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PREFACE

“It’s stainless steel, it shouldn’t rust”

This is often the kind of statements heard from individuals when discussing a failure of process piping or equipment. This is also an indication of how little is actually understood about stainless steel and the applications where it is used.

For years the food, beverage and pharmaceutical industries have used stainless steels in their process piping systems. Most of the time stainless steel components provide satisfactory results. Occasionally a catastrophic failure will occur. The purpose of the information contained within this document is to bring an understanding to stainless steel, it's uses, and why it will fail under certain conditions.

In the following pages we will discuss the different classes of stainless steel, heat treatment, corrosion, welding, and finally material selection. As with any failure, it is imperative the cause of the failure be identified before a proper fix can be recognized. Most often the cause of the failure is identified as the wrong material being used in the wrong application. We can not solve problems by using the same kind of thinking we used when we created them.

We have strived in this document to provide engineers, purchasing agents, and plant personnel with a tool to enhance their knowledge of stainless steel and it uses as related to their present and future applications.

STEEL

Stainless

What is stainless steel? Stainless steel is not a single alloy, but a large family of alloys with different properties for each member. There are hundreds of grades and sub grades in the stainless steel family, each designed for a special application. Chromium is the magic element that transforms iron into stainless steel. Stainless steel must contain at least 10.5% chromium to provide adequate resistance to rusting, and the more chromium the alloy contains, the better the corrosion resistance becomes. There is, however an upper limit to the amount of chromium the iron can hold. Therefore additional alloying elements are necessary to develop corrosion resistance to specific medias.

We must remember that stainless steel is an alloy of iron. According to its definition, stainless steel must contain a minimum of 50% iron. If it contains less iron, the alloy system is named for the next major element. For example, if the iron is replaced with nickel-so that the iron is less than 50%-then it is called a nickel alloy.

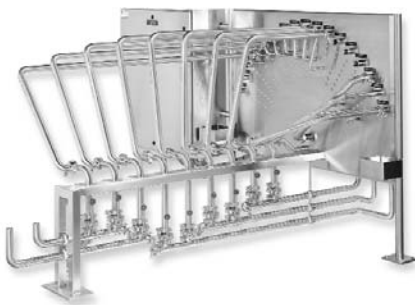
Chromium imparts a special property to the iron that makes it corrosion resistant. When the chromium is in excess of 10.5%, the corrosion barrier changes from an active film to a passive film. While the active film continues to grow over time in the corroding solution until the base metal is consumed, the passive film will form and stop growing. This passive layer is extremely thin, in the order of 10 to 100 atoms thick, and is composed mainly of chromium oxide which prevents further diffusion of oxygen into the base metal.

But, chromium also is stainless steel's Achilles heel, and the chloride ion is stainless steel's nemesis. The chloride ion combines with chromium in the passive layer, forming soluble chromium chloride. As the chromium dissolves, free iron is exposed on the surface and reacts with the environment forming rust. Alloying elements like molybdenum will minimize this reaction.

Other elements, as illustrated in Table I (page 1), may be added for special purposes. These purposes include: high temperature oxidation resistance, sulfuric acid resistance, greater ductility, high temperature creep resistance, abrasion resistance, or high strength. Of all these elements, only chromium is required in order for stainless steel to be stainless.



Table I: Stainless Steel Alloying Elements and Their Purpose



| | |
|------------|---|
| Chromium | Oxidation Resistance |
| Nickel | Austenite former - Increases resistance to mineral acids Produces tightly adhering high temperature oxides |
| Molybdenum | Increases resistance to chlorides |
| Copper | Provides resistance to sulfuric acid Precipitation hardener together with titanium and aluminum |
| Manganese | Austenite former - Combines with sulfur Increases the solubility of nitrogen |
| Sulfur | Austenite former - Improves resistance to chlorides Improves weldability of certain austenitic stainless steels Improves the machinability of certain austenitic stainless steels |
| Titanium | Stabilizes carbides to prevent formation of chromium carbide Precipitation hardener |
| Niobium | Carbide stabilizer - Precipitation hardener |
| Aluminum | Deoxidizer - Precipitation hardener |
| Carbon | Carbide former and strengthener |

STAINLESS

Steel Classification



There are five classes of stainless steel: austenitic, ferritic, martensitic, duplex, and precipitation hardening. They are named according to how their microstructure resembles a similar microstructure in steel. The properties of these classes differ but are essentially the same within the same class. Table II (page 2) lists the metallurgical characteristics of each class of stainless steel.



Table II: Metallurgical Characteristics

| | |
|-------------------------|---|
| Austenitic | Non-magnetic Non-hardenable by heat treatment Single phase from 0° (K) to melting point Crystallographic form – face centered cubic Very easy to weld |
| Ferritic | Magnetic Non-hardenable by heat treatment Crystallographic form – body centered cubic Low carbon grades easy to weld |
| Duplex | Magnetic Non-hardenable by heat treatment Contains both austenite and ferrite Easy to weld |
| Martensitic | Magnetic Heat treatable to high hardness levels Crystallographic form – distorted tetragonal Hard to impossible to weld |
| Precipitation Hardening | Magnetic Crystallographic form – martensitic with microprecipitates Heat treatable to high strength levels Weldable |

| | |
|-----------------|---|
| Characteristics | Non-magnetic, Usually Very ductile Work hardenable Lower strength Not subject to 885°F (475°C) embrittlement Not subject to ductile – brittle temperature range Not subject to hydrogen embrittlement Will chloride stress corrosion crack |
| Examples | Type 304, 304L, 304H, 304N, 304LN, 321, 347 Type 316, 316L, 316H, 316N, 316LN, 316Ti Type 317, 317L, 317LM, 904L AL6XN, 254 SMO, 25-6Mo, 1925hMo Type 308, 309, 310 |

These are the most popular of the stainless steels because of their ductility, ease of working and good corrosion resistance. All were derived from the 18Cr-8Ni stainless steels. Their corrosion resistance may be compared to the rungs on a ladder with Type 304 on the first rung and the other grades occupying the successive rungs. The most common grade is

Table III: Austenitic Stainless Steel

Type 304/304L, which makes up over 60% of all the stainless steel made in the United States today. The other grades are developed from the 18–8 base by adding alloying elements to provide special corrosion resistant properties or better weldability. For example, adding titanium to Type 304 makes Type 321, the workhorse of the intermediate temperature materials. Adding 2% molybdenum to Type 304 makes Type 316, which has better chloride corrosion resistance. Adding more chromium gives Type 310 the basis for high temperature applications. The major weakness of the austenitic stainless steels is their susceptibility to chloride stress corrosion cracking. Table III (page 2) lists characteristics, properties and examples of these alloys.



Ferritic Stainless Steel:

Until the early 1980s, these alloys were not very popular because the inherent high carbon content made them extremely brittle and imparted relatively poor corrosion resistance. Research in the late 1960s, using vacuum electron beam melting, led to a new class of alloys sometimes called the "Superferritic Stainless Steels" of which E-Brite 26-1,[®] was the first. Then in the late 1970s a new steel refining technique, Argon Oxygen Decarburization (AOD), was developed. This technique, together with the addition of titanium or niobium, allowed the commercial development of extremely corrosion resistant grades. Today SEA-CURE[®] stainless, one of the most popular superferritic alloys, is widely used in marine applications since its corrosion resistance in seawater is essentially the same as

that of titanium. The most widely used ferritic stainless steel is Type 409, a 10.5% Ce alloy with no nickel, used for automotive exhaust systems. Ferritic stainless steels are resistant to chloride stress corrosion cracking, and have high strength. Grades like SEA-CURE stainless have the highest modulus of elasticity of the common engineering alloys, which makes them highly resistant to vibration. Table IV (page 3) lists characteristics, properties and types of these alloys.

Table IV: Ferritic Stainless Steels

| | |
|-----------------|---|
| Characteristics | Magnetic High ambient temperature strength Low work hardening Resistant to chloride stress corrosion cracking Subject to 885°F (475°C) embrittlement at temperatures as low as 600°F (315°C) Subject to hydrogen embrittlement Subject to ductile-brittle temperature embrittlement |
| Examples | Type 405, 409 Type 430, 430Ti, 439 Type 444, E-Brite 26-1 SEA-CURE Stainless, 29-4, 29-4C, 29-4-2 |



Duplex Stainless Steel:

Although these alloys were developed in 1927, their usefulness was not realized until the 1960s. They are characterized by having both austenite and ferrite in their microstructure, hence the name Duplex Stainless Steel. Duplex stainless steels exist in a narrow nickel range of about 4-7%. A ferrite matrix with islands of austenite characterizes the lower nickel grades, and an austenite matrix with islands of ferrite characterizes the higher nickel range. When the matrix is ferrite, the alloys are resistant to chloride stress corrosion cracking. When the matrix is austenitic, the alloys are sensitive to chloride stress corrosion cracking. High strength, good corrosion

Table V: Duplex Stainless Steels

| | |
|-----------------|--|
| Characteristics | Magnetic Contains both austenite and ferrite High strength Subject to 885°F (475°C) embrittlement at temperatures as low as 600°F (315°C) Subject to hydrogen embrittlement Subject to ductile-brittle temperature embrittlement Resistant to chloride stress corrosion cracking if ferritic network |
| Examples | Alloy 2205 Carpenter 7-Mo PLUS Ferrallium 255, 2507 |

resistance and good ductility characterize them. One alloy, Carpenter 7-Mo PLUS,[®] has the best corrosion resistance against nitric acid of any of the stainless steels because of its very high chromium content and duplex structure. Table V (page 3) lists the characteristics, properties and examples of these alloys.

Martensitic Stainless Steels:

These were the first stainless steels developed because of the inability to obtain low carbon steel. Basically, they are stainless tool steels because they use the same hardening and tempering mechanisms. These grades are very common, from the blade in your pocket Swiss Army knife, to the scalpel the surgeon uses when he makes that first incision for a heart bypass operation. Martensitic stainless steels are used in bearing races for corrosion proof bearings and other areas where erosion-corrosion is a problem. These stainless steels are not especially corrosion resistant, barely as good as Type 304,

but are infinitely better than the carbon steels they replace. Like carbon tool steels, martensitic stainless steels derive their excellent hardness from the carbon added to the alloy. Their ability to maintain a keen edge comes from their high hardness and corrosion resistance. Table VI (page 4) lists the characteristics and some examples of these alloys.



Table VI: Martensitic Stainless Steels

| | |
|-----------------|---|
| Characteristics | Magnetic Metallurgical structure is martensite Heat treatable to very high strengths and hardness – stainless tool steel Difficult to weld |
| Examples | Types 410, 420 Types 440A, 440B, 440C |

Precipitation Hardening Stainless Steel:

These steels are the latest in the development of special stainless steels and represent the area where future development will most likely take place. They are somewhat soft and ductile in the solution-annealed state, but when subjected to a relatively low precipitation hardening temperature, 1000°F (540°C), their strength more than doubles and they become very hard. The metallurgical structure of the common grades is martensitic, but some of the special high nickel grades are austenitic. The strengthening mechanism comes from the formation of submicroscopic precipitates, which are compounds of aluminum, copper, titanium, or

Table VII: Precipitation Hardening Stainless Steels

| | |
|-----------------|---|
| Characteristics | Magnetic Extremely high strength after precipitation heat treatment Reasonably ductile in solution annealed condition Corrosion resistance similar to Type 304 |
| Examples | 17-7PH, 17-4PH, 13-5PH, 15-8PH Custom 450, Custom 455, AM 350, AM 355 |

molybdenum. These precipitates provide resistance to strain exerted on the structure. The precipitates are so small they can be observed only at extremely high magnifications with special electron microscopes. Their action may be understood by the analogy of a deck of cards to a block of steel. When a force is placed upon the cards, the cards in the deck easily move in response to the force. If the block of steel is given the low temperature aging treatment, small precipitates form, similar to placing sea sand on the surface of the cards. Now, it takes much more force to cause the cards to move; so, the material is much stronger. The primary use of precipitation hardening steels is where high strength and corrosion resistance are required. Aerospace and military applications have dominated the applications in the past, but new uses in instrumentation and fluid control are being found. Table VII (page 4) lists the characteristics and some examples of these alloys.



NICKEL BASED Alloys

Many consider these alloys to be stainless steel. But if you recall, by definition in order for stainless steel to be stainless steel it must contain a minimum of 50% iron. The iron ratio in nickel based alloys are considerably less than 50%. Within nickel based alloys there are four classifications. Group A is nickel and nickel-copper alloys such as Monel 400; Group B is Chromium bearing alloys as in Hastelloy C-22 and C-276; Group C is Nickel-Molybdenum alloys such as Hastelloy B2, B3 and B4; and Group D is Precipitation-hardening alloys as are Monel K-500 and Inconel alloy 718.



The wide range of nickel based alloys available are used for their resistance to corrosion and retention of strength at elevated temperatures. Many severe corrosion problems can be solved through the use of these alloys. However, they are not universally corrosion resistant. The proper alloy must be carefully selected for a specific application. Nickel and nickel based alloys are very resistant to corrosion in alkaline environments, neutral chemicals and many natural environments. In addition, many nickel based alloys show excellent resistance to pitting, crevice corrosion and stress corrosion cracking in chloride environments.

The alloy strength is controlled by the chemical composition and the metallurgical structure. Only the martensitic and precipitation hardening stainless steels can be heat treated to obtain higher strength. Strengthening, or an increase in the ultimate and yield strengths, of the other grades must be achieved by cold working the structure. Heat treatment of the austenitic, martensitic and duplex grades is used to remove residual stress and, in the case of the austenitic stainless steels, to reduce the probability of chloride stress corrosion cracking. Heat treatment is also used to dissolve any undesirable metallurgical phases that may be present.

Heating and cooling the various grades of stainless steel must be done with caution. Be very careful using acetylene, MAP or propane torches to heat the stainless steel. If a reducing flame is used, excessive carbon may be transferred to the metal resulting in the formation of chromium carbide and ultimately, failure of the part.

Before attempting heat treatment of a particular grade of stainless steel, always refer to the heat

STRENGTH & Heat Treatment

treatment data for that particular grade. For example, slow cooling a high carbon austenitic stainless steel from the solution anneal temperature may lead to precipitation of chromium carbide. This will result in poor corrosion resistance and low ductility. Holding a ferritic or duplex stainless steel within the 885°F (475°C) embrittlement temperature range which can be as low as 600°F (315°C)-may lead to brittleness at room temperature. Heating high chromium, high molybdenum austenitic stainless steel to a temperature below the specified minimum heat-treating temperature, may lead to precipitation of second phase compounds along the grain boundaries. When placed in service, these alloys may corrode or fail because of low ductility problems. Always check on the nature of the alloy before attempting any type of heat treatment. Table VIII (page 6) compares the strengths of selected alloys within the various classes of stainless steel.

Table VIII: Properties of Stainless Steel Alloys, ASTM Minimums, Unless Otherwise Stated

| Alloy | UNS number | Ultimate strength, psi | Yield strength, psi | Elongation, percent minimum | Modulus of elasticity | Hardness typical |
|---|------------|------------------------|---------------------|-----------------------------|-----------------------|------------------|
| Austenitic Stainless Steels | | | | | | |
| Type 304 | S30400 | 75,000 | 30,000 | 35 | 29,000,000 | 80 RB |
| Type 304L | S30403 | 70,000 | 25,000 | 35 | 29,000,000 | 75 RB |
| Type 316 | S31600 | 75,000 | 30,000 | 30 | 28,000,000 | 80 RB |
| Type 316L | S31603 | 70,000 | 25,000 | 35 | 28,000,000 | 80RB |
| AL-6XN | N08367 | 112,000 | 53,000 | 50 | 27,000,000 | 90 RB |
| Ferritic Stainless Steels | | | | | | |
| Type 430 | S43000 | 60,000 | 30,000 | 20 | 29,000,000 | 85 RB |
| Type 439 | S43035 | 60,000 | 30,000 | 20 | 29,000,000 | 90 RB |
| Type 409 | S40900 | 55,000 | 30,000 | 20 | 29,000,000 | 85 RB |
| SEA-CURE | S44660 | 90,000 | 75,000 | 25 | 31,500,000 | 95 RB |
| Duplex Stainless Steels | | | | | | |
| Alloy 2205 | S31803 | 90,000 | 65,000 | 25 | 29,000,000 | 30 RC |
| 7Mo PLUS | S32950 | 90,000 | 70,000 | 20 | 29,000,000 | 30 RC |
| Alloy 255 | S32550 | 110,000 | 80,000 | 15 | 30,500,000 | 32 RC |
| Martensitic Stainless Steels, Maximum Strength | | | | | | |
| Type 410 | S41000 | 190,000 | 150,000 | 15 | 29,000,000 | 41 RC |
| Type 420 | S42000 | 240,000 | 200,000 | 5 | 29,000,000 | 55 RC |
| Type 440C | S44050 | 280,000 | 270,000 | 2 | 29,000,000 | 60 RC |
| Precipitation Stainless Steels | | | | | | |
| 17-7 PH | S17700 | 210,000 | 190,000 | 5 | 32,500,000 | 48 RC |
| 17-4 PH | S17400 | 190,000 | 170,000 | 8 | 28,500,000 | 45 RC |
| Custom 455 | S45500 | 230,000 | 220,000 | 10 | 29,000,000 | 48 RC |

THE BASICS of Corrosion



What is Corrosion?

Technically, corrosion is the tendency of any metal to return to its most stable thermodynamic state. Namely, that is the state with the most negative free energy of formation. More simply stated, it is a chemical reaction of the metal with the environment to form an oxide, carbonate, sulfate, or other stable compound. In most cases, using a different alloy, material, proper coating, or impressed current can prevent corrosion problems. When a metal part fails in service, it is essential to determine the cause of the failure so that the replacement part can be manufactured from the proper alloy to prevent future failure. Many times a failed part is replaced with the same alloy. For example, if a piping system is made

from Type 304L stainless steel and it fails by chloride stress corrosion cracking, replacing with the same alloy will assure failure within the same time frame. If a change of alloy is made, say to a 6%Mo stainless steel such as AL-6XN[®], the piping may last for the lifetime of the system.

Corrosion can be broadly classified in two forms:

- (1) chemical dissolution of the metal and
- (2) galvanic, or electrically driven. Abrasion, fretting and erosion sometimes are classified as corrosion mechanisms, but technically they are a mechanical metal removal process as compared to a chemical removal process. Chemical reaction may accompany the mechanical removal process to speed up the dissolution, but the chemical reaction will fit into the two basic forms. Some authorities list other

types of corrosion, but the other types generally are modifications of one of the existing corrosion forms. A correct alloy choice for one type of corrosion mechanism may be entirely the wrong choice for another. Therefore, a proper diagnosis of the failure is essential to make the correct material choice.

Within these two basic classifications there are five types of corrosion: 1. General or uniform corrosion; 2. Intergranular corrosion; 3. Galvanic corrosion, including pitting and crevice corrosion; 4. Stress corrosion cracking; and, 5. Microbiologically induced corrosion (MIC). Many times, a metal starts to corrode by one mechanism, for example pitting corrosion, and then fails by a second mechanism, stress corrosion cracking.



General or Uniform Corrosion

Uniform corrosion occurs over large areas of the metal surface.

This is the most common form of corrosion with steel and copper.

It is the easiest form of corrosion to measure, and service lifetime is easy to calculate. This is the only form of corrosion that may be accurately calculated for lifetime before failure and the only corrosion mechanism in which increased section thickness gives longer life. This type of corrosion is measured by corrosion rate, usually reported as mpy (mils per year), mm/y (millimeters per year), ipm (inches per month), or mg/sdm/yr (milligrams per square decimeter per year). This type of corrosion may be minimized in the active metals by painting the surface, and unexpected failures can be avoided by periodic inspections.

Acid cleaning of metals is an exaggerated example of general corrosion. Every time a copper or carbon steel surface is acid cleaned, the metal walls are thinned due to uniform corrosion. Stainless steel is subject to general corrosion in many acids and some salt solutions. They are not subject to general corrosion in water; therefore, no data is available.

Uniform corrosion can be reduced or even prevented by proper selection of materials that are resistant to the corrosive environment. Certain elements make the alloy more resistant to different media. For example, high chromium content imparts oxidation resistance. Therefore, look for high chromium for use with nitric acid, the higher the better. High chromium is useful for high temperature oxidation resistance; so, any stainless steel is better than carbon steel in elevated temperature applications. High copper content in stainless steel imparts resistance to sulfuric acid, as with Carpenter 20Cb-3,[®] stainless steel. High nickel content gives resistance to reducing acids and produces a tightly adhering oxide film in high temperature oxidation.

Basic Corrosion Resistance

A metal derives its corrosion resistance by forming a protective oxide film on the surface. Metals may be classified in two categories-active and passive, depending on the nature of the oxide film.

With active film metals, the oxide film continuously grows until it reaches a limiting thickness then sloughs off, continues to grow, sloughs off-repeating this process until the metal is completely consumed.

Examples of metals with active oxides are iron, copper and zinc. Passive film metals form an extremely thin oxide layer, in the order of 10-100 atoms thick, then stop growing. This film remains stable until something upsets the equilibrium.

Examples of metals with passive films are stainless steel, titanium, gold, platinum, and silver.



A useful tool in determining corrosion resistance is the "Y" of corrosion shown in Figure 1 (page 8). This chart divides the alloys into three classes: those resistant to oxidizing acids on the left, those resistant to reducing acids on the right, and those resistant to a mixture of the two in the center. Oxidizing acids are those acids that oxidize the metals they come in contact with, and are themselves, reduced in the process. Reducing simply dissolves the metal without a change in valence or a release of hydrogen in the process. Corrosion resistance increases as you move up the chart. This chart indicates relative corrosion resistance.

By using the published tables of general corrosion rates, it is possible to determine the resistance of a given alloy to a given environment. The Corrosion Data Survey or the computer program, Corsur-both published by the National Association of Corrosion Engineers (NACE)-are excellent resources. Alloy selection can be simplified, or at least narrowed down, using these tables.

Corrosion tables are based on isocorrosion curves. An isocorrosion curve for type 316 stainless steel in sulfuric acid is presented in Figure 2 (page 8). This curve shows the variation in corrosion rate with temperature and concentration. Similar curves are available for most alloys in many media, and generally are available from reputable material producers.

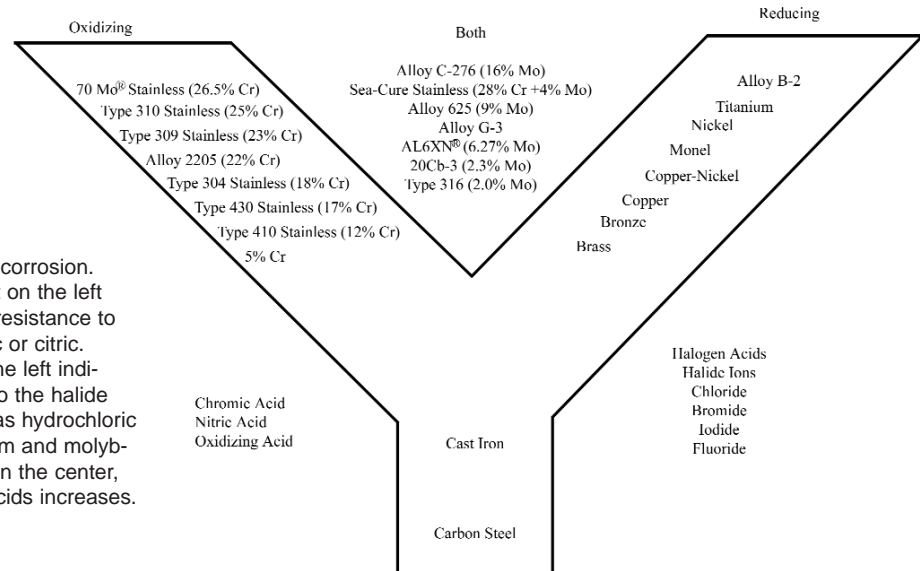


Figure 1: The "Y" of uniform corrosion. Increasing chromium content on the left means increasing corrosion resistance to oxidizing acids, such as nitric or citric. Increasing alloy content on the left indicates increasing resistance to the halide ions or reducing acids such as hydrochloric acid. When both the chromium and molybdenum content increase, as in the center, resistance to both types of acids increases.

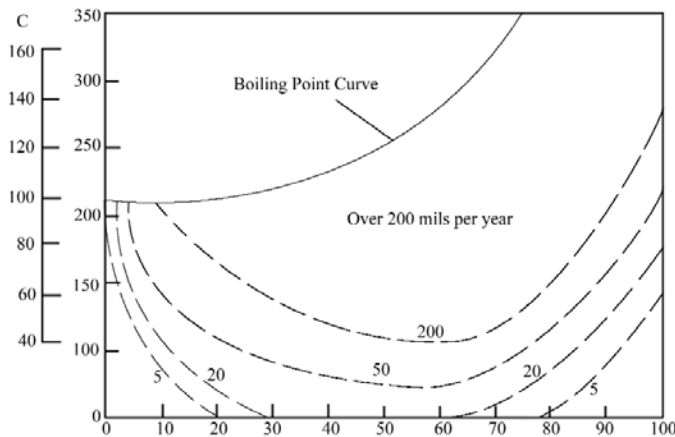


Figure 2: Isocorrosion curve for Type 316 in sulfuric acid at temperatures up to 350°F (175°C) The boiling point curve represents the boiling point of the sulfuric acid -- water mixture. Mills per year is 0.001 x mpy = inches per year.

GALVANIC Corrosion

Galvanic corrosion occurs whenever two electrically different metals are connected in a circuit and are in an electrically conductive solution. This type of corrosion requires three conditions: two metals that differ in the galvanic or electromotive series, an electrically conductive path between the metals and both metals submerged in a conductive solution. A variation of galvanic corrosion can occur with passive film metals. If the alloy loses the passive film in one spot, then it becomes active in that area. Now the metal has both passive and active sites on the same surface. This is the mechanism for pitting and crevice corrosion. Table IX (page 9) is a list of materials and their relative position in the galvanic series.

Table IX: A Simplified Galvanic Series of Metals and Alloys

| Metal | Volts | Corresponding Alloy |
|---|-------|--|
| Corroded end (anodic or least noble) | | |
| Magnesium | -1.55 | Magnesium |
| Aluminum | -1.33 | Aluminum |
| Zinc | -0.76 | Zinc |
| Iron | -0.44 | Steel, iron, stainless steel (active), alloy C (active) |
| Nickel | -0.23 | Nickel (active), Alloy 600 (active), Alloy B-2 |
| Hydrogen | 0.00 | |
| Copper | +0.34 | Brass, copper, Monel, nickel (passive), alloy 600 (passive), stainless steel (passive) |
| Silver | +0.80 | Silver |
| Gold | +1.36 | Gold |

This table allows selection of metal pairs that are galvanically compatible. In general, when an anode, for example aluminum, is connected to a cathode or noble metal in salt water, the anode will corrode and the cathode will be unaffected.

However, there is another factor called "area relationship"; if the anode is very large, such as a vessel wall, and the cathode is small like a bolt head, the galvanic action is slight. But, if the anode is small and the cathode is large, the anode will corrode very rapidly.



PITTING Corrosion

Pitting corrosion is a form of galvanic corrosion in which the chromium in the passive layer is dissolved leaving only the corrosion prone iron. The voltage difference between the passive and active layer on an austenitic stainless steel is +0.78 volts. Acid chlorides are the most common cause of pitting in stainless steel. Chlorides react with chromium to form the very soluble chromium chloride (CrCl_3). Thus, chromium is removed from the passive layer leaving only the active iron. As the chromium is dissolved, the electrically driven chlorides bore into the stainless steel creating a spherical, smooth wall pit. The residual solution in the pit is ferric chloride (FeCl_3), which is very corrosive to stainless steel. This is the reason ferric chloride is used in so many of the corrosion tests for stainless steel. When molybdenum and/or nitrogen is used as an alloying element in stainless steel, the pitting corrosion resistance improves. In an attempt to quantify the effect of alloying elements, a relationship of the various elements responsible for corrosion resistance was developed. The resulting equation is called the pitting resistance equivalent number, or PREN. It has a number of different coefficients of which the most commonly used form is detailed on the next page.

$$\text{PREN} = \%Cr + 3.3(\%Mo) + 16(\%N)$$

A PREN of 32 is considered the minimum for seawater pitting resistance.

Three factors influence pitting corrosion: chloride content, pH, and temperature. In general, the higher the temperature and chloride content and the lower the pH, the greater the probability of pitting. For a given chloride content, a higher temperature and lower pH encourage pitting. Conversely, a lower

temperature and a higher pH reduce pitting. The worst conditions occur with acid chlorides, and less dangerous conditions occur with alkaline or high pH chlorides. Pitting can occur rapidly once it starts. For example, under the right conditions of chloride content, pH and temperature, a type 304 tube with a .035" (0.89mm) wall thickness will pit through in less than 8 hours.

Increasing the molybdenum in the alloy produces greater resistance to pitting. Therefore high molyb-

denum – high chromium alloys generally provide the best pitting resistance. Figure 3 (page 10) shows the relationship of pitting, molybdenum content, pH, and chloride content.

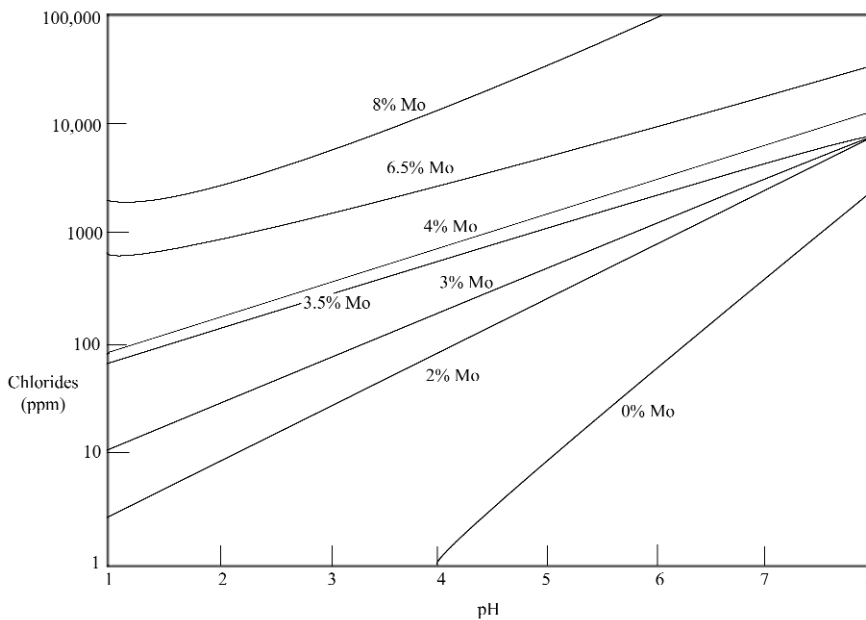


Figure 3: Pitting corrosion relationship as a function of chloride content, pH and molybdenum content of austenitic chromium alloys. Temperature range, 150-180° F (965-80° C), Pitting is not a problem below the line, but may be severe above the line.

Table X (page 10) lists alloys within the molybdenum contents shown on the graph. The molybdenum line represents the threshold at which pitting starts. Above the line pitting can occur rapidly while below the line pitting corrosion will not take place. This chart is very helpful in determining the amount of chloride and pH that can be tolerated for a given alloy class.

Table X: Alloy grades according to molybdenum content



| Molybdenum Content | Applicable Alloys |
|--------------------|---|
| 0 | Types 301, 302, 303, 304, 304L, 304N, 304LN, 305, 308, 309, 310, 321, 347 |
| 2 | Types 316, 316L, 329 |
| 3 | Types 317, 317L |
| 3.5 | Alloy 825 |
| 4 | Alloy 904L, Types 317LM, 317LMN |
| 6 | AL-6XN, 25-6Mo, 254SMO, Alloy G, Alloy G-3 |
| 9 | Alloy 625 |

CREVICE Corrosion

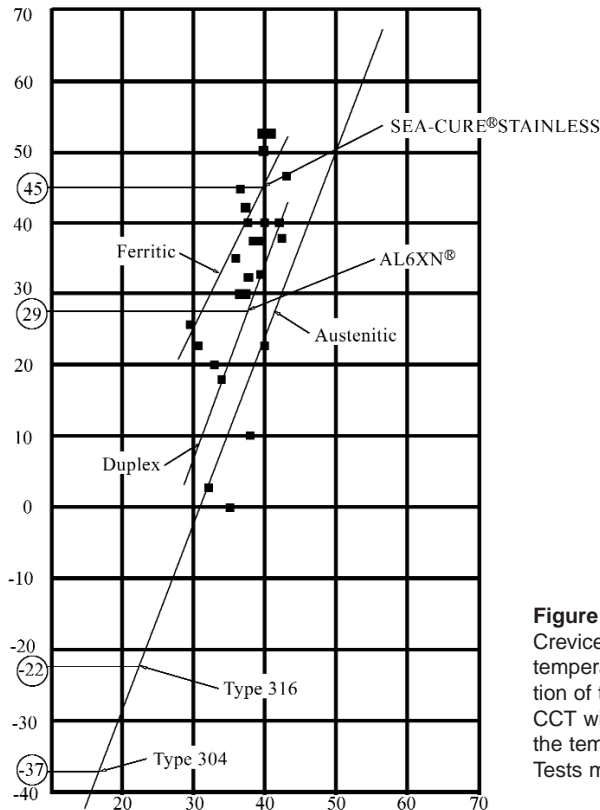


Crevice corrosion is another form of galvanic corrosion, which occurs when the corroding metal is in close contact with anything that makes a tight crevice. Crevice corrosion is usually the first to occur and is predictable as to when and where it will take place.

Like pitting, a conductive solution must be present; and, the presence of chlorides makes the reaction proceed at a fast rate. Crevice corrosion depends on the environmental temperature, alloy content and metallurgical category of the alloy. Also, there is a relationship between the tightness of the crevice and the onset time and severity of corrosion. There is a "critical crevice corrosion temperature" (CCCT) below which corrosion will not occur. Figure 4 (page 11) is a plot of the PREN versus CCCT and metallurgical category. Table XI (page 10) lists the PREN for some of the more common alloys. These values are based on the lower composition value for each alloy addition; therefore, the results are

Table XI: PREN number for Various Alloys

| Metallurgical Category | Alloy | PREN |
|------------------------|--------------------|------|
| Austenitic | Type 304, 304L | 18.0 |
| | Type 304N, 304LN | 19.6 |
| | Type 316, 316L | 22.6 |
| | Type 316N, 316LN | 24.2 |
| | Type 317, 317L | 27.9 |
| | Type 317LMN | 31.8 |
| | AL-6XN | 42.7 |
| | Alloy 625 | 46.4 |
| | Alloy C-276 | 73.9 |
| | 20Cb-3 | 25.6 |
| Duplex | Alloy 2205 | 30.5 |
| | 7-MoPLUS | 31.7 |
| Ferritic | SEA-CURE Stainless | 49.5 |
| | Type 430 | 16.0 |
| | Type 439 | 17.0 |
| | Type 444 | 23.3 |



conservative. The greater the difference between the CCCT and the operating temperature, the greater the probability that crevice corrosion will occur. This chart is very useful in determining the effect of temperature on corrosion by indicating the approximate temperature at which pitting corrosion begins. The effect of temperature on pitting corrosion is not as clear as that for crevice corrosion, but by adding approximately 100° F (60° C) to the CCCT, the approximate temperature at which pitting starts can be determined.



Figure 4: Critical Crevice corrosion temperature as a function of the PRE Number. CCT will not occur below the temperature indicated. Tests made 6% ferric chloride.

INTERGRANULAR Corrosion

All metals are composed of small grains that are normally oriented in a random fashion. These grains are each composed of orderly arrays of atoms with the same spacing between the atoms in every grain. Because of the random orientation of the grains, there is a mismatch between the atomic layers where the grains meet. This mismatch is called a "grain boundary." In a typical stainless steel product, there are about 1,000 grain boundaries that intersect a one-inch (25 mm) line drawn on the surface.

Grain boundaries are regions of high-energy concentration. Therefore, chemical or metallurgical reactions usually occur at grain boundaries before they occur within the grains. The most common reaction is formation of chromium carbide in the heat-affected zone (HAZ) during welding. These carbides, formed along the grain boundaries, are called "sensitization." Because the carbides require more chromium than is locally available, the carbon pulls chromium from the area around the carbon. This leaves a low chromium grain boundary zone and creates a new low chromium alloy in that region. Now there is a mismatch in galvanic potential between the base metal and the grain boundary; so, galvanic corrosion begins. The grain boundaries corrode, allowing the central grain and the chromium carbides to drop out as if particles of rusty sand. The surface of the metal develops a "sugary" appearance as illustrated in Figure 5 (*page 12*).

Carbides are formed when heating occurs, such as welding, heat treatment or metal fabrication. Understanding how they form makes it relatively easy to control their formation. For example, always use a low carbon grade of stainless steel when welding is to be done. These grades are very common today since the development of argon – oxygen – decarburization (AOD) refining about 25 years ago. Almost all stainless steel is made using this method since it allows very precise control of the alloying elements, and it is possible to routinely obtain carbon levels of approximate 0.025%, a level at which no chromium carbide particles form in the HAZ during welding. These grades are normally designated as "L" grades such as Types 304L, 316L or 317L. Always use the "L" grades if there is any

chance that the system will be welded. But if the part is to be used continuously at temperatures above 900° F, it will still sensitize over time. The only solution is to use a "stabilized" grade, one in which titanium, columbium (niobium) or both are added to react with the carbon forming stable grains of titanium or niobium carbide thus stabilizing the alloy. The type 304 equivalent stabilized with titanium is type 321, and the type 304 equivalent stabilized with niobium

is type 347. Stabilized grades should be used whenever the steel is held for long periods in the temperature range of 800° to 1500° F (425° to 800° C). Sigma or "chi" phase may be minimized by avoiding the temperatures where they form, or by using alloys high in nickel and nitrogen.

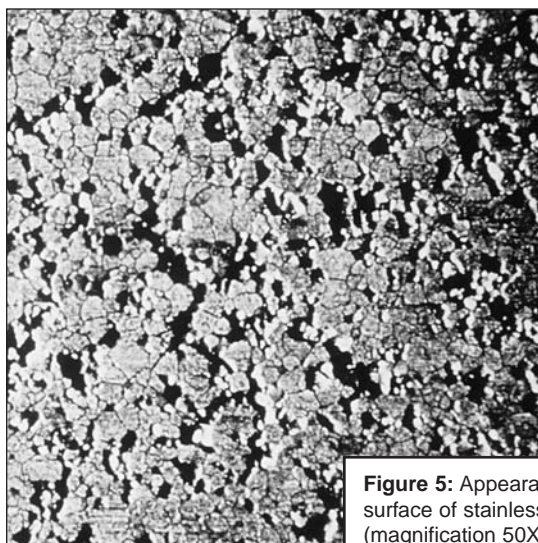


Figure 5: Appearance of the surface of stainless steel (magnification 50X) that has undergone intergranular corrosion. This is sometimes called "sugared."

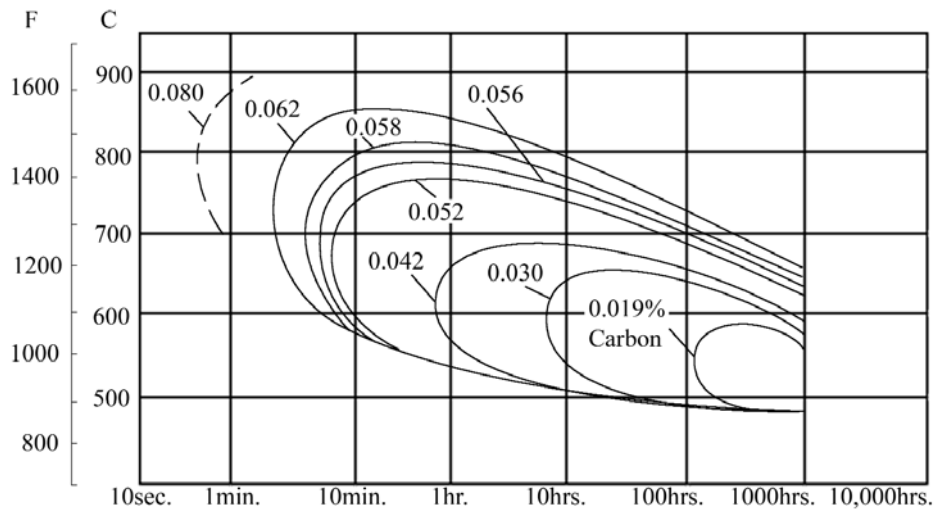


Figure 6 (page 13) shows the effect of temperature, time and carbon content on the formation of chromium carbide. It is critical to get past the nose of the carbon content curve as fast as possible. If it is not possible to cool fast enough to get past the nose of the curve, carbide precipitation will occur. Additionally if a part operates within the maximum upper and lower limits of the curve carbide precipitation will also occur.

Chromium carbide is not the only compound that can cause intergranular corrosion. Other compounds are delta ferrite, sigma phase (a chromium-

iron compound), chi phase (a chromium-iron-molybdenum compound), and several other compounds that are found less often. Special mention should be made concerning delta ferrite. All stainless steels are compounded to have a certain amount of delta ferrite in the microstructure to minimize micro cracking during cooling of the weld. The Welding Research Council recommends a range of 2-5%, with most welds measuring at 2%. However, when delta ferrite is exposed to high chloride waters including many hot water systems-the chloride begins to attack the delta ferrite corroding it preferentially and leakage occurs.

Figure 6: Effect of carbon on the time required for formation of harmful chromium carbide. Carbide precipitation occurs inside the loop to the right of the various carbon content curves.



STRESS Corrosion Cracking

Stress corrosion cracking (SCC) is one of the most common and dangerous forms of corrosion. Usually it is associated with other types of corrosion that create a stress concentrator that leads to cracking failure.

Nickel containing stainless steel is especially susceptible to chloride induced SCC. Figure 7 (page 14) indicates the maximum susceptibility is in the nickel range of about 5-35% and that pure ferritics, such as Types 430, 439, and 409 are immune. The point of maximum susceptibility occurs between 7-20% nickel. This makes types 304/304L, 316/316L, 321, 347, etc., very prone to such failure.

Stress corrosion cracking (SCC) has three components: alloy composition, environment and the presence of tensile stress. All metals are susceptible to stress corrosion cracking, as Table XII (page 14) indicates.

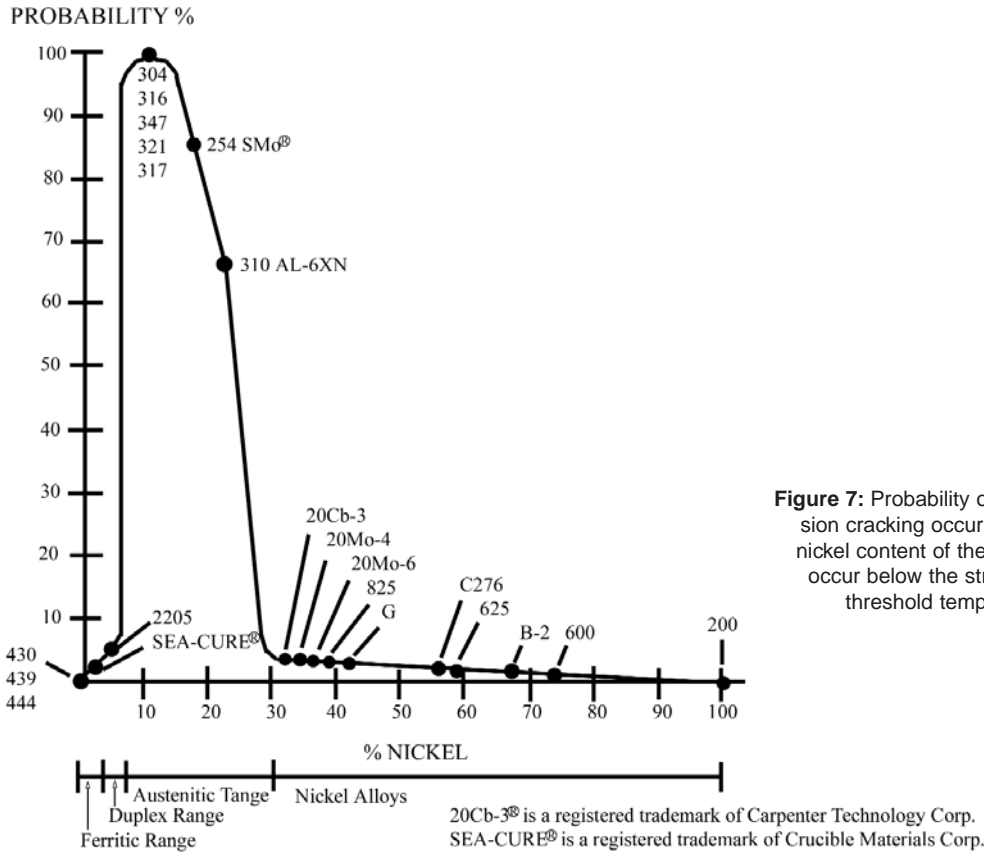


Figure 7: Probability of chloride stress corrosion cracking occurring as a function of the nickel content of the alloy. Cracking will not occur below the stress corrosion cracking threshold temperature, but will above.



Table XII: Alloy Systems Subject to Stress Corrosion Cracking

| ALLOY | ENVIRONMENT |
|---|--|
| Aluminum alloys | Air, Seawater, Salt and chemical combinations |
| Magnesium alloys | Nitric acid, Caustic, Salts, Coastal atmospheres |
| Copper alloys | Ammonia and ammonium hydroxide, Amines, Mercury |
| Carbon steel and iron | Caustic, Anhydrous ammonia, Nitrate solutions |
| Martensitic and precipitation hardening stainless steel | Seawater, Chlorides, Hydrogen sulfide |
| Austenitic stainless steel | Chlorides, both organic and inorganic, Caustic solutions, Sulfurous and polythionic acid |
| Nickel alloys | Caustic above 600 F (315 C), Fused caustic, Hydrofluoric acid |
| Titanium alloys | Seawater, Salt atmospheres, Fused salt |

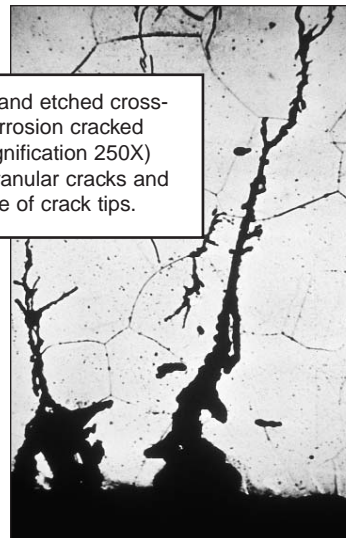
It doesn't take much chloride to cause failure (a few parts per million will do the job) providing that the pH is low and oxygen is present. Temperature is important, and there is a threshold temperature below which the steel will not crack. This is related to the critical pitting temperature; therefore, the

threshold temperature increases as the molybdenum content increases. Type 304 may SCC at room temperature, whereas the six percent Mo alloys have a threshold temperature in the range of 450° F (239° C).

The stress component is more subtle. First the stress must be tensile, and it must exceed the yield strength of the component. This sounds simple enough, but any time a component is bent or straightened, or when any physical exertion is made to place the material into a fixed shape, the yield strength is exceeded. Next, matters can be complicated by stress multiplication factors. If a pit or other sharp notch is present, the residual stress is multiplied several times resulting in a stress far in excess of the tensile yield strength. Thus, SCC usually starts with pitting or crevice corrosion as a precursor to forming a stress concentrator.

When the cracks form, they usually are transgranular as illustrated in Figure 8 (page 15). That is, they crack through the grain. Cracking occurs rapidly progressing through the grain, terminating in a feathery cluster of small cracks. This is a character-

Figure 8: Polished and etched cross-section of stress corrosion cracked stainless steel (magnification 250X) showing the transgranular cracks and feathery appearance of crack tips.



istic that distinguishes SCC from other types of cracking.

Using microprobe analysis, or electron

dispersive spectroscopy (EDS), on the crack surface to look for the presence of chlorine, we can observe conclusive evidence that SCC has occurred.



MICROBIOLOGICALLY Influenced Corrosion

Microbiologically influenced corrosion (MIC) is a recently discovered phenomenon. Actually, it is not a separate corrosion mechanism, rather a different agent that causes corrosion of metals. It is not limited to stainless steel as Table XIII (page 16) indicates. Some form of bacteria action attacks most metals. The mechanism is usually general or crevice corrosion under the bacteria colonies as seen in Figure 9 (page 16).

In some cases, the metabolic byproducts react with the environmental solution to create a very corrosive media. An example is the reaction of chlorine in water with the manganese dioxide byproduct from gallionella bacteria on the surface of the stainless steel. This reaction generates hydrochloric acid, which causes rapid pitting of many common grades of stainless steel.

One of the most common forms of MIC is the metabolic byproduct of the sulfur-fixing bacteria that produces sulfurous or sulfuric acid. These bacteria cause rapid corrosion of the lower alloy stainless steels, like Types 304L or 316L, resulting in through wall crevice corrosion under the bacteria colonies.

Other than the use of bactericides, such as chlorine or ozone, the usual solution to this type of corrosion is to use a 6% molybdenum alloy such as AL-6XN, (a superaustenitic stainless steel) or the highly alloyed nickel alloys. Therefore, if MIC corrosion is taking place, it is best to use one of these alloys.

Table XIII: Corrosive Microorganisms

| ORGANISM | ACTION | PROBLEM |
|---|---|---|
| Desulfovibro Clostridium Thiobacillus | Hydrogen sulfide producer (sulfate reducers) | Corrosive to metals Reduces chromates Destroys chlorine Precipitates zinc |
| Thiobacillus | Produces sulfuric acid | Corrosive to metals |
| Nitrobacter Nitrosomonas | Produces nitric acid | Corrosive to active film metals |
| Gallionella Crenothrix Spaerotilus | Converts soluble ferrous ions to insoluble ferric oxide Converts soluble manganese ions to insoluble manganese dioxide | Produces iron oxides and forms crevices Produces manganese dioxide that can form crevices, or can react with chlorine to produce hydrochloric acid |



Figure 9: Crevice corrosion under bacteria colony on the inside of a stainless steel tube (magnification 5X)



WELDING

Stainless Steel

Stainless steel is normally joined by welding. Welding provides high strength joints with minimum flow restrictions and prevents crevice corrosion, the major concern with screw thread joints. Threaded connectors form tight crevices that often corrode. However, elimination of crevices does not guarantee trouble free operation. Extreme care must be taken during welding, as many installation problems occur because the basic rules of stainless steel welding are violated. These rules include:

1. Always use high purity inert welding gases and cover gases. After welding, both the inside and outside weld surfaces should be silver, light gold or straw color at worst. If the welds are black, then corrosion resistance has been compromised.
2. If two surfaces are tack welded to hold them in place prior to making the primary weld, make sure the tack welds are well purged with inert gas and free from any oxidation. Oxidation along the edges of the tack welds can lead to a leak path in the weld.

3. Always clean the surfaces prior to welding to remove all organic materials, moisture and dirt.
These contaminants will react either with the chromium to produce chromium carbide or decompose during welding to create hydrogen gas resulting in porosity.
4. Always use oxide-grinding wheels, not silicon carbide for any dressing of weld surfaces. The carbide may react with the chromium, which decreases the corrosion resistance of the weld metal.
5. Because stainless steel has lower heat conductivity than carbon steel, 30% less heat input generally is required. Also, the welds take longer to cool. Maintain short arc length and use staggered beads for very long welds to reduce heat input.
6. The coefficient of thermal expansion for austenitic stainless steel is higher than for carbon steels and ferritic or martensitic stainless steels. Therefore, keep the base metal restraint to a minimum to prevent distortion of the system.
7. If multiple weld passes are required, maintain the interpass temperatures at less than 200° F (100° C) to prevent cracking and distortion of the system.
8. Avoid crater cracks by controlling the size of the termination weld pool. If crater cracks occur, remove by grinding with an aluminum oxide wheel before proceeding.



Specific Requirements for 6% Molybdenum Stainless (AL-6XN[®])

- Use a weld filler alloy on all field welds-for orbital welds use weld rings, for other welds, wire or weld rings may be used. The filler alloy must have higher molybdenum content than the AL6XN to compensate for alloy dilution on cooling. Typically a 9% Molybdenum alloy (Alloy 625) is used. If Alloy 625 is not available Alloy C 276 (15% Mo) may be substituted.
- Use an inert gas for both the weld and shield gas. Either helium or argon may be used, although argon is normally used. Where possible use 3 – 5% nitrogen additions to both the torch and shielding gas. This added nitrogen compensates for the nitrogen lost from the alloy during welding.
- Make sure the heat tint on the tubing is a light straw yellow at the darkest. A silver weld and heat-affected zone are the best. Any darker weld heat tints must be removed before placing in service. Dark blue heat tints are the most susceptible to corrosion. Remove by grinding followed by acid

cleaning/passivation. A poorly cleaned surface may be just as susceptible to attack as the original heat tint.

- Do not preheat the weld unless the material is below 50° F. When the material is below the dew point, allow it to warm up to above the condensation temperature to prevent moisture condensing on the surface. Remember: moisture causes heat tints.
- Ignite the weld within the area to be welded. If that is impossible, grind the ignition point to remove it completely.



Why “overalloy” AL-6XN weld areas?

Why "over alloy" AL-6XN, weld areas?

Because of two words- Intergranular Corrosion. Although AL-6XN is classified as a single phase alloy, when it is melted as in welding, it will solidify as a two phase alloy with 1) Being austenite, and 2) Being chi phase. Chi phase, a chromium-iron-molybdenum compound depletes the grain boundary of molybdenum and chromium reducing corrosion resistance. By over alloying as with alloy 625 weld insert rings, the alloy balance and therefore corrosion resistance is restored to the base alloy. All metals are composed of small grains that normally are oriented in a random fashion.

These grains each are composed of orderly arrays of atoms, with the same spacing between the atoms in every grain. Because of the random orientation of the grains, there is a mismatch between the atomic layers where the grains meet. This mismatch is called a grain boundary. In a typical stainless steel product, there are about 1,000 grain boundaries that intersect a one-inch or 25 mm line drawn on the surface.

Grain boundaries are regions of high-energy concentration. Therefore, chemical or metallurgical reactions usually occur at grain boundaries before they occur within the grains. The most common reaction is formation of chromium carbide in the heat-affected zone (HAZ) during welding. These carbides form along the grain boundaries. Because the carbides require more chromium than is locally available, the carbon pulls chromium from the area around the carbon. This leaves a grain boundary zone, low in chromium, creating a new, low chromium alloy in that region. Now there is a mismatch in galvanic potential between the base metal and the grain boundary, so galvanic corrosion

begins. The grain boundaries corrode, allowing the central grain and the chromium carbides to drop out as so many particles of rusty sand. The surface of the metal develops a "sugary" appearance.

Several compounds may cause intergranular corrosion in addition to chi phase and chromium carbide. Another compound is sigma phase, a chromium-iron compound. Note, these are compounds, not a random mixture or alloy.

These compounds usually are formed when some type of heating occurs, such as welding, heat treatment, or metal fabrication. Understanding how they form makes it relatively easy to control their formation. For example, always use a low carbon grade of stainless steel when welding is to be done. Today these grades are very common ever since the invention of argon - oxygen - decarburization (AOD) refining about 25 years ago. Almost all stainless steel is made by this method since it allows very precise control of the alloying elements, and it is possible to obtain routinely carbon levels in the range of 0.025 percent, a level at which no chromium carbide particles form in the HAZ during welding. These grades normally are designated as "L" grades, like Types 304L, 316L or 317L. Always use the "L" grades if there is any chance that the system will be welded. Another way of controlling the formation of chromium carbide is to use a stabilizing element addition to the stainless steel. These are titanium and niobium (columbium). The Type 304 equivalent with titanium is Type 321, and the Type 304 equivalent with niobium is Type 347. Stabilized grades should be used whenever the steel is held for long periods in the temperature range of 800 to 1500°F (425 to 800°C). Sigma or chi phase may be minimized by avoiding the temperature range where they form, or by using alloys high in nickel and nitrogen.



ORBITAL Welding Equipment

Welds may be done with standard orbital welding equipment consisting of a solid-state DC power supply, associated cables, and an enclosed weld head. The weld head contains an internal rotor which holds a tungsten electrode, which rotates around the work to do the weld. The portable power supply, which plugs into 115V VAC, controls the entire weld sequence including an inert-gas pre-purge arc strike, rotation delay, rotational speed (RPM), and multiple timed levels of welding current with pulsation. This is followed by a downslope which gradually terminates the current, and a postpurge to prevent oxidation of the heated material. These weld parameters are dialed into the power supply from a weld schedule sheet after determination of the proper parameters from test welds done on tubing samples. Fusion welds with automatic orbital TIG welding equipment is practical on tubing or small diameter pipe in sizes from 1/8 inch OD tubing to 6" schedule 10 pipe, and on wall thicknesses up to 0.154 wall.



AL-6XN is easily weldable with weld parameters, including travel speed (RPM) and weld currents, comparable to 316L stainless steel. Weld appearance is excellent with a smooth, shiny, flat weld bead on both the OD and ID. For welds with weld insert rings, the inserts are simply placed between the two sections to be welded and fusion welded as usual, except for a slight increase in welding current to compensate for the increased thickness of material contributed by the insert ring. These welds also have a pleasing appearance, with a slight crown on the OD and some inner-bead reinforcement.



Autogenous (without filler) Welding for 6% Molybdenum Stainless (AL-6XN®)

Autogenous welding can be used with the following precautions:

- Use of 3 to 5 volume percent nitrogen in the shielding gas and a post-weld anneal above 2150° F (1180° C) followed by rapid cooling and pickling if a protective atmosphere was not used during annealing.
- The duration of the anneal must be sufficient to re-homogenize the weld segregation.

- The G48-B crevice test can be used to assess the quality of autogenously welded and annealed AL-6XN alloy.

In many applications, a post-weld anneal and pickle may not be possible, as in large vessel fabrication or field welding of piping systems. In these cases, the exposure conditions must be carefully reviewed to determine if autogenous welds are satisfactory. Autogenous AL-6XN® welds are more resistant to corrosion than similar welds of types 316L, 317L and 904L. Their corrosion resistance is approximately that of alloy 904L base metal and superior to that of types 316L and 317L base metal.

SELECTION

Alloy



When a corrosion problem is encountered, review the solution chemistry to determine if a change can be made to eliminate the corroding condition. For example, if carbon steel is rapidly oxidizing in steam, is it possible to adjust the pH upward and add hydrazine, or one of its derivatives, to combat the dissolved oxygen? If the system is being cleaned with muriatic acid, which is dangerous to stainless steel, can the acid be changed to one more friendly to the stainless steel such as nitric, citric or sulfamic? If the pH is being lowered using carbon dioxide sparging and chloride pitting occurs, can a mineral acid such as sulfuric or phosphoric acid be substituted to prevent acid bubbles from forming on the surface causing crevice corrosion?

If it is not possible to modify the environment, the alloy must be changed. Use the following selection process to narrow down the alloy options. This same procedure can be used in selecting an alloy for the initial design.

1. Review the nature of the environment with respect to chemical composition, temperature, pH, and velocity. Always assume the worst-case scenario. Use the corrosion rate charts or tables to determine those alloys with the best uniform corrosion resistance. If the solution is a single composition, selection will be rather easy. If it is a complex solution of two or more components, determine the corrosion rates in each component individually. Keep in mind the corrosion rates may be accelerated or slowed down in each environment. Many complex solutions require the use of corrosion racks with different alloys exposed to a test environment to determine the best alloy.
2. Always determine if chlorides are present. If they are-and they usually are-select the best alloy for pitting resistance as a function of pH and chloride content, using the chart in Figure 3 (*page 9*).
3. Next, pick the proper alloy using its PREN number for the temperature based on crevice corrosion; see Figure 4 (*page 11*).
4. Determine the best carbon range to prevent intergranular corrosion using Figure 6 (*page 13*), or use a low carbon grade as a general rule.
5. Finally, pick the best alloy that will not stress corrosion crack based on Figure 7 (*page 14*).
6. Consider the metallurgical and mechanical characteristics of each candidate alloy. If you are not that familiar with each alloy and its limitations, contact a reputable and qualified material producer for assistance. Many tests have been conducted in many environments, and a wealth of information is available. There is an alloy, material or design modification out there that will solve your problem.

Conclusion

The correlation between metallurgical factors and corrosion resistance is straightforward. Inclusion of corrosion control and the correct material selection in the design process is the most efficient means of controlling corrosion and therefore high replacement costs, or catastrophic system failure. If corrosion control is not considered in the design stage, the subsequent costs are usually much greater than the initial investment at the onset.

TRADEMARK

Acknowledgements

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DOCUMENT

References

1. Tverberg, J.C., "A Stainless Steel Primer", Flow Control Magazine, August 2000, September 2000, October 2000
2. Uhlig, Herbert H., "The Corrosion Handbook", John Wiley & Sons, New York, 1951
3. Tverberg, J.C., "Conditioning of Stainless Steel Surfaces for Better Performance", Stainless Steel World, April 1999, Zutphen, The Netherlands
4. Zapffe, Carl, "Stainless Steels", The American Society for Metals, Cleveland, Ohio, 1949
5. Parr, J. Gordon and Hanson, Albert, "Introduction to Stainless Steel", The American Society for Metals, 1965
6. Ibid,
7. "Metals and Alloys in the Unified Numbering System", 8th Edition, Society of Automotive Engineers and the American Society for Testing and Materials, HS-1086/DS-56G, January 1999
8. Parr and Hanson, Op cit, Ref.4
9. Ibid.
10. Ibid.
11. Ibid.
12. Ibid.
13. Fontana, Mars G & Greene, Norbert D., Corrosion Engineering, McGraw-Hill Book Co., New York, 1978
14. Rockel, M.B., "Use of Highly Alloyed Stainless Steels and Nickel Alloys in the Chemical Industry",ACHEMA Conference, Frankfurt, Germany June 1978
15. Kovach, C.W. and Redmond, J.D. "Correlations Between the Critical Crevice Temperature, PRE-Number, and Long-Term Crevice Corrosion Date for Stainless Steels" Paper 267, Corrosion 95, National Association of Corrosion Engineers
16. Tverberg, J.C., & Welz, J.T., "Carbon Dioxide Assisted Corrosion of Stainless Steel" International Water Conference, IWC-98-59, Engineers•Society of Western Pennsylvania, October 19-21, 1998
17. Tverberg, J.C., Piccow, K., and Redmerski, L. "The Role of Manganese Fixing Bacteria on the Corrosion of Stainless Steel", Paper 151, Corrosion 90, National Association of Corrosion Engineers
18. Tverberg, J.C., Op cit, Ref. 2