American Welding Society

The Practical Reference Guide for

Causes and Cures

THE PRACTICAL REFERENCE GUIDE for CORROSION OF WELDS— CAUSES AND CURES

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AUTHOR NOTES

The primary objective of this Practical Reference Guide is to review several common causes of weld corrosion, along with suggested cures. Additionally, several case histories are documented as examples of these solutions. To meet these objectives, I relied on my 28 years experience in Materials Consulting for the Du Pont Company as well as more recent consulting efforts for Weber & Associates. It is my hope this Guide will increase your basic knowledge of corrosion, aid you in your career efforts, and lead you to pursue additional training in this very interesting subject.

Dealing with weld corrosion requires a basic understanding of the various corrosion mechanisms. Therefore, I have included general information on several corrosion mechanisms as well as weld corrosion. For those interested in greater depth of treatment, a short list of additional references is noted at the end.

I must first thank Debrah Weir, Corporate Director of Marketing for AWS, who persisted in her request for the preparation of a basic primer on weld corrosion. After more than 2 years of delays, I finally acquiesced and blocked out the time to prepare this text. The new digital camera technology simplified capturing photographs of metal samples and these are used liberally throughout the text. Additionally, thanks are given to Dr. Richard Campbell, Welding Solutions, Inc., Steven Springer, Du Pont Company, and Greg Kobrin, Beaumont, TX for their editing comments. Also, a second thanks to them, to Ray Strong, Beaumont, TX, and to Don Johnson, Mt. Juliet, TN, for supplying samples, slides, photographs, or data. A few figures have also been included from the *AWS Welding Handbook,* Volume 4.

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Introduction

Corrosion, resulting in the severe degradation of materials, is one of the most expensive engineering problems in our industrial society; estimates have been made that the *annual* cost of corrosion in the U.S. exceeds 100 billion dollars. As you might imagine with the financial stake so high, manufacturers and end users expend significant amounts of engineering time and money avoiding, protecting against, or repairing damages from corrosion. A very large majority of industry must, or should, consider the environmental effects on its products or equipment and guard against premature failure due to corrosion.

Most of us are aware of a very common corrosion problem, corrosion of our automobiles. If you have lived near a coastal water area, or in the snow belt areas that keep the roads clear of ice and snow by spreading salt on the highways each winter, you are probably familiar with the rusted-out car bodies that occur quite quickly when exposed to the moist salt-air environment. Our automakers spend considerable effort to protect their products from frame and body corrosion by these severe environments, but quite often, Mother Nature wins the battle.

Other common examples of items needing corrosion protection include bridges, electrical connections in appliances and electronic devices, chemical processing plants, water pipes, hot water heaters, structural steel, welds; the list is endless. Suffice it to say that corrosion is a pervasive problem and industry must first understand corrosion before they can take steps to solve the unique problems it presents.

Welded structures are often subjected to corroding environments; in some cases, the weld and base metal corrode uniformly at the same rate. In other cases, the results are accelerated corrosion of the weld compared to the base metal, or the base metal may corrode at a much faster rate leaving the weld metal relatively intact. Welding, and its associated heat input, can also contribute to other corrosion problems; these will be discussed in greater detail later.

A logical starting point for dealing with corrosion of welds is to define corrosion and then list the various types of corrosion that can occur, with examples. Definitions used are those developed by Dr. Mars Fontana and/or NACE. There are many different forms of corrosion recognized that include the various corrosion mechanisms, and the most common are defined and discussed below. The next logical step after defining the various forms of corrosion is to then develop methods for avoidance of each and these are also listed following each definition. Several case histories are also noted to demonstrate actual, practical solutions.

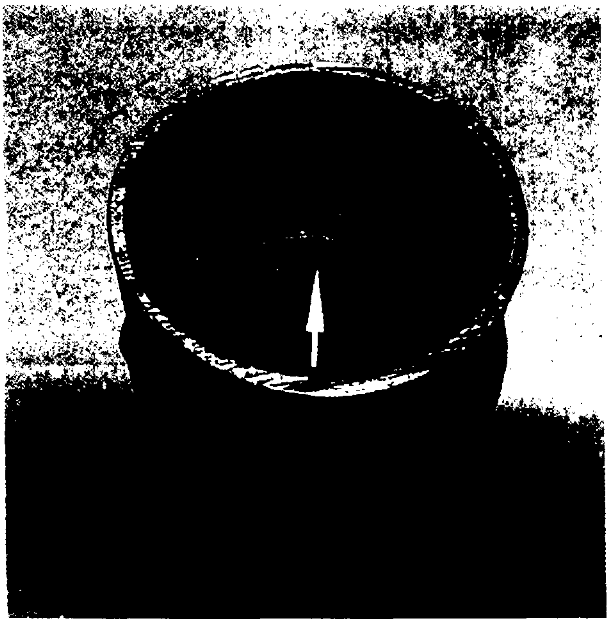


Figure 1. Carbon steel pipe butt joint weld showing severe internal corrosion of weld root and heat affected zone.

Corrosion

Corrosion has been defined as *"The destruction of a metal by chemical or electrochemical reactions with its environment."* In today's world of ever-increasing materials available to the designer, this definition must be expanded to cover other materials in addition to metals since environmental failures of nonmetallics also occur. And since many nonmetallics are joined (welded), the degradation of nonmetallics must be dealt with when selecting them for a particular application. Since our primary interest is in weld corrosion of metals, the discussion of weld corrosion will be limited to consideration of metals only.

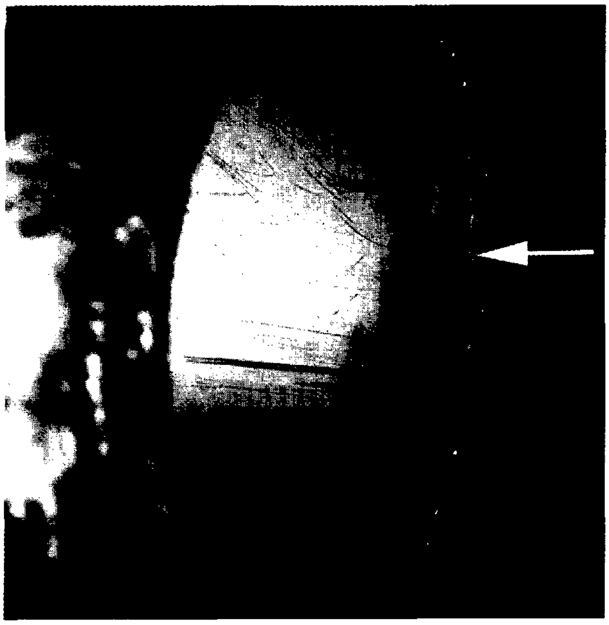


Figure 2. Section of stainless steel piping showing severe corrosion of weld root. Arrow points to an area of complete perforation.

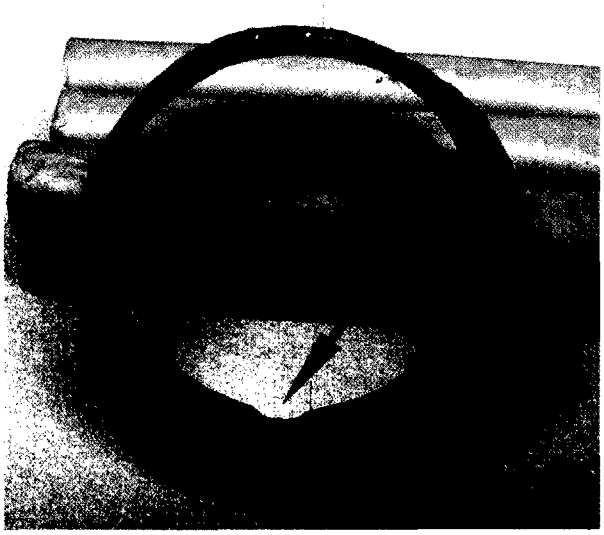


Figure 3. Pipe section showing localized corrosion of longitudinal seam weld.

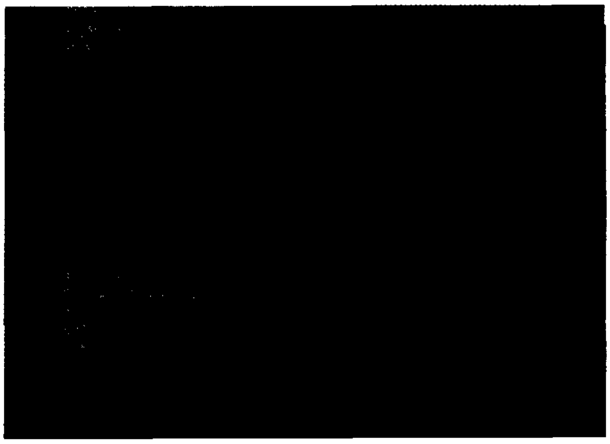


Photo courtesy of Don Johnson, Mt. Juliet, TN.

Figure 4. Severe general corrosion of a very old cast steel cannon barrel recovered after many years of being submerged in seawater. Note heavy scale of iron oxides that have completely filled the cannon bore.

Within metallic systems exposed to aqueous corrosive environments, anodes (the positive electrode) and cathodes (the negative electrode) of different potentials, or voltages, are formed. These areas of differing potentials can be formed several ways: by dissimilar alloys used in combination, by weld metal versus base metal, by mill scale versus clean metal surfaces, by segregated constituents within a metal structure, or by concentration cells within the corrosive environment itself. There are several general statements that can be made regarding metal corrosion:

- Corrosion of metals always occurs at the anode (oxidation), with the cathode (reduction) being protected.
- There is electron flow between the anode and cathode during corrosion.
- Nascent, or atomic, hydrogen (H^+) is always formed at the cathode during corrosion.

With these general truths in mind, we will now move to the various forms of corrosion.

General Corrosion

The most common form of corrosion is referred to as General Corrosion; an alternate term is Uniform Attack. One formal definition is "*A chemical or electrochemical reaction which proceeds uniformly over the entire exposed surface, or over a large percentage of the exposed surface.*" During this type of corrosion, the material corrodes quite evenly over its surface, or the majority of its surface, that is exposed to the corroding environment.

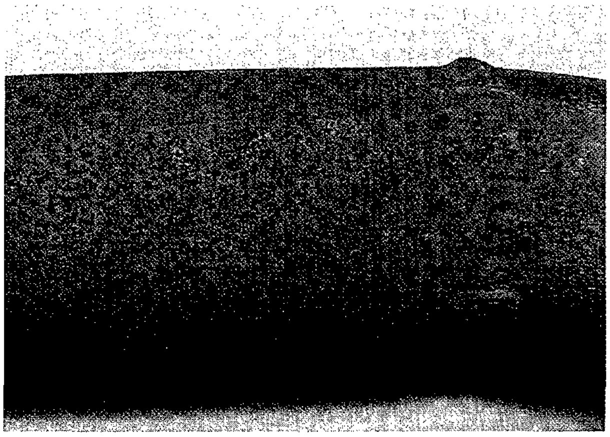


Figure 5. A carbon steel piping exterior showing moderate general corrosion of the pipe exterior and butt joint weld.

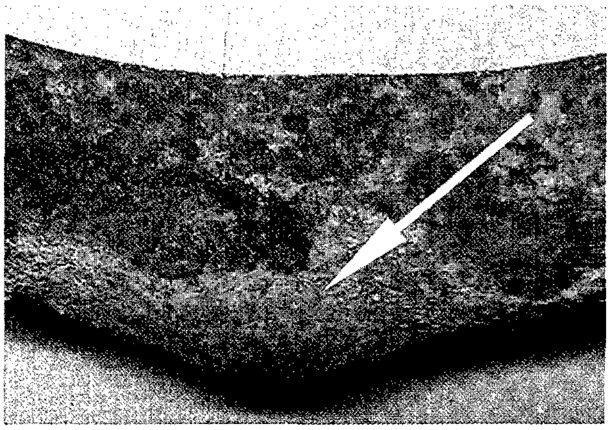


Figure 6. Bulge in boiler tube caused by loss of wall thickness by general corrosion and internal pressure on the thinned pipe wall.

A piece of 10 gauge, uncoated, plain carbon steel left outside and exposed to the rain and sun will usually corrode in a general manner with time. The entire surface begins to "rust" and turn a dark reddish brown color (see Figure 5). If sufficient time passes, the original metal thickness is reduced in a uniform or general manner, and eventually the entire piece will transform back to its natural state of iron oxides. The steel combines with oxygen and hydrogen during the corrosion process, which is aided by moisture. The iron oxides and iron hydroxides form a scale on the surface and while the scale would seem to offer protection from further corrosion, it does not in this example. In fact, the porous and relatively lightly adhering scale of iron oxide and iron hydroxide may even promote faster corrosion by absorbing moisture and trapping it in close contact with the steel. (Protective corrosion scales will be discussed in greater detail when we review corrosion of the austenitic stainless steels.)

Generally, when carbon steels corrode uniformly and corrosion scales form, the thickness of the scale can be about 7 to 10 times as thick as the original metal thickness consumed to form the scale. Thus, a 1/4 inch steel plate completely corroded can form a scale of 1.5 inches to 2 inches or more. Aluminum alloys also can form thick scales in some exposures, and this scale formation has been termed "blooming." These aluminum scales are quite loose, almost fluffy in nature, are very unprotective, and can be easily removed with a little light mechanical scraping.

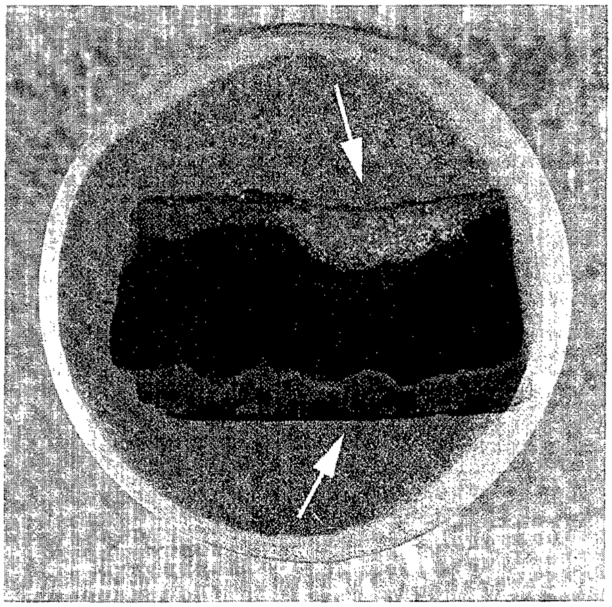


Figure 7. Metallurgical mount of carbon steel plate cross-section showing depth of oxidation scaling at arrows due to exposure to hot gases.

Many other examples of general corrosion can be listed. A few are: copper in a weak nitric acid solution will dissolve; steel immersed in sea water eventually becomes entirely consumed; aluminum in a caustic solution will dissolve; water pipes in houses become quite thin and fail; bolted connections suffer corrosion and fail.

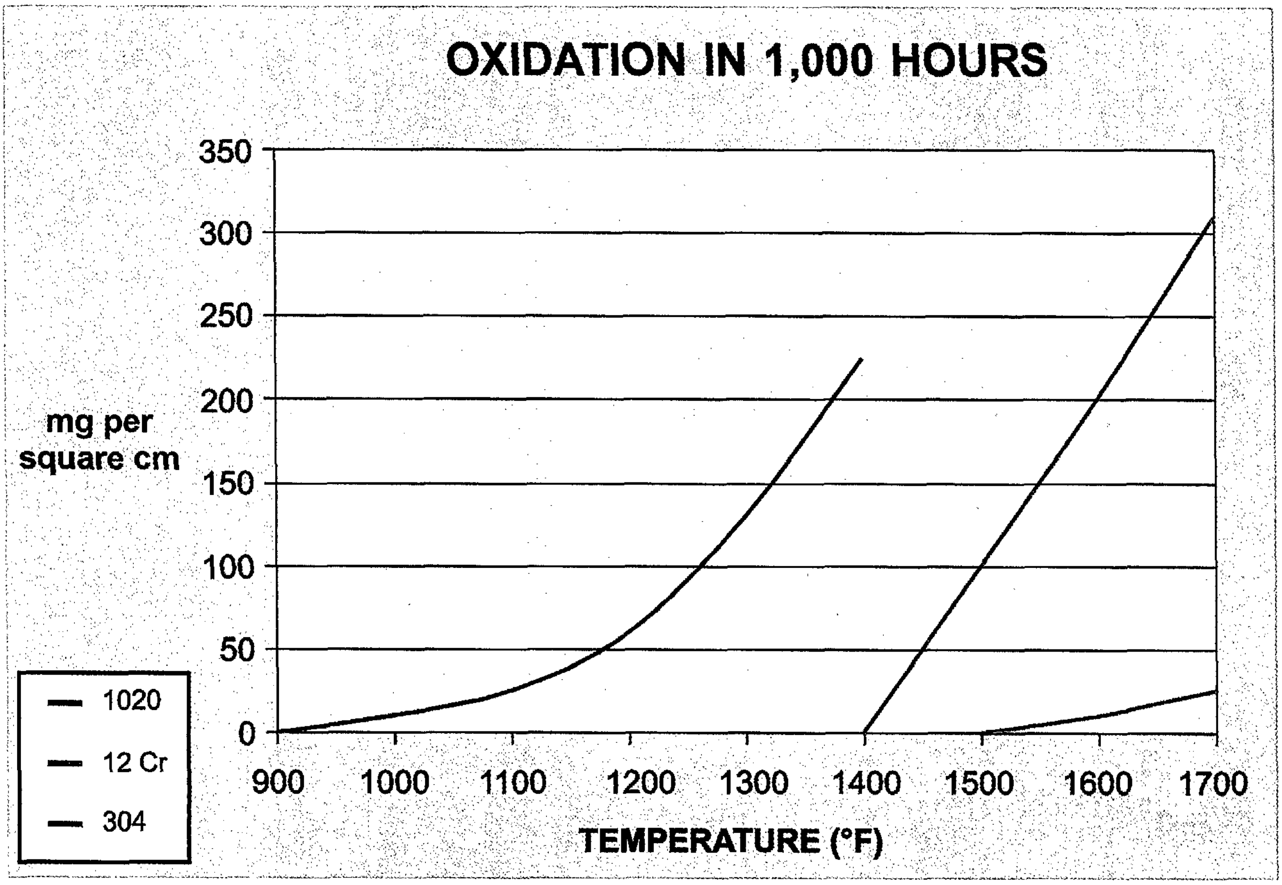


Figure 8. Curves showing weight gain in 1,000 hour hot air exposure tests for three materials. The carbon steel begins to oxidize (gain weight) at about 900°F and begins to oxidize very rapidly. The 12 Cr alloy and the 304 stainless steel have much better oxidation resistance and are useful at much higher temperatures.

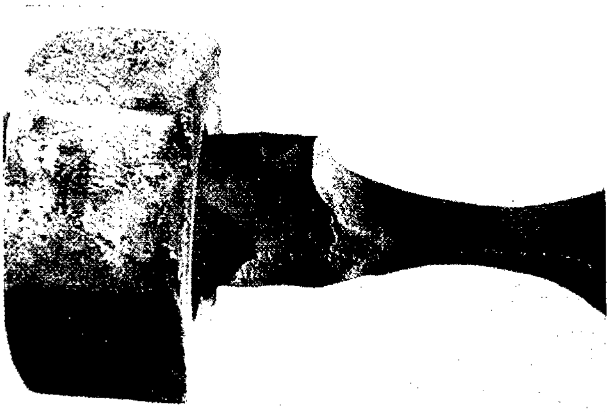


Figure 9. Shank of stud and nut showing severe general corrosion of stud.

We usually describe the rate of general corrosion in terms of the thickness lost per unit time. A common term in the U.S. is mils per year (mpy) thickness loss. A mil is 0.001 inch, and an acceptable corrosion rate for steel used in common applications such as storage tanks or petrochemical equipment is usually 10 mpy or less, depending on the particular application. Corrosion data are also given in inches per year (ipy), but this approach becomes a bit impractical when dealing with normally acceptable corrosion rates. To demonstrate this, a 7 mpy rate can also be written as 0.007 ipy, requiring the use of several zeroes and a decimal point in the ipy format.

Corrosion rates can be determined by exposing a specimen to the corroding environment and measuring the actual metal thickness loss with time. Corrosion rates are more commonly determined in lab or field corrosion testing by weighing the metal specimen before and after exposure. Then, with a formula using the measured weight loss, exposure time, exposed specimen area, and a material density factor, the corrosion rate in mpy (the loss of thickness versus time) can be calculated. One convenient formula for calculating the corrosion rate, in mils per year, of small corrosion test coupons can be found in the National Association of Corrosion Engineers' (NACE) *NACE Corrosion Engineer's Reference Book.* The formula is:

$$\text{mpy} = C \times \text{weight loss} \times K / (\text{area} \times \text{time})$$

where:

C is 2,820
Weight loss is measured in grams
K is a density factor (1.000 for carbon steel)
Area of the sample is measured in square inches
Time is measured in days

The above formula can be easily programmed on a computer such that data entries for calculation need only include the weight loss, specimen area, material, and time of exposure. Density factor charts from the Reference Book can be preloaded into the computer program, and the computer instructed to automatically select the correct C values and density factors for the various alloys needed to calculate the corrosion rate for each test. Alternate forms for the formula are also given in the Reference book to permit using different units for the exposure time, weight loss, and corrosion rate, but the appropriate C and K values must also be incorporated. An example of the formula use follows:

A carbon steel coupon with an exposed surface area of 2.5 square inches was exposed for 20 days. The measured weight loss was 0.15 grams, and its density factor is 1.0. The calculation is:

$$\text{mpy} = (2{,}820 \times 0.15 \times 1.0) / (2.5 \times 20) = 8.46 \text{ mpy}$$

Avoiding General Corrosion

To protect against general corrosion, the most obvious solution is to avoid contact between the metal and the corroding environment. Keep bare steel parts in a controlled environment (low humidity, room temperature) and you will usually eliminate the possibility of general corrosion. Simply stated, eliminate the corrosive environment from contact with the metal and no corrosion occurs. Often, as you may imagine, this is not the practical solution, so other methods had to be developed.

For many alloys exposed to uniform corrosion conditions, one approach is to add a "corrosion allowance." In practice, this means making the item thicker than that required by the engineering design. Instead of using 1/4 inch steel plate when the known general corrosion rate is 10 mpy, select a plate thickness of 3/8 inch, and the extra 1/8 inch of steel thickness will withstand an additional 6 years of service if corrosion occurs on both sides. If corrosion will only occur on one side, an additional 12 years of life is gained. Corrosion allowances are often a very effective and economical approach for many alloys and conditions of general corrosion.

Another common method to reduce atmospheric corrosion of steel is to apply a protective coating to the metal surface to exclude the corroding environment from the metal surface; a coat of paint properly applied will provide excellent protection for an extended period of time. A protective coating often applied to steel to improve resistance to atmospheric exposure is zinc. Zinc coatings, also called "galvanizing," can be applied to the steel surface by several different methods. Dipping fabricated steel structures into molten zinc is a common method, and is called "hot dip galvanizing." Zinc coatings can also be applied by electroplating or spray painting. The zinc not only acts to exclude the environment from the metal surface, but can also protect carbon steel through a galvanic reaction even if the zinc coating is damaged and incomplete. The zinc will preferentially corrode, and the steel base metal is protected. Galvanic protection will be discussed in greater detail under the topic of Galvanic Corrosion.

There are other methods for controlling general corrosion and they include lining the metal that will corrode with a protective one, adding corrosion inhibitors to the corroding environment, anodic or cathodic protection of the component, or upgrades to other metals having better corrosion resistance. (Anodic protection refers to the practice of using sacrificial anodes to protect the structure, and cathodic protection refers to the use of impressed current for the same purpose.) Of all the various forms of corrosion, the corrosion engineer usually prefers to deal with general corrosion because its effects are more often well known and usually more predictable. General corrosion usually results in a long-term condition prior to failure, and its avoidance is usually straightforward. It does, however, constitute a major portion of the economic loss suffered by industry, and its detriment cannot be minimized.

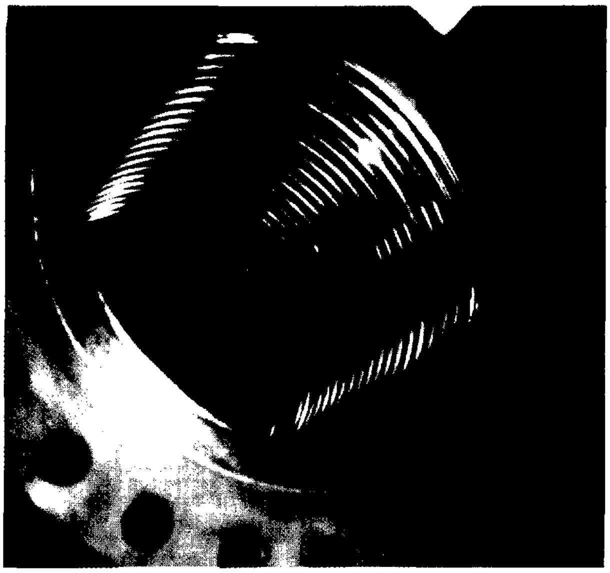


Figure 10. A large steel nozzle and flange lined with tantalum to withstand severe corrosive conditions. In this case, the tantalum lining is a loose liner and will not withstand a vacuum service. If vacuum conditions are possible, a tantalum-clad steel must be used rather than a loose lining.

Pitting Corrosion

Pitting corrosion differs from general corrosion primarily in that pitting corrosion damage is quite localized rather than covering the entire surface. It is defined as "*Extremely localized corrosion, resulting eventually in holes in the metal.*" The total area based on the pits' diameters is usually quite small compared to the total exposed surface area of the component. Pitting damage can occur at a very few locations on a large part, causing complete perforation of the part, and render it useless even though the majority of the component has suffered little or no corrosion damage. A good example of this is the hot water heater found in our homes. The majority of the heater interior may be in very good condition, but the heater may leak due to a single pit that extends entirely through the pressure containing shell.

Pitting mechanisms are often quite complex and considerable research has been done in trying to understand the pitting mechanism and its avoidance. Corrosion pits can occur randomly over a metal's entire surface, or be very localized in quite small areas. The pits can be large in diameter and shallow, or very small in diameter, deep, and perforate the metal thickness. The nature of pitting depends on many factors such as the alloy type, surface condition of the metal, the exposure environment, temperature and concentration of the corrodent, and others. Measurement of pitting rates is usually done by measuring pit depth versus time; the normal mpy measurement method based on weight loss has little value for pitting measurements since very often, only minor weight loss occurs from pitting compared to general corrosion, yet failure may occur quickly due to perforation.

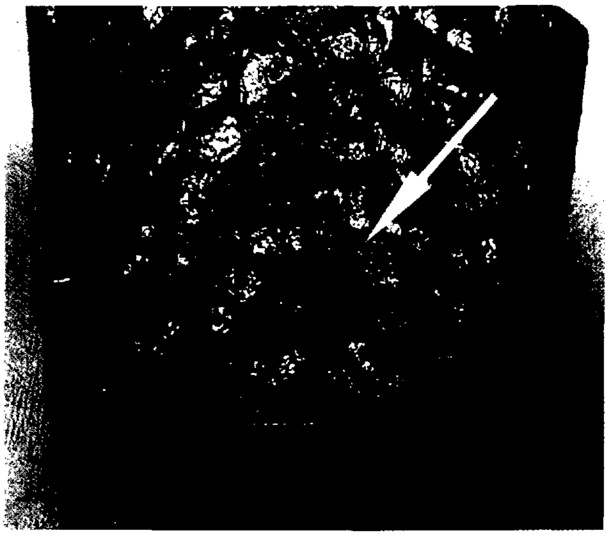


Figure 11. Interior pipe wall of carbon steel boiler feed water line showing severe oxygen pitting due to poor water quality control. Note rusty pit at arrow showing complete perforation of pipe wall.

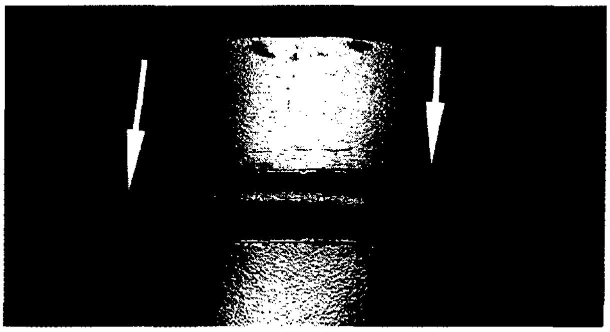


Figure 12. Pitting of 304 stainless steel piping weld at arrows due to external wet insulation containing chlorides.

Avoiding Pitting Damage

To avoid pitting damage, several methods can be used. Protective coatings are very effective provided the coatings are completely continuous over the entire surface and contain no breaks. Quite often, when organic coatings are used to avoid pitting, and the coating contains scratches or coating breaks, pitting not only occurs, but also often at a much higher rate than if there were no coating at all. This increased pitting rate is due to the relatively small area of metal actually exposed to the pitting agent's inherent driving force; most of the surface is protected but a very small area is subject to more severe pitting.

Alloy upgrades are another common solution; if carbon steel is failing by pitting in water services, a switch to a copper-based alloy may solve the problem. If 304 stainless steel (304 sst) pits in an environment, an upgrade to the 316 sst grade containing 2–3% molybdenum (Mo) often is the answer since its addition significantly improves pitting resistance in the 300 series. Electrochemical protection methods are also effective in reducing or eliminating pitting damage, and corrosion inhibitors may reduce the pitting attack.

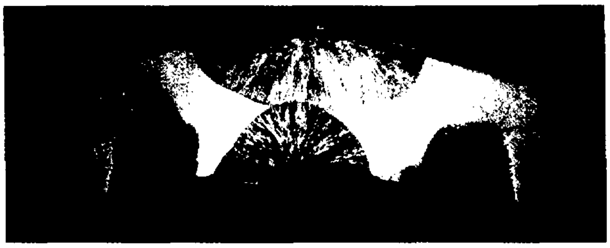
Intergranular Corrosion

This form of corrosion is defined as "*Localized attack at, and adjacent to grain boundaries, with relatively little corrosion of the grains.*" Metal structures are composed of very small grains, or crystals, with a particular structure, and arranged in random patterns separated by grain boundaries. The grains in metals have one of several geometric crystal structures such as body centered cubic, body centered tetragonal, face centered cubic, or hexagonal close packed. The individual grains grow during solidification of the metal, and where two grains come together at different orientations, the line or irregular plane of contact is called the grain boundary. Examination of the metal structure at high magnification will show these individual grains and grain boundaries.

Often, intergranular corrosion, or intergranular attack (IGA), is due to the lack of proper heat treatment of the base metal. Welding that is not followed by post-weld heat treatment is often the root cause of IGA since the heat of welding reduces the corrosion resistance of the metal by affecting its original heat treatment. One of the common examples of

From *AWS Welding Handbook*, Vol. 4.

Figure 13. Severe IGA of 300 series sst weld heat affected zone due to hot nitric acid service. See Figure 14 for cross section.



From *AWS Welding Handbook*, Vol. 4.

Figure 14. Cross-section of corrosion in Figure 13 showing depth of IGA.

IGA is the result of welding 304 sst without subsequent post-weld heat treatment, and then exposing it to severe environments such as hot, concentrated nitric acid. Corrosion of the grain boundaries and areas adjacent to the grain boundaries can result in a condition called "sugaring" or more appropriately, "grain dropping." Because of the corrosion at the connecting boundaries, the grains actually fall or "drop" out of the metal surface. Running a finger over a sample suffering very severe IGA prompted the term "sugaring" since the grains can become loose and feel like sugar crystals spilled onto a tabletop. (Note: In welding terms, the term "sugaring" is also commonly used to describe the oxidation of a root pass on stainless steels due to improper purging, or the oxidized surface of a weld due to improper shielding.)

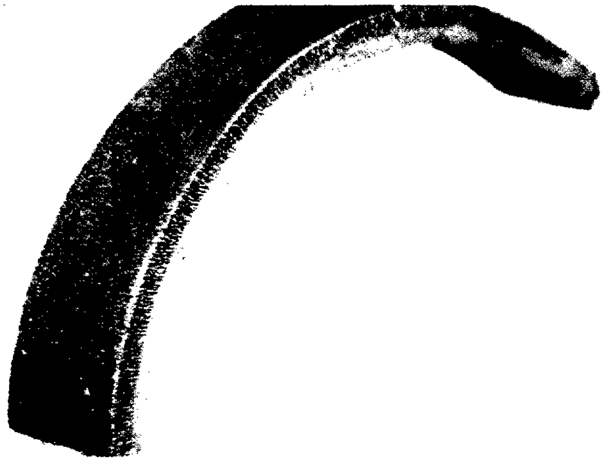


Figure 15. Exterior of sparger piping section showing severe IGA to a depth of near mid-wall. The IGA was due to improper heat treatment of the pipe.

Many alloys are subject to IGA when exposed to a variety of environments but IGA of the 300 series stainless steels is one of the most common occurrences. To aid our understanding how welding affects the 300 series stainless steels we must discuss the effect of "sensitization," the term given to the phenomenon of precipitation of chromium carbides at grain boundaries, a precursor to selective grain boundary corrosion. Austenitic stainless steels are subject to sensitization and IGA, and this alloy family will be reviewed as one example.

The 300 series stainless steels are primarily alloys of chromium, nickel, and iron, with minor amounts of carbon. Most standard grades in the 300 series have a carbon content maximum of 0.08%. To maximize these alloys' corrosion resistance, they are given a "solution anneal, water quench" heat treatment (SAWQ) which takes the alloying elements into solid solution. After such a heat treatment, welding can cause sensitization by exposing portions of the metal to the sensitizing temperature range of 800–1650°F. In fact, welding causes the base metal to be exposed to this temperature range twice; once on heating and again on cooling back to room temperature. Thus, welding on the 300 series alloys usually results in some degree of sensitization, from minor to severe, depending on the rate of cooling which can be affected by the welding process, the base metal thickness, electrode size, etc. Because of this sensitization problem, the 300 series alloys are seldom preheated when fabricating for corrosive service since this only increases the time of exposure to the sensitizing conditions.

Sensitization of the 300 series refers to the formation of complex chromium carbides along the boundaries between adjacent grains. The chromium necessary for corrosion resistance of the grains becomes combined with the carbon. The net result of sensitization is to lower the chromium content of a very thin zone at the grain boundary. This "chromium depletion" of the very narrow zone causes it to have insufficient chromium for corrosion resistance, leading to subsequent corrosion of the depleted areas or zones when exposed to corroding environments.

Photo courtesy of S. D. Reynolds, Jr., Consultant, Oviedo, FL.

Figure 16. IGA of austenitic stainless steel.

Avoiding Intergranular Attack

The most obvious method to avoid IGA based on the above is to not expose the 300 series to corroding environments except when they are in the SAWQ condition. This sounds simple enough; when fabrication welding has been completed, heat the component to 1800–2150°F, water quench it or cool it very rapidly with water sprays to maximize its corrosion resistance. While this approach can often be done on many items, it unfortunately is not the entire solution. Many fabricated structures, when given this very severe heat treatment, can end up with severe distortion and may no longer be acceptable for use. And, for very large components, it may not possible to solution anneal the entire structure due to size and/or furnace limitations. Localized heat treatment is not a solution either because the entire structure must receive the solution anneal, water quench treatment in a single operation.

An alternate method to avoid as-welded IGA is called "stabilization"; it is the addition of appropriate amounts of the element titanium, or columbium (also known as niobium) to the alloy. These elements preferentially combine with the existing carbon to form stable titanium or columbium carbides, making the carbon unavailable to form chromium carbides. Thus, the carbon is present for increased alloy strength, there is no chromium depletion, and the IGA corrosion resistance is improved. Type 321 sst has titanium as its stabilizer in amounts from 5x to 8x the actual carbon content. Type 347 sst uses columbium as its stabilizer in combined amounts equal to at least 10x the carbon content.

A third method of avoiding IGA is to lower the initial carbon content of the alloys. As stated earlier, the maximum carbon content of the standard grades is 0.08%. Initially, steel makers were not able to consistently manufacture the sst grades with lower carbon, and thus the stabilizers noted above were first developed. However, eventually they developed techniques to lower the carbon maximum to 0.03%. These grades were labeled with the suffix "ELC" denoting extra low carbon, and the result was a significant reduction of sensitization during welding. Today, these low carbon grades are denoted by the "L" suffix. Thus, for known IGA services where as-welded usage is required, 304L sst is selected rather than the standard grade 304 sst. Similarly, low carbon versions are available as 316L, 317L, and most all the other standard 300 series alloys. Low carbon filler metals are used in fabricating the L grades.

Selective Leaching

This form of corrosion is defined as *"The removal of one element of a solid solution alloy by corrosion."* One of the early common types of selective leaching corrosion of brass alloys was named "dezincification." Brass is an alloy made primarily of copper and zinc and if the zinc was preferentially removed from the alloy by corrosion, it was termed dezincification. This naming approach was tolerable for the selective removal of zinc, since it rolls off the tongue relatively easily. However, the description "selective leaching of (the element being removed)" is the preferred approach, especially when you consider the difficulty of pronouncing the original terminology when the element such as praseodymium is selectively removed. Adding the prefix "de" and the suffix "ification" to that element is more than most can clearly pronounce. However, another term often used is "denickelification" denoting the selective leaching of nickel from an alloy.

During selective leaching, one element is removed, often leaving a residue or spongy matrix of the remaining elements having reduced mechanical strength. In some cases, when conditions are favorable, one element is removed and replaced by another. A carbon steel valve used in a water line in an underground copper mine, and exposed to the mine water containing an extremely high copper concentration, eventually became a "copper" valve on its lower portion. The steel had been removed and replaced with copper from the copper-rich water. This very unusual condition was found when the valve failed and required replacement.

Avoiding Selective Leaching

The primary approach is to avoid exposing alloys to environments that cause selective leaching. Further study of selected alloy families will usually result in noting specific environments to avoid. Also, additional elements such as arsenic or antimony can be added to the copper alloys to reduce selective leaching. Elements that can be selectively leached include the aluminum from copper-aluminum alloys, nickel from copper-nickel alloys, and the "parting," or separation of silver-gold alloys. The occurrence of selective leaching is quite minimal today because of our increased understanding of the mechanism, the addition of elements to reduce the problem, and the avoidance of exposure combinations leading to this form of corrosion.

Stress Corrosion Cracking

Defined as *"cracking caused by the simultaneous presence of stress, oxygen, and a corrosive medium,"* this corrosion phenomenon is one of the more difficult and costly corrosion types to avoid. Early stress corrosion cracking (SCC) failures were little understood and often had catastrophic results. SCC is often associated with little or no general corrosion damage as well as dramatic failures in unexpected circumstances. A very early example of SCC was the cracking of deep-drawn brass cartridge cases used in ammunition manufacture. The ammunition was often stored near the horse stables and the net result was ammonia SCC of the cold worked brass cartridges. Other examples include cracking failures of carbon steel in caustic service (NaOH), austenitic stainless steel failures in hot chloride environments, and quenched and tempered steels in many corrosive environments containing cyanides or sulfides.

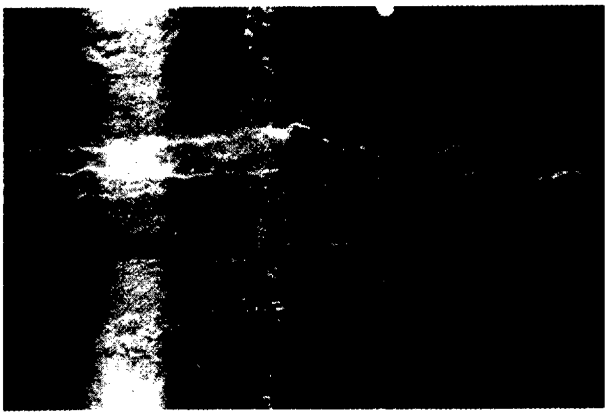


Figure 17. Weld in carbon steel plate showing cracking at arrows. Cracking was due to a caustic environment of as-welded steel.

As SCC failures began to be documented, considerable research into the cracking mechanisms was initiated and our understanding of the causes grew considerably. Today, we have discovered many combinations of metals and environments that are particularly susceptible to SCC. Metals can crack in environments of caustics, chlorides, cyanides, ammonia, sulfates, and hydrogen sulfide to name a few. The corrosion engineer must be familiar with the conditions that promote SCC and avoid them. Table 1 lists several alloys and the environments that will promote SCC.

Table 1. Environments causing SCC of several common alloys.

Alloys	Environments Promoting SCC			
Carbon Steel	Cyanides	Caustics	Nitrates	Ammonia
Copper, Brass	Amines	Carbon Dioxide	Ammonia	Nitrates
300 Series sst	Chlorides	Acidified H_2S	Caustics	Nitrates
High Ni Alloys	HCl acid	HF acid	Chlorides	Caustics

With SCC, stress is a primary requirement for the cracking mechanism. Stress can be induced into a component by several different sources: applied stress during the service application; residual stress from cold working (drawing, forming) during manufacture; residual stress from welding; or the combined stresses from these multiple sources. The amount of stress required to promote SCC is often referred to as the "threshold stress"; for many alloys, the threshold stress range falls between 3,000–15,000 psi. Below this threshold, SCC is often unlikely to occur. The other factors necessary for SCC are the necessary chemistry (chlorides, nitrates, cyanides, etc.), moisture, and oxygen or an oxidizing agent. Increased temperature may also be a significant factor.

Figure 18. Section of 316 sst piping showing severe SCC from external chlorides. See Figure 19 for close-up of cracking.

Avoiding Stress Corrosion Cracking

During welding, the residual stress levels can often be equivalent to the yield strength values for the metals being welded. Thus, for a metal having a yield strength of 35 ksi (one ksi equals 1,000 psi),

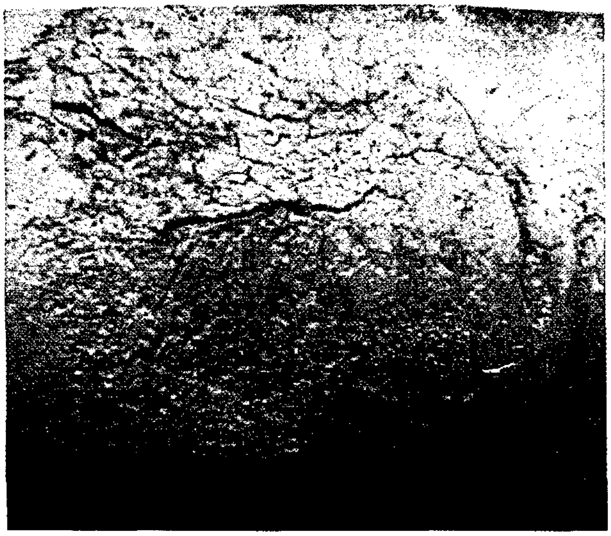


Figure 19. Close-up of Figure 18 showing severe cracking of pipe wall.

as-welded components often have sufficient levels of residual stress to promote cracking in an SCC environment. An obvious solution for reducing residual stress from welding, and the susceptibility to SCC, is to stress relieve the welded component to reduce its residual stress level below the threshold stress level required for SCC. This approach works very well for the carbon and low alloy steels. For service in SCC environments such as caustics and cyanides, carbon and low alloy steel welded components or piping cold bends are often stress relieved at temperatures of 1100–1300°F. An alternate stress relief method is to normalize the components at 1650–1750°F for several minutes followed by still-air cooling.

Figure 22 shows the approximate yield strength of a plain carbon steel in ksi versus temperature. There is very little yield strength reduction up to about 650°F, but above that, the yield strength begins to fall quickly. A typical stress relief temperature for

Figure 20. SCC of weld and HAZ of 317L plate butt weld by service chlorides. Note corrosion pitting of the weld and parent plate.

Figure 21. Photomicrograph at 400x magnification showing typical transgranular, branched, cracking of 304 stainless steel in a hot chloride environment.

plain carbon steel is 1100°F; Figure 22 shows its yield strength at that temperature to be about 5 ksi, which is well below the threshold stress level for most SCC environments.

Figure 23 represents cracking data based on NACE guidelines, and it shows the "safe" zone for the high strength, low alloy, 4142 with a maximum hardness of Rc 22 max when exposed to a hydrogen sulfide environment such as that found down-hole in oil well services.

As effective as stress relief is in avoiding SCC for some alloys, it is usually not the proper approach for the austenitic materials such as 304 or 316 sst in chloride environments. Recall that these alloys are usually selected for their improved corrosion resistance, and that they suffer sensitization when held in the 800–1650°F range. The typical stress relieving sequence for these alloys (1650°F, slow cool) will reduce their residual stress but usually leaves the materials severely sensitized thereby lowering their general corrosion resistance.

The usual solution for avoiding SCC in austenitic materials is to substitute alloys resistant to chloride SCC. This is accomplished by selecting those alloys having a much higher nickel content which significantly reduces the chloride SCC tendencies. Avoiding SCC for austenitic sst grades requires increasing the nickel content to 30% or even higher depending on the severity of the environment. Figure 24 plots the time to failure in a hot chloride environment versus nickel percent. This curve clearly shows the extreme susceptibility of the 300 series stainless steels, with a nickel content of 8–12 percent, to crack in hot chloride environments.

Erosion/Corrosion

Defined as *"The increase in corrosion rate due to the relative motion between the corrosive fluid and the metal surface,"* this corrosion type is often found in pumping and piping systems or any case where a fluid flows across or impinges onto a metal surface. The increase in corrosion rate caused by the fluid motion can be minor or catastrophic. A common erosion/corrosion problem occurs in tubular heat exchangers; these units use a shell and tube design to heat or cool liquids. One fluid is contained on the outside of the tubes in a shell configuration and the second fluid flows through the tubes. Corrosion often occurs within the tubing due to high fluid velocities, leaving a "horseshoe" pattern of corrosion damage on the tube wall interior. Copper-base alloys are used to replace carbon steel in water services to avoid this problem. Often, there is a "threshold velocity" of the fluid and metal combination below which corrosion rate increases do not occur. Corrosion testing will aid in determining what fluid velocities must be avoided for particular combinations of fluids and alloys.

Avoiding Erosion/Corrosion

One of the more common velocity thresholds was determined for the combination of room temperature 90–93% sulfuric acid and carbon steel piping. This concentration of sulfuric acid is commonly used in many industrial applications and is often shipped by rail or truck. It was found that carbon steel performed quite well when the sulfuric acid velocity in the piping system is kept below about 3 feet per second. A more conservative value of 1.5–2.0 feet per second is often used in piping

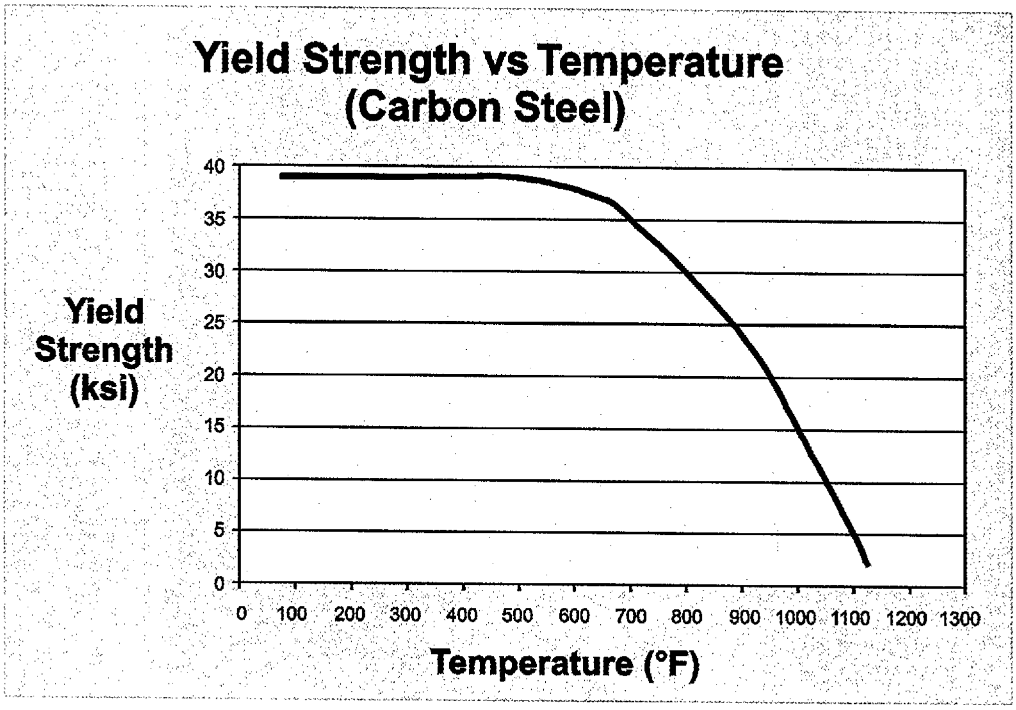


Figure 22. Yield strength of plain carbon steel versus temperature.

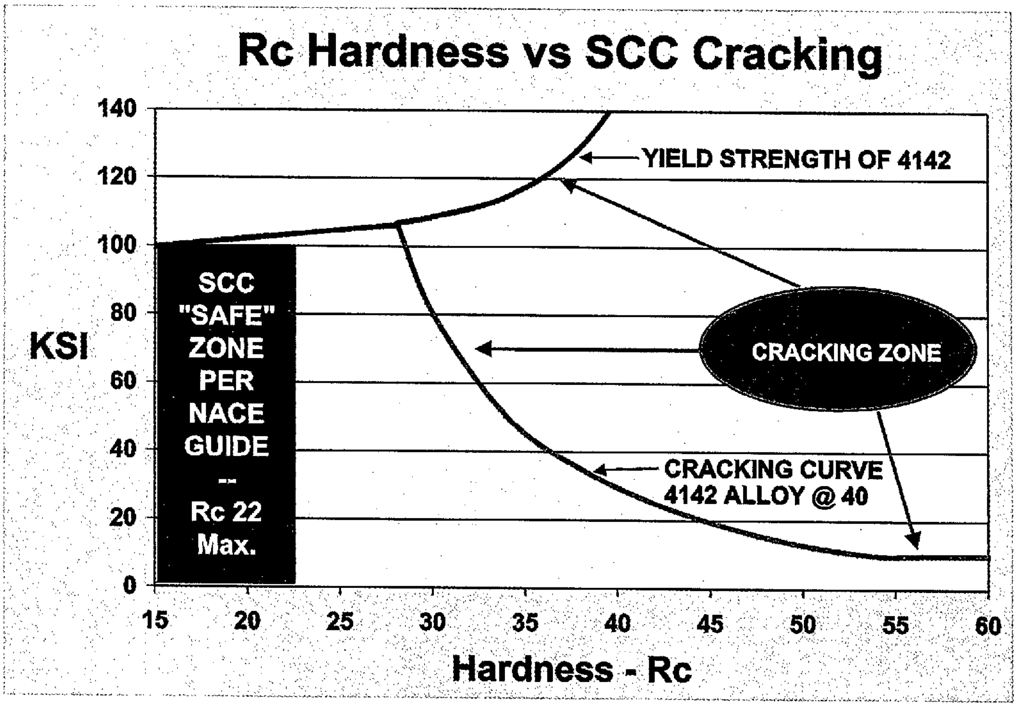


Figure 23. Curve showing "Safe" and "Cracking" zones for a 4142 alloy versus hardness in a hydrogen sulfide environment.

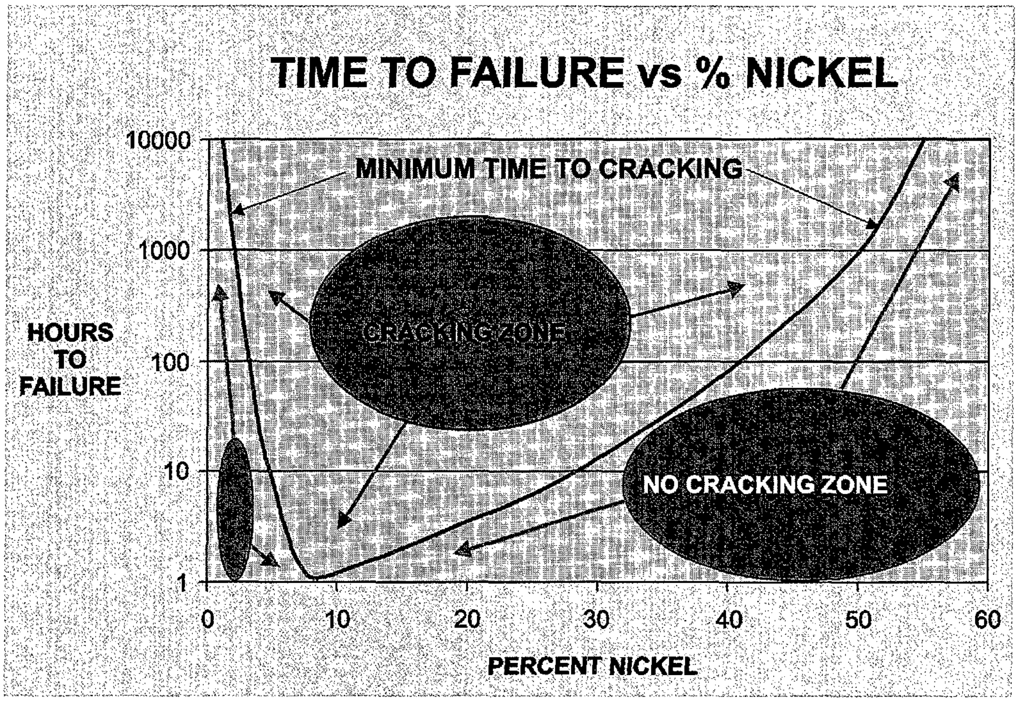


Figure 24. Time to failure versus percent nickel in hot chloride environment.

design to offer protection against unexpected increases in velocity due to turbulence caused by branch connections or elbows.

When fabricating piping systems for 90–93% sulfuric acid, it is imperative to avoid excessive joint penetration of butt welds. This condition can significantly reduce the inside diameter of the piping cross section and cause turbulence, leading to fluid velocity increases and premature corrosion failures. Piping erosion/corrosion failures due to excessive weld penetration and its resulting turbulence usually occur downstream of the weld where the increased velocity dramatically increases the corrosion rates. Likewise, incomplete joint penetration can lead to increased turbulence, but usually not as severe as excessive joint penetration.

If erosion/corrosion is a potential problem for a proposed piping system, it becomes imperative that complete joint penetration, without excess, is the goal. Welder training and proper inspection techniques such as radiography will aid in reaching the goal of long service life. Alternate methods of achieving a smooth inside diameter at the weld joints include modifying weld joint geometry and the use of consumable inserts. The fluid velocity can also be kept below the threshold velocity value by increasing the piping diameter. Turbulence and impingement can also be avoided in other types of equipment through design considerations such as impingement baffles or alloy upgrades.

Crevice Corrosion

Defined as *"Intense, localized corrosion within crevices, usually associated with small volumes of stagnant solution,"* this corrosion type can be quite prevalent in flanged and bolted piping systems. An alternate term often used for this type of corrosion is "Concentration Cell" corrosion; this concentration cell form may also be considered a separate type of corrosion. Key words in the definition are "stagnant solution." Consider a circulating fluid contained within piping and equipment: the majority of the equipment is exposed to free flowing liquid while flanged joints often contain the solution in a stag-

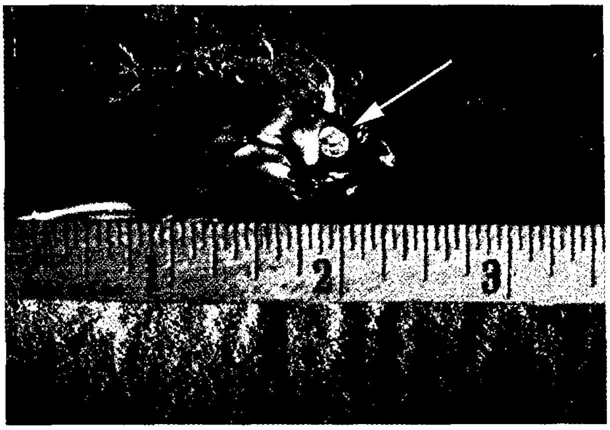


Figure 25. Interior of tubing showing erosion/corrosion. Note polished surfaces of typical erosion pattern. Perforation occurred at arrow.

Figure 26. Erosion/corrosion damage in piping due to severe turbulence of process fluid caused by welding Schedule 40 pipe to a thicker Schedule 80 elbow resulting in an abrupt change in inside diameter.

nant, quiescent condition. The presence of both flowing and stagnant fluids within a system can lead to differences of ion concentrations within the liquid. Areas beneath the flange or gasket often contain different concentrations of metal ions or oxygen than the open surfaces. These differences can lead to selective corrosion adjacent to or beneath the crevice formed. Additionally, surface scales or surface debris on metals can also create concentration cells leading to crevice corrosion. Crevice corrosion can also occur when metals are in direct contact creating a tight crevice between them (see Figure 31).

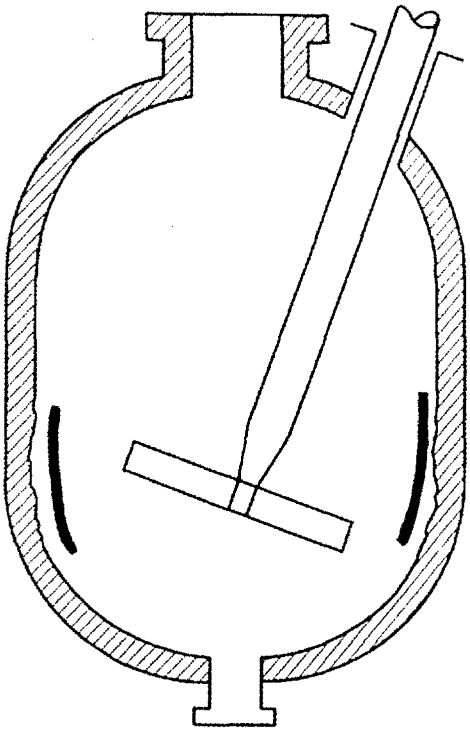


Figure 27. Cutaway sketch of mixing vessel showing erosion/corrosion damage of interior shell, with protective baffle section added later to minimize further damage.

Avoiding Crevice Corrosion

With the great number of crevices formed in manufacturing and assembling complex equipment, and the likelihood of metal surface scales or debris forming, the normal solution for crevice corrosion is to select alloys not subject to damage in the particular services. Efforts to avoid crevice corrosion by selecting "non-wicking" (non-absorbent) gaskets have been successful in some cases, but in others, crevice

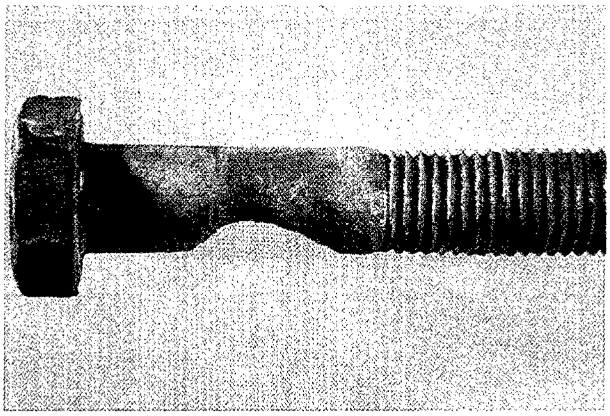


Figure 28. Shank of bolt showing crevice corrosion of shank at area of bolt where it was in contact with a flange and gasket.

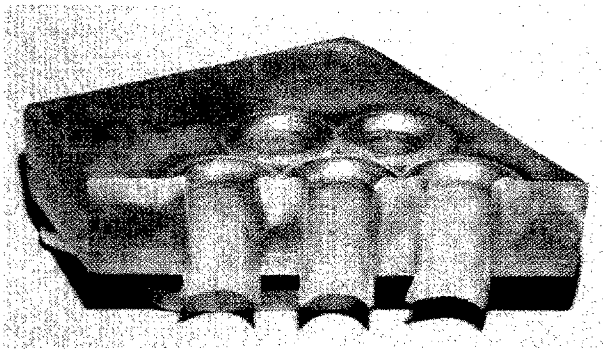


Figure 30. Mockup of heat exchanger tube sheet and tubes showing geometry of tubes, tube sheet, and weld joint.

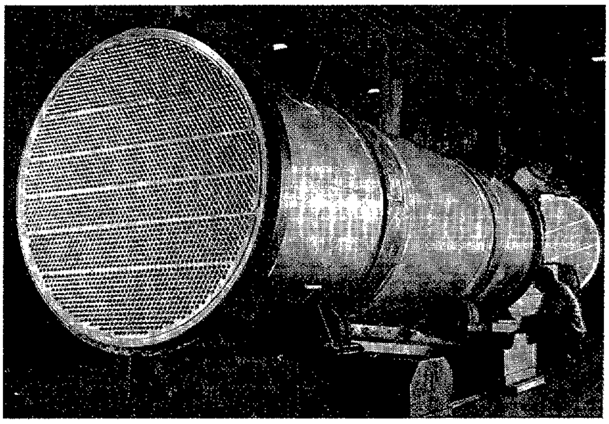


Figure 29. Shell and tube heat exchanger, showing face of one tube sheet.

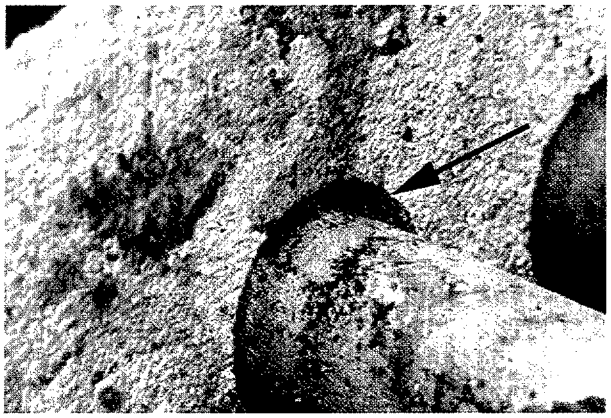


Photo courtesy of Ray Strong, Beaumont, TX.

Figure 31. Back side of a carbon steel tube sheet of a shell and tube heat exchanger showing crevice corrosion of tubesheet at tubesheet hole.

corrosion continued unabated. One of the primary advantages of welded piping joints over flanged systems is to eliminate crevices at the joints. Again, it is imperative that weld quality is sufficient to totally eliminate the crevice; incomplete joint penetration and incomplete fusion of the root joint must be eliminated for this approach to be successful.

Galvanic Corrosion

Galvanic corrosion is defined by the statement *"A potential (voltage) difference exists between two dissimilar metals when they are immersed in a corrosive or conductive solution; this permits electron flow and corrosion of the less resistant metal."* Immersing copper and zinc electrodes into a solution of sulfuric acid created the well-known example of an early battery. Corrosion occurs at the anode, in this case the zinc, and electron flow occurs. Today's car batteries often use the corrosion of lead anodes in sulfuric acid to achieve current flow.

There has been considerable discussion of galvanic effects regarding corrosion; the most often cited anode/cathode combinations in salt water are usually listed showing which alloys are anodic to others.

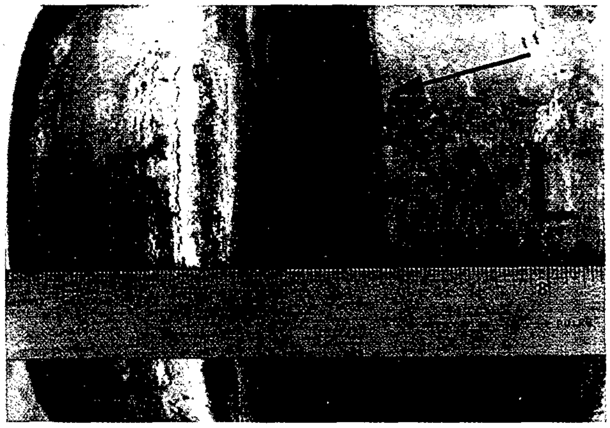


Figure 32. Joint of carbon steel and aluminum water piping exposed to atmospheric corrosion. Note severe scaling and corrosion of steel pipe at arrow caused by galvanic corrosion. The steel pipe several inches away from the aluminum shows only minimal corrosion.

Table 2. Galvanic series in saltwater.
(Note some alloys can be active and passive.)

Anodic—Least Noble	50/50 Pb/Sn Solder	Copper
Magnesium	304 sst (active)	Red Brass
Zinc	316 sst (active)	70/30 Cu/Ni
Cadmium	Lead, Tin	Nickel (passive)
Aluminum (Cu bearing)	Mn Bronze	Inconel (passive)
Carbon Steel	Naval Brass	Monel
Cast Iron	Nickel (active)	304 sst (passive)
Ni-Resist	Inconel (active)	316 sst (passive)
410 sst	Aluminum Bronze	**Cathodic—Most Noble**
Note: Read Table 2 down, by columns, starting at Anodic end (Magnesium).		

Table 2 shows the ranking of several alloys with rankings from strongly anodic to strongly cathodic categories in seawater. The further two alloys are apart from each other in this hierarchical ranking, the more likely the anodic metal will corrode in a saltwater environment when coupled with the second. However, it must be kept in mind that this list is accurate only for the saltwater exposure, and conclusions cannot be made regarding other solution exposures without testing. Galvanic corrosion, as a primary mode of failure, is actually quite rare in most industrial environments. Numerous piping systems use combinations of carbon steel piping connected to stainless valves selected for erosion/corrosion resistance and do not suffer galvanic corrosion problems. Many other dissimilar metal combinations are likewise used with little or no galvanic corrosion.

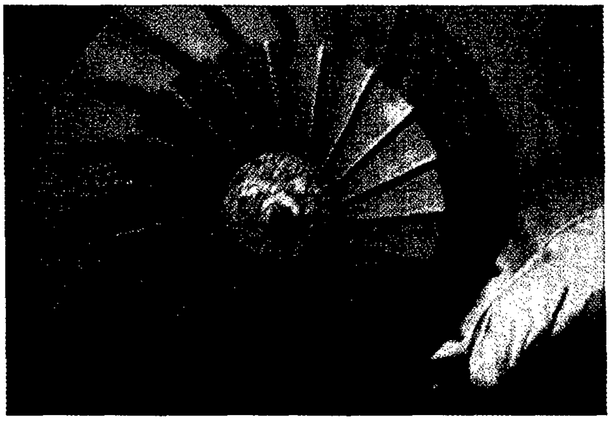


Figure 33. Titanium impeller with 410 stainless steel washer and retainer nut. Note corrosion of 410 sst due to galvanic corrosion; the titanium was protected.

As mentioned earlier, we can use these galvanic differences to protect steel structures. Many offshore oil platforms made from carbon steel have large "anodes" of zinc or zinc alloys attached to them to protect the steel. The zinc anodes preferentially corrode, thereby protecting the steel from corrosion. As the zinc anodes disappear over time, they must be replaced on some frequency to maintain protection. The number and location of the anodes must be carefully thought out to provide complete protection. The "throwing power" of zinc and its alloys refer to the area of steel one anode will protect, and it can be considerable depending on several factors such as alloy content, size, temperature, and water quality.

An obvious question that arises is why we don't use zinc anodes to protect our hot water heaters from corrosion. Unfortunately, zinc behaves as an anode to protect steel only below temperatures of about 150°F or so, and thus, when subjected to hot water, the combination of zinc and steel often causes the steel to corrode preferentially. This reversal of the role of zinc is also affected by water quality, especially in the presence of bicarbonates.

Avoiding Galvanic Corrosion

Generally, little is needed to avoid galvanic corrosion for most industrial applications since it seldom occurs. However, some industries must take careful precautions in selecting metal combinations to avoid problems. The most common solutions to galvanic corrosion are the selection of alloys that exhibit similar potentials for the anticipated service, or the use of nonmetallics as one of the material couples. Another technique used with limited success is the electrical isolation of the alloy combination to eliminate electron flow between the two metals.

An interesting, but undocumented, tale made the rounds many years ago when the state of Arizona, being the "Copper" state, decided to make license plates of copper to support the state's important industry. As you might expect, corrosion engineers were not consulted in this legislative decision, and when the first order of new plates were attached, using the galvanized bolts most commonly used, galvanic corrosion occurred on the bolts strewing the streets with copper plates. Needless to say, the use of copper plates was abandoned. Today, most license plate attachment bolting is nylon that will not suffer such problems.

Miscellaneous Corrosion Mechanisms

The forms of corrosion noted above are the most common ones; other forms and subsets include fretting corrosion, cavitation erosion, microbiological pitting, hydrogen grooving and hot hydrogen damage (hydrogen attack). These mechanisms are less common than the forms noted above and will be discussed only briefly.

Fretting corrosion is defined as "*Corrosion damage occurring at the interface of two surfaces in contact, one or both of which are metals, subject to slight relative slip.*" The relative motion is usually very slight and is often caused by vibration. Fretting corrosion is usually associated with colored iron oxide deposits on the metal surface and, if severe enough, surface pitting. The surface deposits are usually very fine-grained in size and often a bright reddish or reddish brown in color.

Fretting corrosion is usually avoided by selecting the proper combinations of metals in contact, one having a greater degree of hardness than the other. Steel in contact with brass seldom suffers fretting, while steel against steel may result in fretting damage. Proper lubrication also reduces fretting corrosion.

Cavitation erosion is damage caused by rapidly alternating pressure differentials within a liquid in contact with a metal with high relative motion between the two. The net effect of pressure reductions is to cause localized boiling of the liquid, forming cavities of vapors within the liquid. As the liquid pressure returns to normal, the cavities collapse by implosion, causing a high speed liquid impact. The metal surface becomes work-hardened, roughened, and can crack by fatigue mechanisms. The net result is rapid, deep, spongy pitting of the metal surface. The most common occurrences of cavitation damage are on engine pistons and pump impellers. Typically, the impeller damage is on the backside of the impeller where pressure differentials tend to be greatest.

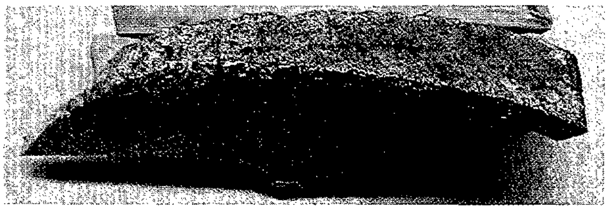


Figure 34. A section of the back side of an impeller suffering severe cavitation damage.

Cavitation damage is usually avoided by proper materials selection. For centrifugal pumps, "throttling" the pump's discharge can reduce cavitation; this ensures the pump is liquid-filled at a constant pressure during operation. A centrifugal pump operating in the cavitation mode has an unusual, loud, identifying sound, as if marbles or ball bearings are being circulated.

Microbiological pitting or MIC (Microbiological Induced Corrosion) is a very interesting corrosion phenomenon caused by biological organisms in natural waters and soils. Both river and well waters can be the source of these organisms that create environments that corrode metals, often with severe pitting results. These organisms can promote corrosion of many different alloys, and mainly cause corrosion problems in both stagnant and low velocity flow environments. Carbon steels and 300 stainless steels are particularly susceptible to this form of corrosion.

Avoiding microbiological pitting is difficult; often substituting high nickel alloys is the only solution. Biocides and other water treatments have been used with mixed results. In some cases, a different water source is required to avoid pitting.

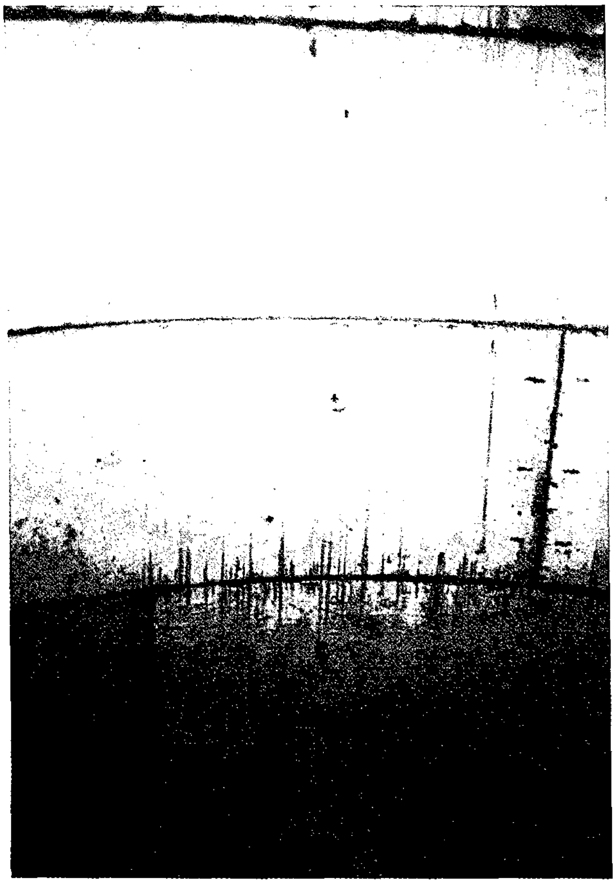


Photo courtesy of Greg Kobrin, Beaumont, TX.

Figure 35. Interior of large 300 series stainless steel storage tank showing MIC damage. Note streaking emanating from horizontal girth welds joining plate sections.

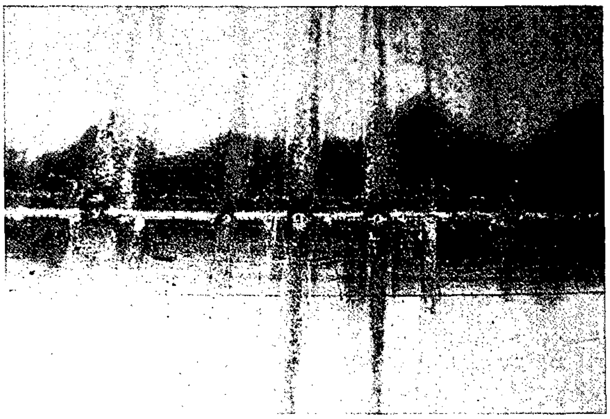


Photo courtesy of Greg Kobrin, Beaumont, TX.

Figure 36. Close-up of girth weld showing MIC pits at girth weld.

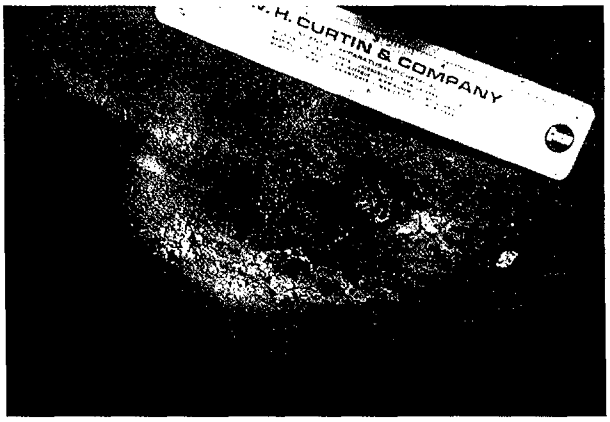


Photo courtesy of Greg Kobrin, Beaumont, TX.

Figure 37. Close-up of a single MIC pit. Corrosion scale covering pit has been removed to show metal damage.

Hydrogen grooving of steel is an unusual corrosion problem. Deep grooving of the steel occurs through a mechanism of general corrosion in or by a stagnant liquid, creating nascent hydrogen, which then coalesces on the metal surface. As the hydrogen bubbles rise and collect, the hydrogen flows along sloped surfaces and reduces the passive iron oxide film that normally provides corrosion protection. Corrosion of the oxide-reduced areas then continues at a more rapid rate. The net result is deep corrosion grooves in the steel, often leading to complete perforation. This form of corrosion is most common in room temperature, concentrated sulfuric acid exposures. Water treatment systems often use sulfuric acid to regenerate water treatment resins on some

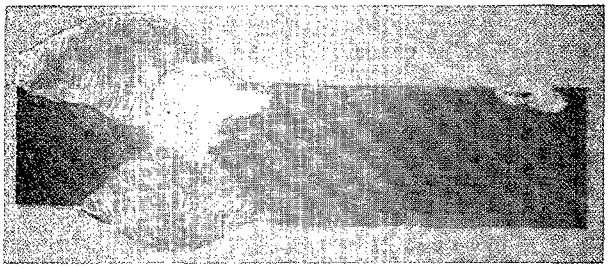


Photo courtesy of Greg Kobrin, Beaumont, TX.

Figure 38. Cross-section of weld showing MIC pitting. Note cavity is much larger beneath the surface. Pitting at right edge is also MIC of parent plate.

scheduled basis; usually this regeneration may occur for just one hour every 24 hours. The hydrogen grooving occurs during the stagnant, no-flow conditions where the hydrogen formed by the normally low corrosion rate collects and reduces the protective film. When pumping is again initiated, the unprotected steel corrodes at a more rapid rate. Tank cars transporting concentrated sulfuric acid are also subject to this form of corrosion, usually in the splash zones above the liquid.

Hydrogen grooving damage is usually corrected by a change in materials; using polypropylene-lined piping is a good solution for piping. Linings in tank cars usually solve the problem for acid transport.

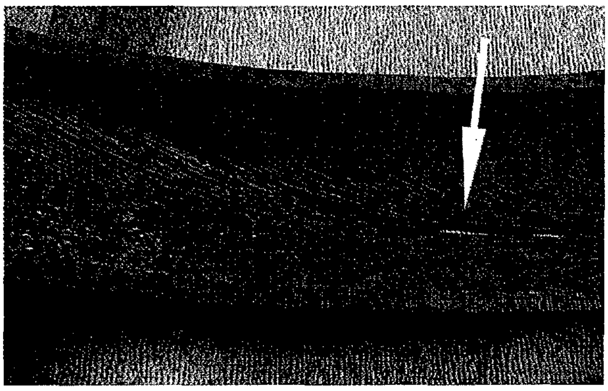


Figure 39. Hydrogen grooving in carbon steel piping due to sulfuric acid. Note deep grooving at right side due to coalescence of hydrogen bubbles.

Hot hydrogen damage ("hydrogen attack") can cause embrittlement of carbon steel when it is exposed to nascent hydrogen at elevated temperatures, usually 750°F or greater. However, failures of steels at temperatures as low as 400°F have been documented for exposures to very high concentrations of nascent hydrogen. The loss of ductility is quite severe, and the steel becomes quite brittle, often leading to catastrophic failures. Considerable study of this problem has been made, especially in the oil refining industry and petrochemical industries. A series of curves referred to as the "Nelsen Curves" show the effect of hydrogen concentrations as partial pressures and the temperature causing embrittlement of various alloys. These curves are very helpful for aiding in selecting alloys resistant to hydrogen attack.

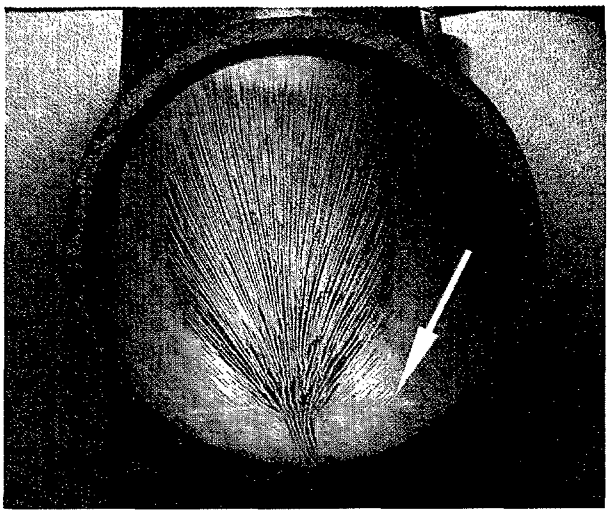
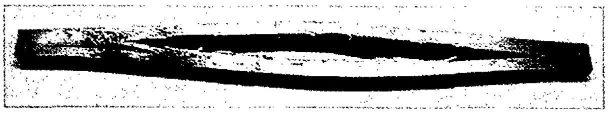


Figure 40. Hydrogen grooving of carbon steel elbow; note grooving, and "bathtub ring" of corrosion at arrow caused by collection of hydrogen.

An obvious solution is to avoid exposure of plain carbon steel to hot hydrogen. If such exposure is required, the molybdenum and chromium contents of the steel must be increased to avoid the effects of hot hydrogen. Other alloying additions can improve the resistance also; the 300 series stainless steels are essentially immune to this form of corrosion.

Another type of hydrogen corrosion is known as "**hydrogen blistering**." This can occur on plate steels in many mildly corrosive services and is caused by the nascent hydrogen formed during normal low corrosion rates being absorbed by the steel plates. As the nascent hydrogen enters the steel structure, it can recombine as molecular hydrogen, requiring a much greater volume. This increase in volume creates intense pressure on the through thickness direction of the steel plate, often resulting in large blisters. These blisters are filled with hydrogen gas and welding repairs must be handled very carefully to avoid injury to repair personnel since hydrogen is highly flammable and explosive (remember the *Hindenburg* blimp catastrophe?). Usually, a compressed air drill, with copious amounts of water flooding the drilling surface, is first used to perforate the blister and relieve the pressure. This also allows the entrapped hydrogen gas to escape and avoid fire or explosion, permitting safe welding repairs to be made.



Sample courtesy of Steve Springer,
Du Pont Company, Old Hickory, TN.

Figure 41. Cross-section of 1 inch thick carbon steel plate showing effects of hydrogen blistering.

Alloying for Corrosion Resistance

In the discussion above, control of several different alloying elements have been referred to as aids in reducing corrosion. To complete the review of alloying effects, various elements and their effects on corrosion will be discussed.

Carbon (C). The effects of carbon content on the sensitization of the 300 series stainless steels have been reviewed above. Carbon content, and the resulting sensitization during welding, can also affect the higher alloys that include the proprietary family of nickel-base alloys such as the Hastelloys, Inconels, Incoloys, and others. Generally, for the plain carbon and low carbon steels, carbon content is not a significant factor in corrosion resistance. However, it must be remembered that carbon content can be a major factor in weldability, mechanical strength, and ductility of many alloys.

Chromium (Cr). This element is one of the most beneficial for improving the corrosion resistance of alloys. By definition, the stainless steels contain at least 12% chromium that dramatically improves an alloy's resistance to oxidizing environments. Chrome plating is also used for the same purpose. The chromium oxide coating formed on exposure to air or oxygen is very adherent and protects the underlying metal from further corrosion damage. While the straight chrome stainless steels are difficult to weld, nickel can be added in sufficient amounts to form the austenitic alloys that are much easier to weld.

Columbium (Cb). This element, as noted above, is added as a stabilizer to reduce sensitization of the 300 series stainless steels and other higher alloys. One proprietary alloy, Carpenter 20 Cb3, with relatively high levels of Cr and Ni for improved resistance to hot sulfuric acid, contains Cb additions as a stabilizer.

Copper (Cu). Additions of copper to steel alloys can improve their atmospheric corrosion resistance without seriously degrading their weldability. Also, the copper-base alloys are quite useful in avoiding corrosion and erosion by waters, both natural and salt water. The copper-base alloys are somewhat limited in oxidizing environments above about 400°F, but are resistant to many reducing environments.

Molybdenum (Mo). Molybdenum additions were previously discussed regarding improved pitting resistance of the 300 series stainless steels and increased resistance of steels to hot hydrogen services. In some high temperature environments, however, Mo can degrade the oxidation resistance of the stainless steels.

Nickel (Ni). Nickel additions to steels significantly increase their general corrosion resistance if added in sufficient quantities. The 300 series stainless steels contain Ni in percentages of 8–12%; nickel-base alloys often have much higher percentages such as 30–75% Ni. Many of the high alloys known for outstanding corrosion resistance in severe environments have 60–75% Ni, including the Hastelloys and Inconels. One nickel-base alloy, Monel 400, contains about 65% Ni and 35% Cu. This alloy is very useful for corrosive service conditions that are reducing in nature or weakly oxidizing.

Titanium (Ti). Titanium is added as a stabilizer to reduce sensitization of the stainless steels and higher nickel-base alloys. Titanium alloys are used in many severe environments, especially those containing chlorides.

Many other elements can also affect the corrosion properties of metals, even when present in small amounts. This category includes sulfur, arsenic, antimony, and others.

Case Histories

To emphasize common solutions to weld corrosion problems, several case histories from past experiences will be reviewed. These solutions must be carefully weighed as to their effectiveness for each particular situation, but they can be quite useful in developing a practical approach to solving field corrosion problems and equipment repairs.

Case 1. A large pressure vessel fabricated from 309 sst for exposure to hot, high pressure, concentrated nitric acid suffered selective corrosion of the interior girth and vertical shell welds in the central zone of the vessel. The shell thickness was about 3″ and had received an original solution anneal, water quench after fabrication to maximize its corrosion resistance for the intended service. Repairs to the shell welds to restore the shell thickness required welding, and this would significantly reduce the benefits of the original heat treatment by sensitization, leading to even more rapid corrosion.

Weld repairs were successfully made to the vessel using a "quench weld" technique. This approach first required the removal of the corrosion-damaged areas by grinding to sound metal. Next, a penetrant test was made to check for cracking; all penetrant test residues were then removed. This was followed by SMAW welding using 1/8 inch diameter E309L electrodes. The quench weld approach required welding a length of only about 2–3 inches of weld, followed by rapidly quenching the weld zone with a dripping wet rag. The surface was dried and a second short zone of weld was applied, followed again by quenching. This sequence was repeated until the shell was restored to the required thickness. Periodically, during the repair cycle, penetrant testing was done to check for quench cracking. This sequential welding and quenching minimized the sensitization of the weld and HAZ and permitted returning the vessel to service. While this quench weld approach is not as beneficial as the original solution anneal, water quench heat treatment, it was sufficient for minimizing the sensitization and future corrosion rates, and permitted continued service for the repaired vessel.

Case 2. Welded tantalum components were suffering selective weld and HAZ corrosion in a severely acidic environment. It was determined that the tantalum welds were not receiving adequate purging during the chamber welding sequence and were suffering oxidation which reduces corrosion resistance and mechanical strength. Unfortunately, tantalum (and zirconium) can be damaged by excessive welding oxidation without exhibiting visible metal color changes. An oxygen meter appeared to be inadequate to determine the necessary absence of oxygen.

"Tattle tale strips," consisting of small, solvent cleaned strips of titanium were placed into the chamber prior to the argon purging sequence. The effectiveness of the chamber purge was then determined by striking the GTAW torch on the titanium and making a fusion pass on its surface. If the chamber purge were inadequate, the titanium would oxidize rapidly leading to an easily detectable color change to blues or purples. When the chamber purge was acceptable for welding the tantalum, the titanium was not oxidized during the fusion pass, and the titanium fusion pass and HAZ remained silver or straw colored, indicating a very low oxygen level had been obtained within the chamber. This approach works well for both tantalum and zirconium chamber welding.

Case 3. 316L sst piping exposed to hot acids suffered severe corrosion at butt joint welds. While quench welding techniques improved the conditions, they were not sufficient for long term service. The 316L filler metal was replaced with 317L filler metal, containing a higher percentage of Mo; weld repairs were completed, and adequate service life was obtained. Often, selective weld corrosion can be reduced or eliminated by upgrading the weld metal to a higher alloy.

A note of caution must be raised regarding 317 and 317L sst. The Mo contents of both have dropped in recent years to the bare minimum required by the specification. The 317 requirement is 3–4% Mo, but rather than the normally found percentages of 3.6% or 3.8% Mo from many years ago, current alloys of these two types often contain only the bare minimum of 3.01% Mo. Occasionally, where 317 sst performed well for years, replacement with the current version having a much lower Mo content has resulted in premature failure. Mill test certificates can be reviewed for selecting heats having the desired Mo content.

Case 4. A large nickel roll used to gather product on its surface as it rotated though a liquid bath of product was exposed to concentrated organic acids and after several years of service, the butt joint weld across the face of the roll joining the rolled plate sections suffered severe corrosion. Weld repairs were required but concern was raised regarding further reduction of the nickel roll's corrosion resistance by the welding heat. A technique was used to minimize the effects of welding: after grinding to remove the damage, a weld pass was made along the groove. The first pass was welded and peened to introduce cold work into the nickel weld. A second weld pass was then completed. The cold work in the first pass from the peening and the heat of welding from the second pass caused recrystallization of the first weld pass, improving its corrosion resistance. The sequence of peening and welding was continued until the groove was completely filled. The "final surface" pass was peened, and one more weld pass was made to recrystallize the previously peened surface pass. The last pass made was then removed by grinding flush, leaving a corrosion resistance surface for continued service.

Case 5. A large, thick, stress relieved carbon steel vessel required weld repairs to several girth welds damaged by localized corrosion. Because of its size and location, the vessel could not be field stress relieved without excessive cost and production delays. Using guidelines from the *National Boiler Inspection Code*, weld repairs were made without the typical post weld stress relief using the following "Temper Bead" approach:

All corrosion damage was removed, followed by dye penetrant inspection. A preheat of 600°F was applied and low hydrogen E7018 electrodes were deposited by the SMAW process, with hot peening of each pass. Again, after the final pass was made and peened, one more additional weld pass was made, bringing the weld surface well above flush. This last pass was then removed by grinding. The net effect of the preheat and welding heat from the intermediate and final passes was stress relief of each previous pass, resulting in a lower residual stress, which met the Code requirement. The vessel was returned to service and it performed without failure for several years.

Case 6. A 304 sst vessel began leaking in one area and penetrant testing showed severe stress corrosion cracking of the shell in an area about 2 feet × 3 feet in size. The SCC was caused by wet insulation containing chlorides in that area. Plans were made to remove a portion of the shell section and replace it, but the question arose as to the proper size of the area to be removed. SCC is not always detected by PT and concern was raised about ensuring the removal of all the area affected by the SCC.

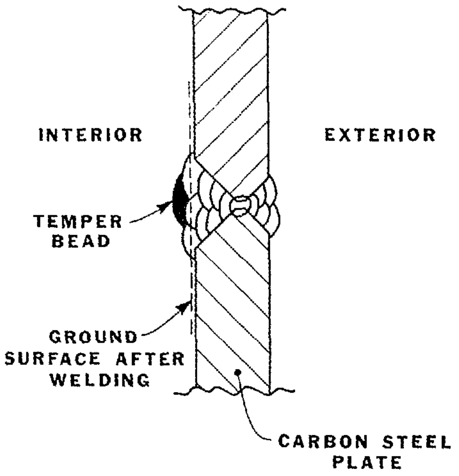


Figure 42. Sketch showing Temper Bead weld repair procedure.

A technique using weld fusion passes was used to determine what area or zone was unaffected by the cracking. A GTAW fusion pass was made near the perimeter of the cracking. As expected, the stress caused by the fusion pass created additional cracks that were then detectable by PT. A second round of fusion passes was made slightly further out from the first, followed by PT. This approach was continued until a perimeter was found that did not exhibit cracking after fusion pass welding. This perimeter was used to define the area to be removed and proved successful during the insert patch weld repairs.

Case 7. A large, nickel-lined, carbon steel distillation column was insulated to maintain hot process temperatures. A mechanic noticed bulging of the insulation at several of the vacuum support rings that encircled the column every 8 feet. The insulation was removed at the support ring and severe corrosion of the carbon steel was present. In fact, the steel had corroded completely away in some areas, exposing the interior nickel lining. The nickel lining thickness was 0.090 inch, and along with the internal structure, was all that was maintaining structural support.

The severe corrosion of the steel was caused by rain entering the insulation at open seams and collecting

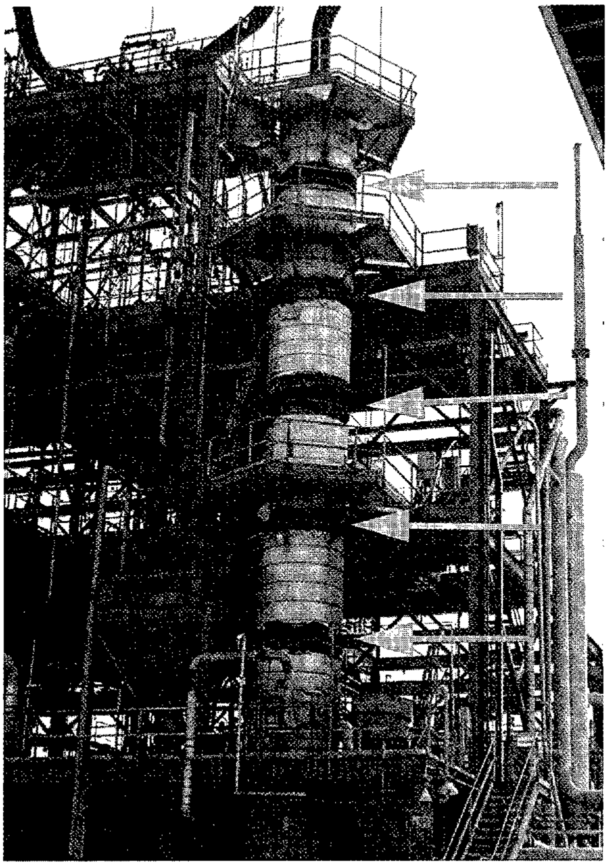


Figure 43. Distillation column with external insulation removed showing corrosion at support rings.

at each support ring. The support rings had been continuously welded, top and bottom, to the column exterior without leaving an open path in the weld seam for the moisture to drain. The high metal temperature of the column and the entrapped moisture led to complete corrosion of the 9/16 inch thick plates at areas just above each support rings. The loss of structural integrity required removal and replacement of the column; vertical support bars were welded onto the column to provide sufficient support for lifting the column out of the building and to the ground.

This case emphasizes the need for a careful review of the welding designs for pressure containing equipment. Needless to say, the new column had drains at four locations on each supporting ring.

Figure 44. Close-up of Figure 43 column exterior just above encircling support ring showing severe scaling and corrosion of carbon steel at the right arrow. The "silver colored" metal beneath the scale at the left arrow is the interior nickel lining.

Summary

Corrosion of welds and welded structures is a very interesting and complex subject, and the discussion above is only a very, very small part of the total information available. For those desiring more information, a short list of corrosion references is attached to assist further study; your local university or college can also direct you to other sources.

Additional References on Corrosion

1. *NACE Corrosion Engineer's Reference Book*, Second Edition.
2. *NACE Process Industries Corrosion.*
3. *ASM Metals Handbook*, Ninth Edition, Volume 13, Corrosion.
4. *Corrosion Resistance of Metals and Alloys*, Second Edition, La Que and Copson.
5. *The Corrosion Handbook*, Uhlig.
6. *Corrosion and Corrosion Control*, Uhlig.
7. *AWS Welding Handbook*, Eighth Edition, Volume 4.