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Characteristics of Food Contact Surface Materials: Stainless Steel

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SUMMARY

This technical review article describes the properties and characteristics of stainless steel in sanitary design when used as a food contact surface, particularly when compliance with the requirements of standards promulgated by 3-A Sanitary Standards, Inc. is intended. It discusses the general characteristics of stainless steels, including ferrite, austenite, cementite, and martensite. It discusses stainless steel categories and grades used in industrial applications and their properties, including both non-magnetic types such as superaustenitic and magnetic types such as ferric and martenistic as well as duplex stainless steel and precipitation hardened stainless steel. Specific emphasis is given to those categories and grades used in food contact applications. The article contains a discussion on the general steps in stainless steel manufacturing, including melting/casting, forming, heat treatment/annealing, descaling, cutting, and finishing, and describes common types of acceptable surface modification and finishing of stainless steel. In addition to the topics listed above, the article describes common types and causes of corrosion of stainless steel, including uniform, pitting, crevice, stress cracking, galvanic, contact, and biologically and microbiologically influenced corrosion. Finally the article discusses methods of preventing corrosion, including surface maintenance and cleaning and a process referred to as "passivation." This article contains micrographs showing, at varying levels of magnification, chemical corrosion and some common surface finishes, including number 4 (150 grit), 2B, and 2D finishes, as well as photographs showing unacceptable product contact surface finishes of welds in stainless steel tubing.

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INTRODUCTION

From a sanitary design perspective, food contact surfaces should be smooth, impervious, free of cracks and crevices, non-porous, non-absorbent, non-contaminating, non-reactive, corrosion resistant, durable, and cleanable *(24).* Further, materials used in food contact surfaces must be non-toxic, and materials containing heavy metals (e.g., lead, cadmium, hexivalent chromium or mercury) or other toxic materials must be avoided. Finally, these surfaces should be fabricated, operated, and maintained in a manner such that these criteria are not compromised. Stainless steel is generally the most preferred and most commonly used material in the design, construction and fabrication of food processing equipment and is specified in the 3-A Sanitary Standards *(1)* as well as in other commonly used food processing equipment standards throughout the world *(20).*

The general advantages of stainless steel over other materials for food contact are as follows:

- corrosion resistance (ranging from fair to outstanding);
- high strength, high hardness, high modulus;
- availability of a wide range of product forms;
- relative ease of machining and fabrication; and
- relatively low cost.

A wide variety of stainless steel materials are available with widely varying composition, surface finish, and functional properties *(2, 4, 5, 6, 7, 8, 23).* In addition, the functionality of stainless steel is impacted by surface treatments and coatings. Thus, an awareness of the properties of the various stainless steels is required by fabricators, as well as by potential users of food equipment.

General characteristics of stainless steel

From a metallurgical perspective, ***steel*** is an iron alloy composed of iron (Fe) and carbon (C), with ferric carbide (Fe_3C) as the base component. However, depending upon formulation/alloying and manufacturing techniques, the iron exists as a solid solution of varied levels of iron and carbon of different crystalline textures (e.g., ferrite, austenite, pearlite, martensite, ledenburite, spheroidite, and cementite) as well as different strengths, hardnesses, and other properties. These properties are dependent upon compositional distribution and chemical combinations of iron and carbon. For example, ***ferrite*** (predominately α- iron and δ- iron) is relatively soft, while ***austenite*** (predominately γ- iron) is much harder, and ***cementite*** (predominately Fe_3C) is extremely hard. ***Martensite*** has intermediate Fe-C levels and mixed chemical species and forms. In general, the crystalline structure of ferrite, austenite, and martesite is usually body-centered cubic, face-centered cubic and needle-like, respectively.

Stainless steel, in general, is an Fe-C alloy with additional alloying elements. These alloying elements may include copper (Cu), chromium (Cr), molybdenum (Mo), manganese (Mn), nickel (Ni), nitrogen (N), phosphorus (P), silicon (Si), sulfur (S), selenium (Se), tungsten (Tn), and titanium (Ti).

Base stainless steels are generally formulated from iron (minimum of 50% by weight), carbon and chromium (minimum 10.5% by weight), and their properties are dependant upon the relative concentrations of these elements. Properties of additional alloying elements will be discussed.

Stainless steel categories and grades, and their properties

More than 150 grades or types of stainless steel exist. The traditional nomenclature to define stainless steel grades is the numbering system of the American Iron and Steel Institute (AISI), a function now under the American Society of Testing and Materials (ASTM) *(2)*. The traditional AISI Stainless Steel Products Manual, currently published by the Iron and Steel Society *(14)*, provides a listing of stainless steel grades, composition, and properties. While AISI grading system has traditionally used a three-digit numbering system, newer grades allocate 1-letter + 5 digit UNS numbers. While the AISI grade designations define the individual grades, they are not specifications as such. Specifications used for stainless steel are from the ASTM. In addition, international specifications are used to identify and distinguish specialized stainless steel products (e.g., welding wire).

The two general categories of stainless steel are ***non-magnetic*** and ***magnetic*** stainless steel. Through working, blending and manufacturing techniques, additional categories of stainless steel (e.g., ***duplex***, ***precipitation hardened***) are also available for specific applications. While there is considerable variation with regard to properties within each of the stainless steel categories, their general properties are summarized in Table 1.

The general classes of stainless steel alloys can be further subdivided according to composition, common AISI grade, crystal structure, specific properties, and applications. A comparison of properties, characteristics, and applications of selected stainless steel grades is presented in Table 2, and the chemical alloy composition of selected stainless steel grades is presented in Table 3.

The most common stainless steels used in food processing and handling equipment are made from Fe-C-Cr alloys and Fe-C-Cr-Ni alloys, with other alloying elements used to varying degrees. Cr, upon exposure to air, gives stainless steel its characteristic high resistance to "stain" (or corrosion) by forming a thin "passive" layer of chromium (III) oxide (Cr_2O_3), iron oxide, and other oxides. The passive layer protects the "active" material (iron), which is susceptible to rust and corrosion. Nickel (when present) provides additional corrosion resistance as well as greater strength and structural hardness to stainless steel. However, as will be discussed, Ni-based stainless steels are more susceptible to one type of corrosion, termed Stress Corrosion Cracking (SCC), than are those without Ni.

In general, alloys formulated at higher carbon levels are of greater structural hardness and strength than those formulated at lower carbon levels. Additional carbon also provides resistance to oxidation and creep. However, the risk of corrosion may be increased with high-carbon stainless steel materials.

In higher grade stainless steels, Mo and/or N (and to a lesser extent Cu) are added to enhance the passivation layer through forming oxides of these elements, thus providing additional corrosion resistance. Mo (which forms molybdenum oxide in the passivation layer) is especially effective at preventing the type of corrosion termed "pitting corrosion."

Enhanced machinability is attained through the addition of P, S, and/or Se. Stainless steels of excellent strength, strength, durability, heat resistance, and corrosion resistance (especially in acid environment) may be attained with the addition of Ti. Because of the relatively high economic cost, Ti-based stainless steels are primarily used in situations where high acid and/or salt levels (e.g., citrus juice, tomato products) may be encountered.

TABLE 1. General properties and stainless steel categories *(2, 23)*

...-gnetic (...stenitic) ...gnetic	No	Very High	High	Cold or work hardened only	Very High	Very High	Very High	Very High
Ferritic	Yes	Medium	Very High	No	Medium	High	Low	Low
Marten-sitic	Yes	Medium	Medium	Yes – quench & temper	Low	Low	Low	Low
...plex	Yes	Medium	Very High	No	Medium	Low	Medium	High
...ipitation ...rdened	Yes	Medium	Medium	Hardened by low heating (aging)	Medium	Low	Low	High

...ion between grades and formulations within each group

...operty of metal which permits it to show considerable elongation with increase in local stresses

Non-magnetic stainless steel

The non-magnetic stainless steels, primarily ***austenitic*** alloys, are generally Fe-C alloys with Cr (ranging to 26%) and Ni (usually less than 35%). As shown in Table 3, other alloying elements may be used, depending upon the grade.

Most of the stainless steel used in the fabrication of food equipment is of the austenitic AISI 300 series. Approximately 50% of all stainless steel produced is 304 stainless steel, formulated at 18% Cr and 8% Ni. As shown in Table 3, type 316, austenitic stainless steel has higher Ni (10%) and Mo levels and is generally considered a higher grade material for food contact surfaces than 304 stainless steel because of its enhanced corrosion resistance. The 3-A Sanitary Standards *(1)* require that food product contact surfaces be of stainless steel that conforms to the applicable composition ranges established by ASTM A 959 or AIST Stainless Steels: Steel Products Manual for 304/304L and 316/316L or corresponding Alloy Cast Institute types or metal that, under conditions of intended use, is at least as corrosion resistant as 304 stainless steel. The 3-A Sanitary Standards *(1)* restrict the use of 303 stainless steel, and expressly prohibit alloys containing lead, leachable copper or other toxic materials. Lower grade austenitic stainless steel alloys (e.g., AISI 100 and 200 Series) are generally not recommended for use in food equipment.

Higher grade alloys, termed ***super-austenitic*** (e.g., AL-6XN, 254SMO), contain higher levels of all alloying elements (especially molybdenum). These alloys have excellent corrosion resistance and strength for use in harsh environments such as marine applications.

Variations with regard to composition and properties are also seen within the stainless steel grades, depending upon the composition. For example, alloys may be formulated at low carbon levels (e.g., 304L, 316L) to enhance weldability. These alloys, however, would have lower strength than the base grade (e.g., 304, 316). Conversely, higher carbon levels may be used for enhanced strength alloys (e.g., 304H, 316H). Thus, modified stainless steel of lower AISI grade may, through compositional modification, exhibit properties similar to those of a higher grade designation.

Magnetic stainless steel

These alloys are less commonly used in food equipment applications than are non-magnetic alloys. However, they may be used for highly specialized applications. They are formulated from Fe-C-Cr alloys, generally without Ni. The two basic categories of magnetic stainless steel are ***ferritic*** and ***martensitic***.

Ferritic stainless steels are Fe-C-Cr alloys formulated at higher Cr and/or lower C than the martensitic alloys. They possess less strength, but higher ductility, than either austenitic or marstensitic alloys; however, they have superior weldability, because of high heat resistance. These stainless steels are primarily used for decorative purposes (e.g., appliances, automobile and architectural trim) and are not commonly used in the manufacture of food equipment. However, as will be described, certain grades of ferritic stainless steel are used in the brewing industry, because of their resistance to Stress Corrosion Cracking (SCC).

Martensitic stainless steels are Fe-C-Cr alloys often used for their high hardenability. In addition to varying amounts of the base alloying elements, sulfur and/or selenium may be added to enhance machinability of certain grades. Martensitic stainless steel grades have a variety of industrial applications (e.g., ball bearings, races, dies, screws, bolts) as well as medical/dental applications (e.g., surgical instruments, dental instruments). Higher carbon martensitic alloys are used for high-grade cutlery and razor blades because of their strength, polishability, and sharpenability. Martensitic stainless steels may also be used in a variety of food contact applications (e.g., utensils, scoops, blades, bushings, bearings, buckets).

Duplex stainless steel

Excellent corrosion resistance and high strength can be attained by the use of ***duplex stainless steel*** alloys, which

TABLE 2. General sub-classes, characteristics, and usage applications of stainless steel alloys *(2, 4, 5)*

General Classification	Common AISI Grades	Characteristics	Applications
A. Non-magnetic Stainless Steel			
1. Austenitic chromium-nickel-manganese	100 Series Type 101, 102 200 Series Type 201, 201	Low strength, durability, and corrosion resistance	General purpose; Furniture; not recommended for food equipment
2. Austenitic chromium-nickel	300 Series Type 301, 302, 303	Relatively higher carbon imparts hardness and machinability; low corrosion resistance	Formed products; low corrosion resistance limits food equipment usage; 303 sometimes used in low corrosion applications
	Type 304	More corrosion resistance, less strength than 303	Most commonly used in food equipment applications
	Type 308, 309	Higher temperature resistance than 304;	Used as a filler metal
	Type 316	More corrosion resistance than 304, enhanced by inclusion of molybdenum	Second most commonly used in food equipment
	Type 321	Higher weldability than 304	Welding applications
3. Superaustenitic Enhanced levels of all alloying elements, especially molybdenum (> 6%)	AL-6XN, 254SMO	High strength, hardness, abrasion resistance, resistance to	Specialized applications; marine environments pitting and other corrosion
B. Magnetic Stainless Steel			
1. Ferritic – chromium and iron alloys	405, 409, 429, 430, 439, 446	High heat resistance, good formability and machinability, poor corrosion resistance	Decorative appliances, automobile and architectural and appliance trim
2. Marstensitic – chromium, iron, carbon alloys	410, 416, 420, 431, 440	High strength, wear resistant;	Dental and surgical instruments; blades polishable bushings, buckets, ball bearings, molds and dies, utensils, cutlery

TABLE 2. General sub-classes, characteristics, and usage applications of stainless steel alloys *(2, 4, 5) (Continued)*

General Classification	Common AISI Grades	Characteristics	Applications
D. Precipitation Hardening – primarily marstensitic (some austenitic)	600 Series	Excellent hardness and by low heat aging process	Specialty applications strength; formed

TABLE 3. General composition of selected grades of stainless steels *(23)*

		Approximate content (% of weight)					
General Category	AISI grade	Carbon (C)[1]	Manganese (Mn)[1]	Chromium (Cr)	Nickel (Ni)	Molybdenum (Mo)	Titanium (Ti)
Austenitic Stainless Steels							
	304	0.08	2.00	17.5 – 20.0	8 – 10.5	--	
	316	0.08	2.00	16.0 – 18.0	10.0 – 14.0	2.0 – 3.0	
	321	0.08	2.00	17.0 – 19.0	9.0 – 12.0	--	5.0
	254SMO	0.02	1.00	18.5 – 20.5	17.5 – 18.5	6.0 – 6.5	1.9
	AL-6XN	0.03	1.00	20.0 – 22.0	23.5 – 25.5	6.0 – 7.0	
Ferritic Stainless Steels							
	405	0.08	1.0	11.5 – 14.5	--	--	--
	430	0.12	1.0	16.0 – 18.0	--	--	--
	446	0.20	1.5	23.0 – 27.0	--	--	--
Martensitic Stainless Steels							
	410	.15	1.0	11.5 – 13.0	--	--	--
	416	.15	1.25	12.0 – 14.0	--	0.6	--
	431	.10	1.0	15.0 – 17.0	--	1.25 – 2.0	--

possess a mixture of ferritic and austenitic crystal structures. In addition to the iron-carbon base, the primary alloying elements are chromium and low levels of nickel. Typically, duplex stainless steel exhibits considerably higher strength than austenitic stainless steel, with corrosion resistance similar to higher grade austenitic alloys, and they possess better corrosion and cracking resistance. Because of a nickel level typically less than half of that found in austenitic stainless steel, they also have a potential price advantage. Higher grades of duplex stainless steel (e.g., ***superduplex***) have high chromium and molybdenum levels. Although type 2205 is the most widely used duplex stainless steel grade, other grades are available (e.g., 326, 329, A219, 2RE60, IC378, IC381). Potential food industry applications for duplex stainless steel are in situations where the corrosion potential is high, such as brewing and fermentation (e.g., brine tanks, brewing tanks, pipelines) or for hot chemical storage and/or transport.

Precipitation hardened stainless steel

This general class of stainless steel refers to materials formed by hardening of stainless steel materials, usually by a low temperature aging heat treatment to develop high tensile strength. Only certain types of stain-

TABLE 4. Stainless steel finishes *(2, 8, 23)*

Stainless Steel Finish Category	Description
Mill Finishes	
No. 0	Hot rolled, annealed, thicker plates
No. 1	Hot rolled, annealed, passivated
No. 2D	Cold rolled, annealed, pickled, passivated
No. 2B	Same as 2D with additional roller polishing
No. 2BA	Bright annealed 2B
Polished Finishes	
No. 3	Coarse abrasive finish
No. 4	Brushed finish
No. 5	Satan finish
No. 6	Matte finish
No. 7	Reflective finish
No. 8	Mirror finish
No. 9	Bead blast finish
No. 10	Heat-colored finish (widely varied)

less steel are hardenable by heating methods, the most common of which are precipitation hardened martensitic (e.g., AISI 601 – 630) stainless steel. Ferritic stainless steel alloys generally cannot be hardened by the precipitation hardening method. Although austenitic stainless steels are generally not readily hardenable by heating, certain precipitation hardened austenitic grades (e.g., AISI 650 – 653, 660 – 665) are available.

Although not hardenable by heating, 300 Series austenitic stainless steel can be hardened by a process known as "work hardening," or "cold working" the material. This is accomplished mechanically by cold rolling down to lighter gauges or by drawing through a die or similar device.

STAINLESS STEEL MANUFACTURING

General manufacturing steps

The gauge and properties, as well as the applicability and uses of stainless steel, are greatly impacted by the manufacturing steps. In addition, strict quality control must be practical to prevent surface etching or the presence of debris (e.g., tramp steel) on the surface which could limit the corrosion resistance quality of the material. The general steps in the manufacture of stainless steel *(29)* are the following:

Melting/Casting. Raw materials are melted together during prolonged heating at intense temperatures in an electric furnace. The molten steel is cast into various forms (e.g., blooms, billets, slabs, tubes).

Forming. This step is generally done by a rolling process, with hot rolling being the most common method. During forming, cast materials are formed into various shapes (e.g., wire, bar, sheets).

Heat Treatment/Annealing. Stainless steel is heated (or annealed) to relieve internal stresses and soften the material. The specific conditions used in this annealing step will vary with the general type of material (e.g., austenitic, ferritic, martensitic).

Descaling. The annealing step causes a surface build-up, or scale, that must be removed. The most common descaling method is ***pickling***, in which a nitric-hydrofluoric acid bath is used to remove the scale. Electro-cleaning, a process by which scale is removed electrochemically, may also be used.

Cutting. In this step, the material is cut into desired blank, shape, size or gauge. Cutting is usually done mechanically by use of a variety of shearing methods with specially designed knives. Flame cutting (using a flame-fired torch) or plasma jet cutting (using ionized gas with an electric arc) may also be used.

Finishing and surface modification

The final surface finish of stainless steel is critical to its properties and applications *(11)*. Thus, finishing is an important step in stainless steel manufacture. Generally, a dull finish is attained through hot rolling, annealing, and descaling (especially if pickling is used). Any surface debris which may have formed during manufacture must also be removed.

FIGURE 1. 2B Mill finish (magnifications shown at 6.3, 12, 25, and 63 X)

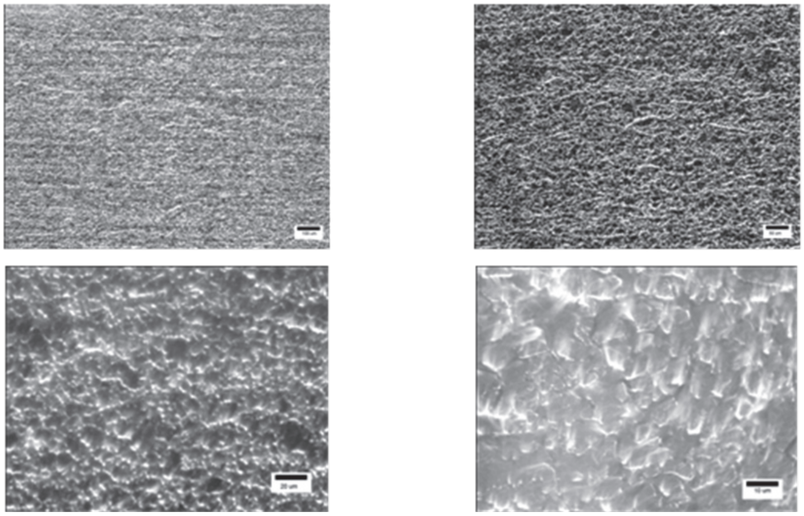
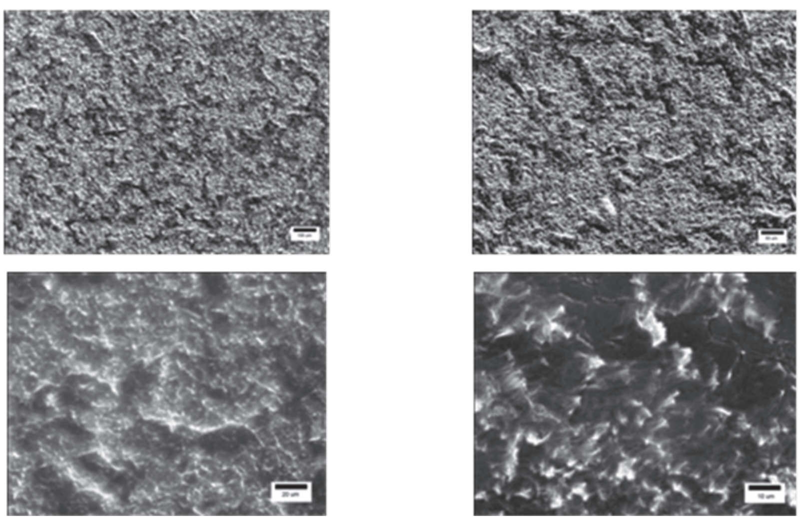


FIGURE 2. 2D Mill finish (magnifications shown at 6.3, 12, 25 and 63 X)



A wide variety of stainless steel surface finishes are available, depending upon the desired applications. The costs of achieving different surface finishes are varied. In general, smoother or more polished surfaces are more expensive than rougher surfaces. Stainless steel finishes are given a number depending upon their characteristics and properties, with higher numbers indicating higher smoothness *(9, 26)*. The general stainless steel finishes are described in Table 4.

A variety of methods of surface modification are used to achieve a desired surface finish *(9, 26)*. In general, hot rolled base stainless steels are not used in food contact applications. The hot rolled annealed (e.g., HRA or No. 0) finish, since it is neither pickled nor passivated (to be described later), does not develop the passive corrosion-resistant layer and has a scaly black finish. No. 1 Finish stainless steel has a rough, dull surface and is also not recommended for food contact surfaces, although it is used in industrial applications.

Mill finishes are attained by direct application of rollers and mechanical abrasives to flat rolled (wrought) stainless steel sheets and are the basic finishes for all flat stainless steel. Differing finishes are attained with hot or cold rolling. For example, cold rolling on polishing rollers is used to obtain a **bright finish**. A No. 2 finish is attained by a cold rolling process. The most common in this series is the 2B finish (shown under magnification in Fig. 1), which is smoother and brighter than the 2D finish (Fig. 2). Bright Annealed (e.g., 2BA) is mechanically polished (or brushed). Because of its superior release properties for higher fat products (e.g., cheese, butter, meats), the 2B mill finish has been traditionally accepted under specific 3-A Sanitary Standards *(1)* and U.S. Department of Agriculture (USDA) guidelines *(28)* for such applications. Certain cold rolled stainless steels of the No. 2 series are used in architectural applications.

Polished finishes are attained by use of a variety of techniques to "polish" stainless steel. Grinding with abrasives and/or buffing withcloth wheels may be used to achieve a **reflective finish**. Further polishing with progressively finer abrasives, extensive buffing with cloth rollers, or electropolishing will result in a **mirror finish**. Additional finishing methods (e.g., tumbling, dry etching/sandblasting, wet etching by use of acid solutions, wire brushing) are used to achieve specific finishes. In some cases, a process termed "bead blasting" is used in which the surface is bombarded with glass beads. While this is an efficient process, it not usually recommended for food contact surfaces because the glass beads tend to degrade into irregular shapes during this process, leaving an irregular surface finish. The lower smoothness polished finish (No. 3) is a ground (80 – 100 grit abrasive) finish, and is not used extensively for food contact surfaces. The No. 4 ground finish (80 – 150 grit), the most commonly used general purpose stainless steel for food contact surfaces, is shown under magnification in Fig. 3. Buffed finishes (No. 5, 6, 7, 8) are generally more expensive and thus not used extensively in the food industry. The 3-A Sanitary Standards *(1)*, as well as USDA guidelines specify that all surfaces, including fabricated, welded and soldered joints, shall be at least as smooth as a No. 4 (150 grit) finish and shall be free of pits, folds, crevices, cracks, and misalignments in the final fabricated form. Examples of welded surfaces that are not considered as smooth as a No. 4 finish are shown in Fig. 4.

The Average Roughness (R_a), measured by the profile method and

FIGURE 3. Number 4 (150 grit) finish (magnifications shown are 6.3, 12, 25 and 63 X)

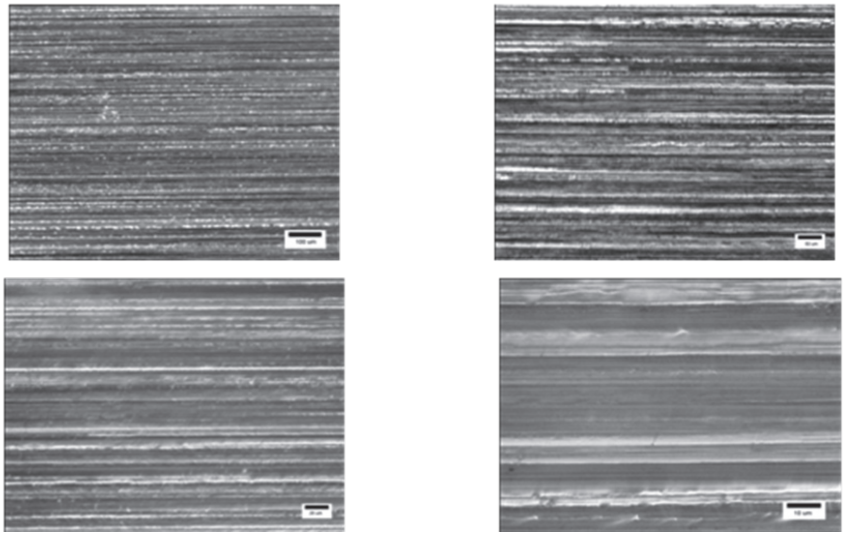
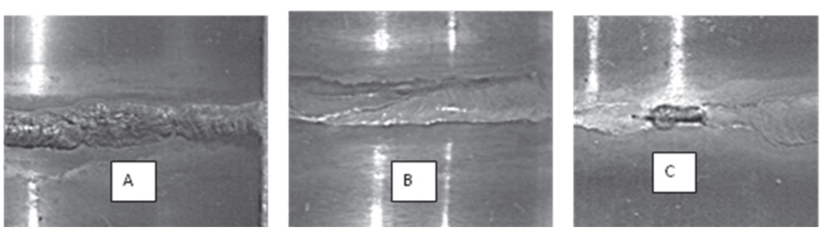


FIGURE 4. Examples of surface texture or finish on the interior surface of welds in metal tubing that are not as smooth as a No. 4 (150 grit) finish. These flaws are the result of improper welding techniques: (A) Inadequate inert gas purge during welding; (B) Over pressure of inert gas during welding; (C) Uneven distribution of heat during welding



expressed in µm, is the roughness parameter most widely used and is accepted by various international bodies, including the International Organization for Standards (ISO standards) and the European Hygienic Engineering Design Group (EHEDG) *(13, 15, 16, 20, 21)*. An R_a of less than 0.8 µm is specified for food contact surfaces by the EHEDG and by the American Meat Institute (AMI) Equipment Design Task Force *(10)* recommendations. Under 3-A Sanitary Standards(1) criteria, an R_a of less than 32 µin. (0.8 µm) is specified and is considered equivalent to a No. 4 finish.

Surface roughness has been generally related to cleanability of stainless steel surfaces *(25)*, with smoother surfaces often considered more cleanable. However, the relationships between surface roughness and cleanability, as well as the relationship between surface roughness and biofilm formation, are not clearly established and need further research *(20, 21, 24),* and many other factors may be important. According to the study by Steiner et. al. *(24),* a 2B mill finish on stainless steel sheets may, in performance, be as cleanable as a No. 4 (150 grit) finish. Under the 3A Sanitary Standards *(1)*, a 2B finish may be now be accepted for certain surfaces, provided that the stainless steel sheets have been inspected and selected to be free of pits, folds, cracks, inclusions, and similar defects. It should be noted, however, that, because mean R_a is not sensitive to individual extreme surface flaws, it is not accepted by 3A as an assurance of the acceptability of a 2B finish on stainless steel sheets that have not been inspected and found free of these serious flaws.

CORROSION OF STAINLESS STEEL

Types of corrosion and their causes

Being composed of an iron-based alloy, nearly all common grades of stainless steel are prone to corrosion by removal of the passive film through continued exposure to incompatible cleaners, abrasive cleaners, abrasive cleaning pads, or chlorine and oxidizing sanitizers. In general, stainless steel does not "rust," a process in which the characteristic flaking red oxide forms on regular steel. If red discoloration occurs, it is due to contamination by iron particles on the surface (or imbedded in the surface) of stainless steel that have rusted. The 3-A Sanitary Standards *(1)* require that any stainless steel or other metal material used be at least as corrosion resistant as 304 stainless steel under the conditions of intended use of the stainless steel, metal, or alloy to be used. Corrosion of stainless steel is shown in Fig. 5.

The general types of stainless steel corrosion *(11, 27)* are as follows:

- **Uniform Corrosion**. This type of corrosion is usually associated with continued exposure to dilute acid or alkaline solutions, or by acute exposure to more concentrated acid or hot alkali. General resistance to this type of corrosion is better in stainless steels formulated with higher levels of Cr. Sulfur addition, which enhances machinability, reduces the resistance to uniform corrosion.
- **Pitting Corrosion**. This type of corrosion results from more localized destruction of the passive layer and subsequent corrosion of the steel alloy below. Pitting corrosion generally is the result of exposure to chlorides, bromides, and other halides and is accelerated by high temperature and lower pH level. Once formed, pitting corrosion has a tendency to continue to grow and is difficult to remove. Stainless steel grades formulated at high Cr

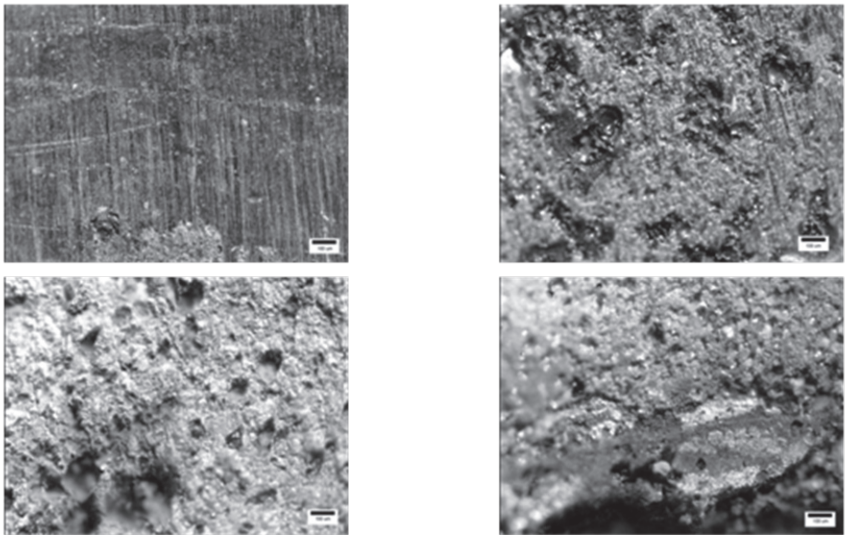


FIGURE 5. Examples of chemical corrosion and the resulting pitting of polished stainless steel surfaces (two upper photos) and on interior surfaces of unpolished tubing (lower left) and unpolished metal tubing at a welded joint (lower right). Magnification shown at 6.3 X)

and Mo and/or N have higher resistance to pitting corrosion. The Pitting Resistance Equivalent (PRE) number, used as an indicator of pitting resistance of stainless steel, is calculated as: PRE = %Cr + 3.3 × %Mo + 16 x %N

- **Crevice Corrosion**. There is a potential for this type of corrosion when crevices are formed during equipment fabrication, or as a result of improper equipment design. Crevice corrosion may occur in any crevice formed during fabrication and/or installation (e.g., under gaskets, incomplete welds, overlapping surfaces). Crevice corrosion is accelerated in equipment use situations which allow the loss of the passive layer through prolonged or stagnant contact with reducing materials (reducing acids).
- **Stress Corrosion Cracking (SCC)**. Stressing stainless steel, either during manufacture or during rigorous usage, can result in localized pinholes or other stress areas, which then become vulnerable to stress corrosion cracking (SCC). For example, continued exposure to high-temperature solutions containing chlorides can lead to stressed areas in stainless steel and SCC. In general, the austenitic stainless steels are most vulnerable to SCC. SCC is related to the Ni content; thus low-Ni stainless steels (e.g., ferritic) are virtually immune. Since SCC is a common problem in the brewing industry, ferritic stainless steel grades are often used in this industry *(17, 22).* Further, since SCC is related to the Ni content, 316 stainless steel offers no advantage over 304 stainless steels with regard to this type of corrosion. However, duplex (e.g., 2205) and superduplex stainless steels offer excellent resistance to SCC. Resistance to SCC can be achieved by certain annealing processes and by using techniques that apply a compressive stress to the surface (e.g., shot peening).
- **Galvanic Corrosion**. Certain solutions can generate this type of corrosion because of the flow of electric current, especially where two dissimilar metals are in contact. Prevention of galvanic corrosion can be achieved by avoiding mixed metal fabrications.
- **Contact Corrosion**. This type of corrosion occurs when small particles of foreign matter (especially carbon) are left on a stainless steel surface. Contact corrosion combines the elements of galvanic and pitting corrosion, in that it starts as a galvanic cell, and, if a pit occurs, will be followed by pitting corrosion. Contact corrosion is usually the result of poor fabrication techniques that allow carbon debris to remain on the final surface. In manufacture, removal of carbon debris is accomplished in the pickling and/or passivation steps. Contact corrosion is best avoided in the cutting, machining, grinding and polishing steps by use of dedicated tools specific to the steel being worked. Good manufacturing practices and specific standard operating procedures (SOPs) should be established and implemented in fabrication shops and in plant equipment installations to prevent cross-contamination of stainless steel materials with mild steels or other dissimilar metals. Most importantly, the same grinders, sanding or polishing tool used for stainless steel should not be used for mild steel.
- **Biological and Microbiologically Influenced Corrosion (MIC)**. In food processing and handling facilities, inadequate cleaning of food equipment may accelerate corrosion of the food contact surface because of residual biological materials (e.g., food soil, other materials) on the surface as a seeding point where corrosion can occur. Microbial biofilms, especially those formed by highly oxidizing bacteria, will also attack the surface of the stainless steel, accelerating pitting corrosion reactions.
- **More Severe Corrosion**. Other types of corrosion may be present in industrial applications where severely corrosive solutions or very high temperatures are used. For example, ***Suphide Stress Corrosion Cracking (SSSC)***, a type of corrosion

caused by hydrogen sulphide exposure, may occur on equipment used in the oil, gas, and related industries. In industrial use involving extremely high temperatures (425–850°C) for a period of time, microstructural breakdown (e.g., carbide precipitation) may cause a defect termed ***Intergranular Corrosion***.

Prevention of corrosion

Selection of a type of stainless steel that is appropriate to the conditions of intended use is critical to preventing and minimizing corrosion of stainless steel surfaces, particularly in high acid, high salt (brine), or high temperature environments. Consideration also needs to be given to the type of cleaning chemicals and cleaning temperatures to which the equipment surfaces will be exposed (see Tables 1 and 2).

Surface maintenance and cleaning/sanitizing. To prevent the problems of corrosion, it is imperative that an adequate preventative maintenance program is implemented for all food equipment. This program should include routine inspection of food contact surfaces for signs of corrosion and assurance that conditions that may induce corrosion (e.g., inadequate draining of solutions) are being avoided. In addition, an adequate cleaning and sanitizing program must be in place, which includes an appropriate frequency as well as validation. Adequate cleaning and sanitizing removes biological materials that can attack the surface with time and serve as a seed point for corrosion. Adequate cleaning also removes mild corrosion. However, strong cleaning and sanitizing chemicals, if used at improperly high concentrations or on surfaces that are not well maintained, could increase the potential for corrosion. Extended contact with lower concentrations of chlorine sanitizers and similar chemicals can also increase the likelihood of corrosion of stainless steel surfaces.

Passivation. The process known as passivation *(18, 19)* is done to maintain the passive (non-reactive) oxide film, to enhance the Cr content on the surface, and to protect the active (reactive) surface from corrosion. In general, this is accomplished by exposing the surface to a solution of nitric acid (or other strong oxidizing acid) at an appropriate concentration and time period. It is recommended that stainless steel surfaces be passivated initially, at a defined frequency thereafter, and after any surface repair, polishing, or other modification. In addition, passivation of stainless steel food contact surfaces is recommended after any surface repair, polishing, or working.

Certain precautions must be followed with regard to passivating stainless steel. It is imperative that the surface to be passivated be clean, as passivation will **not** remove surface contaminants that result from fabrication or other residues from food processing operations. Such surface contaminants will also impede the effectiveness of the passivation process. In the fabrication of stainless steel, diligent care must be used to assure that the surface is free of embedded iron particles (caused by ferrous grinding methods), high carbon "tramp" steel, machine lubricants and other oils, crayon, paint, other markings, and/or shop dirt. If not adequately removed, these contaminants could lead to pitting, rusting and crevice or crack formation. Additional fabrication defects that may enhance corrosion include heat tint from welding, weld flux, arc strikes and spatter. It is imperative that new equipment delivered from the manufacturer be inspected and cleaned appropriately prior to passivation, as the surfaces may have an oily film or other surface residues.

Prior to passivation of a stainless steel surface, it is recommended that an expert be contacted for assistance. Detailed procedures for cleaning/passivation using nitric acid and other acids are provided under ASTM A380 *(3)*. In general, a complete passivation process may involve the following steps: cleaning, degreasing, inspection, passivation (immersion or spraying) following recommendations, and neutralization /rinsing. Extreme care, with regard to worker safety as well as environmental discharge, must be exercised when using strong passivating/oxidizing chemicals. In addition, these chemicals, if not neutralized appropriately, will corrode non stainless steel surfaces (e.g., non-product contact surfaces, sewer drains and piping) and will etch or damage concrete or tile floors. Any leak or spill must be immediately diluted with water or neutralized with a basic solution.

Removal of corrosion

Once formed, corrosion on stainless steel can be difficult to remove. Mild corrosion can be removed by rigorous cleaning or, in some cases, the re-working of surfaces. More severe corrosion usually requires more rigorous treatment, such as a passivation treatment. However, severe pitting corrosion may not be removable by passivation, and may therefore require more rigorous treatment (e.g., pickling paste) for removal.

SUMMARY AND CONCLUSIONS

It is clear from the foregoing discussion that not all stainless steels are created equal. Fabricators/manufacturers of food processing equipment must consider food types, cleaning/sanitizing/sterilization processes, and all environments of intended use when selecting stainless steel material types. Food processors must be aware of the general properties and of the diversity of stainless steels. If the wrong type of stainless steel is selected for severe use applications, it will surely fail and cause processed food products to be unacceptable for market or human consumption.

As part of food safety audits by regulatory officials and/or third party entities, food processors/manufacturers are increasingly asked to obtain and provide assurances from equipment suppliers that the equipment has met appropriate standards, where applicable, and to ensure that food contact materials are non-toxic. Alloys containing the heavy metals lead, cadmium, hexivalent chromium or mercury, must be avoided when choosing food contact materials.

If appropriate standards are not available for "one-of-a-kind" processes or non-standardized equipment, it is recommended that experts be consulted prior to designing, manufacturing or buying equipment for assurances that the equipment is cleanable, durable and safe under the conditions of intended use. Finally, strict attention should be paid to maintenance of food processing equipment, as well as to validating cleaning, sanitizing or sterilization operations, prior to placing any food processing equipment into service.

REFERENCES

1. 3-A Sanitary Standards, Inc. Available at: www.3-a.org. Accessed 10 January 2012.
2. Anonymous. 2005. Stainless steel – Introduction to the grades and families. AZo materials – The A to Z of Materials. *AZo J. Materials Online*. Available at: http://www.azom.com/articleaspx?ArticleID=2873. Accessed 10 January 2012.
3. Anonymous. 2007. Passivation of stainless steel: Summary of guidelines recommended by 3-A Sanitary Standards and the European Hygienic Engineering Design Group (EHEDG). *Trends in Food Sci. Technol*. 18, (1, EHEDG Yearbook 2007): S112–S115.
4. Anonymous. 2011a. Austenitic stainless steels. Available at: http://www.gowelding.com/met/austenitic.html. Accessed 22 October 2011.
5. Anonymous. 2011b. Frequently asked questions. The Stainless Steel Information Center. Available at http://www.ssina.com/faq/index.html. Accessed 22 October 2011.
6. Anonymous. 2011c. How products are made–stainless steel. Available at: http://www.enotes.com/how-products-encyclopedia/stainless—steel/html. Accessed 22October 2011.
7. Anonymous. 2011d. Stainless steel. Answers.com. Available at: http://www.answers.com/topic/stainless-steel. Accessed 22 October 2011.
8. Anonymous. 2011e. Stainless steels. Available at: http://www.materialsengineer.com/E-Stainless-Steel.htm. Accessed 22 October 2011.
9. ASTM. 1997. Standard specifications for general requirements for flat-rolled stainless steel and heat resisting steel plate, sheet, and strip. American Society for Testing and Materials, West Conshohocken, PA.
10. Bilgili, S. F. 2006. Sanitary/hygienic processing equipment design. *Worlds Poultry Sci. J.* 62(1):115–122.
11. Cowan, C. T. 1977. Corrosion of stainless steel: How to prevent it. *Food Eng. Int.* 2(9) 34–37.
12. Daufin, G., L. Kerherve, and J. Richard. 1977. The effect of surface finish on stainless steel on its cleaning and resistance to pitting corrosion. *Industries Aliment. et Agricoles* 95(1): 43–51.
13. Eastwood, C. A., D. L. Woodall, D. A. Timperley, G. J. Curiel, P. Peschel, and G. Hauser. 1993. Welding stainless steel to meet hygienic requirements. Document 9. European Hygienic Engineering Design Group (EHEDG). Available at: http://www.ehedg.org/. Accessed 10 January 2012.
14. Iron and Steel Society. 2011. Stainless steel products manual. Available at: http://www.techstreet.com/info/iss.html. Accessed 22 October 2011.
15. ISO. 1984. Surface roughness – terminology — Part 1; Surface and its parameters. ISO 4287-1, International Organization for Standards, Geneva, Switzerland. Available at: http://www.iso.org/iso/home.html. Accessed 10 January 2012.
16. ISO. 1984. Surface roughness — terminology — Part 2; Surface and its parameters. ISO 4287-2, *International Organization for Standards*, Geneva, Switzerland. Available at: http://www.iso.org/iso/home.html. Accessed 10 January 2012.
17. Klang, L., and G. Gemmel. 1984. How to combat stress corrosion cracking. *Brewing & Distilling Int*. 14, (5): 30–32, 34, 43.
18. Maller, R. R. 1998a. Passivation of stainless steel. *Dairy Food Environ. San*. 18(5): 294–298.
19. Maller, R. R. 1998b. Passivation of stainless steel. *Trends Food Sci. Technol.* 9(1): 28–32.
20. Milledge, J. J., and R. Jowitt. 1980. The cleanability of stainless steel as a food contact surface. *Inst. Food Sci. Technol*. 13:57–62.
21. Milledge, J. J. 2011. Cleanability of stainless steel used as a food contact surface. Available at: http://johnmilledge.yolasite.com/. Accessed 22 October 2011.
22. Redmond, J. D. 1984. Solving brewery stress corrosion cracking problems. *Technical Quarterly, Master Brewers' Assoc. of the Americas*. 21 (1):1–7.
23. Sourmail, T., and H. K. D. H. Bhadeshia. 2005. Stainless steels. University of Cambridge. Available at: http://www.searchsteel.com/2009/10/thong-tin-them-ve-thep-khong-gi.html. Accessed 22 October 2011.
24. Schmidt, R. H., and Erickson, D. J. 2005. Sanitary design and construction of food equipment. Univ. of Florida Coop. Ext. Serv. FSHN 0409/FS119, Available at: http://edis.ifas.ufl.edu/FS119. Accessed 10 January 2012.
25. Steiner, A. E., M. M. Maragos, and R. L. Bradley. 2000. Cleanability of stainless steel surfaces with various finishes. *Dairy Food Environ. San.* 20(4):250–266.
26. Timperley, D. A., and G. G. Lawson. 1979. Test rigs for the evaluation of hygiene in plant design. *In* R. Jowitt, (ed.). Hygienic design and operation of food plants, Horwood Ltd.
27. Tuthill, A., and R. Avery. 1992. Specifying stainless steel surface treatments. *Adv. Mater. Procs*. 160 (12):34–38.
28. Tuthill, A. H., and R. A. Covert. 2000. Stainless steels: An introduction to their metallurgy and corrosion resistance. *Dairy Food Environ. San*. 20(6):506–517.
29. USDA. 2005. USDA guidelines for the sanitary design and fabrication of dairy processing equipment. Available at www.ams.usda.gov. Accessed 10 January 2012.
30. Werra, B. 1974. Metallurgy and processing of stainless steel from mill to finished product. *J. Milk Food Technol*. 37(12):612–617.