

Chapter 1

Introduction to Stainless Steels

STAINLESS STEELS are iron-base alloys that contain a minimum of about 12% Cr, the amount needed to prevent the formation of rust in unpolluted atmospheres (hence the designation *stainless*). Few stainless steels contain more than 30% Cr or less than 50% iron. They achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide film. This oxide forms and heals itself in the presence of oxygen. Other elements added to improve particular characteristics include nickel, manganese, molybdenum, copper, titanium, silicon, niobium, aluminum, sulfur, and selenium. Carbon is normally present in amounts ranging from less than 0.03% to over 1.0% in certain grades. Figure 1 provides a useful summary of some of the compositional and property linkages in the stainless steel family.

Production of Stainless Steels

With specific restrictions in certain types, the stainless steels can be shaped and fabricated in conventional ways. They are produced in cast, powder metallurgy (P/M), and wrought forms. Available wrought product forms include plate, sheet, strip, foil, bar, wire, semifinished products (blooms, billets, and slabs), and pipe and tubing. Coldrolled flat products (sheet, strip, and plate) account for more than 60% of stainless steel product forms. Figure 2 illustrates the most commonly employed mill processes for making various wrought stainless steel products. Production of stainless steels is a two-stage process involving the melting of scrap and ferroalloys in an electric-arc furnace (EAF) followed by refining by argon oxygen decarburization (AOD) to adjust the carbon content and remove impurities. Alternative, melting and refining steps include vacuum induction melting, vacuum arc remelting, electroslag remelting, and electron beam melting. Melting and refining of stainless steels is, however, most frequently accomplished by the EAF/AOD processing route. In fact, about 90% of all stainless steel produced in the United States is processed by EAF melting followed by AOD.

During the final stages of producing basic mill forms—sheet, strip, plate and bar—and bringing these forms to specific size and tolerances, the materials are subjected to hot reduction with or without subsequent cold rolling operations, annealing, and cleaning. Further steps are required to produce other mill forms, such as wire and tube.

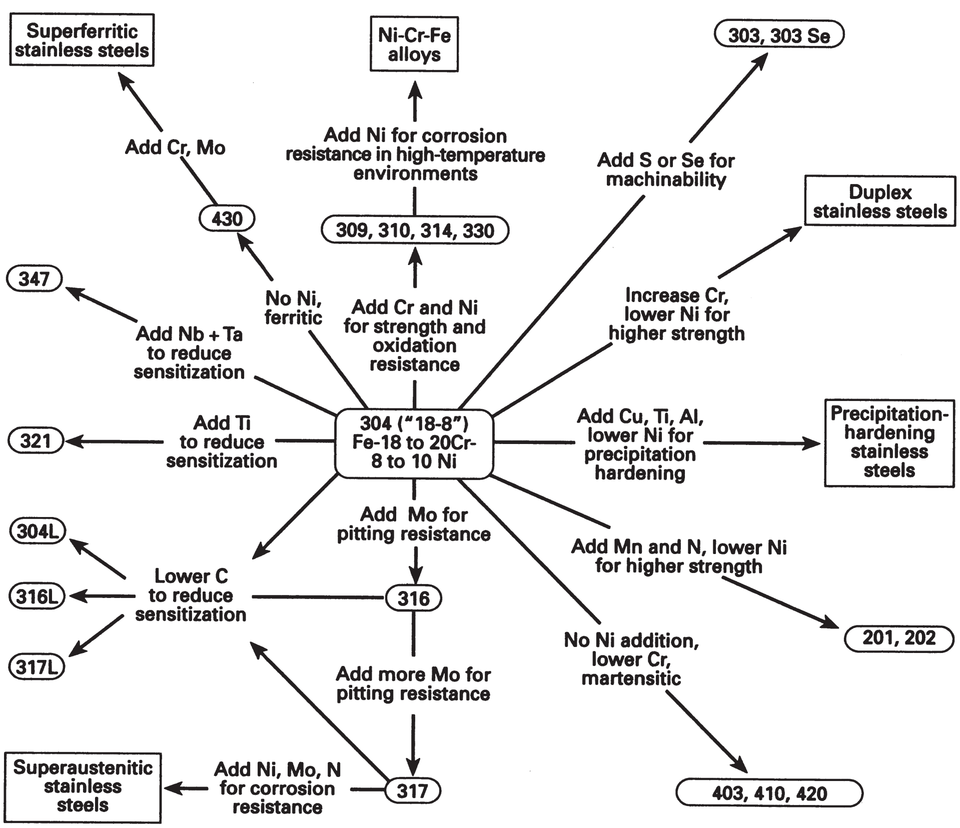

Fig. 1 Composition and property linkages in the stainless steel family of alloys

Applications for Stainless Steels

Stainless steels are used in a wide variety of applications. Most of the structural applications occur in the chemical and power engineering industries, which account for more than a third of the market for stainless steel products (see the following table). These applications include an extremely diversified range of uses, including nuclear reactor vessels, heat exchangers, oil industry tubulars, components for chemical processing and pulp and paper industries, furnace parts, and boilers used in fossil fuel electric power plants. The relative importance of the major fields of application for stainless steel products are as follows:

Application	Percentage
Industrial equipment	
Chemical and power engineering	34
Food and beverage industry	18
Transportation	9
Architecture	5
Consumer goods	
Domestic appliances, household utensils	28
Small electrical and electronic appliances	6

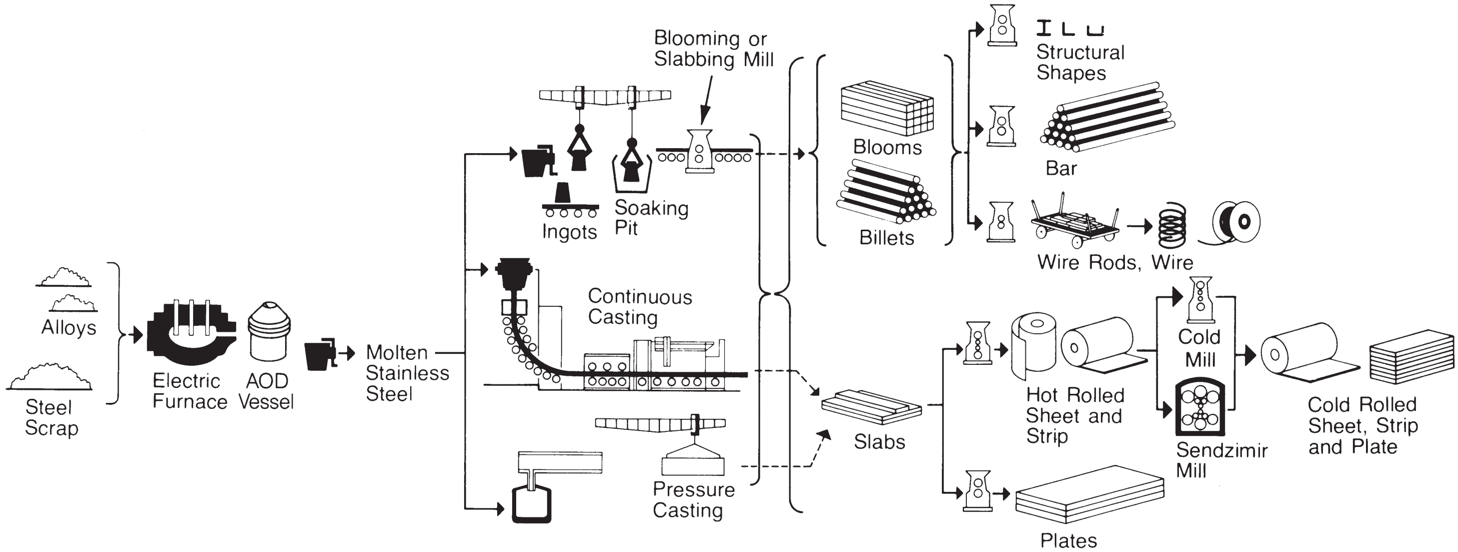

Fig. 2 Stainless steel manufacturing routes

Some of these applications involve exposure to either elevated or cryogenic temperatures; austenitic stainless steels are well suited to either type of service.

Designations for Wrought Stainless Steels

In the United States, wrought grades of stainless steels are generally designated by the American Iron and Steel Institute (AISI) numbering system, the Unified Numbering System (UNS), at the proprietary name of the alloy. In addition, designation systems have been established by most of the major industrial nations. Of the two institutional numbering systems used in the United States, AISI is the older and more widely used. Most of the grades have a three-digit designation; the 200 and 300 series are generally austenitic stainless steels, whereas the 400 series are either ferritic or martensitic. Some of the grades have a one-letter or two-letter suffix that indicates a particular modification of the composition.

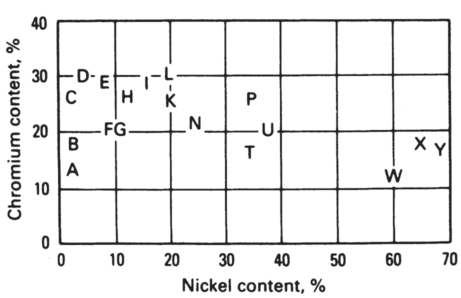

Fig. 3 Chromium and nickel contents in ACI standard grades of heat-resistant and corrosion-resistant steel castings. See text for details.

The UNS system includes a considerably greater number of stainless steels than AISI because it incorporates all of the more recently developed stainless steels. The UNS designation for a stainless steel consists of the letter S, followed by a five-digit number. For those alloys that have an AISI designation, the first three digits of the UNS designation usually correspond to an AISI number. When the last two digits are 00, the number designates a basic AISI grade. Modifications of the basic grades use two digits other than zeroes.

For stainless steels that contain less than 50% iron, the UNS designation consists of the letter N (for nickel-base alloys), followed by a five-digit number. Examples include some of the more highly alloyed austenitic grades described in Chapter 2.

Designations for Cast Stainless Steels

Cast stainless steels are most often specified on the basis of composition using the designation system of the High Alloy Product Group of the Steel Founders' Society of America. (The High Alloy Product Group has replaced the Alloy Casting Institute, or ACI, which formerly administered these designations.). The first letter of the designation indicates whether the alloy is intended primarily for liquid corrosion service (C) or high-temperature service (H). The second letter denotes the nominal chromium-nickel type of the alloy (Fig. 3). As nickel content increases, the second letter of the designation changes. The numeral or numerals following the first two letters indicate maximum carbon content (percentage × 100) of the alloy. Finally, if further alloying elements are present, these are indicated by the addition of one or more letters as a suffix. Thus, the designation of CF-8M refers to an alloy for corrosion-resistant service (C) of the 19Cr-9Ni type (Fig. 3), with a maximum carbon content 0.08% and containing molybdenum (M).

Classification of Stainless Steels

Historically, stainless steels have been classified by microstructure and are described as austenitic, martensitic, ferritic, or duplex (austenitic plus ferritic). In addition, a fifth family, the precipitation-hardenable (PH) stainless steels, is based on the type of heat treatment used rather than the microstructure. It should be noted that many of the wrought grades described below have cast counterparts. Chapters 7 and 8, which deal with cast corrosion-resistant and heat-resistant stainless steels, respectively, should be consulted.

Austenitic stainless steels constitute the largest stainless steel family in terms of alloys and usage. They include these grades:

- Iron-chromium-nickel grades corresponding to both standard AISI 300-series alloys and modified versions of these alloys. Such alloys, which are based on type 304 (18-8) stainless steel, as shown in Fig. 1, generally contain 16 to 26% Cr, 10 to 22% Ni, and small amounts of other alloying elements such as molybdenum, titanium, niobium, and nitrogen.
- Iron-chromium-manganese-nickel grades corresponding to both standard AISI 200-series alloys and modified versions of these alloys. In these alloys, manganese (5 to 18%) replaces some of the nickel. Nitrogen alloying is also common with these alloys.

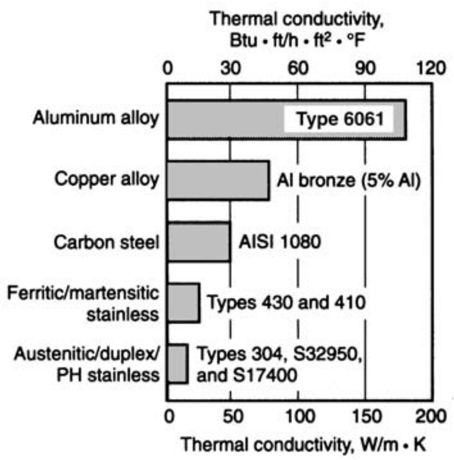

Fig. 4 Comparison of thermal conductivity for carbon steel, copper alloy, aluminum alloy, and stainless steels

- Highly alloyed iron-nickel-chromium stainless steels for more severe corrosive environments. Nickel contents in these alloys can be as high as 35%. Molybdenum and copper additions are also common.
- Superaustenitic grades (see Fig. 1) containing 6% Mo as well as liberal amounts of chromium, nickel, and nitrogen for improved corrosion resistance.

Ferritic stainless steels are nonhardenable iron-chromium alloys. They include the following:

- Standard 400-series alloys as well as modified versions of these alloys containing 11 to 27% Cr, 0.08 to 20% C, and small amounts of ferrite stabilizers, such as aluminum, niobium, and titanium.
- More recently developed low-interstitial-content (low carbon/nitrogen) grades containing higher chromium (up to 30%), molybdenum (up to 4%), and nickel (up to 2%). Such grades, which exhibit excellent resistance to stress-corrosion cracking (SCC), are referred to as superferritics (see Fig. 1).

Martensitic stainless steels are similar in composition to the ferritic group but contain higher carbon and lower chromium to permit hardening by heat treatment. They include the following:

- Standard 400-series containing 11 to 18.0% Cr, up to 1.20% C, and small amounts of manganese and nickel.
- Nonstandard grades, including free-machining grades, heat-resistant grades, and grades for gears and bearings.

Duplex stainless steels are supplied with a microstructure of approximately equal amounts of austenite and ferrite. These alloys contain roughly 22 to 25% Cr, 5 to 7% Ni, up to 4% Mo, as well as additions of copper and nitrogen. Some of the more highly alloyed, corrosion-resistant grades are referred to as superduplex stainless steels.

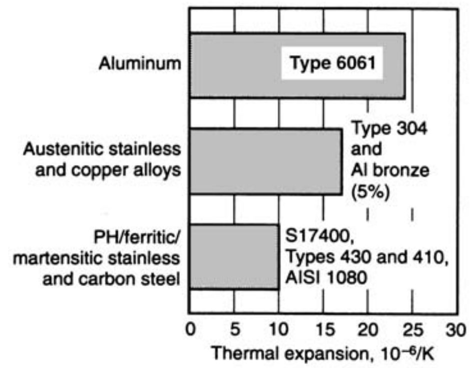

Fig. 5 Comparison of thermal expansion for carbon steel, copper alloy, aluminum alloy, and stainless steels

Duplex stainless steels are not covered by the standard AISI 200, 300, or 400 groups. While most have UNS numbers, some are also referred to by their chromium and nickel contents. For example, alloy 2205 contains 22% Cr and 5% Ni.

Precipitation-hardenable stainless steels are chromium-nickel alloys containing alloy elements such as aluminum, copper, or titanium, which allow them to be hardened by a solution and aging heat treatment. They are further classified into subgroups as martensitic, semiaustenitic, and austenitic PH stainless steels. These steels are generally referred to by their tradename or UNS number.

Physical and Mechanical Properties of Stainless Steels

The physical and mechanical properties of stainless steels are quite different from those of commonly used nonferrous alloys such as aluminum and copper alloys. However, when comparing the various stainless families with carbon steels, many similarities in properties exist, although there are some key differences. Like carbon steels, the density of stainless steels is ~8.0 g/cm^3, which is approximately three times greater than that of aluminum alloys (2.7 g/cm^3). Like carbon steels, stainless steels have a high modulus of elasticity (200 MPa, or 30 ksi) that is nearly twice that of copper alloys (115 MPa, or 17 ksi) and nearly three times that of aluminum alloys (70 MPa, or 10 ksi).

Differences among these materials are evident in thermal conductivity, thermal expansion, and electrical resistivity, as well. Figure 4 shows the large variation in thermal conductivity among various types of materials; 6061 aluminum alloy (Al-lMg-0.6Si-0.3Cu-0.2Cr) has a very high thermal conductivity, followed by aluminum bronze (Cu-5Al), 1080 carbon steel, and then stainless steels. For stainless steels, alloying additions, especially nickel, copper, and chromium, greatly decrease thermal conductivity.

Thermal expansion (Fig. 5) is greatest for type 6061 aluminum alloy, followed by aluminum bronze and austenitic stainless alloys, and then ferritic and martensitic alloys. For austenitic stainless alloys, additions of nickel and copper can decrease thermal expansion. Stainless steels have high electrical resistivity (Fig. 6). Alloying additions tend to increase electric resistivity. Therefore, the ferritic and martensitic stainless steels have lower electrical resistivity than the austenitic, duplex, and PH alloys, but higher electrical resistivity than 1080 carbon steel. Electrical resistivity of stainless steels is ~7.5 times greater than that of aluminum bronze and nearly 20 times greater than that of type 6061 aluminum alloy.

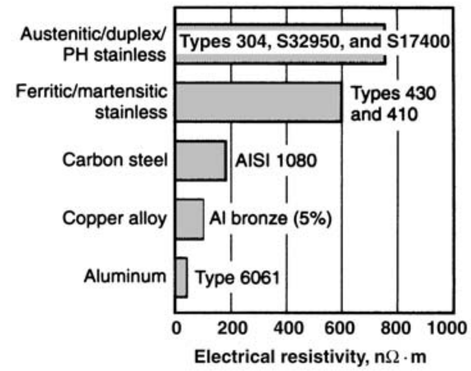

Fig. 6 Comparison of electrical resistivity for carbon steel, copper alloy, aluminum alloy, and stainless steels

Table 1 lists tensile properties and toughness for selected stainless alloys representing the five families. The four grades listed under austenitic alloys have relatively low yield strength compared with the heat-treatable alloys, but they have the highest tensile ductility and toughness. Two austenitic alloys,, S20161 (Gall-Tough) and S21800 (Nitronic 60) were specifically developed to have superior resistance to galling and metal-to-metal wear for stainless steels. Alloy N08020 (20Cb-3) is a high-nickel (33%) stainless steel alloy for use in harsh corrosive environments.

The ferritic stainless steels (type 405 and 409) listed have tensile yield strengths similar to those of the austenitic grades but lower values for ultimate tensile strength ductility, and toughness. However, strength, ductility, and toughness are still excellent compared with those of other materials, such as 6061 aluminum alloy and aluminum bronze.

Alloy S32950 (20Mo-6), the duplex stainless alloy listed in Table 1, has twice the tensile yield strength of the austenitic and ferritic grades and approximately half the toughness. Again, its toughness is far superior to that of alloys that are heat treated and hardened.

The martensitic alloys listed in Table 1 have a large variation in strength, ductility, and toughness. In the annealed condition, their properties are similar to those of the ferritic alloys, with strength increasing and ductility decreasing with increasing carbon content. The higher-carbon-containing alloys, type 420 and type 440C, are generally tempered at a low temperature (330 °C, or 625 °F maximum) to

Table 1 Properties of selected stainless steels relative to various ferrous and nonferrous alloys

UNS or AISI type	Condition	Rockwell hardness	Average tensile properties: Yield strength, 0.2% offset, MPa	Yield strength, 0.2% offset, ksi	Ultimate tensile strength, MPa	Ultimate tensile strength, ksi	Elongation in 50.8 mm (2.0 in.), %	Reduction of area, %	Charpy V-notch impact strength, J	Charpy V-notch impact strength, ft · lbf
Austenitic stainless										
Type 304	Annealed	81 HRB	241	35	586	85	60.0	70.0	≥325	≥240
N08020	Annealed	84 HRB	276	40	621	90	50.0	65.0	271	200
S20161	Annealed	93 HRB	365	53	970	140	59.0	64.0	≥325	≥240
S21800	Annealed	95 HRB	414	60	710	103	64.0	74.0	≥325	≥240
Ferritic										
Type 405	Annealed	81 HRB	276	40	483	70	30.0	60.0	…	…
Type 430	Annealed	82 HRB	310	45	517	75	30.0	65.0	217	161
Duplex										
S32950	Annealed	100 HRB	570	82	760	110	38.0	78.0	157	116
Martensitic										
Type 410	Annealed	82 HRB	276	40	517	75	35.0	70.0	…	…
	Oil quenched from 1010 °C (1850 °F) and tempered:									
	at 250 °C (500 °F)	43 HRC	1089	158	1337	193	17.0	62.0	76	56
	at 593 °C (1100 °F)	26 HRC	724	105	827	120	20.0	63.0	52	38
Type 420	Annealed	92 HRB	345	50	655	95	25.0	55.0	…	…
	Oil quenched from 1038 °C (1900 °F) and tempered at 316 °C (600 °F)	52 HRC	1482	215	1724	250	8.0	25.0	20	15
Type 440C	Annealed	97 HRB	448	65	758	110	14.0	30.0	…	…
	Oil quenched from 1038 °C (1900 °F) and tempered at 316 °C (600 °F)	57 HRC	1896	275	1975	285	2.0	10.0	2	3
Precipitation hardened										
S45500	Annealed	31 HRC	793	115	1000	145	14.0	70.0	…	…
	Water quenched from 1038 °C (1900 °F) and aged:									
	at 482 °C (900 °F)	49 HRC	1620	235	1689	245	10.0	45.0	12	9
	at 566 °C (1050 °F)	40 HRC	1207	175	1310	190	15.0	55.0	47	35
S17400	Annealed	31 HRC	793	115	965	140	12.0	50.0	…	…
	Water quenched from 1038 °C (1900 °F) and aged:									
	at 482 °C (900 °F)	44 HRC	1262	183	1365	198	15.0	52.0	21	16
	at 621 °C (1150 °F)	33 HRC	869	126	1131	164	17.0	59.0	75	55
Carbon steel										
AISI 1080	Annealed	97 HRB	455	66	821	119	15.0	22.0	…	…
	Oil quenched from 816 °C (1500 °F) and tempered at 204 °C (400 °F)	42 HRC	980	142	1304	189	12.0	35.0	…	…
Aluminum alloy										
Type 6061	Annealed	…	55	8	124	18	25.0	…	…	…
	Aged	56 HRB	276	40	311	45	12.0	…	…	…
Copper alloy										
Al bronze (95 Cu-5 Al)	Annealed	45 HRB	173	25	380	55	65.0	…	…	…

maximize their strength. On the other hand, type 410 is tempered over a wide temperature range, from 260 to 650 °C (500 to 1200 °F). The tensile properties of type 410 are similar to those of carbon steel (AISI 1080).

The martensitic PH alloys, such as S45500 (Custom 450) and S17400 (17-4PH), have higher annealed strength and lower ductility than the martensitic alloys and are aged at temperatures ranging from 480 to 620 °C (895 to 1150 °F). Their strength is dependent on the hardener (titanium, niobium, copper), the amount of hardener, and the aging temperatures used. Toughness is either similar or superior to the martensitic alloys at a given strength level.

Factors in Selection of Stainless Steels

The selection of stainless steels can be based on corrosion resistance, fabrication characteristics, availability, mechanical properties in specific temperature ranges, and product cost. However, corrosion resistance and mechanical properties are usually the most important factors in selecting a grade for a given application.

Characteristics to be considered in selecting the proper type of stainless steel for a specific application include these:

- Corrosion resistance
- Resistance to oxidation and sulfidation
- Strength and ductility at ambient and service temperatures
- Suitability for intended fabrication techniques
- Suitability for intended cleaning procedures
- Stability of properties in service
- Toughness
- Resistance to abrasion, erosion, galling, and seizing
- Surface finish and/or reflectivity
- Physical property characteristics, such as magnetic properties, thermal conductivity, and electrical resistivity
- Total cost, including initial cost, installed cost, and the effective life expectancy of the finished product
- Product availability

Corrosion resistance is frequently the most important characteristic of a stainless steel but often is also the most difficult to assess for a specific application. General corrosion resistance to pure chemical solutions is comparatively easy to determine, but actual environments are usually much more complex.

General corrosion is often much less serious than localized forms such as SCC, crevice corrosion in tight spaces or under deposits, pitting attack, and intergranular attack in sensitized material such as weld heat-affected zones. Such localized corrosion can cause unexpected and sometimes catastrophic failure while most of the structure remains unaffected, and, therefore, it must be considered carefully in the design and selection of the proper grade of stainless steel.

Corrosive attack can also be increased dramatically by seemingly minor impurities in the medium that may be difficult to anticipate but that can have major effects, even when present in only parts-per-million concentrations. These effects can include heat transfer through the steel to or from the corrosive medium, contact with dissimilar metallic materials, stray electrical currents, and many other subtle factors. At elevated temperatures, attack can be accelerated significantly by seemingly minor changes in atmosphere that affect scaling, sulfidation, or carburization.

Despite these complications, a suitable steel can be selected for most applications on the basis of experience, perhaps with assistance from the steel producer. Laboratory corrosion data can be misleading in predicting service performance. Even actual service data have limitations, because similar corrosive media may differ substantially because of slight variations in some of the corrosion conditions listed previously. For difficult applications, extensive study of comparative data may be necessary, sometimes followed by pilot plant or in-service testing. Other important factors that must be considered when selecting a stainless steel for a corrosion application include the following:

- Chemical composition of the corrosive medium, including impurities
- Physical state of the medium: liquid, gaseous, solid or combinations thereof
- Temperature
- Temperature variations
- Aeration of the medium
- Oxygen content of the medium
- Bacteria content of the medium
- Ionization of the medium
- Repeated formation and collapse of bubbles in the medium
- Relative motion of the medium with respect to the steel
- Chemical composition of the metal
- Nature and distribution of microstructural constituents
- Continuity of exposure of the metal to the medium
- Surface condition of the metal
- Stresses in the metal during exposure to the medium
- Contact of the metal with one or more dissimilar metallic materials
- Stray electrical currents
- Differences in electric potential
- Marine growth such as barnacles
- Sludge deposits on the metal
- Carbon deposits from heated organic compounds
- Dust on exposed surfaces
- Effects of welding, brazing, and soldering

More detailed information on selection of stainless steels for use in various environments can be found in the chapters that follow (describing specific alloy groups/families), the data sheets contained therein, alloy producer product literature, and the Selected References listed subsequently.

Fabrication Characteristics

Stainless steels can be fabricated by methods similar to those used for carbon steels and other common metals. However, changes in fabrication methods may be necessary to the extent that stainless steels differ in yield strength and rate of work hardening. All have work hardening rates higher than common carbon steels, but the austenitics are characterized by large increases in strength and hardness with cold work. With the exception of the resulfurized free-machining grades, all stainless steels are suitable for crimping or flattening operations. The free-machining grades will withstand mild longitudinal deformation but may exhibit some tendency to splitting. In spite of their higher hardness, most martensitic and all of the ferritic types can be successfully fabricated. Tables 2 and 3 compare the relative fabrication characteristics of commonly used stainless steels.

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Table 2 Relative fabrication characteristics of stainless steels

	Austenitic					Ferritic		Martensitic		
Characteristic	201, 202, 301, 302, 304, 304L,305	303(a)	309S, 310S	316, 316L, 317, 317LMN	321, 347	430, 439	405, 442, 446	403, 410	420	440A, 440C
Air hardening	No	No	No	No	No	No	No	Yes	Yes	Yes
Blanking	F	F	F	F	F	E	E	E	E	G
Brazing	G	G	G	G	G	G	G	G	G	G
Buffing	G	…	G	G	G	G	G	G	G	G
Drawing, deep	E	…	G	E	G	E	F	E	NR	NR
Forming, cold	G	F	G	G	G	G	F	G	F	NR
Forming, hot	G	F	G	G	G	G	G	G	G	G
Grinding, ease of	F	G	F	F	F	F	F	G	E	E
Grinding (magnetic)	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Hardenable by heat treatment	No	No	No	No	No	No	No	Yes	Yes	Yes
Machining	F	E	F	F	F	G	F	G	F	NR
Polishing	G	G	G	G	F	G	G	G	G	G
Punching (perforating)	F	…	F	F	F	G	G	G	G	G
Riveting, cold	G	F	G	G	G	G	G	G	NR	NR
Riveting, hot	G	F	G	G	G	G	G	G	NR	NR
Shearing, cold	F	F	F	F	F	G	G	G	G	F
Soldering	G	G	G	G	G	G	G	G	G	G
Spinning	G	…	G	G	G	G	F	F	NR	NR
Welding	E	NR	E	E	E	F	F	F	F	F

E, excellent; G, good; F, fair; NR, not generally recommended (poor). (a) Chemistry designed for improved machining (as are other grades, i.e., 416, 420F, 430F, 440F)

Table 3 Fabrication characteristics of stainless steels

Type No.	UNS No.	Machinability	Adaptable for hot forging	Readily formable by bending	Readily joinable by fusion welding	Readily shaped by deep drawing (cold)	Readily joinable by resistance welding	Readily joinable by soldering and brazing	Physical and mechanical properties satisfactory for spinning	Readily heat treatable for hardening and for mechanical properties
Austenitic										
201	S20100	S	S	S	S	S	S	S	S	…
202	S20200	S	S	S	S	S	S	S	S	…
301	S30100	S	S	S	S	S	S	S	S	…
302	S30200	S	S	S	S	S	S	S	S	…
303	S30300	B	S	…	…	…	…	S	…	…
304	S30400	S	S	S	S	S	S	S	S	…
304L	S30403	S	S	S	S	S	S	S	S	…
305	S30500	S	S	S	S	S	S	S	B	…
309S	S30908	S	S	S	S	S	S	S	S	…
310S	S31008	S	S	S	S	S	S	S	S	…
316	S31600	S	S	S	S	S	S	S	S	…
316L	S31603	S	S	S	S	S	S	S	S	…
S17	S31700	S	S	S	S	S	S	S	S	…
317LMN	S31726	S	S	S	S	S	S	S	S	…
321	S32100	S	S	S	S	S	S	S	S	…
347	S34700	S	S	S	S	S	S	S	S	…
Ferritic										
405	S40500	S	S	S	S	S	S	S	S	…
430	S43000	S	S	S	S	S	S	S	S	…
439	S43035	S	S	S	S	S	S	S	S	…
430F	S43020	B	S	…	…	…	…	S	…	…
442	S44200	S	S	S	…	…	…	S	…	…
446	S44600	S	S	S	S	…	…	S	S	…
Martensitic										
403	S40300	S	S	S	S	…	S	S	…	S
410	S41000	S	S	S	S	S	S	S	S	S
416	S41600	B	S	…	…	…	…	S	…	S
420	S42000	S	S	…	…	…	…	S	…	S
420F	S42020	B	S	…	…	…	…	S	…	S
440A	S44002	S	S	…	…	…	…	S	…	S
440C	S44004	S	S	…	…	…	…	S	…	S
440F	S44020	B	S	…	…	…	…	S	…	S

S, suitable for application; B, better adapted for application

Publication title	Product code
Alloy Digest Sourcebook: Stainless Steels	#06940