

PEER REVIEWED SUBMISSION

Stainless Steel in the Brewery

By John C. Tverberg

Trent Tube, East Troy, Wisconsin, USA.

ABSTRACT

This review describes the five metallurgical classifications of stainless steel, the five distinct corrosion mechanisms, welding guidelines and selection methods. Characteristics and specific types of each class of stainless steel are given. Next, the five corrosion mechanisms are explained and guidelines are presented for selecting the proper stainless steel for each corrosive environment. Welding guidelines for proper installation are listed. Finally a selection procedure is suggested for choosing the proper stainless steel for each corrosive environment.

Keywords: stainless steel, stainless steel types, corrosion, stainless steel corrosion, corrosion mechanisms, stainless steel welding, alloy selection

SINTÉSIS

Este análisis describe las cinco clasificaciones metalúrgicas de acero inoxidable, los cinco mecanismos de corrosión, las directrices sobre soldaduras y los métodos de selección. Se darán las características y tipos específicos de cada clase de acero inoxidable. Posteriormente, se explican los cinco mecanismos de corrosión y se presentan las directrices para seleccionar el acero inoxidable apropiado para cada ambiente corrosivo. Se enlistan las directrices sobre soldaduras para la instalación apropiada. Finalmente se sugiere un procedimiento de selección para escoger el acero inoxidable apropiado para cada ambiente corrosivo.

INTRODUCTION

Stainless steel is widely used in the brewery because of its resistance to corrosion. Usually it works great, but there are situations where it fails miserably. As one irreverent wag once said, "Stainless steel is the wonder metal - You wonder where it will fail next." When stainless steel does fail, it is almost always because the wrong grade was selected. Very few people understand why the different grades of stainless steel exist, so there are many misapplications, and with misapplications come fail-

ures. Part of the selection process requires an understanding of the corrosion mechanisms and the reasons for the different grades.

All metals are prone to corrosion. There is no single metal or alloy that will not corrode in a given environment. Fortunately, not all metals corrode in the same environment, so we have a choice in selecting the proper grade for each application. Selecting the best alloy for the service environment is not difficult, but it does require knowledge of what is taking place. There are generalized selection methods that allow choosing the best group of alloys, many times the correct alloy, which we will cover in this article. But as good as a selection method is, there is no substitute for actual testing of the candidate alloys in the corrosive environment.

We must remember that stainless steel is an alloy of iron. Therefore, when it fails by corrosion, rust is usually involved. By definition, stainless steel must contain a minimum of 50% iron. If it contains less iron, then the alloy system is named for the next major element. For example, if the alloy is high in nickel, so the iron is less than 50%, then it is called a nickel alloy.

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.

John Tverberg served as Vice President of Technology for Trent Tube Division of Crucible Materials Corporation, East Troy, WI from 1986 until March 2001 when retired and now serves as a consultant to Trent Tube. He is owner of the firm Metals and Materials Consulting Engineers. He holds B.Sc. and M.Sc. degrees in metallurgical engineering with a minor in chemistry from the University of Arizona, was an exchange scientist with EURATOM to Germany, is a licensed professional engineer and author of numerous papers, and is a member of ASME, ASM International, ISPE, and NACE. He can be contacted via Telephone at (262) 392-3113.

Email: mmce@netwurx.net

Chromium is the unique (some would say “magic”) element that transforms iron into stainless steel^[9]. 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 oxidation resistance becomes. But there is an upper limit to the amount of chromium the iron can hold, which is about 29%. Chromium imparts a special property to the iron that makes it corrosion resistant. When chromium is in excess of 10.5% the corrosion barrier changes from an active film to a passive film. An active film forms continuously over time in the corroding solution, sloughs off, and continues to grow until the base metal is consumed. A passive film forms quickly, then stops growing. This passive layer is extremely thin, in the order of 10 to 100 atoms thick^[6] or 30 to 300 Angstroms. It 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 its nemesis. Chloride combines with the chromium in the passive layer and forms soluble chromium chloride. As the chromium dissolves, active iron is exposed on the surface, which reacts with the environment to form rust. Alloying elements, like molybdenum, minimize this reaction.

Other elements, Table 1, may be added for special purposes such as high temperature oxidation resistance, sulfuric acid resistance, greater ductility, high temperature creep resistance, abrasion resistance or high strength. None of these elements make stainless steel stainless, only chromium can do that.

TABLE 1

Stainless steel alloying elements and their purposes.

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
Nitrogen	Austenite Former Improves Resistance to Chlorides
Sulfur	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

THE TYPES OF STAINLESS STEEL

History

Stainless steels are a rather recent addition to the materials world. Chromium additions to iron were first made to improve the strength of military ordnance. Most of these efforts failed because the steels of early 1800s were so high in carbon that the alloys were extremely brittle. The first published article on improved acid corrosion resistance of iron by the addition of chromium was by the Frenchman Berthier in 1821^[11]. The first application was in 1869 when Baur established the Chrome Steel Works in Brooklyn, New York. Baur produced low chromium steel for jail bars, mining tools and burglarproof safes. In 1874 Baur supplied the low chromium steel for St. Louis’ Eads Bridge over the Mississippi. The steel is quite strong and still shows limited resistance to rusting.

In 1904 Leon Guillet in France, produced low carbon and high chromium steel alloys that correspond to many of the martensitic and ferritic stainless steels used today. Because he categorized the compositions and properties of the stainless steels, Guillet is given the distinction as discoverer of the metallurgy of stainless steel. The credit for discovery of the corrosion resistance of stainless steel goes to P. Monnartz in Germany in 1911 when he published the first detailed data on the corrosion of stainless steel as a function of composition. In 1912 Eduard Maurer at Germany’s Krupp Iron Works, patented the first austenitic stainless steel. In 1913 Harry Brearly, Sheffield, England, discovered the relationship between heat treatment and corrosion resistance, which led to the patenting of the first martensitic stainless steels. For these achievements, Maurer and Brearly are given the distinction as co-discoverers of the industrial usefulness of stainless steel^[3]. Their developments include three of the classifications of stainless steels in use today: martensitic stainless steel, ferritic stainless steel and austenitic stainless steel. Duplex stainless steel was developed in 1927 and precipitation hardening stainless steel in 1946.

Numbering System

Originally, stainless steels were classified as Class I, II or III, depending on the chromium content^[3]. Later this was changed to the present system, based on the similarity of the microstructure to that of steel. Next, the American Iron and Steel Institute (AISI) further classified the alloys by assigning type numbers. The 300 series represent the austenitic and duplex stainless steels, and the 400 series represent the ferritic and martensitic stainless steels. They also include a 200 series for manganese rich austenitic steels. The 200 series steels, developed in the 1930s, replaced the 8% nickel with 4% nickel, 7% manganese and 0.25% nitrogen. These grades show up whenever the price of nickel becomes outrageously high or when nickel is in short supply.

About 20 years ago the Society of Automotive Engineers established the Unified Numbering System^[5], or UNS, in which all alloys are categorized according to type and given a unique five-digit number. All stainless steels have an “S” prefix and nickel alloys an “N” prefix. In the case of the stainless steels, the Type number usually is incorporated into the UNS number. For example Type 304 is S30400, 304L is S30403, 316 is S31600 and 316L is S31603.

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 2 lists the metallurgical characteristics of each class of stainless steel.

**TABLE 2
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

Austenitic Stainless Steels

These are the most popular of the stainless steels because of their ductility, ease of working and good corrosion resistance^[3]. All were derived from the 18Cr-8Ni stainless steels developed by Maurer. 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 Type 304/304L, which makes up over 60% of all the stainless steel made in the United States today. Other grades are developed from the 18–8 base by adding alloying elements to provide special corrosion resistance, improved 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 a susceptibility to chloride stress corrosion cracking, but increasing the nickel to above 35% greatly reduces this problem. Table 3 lists the characteristics of the austenitic stainless steels and gives some examples of these alloys.

**TABLE 3
Austenitic Stainless Steels.**

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®, 254SMO®, 25-6Mo®, 1925hMo® Type 308, 309, 310

Ferritic Stainless Steels:

Until the early 1980s these alloys were not very popular because their inherent high carbon content made them extremely brittle and imparted relatively poor corrosion resistance^[3]. Alloy research in the late 1960s, using vacuum electron beam melting, led to a new group of alloys called the “Superferritic Stainless Steels”, of which E-Brite 26-1® was the first. Then in the late 1970s a new steel refining technique called Argon Oxygen Decarburization, or 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 any application with high chloride, especially marine applications since its corrosion resistance in seawater is essentially the same as titanium’s. The most popular ferritic stainless steel is Type 409, a 10.5% Cr alloy with no nickel, used mostly in automotive exhaust systems. Ferritic stainless steels are essentially resistant to chloride stress corrosion cracking, have high strength, and grades like SEA-CURE Stainless have the highest modulus of elasticity of the common engineering alloys, making them highly resistant to vibration. Table 4 lists characteristics, properties and types of these alloys. One property, the 885°F (475°C) embrittlement, limits the thickness of many of these alloys to

**TABLE 4
Ferritic Stainless Steel.**

Characteristics	Magnetic High Ambient Temperature Strength Low Work Hardening Resistant to Chloride Stress Corrosion Cracking Subject to 885°F (475°C) Embrittlement 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, Alloys 29-4, 29-4C®, 29-4-2

about 0.125 inches (3 mm), so as attractive as the properties are, they cannot be used for heavy sections as brew kettles. However, they can be used as wallpaper, or liners.

Martensitic Stainless Steel:

These were the first stainless steels developed because of the inability to obtain low carbon steel [3]. Basically, they are stainless tool steels because they have 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 by-pass operation. They are used in bearing races for corrosion resistant bearings and in areas where erosion-corrosion is a problem. Martensitic stainless steels are not especially corrosion resistant, barely as good as Type 304, but they are far 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. The ability to maintain edge integrity comes from their high hardness and corrosion resistance. Table 5 lists the characteristics and some examples of these alloys.

TABLE 5
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

Duplex Stainless Steel:

Although these alloys were developed in 1927, their usefulness was not realized until the 1960s [3]. They are characterized by having both austenite and ferrite in their microstructure, hence the name “duplex”. They exist in the narrow nickel range of about 4 – 7%. Microstructure wise, 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 highly resistant to chloride stress corrosion cracking and when the matrix is austenitic the alloys are sensitive to chloride stress corrosion cracking. High strength, good corrosion resistance and good ductility characterize them. One alloy, Carpenter 7-Mo PLUS®, has the best corrosion resistance to nitric acid of any of the stainless steels because of its very high chromium content and duplex structure. Table 6 lists the characteristics, properties and examples of these alloys.

Precipitation Hardening Stainless Steel

These steels represent the latest development of the special stainless steels and, most likely, represent the area where future alloy development will take place. The common precipitation hardening grades have the corrosion resistance of Type 304

TABLE 6
Duplex Stainless Steels.

Characteristics	Magnetic Contains Both Austenite and Ferrite High Strength Subject to 885° F (475°C) Embrittlement 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®, Alloy 2507

stainless steel, but many of the newer grades have outstanding corrosion resistance. The alloys are somewhat soft and ductile in the solution-annealed state, but when subjected to a relatively low precipitation hardening temperature, ~1000°F (540°C), strength more than doubles and they become very hard [3]. 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 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. The hardening mechanism may be understood by the analogy of a deck of cards to a block of steel. If the steel is in the annealed state, a force on the steel easily causes distortion, the same as a force on the deck of cards causes the cards to slide easily in response to the force. If the block of steel is given a thermal aging treatment, small precipitates form, like sprinkling sea sand between the cards in the deck. Now it takes much more force to cause the cards to move, so the material is much stronger. The primary application for precipitation hardening steels is where high strength, weight restrictions and corrosion resistance is required. Aerospace and military applications have dominated the applications in the past, but new uses in instrumentation and fluid control are being developed. Table 7 lists the characteristics and some examples of these alloys.

TABLE 7
Precipitation Hardening Stainless Steel.

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®

Strength and Heat Treatment

Table 8 compares the strength of selected alloys within the various classes of stainless steel. 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 of the austenitic, ferritic and duplex grades must be achieved by cold working the structure. Heat treatment of these grades removes residual stress, and, in the case of the austenitic stainless steels, reduces the probability of chloride stress corrosion cracking, and dissolves any undesirable metallurgical phases that may be present.

Heating and cooling 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 heat-treating a particular grade of stainless steel, always refer to the heat treatment instructions for that alloy. 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) temperature range, which can be as low as 600° F (315° C), may lead to brittleness at room tem-

perature. Heating high chromium, high molybdenum austenitic stainless steel to a temperature below the specified minimum heat-treating temperature may lead to precipitation of deleterious second phase compounds along the grain boundaries. When placed in service these alloys may corrode or fail because of low ductility problems. Always check the characteristics of the alloy before attempting any type of heat treatment.

The Basics of Corrosion

What is corrosion? Technically, it is the tendency of a metal to return to its most stable thermodynamic state that 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, nitride, carbonate, sulfate or other stable compound. Corrosion is expensive, costing the industrial nations more than \$3 Billion a year. Corrosion affects every facet of our life, especially in the brewery. Hot water lines pit and stress corrosion crack and must be replaced. Brew kettles crack in service. Chemical tanks pit and crevice corrode. Welds corrode and leak, leaving a deposit of rust and lime over everything. In most cases a different alloy, material, coating or impressed current can solve the problem.

It is absolutely essential to determine the cause of failure so replacement parts can be made from the proper alloy to prevent future failures. When a failed part is replaced with the same

TABLE 8
Properties of Stainless Steel Alloys, ASTM Minimums Unless Otherwise Stated.

Alloy	UNS Number	Ultimate Strength, psi	Yield Strength, psi	Elongation, % 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	80 RB
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	32,550,000	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

alloy the same type of failure will happen again. Albert Einstein said it best: "We can't solve problems by using the same kind of thinking we used when we created them." For example, if a control valve is made from Type 304L stainless steel and it fails by chloride stress corrosion cracking, replacing with the same alloy will assure failure the same way. If we change the alloy, perhaps to a 6% Mo stainless steel, such as AL-6XN®, the valve may last for the lifetime of the system.

Corrosion can be broadly classified in two forms: where the metal dissolves chemically, and where the metal dissolution is electrically driven⁽¹⁾. 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
5. MIC or microbiologically induced corrosion

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 for 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 expressed by a corrosion rate, usually reported as mpy (mils per year), mm/y (millimeters per year) or ipm (inches per month). This type of corrosion may be minimized in the active metals by painting the surface and unexpected failures can be avoided by periodic inspections. You never want to paint a passive metal for reasons to be explained later.

Over time both carbon steel and copper will thin because of uniform corrosion. Every time a copper or carbon steel system is acid cleaned, the metal walls are thinned because of uniform corrosion. Stainless steel, on the other hand, is subject to general corrosion in some acids and salt solutions, but not subject to general corrosion in water; therefore no data are available.

Uniform corrosion can be reduced or even prevented by proper selection of the alloy. Certain elements make stainless steel more resistant to different media. For example, high chromium imparts oxidation resistance. Therefore look for high chromium for use with nitric acid or other oxidizing acids, the higher the chromium the better. High chromium is useful for high temper-

ature oxidation resistance, so any stainless steel is better than carbon steel in elevated temperature applications. High copper in stainless steel improves resistance to sulfuric acid, as with Carpenter 20Cb-3® Stainless Steel. High nickel gives resistance to reducing acids and produces a tightly adhering oxide film in high temperature oxidation.

A useful tool in illustrating corrosion resistance is the "Y" of corrosion, Figure 1. 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 are in the center. Oxidizing acids oxidize the metals they come in contact with and the acids are reduced in the process. Reducing acids simply dissolve the metal and release hydrogen in the process. Corrosion resistance increases as you move up the chart, indicating relative corrosion resistance.

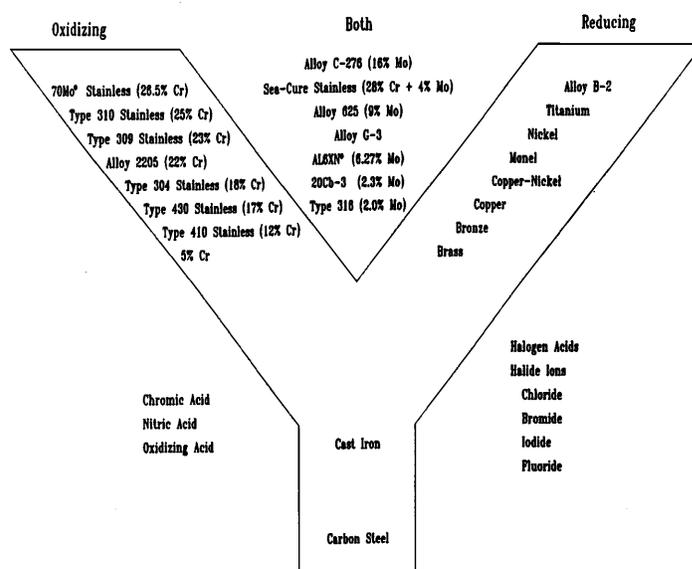


FIGURE 1

The "Y" of corrosion. Increasing chromium content on the left means increasing corrosion resistance to oxidizing acids such as nitric, citric or oxalic. Increasing alloy content on the right indicates increasing resistance to halide ions or reducing acids such as hydrochloric. When both the chromium and molybdenum content increase, as in the center, resistance to both environments increase.

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, Houston, Texas, are excellent resources. Alloy selection can be simplified, or at least narrowed down using these tables. But, be warned, significant research may be required to come up with the best alloy

Corrosion tables are based on isocorrosion curves. An isocorrosion curve for type 316 stainless steel in sulfuric acid is presented in Figure 2. 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.

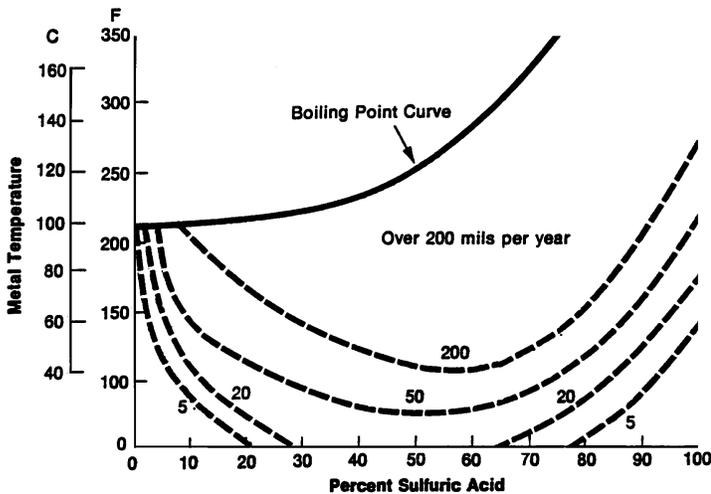


FIGURE 2

Isocorrosion curve for Type 316 stainless steel in sulfuric acid at temperatures up to 350°F (175°C). The boiling point line indicates where the sulfuric acid - water mixture boils. Mils per year is 0.001 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; it 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.

TABLE 9

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
Protected End (Cathodic or Most Noble)		

This is mechanism for pitting and crevice corrosion. Table 9 is a list of materials and their relative position in the galvanic series. 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, for example stainless steel, the anode will corrode and the cathode will be unaffected. The navy protects its ships by installing a sacrificial anode in hulls. But 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 where the chromium in the passive layer is dissolved leaving an active site with corrosion prone iron. The voltage difference between the passive and active layer on austenitic stainless steel is about +0.78 volts. Acid chloride is the most common cause of pitting in stainless steel. Chloride reacts with chromium to form the very soluble chromium chloride, CrCl₃. 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, Figure 3. The residual solution in the pit is ferric chloride, FeCl₃, which is very corrosive to stainless steel. This is the reason fer-



FIGURE 3

A typical chloride pit in stainless steel. These pits usually are spherical and have smooth walls. Magnification 250X.

ric chloride is used as a corrosion test for stainless steel. When molybdenum and/or nitrogen is added as an alloying element in stainless steel, the pitting corrosion resistance improves. An attempt to quantify the effect of alloying elements resulted in an equation called the pitting resistance equivalent number or

PREN^[4]. It has a number of different coefficients, but the most common equation^[2] is:

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

A PREN of 32 is considered a 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 a lower pH influence pitting, and conversely, a lower temperature and a higher pH reduce pitting. The worst conditions occur with acid chlorides (acidic environments containing the ion Cl^- , such as low-pH waters with sodium chloride or calcium chloride at concentrations above 70 mg/L and in brewkettles, hot water tanks, similar hot environments), 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 0.035-inch (0.89 mm) wall will pit through in less than 8 hours.

Increasing the molybdenum in the alloy produces greater resistance to pitting. Therefore high molybdenum – high chromium alloys generally provide the best pitting resistance. Figure 4 shows the relationship of pitting, molybdenum content, pH and chloride content. Table 10 lists alloys within the molybdenum contents shown on the graph. The molybdenum line represents the point where pitting starts, above the line pitting occurs, below the line no pitting. This is the threshold below which pitting corrosion will not take place, and the higher above the threshold, the more rapidly pitting occurs. This chart is very helpful in determining the amount of chloride and pH that can be tolerated for a given alloy class.

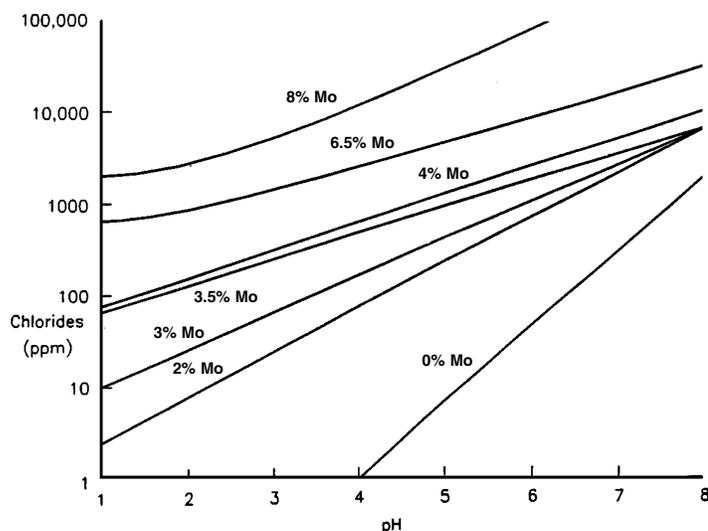


FIGURE 4

Pitting corrosion as a function of chloride content, pH and molybdenum content of austenitic chromium – nickel alloys. Temperature range 150 - 180° F (65 - 80° C). Pitting is not as problem below the line, but may be severe above the line.

TABLE 10

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 that occurs when the corroding metal is in close contact with anything that makes a tight crevice. The tighter the crevice, the worse the crevice corrosion potential. Crevice corrosion usually is 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 chloride makes the reaction proceed at a faster 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. For example, one should never wrap stainless steel pipe with neoprene and tightly clamp it in a pipe hanger, especially if airborne chlorides are present. The pipe will crevice corrode under the neoprene. There is a critical crevice corrosion temperature (CCCT) below which corrosion won't occur, but will above. Figure 5 is a plot of the PREN versus CCCT and metallurgical category. Table 11 lists the PREN for some of the more common alloys.

TABLE 11

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
7-MoPLUS®		31.7
Ferritic	SEA-CURE® Stainless	49.5
	Type 430	16.0
	Type 439	17.0
	Type 444	23.3

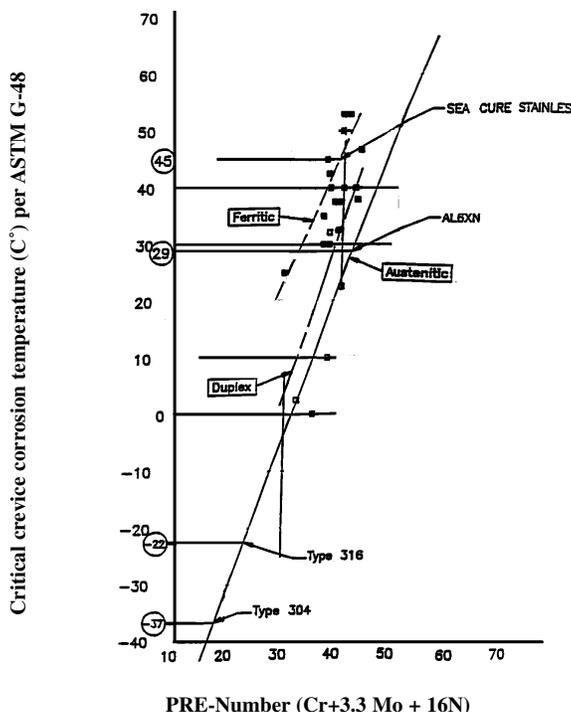


FIGURE 5

Critical crevice corrosion temperature (CCCT) as a function of the PREN number and alloy type. CCCT will not occur below the temperature indicated, but will above. Tests made in ferric chloride.

These values are based on the lower composition value for each alloy addition; therefore the results are 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 indicating the approximate temperature where pitting corrosion begins.

The effect of temperature on pitting corrosion is not as clear-cut as that for crevice corrosion. But, by adding approximately 100° F (60°C) to the CCCT will give the approximate temperature where pitting starts.

A variation of crevice corrosion was observed in pitting and stress corrosion cracking of a hot water piping system in a brewery [10]. The cause was later traced to the presence of carbon dioxide, which was added to the water to adjust pH after cold lime softening. This mechanism was later explained by the carbon dioxide bubbles, which collected chloride ions by electrophoresis, collecting on the inside pipe surface and forming a low pH crevice [7], which formed the pits.

Intergranular Corrosion

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 1000 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 begin 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. This is 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 grain boundary zone, low in chromium, creating a new, low chromium alloy in that region as illustrated in Figure 6. 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 grains of rusty sand. The surface of the metal develops a “sugary” appearance as illustrated in Figure 7. When a piece of metal with intergranular corrosion is dropped, the sound made is of a dull “thud” rather than a metallic ring.

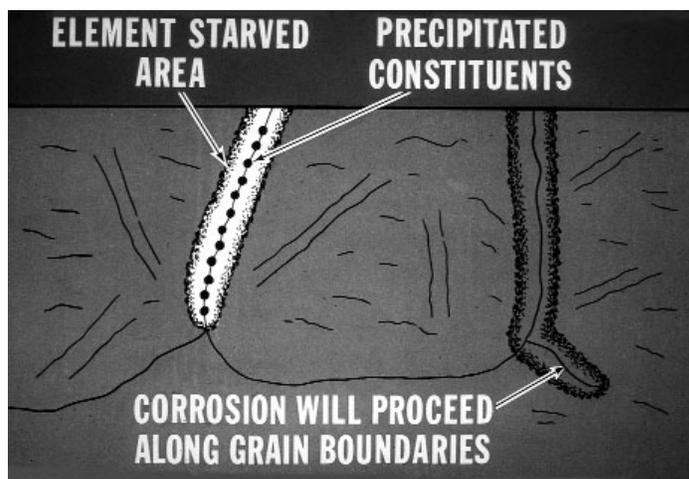


FIGURE 6

Mechanism for the formation of chromium carbide along the grain boundaries in stainless steel. The resulting area along the grain boundaries is depleted in chromium, therefore corrodes rapidly by galvanic corrosion.

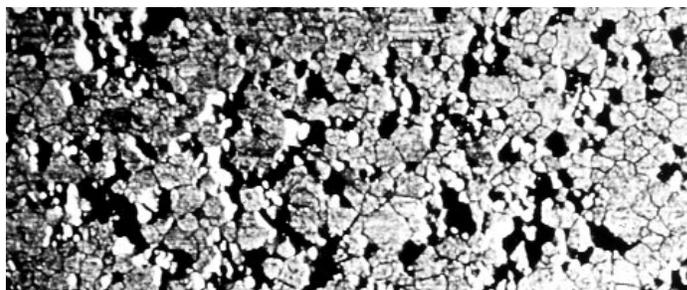


FIGURE 7

Appearance of a stainless steel surface that has undergone intergranular corrosion. This surface sometimes is called “sugared”. Magnification 50X.

Pipe and component welds in older breweries most often fail by this mechanism. Failures are characterized by leaks developing in the heat-affected zone along the grain boundaries. Then stress corrosion cracking sets in and leakage begins all over the pipe.

These compounds 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 or "L" grade of stainless steel when welding is to be done. These grades are very common today, 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 routinely obtain carbon levels in the range of 0.025%, 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. 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 800-1500°F (425-800°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.

Figure 8 shows the effect of temperature, time and carbon content on the formation of chromium carbide. The critical point is to get past the nose, or carbide-formation curve boundary, 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, then carbide precipitation will occur. Or, if the part is to operate within the maximum upper and lower limits of the curve then carbide precipitation will occur also.

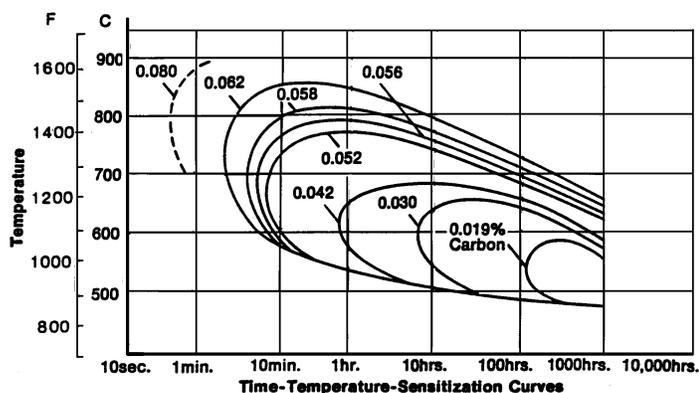


FIGURE 8

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.

Chromium carbide is not the only compound that can result in intergranular corrosion. Other compounds are delta ferrite, sigma phase (a chromium-iron compound), chi phase (a chromium-iron-molybdenum compound) and several other less common compounds. Special mention should be made concerning delta ferrite. All stainless steel is compounded to have a certain amount of delta ferrite in the microstructure to minimize microcracking during cooling of the weld. The welding research council recommends a range of 2 – 5% and most welds measure at 2%. However, when the delta ferrite is exposed to high chloride waters, and that includes most hot water systems in the brewery, the chloride begins to attack the delta ferrite, corroding it preferentially, and leakage occurs. An example of this is illustrated in Figure 9, where a seemingly benign water system begins to leak. The corrosion path is through the delta ferrite as seen in Figure 10. The answer is to use a lower ferrite containing steel, not an easy option, or to use a higher nickel welding wire. Any microcracks that may develop are less harmful than the corrosion potential.

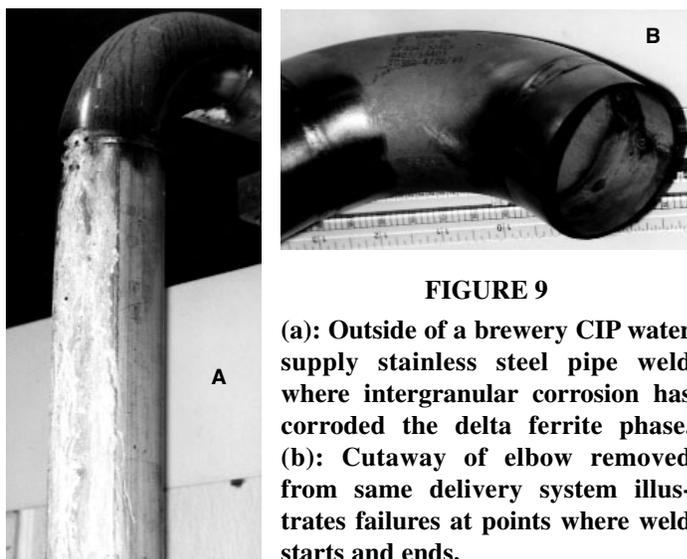


FIGURE 9

(a): Outside of a brewery CIP water supply stainless steel pipe weld where intergranular corrosion has corroded the delta ferrite phase. (b): Cutaway of elbow removed from same delivery system illustrates failures at points where weld starts and ends.

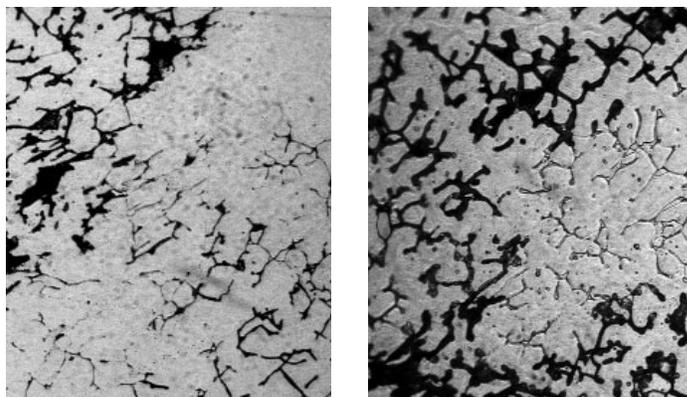


FIGURE 10

Appearance of a weld in which the delta ferrite was preferentially attacked by the chlorides in the water. Corrosion eventually penetrated the wall. Magnification 500X.

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is one of the most common and dangerous forms of corrosion that may develop in the brewery. 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 11 indicates that maximum susceptibility is in the nickel range of about 5 – 35% and that pure ferritics, such as Types 430, 439 and 444 are immune. The point of maximum susceptibility occurs between 7 and 20 % nickel. This makes Types 304/304L, 316/316L, 321, 347, etc., very prone to such failure.

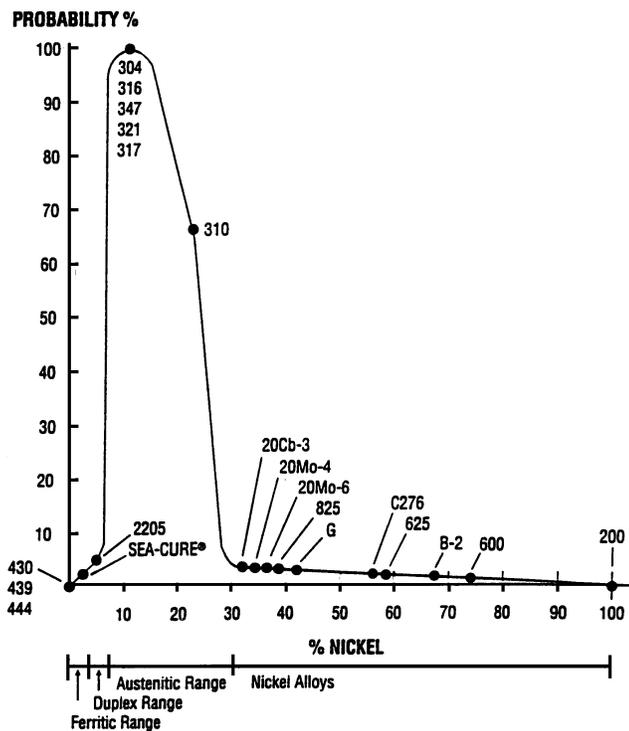


FIGURE 11

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.

Stress corrosion cracking has three components: alloy composition, environment, and the presence of tensile stress. All metals are susceptible to stress corrosion cracking as Table 12 indicates.

It doesn't take much chloride to cause failure, only a few parts per million, providing the pH is low and oxygen is present. Temperature is very important, since there is a threshold temperature below which the steel will not crack. This threshold temperature is related to the critical pitting temperature, therefore the threshold temperature increases as the molybdenum content increases. Type 304 may SCC at room temperature, Type 316 around 115° F (50° C), AL-6XN at 450° F (240° C) and SEA-CURE Stainless at 750° F (400° C).

TABLE 12

Alloy systems subject to stress corrosion cracking.

Alloy	Environment
Aluminum Base	<ul style="list-style-type: none"> • Air • Seawater • Salt and Chemical Combinations
Magnesium Base	<ul style="list-style-type: none"> • Nitric Acid • Caustic • Salts • Coastal Atmospheres
Copper Base	<ul style="list-style-type: none"> • Ammonia & Ammonium Hydroxide • Amines • Mercury
Carbon Steel	<ul style="list-style-type: none"> • Caustic • Anhydrous Ammonia • Nitrate Solutions
Martensitic and Precipitation Hardening Stainless Steel	<ul style="list-style-type: none"> • Seawater • Chlorides • Hydrogen Sulfide Solutions
Austenitic Stainless Steel	<ul style="list-style-type: none"> • Chlorides, Both Inorganic and Organic • Caustic Solutions • Sulfurous and Polythionic Acids
Nickel Base	<ul style="list-style-type: none"> • Caustic above 600° F (315° C) • Fused Caustic • Hydrofluoric Acid
Titanium	<ul style="list-style-type: none"> • Seawater • Salt Atmospheres • Fused Salt

The stress component is more subtle. The stress must be tensile and it must exceed the yield strength of the component. This sounds simple enough, but anytime the part is bent, straightened or when any physical exertion is made to place the material into a fixed shape, the yield strength is exceeded. Next we complicate the picture by stress multiplication factors. If a pit or other sharp notch is present, then the residual stress is multiplied by 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 by forming a stress concentrator.

When the cracks form, they usually are transgranular as illustrated in Figure 12. These crack through the grain. Cracking occurs rapidly, and progresses through the grain, terminating in a feathery cluster of small cracks. This is a characteristic 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 gives conclusive evidence that SCC has occurred.

Brewery failures are most often associated with SCC. This usually is because of the wide use of Type 304/304L, chloride in the water and elevated temperature of the system. Most often this occurs in the hot water piping, but occasionally it happens in other locations. An example of this is a brew kettle that began to show multiple leaks after several years' service. Figure 13

shows the extensive weld repairs attempted on the kettle, and once made, only to begin to leak again. Figure 14 shows why the weld repair failed, namely because the welds were not deep enough to cover the cracks on the inside of the vessel. The only recourse, once cracking begins, is to replace the steel with a



FIGURE 12

Polished and etched cross section of stress corrosion cracked stainless steel, magnified 250X, showing the transgranular cracks and feathery appearance of the crack tips.

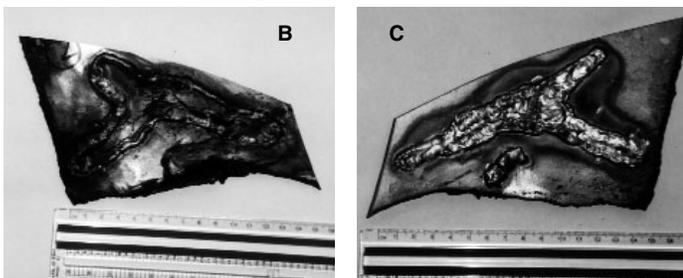
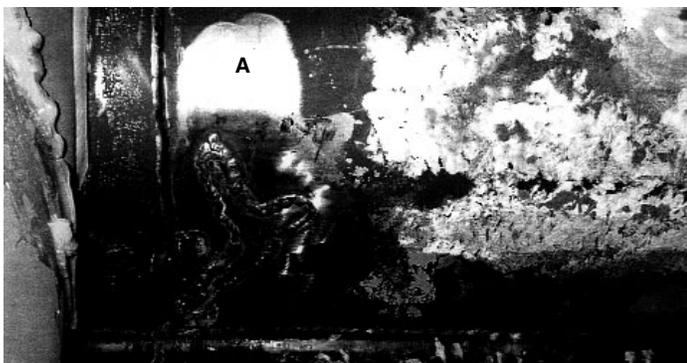


FIGURE 13

a): A weld repair over a crack on the outside of a brew kettle. The initial cracking was because of chloride stress corrosion cracking. The weld repair failed because cracks were still present on the interior surface, which acted as stress risers to once again caused cracking. (b): Closeup of the external surface. (c): close-up of wort-contact surface from weld repair.

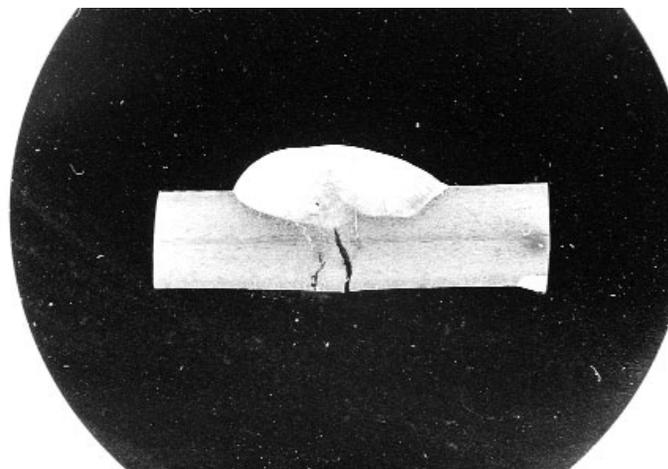


FIGURE 14

The weld repair from Figure 13 failed because the cracks still were present on the interior of the tank. Once the kettle went back in operation the cracks continued into the weld metal and the kettle began to leak again in the same location.

grade that is not subject to SCC, such as a duplex stainless or one with a threshold temperature above the operating temperature. Is it possible to treat the water so this type of failure will not take place? Yes, but one must be extremely careful to make sure no chlorides are present and that the Langelier Scaling Index is above the pH of the system. (see Appendix A). And if the vessel is jacketed for steam heating, then the steam must be from non chloride containing water, preferably reverse osmosis or deionized water, because chloride is carried across in the steam.

Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) is a recently recognized 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 13 indicates. Most metals are attacked by some type of bacteria action. The mechanism usually is general or crevice corrosion under the bacterial colonies as seen in Figure 15.

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^[8]. 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 to produce 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. Areas of specific concern in the brewery include the pasteurizer and brewery effluent lines, especially in the welds or drain lines. In the pasteurizer MIC corrosion usually takes place in the cooling zones along welds, but can occur in the sump tank as well.

TABLE 13
Corrosive microorganisms and their attack of metals.

Organism	Action	Problem	Metals Attacked
Desulfovibro Clostridium Thiobacillus	<ul style="list-style-type: none"> Hydrogen Sulfide, Sulfurous and Polythionic Acid Producers (Sulfate Reducers) 	<ul style="list-style-type: none"> Produces Sulfurous and Polythionic acids Reduces Chromates Destroys Chlorine Precipitates Zinc 	<ul style="list-style-type: none"> Copper, Brass and Other Copper Alloys Low Molybdenum, Low Copper Stainless Steels Iron and Steel Aluminum
Thiobacillus	<ul style="list-style-type: none"> Sulfuric Acid Producer 	<ul style="list-style-type: none"> Produces Sulfuric Acid 	<ul style="list-style-type: none"> Copper, Brass and Other Copper Alloys Iron and Steel Low Molybdenum, Low Copper Stainless Steels Aluminum Titanium in Oxidizing Environments
Nitrobacter Nitrosomonas	<ul style="list-style-type: none"> Nitric Acid Producers 	<ul style="list-style-type: none"> Produces Nitric Acid 	<ul style="list-style-type: none"> Copper and Copper Alloys Iron and Steel Aluminum
Gallionella Crenothrix Spaerotilus	<ul style="list-style-type: none"> Converts Soluble Manganese Iron and Iron Compounds into Insoluble and Manganese Oxides 	<ul style="list-style-type: none"> Manganese Dioxide Reacts with Chlorine, Chlorine Dioxide, Perchlorates to Produce Hydrochloric Acid Iron Oxide Reduces Heat Transfer 	<ul style="list-style-type: none"> Low Molybdenum Stainless Steels Iron and Steel Aluminum Copper and Brass

The responsible bacteria usually are the sulfur fixing types. These areas should be routinely checked since the pasteurizer is too expensive to ignore.

Other than the use of bactericides such as chlorine or ozone, the usual solution is to use a 6% molybdenum alloy like AL-6XN®, a superferritic like SEA-CURE® Stainless, or the highly alloyed nickel alloys. Therefore, if MIC corrosion is taking place, use one of these alloys.



FIGURE 15

Crevice corrosion under a confirmed sulfur fixing bacteria colony on the inside of a stainless steel tube. Magnification 5X.

Welding Stainless Steel

Stainless steel normally is joined by welding. Welding provides high strength joints with minimum flow restrictions and prevents the major concern with screw thread joints, namely crevice corrosion. 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, and 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 and heat-affected zones should be silver, light gold or straw color at worst. If the welds or heat-affected zones are black, then the corrosion resistance has been compromised [6].
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 will react either with the chromium to produce chromium carbide or decompose during welding to create hydrogen gas resulting in porosity.
4. Always use aluminum 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 carbon steel, ferritic or martensitic stainless steels. Therefore, keep the base metal restraint to a minimum to prevent distortion and adding residual stress to 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. Above all, during welding, keep the surfaces clean, dry, and well covered with an inert gas and free from oxide.

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.

Alloy Selection

When a corrosion problem is encountered, always review the system chemistry first to determine if a change can be made to eliminate the corrosion condition. For example, if carbon steel is rapidly oxidizing in steam, is it possible to adjust the pH upward and to add hydrazine, or one of its derivatives, to combat the dissolved oxygen? If the system is being cleaned with muriatic acid (which is deadly to stainless steel) can the acid be changed to one that is more friendly to 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 like sulfuric or phosphoric acid be substituted to prevent acid bubbles from forming on the surface and causing crevice corrosion?

If it is not possible to modify the environment, then the alloy must be changed. Use the following selection process to narrow down the alloy options. This same procedure can be used to select 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, because it usually will occur. Use the corrosion rate charts or tables to determine those alloys with the best uniform corrosion resistance. If the corroding solution is a single composition, then the 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 that the rates may be accelerated or slowed down in such environments. Many complex solutions require the use of corrosion racks with different alloys exposed to the 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 4.

3. Select the proper alloy using its PREN number for the temperature based on crevice corrosion, Figure 5.

4. Determine the best carbon range to prevent intergranular corrosion using Figure 8, or use a low carbon grade as a general rule.

5. Choose the best alloy that will not stress corrosion crack based on Figure 11.

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. Someone may have had the same problem and an answer may already exist. There is an alloy, material or design modification out there that will solve your problem.

CONCLUSION

A review of stainless steel, the metallurgical types, properties, corrosion mechanisms selection criteria and welding guidelines for their use in breweries has been presented. This is an inductory explanation of the use of these alloys and is not intended as a comprehensive treatment of the science and engineering of stainless steel which is beyond the scope of this discussion. Appendix A presents an example of an interdisciplinary tool that may be used to evaluate the tendency for the water used in a brewery to scale and form a crevice that can lead to crevice corrosion. Appendix B presents a glossary of selected metallurgical terms used in this article. By considering the application and factors as identified within this review, the brewery can specify acceptable materials to provide a long life of excellent performance.

TRADEMARK ACKNOWLEDGEMENTS

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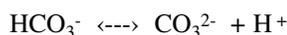
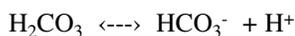
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APPENDIX A

Langelier Scaling Index

The Langelier Scaling Index (LSI) provides an indicator of calcium carbonate saturation of water. LSI approximates the base 10 logarithm of the calcite saturation level using pH and temperature as the main variables. The LSI can be interpreted as the pH change required to bring water and calcium carbonate to equilibrium at a given temperature. Water with a LSI of 1.0 is one pH unit above saturation. Reducing the pH by one unit will bring the water into equilibrium because the portion of total alkalinity present as CO_3^{2-} decreases as the pH decreases, according to the equilibriums described by the dissociation of carbonic acid:



If LSI is negative: No potential to scale, the water will dissolve CaCO_3

If LSI is positive: Scale can form and CaCO_3 precipitation may occur

If LSI is close to zero: Borderline potential to form scale

To calculate the LSI, it is necessary to know the alkalinity (as mg/L CaCO_3), the calcium hardness (mg/L Ca^{++} as CaCO_3), the total dissolved solids (mg/L TDS), the actual pH, and the temperature of the water (deg C). If TDS is unknown, but the conductivity is, one can estimate mg/L TDS using the conversion table in the referenced web site.

LSI is defined as: $\text{LSI} = \text{pH} - \text{pH}_s$

Where: pH is the measured water pH
 pH_s is the pH at saturation in calcite or calcium carbonate and is defined as:

$$\text{pH}_s = (9.3 + A + B) - (C + D)$$

Where:

$$A = (\text{Log}_{10} [\text{TDS}] - 1) / 10$$

$$B = -13.12 \times \text{Log}_{10} (\text{deg C} + 273) + 34.55$$

$$C = \text{Log}_{10} [\text{Ca}^{++} \text{ as } \text{CaCO}_3] - 0.4$$

$$D = \text{Log}_{10} [\text{alkalinity as } \text{CaCO}_3]$$

Example:

Langelier Index Calculation at 25 °C (room temperature) and 82°C (rinse tank cycle).

Water Analysis:

$$\text{pH} = 7.5$$

$$\text{TDS} = 320 \text{ mg/L}$$

$$\text{Calcium} = 150 \text{ mg/L (or ppm) as } \text{CaCO}_3$$

$$\text{Alkalinity} = 34 \text{ mg/L (or ppm) as } \text{CaCO}_3$$

LSI Formula:

$$\text{LSI} = \text{pH} - \text{pH}_s$$

$$\text{pH}_s = (9.3 + A + B) - (C + D) \text{ where:}$$

$$A = (\text{Log}_{10}[\text{TDS}] - 1)/10 = 0.15$$

$$B = -13.12 \times \text{Log}_{10}(\text{°C} + 273) + 34.55 = 2.09 \text{ at } 25^\circ\text{C} \\ \text{and } 1.09 \text{ at } 82^\circ\text{C}$$

$$C = \text{Log}_{10}[\text{Ca}^{++} \text{ as } \text{CaCO}_3] - 0.4 = 1.78$$

$$D = \text{Log}_{10}[\text{alkalinity as } \text{CaCO}_3] = 1.53$$

Calculation at 25°C:

$$\text{pH}_s = (9.3 + 0.15 + 2.09) - (1.78 + 1.53) = 8.2$$

$$\text{LSI} = 7.5 - 8.2 = -0.7$$

Hence No Tendency to Scale

Calculation at 82°C:

$$\text{pH}_s = (9.3 + 0.15 + 1.09) - (1.78 + 1.53) = 7.2$$

$$\text{LSI} = 7.5 - 7.2 = +0.3$$

Hence Slight Tendency to Scale

(From: <http://www.corrosiondoctors.org/NaturalWaters/Langelier.htm>)

APPENDIX B

Glossary of Metallurgical Terms

Chi Phase:

A compound of variable composition containing approximately 33% chromium, 33% iron and 33% molybdenum. Chi phase forms in the temperature range of 1300 - 1800° F (700 -1000°C) in many corrosion resistant alloys with lower nickel content. It can be minimized by higher nickel and nitrogen additions to the alloy composition. Its presence may lead to embrittlement, loss of ductility and reduced corrosion resistance. It may be eliminated by high temperature heat treatment, >2100° F (1150°C), combined with hot working at temperatures above 1800°F (1000°C).

Cold Working:

The process of producing permanent deformation in a metal by mechanical means at a temperature below the metal's recrystallization temperature. This temperature is variable depending on the metal and any alloying elements present. For stainless steel this temperature is about 900°F (480°C). Cold worked metals are characterized by higher hardness, higher strength, lower ductility and higher sensitivity to chloride stress corrosion cracking in the austenitic stainless steels.

Delta Ferrite:

A metallurgical compound present in low nickel austenitic stainless steels at high temperatures, usually at temperatures above 2500° F (1400°C) that may be stable at room temperature when the alloy is rapidly cooled from this temperature. Delta ferrite is a component of most austenitic stainless steel welds. In the presence of chlorides delta ferrite will preferentially corrode. Delta ferrite can be eliminated by a combination of cold working and heat treatment at temperatures above 1850 °F (1010°C).

Hot Working:

The process of producing permanent deformation in a metal by mechanical means at temperatures above the recrystallization temperature. Hot worked metals are characterized by low hardness, lower strength, higher ductility and reduced sensitivity to chloride stress corrosion cracking in the austenitic stainless steels.

Sigma Phase:

A metallurgical compound containing 40 – 55% Cr and 60 – 45% Fe that forms in the temperature range of 1000 - 1500°F (530 - 815°C). It is similar to chi phase in its effects on stainless steel. It can be eliminated by heat treatment above 1800°F (1000°C) when accompanied by hot working.