbine blades, propellors, stirrer blades, etc.). A regular hydraulic regime in the fluid is extremely important. A good surface condition decreases the number of potential sites for the formation of vapour bubbles. An increase in fluid pressure is often sufficient to maintain a single phase fluid, thus avoiding the formation of vapour bubbles. Plastic or rubber coatings have often proved to be effective, although the problems of adherence between the coating and the metal are frequently an obstacle.

Example: Erosion corrosion can also be aggravated by faulty workmanship. For example, burrs left at cut tube ends can upset smooth water flow, cause localized turbulence and high flow velocities, resulting in erosion corrosion. A combination of erosion and corrosion can lead to extremely high pitting rates.

Mechanism: There are several mechanisms described by the conjoint action of flow and corrosion that result in flow-influenced corrosion:

Mass transport-control: Mass transport-controlled corrosion implies that the rate of corrosion is dependent on the convective mass transfer processes at the metal/fluid interface. When steel is exposed to oxygenated water, the initial corrosion rate will be closely related to the convective flux of dissolved oxygen towards the surface, and later by the oxygen diffusion through the iron oxide layer. Corrosion by mass transport will often be streamlined and smooth.

Phase transport-control: Phase transport-controlled corrosion suggests that the wetting of the metal surface by a corrosive phase is flow dependent. This may occur because one liquid phase separates from another or because a second phase forms from a liquid. An example of the second mechanism is the formation of discrete bubbles or a vapor phase from boiler water in horizontal or inclined tubes in high heat-flux areas under low flow conditions. The corroded sites will frequently display rough, irregular surfaces and be coated with or contain thick, porous corrosion deposits.

Erosion-corrosion: Erosion-corrosion is associated with a flow-induced mechanical removal of the protective surface film that results in a subsequent corrosion rate increase via either electrochemical or chemical processes. It is often accepted that a critical fluid velocity must be exceeded for a given material. The mechanical damage by the impacting fluid imposes disruptive shear stresses or pressure variations on the material surface and/or the protective surface film. Erosion-corrosion may be enhanced by particles (solids or gas bubbles) and impacted by multi-phase flows. The morphology of surfaces affected by erosion-corrosion may be in the form of shallow pits or horseshoes or other local phenomena related to the flow direction.
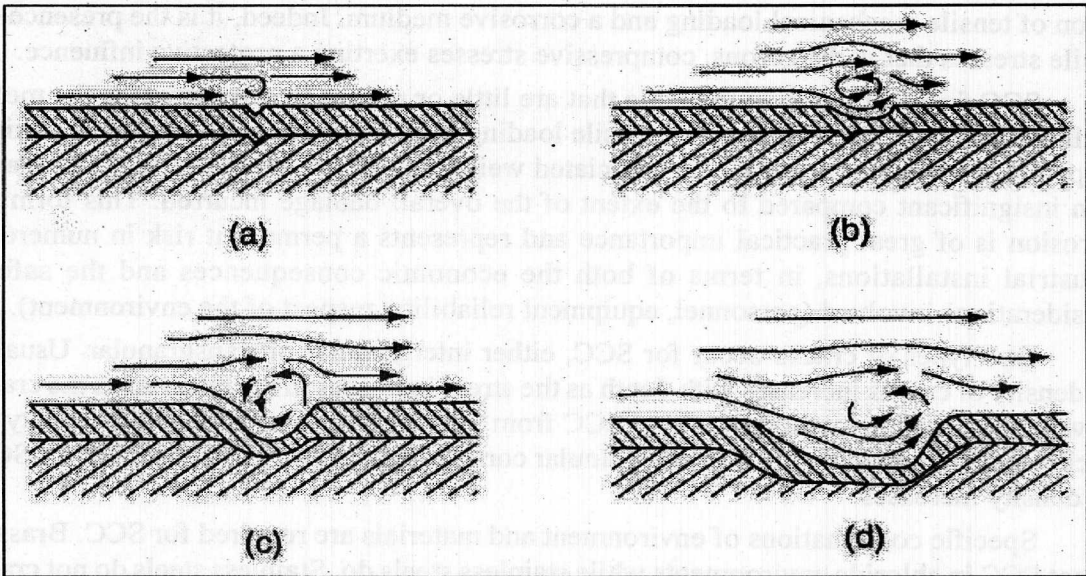
Fig. 8 : Schematic of erosion corrosion

Relevant Standards:

- G32-06 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus.
- G73-04 Standard Practice for Liquid Impingement Erosion Testing
- G76-07 Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets
- G117-02 Standard Guide for Calculating and Reporting Measures of Precision Using Data from Interlaboratory Wear or Erosion Tests
- G134-95(2006) Standard Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet
- G40-05 Standard Terminology Relating to Wear and Erosion.

Preventive Measures:

i) Materials with better resistance to erosion corrosion,

ii) Design,

iii) Alteration of the environment,

iv) Coatings, and

v) Cathodic protection.

Stress corrosion:

Stress corrosion cracking (SCC) is a process involving the initiation of cracks and their propagation, possibly up to complete failure of a component, due to the combined

action of tensile mechanical loading and a corrosive medium. Indeed, it is the presence of tensile stresses that is dangerous, compressive stresses exerting a protective influence.

SCC frequently occurs in media that are little or non-aggressive towards the metal or alloy concerned in the absence of tensile loading (e.g. austenitic stainless steels in high temperature water and steam). The associated weight losses are generally very small and even insignificant compared to the extent of the overall damage incurred. This form of corrosion is of great practical importance and represents a permanent risk in numerous industrial installations, in terms of both the economic consequences and the safety considerations involved (personnel, equipment reliability, respect of the environment).

Two types of cracks occur for SCC, either intergranular or transgranular. Usually the density of cracks increases with depth as the stress increases in the material as the crack grows. One possible method of telling SCC from intergranular corrosion is the density of cracks as a function of depth. For intergranular corrosion the density decreases but for SCC the density increases.

Specific combinations of environment and materials are required for SCC. Brasses do not SCC in chloride environments while stainless steels do. Stainless steels do not crack in ammonia environments but brasses do.

There is no known category of commercial metals and alloys that is fully immune to SCC. Even materials such as glasses, plastics and rubbers can also be prone to this type of attack in certain conditions. The time necessary for a part to fail by SCC can vary from a few minutes to several years.

Example : An example of residual stress resulting in stress corrosion cracking of brass is after deep drawing. Large hoop residual tensile stresses are present after the deep drawing process. If an aggressive environment is placed on the brass, cracks will appear due to the conjoint action of the stress and the environment. In its early days this was called "season cracking" as it occurred during the monsoon season in India on brass bullets and cartridge shells due to ammonia from rotting vegetation rendering them useless as they stress corrosion cracked. Similarly "caustic embrittlement" is due to sodium hydroxide in combination with residual stresses on steels.

Mechanism: Stress Corrosion Cracking Mechanisms:

Regions where stress corrosion cracks are viable can be related to the potentiodynamic scans for passive materials. Two regions are possible, one at the start potential for passive films or the pit nucleation potential and a second at the active to passive transition at much lower potentials. It should be noted that at both these potentials the passive film is somewhat unstable. In one case it is just on the verge of forming and in the second case it is just on the verge of breakdown. Therefore SCC could be viewed as amplification of instability in passive films. Importantly, SCC can be viewed as an ANODIC process as anodic current is required for SCC to occur. It is this fact that separates it from hydrogen embrittlement which has many of the same features but is cathodic in control.

Stress corrosion cracking can be separated into two distinct regions, crack initiation and crack propagation.

Crack Initiation

Cracks can be initiated by several mechanisms:-

a) Mechanical Features.

Cracks will often initiate at features such as scratches, nicks or dents on the surface of the metal. In this case the local environment or local stress conditions favor enhanced dissolution, poor formation of a passive film or in-situ damage to a protective film.

b) Local galvanic cells initiating dissolution.

Local corrosive effects dominate the process where the local galvanic cell locally dissolves one phase of the material. This will also localize the stress on the material. The crack in this case may initiate in a transgranular mode or an intergranular mode. One example of the latter would be intergranular cracks during SCC of sensitized stainless steels.

c) Pitting type crack initiation.

The pitting potential is related to formation of pits and there is some correlation between the pitting potential and the potential for stress corrosion cracking. A 10:1 ratio of pit depth to width was suggested to be needed for a pit to initiate a crack. The local environment in a pit may also be important in the crack growth process. For example, the environment in a pit mat favor crack growth by intergranular crack growth. Several studies were made employing a pit as an effective crack in the surface to be used in linear elastic fracture mechanics approach. These have met with some success. However electrochemical effects can nullify this approach.

d) Initiation at stress induced phenomena.

Slip lines intersecting the surface can have a double effect. One is to provide local anodes as the site is very active. The second is to rupture passive films on the surface and locally form dissolving regions.

Once a crack has initiated, then it will grow. As pointed out above the growth mechanism may not be the same as the initiation process. Several mechanisms were proposed to explain the observed features of SCC crack growth.

Crack Growth Mechanisms

One important feature for SCC cracks is that some show clear evidence of stopping and starting. The cracks do not continually grow to failure. The mechanisms proposed try and take this factor into account.

a) Film Rupture Mechanism.

The tensile stress ruptures films at the crack tip and the crack grows rapidly from the bare metal exposed until the crack tip can repassivate in some cases or grow slowly to failure in other cases. Unfortunately, SCC cracks often have significant

features on their faces which should be removed by local dissolution effects. In addition the crack plane in transgranular failure is often not the active slip system in the metal. Others have suggested a similar model in which the film is formed by a tarnish process. Intergranular corrosion is proposed to occur by preferential oxidation of the grain boundaries.

b) Film Cleavage Mechanism.

In this mechanism, the surface film grows and may increase in internal stress with thickness. This combined with the applied tensile stress induces brittle failure in the film which propagates across into the metal and provides a period of crack growth. The loss of the film stress and plasticity in the metal than blunts the crack and stops it growing to give periods of crack growth followed by rest while the film grows back to the conditions for cleavage.

c) Adsorption Induced Cleavage.

During the electrochemical process atoms are absorbed on the surface that weakens the bonds. The stress to initiate a crack then decreases and a crack grows until it is blunted by plastic deformation or grows out of the adsorbed region.

d) Adsorption Induced Plasticity.

The adsorption of specific ions in this cases reduces the critical resolved shear stress for dislocation mobility. Dislocations can then move locally under the influence of the tensile stress. This is different from the above model where the cohesive strength was decreased but not the resolved shear stress as in this case.

e.) Atomic Surface Mobility.

At the crack tip atoms move away from the tip and vacancies move in by a surface diffusion process coupled with electrochemical activity. There is not a lot of support for this mechanism at present.

f) Corrosion Tunnel Model.

In this case, corrosion tunnels are formed by active corrosion alone emerging slip lines. When sufficient metal is removed in the tunnels, then the undissolved regions between them fracture by ductile overload and some crack growth occurs until it is plastically blunted and the process starts again. A later modification suggested the tunnels were slots on an atomic scale, which can only be formed in stainless steels by SCC conditions.

Many of these mechanisms cannot be verified easily by experimental methods. It is suspected that there is no universal model for SCC growth and initiation. Each specific combination of metal environment and stress can produce different fracture evidence. In general SCC fracture surfaces look brittle in nature with evidence of non-continual crack growth. Unfortunately, cross sections of samples show some evidence of local ductility or plastic flow as well. This tends to ad to the confusion surrounding mechanistic studies of the process.
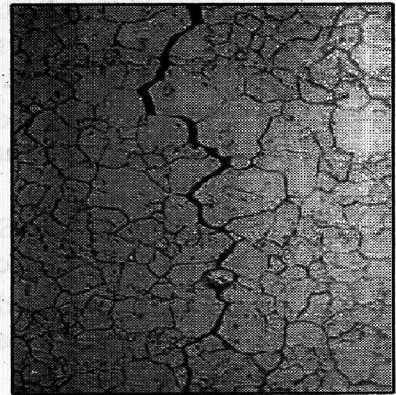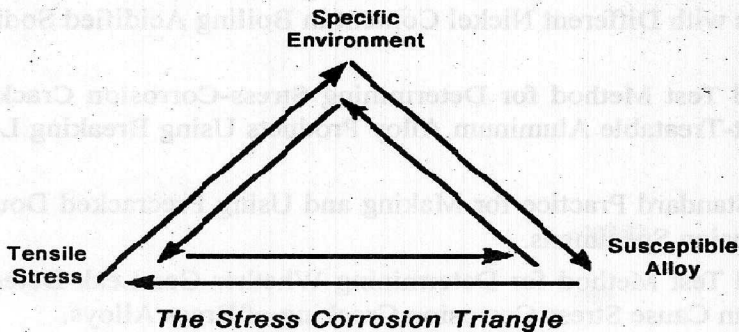
Fig. 9 : *The stress corrosion triangle, and intergranular SCC*

Relevant Standards:

- G30-97 (2003) Standard Practice for Making and Using U-Bend Stress-Corrosion Test Specimens.

- G35-98 (2004) Standard Practice for Determining the Susceptibility of Stainless Steels and Related Nickel-Chromium-Iron Alloys to Stress-Corrosion Cracking in Polythionic Acids.

- G36-94 (2006) Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution.

- G37-98 (2004) Standard Practice for Use of Mattsson's Solution of pH 7.2 to Evaluate the Stress- Corrosion Cracking Susceptibility of Copper-Zinc Alloys.

- G38-01 (2007) Standard Practice for Making and Using C-Ring Stress-Corrosion Test Specimens.

- G39-99 (2005) Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens.

- G41-90 (2006) Standard Practice for Determining Cracking Susceptibility of Metals Exposed Under Stress to a Hot Salt Environment.

- G47-98 (2004) Standard Test Method for Determining Susceptibility to Stress-Corrosion Cracking of 2XXX and 7XXX Aluminum Alloy Products.

- G49-85 (2005) Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens.

- G58-85 (2005) Standard Practice for Preparation of Stress-Corrosion Test Specimens for Weldments.

- G64-99 (2005) Standard Classification of Resistance to Stress-Corrosion Cracking of Heat-Treatable Aluminum Alloys.

- G103-97 (2005) Standard Practice for Evaluating Stress-Corrosion Cracking Resistance of Low Copper 7XXX Series Al-Zn-Mg-Cu Alloys in Boiling 6% Sodium Chloride Solution

- G123-00 (2005) Standard Test Method for Evaluating Stress-Corrosion Cracking of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution.

- G139-05 Standard Test Method for Determining Stress-Corrosion Cracking Resistance of Heat-Treatable Aluminum Alloy Products Using Breaking Load Method.

- G168-00 (2006) Standard Practice for Making and Using Precracked Double Beam Stress Corrosion Specimens.

- G186-05 Standard Test Method for Determining Whether Gas-Leak-Detector Fluid Solutions Can Cause Stress Corrosion Cracking of Brass Alloys.

Preventive Measures:

i) Elimination of residual stresses by stress relieving heat treatments.

ii) Purification of the medium.

iii) Choice of the most appropriate material.

iv) Improvement of the surface condition.

v) Avoid surface machining stresses.

vi) Performing peening treatments on welds to induce surface compressive stresses.

vii) Applying external protection methods (cathodic protection, inhibitors and organic or inorganic protective coatings).

OTHER FORMS OF CORROSION

Hydrogen Embrittlement:

The presence of hydrogen atoms in a metal crystal lattice can be extremely detrimental, leading to a catastrophic loss of mechanical strength and ductility. It is generally accepted that the hydrogen is first of all adsorbed on the metal surface before penetrating the lattice, where it diffuses in ionic form (i.e. as protons). The hydrogen atoms can have various origins the surrounding atmosphere containing hydrogen or hydrogenated compounds (H_2S, NH_3, H_2O, etc.), electroplating processes during which the proton reduction reaction occurs, electrochemical corrosion during which the cathodic reaction is proton reduction. Once they have penetrated the crystal lattice, hydrogen atoms can cause several types of damage.

Precipitation of brittle hydrides: this occurs in titanium and other metals with a high affinity for hydrogen (Ta, Zr, V, Pd, etc.).

Recombination to molecular hydrogen: when the metal contains macroscopic discontinuities or microscopic defects, these can represent sites for the recombination of hydrogen atoms. The hydrogen molecules are unable to diffuse away into the lattice and it is possible to build up high local pressures, leading to the formation of flakes and blisters, and "ladder-type" cracking.

Hydrogen embrittlement: by interacting with lattice dislocations, hydrogen atoms cause a marked loss in the plastic strain capacity of the metal, which becomes brittle.
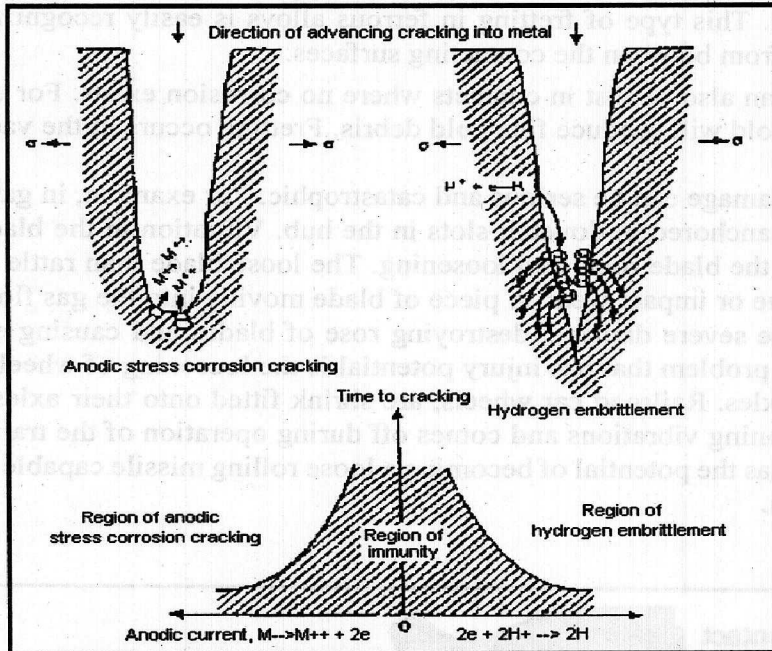

Fig. 10* : *Schematic differentiation of anodic stress-corrosion cracking and cathodically sensitive hydrogen embrittlement

Preventive Measures:

For prevention of blistering: use sound steels containing few inclusions and defects, use coatings "impermeable" to hydrogen (nickel or enamel coated steel tanks, austenitic stainless steel cladding, rubber, polymers, etc.), employ inhibitors in the case of an aggressive medium operating in a closed circuit, etc.

For prevention of hydrogen embrittlement: reduce the corrosion rate, modify the electroplating conditions, change the alloy, take appropriate precautions during welding and so on.

This form of corrosion is discussed in detail, in one of the lectures of this training program.

Fretting Corrosion:

Fretting corrosion is a combined wear and corrosion process in which material is removed from contacting surfaces when motion between the surfaces is restricted to very small amplitude oscillation (as low as 3 or 4 nm). Usually the condition used in machine components that are considered fixed and not expected to wear. Pressed on wheels can often fret at the shaft/wheel hole interface.

Oxidation is the most common element in the fretting process. In oxidizing systems, fine metal particles remove by adhesive wear are oxidized and trapped between the fretting surfaces the oxides act like an abrasive (such as lapping rogue) and increase the rate of material removal. This type of fretting in ferrous alloys is easily recognized by the red material oozing from between the contacting surfaces.

Fretting can also persist in contacts where no corrosion exists. For example, gold fretting against gold will produce fine gold debris. Fretting occurs in the vacuum of outer space.

Fretting damage can be serious and catastrophic. For example, in gas turbines, the blades are often anchored in dovetail slots in the hub. Vibration in the blade system can cause fretting in the blade roots and loosening. The loose blade than rattle and break out because of fatigue or impact wear. A piece of blade moving into the gas flow through the turbine can cause severe damage, destroying rose of blades and causing engine failure. Another fretting problem that has injury potential is the loosening of wheels or flywheels from shafts or axles. Railroad car wheels, are shrink fitted onto their axles. If the wheel loosens from running vibrations and comes off during operation of the train, it can cause derailment and has the potential of becoming a loose rolling missile capable of penetrating nearby buildings.
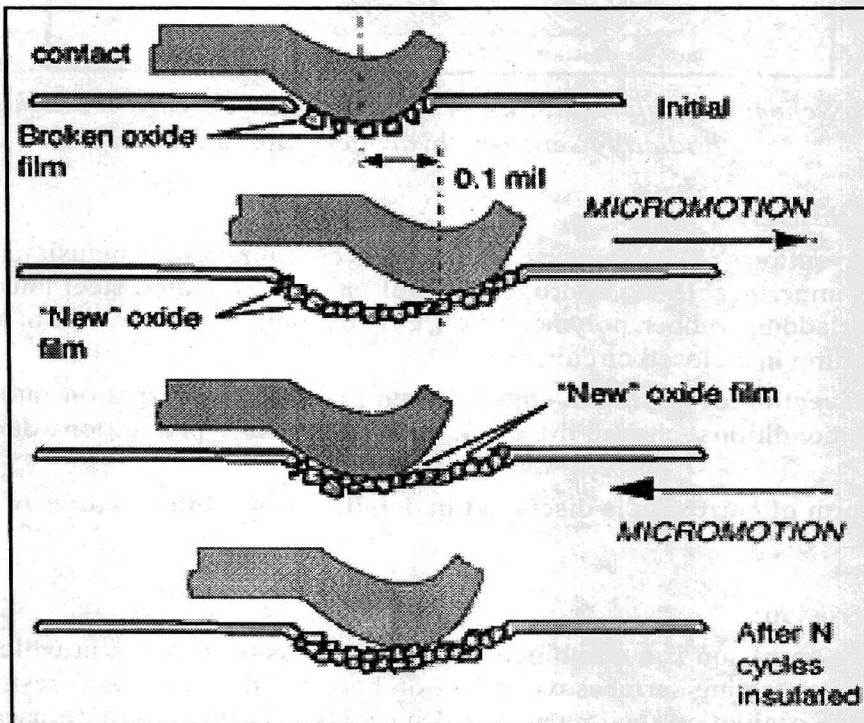

Fig. 10 : Fretting corrosion

Preventive Measures:

- Lubrication with oils or greases, to reduce friction and exclude oxygen from the interface.
- Increase in the hardness of one or both materials in contact. Certain material combinations show better friction behaviour than others. Surface hardening treatments can be beneficial.
- Use of seals to absorb vibrations and exclude oxygen and/or moisture.
- Reduction of the friction loads in certain cases, or on the contrary, increase of the friction loads to attenuate vibrations.
- Modification of the amplitude of the relative movement between the two contacting surfaces.

Stray Current Corrosion:

When a direct current flows through an unintended path and the flow of electrons supports corrosion. This can occur in soils and flowing or stationary fluids.

Preventive Measures:

- Insulating the structure to be protected or the source of current
- Earthing sources and/or the structure to be protected.
- Applying cathodic protection
- Using sacrificial targets.

Microbial Corrosion:

This general class covers the degradation of materials by bacteria, moulds and fungi or their by-products. It can occur by a range of actions such as:

Attack of the metal or protective coating by acid by-products, sulphur, hydrogen sulphide or ammonia.

Direct interaction between the microbes and metal which sustains attack.

Preventive Measures:

- Selection of resistant materials
- Frequent cleaning
- Control of chemistry of surrounding media and removal of nutrients
- Use of biocides
- Cathodic protection.

Thermogalvanic Corrosion:

Temperature changes can alter the corrosion rate of a material and a good rule of thumb is that 10°C rise doubles the corrosion rate. If one part of component is hotter than another the difference in the corrosion rate is accentuated by the thermal gradient and local attack occurs in a zone between the maximum and minimum temperatures.

Preventive Measures:

· Design out the thermal gradient
· Supply a coolant to even out the difference.

Corrosion Fatigue:

The combined action of cyclic stresses and a corrosive environment reduce the life of components below that expected by the action of fatigue alone.

Corrosion-fatigue differs from SCC by the fact that the applied stresses are no longer static, but cyclic (periodically fluctuating or alternating loads).

In the case of steels, the conventional fatigue limit determined from so-called Wöhler curves (applied stress as a function of cycles to failure ä = f(N)) does not exist for tests performed in a corrosive medium. Whatever the stress level, failure will eventually occur after a finite number of cycles. The cracks are generally transgranular in nature, with little tendency for branching. However, a few small secondary cracks may appear in the vicinity of the main crack. Although there is no direct relationship between the sensitivity to corrosion-fatigue and the mechanical properties of the material, high strength alloys tend to be most highly prone.

Preventive Measures:

- Decreasing the tensile stresses
- Applying mechanical surface treatments such as peening
- Coating the material
- Improvement of the surface condition by polishing
- Corrosion inhibitors
- Good design that reduces stress concentration
- Avoiding sudden changes of section
- Removing or isolating sources of cyclic stress

CONCLUSION

"Murphy's Laws" may be used to summarize our comments on corrosion. For example, "Anything that can go wrong will go wrong," and "Anything that has been put together will fall apart sooner or later." We can paraphrase that and say, "Anything that has been put together by man sooner or later will corrode." And add, "It needs the attention of a corrosion engineer before the corrosion starts."

Appendices:

- List of ASTM standards
- List of NACE standards
- List of corrosion related ISO standards
- Corrosion data

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18) *http://hyperphysics.phy-astr.gsu.edu/hbase/chemical/corrosion.html*

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