

A PICTORIAL GUIDE:

COMMON TYPES OF CORROSION

CONCENTRATION CELL CORROSION

Concentration cell corrosion occurs when two or more areas of a metal surface are in contact with different concentrations of the same solution. There are three general types of concentration cell corrosion:

- (1) Metal ion concentration cells
- (2) Oxygen concentration cells, and
- (3) Active-passive cells.

Metal Ion Concentration Cells

In the presence of water, a high concentration of metal ions will exist under faying surfaces and a low concentration of metal ions will exist adjacent to the crevice created by the faying surfaces. An electrical potential will exist between the two points. The area of the metal in contact with the low concentration of metal ions will be cathodic and will be protected, and the area of metal in contact with the high metal ion concentration will be anodic and corroded. (See Pitting Corrosion)

Preventative Measures:

Sealing the faying surfaces with a protective coating to exclude moisture can eliminate this condition.

Oxygen Concentration Cells

Water will normally contain dissolved oxygen. An oxygen cell can develop at any point where the oxygen in the air is not allowed to diffuse uniformly into the solution, thereby creating a difference in oxygen concentration between two points. Oxygen concentration cells are typically found under either metallic or nonmetallic deposits (dirt) on metal surfaces and under faying surfaces such as riveted lap joints. Oxygen cells can also develop under gaskets, wood, rubber, plastic tape, and other materials in contact with the metal surface. Corrosion will occur at the area of low-oxygen concentration (anode).

Preventative Measures:

This type of corrosion can be minimized or eliminated by using a suitable protective coating that seals and prevents water permeation/incursion, maintaining clean surfaces, and avoiding the use of material that permits wicking of moisture between faying surfaces.

Active-Passive Cells

Active-passive cells can corrode metals that depend on a tightly adhering passivating film (usually an oxide) for corrosion protection. The corrosive action usually starts as an oxygen concentration cell. Salt deposits on the metal surface in the presence of water containing oxygen can create the oxygen cell. If the passive film is broken beneath the salt deposit, the active metal beneath the film will be exposed to corrosive attack. An electrical potential will develop between the large area of the cathode (passive film) and the small area of the anode (active metal). Rapid pitting of the active metal will result.

Preventative Measures:

This type of corrosion can be avoided by use of protective coatings and frequent cleaning of the metal surface.

CORROSION IN CONCRETE

Concrete is a widely used structural material that is frequently reinforced with carbon steel rods (rebar), post-tensioning cable or pre-stressing wires. Steel, which is necessary to maintain the strength of the cementaceous structure, is subject to corrosion. The cracking associated with corrosion in concrete is a major concern in areas with marine environments and in areas which use de-icing salts.



The photo above (left) shows cracking and staining of a concrete seawall. Pitting corrosion in the photo above (right) occurred on the aluminum railing on a concrete causeway over an inlet to the Atlantic Ocean.

There are two theories on how corrosion in concrete occurs:

1. Salts and other chemicals enter and permeate the concrete and cause corrosion of metal reinforcing elements. Corrosion of the metal elements leads to expansive forces that cause cracking and bursting of the concrete structure.
2. Cracks in the concrete allow moisture and salts to reach the metal elements and cause corrosion.

Both possibilities have their advocates, and it is also possible that corrosion in concrete occurs by either or a combination of both mechanisms.

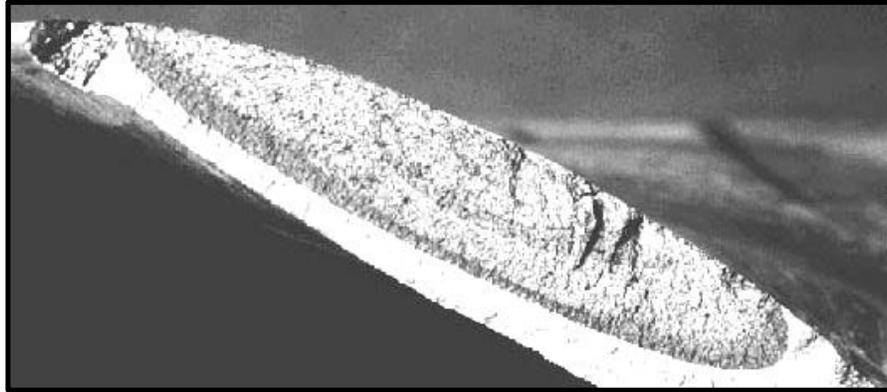
Preventative Measures:

Coating the metal reinforcing elements with a protective coating, and the use of chemical admixtures controls corrosion in new concrete. These methods are very effective, and most concrete structures, even in marine environments, can be effectively protected from corrosion.

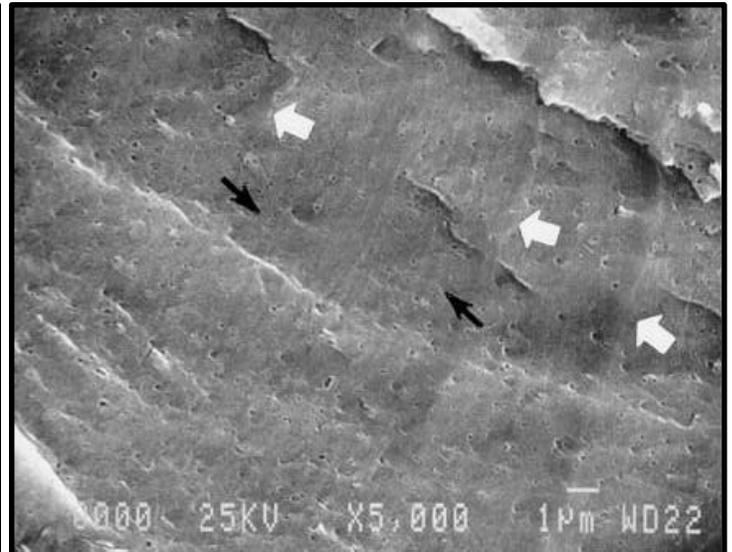
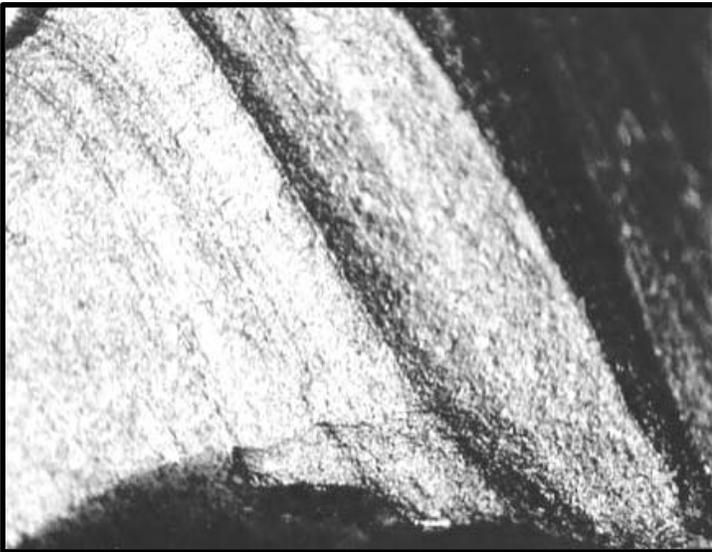
Remedial action for old concrete structures can include repairing the cracked and spalled concrete, coating the surface to prevent further entry of corrosive chemicals into the concrete, and cathodic protection (See Galvanic Corrosion).

CORROSION FATIGUE

Corrosion fatigue is a special case of stress corrosion caused by the combined effects of cyclic stress and corrosion environment. No metal is immune from some reduction of its resistance to cyclic stressing if the metal is in a corrosive environment. Damage from corrosion fatigue is greater than the sum of damage caused from cyclic stresses and corrosive environment independently.



The "beach marks" on the propeller shown above mark the progression of fatigue.



Similar beach marks are shown on the aerospace part (above, left). The high magnification scanning electron microscope image (above, right) shows striations (individual crack progression marks). The part shown above is also discussed in the section on fretting corrosion.



An infamous example of corrosion fatigue occurred in 1988 on an airliner flying between the Hawaiian islands (left). This disaster, which cost one life, prompted the airlines to look at their airplanes and inspect for corrosion fatigue.

Preventative Measures:

Control of corrosion fatigue can be accomplished by using a suitable protective coating and/or by minimizing cyclic stresses.

CREVICE CORROSION

(A.K.A. CONTACT CORROSION)

Crevice corrosion is produced at the contact point of metals with metals or metals with nonmetals. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints. Whether or not stainless steels are free of pit nuclei, they are always susceptible to this kind of corrosion because a nucleus is not necessary.



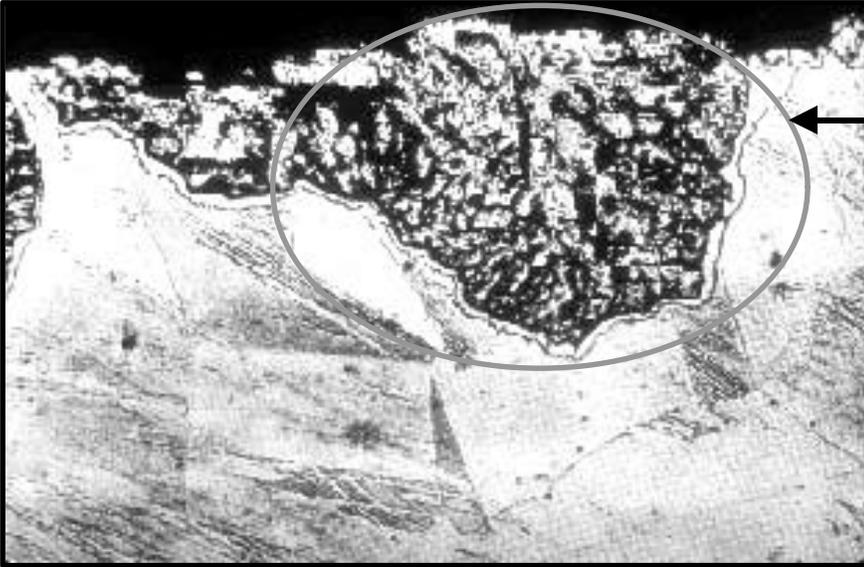
The crevice corrosion shown above occurred when an aerospace alloy (titanium - 6 aluminum – 4 vanadium) was used instead of a more corrosion-resistant grade of titanium. Special alloying additives are added to titanium to make alloys, which are crevice corrosion resistant, even at elevated temperatures.

Preventative Measures:

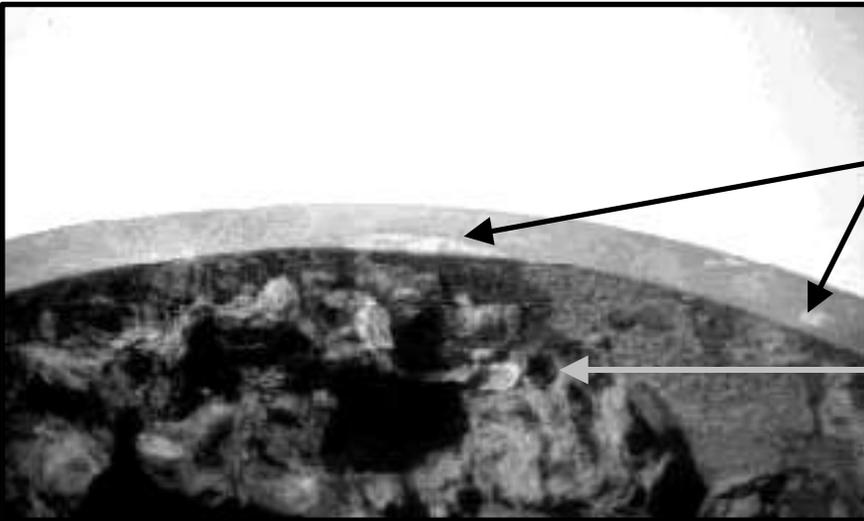
Cleanliness, the proper use of sealants, and protective coatings are effective means of controlling this problem. Molybdenum-containing grades of stainless steel (e.g. 316 and 316L) have increased crevice corrosion resistance.

DE-ALLOYING

De-Alloying is a rare form of corrosion found in alloys such as copper alloys and gray cast iron and other alloys. De-Alloying occurs when the alloy loses the active component of the metal and retains the more corrosion resistant component in a porous "sponge" on the metal surface. It can also occur by re-deposition of the noble component of the alloy on the metal surface.

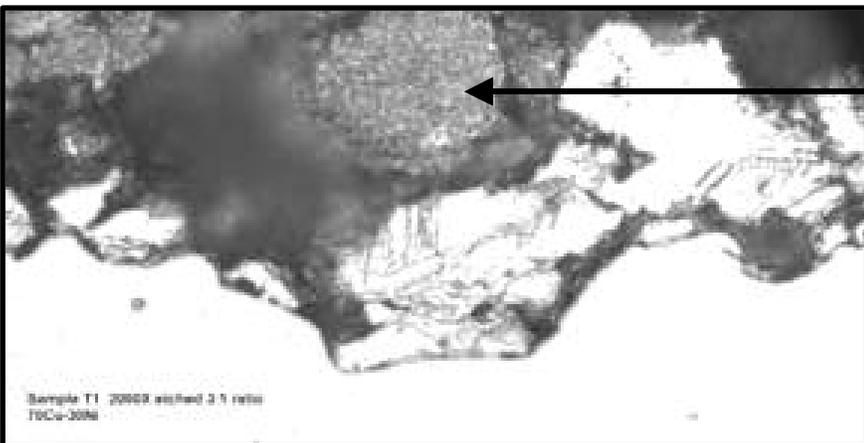


The brass (left) dezincified leaving a porous (spongy) copper plug on the surface.



The gray cast iron water pipe shown at left has graphitized and left graphitic surface plugs which can be seen on the cut surface.

The rust tubercles or bubbles are also an indication of pitting corrosion (See Pitting Corrosion).



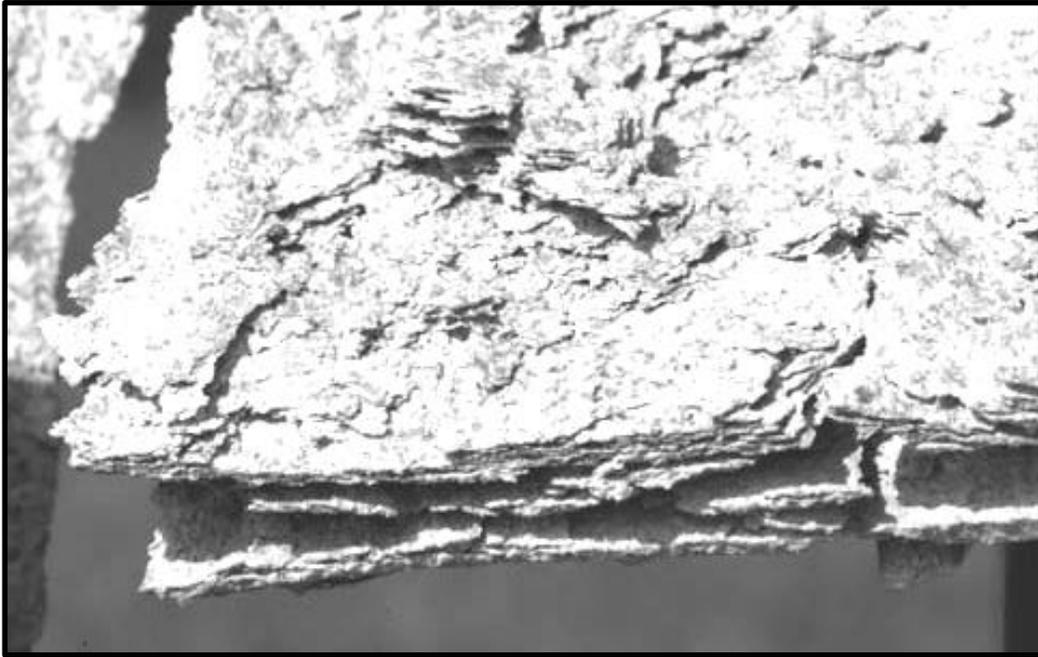
This photo (left) shows a layer of copper on the surface of a de-alloyed 70% copper-30% nickel cupronickel heat exchanger tube removed from a ship. Stagnant seawater is so corrosive that even this normally corrosion-resistant alloy corroded. Virtually all copper alloys are subject to de-alloying in conducive environments.

Preventative Measures:

This type of corrosion is accomplished by using a suitably protective coating or by the use of more resistant alloys such as inhibited brasses and malleable or nodular cast iron

EXFOLIATION CORROSION

Exfoliation, a form of intergranular corrosion, manifests from the forced displacement of surface metal grains by the force of expanding corrosion products occurring at the grain boundaries just below the surface. It is visible evidence of intergranular corrosion and most often seen on extruded sections where grain thickness is less than in rolled forms. This form of corrosion is common on aluminum, and it may occur on carbon steel.



The photo above shows exfoliation of aluminum. Exfoliation of carbon steel is apparent in the channel on the coating exposure panel below. The expansion of the metal caused by exfoliation corrosion can create stresses that can bend or break connections and lead to structural failure (see also Corrosion in Concrete).

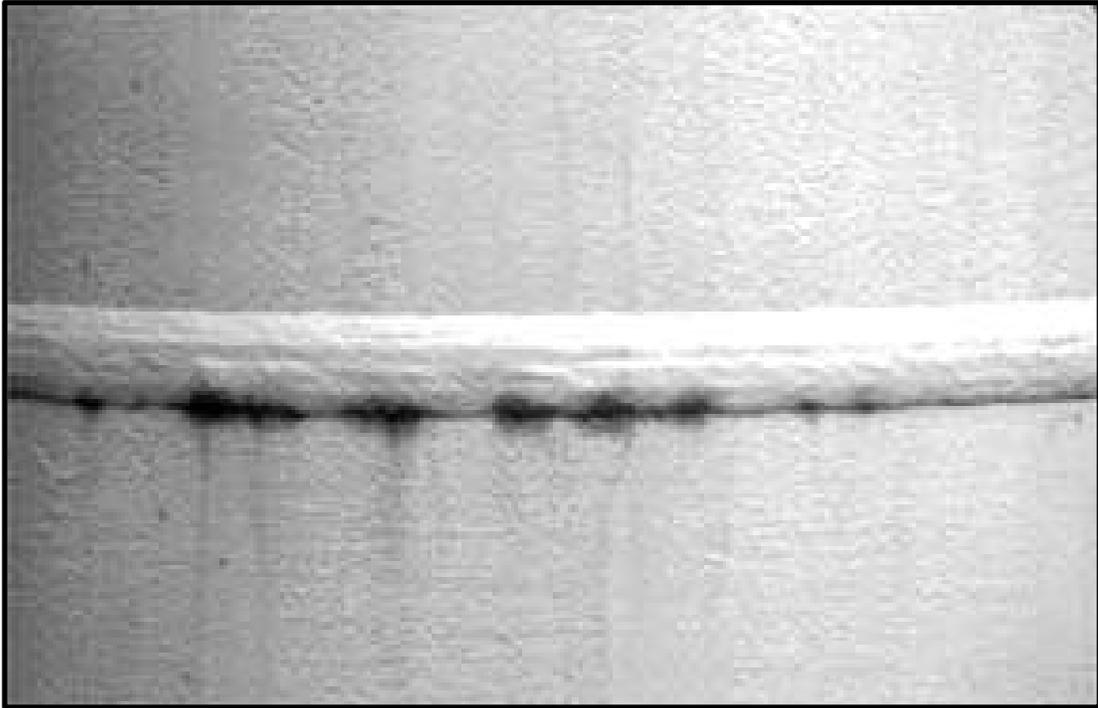


Preventative Measures:

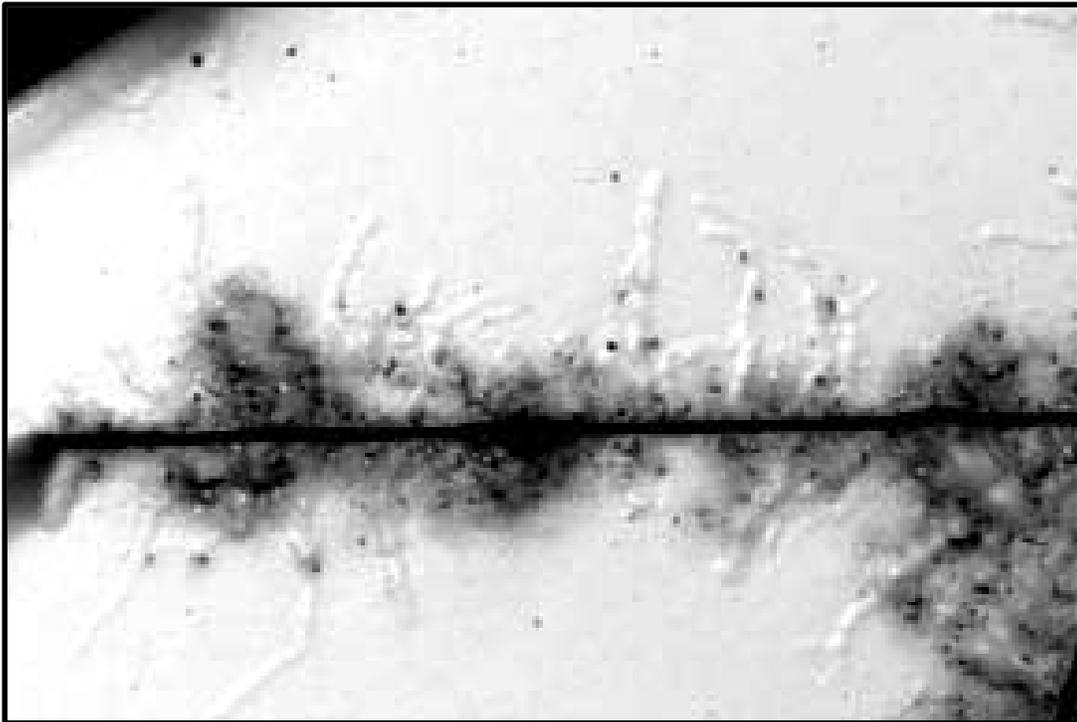
This type of corrosion can be controlled by using a suitable protective coating, or by using stabilized stainless steels (321 or 347) or by using low-carbon stainless grades (304L or 316L).

FILIFORM CORROSION

This type of corrosion occurs under painted or plated surfaces when moisture permeates through the coating. Lacquers and "quick-dry" paints are most susceptible to the problem. Their use should be avoided unless absence of an adverse effect has been proven by field experience.



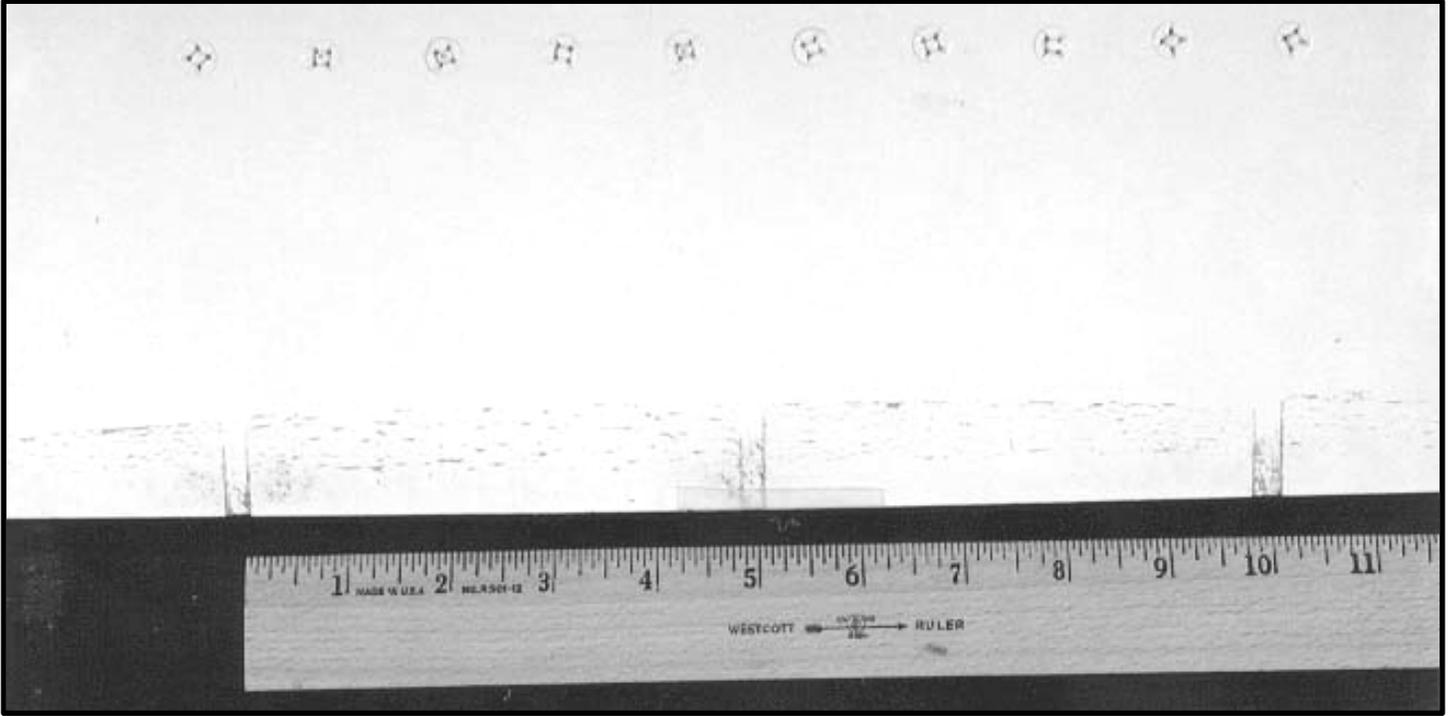
The photograph above shows filiform corrosion causing bleed-through on a welded tank. The photograph below shows "worm-like" filiform corrosion tunnels forming under a coating at NASA's Kennedy Atmospheric Test Site. *Preventative Measures:*



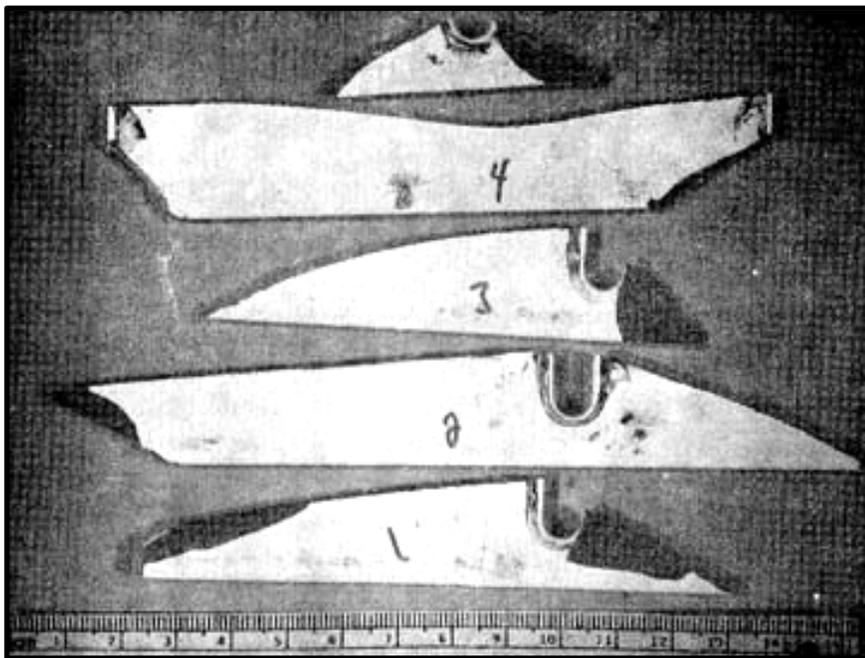
Using a protective coating with low water vapor transmission characteristics and excellent adhesion can control this type of corrosion.

FRETTING CORROSION

The rapid corrosion that occurs at the interface between contacting, highly loaded metal surfaces when subjected to slight vibratory motions is known as fretting corrosion. This type of corrosion is most common in bearing surfaces in machinery, such as connecting rods, splined shafts, and bearing supports, and often causes a fatigue failure. It can occur in structural members such as trusses where highly loaded bolts are used and some relative motion occurs between the bolted members.



The fretting on a large aluminum part (above left) led to deposits of debris (shown in the cross sections below). The vibratory motions rubbing back and forth also produced the fatigue cracks shown in the section on fatigue corrosion.



Preventative Measures:

Using a protective can retard this type of corrosion or the contacting surfaces can be well lubricated so as to exclude direct contact with air.

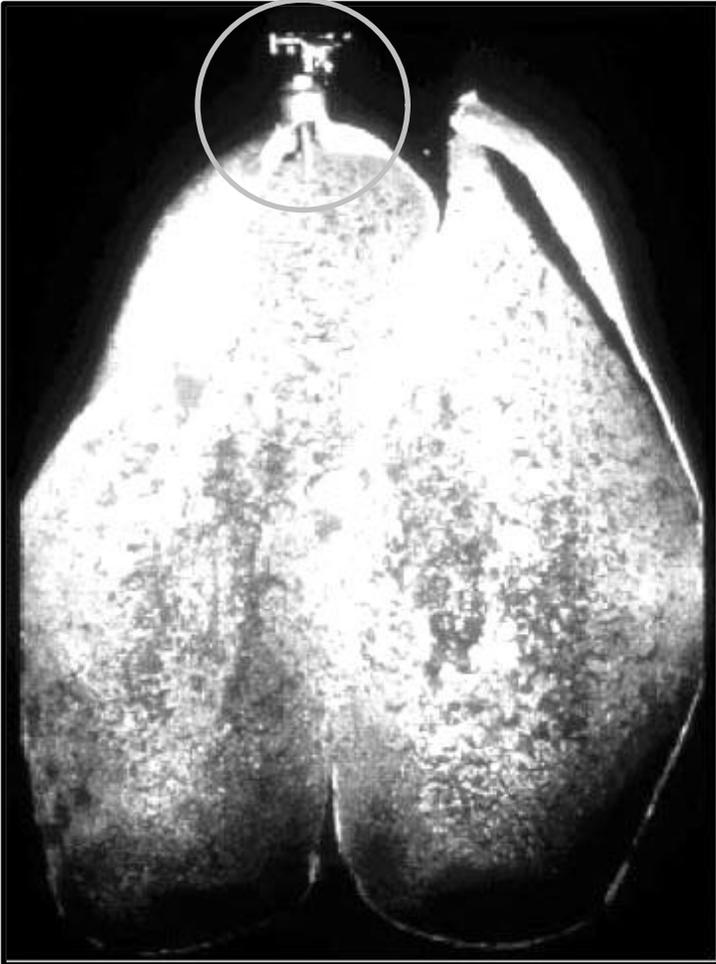
GALVANIC CORROSION

Galvanic corrosion is an electrochemical reaction between two dissimilar metals in the presence of an electrolyte and an electron conductive path. This form of corrosion is characterized by the presence of aggravated corrosion at the joint between the dissimilar metals. For example, when aluminum alloys or magnesium alloys are in contact with steel (carbon steel or stainless steel), galvanic corrosion can occur at the juncture.

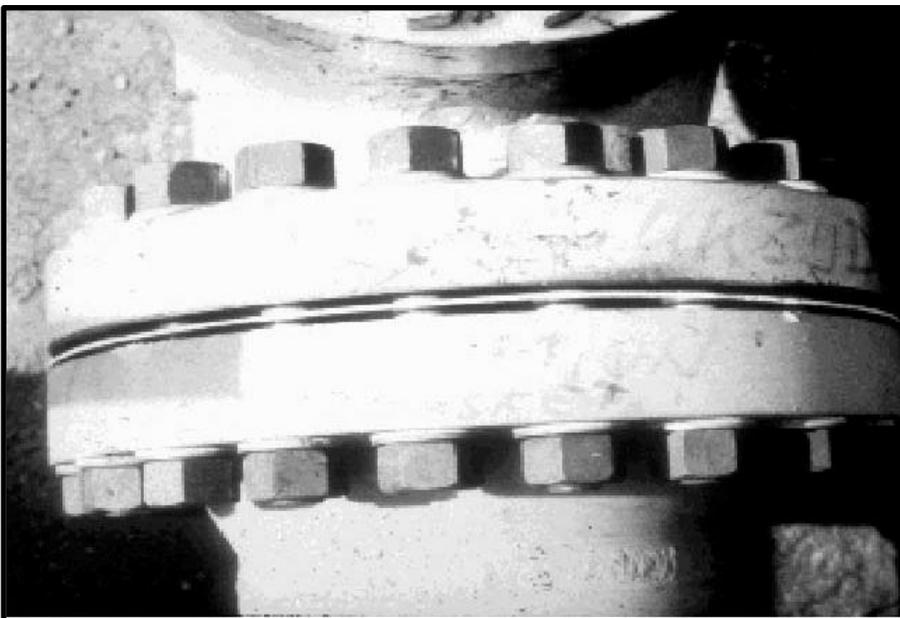
Inherent differences in metal potentials produce galvanic differences (Ref. the galvanic series, see Galvanic Corrosion). If electrical contact is made between any two of these materials in the presence of an electrolyte, a galvanic cell (battery) is formed and current will flow between them.

The farther apart the metals are in the galvanic series, the greater the galvanic corrosion effect or rate will be. The more active metal is the anode or the one that will corrode, while the cathode will not corrode.

Cathodic protection can also be used to control galvanic corrosion effects. This incorporates a sacrificial anode which corrodes while protecting the anode (Galvanization).



The scuba tank (left) suffered galvanic corrosion when the brass valve and the steel tank were wetted by condensation.



Electrical isolation flanges like those shown below are used to prevent galvanic corrosion. Insulating gaskets, usually polymers, are inserted between the flanges, and insulating sleeves and washers isolate the bolted connections.



The photograph above illustrates a stainless steel screw causing galvanic corrosion of aluminum. The corrosion in this photograph resulted after only six months exposure.

Preventative Measures:

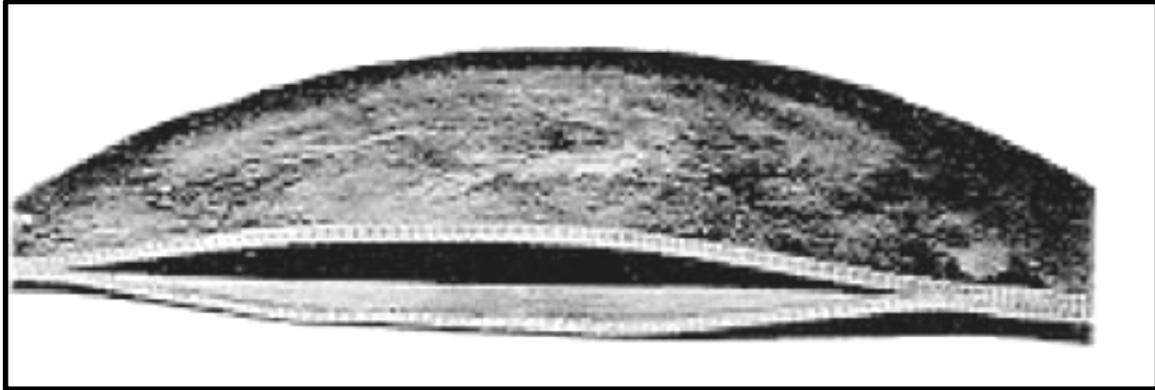
This type of corrosion can be controlled by using a suitable protective coating to electrically isolate dissimilar metals, or by using metals closer to each other in the galvanic series.

HYDROGEN EMBRITTLEMENT

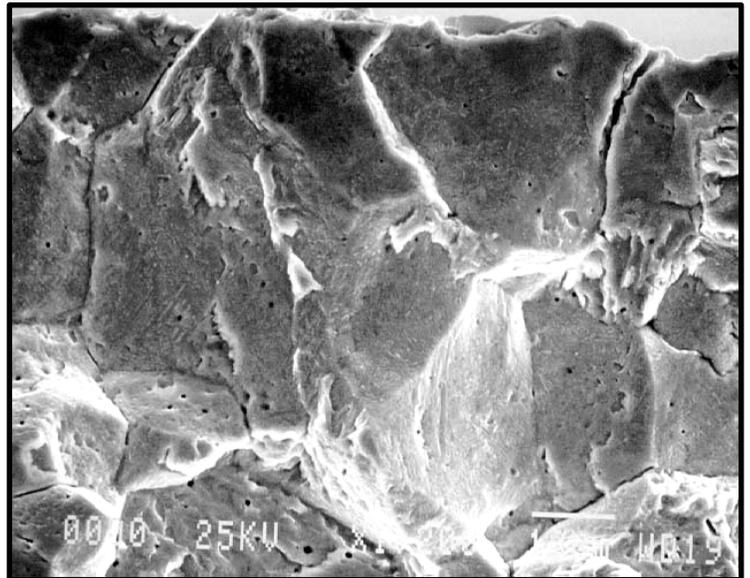
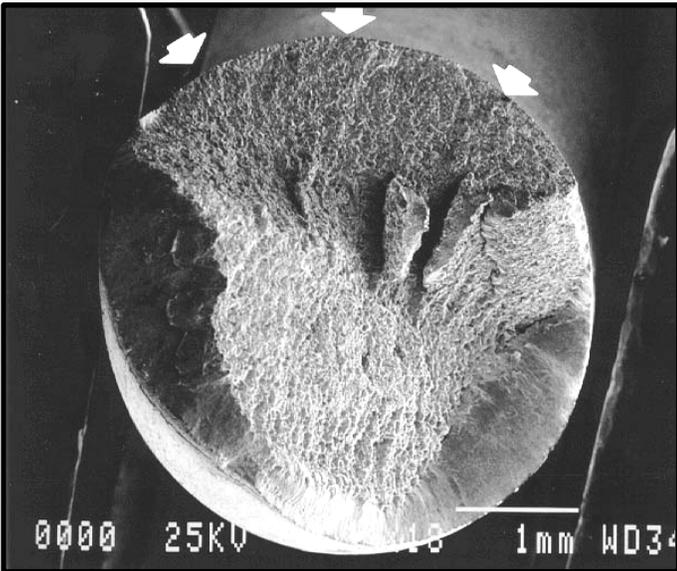
(A.K.A. HYDROGEN DAMAGE)

Hydrogen embrittlement is an engineering consideration with high-strength steels, titanium, and some other metals.

Hydrogen blistering can occur when hydrogen enters steel as a result of the reduction reaction on a metal cathode. Single-atom nascent hydrogen atoms diffuse through the metal until they meet and bond with another nascent hydrogen, usually at inclusions or defects in the metal. The resultant diatomic hydrogen molecules are then too large to out-gas and become trapped. Eventually a gas blister builds up and may split the metal as shown in the photo below.



Hydrogen blistering is controlled by minimizing corrosion in acidic environments. It is not a problem in neutral or caustic environments or with high-quality steels that have low impurity and inclusion levels.



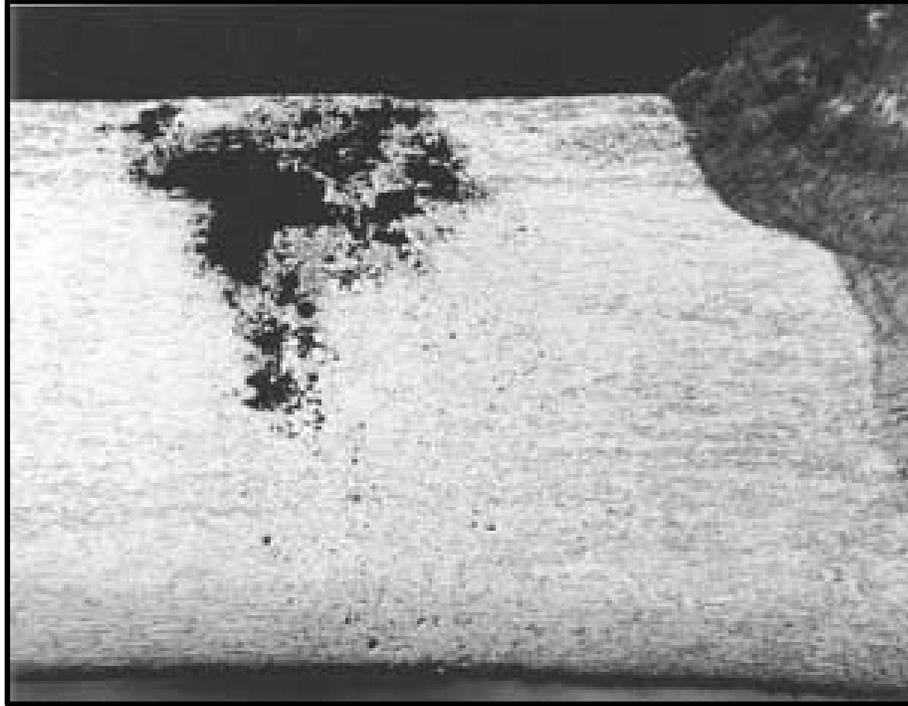
Failure analysis of a broken spring at high magnification (above, left) and using a scanning electron microscope (above right) revealed intergranular cleavage characteristic of hydrogen assisted cracking (hydrogen embrittlement). The part was zinc plated during refurbishment, and the hydrogen, which entered the metal during the plating process, had not been baked out. A post-plating bake procedure should be standard for high strength steels.

Preventative Measures:

This type of corrosion can be controlled by using a suitable protective coating to eliminate water-source hydrogen (electrolysis), eliminating hydrogen from the environment (acidity) or by the use of resistant alloys.

INTERGRANULAR CORROSION

Intergranular corrosion occurs on or adjacent to the grain boundaries of an alloy. A highly magnified cross section of commercial alloys will show a granular structure. Individual grain has a clearly defined boundary that chemically differs from the metal within the grain center. Heat treatment of stainless steels and aluminum alloys accentuates this problem.



The picture above shows stainless steel, which corroded in the heat affected zone a short distance from the weld.

Intergranular corrosion type of corrosion is typical in austenitic stainless steels.

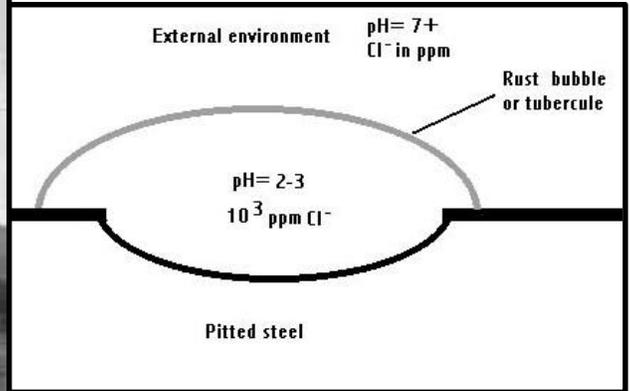
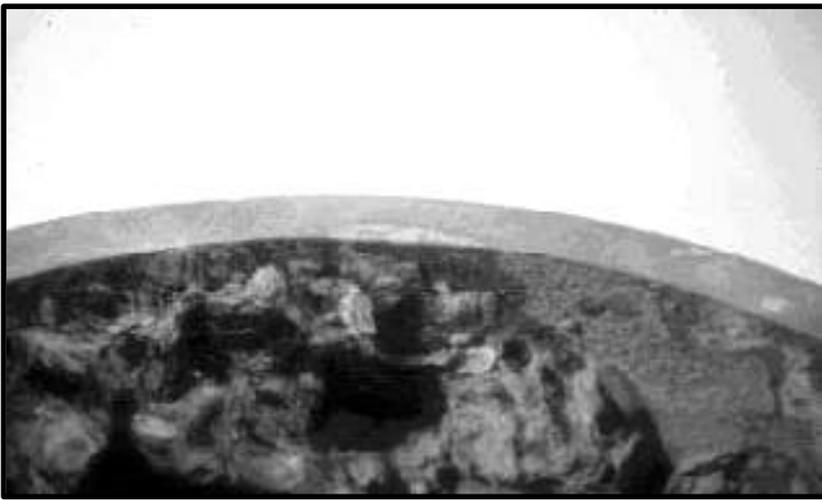
Heat-treatable aluminum alloys (2000, 6000, and 7000 series alloys) can also have this problem. See exfoliation corrosion.

Preventative Measures:

This type of corrosion can be controlled by using a suitable protective coating, using stabilized stainless steels (321 or 347) or by using low-carbon stainless grades (304L or 316L).

PITTING CORROSION

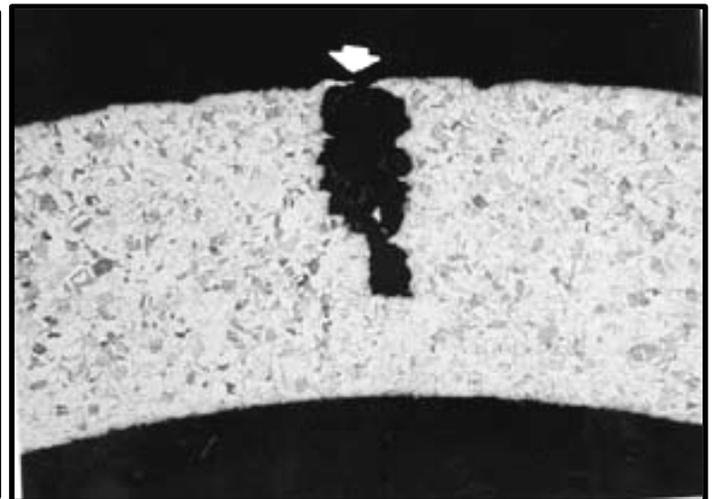
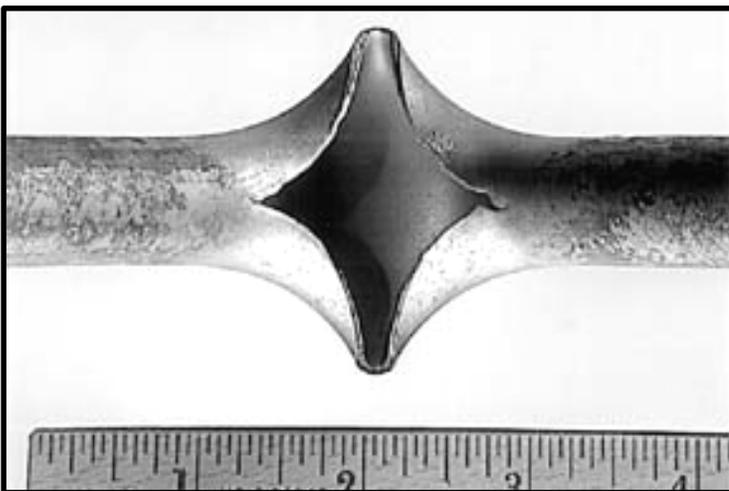
Passive metals, such as stainless steel, resist corrosive media and can perform well over long periods of time. However, if corrosion does occur, it forms at random in pits. Pitting is most likely to occur in the presence of chloride ions, combined with such depolarizers as oxygen or oxidizing salts.



Left: Rust bubbles or tubercles on cast iron. Such bubbles are indicators that pitting is occurring.

Right: The chemistry of pitting corrosion.

Rust bubbles or tubercles on cast iron (left) indicate that pitting is occurring. The environment inside a rust bubbles is almost always higher in chlorides and lower in pH (more acidic) than the overall external environment. This leads to concentrated attacks which result in the formation and aggravation of pits. Similar changes in environment occur inside crevices, stress corrosion cracks, and corrosion fatigue cracks. All of these forms of corrosion are sometimes included in the term "occluded cell corrosion."



Pitting corrosion can lead to unexpected catastrophic system failure. The split tubing (above left) was caused by pitting corrosion of stainless steel. A typical pit on this tubing is shown in the photo above right (white arrow). Sometimes pitting corrosion can be quite small on the surface and very large below the surface.

Preventative Measures:

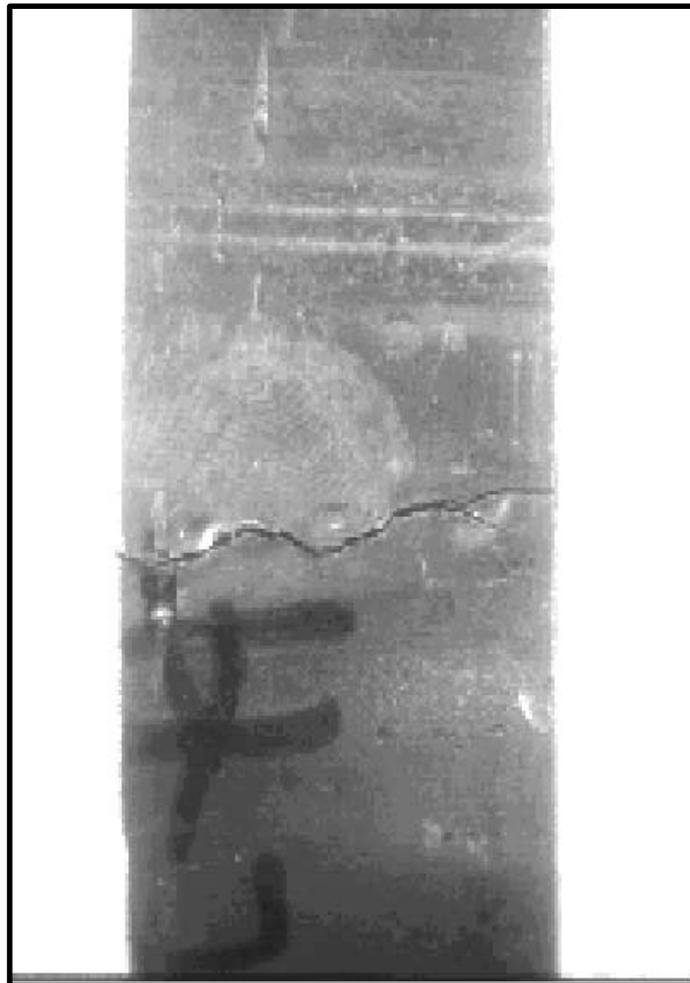
This type of corrosion can be controlled by using a protective coating, maintaining clean surfaces, use of inhibitors or by cathodic protection for immersion service.

STRESS CORROSION CRACKING

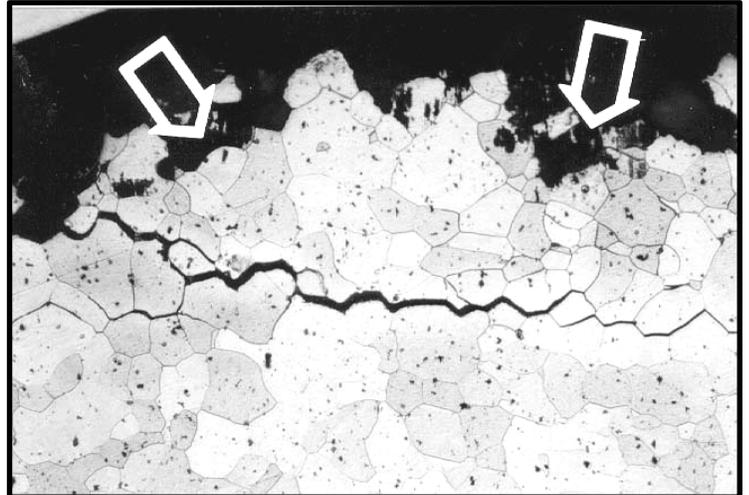
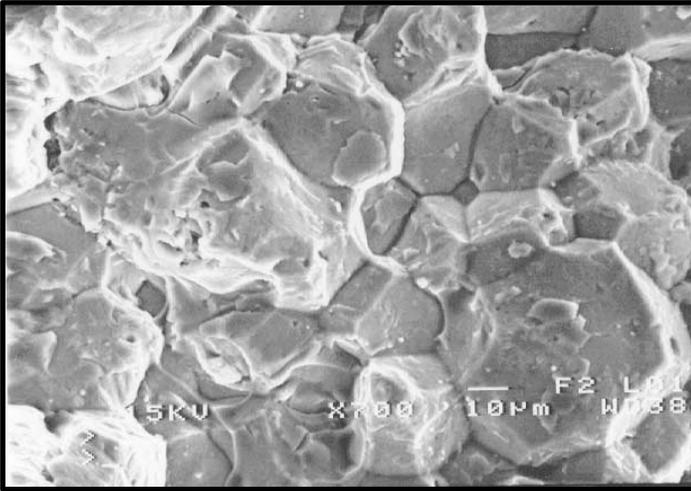
Stress Corrosion Cracking (SCC) is manifested by the simultaneous effects of tensile stress (i.e. applied loads, residual manufacturing stresses, or combination of both) and corrosive environment.



Above: Under magnification, river-like branching patterns are unique to SCC and are used in failure analysis to identify when this form of corrosion has occurred.



The photo above shows SCC of an insulated stainless-steel condensate line. Condensing water contaminated the insulation and caused chlorides to leach from the insulation onto the hot metal surface. This is a common problem on steam and condensate lines.



The failure above occurred on an aluminum alloy subjected to residual stresses and salt water. These two photos show intergranular SCC of an aluminum aerospace part. The intergranular nature of this type of corrosion can be seen in the scanning electron microscope image on the left and in the microscopic cross section on the right. The arrows indicate the primary crack shown in both pictures. Note that secondary cracks are also apparent. Secondary cracks are common in stress corrosion cracking.

Preventative Measures:

This type of corrosion can be controlled by using a suitable protective coating, which will eliminate water permeation/entrapment, or by changing the alloy's heat treatment.

UNIFORM CORROSION

(A.K.A. GENERAL CORROSION, UNIFORM ETCH CORROSION)

Uniform corrosion is a surface effect which results from a uniform chemical etching of the metal surface. Etching may be caused by any chemical agent which is capable of attacking the metal surface. This type of corrosion on polished surfaces first manifests as a dulling of the surface followed by roughening or a 'frosted' appearance of the once polished metal surface. Discoloration or dulling as a result from exposure to elevated temperatures should not be confused with uniform corrosion.

This is the most common form of corrosion and is of little engineering significance. Due to the obvious manifestations of this form of corrosion, structures affected with this corrosion are maintained long before structural integrity is affected.

Preventative Measures:

Use of chemical resistant protective coatings or chemically resistant alloys will control this form of corrosion.



The facilities shown in the photo above illustrate how general corrosion can progress unchecked in the absence of control measures.