

Stainless Steels: An Introduction to Their Metallurgy and Corrosion Resistance

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SUMMARY

The structure and properties of stainless steel alloys are reviewed. Comments on the varieties of nomenclatures for stainless steels are included, and examples are given of the differences between a number of grades. Corrosion principles and forms of corrosion as they apply to stainless steels are discussed. The various types, shapes and surface finishes available are considered.

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INTRODUCTION

Worldwide, in industry, in business and in the home, metals called stainless steels are used daily. It is important to understand what these materials are and why they behave the way they do. This is especially true because the word "stainless" is itself somewhat of a misnomer; these materials can stain and can corrode under certain conditions. People need to know why these metals are usually bright and shiny and why they sometimes depart from this expected appearance. In this paper, we hope to explain some of these phenomena and provide a

better understanding of stainless steels, especially to the non-metallurgist.

Industries are concerned with integrity of equipment and product purity. To achieve these, stainless steels are often the economical and practical materials of choice for process equipment. However, before intelligent decisions can be made regarding the proper selection from the various types of stainless steel, it is necessary to have an understanding of what stainless steels are. It is important to know what different grades of stainless steel are available, why they perform satisfactorily

and why they sometimes do not. In most cases, selection of the proper stainless steel leads to satisfactory performance.

COMPOSITION, NOMENCLATURE AND GENERAL PROPERTIES

Most metals are mixtures of a primary metallic element and one or more intentionally added other elements. These mixtures of elements are called alloys. Stainless steels are alloys, as are brasses (copper + zinc), bronzes (copper + tin), the many aluminum alloys, and many other metallic materials. In general, solid metals and alloys consist of randomly oriented grains that have a well-defined crystalline structure, or lattice, within the grains. In stainless steels, the crystalline structures within the grains have been given names such as ferrite, austenite, martensite, or a mixture of two or more of these. Many of the properties of stainless steels depend upon which crystalline lattice occurs. Examples of these crystal structures are given in *Fig. 1*, where the black dots represent atoms and the lines are present to help the structure to be seen.

Figure 1. Crystal structures of stainless steels

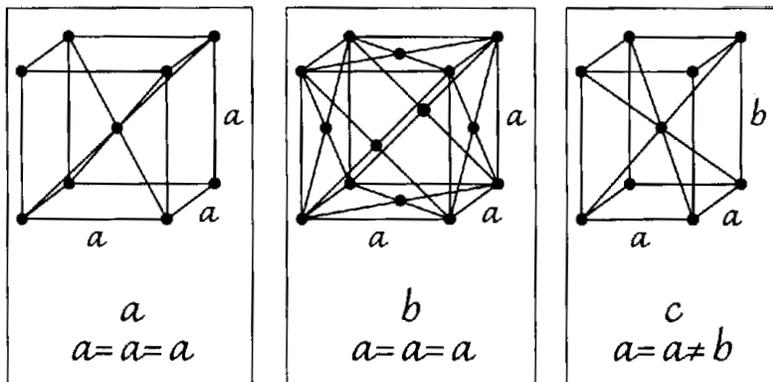
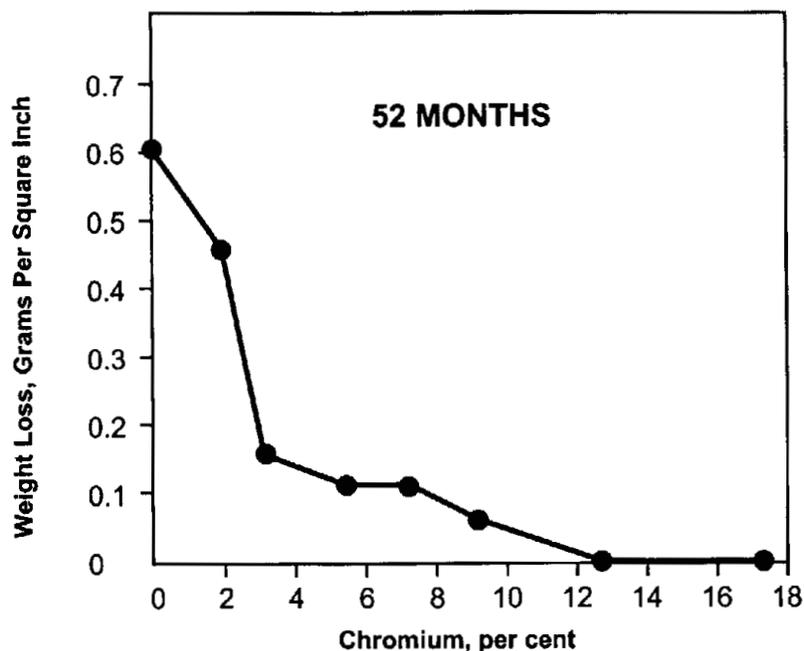


Figure 2. The influence of chromium on the atmospheric corrosion of low carbon steel



Ferrite is the basic crystal structure of iron or low-alloy steel at ambient temperatures. To understand it, envision a cube with an atom at each of the eight corners and in the geometric centre of the cube. This body-centred cubic structure (Fig. 1a) is repeated regularly in three dimensions throughout the grain until it meets a grain of different orientation. At these contacts are areas termed grain boundaries. Grain boundaries consist of many things, including the interface, defects, impurities and

grains of other substances. They can be quite complicated and often play an important role in the mechanical properties and corrosion behaviour of metals.

Austenite is the crystal form of unalloyed iron in the grains at higher temperature ($>800^{\circ}\text{C}$). It is different from ferrite. As in ferrite, there is an atom at each corner of a cube, but instead of one in the geometric centre, there is one in the centre of each of the six faces of the cube. This face-centred cubic array

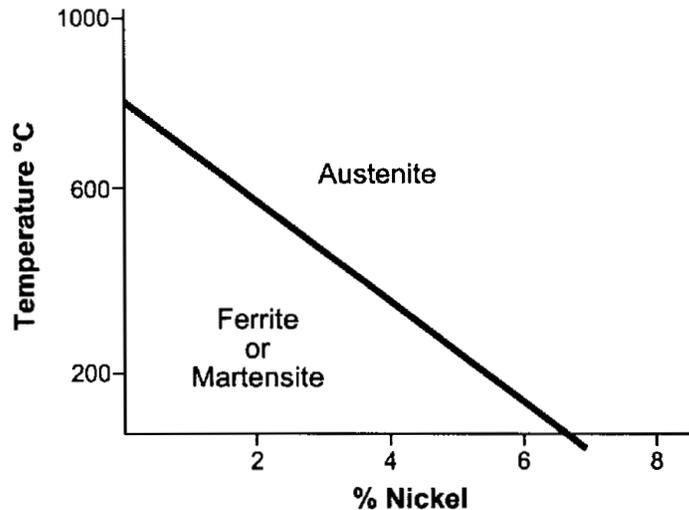
(Fig. 1b) becomes stable at room temperature if nickel, manganese, nitrogen, or carbon is added, singly or in combination, to iron or iron/chromium alloys. The resulting materials are called austenitic stainless steels. In general, they are easier to shape and bend, more weldable, and less brittle than ferritic alloys.

Martensite is a stable structure at ambient temperature and more similar to ferrite than to austenite. It also has a body-centred structure (Fig. 1c), but one axis of the cube has been elongated to form a tetragonal structure, that is, a crystal having all three axes at right angles and with two equal sides and one unequal. It is produced by heat treating or cold working cubic crystals of ferrite or austenite. Martensite is the hardest, and strongest of the three crystalline forms, but it is also the least workable. In fact, these alloys are seldom intentionally deformed.

As mentioned previously, alloys are combinations of two or more elements, at least one of which is always a metal. All of the many and varied stainless steels are alloys. They are always iron-chromium alloys, but they often contain other elements, such as molybdenum or nickel. The better known varieties of stainless steel are wrought (hot-rolled or hot-forged after casting into an ingot). There are also cast counterparts that have properties similar to those of most of the wrought grades but that are altered slightly in composition in order to improve casting properties. To define the different materials, the publication *Metals and Alloys in the Unified Numbering System* (1) lists over 250 types within the broad definition of stainless steels. These are iron base alloys containing more than 11% chromium. Various grades also contain nickel, molybdenum, manganese, nitrogen and other alloying elements. As can be seen in Fig. 2 (6), chromium's primary effect is to impart corrosion resistance. The diagram shows the influence of chromium on corrosion when it is added to iron or steel. As can be seen, when it reaches

Figure 3. Effect of adding nickel to Fe-Cr alloys

Effect of Nickel Addition to Fe-Cr Alloys



11-14%, corrosion is practically negligible in the atmosphere. Nickel in stainless steel promotes austenite stability and reduces the temperature at which austenite can exist. *Figure 3* illustrates this effect. Above the diagonal line in the diagram, austenite is stable at the indicated temperature; below the line, either ferrite or martensite is the stable crystal structure.

Manganese is similar to nickel when it is added to or substituted for nickel and also increases strength. Molybdenum increases the resistance to localized corrosion phenomena, such as pitting and crevice corrosion. Nitrogen also improves resistance to crevice corrosion, as well as increasing strength and acting as an austenite stabilizer. Elements such as copper and silicon improve corrosion resistance in special environments, and silicon also improves casting properties.

To reduce confusion and simplify nomenclature, standard numbering systems have been developed for the various stainless steel alloys. For many years in the United States, the three-digit method of the American Iron and Steel Institute (AISI) was common for wrought stainless steels. Another letter and number system, that of the Alloy Casting

Institute, applied to the cast grades. These early systems divided stainless steel alloys into groups according to crystal structure. However, many of the newer alloys did not fit into the earlier categories, and it became necessary to have a more complete system. Therefore, these older nomenclatures are now being replaced by the Unified Numbering System (UNS)(1) developed by the Society for Automotive Engineers (SAE) and the American Society for Testing and Materials (ASTM). These groups have developed a six-character notation that assigns a unique designator to metals and alloys in a way that consistently defines a material. For example, the UNS number S30403 replaces AISI 3041; the final two digits, 03, indicate the maximum permitted carbon content. In other alloys, the various digits may refer to other parameters; so it cannot always be assumed that the latter numbers mean carbon content. The equivalent cast alloy is J92500, which formerly was ACI CF-3. It should also be noted that the letter before the numbers in the Unified Numbering System pertains to different alloy classes. All letters used will not be defined here, but those of importance will be mentioned. The S refers to heat and corrosion steels (including stainless

steels), valve steels and iron-base "superalloys", the J to cast steels (except tool steels), and N to nickel and nickel alloys. The UNS system also provides for classification of many of the newer, more complex alloys that would not fit into the old system, and it covers many types of alloys in addition to the stainless steels.

It should be noted that in other countries different nomenclatures and systems may be used. For example, in Europe the EN system of numbering alloys is in common usage. With this method, S30400 (304) and S31600 (316) are replaced by the numbers 1.4301 and 1.4401, respectively. Most stainless steels have similar designations, some of which are given in *Tables 2* and *3*.

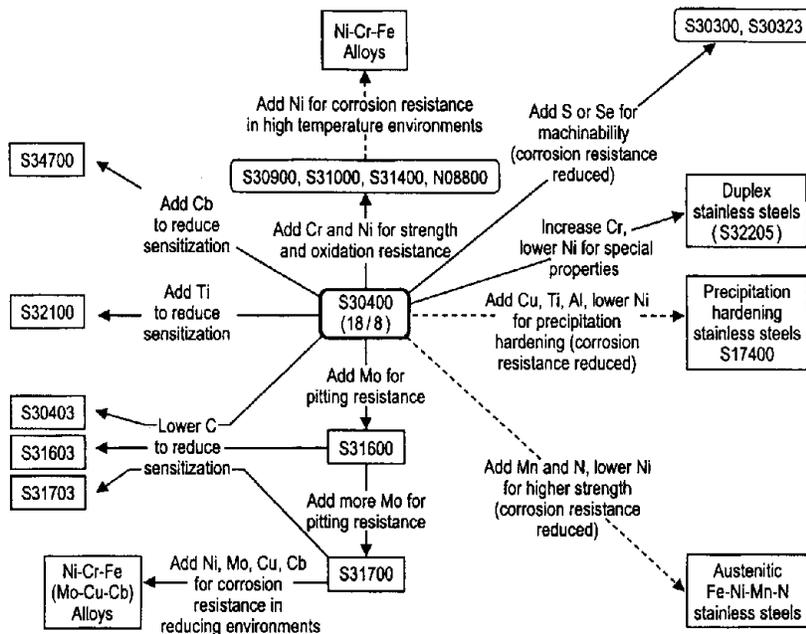
Figure 4 (6) shows how composition variations have led to many related stainless steels that have evolved from the basic S30400 (304) composition. By altering the composition, as indicated by the arrows and text in the figure, various compositions are produced to meet particular needs. In many cases, this is done by adding or omitting small amounts of other constituents without making major changes in the primary alloy content.

COMMON STAINLESS STEEL ALLOY SYSTEMS

Austenitic alloys - iron-chromium-nickel and iron-chromium-manganese-nickel alloys

Some of these alloys also contain nitrogen, copper, silicon, and other elements for special purposes. They have an austenitic, i.e., face-centred cubic crystal structure within the grains. To obtain this structure, the austenite/ferrite transition temperature is suppressed by the addition of alloying agents, primarily nickel, but also manganese and nitrogen, so that the resulting austenite is stable at ambient temperature (see *Fig. 3*). These alloys are grouped in the 300 and 200 series, respectively, in the old AISI system. They are non-magnetic, unless heavily cold-worked, and hardenable only by cold work. The primary alloy of this type is S30400 (304), 18-20% Cr, 8-10.5%

Figure 4. Some compositional modifications of 18/8 austenitic stainless steel to produce special properties. Dashed lines show compositional links to other alloy systems.



Ni, and the balance iron. It is commonly referred to as 18-8 stainless steel because of the approximate chromium and nickel contents. Common applications are for an almost endless variety of equipment, including vessels, piping, and tubing used in producing and processing industrial products. Many consumer products such as sinks and wash basins, cooking utensils, pots and pans, and flatware are made from this alloy. When welded fabrication is employed, the low-carbon grade S30403 (304L) is frequently used.

Ferritic alloys - iron-chromium alloys

These have a body-centred cubic crystal structure. They have the corrosion behaviour of stainless steels but are sometimes difficult to weld and fabricate. They are magnetic and hardenable only by cold work. An example is 543000 (430), 16-18%Cr, in the iron base. Less expensive consumer products, including automotive and appliance trim and flatware, are often made from ferritic alloys.

Martensitic alloys

These are iron-chromium alloys but higher in carbon and other hardening agents than the ferritic alloys. They are magnetic, hardenable by heat treatment, and somewhat difficult to weld and fabricate. S41000 (410), 11.5-13.5% Cr, 0.15max% C, and the balance iron is typical of these grades. Common uses are in making corrosion resistant bearings, knife and shear blades, and valve and compressor parts.

Precipitation or age-hardening alloys

These are primarily iron-chromium-nickel alloys to which other elements have been added to form compounds of small grains which precipitate when heated to intermediate or high temperature (500°C to 900°C) for a period of time. When present, these small grains strain the crystal and “harden” or strengthen the alloy. S17400 (17-4PH), 15-17.5% Cr, 3-5% Cu, 0.15-0.45% Cb, 3-5% Ni, and the balance iron is a common composition. These alloys are used where a combination of high

strength and corrosion resistance is needed. Many of them can be shaped and formed in the soft or annealed condition and subsequently hardened or “aged”. One of the best known uses of age-hardened stainless steels is for golf club heads.

Duplex alloys

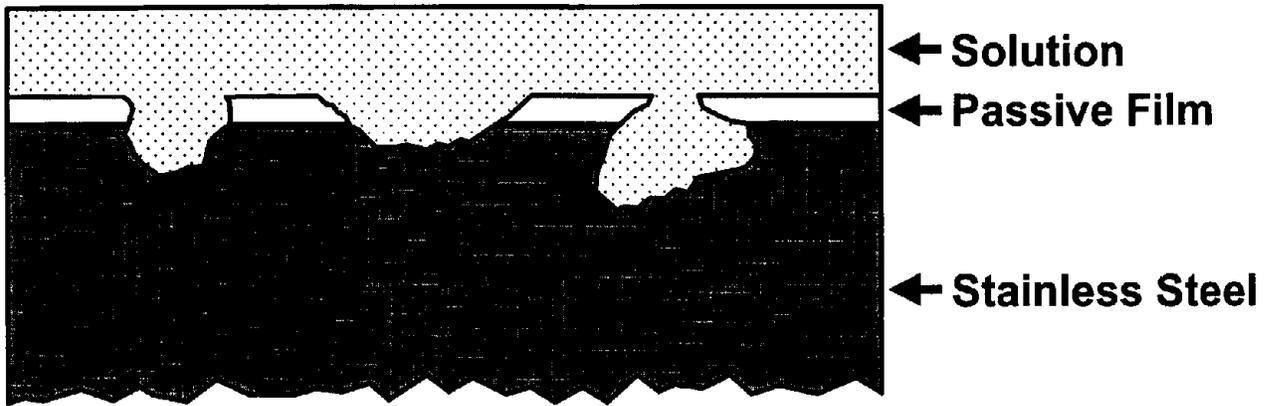
These are usually iron-chromium-nickel alloys with a nickel content lower than that of the austenitic grades. Some may also contain molybdenum or other elements. The duplex structure has grains of both austenite and ferrite. Duplex alloys are typically stronger than alloys that are solely austenitic, and their corrosion resistance is often at least as good as that of the alloys they replace. Duplex alloys are used in chemical, process, and petroleum industries, especially where better resistance to chloride stress corrosion cracking is required.

PRODUCTION OF STAINLESS STEELS

For many years, stainless steels were both melted and refined in an electric arc furnace. These steps are now frequently separated, with the molten charge in the electric furnace transferred to a separate unit for adjusting of composition and removal of impurities. Such operations normally use oxygen-inert gas injection (Argon Oxygen Decarburization, AOD) or oxygen injection under vacuum (Vacuum Oxygen Decarburization, VOD). These techniques permit the production of purer, cleaner steels with much more carefully controlled compositions.

Stainless steels require care during fabrication (5, 6). Their properties can vary depending on prior thermal and mechanical operation. Austenitic stainless steels are almost always placed in service in the annealed condition. This means they are quenched in water or other fast cooling media from the annealing temperature (1040°C -1130°C). Thus, annealing has a different meaning than it has for carbon or low-alloy steels, which are generally slow-cooled from the annealing temperature. For austenitic stainless steels,

Figure 5. Pitting corrosion



lack of, or improper, annealing may result in intergranular corrosion problems because of precipitated carbides at grain boundaries of the microstructure. Producers are well aware of this and ship only annealed material unless they are asked to do otherwise, although it is always best to specify the heat treatment. However, using low carbon or titanium or columbium stabilized grades is additional protection from this problem.

INTRODUCTION TO THE CORROSION BEHAVIOUR OF STAINLESS STEELS

The aqueous corrosion of metals is generally considered an electrochemical action. That is, there are alternating sites of differing electrochemical activity on a metal surface. These sites act like the anodes and cathodes in a battery. At the anode, the metal oxidizes (corrodes), reacting with the environment to form rust or some other corrosion product. At the cathode, a reduction reaction such as the reduction of oxygen takes place. This completes the electrochemical cell and corrosion proceeds. In order to prevent corrosion, these cells must be interrupted in some manner.

The unique corrosion resistance of stainless steels is attributed to the existence of a thin, adherent, inac-

tive passive film that covers the surface. This film can conveniently be thought of as chromium oxide, but it also contains small amounts of the other elements in the alloy. Some investigators of the subject consider the film to be something other than an exact oxide, and they may be correct, but it is easier to think of the film as an oxide. Many people think stainless steel must be given a “passivating” treatment for this film to form properly. This is not true; if the surface is clean and free of contamination, the film forms instantaneously on exposure to air, aerated water, nitric acid, or other oxidizing media. It is extremely durable and reforms spontaneously.

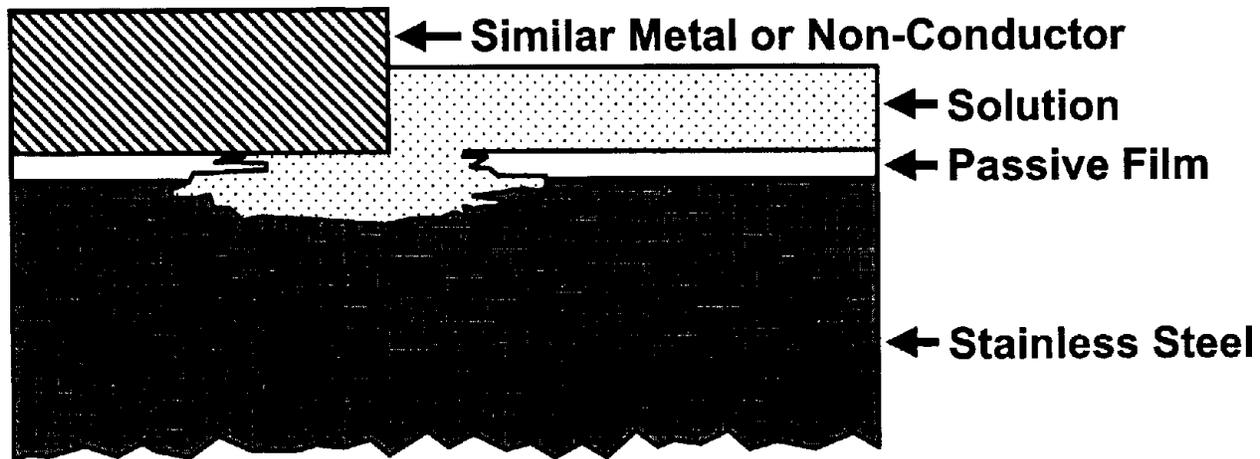
Because of this protective film, stainless steels do not corrode as carbon or low alloy steels or cast iron do. These materials “rust” or corrode uniformly through constantly changing anodes and cathodes on the surface. However, except in solutions such as hydrochloric acid, this general corrosion or uniform attack practically never occurs on stainless steels. The terms “corrosion rate” and “corrosion allowance” are usually meaningless when applied to stainless steels. While factors such as chemical environment, pH, temperature, equipment design, fabrication methods, surface finish, contamination, and maintenance procedures can affect the corrosion of stainless steels, they usually

cause only some form of localized corrosion. To explain this further, the various types of localized corrosion—pitting, crevice corrosion, intergranular corrosion, stress corrosion cracking, and galvanic corrosion—will be considered separately.

Pitting and crevice corrosion

Because pitting and crevice corrosion are very similar and the factors that affect their occurrence are essentially the same, these two phenomena will be considered together. Pitting (*Fig. 5*) is highly localized corrosion at individual sites on the surface of the metal. The figure also shows that pits vary in size, shape, and morphology. Some pits are broad and not very deep while some penetrate quite deeply and others may undercut the passive film and spread out beneath it. Crevice corrosion (*Fig. 6*) is the attack that occurs at the interface between the corroding metal and another substance, usually one that is not electrically conductive. The corrosion usually spreads into the crevice beyond the point of contact. Both types of corrosion happen on stainless steel in certain media, especially those containing chlorides. Pitting can occur because of minor discontinuities in the passive film, inclusions or defects in the stainless steel, or dirt and contamination on

Figure 6. Crevice corrosion



the surface. Examples of common crevices are joints with gaskets, at points where scale or hard biofouling attaches and in places where materials overlap. Because the area of the attack is very small in comparison to the overall area of the metal surface, corrosion can be very intense and rapid at the site of attack. The most important single fact in the initiation of crevice corrosion is the presence of chloride ions, although higher environmental temperatures, oxygen or easily reducible ions such as ferric ions, and acid pH values can also have deleterious effects. Pitting is less apt to occur in aqueous solutions moving at moderate to high velocities than in stagnant ones.

Although we have previously said that pitting and crevice corrosion are essentially the same, some differences should be mentioned. Crevice corrosion can occur in environments that normally do not cause pitting in boldly exposed sheet or plate, particularly in tight stationary crevices in slow-moving solutions.

If the environment cannot be controlled, by reducing acidity, or chloride content or by increasing solution velocity, more highly alloyed grades may be used to control pitting and crevice corrosion. This is usually done by adjusting chromium and nickel content and adding more molybdenum (and, to a lesser ex-

tent, nitrogen) to the alloys. The pitting resistance of a common material such as S30400 with no added molybdenum can be markedly improved in this way. Alloys such as S31600 (2-3% Mo), S31700 (3-4% Mo), N08904 (4-5% Mo), and the 6-7% Mo alloys have increasing pitting and crevice corrosion resistance with increasing molybdenum content. Good design and fabrication techniques that produce smooth, clean surfaces, rounded corners, and “drain away” designs also help resist pitting and crevice corrosion.

Intergranular corrosion

If an austenitic stainless steel of normal carbon content (0.03-0.08% C) is heated in the temperature range from 425°C (800°F) to 815°C (1500°F), chromium carbides are precipitated at grain boundaries and the structure is said to be “sensitized.” The chromium-depleted zone around each grain is more susceptible to attack in some media, particularly acids. Exposure to this critical temperature range can result from improper annealing, stress relieving, or heating during forming and welding. *Figure 7* is a representation of what can happen. As is seen, corrosion has proceeded from the surface down the grain boundaries to the extent that the grains can become detached and the surface is sometimes said to have “sugared”.

Other than heat treatment, there are usually two solutions to sensitization: use of a low-carbon alloy such as S30403 (304L) or use of an alloy containing, or “stabilized” with, titanium, S32100 (321), or columbium, S34700 (347). In the first case, there is insufficient carbon in the alloy to form large amounts of chromium carbides and thus reduce chromium in the grain boundaries. In the latter case, the carbon is pre-combined with titanium or columbium and is therefore not available to the chromium. The titanium and columbium carbides are dispersed in the matrix of the grains and not localized at grain boundaries to promote intergranular corrosion. In recent years, as the AOD and VOD processes have become more successful and low carbon alloys easier to produce, the low carbon grades of stainless steel have largely supplanted the stabilized alloys for welded fabrication. Because of their ease of production, they are also replacing the standard carbon grades for many applications.

Stress corrosion cracking

The phenomenon of stress corrosion cracking (*Fig. 8*) of austenitic stainless steels in chloride-containing environments is not unique to stainless steels. Many types of alloys are susceptible to similar effects in different media, such as brass alloys

Figure 7. Intergranular attack in a sensitized austenitic alloy produced by exposure to a boiling sulfuric acid-ferrous sulfate solution. Prolonged exposure causes grains to detach from surface. (100x)

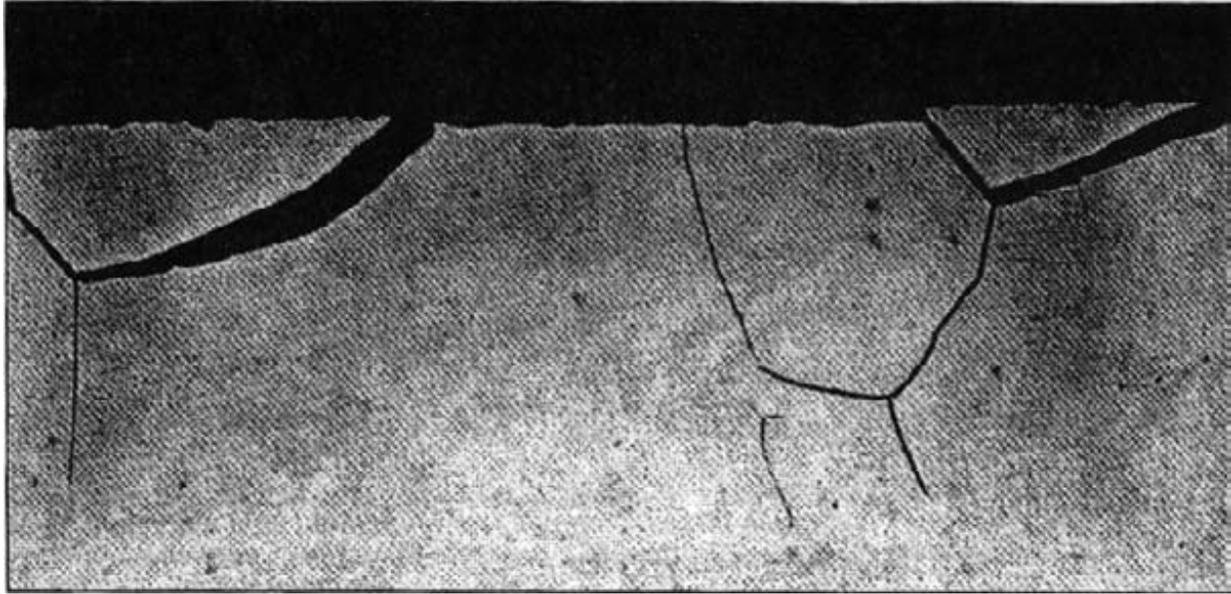


Figure 8. Transgranular chloride stress corrosion cracking of an austenitic stainless steel



in ammoniacal environments and carbon and alloy steels, including stainless steels, in strongly alkaline solutions. Chloride stress corrosion cracking, the most common form of environmentally induced cracking in austenitic stainless steels, requires the presence of chloride ions, tensile stresses, and elevated tempera-

ture. If these are moderate to low, oxygen is also required for stress corrosion cracking to occur. The necessary tensile stresses are almost always residual rather than applied. It is not the load put on a stainless steel vessel that leads to cracking, but how it is formed and welded. In properly annealed material, the

cracking is characteristically transgranular (across the grains). In poorly heat-treated and in weld heat-affected zones where carbides have precipitated at grain boundaries, the cracking is intergranular (at the grain boundaries). Minimum levels of chloride content, temperature, and stress are not known, because these variables are interrelated. The phenomenon is usually controlled by proper alloy selection, although altering the environment and reducing residual stresses can sometimes be effective. In general, ferritic and duplex stainless steels have more resistance to chloride stress corrosion cracking and are often substituted. Austenitic iron-nickel-chromium alloys also have increased resistance at nickel contents above 20%. In fact, some of the 6-7% Mo alloys with 17-23% Cr and 17-26% Ni have good resistance to chloride stress corrosion cracking. However, virtual immunity is probably found in austenitic alloys only when nickel levels are above 35% (4).

Galvanic corrosion

Galvanic corrosion, or dissimilar metal corrosion, is usually not a problem for stainless steels but can affect other metals in contact with them. For galvanic corrosion to take

TABLE 1. Galvanic series of some metals and alloys in sea water.

	Metal or Alloy	Potential vs. SHE ¹
Active (anodic)	Magnesium	-1.49
	Zinc	-0.81
	Cadmium	-0.64
	Aluminum	-0.61
	Steel	-0.38
	S30400 Stainless Steel (active)	-0.36
	Lead	-0.32
	Tin	-0.27
	Admiralty Brass	-0.12
	Hydrogen	0.00
	Copper	+0.02
	Nickel	+0.10
	N04400 (Monel Ni/Cu Alloy)	+0.13
	Titanium	+0.14
	S30400 Stainless Steel (passive)	+0.15
	Silver	+0.16
	Graphite	+0.49
Platinum	+0.50	
Passive (cathodic)	Gold	+0.50

¹SHE: Standard Hydrogen Electrode

place, two or more metals of different electrochemical activity need to be in intimate contact in an electrolyte solution. An abbreviated galvanic series, or electrochemical activity series, of materials in seawater is given in *Table 1* (5). The standard hydrogen electrode is used as a reference against which electrochemical activity of a material is measured: The activity of hydrogen is set at zero and other materials are measured as more

active (-) or more passive (+) with regard to it. In this table, the more negative or active metals (at the top of the table) will corrode preferentially to any less active metal to which they are electrically coupled. If the surface area of the active component is small in relation to that of the other member of the couple, the corrosion rate can be very high. Such would be the case if carbon steel bolts or rivets were used to connect

stainless steel sheet or plate. Sometimes, when the film is disrupted, stainless steel can become the active metal (as shown in *Table 1*) and corrode in an active manner. Also, once pitting and crevice corrosion begin, these forms can be considered galvanic corrosion. In both cases, the result is a small active area (the pits or the crevices) surrounded by a large area of film-protected, inactive stainless steel. Most galvanic corrosion problems can be avoided by proper design or electrical insulation.

DESIGN AND SELECTION OF STAINLESS STEEL EQUIPMENT

By factoring the properties of stainless steel into the design of equipment, a great number of benefits can be realized. Unwanted corrosion can be prevented and product purity ensured. Because stainless steels are easy to clean and maintain, a number of different products can be produced in the same equipment. If properly utilized, equipment made of stainless steel can be expected to last for many years.

In selecting austenitic stainless steels, a number of factors other than corrosion performance should be considered. Among these are their usually attractive appearance, good mechanical properties, and excellent fabrication characteristics. On a life-cycle basis, the alloys are often the most cost-effective. The common alloys are usually readily available. They are a valuable recycling product and because of their lack of reactivity do not contaminate the environment. Recently many of the low carbon grades have been "dual" certified. That is, they are guaranteed to have not only low carbon contents but also the mechanical properties of the higher carbon grade.

Tables 2 and *3* give the nominal chemical composition and minimum mechanical properties of some representative wrought stainless steel alloys. The compositions are for wrought alloys and are taken from *Metals and Alloys in the Unified Numbering System* (1). The mechanical properties are also for wrought alloys and are from the *Steel Products Manual of the Iron and Steel*

TABLE 2. Chemical composition of some common stainless steels.

(Composition in Weight Per Cent - Balance Iron)								
UNS Number	EN Number	AISI Type	ACI Type	C	Cr	Mo	Ni	Structure ³
517400 ¹	1.4542	17-4PH ²	CB-7CU-1	.07max	15.0-17.5	-	3.0-5.0	PH
541000	1.4006	410	CA-15	.15max	11.5-13.5	-	-	Mart
S43000	1.4016	430	-	.12max	16.0-18.0	-	-	Ferr
S30400	1.4301	304	CF-8	.08max	18.0-20.0	-	8.0-10.5	Aus
S30403	1.4306	304L	CF-3	.03max	18.0-20.0	-	8.0-12.0	Aus
S31600	1.4401	316	CF-8M	.08max	16.0-18.0	2.0-3.0	10.0-14.0	Aus
S31603	1.4404	316L	CF-3M	.03max	16.0-18.0	2.0-3.0	10.0-14.0	Aus
S31703	1.4438	317L	CG-3M	.03max	18.0-20.0	3.0-4.0	11.0-15.0	Aus
N08904	1.4539	904L ²	CN-3M	.02max	19.0-23.0	4.0-5.0	23.0-28.0	Aus
S31803 ¹	1.4462	2205 ²	CD3MN	.03max	21.0-23.0	2.5-3.5	4.5-6.5	Dup
S32205	1.4462	2205N ²	CD3MN	.03max	22.0-23.0	3.0-3.5	4.5-6.5	Dup

¹S17400 also contains 3.0-5.0% Copper and .15-.45% Niobium (Columbium).

S31803 also contains .08-.20% Nitrogen.

S32205 also contains .14-.20% Nitrogen.

²These are not AISI Types, but the common names used in North America.

³Structure names are abbreviated. PH is a Precipitation Hardening Martensite, Mart is Martensite, Ferr is Ferrite, Aus is Austenite and Dup is Duplex (Ferrite + Austenite).

Society (2). In general, mechanical properties are not the critical factor in selecting stainless steels, but they are more than adequate for most uses. Almost all of these wrought alloys have cast counterparts, which differ only slightly in chemical composition and in mechanical properties. These are indicated by the ACI numbers. For example, S30400 (304) has a cast version, J92600 (CF-8). The wrought alloy has a composition of 0.08% max C, 18-20% Cr, 2% max Mn, 8-10.5% Ni, 1% max Si. The cast alloy has 0.08% max C, 18-21% Cr, 1.5% max Mn, 8-11 % Ni, 2% max

Si. Except for slightly higher amounts of Cr, Mn and Ni, only silicon is noticeably higher, at 2%. This increased silicon is permitted for higher fluidity and better casting properties in the liquid phase. Similarly, S31600 (316) has a cast version, J92900 (CF-8M), which has similar variations permitted. Castings also are heat-treated to produce a small amount of ferrite in the microstructure, which reduces cracking during welding. The EN-numbered alloys may also differ slightly in chemical composition and mechanical properties but are very similar. Minor alloying elements and im-

purity levels in the various systems can also be different, but not to any significant degree.

COMMON STAINLESS STEEL ALLOYS

The following list of some of the more common stainless steel alloys currently in use is not complete, but it gives examples of the various grades of alloys.

S43000 (430). This common ferritic, iron-chromium stainless steel is used for applications such as tableware and appliance trim where

TABLE 3. Minimum mechanical properties of some common wrought stainless steels alloys are in the annealed condition except where noted.

UNS Number	EN Number	AISI Type	Yield Strength ³ Mpa(ksi)	Tensile Strength Mpa (ksi)	Elongation %
S17400 ¹	1.4542	17-4PH ²	1172 (170)	1310 (190)	10
S41000	1.4006	410	207 (30)	448 (65)	22
S43000	1.4016	430	207 (30)	448 (65)	22
S30400	1.4301	304	207 (30)	517 (75)	40
S30403	1.4306	304L	172 (25)	483 (70)	40
S31600	1.4401	316	207 (30)	517 (75)	40
S31603	1.4404	316L	172 (25)	483 (70)	40
S31703	1.4438	317L	207 (30)	517 (75)	40
N08904	1.4539	904L ²	220 (31)	490 (71)	35
S31803	1.4462	22057	450 (65)	620 (90)	25
S32205	1.4462	2205N2	450 (65)	620 (90)	25

¹Solution annealed at 927°C (1700°F), cooled and hardened at 482°C (900°F) for 1 hour, and air cooled.

²These are not AISI Types, but common names used in North America.

³Stainless steels do not have a true yield strength as do carbon and low alloy steels. This property has been measured at the 0.2% offset strength on the stress/strain curve for stainless steels.

extensive welding and forming are not required and low cost is desired.

S30400 (304). The most widely used of all stainless steels, this is an austenitic iron-chromium-nickel alloy. S30400 finds applications in a broad spectrum of industries including beverage, food, pharmaceutical, petroleum refining, consumer product, electric power, chemical process and architecture. It has good corrosion resistance in a wide range of environments as well as good formability, weldability, and moderate cost.

S30403 (304L). This low-carbon version of S30400 (304) has superior resistance to intergranular corrosion following welding or stress relieving and is suggested for equipment that

is fabricated by welding and cannot be subsequently annealed.

S31600 (316). This most popular austenitic iron-chromium-nickel-molybdenum stainless steel has corrosion resistance superior to that of S30400 (304), particularly where pitting and crevice corrosion may be a problem.

S31603 (316L). This low-carbon version of S31600 (316) has intergranular corrosion resistance similar to that of S30403 (304L). It is suggested where welding is required and improved corrosion resistance is desired.

S31703 (317L). The higher molybdenum, low-carbon version of S31600, with even better resistance to pitting and crevice corrosion is

used for special applications in pulp and paper, food and beverage, and chemical process industries.

S31803 (2205). This example of a duplex, austenitic-ferritic iron-chromium – nickel - molybdenum-nitrogen stainless steel has good resistance to chloride stress corrosion cracking. A more controlled chemistry version, S32205, is commonly available. Both have higher strength than either the austenitic or ferritic grades.

N08904 (904L). This material, a very low-carbon austenitic iron-chromium-nickel-molybdenum-copper stainless steel, has corrosion resistance superior to that of S31703 (317L). The addition of about 1.5% copper improves resistance to cor-

rosion in some acids. N08904 may be available only on special order from selected mills.

OTHER STAINLESS STEEL ALLOYS

As mentioned previously, there are many stainless steel alloys other than the ones discussed in this paper and shown in *Tables 2* and *3*. One of them, S30300 (303), has sulfur added to it to improve machinability. However, corrosion resistance suffers greatly, especially at sites of sulfide or similar inclusions. Other compositions, such as S30900 (309) and S31000 (310) and their variations, contain increased chromium and nickel to improve their strength and corrosion resistance at high temperatures. Cast alloys such as J92600 and J92620 are basically S30400 (304) and S30403 (304L) with up to 2% added silicon to increase fluidity in the liquid phase and improve casting properties.

Another group of stainless steel alloys to which we have previously referred but that are not in *Tables 2* and *3* are those containing 6-7% molybdenum. These so-called "super austenitic stainlesses" also contain about 17-23% Cr and 17-26% Ni, with some variations. There are six or eight alloys in this class, some of which contain nitrogen or other elements. They are mostly proprietary to their manufacturers and it is difficult to choose between them; it does not seem fair to emphasize one over the others. Their main attributes are their resistance to pitting and crevice corrosion. In most cases they are superior to lower-molybdenum alloys in saline solutions at ambient and slightly elevated temperature. As mentioned before, they also have useful resistance, but not immunity, to chloride stress corrosion cracking.

AVAILABLE PRODUCT FORMS

There is considerable variation in the availability of all alloys in all product forms. The more common materials such as S30400, S30403, S31600, and S31603 can usually be

purchased "off-the-shelf" from warehouses and producers in standard shapes and sizes, but less common alloys often require special requests and long delays.

Plate is a flat-rolled product over 254 mm (10 in) in width and over 4.76 mm (0.1875 in) in thickness. It is produced from hot-rolled material and has a relatively rough surface finish compared to cold-rolled, or cold-rolled and polished, sheet or strip.

Sheet is a flat-rolled product 610 mm (24 in) and over in width and under 4.76 mm (0.1875 in) in thickness.

Strip is also a flat-rolled product, but it is under 610 mm (24 in) in width and, like sheet, under 4.76 mm (0.1875 in) in thickness.

Bar or rod are straight lengths that can be round, oval, square, rectangular, or other in cross-section. They are produced by a number of different methods such as hot-rolling, forging, extruding, and/or cold-drawing.

Wire is usually round or oval in cross-section. It is a cold-reduced product that is drawn from small diameter bars or rods.

Tubing of various types are hollow products, round or any other shape in cross-section. They are made from sheet or strip and can be either seamless or welded.

Pipe is often a welded, relatively large diameter, hollow, round product made from strip, sheet or plate, it can also be extruded from billets and be seamless.

Shapes is a catchall term that includes a wide variety of angles, U-sections, and similar forms produced by rolling or extruding.

Fittings, flanges, forgings, etc. are specialty products that are widely available in numerous standard and non-standard sizes.

Castings refer to the cast counterparts of most of the common grades of wrought stainless steel. The composition of these may be slightly altered to ensure good castability and properties, but their corrosion resistance is comparable to the equivalent wrought products. The shapes and applications are almost limitless.

COMMON SURFACE FINISHES ON STAINLESS STEEL

The product forms mentioned above are commercially available in various surface finishes, most of which are described in ASTM Specification A480/A480M - 96a (3). It is generally necessary to specify a particular surface finish when ordering stainless steel products and equipment. The different finishes are described by a system of numbers, letters and, sometimes, words. However, a given finish is often produced by different sequences and methods of operation by different producers. It may be important to know these processing steps, if surface finish or appearance is critical. A few standard finishes in common use are defined below.

No. 1 Finish or *HRAP*. Hot-rolled, annealed and pickled (chemically descaled) is the common finish on stainless steel plate. Other finishes must be specially requested for product over 3/16 in. in thickness. This finish is rougher and may have more defects than the cold-rolled and/or abraded finishes to be described. It is generally used in industrial applications where smoothness is not particularly important.

No. 2B Finish. This bright, cold-rolled finish is produced when annealed and descaled flat products receive a final light cold rolling pass on polished rolls. This general purpose finish can be used as is or for products to be subsequently polished, and is most often seen on sheet and strip products.

No. 4 Finish. This is a general-purpose polished finish primarily used on sheet and strip for a wide variety of industrial and consumer products. To produce it, a 2B finish surface is initially ground with coarser abrasives but is polished last with abrasives of approximately 120 to 150 mesh. It is commonly called a "brushed" finish. It does not show fingerprints or water spots as readily as unabraded finishes.

Electropolished Finish. Surface material is electrochemically dis-

solved, leaving a bright, mirror-like appearance. Some people believe that electropolished items are easier to clean and sanitize and have better corrosion resistance. This finish is widely used for process equipment in the food and beverage industries.

Options other than these four finishes and those in ASTM A480—480M—96a (3) may be requested. Some of them are produced by rolling, some by abrading with different size grit, and some by a combination of the two processes. Mirror-like finishes similar to electropolished ones can be produced by abrading with very fine polishing grit or compounds. Embossed patterns made with special rolls are common.

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