High-Performance Stainless Steels

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The Front Cover shows a heat exchanger with SAF 2507® tubes for aggressive chloride service

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INTRODUCTION

The “high-performance stainless steels” are a family of stainless steels which have distinctly superior corrosion resistance in a wide variety of aggressive environments when compared with the standard stainless steel grades such as Type* 304L, which contains only 18% chromium and 8% nickel (18-8), and Type 316L, which contains similar chromium and nickel and 2% molybdenum (18-10-2). Their superiority in resisting pitting and stress corrosion cracking is especially evident in environments containing the chloride ion. This performance is obtained by using a high level of chromium, nickel, molybdenum, and nitrogen alloying for corrosion resistance, and by producing these grades with very low carbon contents to preserve this resistance while allowing hot fabrication and welding. The commercial origins of the high-performance stainless steels came with the advent of steel melting and refining technologies that made it possible to economically produce compositions having very low carbon content and close composition control. Among these technologies are vacuum melting, electron beam remelting, electroslag remelting, and, most notably today from a commercial standpoint, vacuum oxygen decarburization (VOD) and argon-oxygen decarburization (AOD). Beginning in the 1970s, these stainless steels have grown in number and in technical and commercial importance. This book provides an introduction to these steels for those whose materials needs extend beyond the capabilities of the standard grades, and for those who will benefit from a discussion of the engineering and corrosion performance properties of the high-performance stainless steels.

There are three primary classifications within the high-performance stainless steels. They are the austenitic, ferritic, and duplex (austenitic-ferritic) families. The stainless steels in each family have general similarities, but there is also a wide range of corrosion resistance and other characteristics. This allows a broad spectrum of existing and potential applications where each family, as well as individual grades, may offer optimum performance for a specific requirement. The higher nickel austenitic grades are generally preferred for severe acid service and for resistance to chloride pitting and stress corrosion cracking. They are often selected for flue gas cleaning equipment handling acid condensates, or acidic solutions containing strong oxidants such as in paper bleaching. Where field fabrication is an important consideration, the austenitic grades are favoured because of their relative ease of welding; grades from this family have been used extensively in offshore and nuclear piping where weld quality is extremely important. If the requirement is for thin sheet, the ferritic grades will usually be most cost-effective; therefore, they have been used as the tube material in many kinds of heat exchangers. The duplex grades are often selected where strength is advantageous. They have been used in pressure vessels for the chemical process industry, and have seen extensive service in heat exchangers. All three families of the high-performance stainless steels will deliver a wide range of resistance to chloride pitting and stress corrosion cracking superior to that of Types 304 and 316; so fabrication considerations often determine the final material choice in the case of chloride service.

The high-performance stainless steels are more technically demanding than Types 304 and 316 with regard to metallurgy and fabrication requirements. This is due to the nature of the steels themselves and the demanding applications in which they are used. A thorough understanding of these stainless steels is necessary to use them successfully. This book provides assistance in making the optimum material selection for a given application, and provides guidance in the fabrication and use of the selected grade. Because of the complexity of applications and large number of grades available, this book can serve only as an introductory guide. The reader is encouraged to consult with manufacturers to learn more fully the advantages, limitations, and specific requirements of individual materials.

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* Refers to ‘AISI Type’.

CLASSIFICATION OF GRADES

AUSTENITIC HIGH-PERFORMANCE STAINLESS STEELS

The austenitic family of high-performance stainless steels shares many characteristics with its standard grade counterpart. These grades in the annealed condition consist primarily of a single phase, face-centred cubic austenite, and are non-magnetic. This structure is characterized by a relatively low yield strength, high work hardening rate and high tensile strength, good ductility and formability, especially good low temperature toughness, and the inability to be hardened (or strengthened) by heat treatment. Besides corrosion resistance, the major difference in comparison with the standard grades is that the high-performance grades rapidly form secondary phases at high temperatures. These phases may be damaging to certain mechanical properties and corrosion resistance, and therefore, the application of these stainless steels at temperatures above 500°C (930°F) is limited. In addition, care must be taken to avoid forming damaging amounts of these phases during high temperature operations such as forging or welding.

A list of notable wrought high-performance austenitic stainless steels is given in *Table 1*. Grades are identified by the name by which they are best known and by their UNS number. Producer names, which in many cases are

Courtesy Wellstream

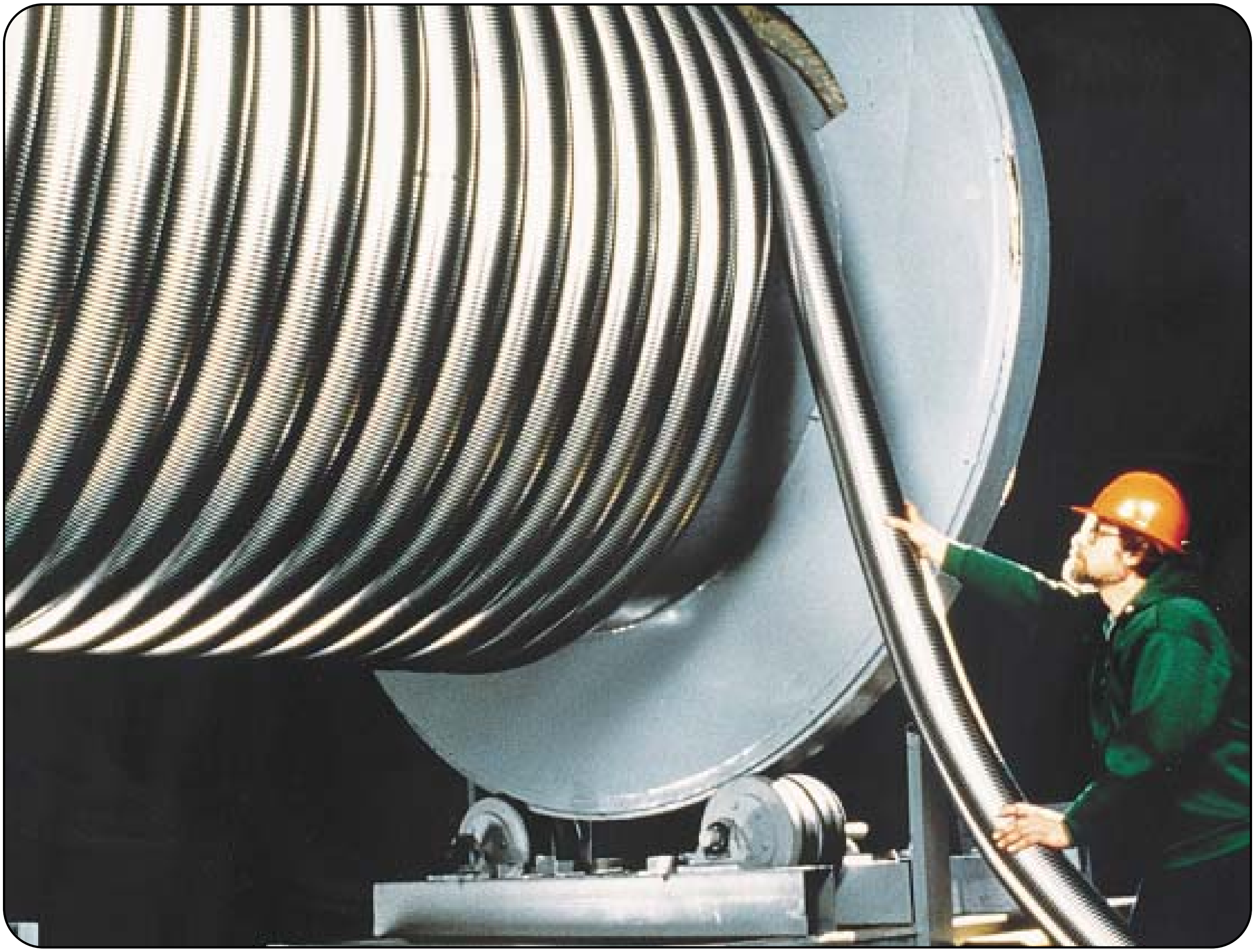

Table 1 Chemical composition of wrought high-performance austenitic stainless steels (wt. pct.)***

Name	UNS Number	Sub Group	C	N	Cr	Ni	Mo	Cu	Other	PRE Number
Type 316L	S31603		0.03	0.10	16.0-18.0	10.0-14.0	2.0-3.0	–	–	23
Type 317L	S31703		0.03	0.10	18.0-20.0	11.0-15.0	3.0-4.0	–	–	28
Alloy 20	N08020	A-1	0.07	–	19.0-21.0	32.0-38.0	2.0-3.0	3.00-4.00	(Cb+Ta): 8xC-1.00	26
Alloy 825	N08825		0.05	–	19.5-23.5	38.0-46.0	2.5-3.5	1.50-3.50	Al: 0.2 max, Ti: 0.6-1.2	28
317LN	S31753	A-2	0.03	0.10-0.22	18.0-20.0	11.0-15.0	3.0-4.0	–	–	30
260			0.03	0.16-0.24	18.5-21.5	13.5-16.5	2.5-3.5	1.00-2.00	–	29
317LM	S31725		0.03	0.10	18.0-20.0	13.2-17.5	4.0-5.0	–	–	31
317LMN	S31726		0.03	0.10-0.20	17.0-20.0	13.5-17.5	4.0-5.0	–	–	32
NAS 204X***		A-3	0.04	–	25.0	25.0	2.75	–	Nb: 10xC	34
310MoLN	S31050		0.03	0.10-0.16	24.0-26.0	21.0-23.0	2.0-3.0	–	Si: 0.50 max	32
700	N08700		0.04	–	19.0-23.0	24.0-26.0	4.3-5.0	–	Nb: 8xC-0.40	33
904L	N08904		0.02	–	19.0-23.0	23.0-28.0	4.0-5.0	1.00-2.00	–	32
904LN			0.02	0.04-0.15	19.9-21.0	24.0-26.0	4.0-5.0	1.00-2.00		34
20Mo-4	N08024		0.03	–	22.5-25.0	35.0-40.0	3.5-5.0	0.50-1.50	–	34
20 Mod	N08320		0.05	–	21.0-23.0	25.0-27.0	4.0-6.0	–	Ti: 4xC min	34
Alloy 28	N08028		0.02	–	26.0-28.0	29.5-32.5	3.0-4.0	0.60-1.40	–	36
20Mo-6	N08026	A-4	0.03	0.10-0.16	22.0-26.0	33.0-37.0	5.0-6.7	2.00-4.00	–	40
25-6MO 1925hMo	N08925		0.02	0.10-0.20	19.0-21.0	24.0-26.0	6.0-7.5	0.8-1.5	–	–
254N***			0.03	0.20	23.0	25.0	5.50	–	–	41
25-6MO 1925hMo	N08926		0.02	0.15-0.25	19.0-21.0	24.0-26.0	6.0-7.0	0.50-1.50	–	41
SB8	N08932		0.020	0.17-0.25	24.0-26.0	24.0-26.0	4.7-5.7	1.0-2.0	–	42
254 SMO	S31254		0.02	0.18-0.22	19.5-20.5	17.5-18.5	6.0-6.5	0.50-1.00	–	42
AL-6XN	N08367		0.03	0.18-0.25	20.0-22.0	23.5-25.5	6.0-7.0	0.75	–	43
YUS 170		A-5	0.03	0.25-0.40	23.0-26.0	12.0-16.0	0.50-1.20	–	–	29
2419 MoN			0.03	0.30-0.50	23.0-25.0	16.0-18.0	3.5-4.5	0.30-1.00	Mn: 5.5-6.5 Nb: 0.1-0.3	39
4565S	S34565		0.03	0.40-0.60	23.0-25.0	16.0-18.0	3.5-5.0	–	Mn: 3.5-6.5	41
B66	S31266	A-6	0.030	0.35-0.60	23.0-25.0	21.0-24.0	5.0-7.0	0.50-3.00	W: 1.0-3.0 Mn: 2.00-4.00	45
3127 hMo	N08031		0.02	0.15-0.25	26.0-28.0	30.0-32.0	6.0-7.0	1.00-1.40	–	48
654 SMO	S32654		0.02	0.45-0.55	24.0-26.0	21.0-23.0	7.0-8.0	0.30-0.60	Mn: 2.0-4.0 Cu: 0.3-0.6	54

** taken from ASTM specifications for plate, sheet, and strip when available or from company data sheets*
*** maximum, unless range or minimum is indicated*
**** nominal chemistry*

trade names, are provided in Appendix 2. Many of these grades were patented when originally developed and, in some cases, the patents may still be in effect. When a range is shown for the chemical composition, it corresponds to the most commonly applicable ASTM standard, usually A 240. When single compositions are shown, this is the "typical" value provided by the producer. The grades in *Table 1* are arranged in the order of increasing molybdenum, chromium, and nitrogen content, or increasing PRE number. The PRE number means the "pitting resistance equivalent" and in this book is defined as PRE = %Cr + 3.3%Mo + 16%N with the percent elements in weight percent. A higher PRE number relates semi-quantitatively to a higher resistance to localized corrosion in chloride-containing environments. The grades also have been divided into six subgroups based on a similarity in localized corrosion resistance. A description of these subgroups follows:

Subgroup A-1 Austenitic Stainless Steels. The stainless steels in this subgroup are designed primarily for application in strong, hot, sulphuric acid solutions. The required corrosion resistance is achieved primarily through the use of high nickel content. The 20Cb-3 and Alloy 825 grades, with about the

AL-6XN®
flexible hosing
for offshore
oil rigs

same chromium and molybdenum as Type 316, are not superior to Type 316 with respect to localized pitting or crevice corrosion resistance. With increasing nickel content, these grades have progressively increasing resistance to chloride stress corrosion cracking. They have a long history of giving excellent service in many chemical industry applications requiring good sulphuric acid or stress corrosion cracking resistance.

Subgroup A-2 Austenitic Stainless Steels. These grades, for example 317LMN, are designed to provide improved localized corrosion resistance in halide environments when compared with Types 316L and 317L. This is accomplished through the use of higher molybdenum and nitrogen contents. Nitrogen, while improving corrosion resistance, also stabilizes the austenite so the nickel can be limited for optimum economy. These grades offer improved performance at a relatively modest cost premium compared with Type 316L. They have been widely used in the absorber towers of flue gas desulphurization (FGD) equipment operating under moderately aggressive pitting conditions.

Subgroup A-3 Austenitic Stainless Steels. These stainless steels, for example 904L, use about 10% more nickel to provide overall balanced performance with regard to reducing acids and chloride stress corrosion cracking. Their copper additions provide additional resistance to many reducing acids.

Subgroup A-4 Austenitic Stainless Steels.
The subgroup A-4 grades, frequently called the 6% Mo grades and including AL-6XN, 1925 HMo, 25-6MO, and 254 SMO, were designed originally to resist localized corrosion in seawater at near-ambient temperatures and in pulp bleach plant environments. This is accomplished by the use of relatively high levels of nitrogen, chromium, and molybdenum to give a PRE number in the range of 40 to 43. They contain high nickel to help stabilize austenite, and, therefore, also provide good general acid and chloride stress corrosion cracking resistance. High nitrogen also gives them a substantial strength advantage compared with the alloys in this family that have no nitrogen. They have been widely used in piping and heat exchangers handling seawater, in many pulp bleach plant applications, and in a variety of chemical and power plant applications.

Subgroup A-5 Austenitic Stainless Steels. High strength is the main attribute of these grades, 4565S for example, and this is accomplished through the solution strengthening effect of nitrogen in the range of 0.25 to 0.50 percent. Corrosion properties vary considerably depending on the amount of chromium, molybdenum, and nickel. The relatively low nickel content (12-18%) puts their resistance to chloride stress corrosion cracking into the A-2 group.

Courtesy Böhler Edelstahl GMbH

Wye Piece in Böhler A911 for offshore application

Group A-6 Austenitic Stainless Steels. These grades, for example 654 SMO, represent the highest level of performance that has yet been achieved among all the high-performance stainless steels. They combine high strength with outstanding localized corrosion resistance, and have good chloride stress corrosion cracking and acid resistance. They will resist stress corrosion cracking in the boiling 45% $MgCl_2$ test and localized corrosion in seawater under severe crevice conditions and temperatures significantly above ambient. They approach the best of the nickel-base alloys with respect to localized corrosion while providing much higher strength. These newer grades have an excellent potential for solving crevice corrosion problems in gasketed joints, systems handling seawater at elevated temperatures, and in many systems operating at high pressure.

FERRITIC HIGH-PERFORMANCE STAINLESS STEELS

The ferritic high-performance stainless steels have an entirely ferritic microstructure except for small amounts of stabilizing carbides and nitrides. This ferritic structure has the unique attribute of being very resistant to chloride stress corrosion cracking, but has limited toughness. The toughness can be further reduced by large section or grain size effects and by the precipitation of embrittling secondary phases. These grades are usually not produced in plate thicknesses because of these toughness limitations. They were developed to provide superior resistance, compared to the 18-8 stainless steels, to chloride stress corrosion cracking and pitting at a lower cost than the high nickel-containing austenitic alloys. They are generally used only for heat exchanger tubing or thin sheet applications. They are not hardenable by heat treatment, but in the annealed condition they exhibit higher strength than many austenitic grades. *Table 2* lists the notable wrought ferritic grades in order of increasing resistance to chloride pitting.

Subgroup F-1 Ferritic Stainless Steels. These grades, for example E-BRITE 26-1, have localized corrosion resistance similar to Type 316, but far superior stress corrosion cracking resistance. This good stress corrosion cracking performance applies to hot, concentrated caustic as well as chloride-containing solutions.

Subgroup F-2 Ferritic Stainless Steels. The grades in this subgroup, which include SEA-CURE, were designed to resist localized corrosion in ambient temperature seawater. They have been used extensively in seawater-cooled power plant condensers. With their high chromium content and moderate molybdenum and nickel content, they are also very resistant to strong organic acids and oxidizing or moderately reducing inorganic acids. However, the use of nickel in many of these grades reduces chloride stress corrosion cracking resistance and increases susceptibility to the formation of damaging secondary phases. All these ferritic

Table 2 Chemical composition* of wrought high-performance ferritic stainless steels (wt. pct.)**

Name	UNS Number	Sub Group	C	N	Cr	Ni	Mo	Cu	Other	PRE Number
Type 444	S44400	F - 1	0.025	0.035	17.5-19.5	1.00	1.75-2.50	–	Ti, Nb	23
26-1S	S44626		0.060	0.040	25.0-27.0	0.50	0.75-1.50	–	Ti	27
E-BRITE 26-1	S44627		0.010	0.015	25.0-27.0	0.50	0.75-1.50	–	Nb	27
MONIT	S44635	F - 2	0.025	0.035	24.5-26.0	3.5-4.5	3.5-4.5	–	Ti, Nb	36
SEA-CURE	S44660		0.030	0.040	25.0-28.0	1.0-3.5	3.0-4.0	–	Ti, Nb	35
AL 29-4C	S44735		0.030	0.045	28.0-30.0	1.00	3.6-4.2	–	Ti, Nb	40
AL 29-4-2	S44800	F-3	0.010	0.020	28.0-30.0	2.0-2.5	3.5-4.2	–	–	40

** taken from ASTM specifications for plate, sheet, and strip when available or from company data sheets*
*** maximum, unless range or minimum is indicated*

Table 3 Chemical composition* of wrought high-performance duplex stainless steels (wt. pct.)**

Name	UNS Number	Sub Group	C	N	Cr	Ni	Mo	Cu	Other	PRE Number
Type 329	S32900		0.080	–	23.0-28.0	2.5-5.0	1.00-2.00	–	–	26
3RE60	S31500		0.030	0.05-0.10	18.0-19.0	4.25-5.25	2.50-3.00	–	Si: 1.40-2.00 Mn:1.20-2.00	27
2304	S32304	D - 1	0.030	0.05-0.20	21.5-24.5	3.0-5.5	0.05-0.60	–	–	22
45M***		D - 2	0.030	0.15	24.3	5.0	1.50	1.00	–	32
44LN	S31200		0.030	0.14-0.20	24.0-26.0	5.5-6.5	1.20-2.00	–	–	30
2205	S31803		0.030	0.08-0.20	21.0-23.0	4.5-6.5	2.5-3.5	–	–	31
2205	S32205		0.030	0.14-0.20	22.0-23.0	4.5-6.5	3.0-3.5	–	–	34
7-Mo PLUS	S32950	D - 3	0.030	0.15-0.35	26.0-29.0	3.5-5.2	1.00-2.50	–	–	32
DP3	S31260		0.030	0.10-0.30	24.0-26.0	5.5-7.5	2.5-3.5	0.20-0.80	W: 0.10-0.50	34
UR 47N			0.030	0.14-0.20	24.0-26.0	5.5-7.5	2.5-3.5	–	–	34
64***			0.030	0.14	25.0	6.40	3.5	–	–	39
255	S32550		0.040	0.10-0.25	24.0-27.0	4.5-6.5	2.9-3.9	1.50-2.50	–	35
DP3W	S39274	D - 4	0.030	0.24-0.32	24.0-26.0	6.0-8.0	2.5-3.5	0.20-0.80	W: 1.50-2.50	36
100	S32760		0.030	0.20-0.30	24.0-26.0	6.0-8.0	3.0-4.0	0.50-1.00	W: 0.50-1.00	37
2507	S32750		0.030	0.24-0.32	24.0-26.0	6.0-8.0	3.0-5.0	0.50	–	38
52N+	S32520		0.030	0.20-0.35	24.0-26.0	5.5-8.0	3.0-5.0	0.50-3.00	–	37

** taken from ASTM specifications for plate, sheet, and strip when available or from company data sheets*
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**** nominal chemistry*

stainless steels resist stress corrosion cracking in sodium chloride tests, but probably not in the magnesium chloride test because of their nickel content (0.5-4.2%).

Subgroup F-3 Ferritic Stainless Steels. The one grade in this subgroup, AL 29-4-2, as with the A-6 austenitic subgroup, is designed to produce the highest level of overall performance available from the ferritic stainless steels. It combines good localized and acid corrosion resistance.

DUPLEX HIGH-PERFORMANCE STAINLESS STEELS

The grades in the duplex family are metallurgically designed to have a microstructure in the annealed condition consisting of approximately equal portions of austenite and ferrite. This is achieved by limiting the nickel content to moderately low levels and increasing the chromium content up to 22-26%. The molybdenum content is kept to about the same level as 317L. Therefore, when the PRE numbers are higher than about 30, as for 317L, it is mostly a result of the higher chromium and nitrogen contents. The duplex structure exhibits properties that take advantage of the better attributes of each of the two phases. Most importantly, these grades provide very high strength along with useful ductility and toughness. They can deliver a good combination of strength, general corrosion, and stress corrosion cracking resistance at moderate cost because they do not contain a large amount of nickel. As with the austenitic family, these grades cannot be hardened by heat treatment. Duplex stainless steels require careful fabrication procedures to avoid damage from secondary phases and to maintain the balance of about equal amounts of ferrite and austenite. They are more demanding than the austenitic stainless steels in this respect. *Table 3* lists the notable wrought high-performance duplex stainless steels.

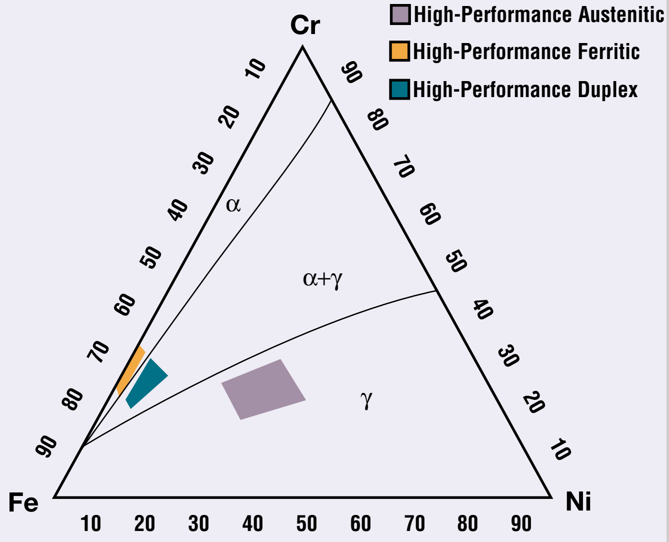
Subgroup D-1 Duplex Stainless Steels. The only grade in this subgroup is 2304. Although it generally does not have better corrosion resistance than the standard austenitic grades, 2304 is included among the high-performance stainless steels because, as with all the second generation duplex grades, it uses low carbon and high nitrogen to give a better combination of fabrication and corrosion properties than the earlier duplex grades. It can be readily welded and offers higher strength and better stress corrosion cracking resistance than Type 316L or Type 317L.

Subgroup D-2 Duplex Stainless Steels. The grades in this subgroup, especially 2205, are the most useful of the duplex family because they combine corrosion performance, ease of fabrication and economical properties. They have great versatility in both fabrication and corrosion resistance. They are superior to Type 316 in resistance to stress corrosion cracking.

Subgroup D-3 Duplex Stainless Steels.
These 25Cr duplex grades, such as Ferralium 255, use higher levels of chromium to produce better localized corrosion resistance than the subgroup D-2 grades, but they are not considered to be seawater-resistant in critical applications. The chromium provides very good resistance to oxidizing acids. They require higher nickel to balance the higher chromium, which improves resistance to reducing acids as well. The high chromium has the disadvantage of accelerating the kinetics of damaging detrimental phase precipitation; therefore, fabrication involving thermal treatment requires close control of thermal conditions. The rapid precipitation kinetics in some instances may limit usable section sizes.

Subgroup D-4 Duplex Stainless Steels.
This subgroup is the most highly alloyed subgroup of the duplex family. The high chromium, molybdenum, nickel, and nitrogen content produces the best corrosion resistance of any of the duplex grades, and higher strength than is obtainable in any high-performance stainless steel. For this reason, these alloys are sometimes called super duplex stainless steels. Resistance to pitting and crevice corrosion in ambient temperature seawater is similar to the 6% Mo austenitic grades in Subgroup A-4. They have yield strengths exceeding 550 MPa (80 ksi). However, their high alloy contents produce restraints on thermal fabricating procedures that are even more stringent than required for the subgroup D-3 grades.

Figure 1 Section of the iron-chromium-nickel system at 1100°C (2012°F) showing the general composition range of ferritic, duplex and austenitic high-performance stainless steels[1]



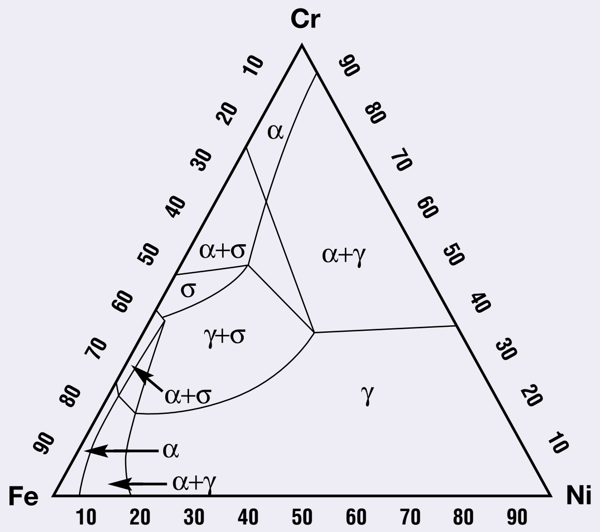
PHYSICAL METALLURGY

PHASE RELATIONS IN THE IRON-CHROMIUM-NICKEL SYSTEM

The high-performance stainless steels are best understood metallurgically by examining the iron-chromium-nickel ternary system and considering modifications introduced by other alloying elements. This ternary system usefully delineates the two primary phases, austenite and ferrite, which distinguish the three structural families. The primary additional elements are molybdenum, nitrogen, and carbon, and, in the case of stabilized ferritic stainless steels, titanium and niobium. These elements, along with chromium, introduce secondary phases that are usually undesirable. A good understanding of the conditions of occurrence and effects of the primary and secondary phases is essential to the successful use of the high-performance stainless steels.

A section of the iron-chromium-nickel system at 1100°C (2012°F) is shown in *Figure 1*. This section provides a reasonably good representation of the primary phase relationships for all these grades at temperatures from about 1000°C (1832°F) to near their solidus temperatures. In this diagram the region of most interest is that which encompasses iron contents of about 50 to 70 percent and chromium contents (plus molybdenum) of about 20 to 30 percent. The shaded regions of *Figure 1* show the general composition range for the three alloy families: austenitic totally within the gamma field (γ), ferritic totally within the alpha field (α), and duplex within the alpha plus gamma field (α + γ).

***Figure 2* Section of the iron-chromium-nickel system at 650°C (1202°F) showing the stability of sigma phase existing over the composition range of many high-performance stainless steels[1]**



This section indicates relatively simple one- or two-phase alloys and generally applies at high temperature for the commercial grades even though they will contain additional alloying or residual element components. The detrimental secondary phases mentioned previously are stable only at temperatures less than about 1000°C (1832°F). The successful commercial production of the high-performance stainless steels, and their fabrication and use, require a relatively simple microstructure and avoidance of detrimental secondary phases during exposure to lower temperatures upon cooling after annealing or welding.

Sigma phase is the most often encountered secondary phase and it is often damaging to both mechanical properties and corrosion resistance. Under equilibrium conditions sigma can form at intermediate temperatures in virtually all these alloys. This is illustrated in *Figure 2*, a section of the iron-chromium-nickel ternary at 650°C (1202°F). From this section, it can be seen that large quantities of sigma can occur in the higher chromium ferritic and duplex grades, and in most of the austenitic grades as well. Because diffusion rates are faster in ferrite than in austenite, reaction kinetics also favour sigma formation in those compositions which contain ferrite. Sigma phase is particularly damaging to toughness in

Courtesy Rolled Alloys

AL-6XN® stainless steel wallpaper for flue gas desulphurization ductwork

the ferrite-containing grades, but also adversely affects toughness and corrosion effects when present in austenite.

The iron-chromium binary phase diagram shown in *Figure 3* provides a good description of phase relationships in the commercial high-performance ferritic stainless steels. When carbon and nitrogen are stabilized with titanium and niobium, the position of the gamma loop is about as shown in the diagram and these compositions structurally will consist entirely of ferrite at chromium levels above about 11%. In the normal solution annealed condition, particles of titanium and niobium carbonitride will occur randomly throughout the ferrite matrix. Sigma phase can form in these alloys at chromium contents above about 20% and at even lower chromium contents when molybdenum is present.

Evidence of alpha prime formation has been detected at chromium contents as low as 12% in commercial alloys containing titanium after prolonged service exposures at elevated temperature. Alpha prime will form rapidly at ferrite chromium contents above about 18%. Molybdenum and other alloying elements will affect the stability ranges and the kinetics of formation of these and other secondary phases, generally promoting their formation. From the standpoint of the commercial production and application of these stainless steels, practices are always designed to maintain a ferritic structure containing only titanium or niobium carbonitrides. A review by J. J. Demo and other excellent papers found in “Source Book on Ferritic Stainless Steels”, edited by R. A. Lula[3] provide a detailed discussion on the metallurgy of the ferritic stainless steels.

Pseudo-binary sections through the iron-chromium-nickel ternary help illustrate the effect of temperature on regions of phase stability for the duplex and austenitic alloys. For the duplex stainless steels, a section through the ternary at 60% iron as proposed by Pugh (*Figure 4*) is useful. Duplex alloys characteristically solidify as ferrite. Increasing amounts of austenite then become stable at lower temperatures to about 1000°C (1832°F).

Figure 3 **Iron-chromium phase diagram showing the stability of sigma (σ) and alpha prime (α′) phases over a broad chromium range at low temperature[1,2]**

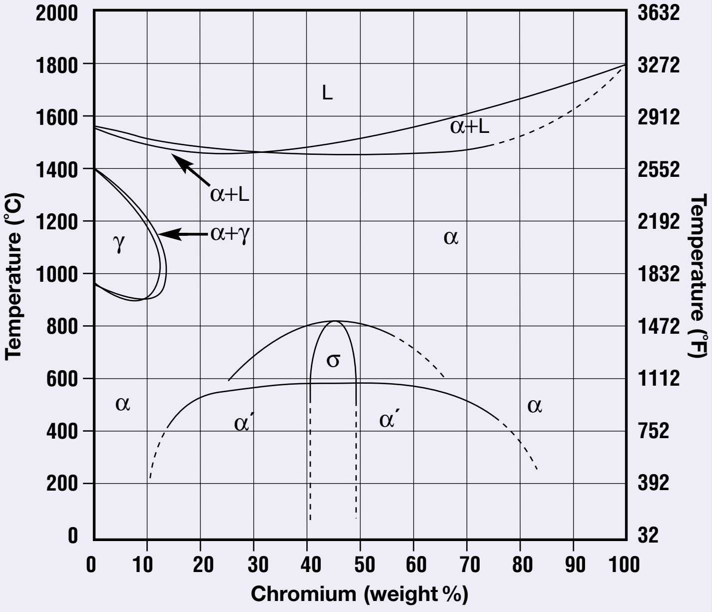


Figure 4 **Section through the Fe-Cr-Ni ternary phase diagram at 60% iron showing the effect of small changes in nickel and chromium on the ferrite and austenite in duplex stainless steels[4]**

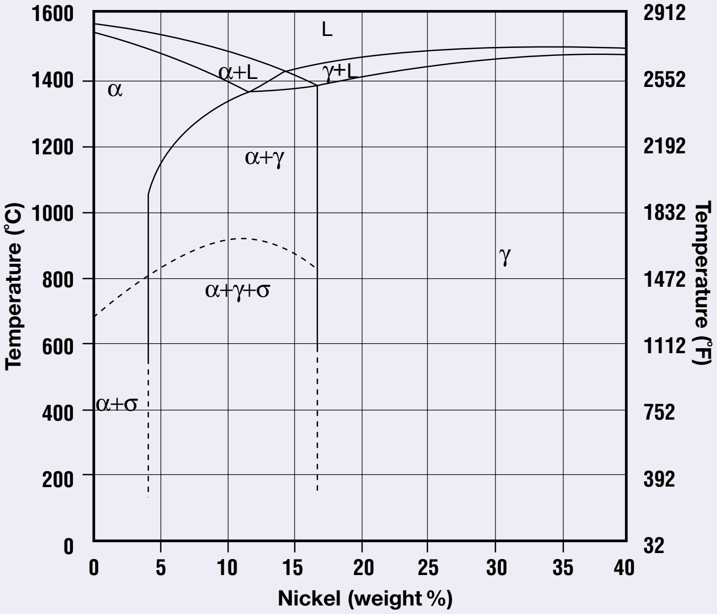


Figure 5 ***Section through the Fe-Cr-Ni ternary phase diagram at 16% nickel showing the solidification mode with respect to austenite and ferrite in austenitic stainless steels***[5]

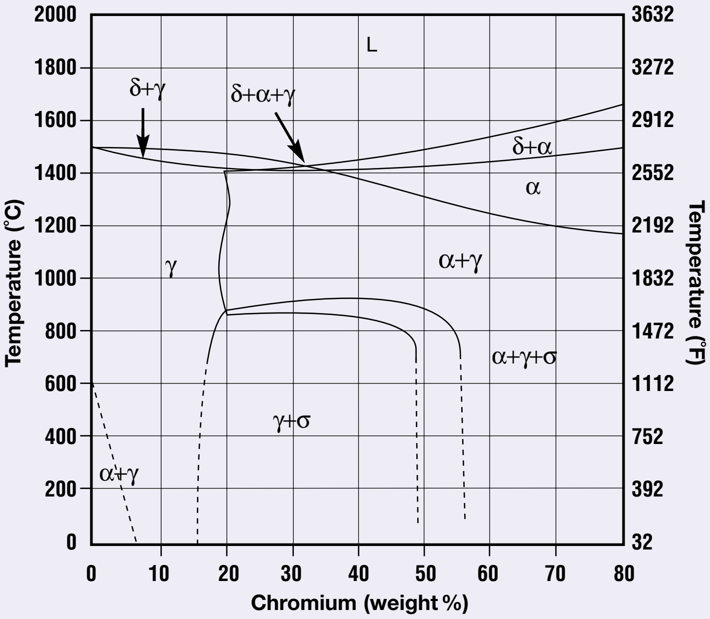
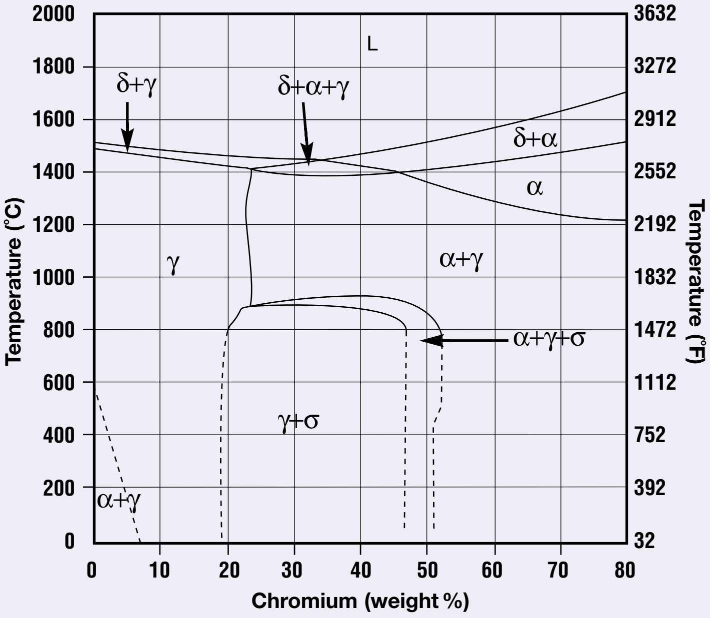


Figure 6 ***Section through the Fe-Cr-Ni ternary phase diagram at 20% nickel showing the solidification mode with respect to austenite and ferrite in austenitic stainless steels***[5]



The relative amounts of ferrite and austenite are critically dependent on the chemical composition and its thermal history. Small changes in composition or thermal treatment can have large effects on the relative volume fraction of these two phases in a finished mill product or component after a thermal treatment such as welding. Phase diagrams have not been developed to take into account the many elements that influence phase balance in the duplex alloys. However, the relative phase-forming tendencies of specific elements as they are known for the austenitic grades will also apply reasonably well to the duplex grades. Because ferrite is the primary solidification phase, it is possible to have more than the equilibrium amount of ferrite in a finished mill product after fabrication, but the opposite is not true with respect to austenite.

Sigma phase is also a stable phase in the high-performance duplex stainless steels as shown in *Figure 4*. The upper temperature limit of sigma phase stability is somewhat higher in the duplex grades than it is in the ferritic grades, approaching about 900°C (1652°F). Alpha prime also can precipitate in duplex alloys, forming in the ferrite phase in the same manner as occurs in the fully ferritic alloys. The use of nitrogen as an alloying element in these stainless steels can result in chromium nitrides also being present, especially when the ferrite content is high.

Temperature-dependent phase relations for the austenitic stainless steels are illustrated in *Figures 5* and *6* with pseudo-binary sections through the Fe-Cr-Ni ternary at 16% and 20% nickel. Depending on composition, these alloys can solidify with austenite phase as the primary dendrites or in a mixed mode of ferrite and austenite. Because austenite grain boundaries are more susceptible to impurity-related phenomena than ferrite or austenite-ferrite boundaries, and because diffusion rates are generally less in austenite, there can be considerable differences in hot cracking, hot working, and segregation behaviour among the various high-performance austenitic stainless steels depending on their mode of solidification. Compositions which produce some ferrite at the time of solidification are less susceptible to solidification and other hot cracking problems. Depending on composition, there is the possibility of equilibrium ferrite existing below the solidus temperature, especially in the lower nickel grades as shown in *Figure 5*. As with the other stainless steel families, sigma and other secondary phases become stable at lower temperature. The upper temperature limit of sigma phase stability in the commercial grades is about 1050°C (1922°F), higher than in the ferritic or duplex grades. The extent to which these phases may occur depends on actual chemistry, solidification rate, segregation effects, and thermal-mechanical treatments. The occurrence of at least a small amount of one or more of these phases should be considered typical in many of the commercial austenitic grades.

SECONDARY PHASES

Simple ternary phase diagrams provide only a starting point for understanding the complex metallurgy of these multi-component alloys. It is also important to know what secondary phases can exist and under what circumstances, because their occurrence can have profound effects on corrosion resistance and mechanical properties. Secondary phases that have been found in the high-performance stainless steels are listed in *Table 4*. They can be classified as either carbides, nitrides, or intermetallic compounds.

Table 4 Secondary phases in high-performance stainless steels

Stainless Steel*	Phase	Symbol	Type	Formula	Temperature Range	Structure	Lattice Constants
D	chromium carbide	–	M_7C_3	$(Cr,Fe,Mo)_7C_3$	950-1050°C	orthorhombic	a=4.52, b=6.99, c=12.11
A, D, F	chromium carbide	–	$M_{23}C_6$	$(Cr,Fe,Mo)_{23}C_6$	600-950°C	cubic	a=10.57-10.68
A, D, F	chromium carbide	–	M_6C	$(Cr,Fe,Mo,Cb)_6C$	700-950°C	cubic	a= 10.93-11.28
D, F	chromium nitride	–	M_2N	$(Cr,Fe)_2N$	650-950°C	hexagonal	a=2.77, c=4.46
D	chromium nitride	–	MN	CrN	–	cubic	–
D	Fe-Mo nitride	–	M_5N	$Fe_7Mo_{13}N_4$	550-600°C	–	a = 6.47
A	Nb-Cr nitride	Z	MN	(NbCr)N	700-1000°C	tetragonal	a=3.03, c=7.37
F	titanium carbo-nitride	–	MC	Ti(CN)	700°C-m.p.	cubic	a=4.32-4.24
F	niobium carbo-nitride	–	MC	Nb(CN)	700°C-m.p.	cubic	a=4.42-4.38
A, D, F	Sigma	σ	AB	(Fe,Cr,Mo,Ni)	550-1050°C	tetragonal	a=8.79, c=4.54
A, D, F	Chi	χ	$A_{48}B_{10}$	$Fe_{36}Cr_{12}Mo_{10}$ $(FeNi)_{36}Cr_{18}(TiMo)_4$	600-900°C	cubic	a=8.86-8.92
D, F	Alpha prime	α′	-	CrFe(Cr 61-83%)	350-550°C	cubic	a=2.877
A, D, F	Laves	η	A_2B	$(FeCr)_2(Mo,Nb,Ti,Si)$	550-900°C	hexagonal	a=4.73-4.82, c=7.26-7.85
D, F	R	R	–	(Fe,Mo,Cr,Ni)	550-650°C	rhombohedral	a=10.903, c=19.347
D	Tau	τ	–	–	550-650°C	orthorhombic	a=4.05, b=4.84, c=2.86

**Code: A = Austenitic, D = Duplex, F = Ferritic*
Source: General Literature

Chromium Carbides.
Chromium carbides are never a significant structural feature in terms of volume fraction because all these stainless steels are melted with low carbon content. Normal annealing temperatures are adequate to solutionize carbon in the stabilized ferritic grades and in the duplex and austenitic grades where the austenite has high solubility for carbon at annealing temperatures. The occurrence of carbides is usually confined to fine intergranular precipitates formed at intermediate temperatures by inadequately rapid cooling from the annealing temperature range or upon cooling after welding. Of the various possible chromium carbides, the $M_{23}C_6$ type is by far the most common. It will usually contain some molybdenum, and generally precipitates over the 550-950°C (1020°F-1740°F) temperature range. Other carbides that have been reported are the M_7C_3 and M_6C types as described in *Table 4*. Intergranularly precipitated carbides can produce intergranular corrosion and also reduce the pitting resistance. These effects are primarily a result of chromium depletion adjacent to the carbide, but depend also on carbide morphology and the time available to heal chromium depletion during cooling through the carbide precipitation temperature range.

Titanium and Niobium (Columbium) Carbonitrides.
These carbonitrides occur primarily in the stabilized ferritic grades, but may also occur to a small extent in the austenitic grades because titanium may be included in the deoxidation procedures. They have negligible effects on the properties of the austenitic grades. When titanium or niobium is used to stabilize carbon and nitrogen in the ferritic grades, the resulting carbonitride forms initially as nitride over the solidification temperature range. The nitride then takes on carbon as the temperature drops through about 1050°C (1920°F). Consequently, these phases do not play a major role in the corrosion behaviour of properly annealed ferritic grades. However, if the annealing temperature is too high, carbon and nitrogen can be re-solutionized and produce sensitization by the precipitation of chromium carbide during cooling through the lower temperature sensitization range. Also, the titanium and niobium carbonitrides are attacked by some strong acids and can act as initiation sites for brittle fracture in the ferritic grades.

Chromium Nitrides.
The use of high nitrogen in the duplex and austenitic high-performance stainless steels favours the occurrence of various chromium nitrides of which Cr_2N is the most common. Nitrogen is quite soluble in these high chromium grades at hot working and annealing temperatures; so these nitrides generally form upon cooling below these temperature ranges. In the austenitic grades, they can precipitate in the sensitization temperature range and usually appear as fine intergranular precipitates that are difficult to distinguish from carbide and sigma phase. In the duplex grades, the morphology of chromium nitride precipitates is highly dependent on prior thermal history. With proper solution annealing and rapid cooling, the typical forty to sixty percent austenite phase balance is adequate to solutionize all of the available nitrogen; so chromium nitride is not normally a microstructural constituent. However, high annealing or hot working temperatures and welding will reduce the amount of austenite available to solutionize nitrogen. In this case even rapid cooling can result in fine spherical and needle-shaped nitride precipitate within the ferrite phase and on ferrite-ferrite and ferrite-austenite grain boundaries. As with chromium carbide, either slow cooling or heating within an intermediate temperature range of about 650-950°C (1200-1740°F) will produce intergranular nitrides that can be deleterious to corrosion resistance.

Sigma Phase.
Sigma phase can form in virtually all of the high-performance stainless steels and it is probably the most important secondary phase in terms of its effects on corrosion and mechanical properties. Its high rate of formation and potentially large volume fraction is favoured by high chromium and molybdenum content. Because high chromium and molybdenum are an essential feature, minimizing the occurrence of sigma phase can be a significant factor in the

successful production and fabrication of the more highly alloyed stainless steels. The upper temperature limit of sigma phase stability is about 1050°C (1920°F). All these grades were developed to be free of sigma phase in the solution annealed condition. However, traces of sigma are not uncommon in solution annealed austenitic grades because of segregation in the starting cast slab or ingot. The rapid precipitation kinetics and high sigma solvus temperature in these highly segregated regions make it almost impossible to produce mill product totally free of sigma. One of the goals in annealing the austenitic grades is to reduce solidification segregation, and thus minimize sigma phase. The duplex and ferritic grades are less prone to solidification segregation, and so any sigma phase that occurs is usually the result of precipitation below the sigma solvus temperature. Precipitation usually occurs on ferrite-ferrite and ferrite-austenite grain boundaries. The formation of sigma phase results in chromium and molybdenum depletion in the surrounding matrix, and this is believed to be the cause of reduced corrosion resistance usually associated with its presence. This effect is most pronounced with sigma produced at low temperature and short times. Homogenization and working treatments can minimize the effect so that small amounts formed during solidification will have little effect in wrought products. Sigma also adversely affects ductility and toughness because it is a hard and brittle phase. These effects are very pronounced in the ferritic and duplex grades and are significant in the austenitic grades as well.

Chi Phase.

Chi phase forms over about the same temperature range and has about the same kinetics of formation as sigma phase. It occurs in the ferritic and duplex grades often concurrent with sigma, but usually in a much smaller volume fraction. If well developed, it can be distinguished optically from sigma by its more blocky morphology and higher reflectivity. Chi also reduces corrosion resistance and toughness, but these effects have been difficult to quantify because it always occurs as a minor phase with sigma.

Alpha Prime.

Alpha prime is a chromium-rich phase that is responsible for the well known 475°C (885°F) embrittlement that occurs in the ferritic and duplex grades. It precipitates as very fine, submicroscopic particles that are coherent within the ferrite matrix. While it cannot be detected by optical microscope, its presence is usually accompanied by increased hardness, a loss of corrosion resistance, and reduced toughness. It occurs over the 350-550°C (660°F-1020°F) temperature range. Its kinetics of formation are considerably slower than those of the higher temperature precipitates (sigma and chi), so it is unlikely to form upon cooling from normal welding or annealing operations. However, the ferritic and duplex stainless steels can become severely alpha prime embrittled during service; so the upper service temperature is usually limited to less than about 300°C (570°F) for these grades.

KINETICS OF PHASE PRECIPITATION REACTIONS

The two principal elements that improve corrosion resistance, chromium and molybdenum, also participate in the formation of many of the damaging intermetallic phases that may occur in the high-performance stainless steels. The rate of formation of these phases can be very rapid. Consequently, the thermal treatments required for processing and fabrication, as well as service thermal cycles, must take reaction kinetics into account to ensure that anticipated corrosion and mechanical properties are obtained. Most of these grades have been developed on the basis of establishing a compromise between maximizing corrosion resistance and retarding precipitation reactions sufficiently to allow for successful processing. Reducing carbon content and adding nitrogen retards many of these precipitation reactions.

Most studies of precipitation kinetics are based on isothermal heat treatments and metallographic and X-ray determinations of early stages of phase precipitation. Isothermal techniques yield rapid kinetics in transformation diagrams. On the other hand, continuous cooling thermal cycles, as usually encountered commercially, generally will retard kinetics. While microstructure is important, property alterations due to precipitation will depend on the stage of development of the precipitate and on the property in question. There are cases where some degree of precipitation can be tolerated and still give useful properties. There are other situations where properties can be affected before precipitates are detected in the microstructure.

AUSTENITIC STAINLESS STEELS

The secondary phase transformation kinetics of a conventional austenitic stainless steel such as Type 316 is characterized by very sluggish chi and sigma transformation (transformation takes hundreds of hours) and carbide kinetics which are highly dependent on the carbon content. In the low carbon grades, the time to initiate carbide precipitation is about thirty minutes to an hour, more than adequate to carry out normal annealing and welding operations without causing sensitization. In the high-performance austenitic stainless steels, the high chromium and molybdenum contents accelerate chi and sigma reactions; this effect is only partially mitigated by the retarding effect of higher nickel and nitrogen. The higher nickel and chromium contents also reduce carbon solubility; so these grades are intolerant of carbon contamination and have very rapid sensitization kinetics. They must be produced with low carbon levels, and many of these grades use a nitrogen addition to further retard carbide precipitation. These grades are a compromise between efforts to obtain better corrosion resistance and to sufficiently delay secondary phase reactions to allow successful processing and fabrication. This has been achieved, but in general, cooling rates must be faster or section sizes must be smaller than they are for the lower alloyed conventional austenitic stainless steel grades.

A transformation diagram for Type 316 stainless steel is shown in *Figure 7* to illustrate the secondary phase initiation times in this relatively low alloy grade. In *Figures 8* and *9*, the accelerating effect of 5% molybdenum and the retarding effect of 0.145% nitrogen are illustrated for a 17Cr-13Ni base composition similar to Type 316. In the 5% molybdenum base composition, the start of both chi and carbide precipitation is in the order of a few seconds without nitrogen; but the use of nitrogen alloying delays the start by an order of magnitude. In these grades, the chi reaction often leads or occurs at about the same time as the start of sigma precipitation, and at about the same time as the start of carbide precipitation.

***Figure 7** Isothermal precipitation kinetics of intermediate phases in Type 316 stainless steel annealed at 1260°C (2300°F)*[6]

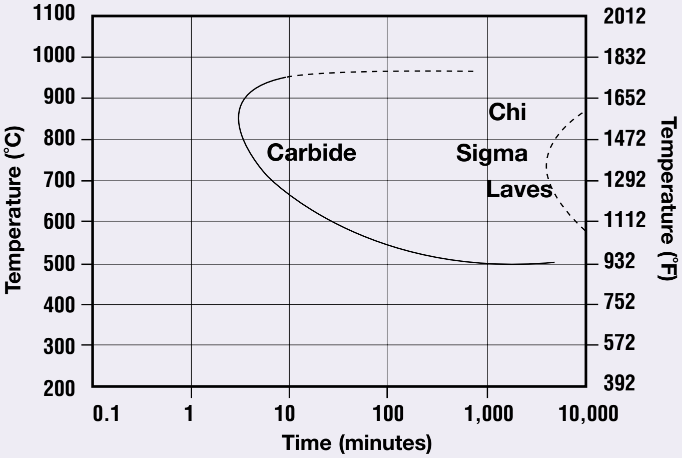


***Figure 8** Isothermal precipitation kinetics of intermediate phases in a 0.05C-17Cr-13Ni-5Mo alloy containing 0.039% nitrogen annealed at 1100°C (2012°F)*[7]

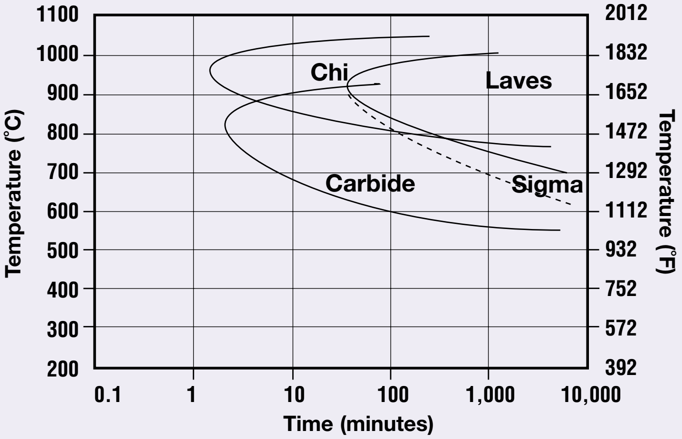
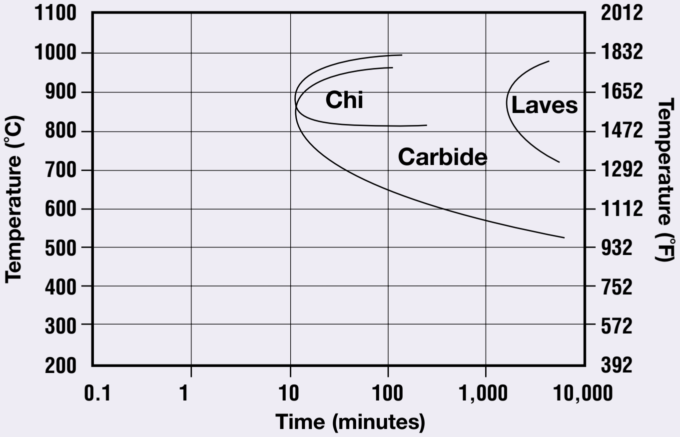


Figure 9 Isothermal precipitation kinetics of intermediate phases in a 0.05C-17Cr-13N-5Mo alloy containing 0.145% nitrogen annealed at 1150°C (2102°F)[7]



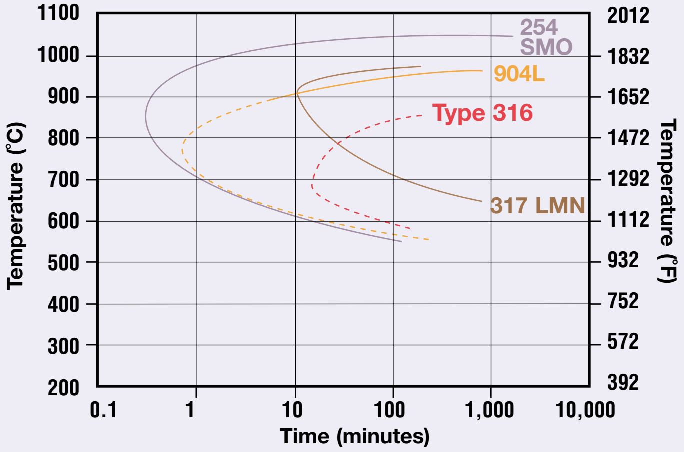
In the high-performance austenitic stainless steels, the volume fraction of intermetallic phases, when they occur, is usually not very large. Precipitation usually occurs on austenite grain boundaries with similar morphological features regardless of the specific phase. Therefore, the various phases are difficult to distinguish among themselves; and because they all have a similar deleterious effect on corrosion properties, it is often convenient to merely identify the start time for "all" precipitates in studies aimed at engineering applications. This has been done for three commercial high-performance grades compared with Type 316 in *Figure 10*. The temperature at the nose of the precipitation start curve for the high performance grades 254 SMO, 904L, and 317LMN is somewhat higher than that of Type 316. This reflects the higher temperature stability of chi and sigma in the high-performance stainless steels compared with the lower temperature stability for carbide in Type 316.

FERRITIC STAINLESS STEELS

The ferritic stainless steels are the least tolerant of secondary phases because of the intrinsic low toughness of the ferrite structure and its low solubility for the interstitial elements, carbon and nitrogen. The commercial high performance ferritic grades listed in *Table 2* are made with what may be described as low (<600 ppm) or very low (<250 ppm) contents of carbon plus nitrogen. However, stabilization is still required and, in both cases, titanium or niobium additions are used to control the detrimental effects of these interstitial elements.

An isothermal transformation diagram for Fe-26Cr alloys with 180 ppm (C+N) is given in *Figure 11*. Chromium carbide and nitride precipitation can occur and lead to intergranular attack if it occurs in the sensitization temperature range of about 500-800°C (930-1470°F). This precipitation will occur in the very low interstitial range as well as at higher levels. In these stainless steels, titanium nitride has very low solubility in ferrite and exists as a stable phase at all temperatures below the solidus. However, substantial solubility exists for the titanium carbide and the niobium nitride and carbide above about 1100°C (2010°F). At lower temperatures, titanium, niobium, and chromium carbide and nitride precipitation can occur but will not generally produce sensitization if it occurs above about 800°C (1470°F). Thus, annealing treatments and successful welding are based on this stabilization effect.

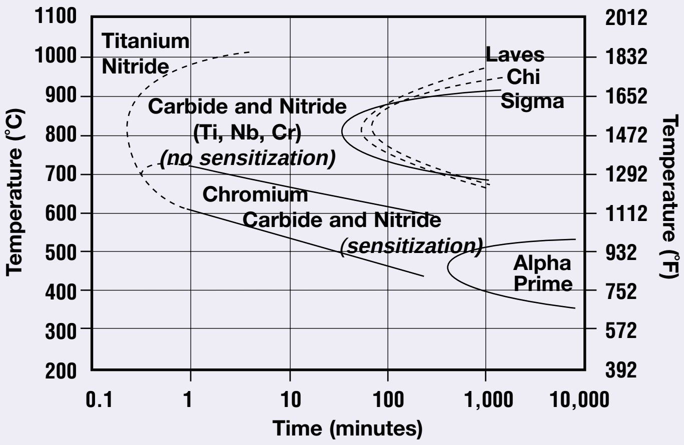
Figure 10 Isothermal precipitation kinetics of several high-performance stainless steels compared with Type 316 stainless steel[8]



Stabilization is believed to occur at these temperatures because the diffusion rate of chromium in ferrite is high enough to replenish chromium depletion associated with the precipitation. The kinetics for precipitation in the stabilization range have not been defined for these stainless steels and so are shown by the dashed curve in *Figure 11*. It is known that water quenching of thin sections can substantially suppress the precipitation. This has been used effectively with the high-performance ferritic family where rapidly cooled thin sections are used in heat exchanger applications.

Precipitation in the 500-800°C (930-1470°F) range will produce sensitization and subsequent intergranular corrosion in corrosive environments for hold times certainly much shorter than the minimum one minute used by Demo[9]. It is believed that the kinetics are similar for the higher interstitial, stabilized alloys, but will depend on the time spent in the high temperature stabilization range before cooling to the sensitization range. The slope of the sensitization C-curve indicates that some chromium replenishment of the sensitized grain boundaries can occur during prolonged holds at sensitization temperatures.

Figure 11 Isothermal precipitation kinetics of intermediate phases in ferritic stainless steels containing 26% chromium, 1-4% molybdenum, and 0-4% nickel[9,10,11,12]



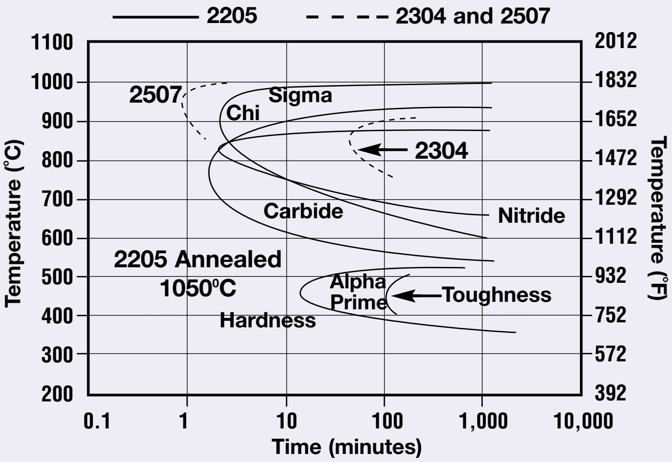
The nose of the sigma precipitation curve lies at about 820°C (1510°F) and 30 minutes for a stabilized 25Cr-4Mo-4Ni stainless steel as shown in *Figure 11*. Chi and laves phase precipitation follows the sigma phase kinetics at low temperatures, but their stability range extends to higher temperatures than does sigma phase. Kinetics are considerably slower than shown in *Figure 11* with the lesser alloyed 26Cr-1Mo versions of these grades. It occurs after about twenty-five minutes in the 26Cr-3Mo-3Ni grade, and the most rapid time of precipitation can be just a few minutes in the 29Cr alloys.

Alpha prime precipitation cannot be detected by optical metallography but will produce substantial changes in mechanical properties, especially a reduction in toughness accompanied by hardening. The alpha prime initiation kinetics shown in *Figure 11* were determined based on initial hardening in a 26Cr-3Mo-3Ni stabilized grade. In this work, some hardening occurred after one year at temperatures as low as 315°C (600°F), but no hardening was observed after three years at temperatures of 300°C (572°F) and 290°C (550°F). The alpha prime transformation kinetics do not appear to vary much with alloy content. This was demonstrated by Nichol et al.[12], who found an initiation time of ten hours for both stabilized 26Cr-1Mo and unstabilized 29Cr-4Mo-2Ni alloys, the same time shown for the 26Cr-3Mo-3Ni grade in *Figure 11*.

DUPLEX STAINLESS STEELS

The kinetics of intermetallic phase precipitation in the duplex stainless steels are influenced by the often simultaneous transformation of delta ferrite to austenite upon cooling through the temperature range of about 1100-600°C (2010-1110°F) and by the strong effect of nitrogen. The phase equilibrium relationships discussed earlier imply that these stainless steels are nearly 100% ferrite at the solidus temperature and nearly 50% ferrite at temperatures below about 1000°C (1830°F). Even upon cooling from normal annealing temperatures of about 1050°C (1920°F), some reversion of ferrite to austenite will take place. This austenite is often termed secondary austenite. Three mechanisms of ferrite reversion to austenite

Figure 12 Isothermal precipitation kinetics of intermediate phases in 2205 compared with 2304 and 2507 duplex stainless steels[13,16]



have been identified. They have been described by Josefsson[13] as 1) a eutectoid reaction producing a lamellar distribution of sigma and austenite in previous ferrite, 2) "Widmanstatten" precipitates of austenite in ferrite, and 3) a diffusionless martensite-like reaction that takes place below about 650°C (1200°F). Therefore, aside from intermetallic phases, the austenite-ferrite microstructure can be quite complex, especially in material rapidly cooled from high temperature.

An isothermal transformation diagram for 2205 duplex stainless steel, constructed from several sources and simplified by ignoring the ferrite reversion to austenite, is given in *Figure 12*. An important feature of this diagram is that the start of chromium carbide and nitride precipitation begins at the relatively slow time of 1-2 minutes, much slower than in the ferritic grades even though stabilizers are not used in this or the other duplex grades. This is due, in part, to the high solubility of interstitial elements in the austenite phase, and possibly also a retardation effect of nitrogen on the carbide kinetics. As a result, the duplex grades are more resistant to sensitization on cooling than are the ferritic grades. The carbide and nitride kinetics are only marginally affected by chromium, molybdenum, and nickel in these grades; so most nitrogen-alloyed duplex stainless steel grades will have kinetics similar to 2205 in regard to these precipitates.

Sigma and chi precipitation occurs at slightly higher temperatures and in approximately the same time as the carbide and nitride precipitation. Although both phases are shown to have the same kinetics and temperature range of stability in *Figure 12*, this is not always the case. In the duplex grades in general, chi phase often lags behind the sigma reaction

Courtesy Sandvik Steel

Seamless tubes in SAF 2507® used for umbilicals in subsea oil and gas extraction

and is stable at slightly lower temperatures. Sigma phase usually occurs in greater amounts than chi. Because it precedes the chi reaction, and because the two phases have similar effects on properties and are difficult to distinguish metallographically, it is often convenient to describe effects of “sigma phase” when dealing with the duplex stainless steels. Duplex grades that are more highly alloyed in chromium, molybdenum, and nickel will have more rapid sigma and chi kinetics than 2205, and the converse exists for the lower alloyed grades. This is illustrated by the dashed curves in *Figure 12* showing the start of sigma and chi formation in grades 2304 and 2507, and occurs because chromium and molybdenum and possibly manganese accelerate the precipitation kinetics. Nickel has a similar accelerating effect, but the effect may be a result of nickel promoting austenite formation with resultant increased chromium and molybdenum partitioning to the ferrite phase. High solution annealing temperatures and continuous cooling tend to reduce the rate of formation of sigma phase.

Alpha prime hardening occurs quite rapidly in the ferrite phase, but not in austenite. Therefore, the effect of alpha prime precipitation on the bulk properties of the duplex stainless steels lags behind the initial formation of alpha prime in ferrite by a substantial margin. This is shown by the two alpha prime initiation curves in *Figure 12*, with one based on hardness and the other on toughness.

MECHANICAL PROPERTIES

While the main driving force for the development of the high-performance stainless steels has been corrosion resistance, enhanced mechanical properties have also been obtained in many instances. This is especially true for the metallurgically more complex duplex grades that have a good combination of strength and toughness when their structures are carefully controlled. It pertains also to the nitrogen-enhanced austenitic grades, which have excellent toughness at strength levels well above the standard grades. This is significant from the standpoint of cost, because thinner sections often can help offset the higher cost associated with higher alloy content. This benefit has been used to advantage in all product forms to reduce the cost of large piping installations, large process units, pressure vessels, and pressure piping, and to reduce the weight of topside structures on offshore platforms.

Because temperature and metallurgical effects on mechanical properties are quite different for each of the three grade groups, they are discussed separately in the following sections. Each section begins with a description of basic mechanical properties for the solution annealed condition as would be provided in mill-produced product. Property changes related to metallurgical effects produced by fabrication, heat treatment, and service are then considered.

AUSTENITIC STAINLESS STEELS

The mechanical properties of the high-performance austenitic grades provide an excellent combination of good strength, ductility, and toughness over a broad temperature range. Their good impact

Courtesy Avesta Sheffield AB

"God and the Rainbow" sculpture from an original idea by Carl Milles in 254 SMO® stainless steel

strengths at low temperatures are unique for such high-strength materials. These grades are stronger than the standard austenitic grades because strength gradually increases as alloy content increases. Most of the alloying elements used to improve corrosion resistance or control phase balance are also solution strengtheners as shown in *Figure 13*. The most potent strengthener in these steels is nitrogen, which is also beneficial to corrosion resistance and for retarding the formation of some intermetallic phases. The effect of nitrogen on strength is shown in *Figure 14*, where a near 50% yield strength increase over Type 304 stainless steel is indicated for a nitrogen content of 0.20%. This strengthening effect diminishes somewhat at higher nitrogen contents, but commercial grades are available containing a nominal 0.50% nitrogen which will meet minimum yield strength specifications of 420-460 MPa (61-67 ksi). While nitrogen and other strengthening elements diminish ductility somewhat as shown in *Figure 14*, these grades still have sufficient ductility to handle most cold forming operations.

Figure 14 Effect of nitrogen on the strength and ductility of Type 304 stainless steel[18]

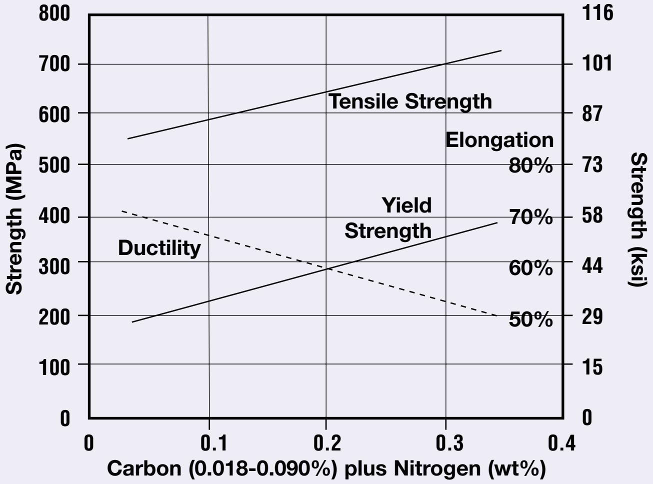
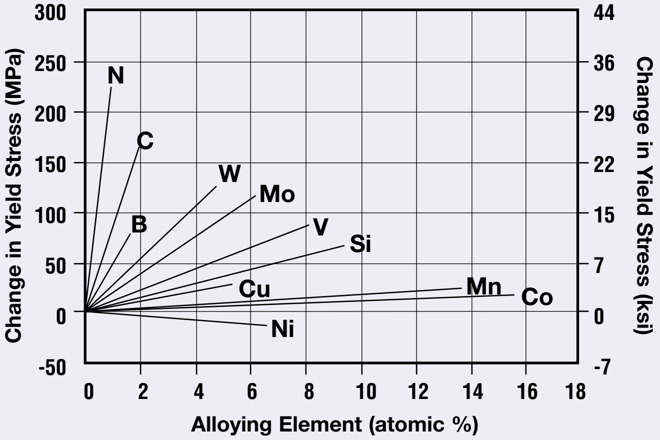


Figure 13 Solid solution strengthening effects by alloying in austenitic stainless steels[17]



A list of the minimum ambient temperature mechanical property requirements for these grades as defined by the ASTM Standard Specification for plate, sheet and strip (A 240) is provided in *Table 5*. A comparison of this table to the grade chemistries given in *Table 1* shows that the specified minimum strengths also increase with substitutional alloy content and nitrogen content. This is illustrated in *Figure 15*, where the minimum specification strengths of representative grades with increasing alloy content are compared with strength data for Type 316L. The ASME Code allowable design stress values given in *Table 6* also reflect these strengthening effects. The allowable stress values for some high-performance grades are more than two times that of Type 316L.

Strength increases at low temperatures as shown in *Figure 16*, and this is accompanied by little loss in ductility. The rate of strengthening at low temperatures is not as great as for Type 316 and most other standard grades because the high performance grades are very stable with regard to martensite transformation. This is an advantage with regard to ductility and toughness, and in applications where low magnetic permeability is required.

These grades also have very good toughness at room temperature, even those that contain substantial nitrogen additions. This is illustrated in *Figure 17*, with fracture toughness and impact data for a group of austenitic stainless

Table 5 Minimum mechanical properties in basic ASTM specifications for high-performance austenitic stainless steels

Name	UNS Number	ASTM Specification	Tensile Strength (minimum)		Yield Strength (minimum)		Elongation (minimum)	Hardness (maximum)	
			ksi	MPa	ksi	MPa	%	Brinell	HRB
Type 316L	S31603	A 240	70	485	25	170	40	217	96
Type 317L	S31703	A 240	75	515	30	205	40	217	96
Alloy 20	N08020	A 240/B 463	80	551	35	241	30	217	96
Alloy 825	N08825	B 424	85	586	35	241	30	–	–
317LN	S31753	A 240	80	550	35	240	40	217	96
260	–	–	80	550	40	275	35	217	–
317LM	S31725	A 240	75	515	30	205	40	217	96
317LMN	S31726	A 240	80	550	35	240	40	223	97
204X	–	–	73	500	30	210	35	187	90
310MoLN	S31050	A 240	80	550	35	240	30	217	96
700	N08700	B 599	80	550	35	240	30	–	90
904L	N08904	A 240/B 625	71	490	31	220	35	–	–
20Mo-4	N08024	B 463	80	551	35	241	30	217	96
20 Mod	N08320	B 620	75	517	28	193	35	–	95
Alloy 28	N08028	B 709	73	500	31	214	40	–	–
20Mo-6	N08026	B 463	80	551	35	251	30	217	96
25-6MO 1925 hMo	N08925/N08926	A 240/B 625	94	650	43	295	35	–	–
254N	–	–	94	650	43	300	35	217	96
SB8	–	–	79	550	37	250	35	–	–
254 SMO	S31254	A 240	94	650	44	300	35	223	97
AL-6XN	N08367	A 240/B 688	100	690	45	310	30	240	–
YUS 170	–	–	100	690	43	300	35	217	97
2419 MoN	–	–	120	820	67	460	30	–	–
4565S	S34565	–	115	800	61	420	35	–	–
3127 hMo	N08031	B 625	94	650	40	276	40	–	–
654 SMO	S32654	A 240	109	740	62	425	35	250	–

Source: Producer Data Sheets

Figure 15 Strengthening effect of nitrogen in high-performance austenitic stainless steels as manifested in ASTM A 240 minimum strength requirements

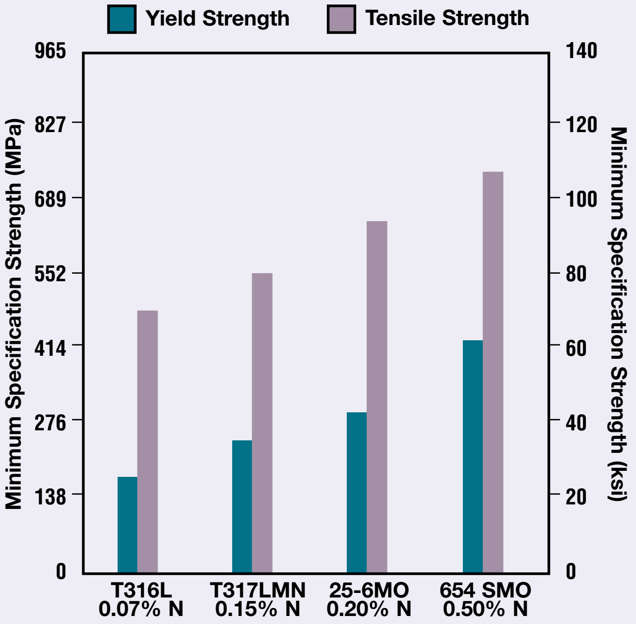


Figure 16 Low temperature strength of high-performance austenitic stainless steels

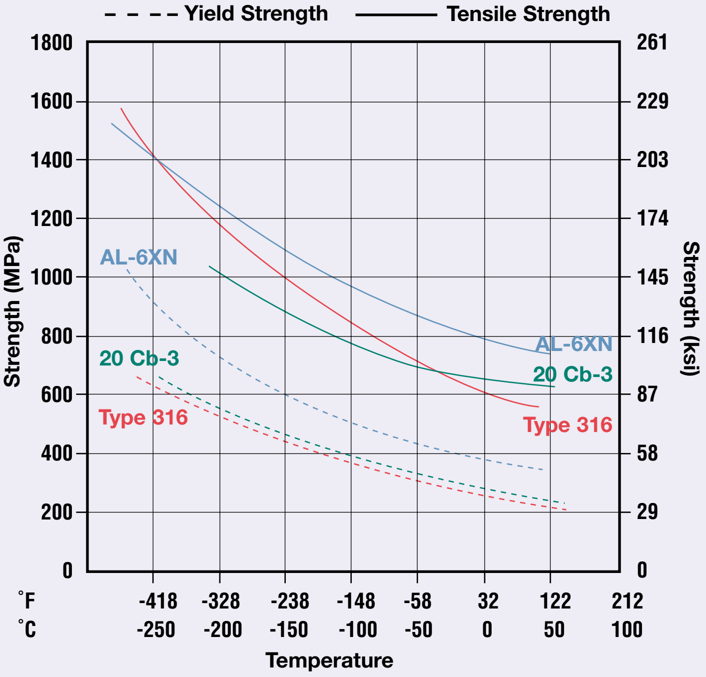


Table 6 High-performance austenitic stainless steels ASME allowable design stress values (ksi)

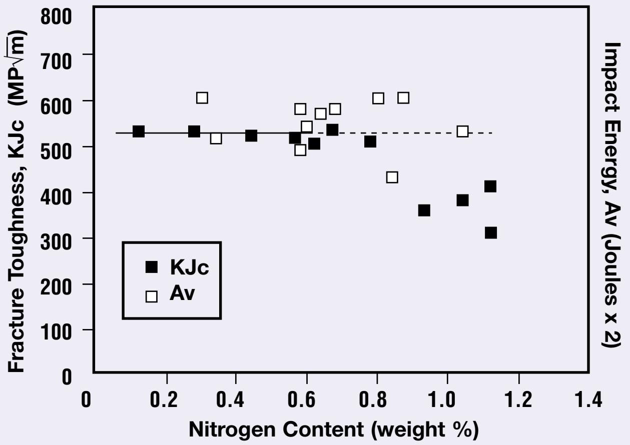
Boiler Pressure Vessel Code, Section VIII, Division I, 1999 Addenda (lowest values for sheet, plate or tube)

Name	UNS Number	ASME Specification	38°C (100°F)	93°C (200°F)	149°C (300°F)	204°C (400°F)	260°C (500°F)	316°C (600°F)	371°C (700°F)	427°C (800°F)
Type 316L	S31603	SA-240	16.7	14.2	12.7	11.7	10.9	10.4	10.0	9.6
Type 317L	S31703	SA-240	20.0	17.0	15.2	14.0	13.1	12.5	12.0	11.5
Alloy 20	N08020	SB-463	22.9	20.6	19.7	18.9	18.2	17.7	17.4	16.8
Alloy 825	N08825	SB-424	23.3	21.4	20.3	19.4	18.5	17.8	17.3	17.0
317LM	S31725	SA-240	20.0	16.9	15.2	14.0	–	–	–	–
317LMN	S31726	A 240	20.5	18.9	16.7	15.6	15.1	–	–	–
310MoLN	S31050	SA-240	22.9	19.9	18.1	16.8	15.9	15.1	–	–
700	N08700	SB-599	22.9	21.0	19.0	17.7	17.1	16.5	–	–
904L	N08904	SB-625	20.3	16.7	15.1	13.8	12.7	11.9	11.4	–
20Mo-4	N08024	SB-463	22.9	20.6	19.2	18.1	17.0	16.0	15.2	14.6
20 Mod	N08320	SB-620	18.7	17.3	16.3	15.4	14.5	13.8	13.2	12.7
Alloy 28	N08028	SB-709	20.7	18.9	17.7	16.5	15.4	14.4	13.6	12.8
20Mo-6	N08026	SB-463	22.9	20.7	19.0	17.5	16.3	15.3	14.5	13.9
25-6MO	N08925	SB-625	24.9	23.2	21.3	19.8	18.3	17.3	16.9	16.9
1925 hMo	N08925	SB-625	24.9	23.5	21.3	19.8	18.3	17.3	16.9	16.9
254 SMO	S31254	SA-240	23.9	23.5	21.4	19.8	18.6	17.9	17.4	–
AL-6XN	N08367	SB-688	27.1	26.2	23.8	21.9	20.5	19.4	18.6	18.0
654 SMO	S32654	SA-240	31.1	31.1	30.3	28.5	27.3	26.6	26.3	25.9
3127 hMo	N08031	B 625	23.5	22.0	19.7	18.3	17.2	16.4	15.7	15.2

steels containing nitrogen ranging to over one percent. Toughness falls off gradually at lower temperatures but is still substantial even at -200°C (-328°F) as shown in *Figure 18*.

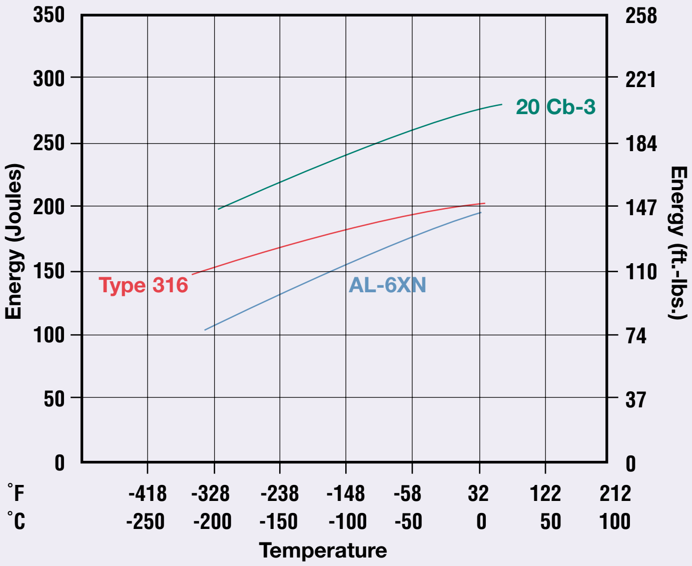
The high-performance austenitic grades also retain their strength advantage over the standard grades at elevated temperatures. Typical short-term elevated temperature strength data compared with Type 316L are given in *Figure 19*. These grades can provide useful service to considerably higher temperatures than the ferritic and duplex grades because they are not subject to alpha prime embrittlement. This is especially true for some of the lower chromium-molybdenum, or higher nickel-alloyed grades such as 20Cb-3. High temperature stress rupture data for this grade are given in *Figure 20*.

Figure 17 Effect of nitrogen in solid-solid solution on the toughness of annealed austenitic stainless steels at room temperature[19]



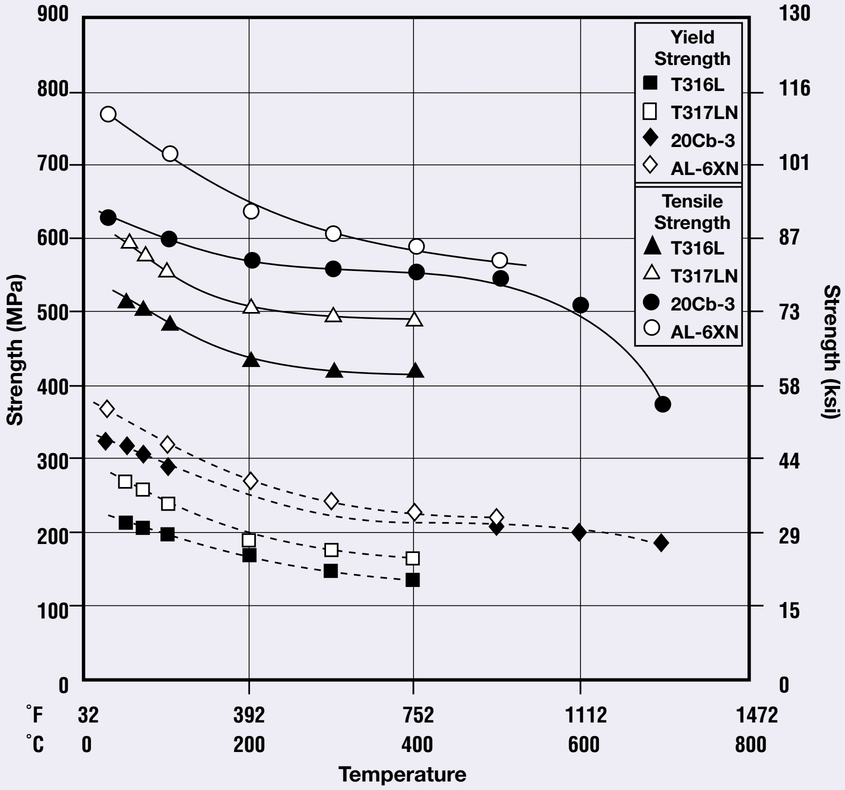
Source: Producer Data Sheets

Figure 18 Low temperature Charpy V-notch impact properties of high-performance austenitic stainless steels



Source: Producer Data Sheets

Figure 19 High temperature strength of austenitic stainless steels



FERRITIC STAINLESS STEELS

The tensile properties of the ferritic grades are characterized as having quite high-yield strength with useful but limited ductility. The high-yield strength is due to the strong solution strengthening effect of molybdenum and nickel in ferrite, and to the strong strengthening effect of small grain size that is typical for the ferrite structure. Tensile strengths are about the same as those found in the standard austenitic grades because ferrite, while having an initial high rate of work hardening at low strains, does not work harden to the same extent as austenite at high strains. The limited ductility is typical of the ferrite structure. A summary of minimum mechanical properties as specified in ASTM A 240 is provided in *Table 7*. Minimum yield strengths are as high as 515 MPa (75 ksi), and typical tensile elongation for mill annealed sheet is about 25-30%. These tensile properties translate into high ASME Boiler and Pressure Vessel design stress values as shown for welded tube in *Table 8*.

The ferritic grades have the shortcoming of exhibiting a distinct ductile-brittle transition temperature. While most mill products are produced with a fairly low transition temperature, the transition can occur at ambient or even higher temperatures if the grain size is coarse, or if intermetallic phases or significant amounts of interstitially dissolved carbon or nitrogen exist in the microstructure. This has presented a problem both in the production of these grades and in their commercial use in heavy sections, especially when welding is involved. This is illustrated in *Figures 21* and *22* for a heat treatment that would simulate the welding of ferritic stainless steels of various carbon and nitrogen contents. These stainless steels have very good toughness and transition temperatures below -50°C (-60°F) as initially stabilize annealed at 815°C (1500°F). However, a subsequent 1150°C (2100°F) anneal and water quench treatment produced a drastic increase in transition temperature even at moderately low

Source: Producer Data Sheets

Figure 20 Stress rupture properties of 20Cb-3 compared with Types 316 and 347 stainless steels at 10,000 hours (extrapolated values)

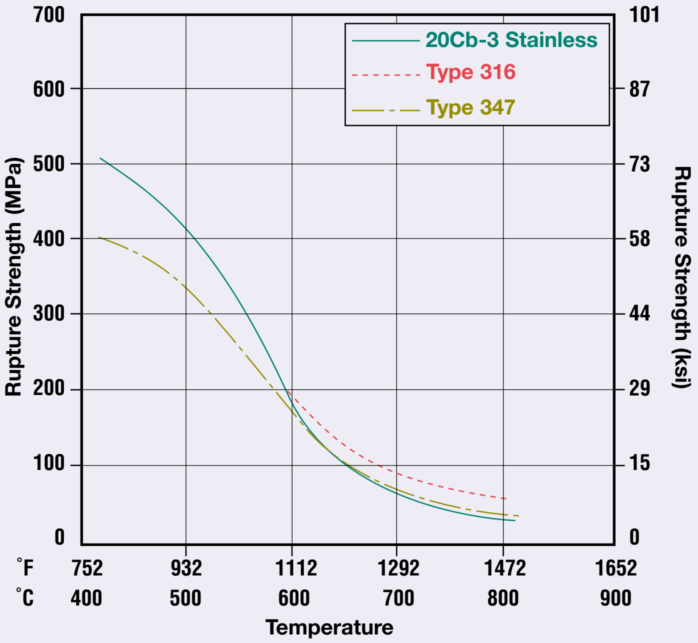


Table 7 Minimum mechanical properties in basic ASTM sheet and plate specifications for high-performance ferritic stainless steels

Name	UNS Number	Tensile Strength (minimum)		Yield Strength (minimum)		Elongation (minimum)	Hardness (maximum)	
		ksi	MPa	ksi	MPa	%	Brinell	HRB
Type 444	S44400	60	415	40	275	22	–	83
26-1S	S44626	68	470	45	310	20	217	96
E-BRITE 26-1	S44627	65	450	40	275	22	187	90
MONIT	S44635	90	620	75	515	20.0	269	28Rc
SEA-CURE	S44660	85	585	65	450	18.0	241	100
AL 29-4C	S44735	80	550	60	415	18.0	255	25Rc
AL 29-4-2	S44800	80	550	60	415	20.0	223	20Rc

Table 8 High-performance ferritic stainless steels ASME allowable design stress values (ksi)

ASME SA 268, Boiler Pressure Vessle Code, Section VIII, Division I, 1999 Addenda (Welded Tube)

Name	UNS Number	38°C (100°F)	93°C (200°F)	149°C (300°F)	204°C (400°F)	260°C (500°F)	316°C (600°F)
Type 444	S44400	14.6	14.6	14.1	13.8	13.5	13.1
26-1S	S44626	16.5	16.5	16.4	16.2	16.0	15.7
E-BRITE 26-1	S44627	15.8	15.8	15.5	15.4	15.4	15.4
MONIT	S44635	21.9	21.2	19.9	19.1	18.7	–
SEA-CURE	S44660	20.6	20.6	20.6	20.3	20.2	20.1
AL 29-4C	S44735	18.2	17.9	17.6	17.5	17.2	17.0
AL 29-4-2	S44800	19.4	19.1	18.8	18.6	18.4	18.1

Figure 21 Effect of nitrogen on toughness for quarter-size Charpy V-notch impact specimens of 17Cr-0.010-0.057N-0.004C ferritic stainless steels heat treated at 815°C + 1150°C for one hour and water quenched[20]

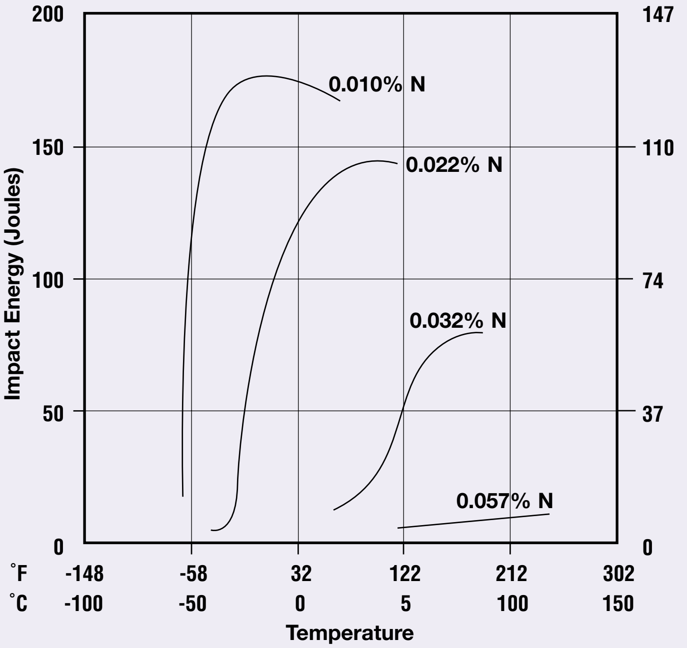
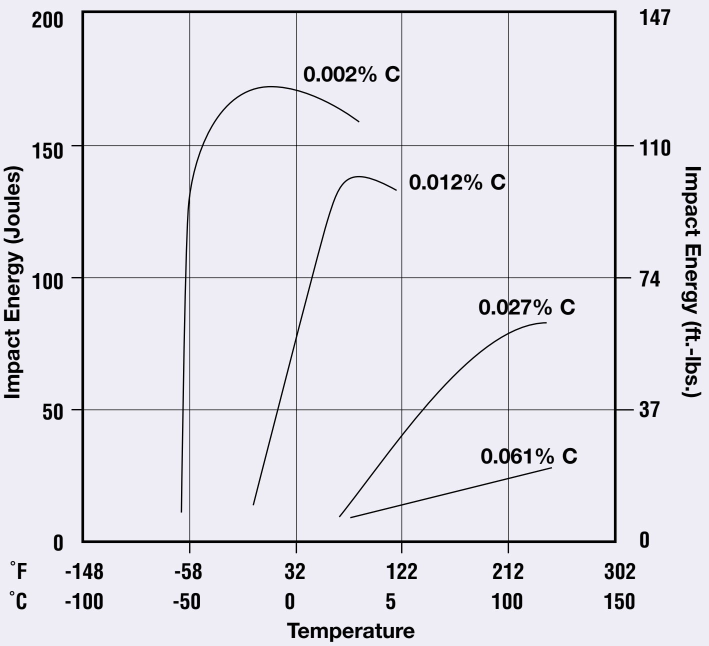


Figure 22 Effect of carbon on toughness for quarter-size Charpy V-notch impact specimens of 17Cr-0.002-0.061C-0.010N ferritic stainless steels heat treated at 815°C + 1150°C for one hour and water quenched[20]



carbon and nitrogen levels. A coarse grain size and precipitation of carbon and nitrogen in the higher carbon and nitrogen ferritic stainless steels caused this loss of toughness. The vacuum-melted, extra low carbon and low nitrogen grades such as AL 29-4-2 have superior ductile-brittle transition temperatures compared with the AOD-refined ferritics.

Ferritic stainless steels also have a service temperature limitation related to the embrittling effect of alpha prime precipitation. For this reason, the ASME Code allowable stresses for most of these grades are limited to 600°F (315°C) maximum. A somewhat lower maximum service temperature should be considered for applications involving extremely long service times.

DUPLEX STAINLESS STEELS

Tensile and yield properties of the duplex grades are quite high. Their ductility is between that of the ferritic and austenitic grades. Strength increases and ductility decreases as the level of alloying increases, especially nitrogen content. The attractive strength properties of the duplex grades are, in part, due to the combined effect of ferrite in raising the yield strength and that of austenite in providing a high tensile strength from strain hardening. Minimum yield strengths for sheet and plate are as high as 550 MPa (80 ksi) as shown in *Table 9*.

The elevated temperature strength of the duplex grades is also quite good (*Figure 23*). ASME Code design stresses are given in *Table 10.* These design stresses are considerably higher than those for either the austenitic or ferritic grades. The ASME Code allowable design stresses are based on the lowest values of either the yield or tensile strength. This adversely affects both the ferritic and austenitic grades and favours the duplex grades. For most duplex grades, ASME Code allowable stresses are limited to 315°C (600°F) because of alpha prime embrittlement; the German TüV code sets a somewhat lower maximum temperature. While this form of embrittlement must be considered, it is not as detrimental to room temperature toughness as in the ferritic grades because the austenite, which makes up half the microstructure, is unaffected by alpha prime precipitation. Therefore, in certain circumstances, it may be possible to consider brief higher temperature service, for example, thin wall heat exchanger tubes where short-time, higher temperature transients occasionally occur. However, many design codes prohibit such a practice.

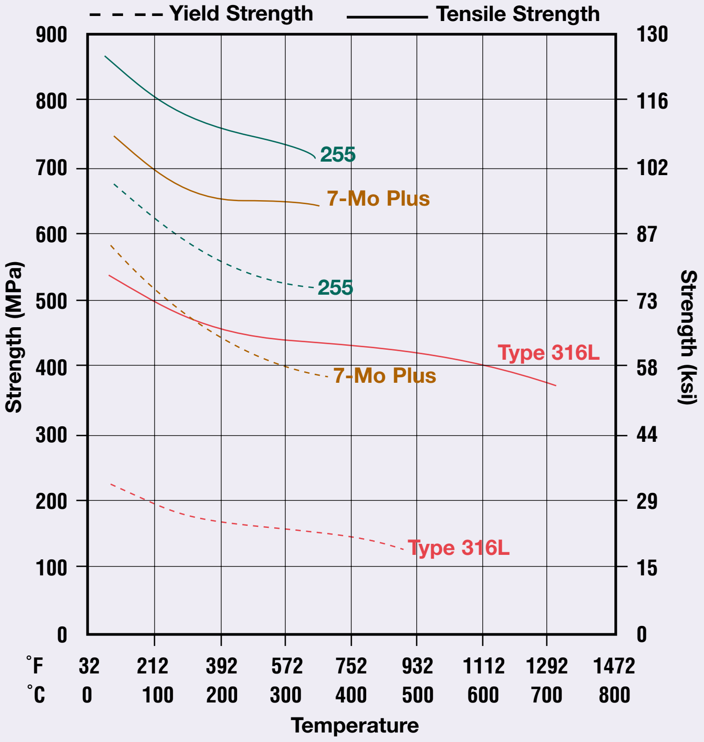
The duplex stainless steels retain toughness down to temperatures low enough for most engineering applications, but not to the extremely low temperature of cryogenic service, for which alloys with a completely austenitic structure are required. Low-temperature Charpy impact data for representative grades tested with the plane of fracture transverse to the rolling direction are given in *Figure 24*. While these grades exhibit a definite transition temperature, they exhibit useful toughness at temperatures as low as about -100°C (-150°F). However, toughness is not isotropic and is reduced by high ferrite content. Commercial grades typically have about 40-60% ferrite in the as-produced solution annealed condition. This ferrite content represents a good compromise among many mechanical and corrosion properties. High ferrite content

Table 9 Minimum mechanical properties in basic ASTM sheet and plate specifications for high-performance duplex stainless steels

Name	UNS Number	Tensile Strength (minimum)		Yield Strength (minimum)		Elongation (minimum)	Hardness (maximum)	
		ksi	MPa	ksi	MPa	%	Brinell	HRB
Type 329	S32900	90	620	70	485	15.0	269	28
3RE60	S31500	92	630	64	440	30.0	290	30.5
2304	S32304	87	600	58	400	25.0	290	32
45M	–	85	588	57	392	40.0	277	29
44LN	S31200	100	690	65	450	25.0	293	–
2205	S31803	90	620	65	450	25.0	293	31
7-Mo PLUS	S32950	100	690	70	485	15.0	293	32
DP3	S31260	100	690	70	485	20.0	290	–
UR 47N	–	100	690	72	500	25.0	–	–
64	–	90	620	65	450	18.0	302	32
255	S32550	110	760	80	550	15.0	302	32
DP3W	S39274	116	800	80	550	25.0	–	32
100	S32760	108	750	80	550	25.0	270	–
2507	S32750	116	795	80	550	15.0	310	32

Source: Producer Data Sheets

Figure 23 High temperature strength of duplex high-performance stainless steels



Source: Producer Data Sheets

Figure 24 Charpy V-notch impact properties of wrought high-performance duplex stainless steels

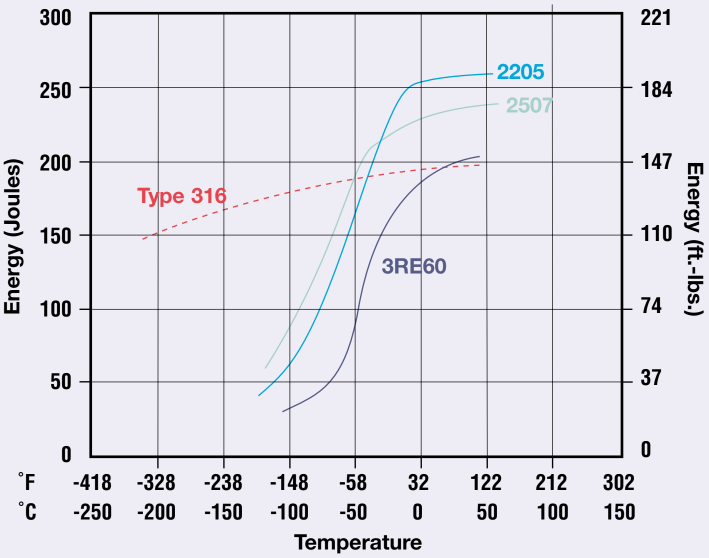


Table 10 High-performance duplex stainless steels ASME allowable design stress values (ksi)

Boiler Pressure Vessel Code, Section VIII, Division 1, 1999 Addenda (lowest values for sheet, plate or tube)

Name	UNS Number	ASME Specification	38°C (100°F)	93°C (200°F)	149°C (300°F)	204°C (400°F)	260°C (500°F)	316°C (600°F)	343°C (650°F)
Type 329	S32900	SA-240	25.7	25.7	24.8	24.3	24.3	–	–
3RE60	S31500	SA-789, SA-790	19.6	18.9	18.1	18.0	18.0	18.0	18.0
2304	S32304	SA-240	24.9	24.0	22.5	21.7	21.3	21.0	–
44LN	S31200	SA-240	28.6	28.6	27.1	26.3	26.1	26.1	–
2205	S31803	SA-240	25.7	25.7	24.8	23.9	23.3	23.1	–
7-Mo PLUS	S32950	SA-240	28.6	28.5	27.0	26.4	26.4	26.4	–
DP3	S31260	SA-240	28.6	28.5	27.1	26.4	26.3	26.3	26.3
255	S32550	SA-240	31.4	31.3	29.5	28.6	28.2	–	–
DP3W	S39274	SA-789, SA-790	33.1	33.1	31.6	31.4	31.4	31.4	–
100	S32760	SA-240	33.1	31.0	29.4	29.0	29.0	29.0	–
2507	S32750	SA-789, SA-790	33.1	33.0	31.2	30.1	29.6	29.4	–

reduces the toughness and the transition temperature, especially when ferrite is in excess of about 80% as shown in *Figure 25*. High ferrite contents are a possibility under certain welding conditions. The duplex structure is also directional in terms of the distribution of ferrite and austenite in wrought products. This will result in lower toughness when the fracture path is parallel to lamellar ferrite bands. Fracture toughness data using J-R curves illustrate this in *Figure 26*, where plate tested at various orientations relative to the rolling direction exhibits increasing toughness as the long specimen direction becomes parallel to the rolling direction.

The fatigue properties of the duplex stainless steels are also quite good as a consequence of their high-yield strengths. Some representative data comparing DP3 to Type 316 stainless steel are given in *Figure 27*.

Figure 25 Effect of ferrite on the Charpy V-notch impact properties of a wrought high-performance duplex stainless steel[21]

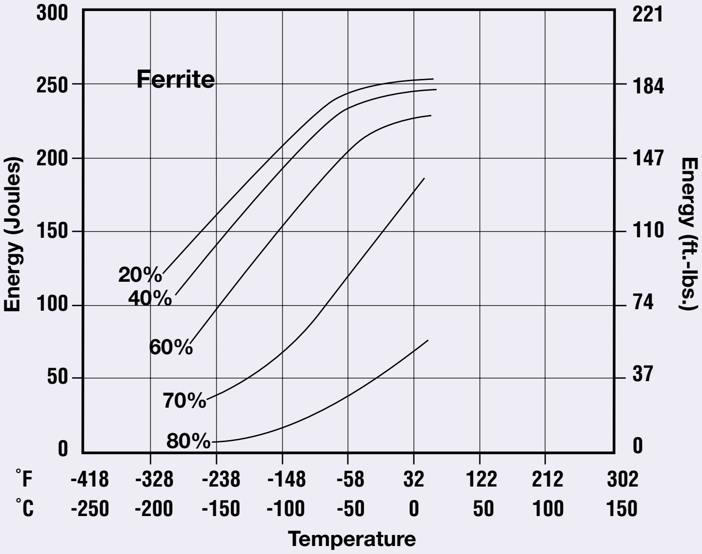
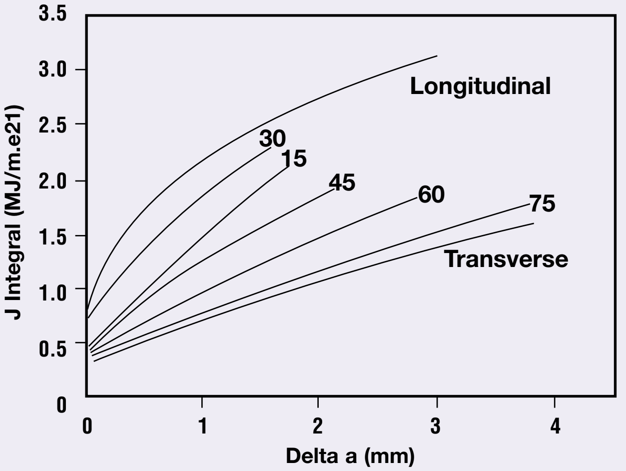
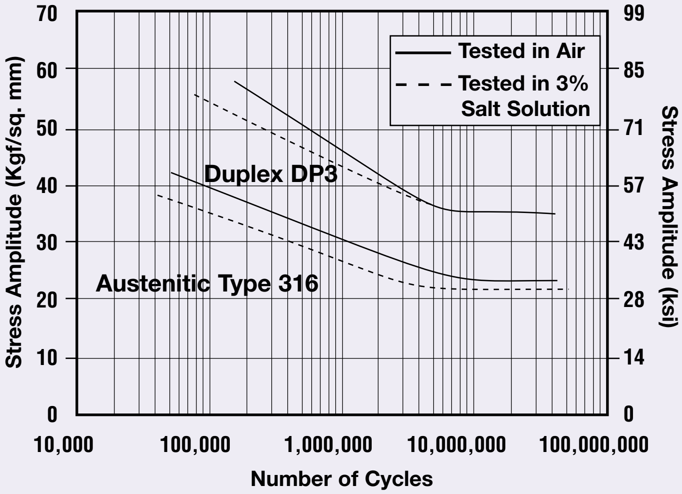


Figure 26 J-R curves for duplex stainless steel specimens machined along different angles from the longitudinal plane[22]



Source: Producer Data Sheets

Figure 27 Fatigue strength of a duplex stainless steel compared with Type 316 austenitic stainless steel at a frequency of 0.5 Hz



PHYSICAL PROPERTIES

Ambient temperature physical properties are given in *Tables 11-13* for each high-performance stainless steel family. Selected elevated temperature values are given in *Tables 14-16*. In each of these tables, data are included for one or more standard grades to provide a basis for comparison. These data are primarily from manufacturers' data sheets, and there are cases where similar grades have identical properties. This suggests that, in some cases, independent property determinations for similar grades may not have been made. Also, in many cases, differences in physical property values among grades are very slight, and it is likely that some of these merely reflect differences in test procedures.

It is useful to compare the properties of each family of high-performance stainless steels with those of Type 316. First, the overall physical properties are not greatly different from those of the standard grades in each grade class. Second, for many physical properties where data are lacking, values for the standard grades may provide a useful approximation.

Table 11 Ambient temperature physical properties of high-performance austenitic stainless steels

Name	UNS Number	Density		Specific Heat		Electrical Resistivity		Magnetic Permeability	Young's Modulus	
		g/cm³	lb/in³	J/kg°K	Btu/lb/°F	micro ohm-m	micro ohm-in.	Oerst.(mu 200H)	GPa	ksi x 1000
Type 316L	S31603	7.95	0.287	469	0.112	0.74	445	1.004	200	29.0
Type 317L	S31703	7.95	0.287	–	–	0.79	475	–	–	–
Alloy 20	N08020	8.08	0.292	502	0.120	1.08	651	1.002	193	28.0
Alloy 825	N08825	8.14	0.294	–	–	1.12	678	1.005	–	28.3
20Mo-6	N08026	8.13	0.294	461	0.110	1.08	651	1.006	186	27.0
317LMN	S31726	8.02	0.290	502	0.112	0.85	512	–	200	29.0
310MoLN	S31050	–	–	–	–	–	–	–	–	–
700	N08700	8.03	0.290	–	–	–	–	–	–	–
904L	N08904	7.95	0.287	461	0.110	0.95	572	<1.02	190	28.0
20Mo-4	N08024	8.11	0.293	456	0.109	1.06	635	–	186	27.0
20 Mod	N08320	–	–	–	–	–	–	–	–	–
Alloy 28	N08028	8.03	0.290	448	0.107	0.99	468	–	200	29.0
SB8	N08932	–	–	–	–	–	–	–	–	–
254 SMO	S31254	7.95	0.287	498	0.119	–	–	1.003	200	29.0
25-6MO 1925 hMo	N08925 / N08926	8.15	0.294	461	0.110	0.88	528	<1.01	192	27.8
AL-6XN	N08367	8.06	0.291	461	0.110	–	–	1.003	195	28.2
YUS 170	–	7.98	0.288	–	–	0.86	518	–	192	27.8
4565S	S34565	8.00	0.290	510	0.122	0.92	554	–	190	28.0
3127 hMo	N08031	8.03	0.290	440	0.105	1.00	602	–	195	28.3
654 SMO	S32654	8.00	0.290	510	0.122	0.78	470	–	188	27.6

Source: Producer Data Sheets

Table 12 Ambient temperature physical properties of high-performance ferritic stainless steels

Name	UNS Number	Density		Specific Heat		Electrical Resistivity		Young's Modulus	
		g/cm³	lb/in³	J/kg°K	Btu/lb/°F	micro ohm-m	micro ohm-in.	GPa	ksi x 1000
E-BRITE 26-1	S44627	7.66	0.280	427	0.102	0.55	330	200	29.0
MONIT	S44635	7.80	0.281	460	0.109	0.64	390	–	–
SEA-CURE	S44660	7.70	0.278	500	0.120	0.66	400	214	31.0
AL 29-4C	S44735	7.66	0.277	448	0.107	0.72	430	–	–
AL 29-4-2	S44800	7.70	0.280	448	0.107	0.72	430	200	29.0

Source: Producer Data Sheets

Table 13 Ambient temperature physical properties of high-performance duplex stainless steels

Name	UNS Number	Density		Specific Heat		Electrical Resistivity		Young's Modulus	
		g/cm³	lb/in³	J/kg°K	Btu/lb/°F	micro ohm-m	micro ohm-in.	GPa	ksi x 1000
Type 329	S32900	7.70	0.280	460	0.110	–	–	200	29.0
3RE60	S31500	7.75	0.280	482	0.115	–	–	200	29.0
2304	S32304	7.75	0.280	482	0.115	–	–	200	29.0
2205	S31803	7.85	0.285	482	0.115	0.80	481	200	29.0
7-Mo Plus	S32950	7.74	0.280	477	0.114	0.78	466	200	29.0
DP3	S31260	7.80	0.281	502	0.120	–	–	200	29.0
UR 47N		7.85	0.285	480	0.114	0.80	481	205	29.7
255	S32550	7.81	0.282	488	0.116	0.84	505	210	30.5
100	S32760	7.84	0.281	–	–	0.85	510	190	27.6
2507	S32750	7.79	0.280	485	0.115	–	–	200	29.0

Source: Producer Data Sheets

Table 14 Elevated temperature physical properties of high-performance austenitic stainless steels

Name	UNS Number	20°C (68°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (754°F)	500°C (932°F)
Elastic Modulus in Tension GPa (ksi x 1,000)							
Type 316L	S31603	200 (29.0)	194 (28.1)	185 (26.9)	177 (25.9)	169 (24.5)	160 (23.2)
Alloy 825	N08825	193 (28.0)	190 (27.6)	185 (26.8)	179 (25.9)	173 (25.1)	167 (24.2)
317LMN	S31726	200 (29.0)	194 (28.1)	186 (27.0)	179 (26.0)	171 (24.8)	163 (23.6)
Alloy 28	N08028	200 (29.0)	195 (28.5)	190 (27.5)	180 (26.0)	170 (24.5)	158 (23.0)
1925 hMo	N08926	193 (28.0)	186(27.0)	179 (26.0)	173 (25.1)	168 (24.4)	162 (23.6)
4565S	S34565	193 (28.0)	187 (27.1)	180 (26.1)	173 (25.1)	165 (24.0)	157 (22.9)
Mean Coefficient of Thermal Expansion - Temperature 20°C (68°F) to T - cm/cm/°C x 10^{-6} (in./in./°F x 10^{-6})							
Type 316L	S31603	15.7 (8.72)	16.5 (9.16)	16.9 (9.38)	17.3 (9.61)	17.6 (9.78)	18.0 (10.0)
Alloy 20	N08020	14.7 (8.16)	14.9 (8.27)	15.2 (8.44)	15.5 (8.61)	15.9 (8.83)	16.1 (8.94)
Alloy 825	N08825	13.1 (7.30)	14.2 (7.88)	14.9 (8.30)	15.3 (8.48)	15.6 (8.64)	15.8 (8.80)
20Mo-6	N08026	14.7 (8.16)	14.8 (8.22)	14.9 (8.29)	15.3 (8.52)	15.7 (8.73)	16.0 (8.89)
317LMN	S31726	16.1 (8.94)	16.6 (9.22)	17.2 (9.55)	17.8 (9.89)	18.5 (10.3)	–
904L	N08904	15.0 (8.33)	15.3 (8.50)	15.7 (8.72)	16.1 (8.94)	16.5 (9.17)	16.9 (9.39)
20Mo-4	N08024	14.0 (7.78)	14.4 (8.00)	14.9 (8.29)	15.6 (8.66)	16.1(8.96)	16.5 (9.17)
Alloy 28	N08028	14.6 (8.11)	15.0 (8.00)	15.5 (8.50)	16.0 (9.00)	16.5 (9.50)	17.0 (9.44)
254 SMO	S31254	–	16.9 (9.40)	–	–	–	–
25-6MO	N08926	–	15.1 (8.40)	–	–	–	–
1925 hMo	N08926	14.4 (8.00)	15.0 (8.33)	15.7 (8.72)	16.1 (8.94)	16.4 (9.11)	16.7 (9.28)
AL-6XN	N08367	–	15.3 (8.5)	–	–	–	16.0 (8.9)
4565S	S34565	13.7 (7.61)	14.5 (8.00)	15.5 (8.60)	16.3 (9.00)	16.8 (9.30)	17.2 (9.50)
3127 hMo	N08031	14.0(7.78)	14.3 (7.94)	14.7 (8.17)	15.1 (8.39)	15.5 (8.61)	15.9 (8.33)
Thermal Conductivity - W/m °C (Btu in/hr ft ^{2} °F)							
Type 316	S31603	14.0 (97)	14.9 (103)	16.0 (111)	17.3 (120)	18.6 (129)	19.9 (138)
Alloy 20	N08020	11.6 (81)	13.1 (91)	15.0 (104)	16.6 (115)	18.2 (126)	19.6 (136)
Alloy 825	N08825	11.1 (77)	12.4 (86)	14.1 (96)	15.6 (108)	16.5 (115)	18.2 (126)
20Mo-6	N08026	11.6 (81)	13.1 (91)	15.0 (104)	16.6 (115)	18.2 (126)	19.6(136)
317LMN	S31726	14.0 (97)	–	–	–	–	–
904L	N08904	11.5 (80)	13.1 (91)	15.1 (105)	–	–	–
20Mo-4	N08024	11.5 (80)	13.1 (91)	14.9 (103)	16.7 (116)	18.3 (127)	19.7 (137)
Alloy 28	N08028	11.4 (79)	12.9 (89)	14.3 (99)	15.6 (108)	16.7 (116)	17.7 (123)
254 SMO	S31254	14.0 (97)	–	–	–	–	–
25-6MO	N08926	16.7 (116)	–	–	–	–	–
AL-6XN	N08367	13.7 (95)	–	–	–	–	–
1925 hMo	N08926	12.0 (83)	12.9 (89)	14.4 (100)	16.5 (114)	18.5 (128)	20.1 (139)
4565S	S34565	14.5 (101)	14.5 (101)	–	–	–	–
3127 hMo	N08031	12.0 (83)	–	–	–	–	–
654 SMO	S32654	8.6 (59)	9.8 (68)	11.3 (78)	12.6 (87)	14.5 (100)	–

Source: Producer Data Sheets

Table 15 Elevated temperature physical properties of high-performance ferritic stainless steels

Name	UNS Number	20°C (68°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (754°F)
Mean Coefficient of Thermal Expansion - Temperature 20°C (68°F) to T - cm/cm/°C x 10^{-6} (in./in./°F x 10^{-6})						
E-BRITE 26-1	S44627	–	9.9 (5.5)	–	–	–
SEA-CURE	S44660	–	9.7 (5.4)	10.2 (5.7)	10.5 (5.9)	10.8 (6.0)
AL 29-4C	S44735	–	9.4 (5.2)	9.7 (5.4)	–	10.4 (5.8)
AL 29-4-2	S44800	–	9.4 (5.2)	–	–	–
Thermal Conductivity - W/m °C (Btu in/hr ft ^{2} °F)						
E-BRITE 26-1	S44627	16.7 (116)	17.9 (124)	19.3 (134)	20.9 (145)	–
SEA-CURE	S44660	16.4 (114)	18.3 (127)	20.5 (142)	22.5 (156)	24.2 (168)
AL 29-4C	S44735	15.2 (105)	16.4 (114)	18.0 (125)	19.6 (136)	–
AL 29-4-2	S44800	15.1 (105)	16.4 (114)	18.0 (125)	19.6 (136)	–

Source: Producer Data Sheets

Table 16 Elevated temperature physical properties of high-performance duplex stainless steels

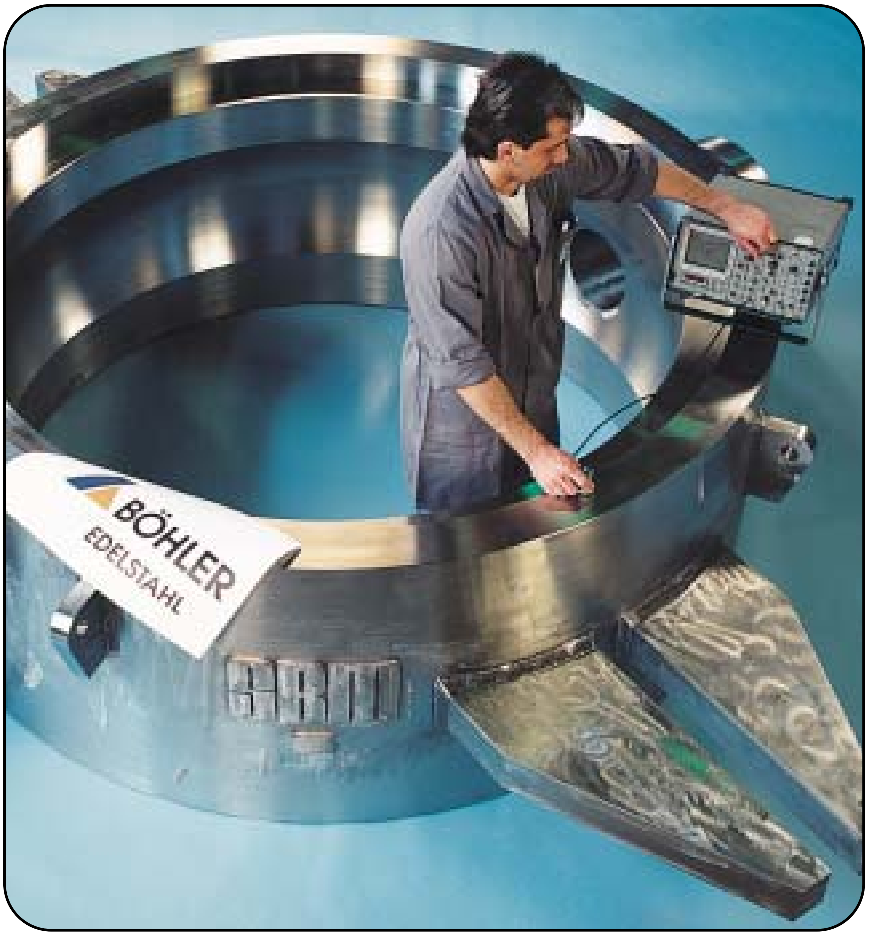
Name	UNS Number	20°C (68°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (754°F)	500°C (932°F)
Elastic Modulus in Tension GPa (ksi x 1,000)							
Type 329	S32900	200(29.0)	195(28.0)	185(27.0)	–	–	–
3RE60	S31500	200 (29.0)	190 (27.6)	180 (26.1)	170 (24.7)	160 (23.2)	150 (21.8)
2304	S32304	200 (29.0)	190 (27.6)	180 (26.1)	170 (24.7)	160 (23.2)	150 (21.8)
2205	S31803	200 (29.0)	190 (27.6)	180 (26.1)	170 (24.7)	160 (23.2)	150 (21.8)
UR 47N	–	205 (29.7)	194 (28.1)	181 (26.2)	170 (24.7)	–	–
255	S32550	210 (30.5)	200 (29.9)	198 (28.7)	192 (27.8)	182 (26.4)	170 (24.7)
2507	S32750	200 (29.0)	190 (27.6)	180 (26.1)	170 (24.7)	160 (23.2)	150 (21.8)
Mean Coefficient of Thermal Expansion - Temperature 20°C (68°F) to T - cm/cm/°C x 10^{-6} (in./in./°F x 10^{-6})							
Type 329	S32900	–	10.9(6.10)	11.0(6.30)	11.6(6.40)	12.1(6.70)	12.3(6.80)
3RE60	S31500	12.6 (7.00)	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
2304	S32304	12.6 (7.00)	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
2205	S31803	12.6 (7.00)	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
7- Mo Plus	S32950	9.5 (5.27)	10.5 (5.83)	11.5 (6.39)	12.4 (6.89)	13.3 (7.39)	13.9 (7.72)
UR 47N		12.0 (6.67)	12.5 (6.94)	13.0 (7.22)	13.5 (7.50)	–	–
255	S32550	11.7 (6.5)	12.1 (6.72)	12.6 (7.00)	13.0 (7.22)	13.3 (7.39)	13.6 (7.56)
2507	S32750	12.6 (7.00)	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
Thermal Conductivity - W/m °C (Btu in/hr ft ^{2} °F)							
Type 329	S32900	–	–	–	–	–	–
3RE60	S31500	16.0 (110)	17.0 (118)	19.0 (132)	20.0 (138)	21.0 (147)	22.0 (153)
2304	S32304	16.0 (110)	17.0 (118)	19.0 (132)	20.0 (138)	21.0 (147	22.0 (153)
2205	S31803	16.0 (110)	17.0 (118)	19.0 (132)	20.0 (138)	21.0 (147)	22.0 (153)
7- Mo Plus	S32950	14.1 (97)	16.4 (114)	19.0 (132)	21.5 (149)	–	–
UR 47N	–	17.0 (118)	18.0 (124)	19.0 (132)	20.0(138)	–	–
255	S32550	13.5 (94)	15.1 (105)	17.2 (119)	19.1 (133)	20.9 (145)	22.5 (156)
2507	S32750	16.0 (110)	17.0 (118)	19.0 (132)	20.0 (138)	21.0 (147)	22.0 (153)

Source: Producer Data Sheets

With regard to elastic constants, Young's Modulus is highest for the ferritic grades and slightly above 200 GPa (29.0 x 10^3 ksi). The lowest values, about 185 MPa (27.0 x 10^3 ksi), are for the high-nickel austenitic grades. Elastic modulus data, determined for a group of these austenitic grades using four different test methods, are given in *Figure 28*.

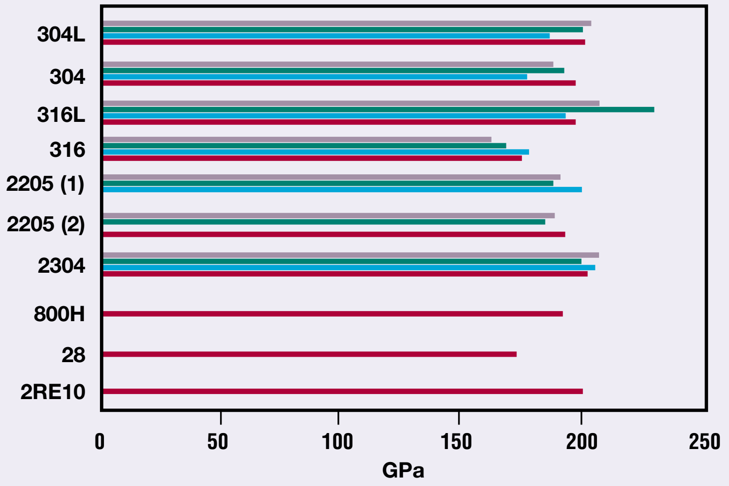
The ferritic grades have slightly lower density and electrical resistivity, and higher melting points than Type 316 and the high-performance austenitic grades. The austenitic grades with very high nickel have slightly higher density and electrical resistivity than Type 316. The austenitic grades with very high

Courtesy Böhler Edelstahl GMbH



Swivel component in Böhler A903 for offshore application

Figure 28 Young's Modulus for a selection of standard and high-performance stainless steels using four different techniques[23]

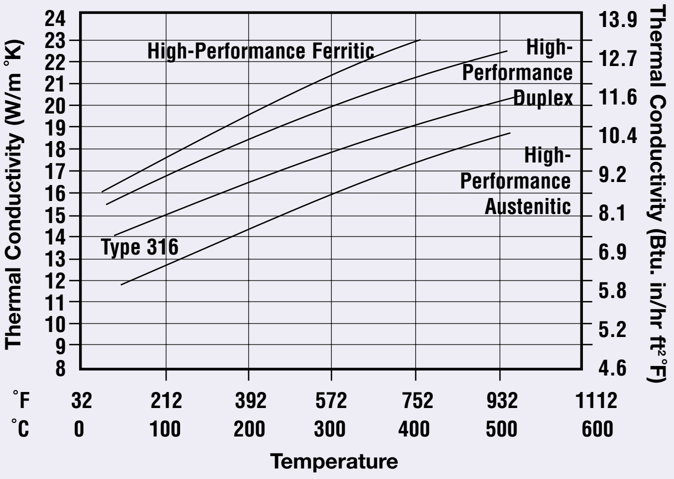


molybdenum also have significantly lower melting temperatures. The duplex grades exhibit intermediate values with respect to these properties.

At elevated temperature, the main differences among these grades are that the ferritic grades have a significantly lower coefficient of thermal expansion and higher thermal conductivity compared with any of the austenitic grades. This will offer advantages in some heat exchanger applications. Among the austenitic grades, very high nickel lowers thermal conductivity and expansivity. The duplex grades exhibit intermediate values for these properties, but are typically closer to those in ferritic stainless steels and carbon steel. Coefficients of thermal conductivity and expansion for the three stainless steel families are shown as a function of temperature in *Figures 29* and *30*.

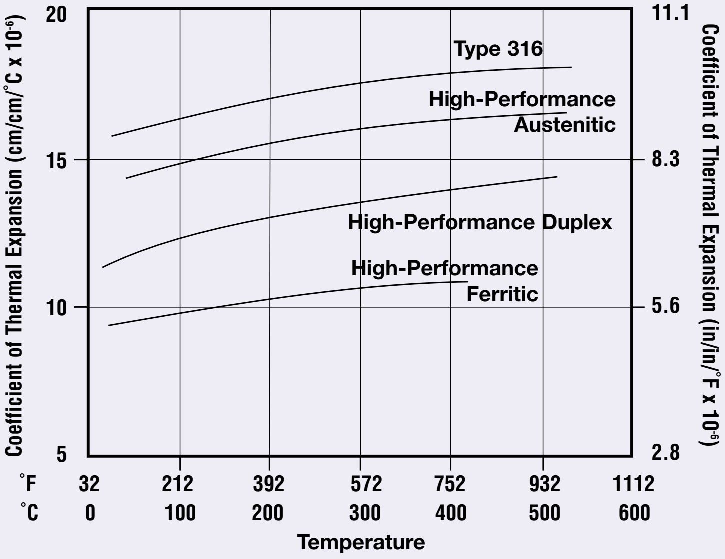
Source: Producer Data Sheets

Figure 29 Thermal conductivity of high-performance stainless steel structure types compared with Type 316 stainless steel



Source: Producer Data Sheets

Figure 30 Mean coefficient of thermal expansivity for different high-performance stainless steel structure types compared with Type 316 stainless steel (from 20°C to T)



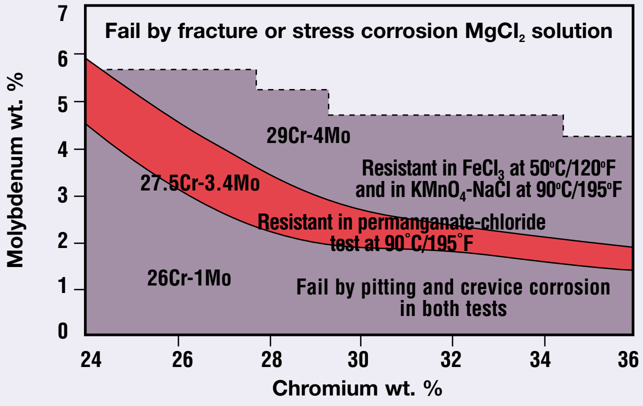
Courtesy
Avesta Sheffield AB

Pressurized peroxide (prepox) reactor made of 2205 duplex stainless steel installed in a Swedish pulp mill

CORROSION RESISTANCE

The outstanding corrosion performance of the high-performance stainless steels is due not only to their high absolute alloy content, but also to the synergistic effects related to the interaction of high chromium and the other alloying elements. For example, even a small amount of nickel in a high chromium ferritic grade will greatly extend its range of passivity in reducing acids. Molybdenum becomes more effective as an agent to resist chloride pitting as chromium content increases. Nevertheless, there are considerable differences among the grades in relation to the environment and the many possible forms of corrosion. An example of this difference among three ferritic grades with respect to pitting, crevice corrosion and stress corrosion cracking is given in *Figure 31*. Perhaps one of the most formidable tasks facing the corrosion engineer using these grades is to identify the optimum grade from a corrosion standpoint.

***Figure 31* *Differences among three high-performance ferritic grades with respect to pitting, crevice, and stress corrosion*[24]**



RESISTANCE TO INORGANIC ACIDS

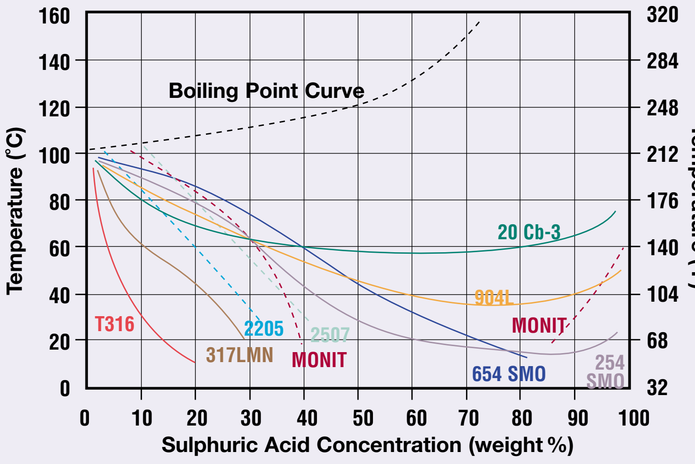
Sulphuric Acid.
The passivity-dependent corrosion behaviour of high performance stainless steels in sulphuric acid solutions is determined largely by the oxidizing power of the specific sulphuric acid environment. Sulphuric solutions can be quite variable in this regard. Mid-range acid concentrations and high temperatures produce weakly oxidizing conditions for pure solutions and, therefore, high general corrosion rates. Aeration and oxidizing ions such as ferric, cupric, nitrate, and chromates will increase the oxidizing potential of dilute solutions and generally allow for stainless steels to maintain passive behaviour over broader acid composition ranges and higher temperatures. The presence of the chloride or other halide ion can lead to pitting when a stainless steel would otherwise be expected to display stable passive behaviour. The presence of the halide ion is an important factor when considering performance in sulphuric acid solutions. The multiplicity of solution factors and the polarization characteristics of any given grade will produce a wide range of possible corrosion rates. Corrosion rates can reach very high values even in grades designed specifically for sulphuric acid service. Thus, while many of these stainless steels are very good in sulphuric acid solutions, it is always prudent to conduct in-plant corrosion tests when selecting materials for this service.

The first stainless steels that could be defined as high-performance stainless steels were those grades developed for sulphuric acid service. These are some of the austenitic grades defined as subgroup A-I in this publication. The grades in this subgroup are characterized by high nickel contents and additions of copper as well as molybdenum. Alloys 825 and 20Cb-3 are general purpose stainless steels suitable for service across the entire acid composition range at temperatures less than about 60°C (140°F). The isocorrosion line for 20Cb-3 in *Figure 32* illustrates typical behaviour for these grades in pure acid solutions. Their useful range is extended to somewhat higher temperatures if oxidizing ions are present as discussed above. However, because these grades contain relatively low molybdenum, the presence of

Source: Producer Data Sheets

Figure 32 Corrosion in non-aerated sulphuric acid - 0.1 mm/yr (4 mpy) isocorrosion curves

(laboratory tests using reagent grade sulphuric acid)



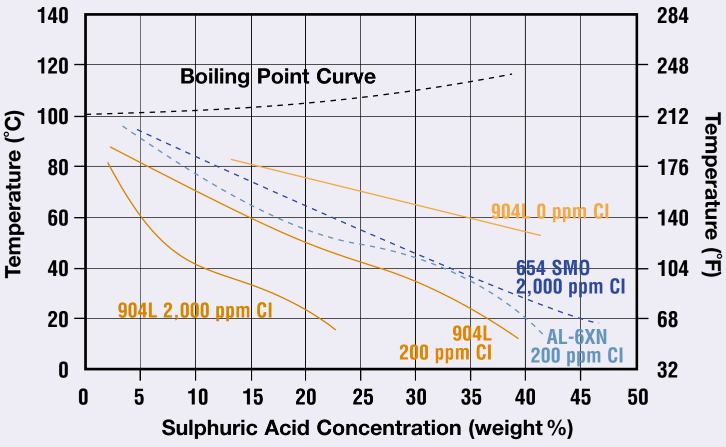
chloride ions seriously reduces their resistance, even in relatively dilute solutions. Alloy 20Mo-6, containing higher molybdenum, was developed to give better resistance under pitting conditions and also provides good resistance to general corrosion in the mid-acid composition range.

Isocorrosion curves for a number of other high-performance stainless steels are also shown in *Figure 32*. These grades can provide good resistance at low acid concentrations. They do not perform as well as the subgroup A-l grades in the mid- to high-acid concentration range primarily because of their lower nickel contents. Some duplex and ferritic grades are also shown in *Figure 32* to give good resistance at low concentration in pure acid solutions. However, the data for these stainless steels apply to the passive condition; duplex and ferritic grades, having lower nickel than austenitic grades, may easily become depassivated (activated), resulting in very high corrosion rates.

Source: Producer Data Sheets

Figure 33 Corrosion in non-aerated sulphuric acid-chloride solutions - 0.1 mm/yr (4 mpy) isocorrosion curves

(laboratory tests using reagent grade sulphuric acid)



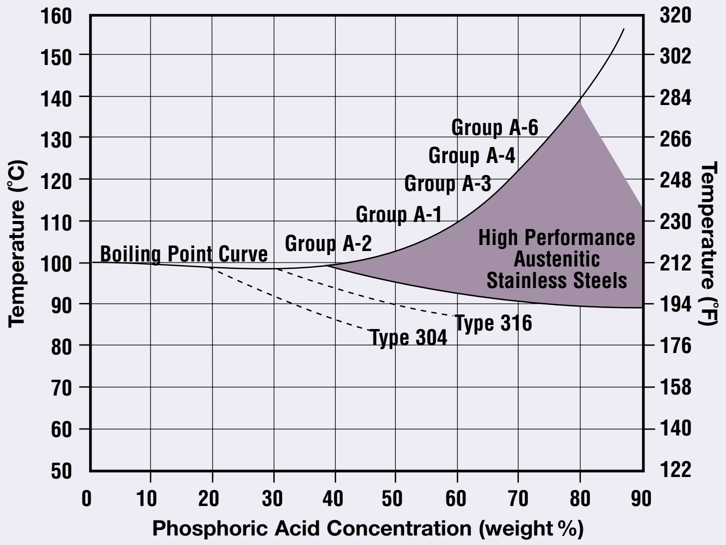
In dilute sulphuric acid solutions containing the chloride or other halide ions where pitting is a possibility, the higher molybdenum austenitic grades in subgroups A-4 to A-6 can give better resistance than the grades in subgroup A-1. This is illustrated in *Figure 33*, which shows corrosion data for acid solutions containing 200 and 2,000 ppm chloride ion. While the presence of chloride will reduce the resistance of all grades, the effect is much less in those grades that contain high molybdenum. The good performance of the grades in subgroups A-4 to A-6 under these conditions makes them good candidates for handling combustion product acid condensates, which often contain chloride, at moderate temperatures, while the grades in subgroup A-1 are more likely to be successful in pickling and chemical process applications where the chloride ion is less prevalent.

Sulphurous Acid.

Sulphurous acid is a relatively weak acid that is normally encountered as condensate in flue gases containing sulphur dioxide. It will cause pitting in Type 304, but can usually be handled with Type 316 provided it is not accompanied by sulphuric acid and chloride or fluoride ions. However, many flue gases can be very acidic and contain halide ions. In these instances, the high-performance stainless steels will offer substantially better corrosion resistance than Type 316.

Source: Producer Data Sheets

Figure 34 Corrosion in pure phosphoric acid solutions - 0.1 mm/yr (4 mpy) isocorrosion curves



Phosphoric Acid.

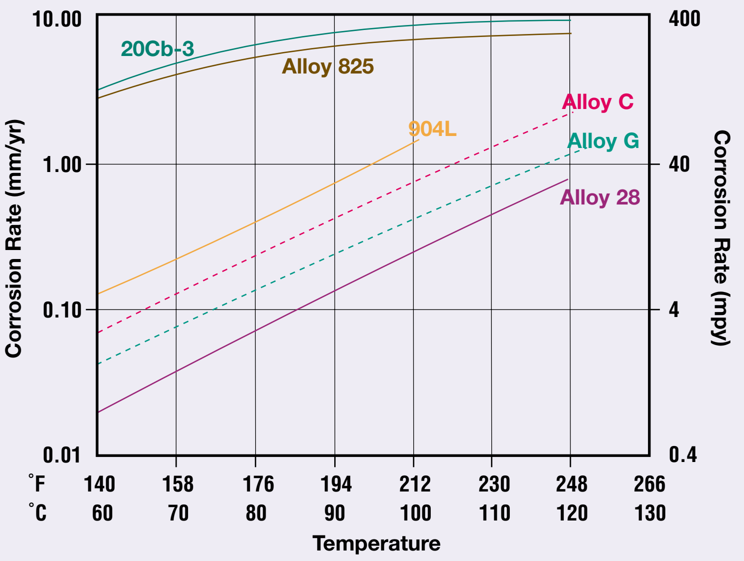
Pure phosphoric acid solutions are less aggressive than sulphuric solutions, but are similar in the sense that they have relatively low oxidizing power. Therefore, stainless steel corrosion rates can be high in the higher acid concentrations at high temperature. Corrosion rates are very sensitive to ions that affect oxidizing potential or that may initiate pitting. Accordingly, nitrate and ferric ions will reduce corrosion rates and chloride and fluoride ions will greatly increase the corrosivity of phosphoric acid solutions. Phosphoric acid solutions can produce intergranular attack of sensitized grain boundaries, and it is essential that low carbon grades free of sensitization be used in hot solutions.

In pure phosphoric acid solutions, Type 304 will handle most acid concentrations from ambient to moderate temperatures. Type 316 will extend the range of usefulness to near the boiling point in solutions containing up to about 30% acid. At higher temperatures and acid concentrations, the high-performance grades will provide good resistance up to boiling temperatures through acid concentrations up to about 80%. Corrosion tests show great variability with this acid, but typical behaviour is illustrated by generalized isocorrosion curves in *Figure 34*. Good performance in the high temperature/high acid concentration range is obtained primarily with grades having high chromium and nickel content and, to a lesser extent, high molybdenum content. The regions shown in *Figure 34* for the various austenitic grade subgroups indicate this general alloying effect. Some of the duplex grades will also give good performance in the mid-range acid concentrations, presumably due to their high chromium and molybdenum contents as well as the use of tungsten and copper in some alloys.

When phosphoric acid solutions contain the fluoride or chloride ions, for example, in phosphoric acid production, stainless steels that contain high chromium and molybdenum give good performance. This is illustrated by tests in a wet-process phosphoric acid solution shown in *Figure 35*.

Source: Producer Data Sheets

Figure 35 Corrosion in 70% phosphoric acid contaminated with 4% sulphuric acid, 60 ppm chloride, 0.5% fluoride, and 0.6% ferric ion



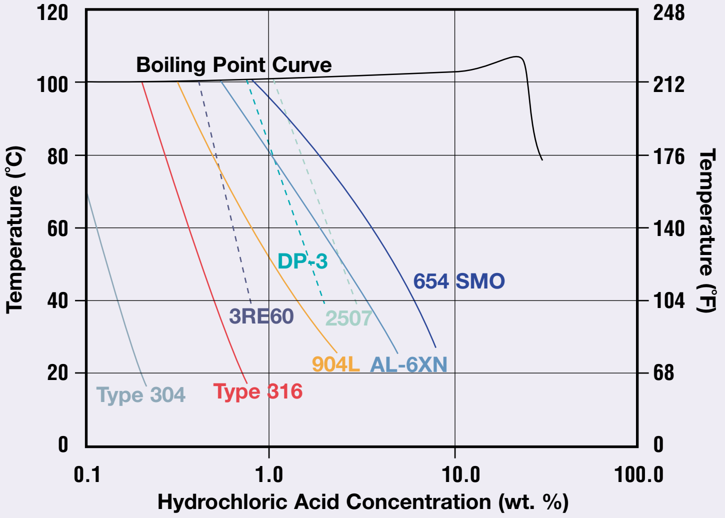


***Figure 36* Corrosion in pure hydrochloric acid solutions - 0.1 mm/yr (4 mpy) isocorrosion curves**

Source: Producer Data Sheets

The high chromium/high molybdenum Alloy 28 and similar grades such as 20Mo-6 perform very well in environments of this kind in contrast to the lower chromium/ molybdenum grades in subgroup A-2.

Hydrochloric Acid.

Hydrochloric acid is a very strong reducing acid. Solutions in all but the weakest concentration readily attack the standard grades at room temperature. In hot solutions corrosion rates are very rapid with hydrogen evolution; so the standard grades are generally not considered suitable for handling this acid. Pitting can also occur in weak solutions, especially if surfaces that have contacted the acid are allowed to dry. Any stainless steel that has been in contact with hydrochloric acid should always be thoroughly rinsed afterward.

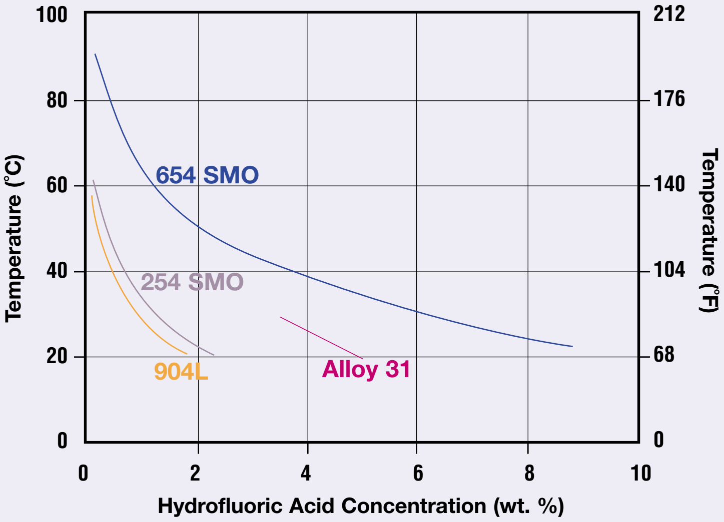
The high-performance stainless steels demonstrate improved resistance to general acid attack because their higher chromium and nickel contents help maintain a stable passive film. They are also more resistant to chloride pitting because of their high chromium and molybdenum contents. The general behaviour of these stainless steels in hydrochloric acid solutions is depicted in *Figure 36*. Even these stainless steels, however, cannot be used to handle concentrated solutions. The most highly alloyed austenitic grades such as 654 SMO can give useful resistance in ambient temperature solutions approaching 10% acid. These grades are candidates for handling dilute acid condensates at low to moderate temperatures. Corrosion rates increase rapidly at higher temperatures so that, at the boiling point, concentrations no greater than about 1% might be considered for these grades. Because of their high chromium contents, the duplex grades can also provide good resistance in up to about 4% hydrochloric acid, and their corrosion rates are somewhat less temperature-sensitive than those of the austenitic grades (*Figure 36*). The ferritic grades, which contain some nickel, also demonstrate good resistance in warm solutions up to about 1% acid; but these grades are readily depassivated, or may not establish passivity in the acid solution if their surfaces are iron contaminated. This tendency to depassivate is also a possibility with the duplex grades which are sensitive to preferential phase dissolution.

Hydrofluoric Acid.

Although this acid is classified as being somewhat weaker than hydrochloric acid, it remains very corrosive to many materials of construction including most stainless steels. Due to the hazardous nature of hydrofluoric acid, any use of the high-performance stainless steels in handling hydrogen fluoride and its solutions should only be considered with extreme caution, and only after thorough evaluation and consideration of all possible safety precautions. The standard stainless steel grades are not considered resistant to any but very dilute hydrofluoric acid solutions even at room temperature. For example, a 0.1% solution at 60°C (140°F) will produce a corrosion rate exceeding 0.60 mm/yr (0.024 in./yr) with Type 304. Some of the high-

Source: Producer Data Sheets

Figure 37 Corrosion in pure hydrofluoric acid solutions - 0.1 mm/yr (4 mpy) isocorrosion curves



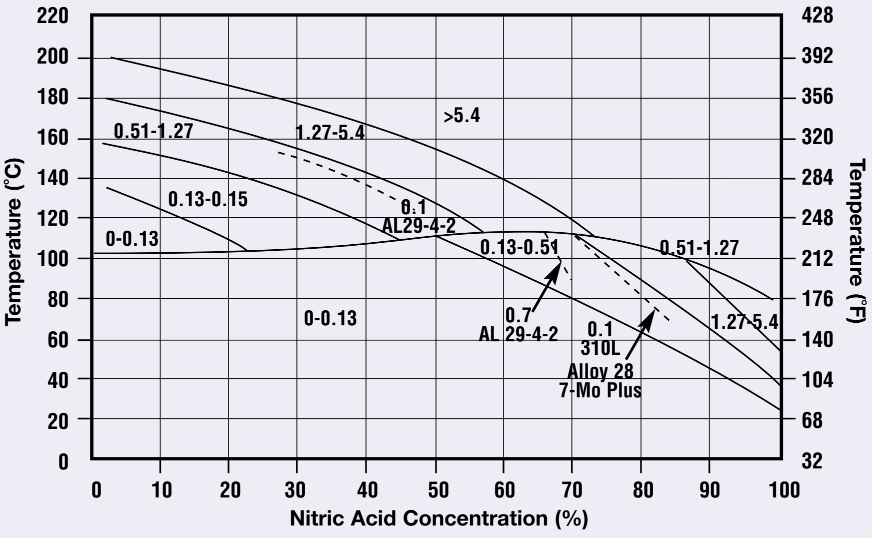
performance stainless steels can give useful service at moderate temperatures and low acid concentrations, especially when aeration or oxidizing salts are present and in mixed solutions with sulphuric acid. In particular, the subgroup A-1 grades such as 20Cb-3 and 825, which contain high nickel and copper, can provide some resistance under these conditions. Grades that contain high chromium and molybdenum along with high nickel and copper provide good resistance in dilute acid, especially if the chloride ion is present. Examples such as 904L, 254 SMO, Alloy 31 and 654 SMO are shown for dilute pure acid solutions in *Figure 37*.

Nitric Acid.
The standard austenitic stainless steel grades have very good resistance to nitric acid solutions at all temperatures up to the boiling point except in solutions of very high acid concentration. This is shown for Type 304 stainless steel in *Figure 38*. Therefore, Type 304L and its stabilized counterparts are used extensively in the production and handling of this acid. Type 316 has a higher corrosion rate than Type 304 because molybdenum is deleterious. Good resistance in nitric acid is obtained by the use of chromium; therefore, the high-performance austenitic grades do not usually offer improved corrosion resistance in solutions of pure nitric acid. Although little information is available, one would expect that these grades might behave similar to Type 316 because of their high molybdenum contents. They can, however, pass standard intergranular sensitization tests as defined in ASTM Standard Practice A 262, and can give good service in various mixed acid solutions containing nitric acid where the performance of Type 304L may be limited.

There have been some special grades developed specifically for severe nitric acid service such as Type 310L and Alloy 800. Serviceability to higher temperatures and high acid concentrations is accomplished with high chromium, low molybdenum, and low impurity content. The higher chromium and lower molybdenum high-performance duplex steel, 7-Mo PLUS, provides a similar improvement and has seen extensive service in severe nitric acid environments. The high chromium ferritic stainless steels that do not use titanium stabilization, such as AL 29-4-2, also have good resistance to high temperature nitric acid liquid and vapour environments. Data for these grades in *Figure 38* illustrate their superiority over Type 304 in nitric acids.

Source: Producer Data Sheets

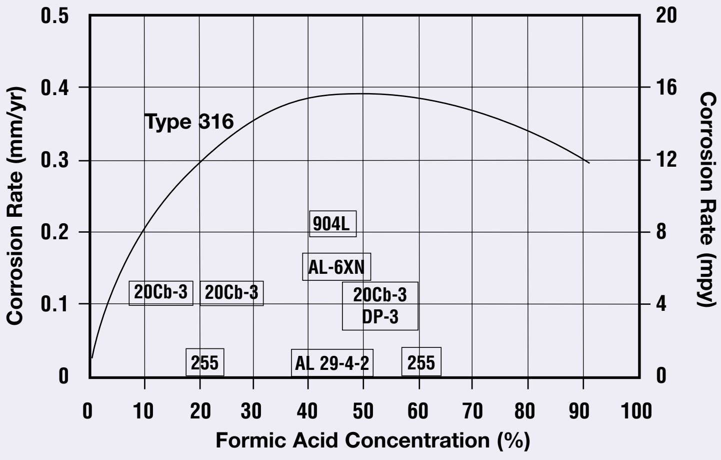
Figure 38 Corrosion of Type 304 stainless steel in pure nitric acid solutions compared with some high-performance stainless steels - isocorrosion curves in mm/yr



Source: Producer Data Sheets

Figure 39 Corrosion in boiling formic acid solutions

(laboratory tests using reagent grade acid)



RESISTANCE TO ORGANIC ACIDS

Formic Acid.

Formic acid is the strongest of the organic acids and will react aggressively with many metals, especially as warm or hot solutions. The corrosivity of formic acid is strongly dependent on the presence of air or other oxidants, and on whether or not the material under consideration depends on a passive film for resistance. Aeration and oxidants will improve the performance of stainless steels in formic acid solutions. Acid concentrations within the range of 30 to 90% may be very aggressive to Type 304 at ambient temperatures and to Type 316 in warm solutions. Therefore, Type 304 is not a candidate for handling anhydrous concentrated acid, but may be considered for storage and transfer applications at ambient temperatures if air or oxidants are present. In the presence of oxidants, Type 316 stainless steel may be used at temperatures somewhat above ambient. Virtually all the high-performance stainless steels will offer a corrosion advantage over Type 316 in hot formic acid solutions. This is illustrated in *Figure 39* with data for boiling solutions showing that a large number of these grades have corrosion rates substantially less than that of Type 316. These data also illustrate that the duplex and ferritic grades have even greater corrosion resistance in formic acid than the austenitic grades. High chromium and molybdenum contents are especially useful in this environment.

Acetic Acid.

Acetic acid is second only to formic acid in terms of the corrosivity of the organic acids. It can become highly reducing at high concentrations, and thus, very corrosive in hot solutions, especially if the chloride ion is present. Type 304 will resist all concentrations at moderate temperatures, and Type 316 will normally resist acid production process conditions to the atmospheric boiling temperature. However, because of their high molybdenum contents, the high-performance stainless steels can give superior service at higher temperatures and when chloride and other contaminants are present. An example of this temperature effect comparing several high-performance stainless steels to Type 316 in an acetic acid-hydroxy acid solution is given in *Table 17*. The benefit of molybdenum in these alloys compared with Type 304, which does not contain molybdenum, is especially noticeable. When oxidizing contaminants such as air and peracids and iron, copper and manganese salts are present, stainless steels, which depend on a

Table 17 Corrosion in acetic-hydroxy acid solutions[25]

Based on approximately 50-day exposures in stripping of acetic acid from a 70% acetic acid containing about 8% hydroxy acids, 20% manganese salts, and residues in a nitrogen blanketed system.

Name	UNS Number	124°C (255°F)		140°C (284°F)	
		mm/yr	mpy	mm/yr	mpy
Type 304	S30400	0.01	0.04	1.12	44
Type 316	S31600	Nil	Nil	0.09	37
Type 317	S31700	Nil	Nil	0.08	3.2
Alloy 20	N08026	<0.00	0.1	0.05	1.8
Alloy 825	N08825	0.01	0.2	0.03	1.2
700	N08700	Nil	Nil	0.01	0.01

passive film, will show improved performance. Under severe process conditions, the high-performance stainless steels would be expected to resist these contaminants. This contrasts with alloys like Monel 400 that do not develop a stable passive film in this environment and consequently will suffer higher corrosion rates. Chlorides present a major hazard of pitting and stress corrosion cracking when processing acetic acid using the standard stainless steel grades. The subgroup A-1 high-performance austenitic grades provide a major benefit over Type 316 in regard to stress corrosion cracking, and the grades in subgroups A-3, A-4, and A-6 would be expected to perform much better in terms of both pitting and stress corrosion cracking.

Many production processes for acetic acid involve an oxidation process that produces other organic acids including formic acid. These mixed acids are also very corrosive at high temperatures. All three types of high-performance stainless steels – ferritic, duplex, and austenitic – are more resistant than Type 316 as shown in *Table 18* for three boiling pure acids, and in *Figure 40* for mixed acetic and formic acids.

Higher C3 Through C8 Organic Acids. The lower chain length acids such as acrylic and propionic acid are very similar to acetic acid in their reactivity to metals and can be quite corrosive at elevated temperatures. The performance of stainless steels in acetic acid suggests that the high-performance stainless steels will give better service than Type 316 at high temperature and can bridge the performance gap between Type 316 and the nickel-base alloys. For example, Alloy 20 has been shown to demonstrate a nil corrosion rate compared with 0.08 mm/yr (3 mpy) for Type 304 in the top extractor of a nitrile-type acrylic acid process.

The higher chain length acids become less corrosive with increasing chain length at any given temperature. In many cases the standard grades are relatively unaffected at low and moderate temperatures; but depending on the temperature, boiling point, and degree of dissociation, a temperature is reached at which corrosion rates increase rapidly. In these circumstances the high-performance stainless steels can be expected to give improved service compared with Type 316.

Source: Sandvik Data Sheets

Figure 40* *Corrosion of austenitic and duplex stainless steels in boiling mixtures of 50% acetic acid and varying proportions of formic acid

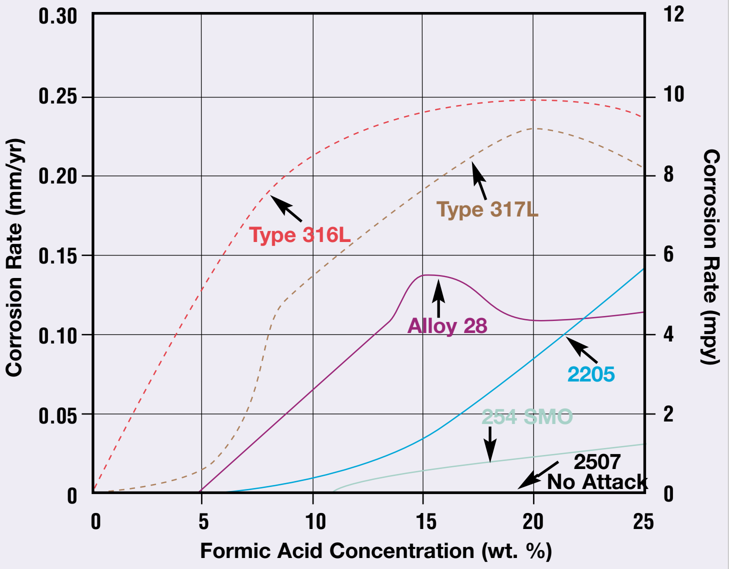


***Table 18* *Corrosion rates in boiling organic acids, mm/yr (mpy)*[26]**

Based on the average of five 48-hour periods in laboratory tests.

Name	UNS Number	45% Formic	88% Formic	10% Oxalic	20% Acetic	99% Acetic
Type 304	S30400	1.2 (48)	2.4 (96)	1.3 (50)	0.03 (1.0)	0.5 (18)
Type 316	S31600	0.3 (11)	0.2 (9)	1.0 (40)	<0.01 (0.1)	0.05 (2)
E-BRITE 26-1	S44627	0.1 (3)	<0.01 (0.1)	0.1 (3)	0.03 (1)	0.01 (0.4)
AL 29-4-2	S44800	0.02 (0.7)	<0.01 (0.1)	0.02 (0.7)	<0.01 (0.1)	<0.01 (0.1)
Alloy 625	N06625	0.1 (5)	0.2 (9)	0.2 (6)	0.03 (1.1)	0.01 (0.4)

Table 19 Corrosion in refined tall oil, mm/yr (mpy)[25]

Laboratory tests conducted in the same oil at various temperatures.

Name	UNS Number	286°C (545°F)	300°C (572°F)	315°C (599°F)	330°C (626°F)
Type 302	S30200	4.57 (180)	12.7 (500)	20.3 (800)	–
Type 316	S31600	0.10 (4)	0.10 (4)	1.35 (53)	12.7 (500)
Type 317	S31700	0.03 (1)	0.03 (1)	0.53 (21)	–
C-276	N10276	0.10 (4)	0.13 (5)	0.10 (4)	–

Fatty Acids.

The industrial fatty acids are generally innocuous to the standard stainless steel grades at low and moderate temperatures. However, at high temperatures, corrosivity increases together with the possibility of pitting and crevice corrosion. This is the case with tall oil recovery and refining, where Type 316 may become unsatisfactory when there is an excess of light ends and at high-end process temperatures. The general effect of increasing temperature on corrosion rates provided in *Table 19* shows that even Type 317 can provide substantially lower corrosion rates compared with Type 316. The more highly alloyed stainless steel grades will provide further resistance to general attack and better resistance to pitting and crevice corrosion. This is illustrated in *Table 20* for three high-performance stainless steels compared with Type 316 in tall oil distillation at 260°C (500°F).

Table 20 Tall oil distillation corrosion

Test coupons exposed 320 days at 230-270°C (450-520°F) in liquid and gas phases.

Name	UNS Number	Molybdenum (wt.%)	Corrosion Rate mm/yr	(mpy)
Type 316L	S31603	2.65	0.89	(35.2)
317LM	S31725	4.32	0.29	(11.6)
317LMN	S31726	4.60	0.28	(11.2)
254 SMO	S31254	6.09	0.20	(0.8)

Source: Producer Data Sheet

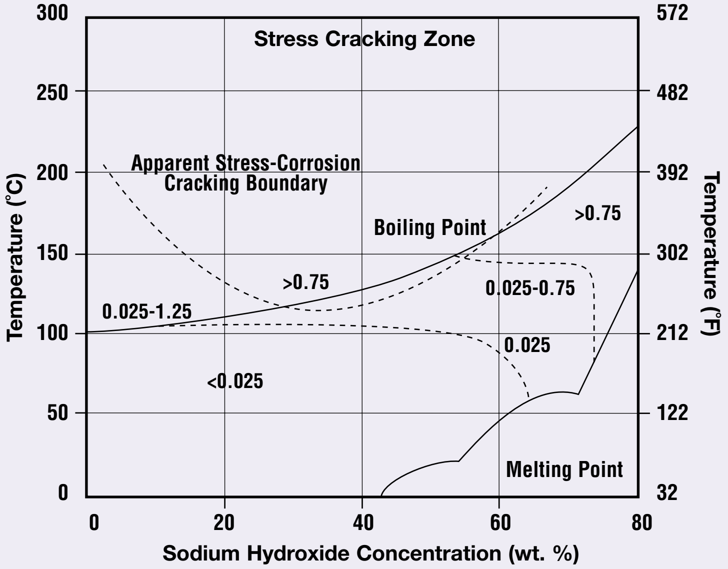
RESISTANCE TO ALKALIES AND ALKALINE SALTS

Carbon steels, the standard stainless steel grades, and the high-performance stainless steels will resist the strong alkalies such as sodium hydroxide (NaOH) and caustic potash (KOH) at ambient and moderate temperatures. The weaker alkalies and alkaline salts such as sodium carbonate (Na_2CO_3) are not very corrosive to these materials up to boiling temperatures. The oxidizing salts such as sodium hypochlorite (NaOCl), however, can be very corrosive to most metals including the stainless steels. Many of the high-performance stainless steels are superior to Types 304 and 316 in strong alkalies at high temperature, and the ferritic grades have been used in severe caustic evaporator applications. They also have some utility in handling certain oxidizing salt solutions such as liquor evaporators and bleach equipment using hypochlorites.

Sodium Hydroxide.

The standard austenitic stainless steel grades are often used to handle strong caustic solutions at temperatures higher than where carbon steels are limited by caustic cracking, about 66°C (160°F), or by product iron contamination. *Figure 41* shows that Types 304 and 316 can be used to slightly above 100°C (212°F) in up to about 50% sodium hydroxide without experiencing excessive

Figure 41 Corrosion of Type 304 and Type 316 in sodium hydroxide solutions - isocorrosion curves in mm/yr[27]



corrosion rates or caustic cracking. However, corrosion rates increase rapidly as the boiling temperature is reached. The austenitic and especially the ferritic high-performance stainless steel grades have significantly lower general corrosion rates at the boiling temperatures of strong sodium hydroxide solutions as shown in *Figure 42*. All but the subgroup A-2 grades, which are not much different in chromium and nickel than Type 316, have corrosion rates about an order of magnitude less than Types 304 and 316 at the boiling temperature. The stabilized ferritic grades are an order of magnitude better, but best performance is achieved with the high-purity ferritic grades, especially those that contain a small amount of nickel which greatly reduces general corrosion rates as shown in *Figure 43*.

Source: Producer Data Sheets

Figure 42 Corrosion of stainless steels in boiling reagent grade sodium hydroxide solutions

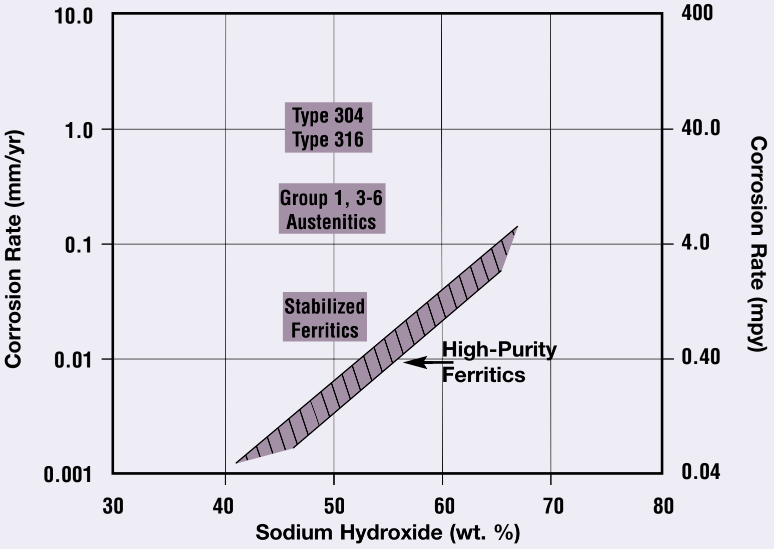


Figure 43 Welded U-bend specimens exposed for 134 hours in 50% NaOH solution at 200°C[28]

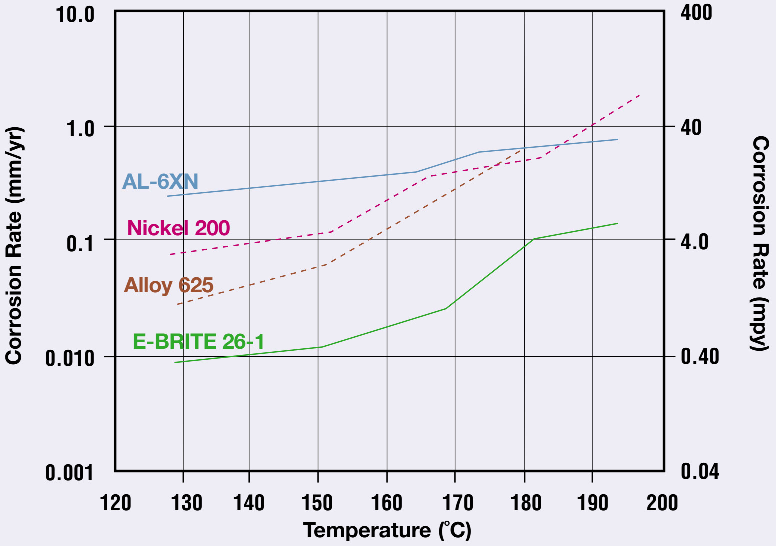
Alkalies Containing Oxidizing Impurities. When strong alkalies contain impurities, especially oxidizing salts, the high-performance stainless steels show good performance. This is especially true of the ferritic grades that have high chromium and low nickel contents as shown in *Table 21* for E-BRITE 26-1 exposed to sodium hydroxide solutions containing NaCl and $NaClO_3$ contaminants. Corrosion rates are somewhat higher than in pure solutions, but still are in a very useful range. These ferritic grades have been used in the high temperature end of multiple-effect evaporators used to produce sodium hydroxide because they can withstand these contaminants better than high nickel grades. Data for the 6% Mo austenitic stainless steel, AL-6XN, given in *Figure 44* indicate that it also can perform well

Table 21 Corrosion of E-BRITE 26-1 (S44627) high-purity ferritic stainless in caustic solutions containing NaCl and $NaClO_3$[29]

% NaOH	% NaCl	% $NaClO_3$	Temperature		Corrosion Rate	
			°C	°F	mm/yr	mils
20	10	–	104	220	0.015	0.6
45	5	–	143	290	0.041	1.6
50	–	–	143	290	0.003	0.1
50	5	–	152	305	0.076	3.0
50	5	0.1	152	305	0.069	2.7
50	5	0.2	152	305	0.028	1.1
50	5	0.4	152	305	0.028	1.1

Source: Producer Data Sheets

Figure 44 Corrosion of high performance stainless steels and other alloys in a simulated caustic evaporator liquid of (wt. %): $43NaOH + 7NaCl + 0.15NaClO_3 + 0.45Na_2SO_4$



in the presence of contaminants and compares very favourably with the nickel 200 and nickel-base alloys at some of the highest temperatures encountered in caustic evaporator service.

Paper pulp mill white liquors also represent oxidant-contaminated alkali environments in which the higher chromium levels of the high performance stainless steels produce reduced corrosion rates compared with the standard austenitic stainless steel and nickel-base alloys. Virtually all of the high-performance grades exhibit not only good general corrosion resistance in white liquors, but also much improved stress corrosion cracking resistance compared with Types 304 and 316 as shown in *Table 22*. This superior stress corrosion cracking resistance applies to most caustic environments.

Table 22 Corrosion in white liquor at 127°C (261°F) in 154-day tests[29]

White liquor: 28%($NaOH+Na_2S$), 7.8%NaCl, 1.5%Na_2CO_3, 3%Na_2SO_4

Name	UNS Number	Corrosion Rate	
		mm/yr	mpy
E-BRITE 26-1	S44627	0.000	0.00
Alloy 600	N06600	0.005	0.20
Type 329	S32900	0.008	0.30
Alloy 800	N08800	0.020	0.80
Alloy 400	N04400	0.023	0.90
Alloy 825	N08825	0.041	1.60
Type 304	S30400	0.168	6.6 (SCC)*
Alloy 625	N06625	0.173	6.80
Type 316	S31600	0.516	20.3 (SCC)*
Carbon Steel	–	0.886	34.90

* SCC - stress corrosion cracking observed

CHLORIDE- AND OTHER HALIDE ION-CONTAINING AQUEOUS ENVIRONMENTS

Pitting and Crevice Corrosion.
Of the many commercial and technical factors responsible for the development of the high-performance stainless steels, none has been more instrumental than the need for grades with good resistance to pitting, crevice corrosion, and stress corrosion cracking in aggressive chloride environments. Thus, the high-performance stainless steels collectively offer better chloride resistance than the standard stainless steel grades. This good performance is obtained by the use of the alloying elements chromium, molybdenum, and nitrogen, all of which are very effective in improving resistance to pitting and crevice corrosion, and high nickel and nitrogen contents for stress corrosion cracking.

The pitting and crevice corrosion of stainless steels occurs by a local breakdown of the passive film, and then the localized development of an anodic corrosion site surrounded by a cathodic area that remains passive. By definition, crevice corrosion requires the presence of a deposit, gasket, or some other crevice-forming object on the surface to initiate corrosion. Otherwise, the two forms of corrosion are essentially identical. Therefore, the various grades of stainless steel behave similarly with regard to these forms of corrosion except that, because crevices help initiate corrosion, resistance to crevice corrosion is usually less than it is to pitting. Because most engineered structures will contain crevices, crevice corrosion is more important from an engineering standpoint. The balance of this discussion will emphasize crevice corrosion with the understanding that general trends will also apply to pitting.

All stainless steels behave similarly with regard to variables that affect susceptibility to crevice corrosion, and the high-performance stainless steels are no exception. Precautions and procedures that should be followed during fabrication and in the operation of systems exposed to the threat of crevice corrosion are often more stringent with the high-performance grades simply because the environments usually are more aggressive. Maintaining surface cleanliness, for example, post-weld removal of surface oxide, is an essential requirement for obtaining satisfactory weld performance in high chloride-containing acid or strongly oxidizing environments. The general environmental effects which promote crevice corrosion in stainless steels include high chloride concentrations, high acidity (low pH), high temperature, high dissolved oxygen content, and any environmental constituent which raises the corrosion potential such as oxidizing metallic ions and dissolved chlorine gas. All these factors must be considered in relation to whether any grade of stainless steel will be suitable for a given situation.

Ranking of Individual Grades.
The evaluation of any grade of stainless steel for its “localized corrosion resistance” is a difficult proposition because of the many variables involved. For this reason it is best to consider any evaluation as applying only to the specific test conditions employed. Nevertheless, it is helpful to have qualitative ratings to make general comparisons and to make initial assessments of suitability for service. The ferric chloride test has been widely used to develop the high-performance stainless steels; consequently, it is used widely to make relative comparisons among them. This test is usually conducted according to methods described by ASTM Standard Test Method G 48 or MTI-2, both of which use an environment consisting of 10% ferric chloride ($FeCl_3 \cdot 6H_2O$) dissolved in distilled water (6% $FeCl_3$). It can provide data based on the pitting of a clean

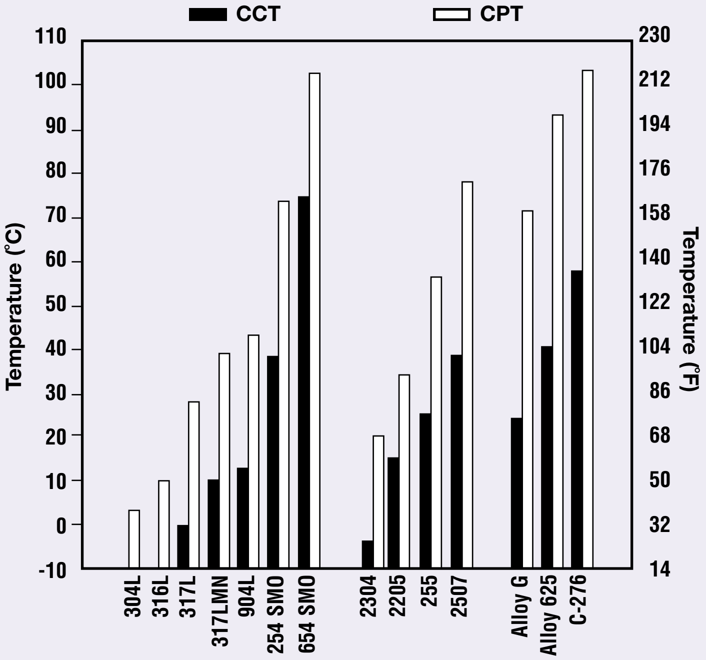
Courtesy Böhler Edelstahl GMbH

Rings and discs made of duplex and super duplex grades for offshore application

surface or corrosion under artificial crevices. This test produces results that define a "critical pitting temperature" or a "critical crevice corrosion temperature." When interpreting data from these tests, many important factors need to be kept in mind. One of these is the inherent variability of the test, which has a standard deviation of about 2.5°C. Thus, when making comparisons among grades, small differences in critical temperatures (≤5°) usually have no significant meaning. Another important consideration is that ferric chloride is highly oxidizing, producing a corrosion potential with stainless steels of about 600 mv versus the standard calomel electrode. This is far above what occurs in many natural environments such as cooling waters. Accordingly, the ferric chloride environment is very aggressive, and the test does not yield results that translate directly to natural environments.

Figure 45 Critical crevice and pitting corrosion temperatures for stainless steels and nickel alloys

(evaluated in 10% ferric chloride per ASTM G48)



The ferric chloride test is conducted by exposing specimens to progressively higher temperatures in 2.5°C temperature intervals until pitting or crevice corrosion initiates over a time interval which is usually an arbitrarily chosen twenty-four hours. The critical pitting temperature (CPT) or critical crevice temperature (CCT) is defined as the minimum temperature at which corrosion occurs. Illustrative data for representative grades evaluated in 10% ferric chloride are given in *Figure 45*. It shows that some critical temperatures are much lower than the temperatures to which standard stainless steels are often exposed in service, thereby illustrating the severity of the test. For this reason it cannot be used as a basis for establishing service temperature limits. The data also illustrate that corrosion is more likely to occur in the presence of crevices because the CCT is always lower than the CPT.

The high-performance stainless steels far outperform the standard Types 304 and 316 stainless steel grades in this test as the data in *Figure 45* show. The performance of some of these grades approaches that of the corrosion resistant nickel-base alloys. There is a great range in performance among the different grades, due largely to chromium, molybdenum, and nitrogen alloying differences. Various formulae have been developed to relate steel composition to critical corrosion temperatures. The most commonly used expression gives a pitting resistance equivalent (PRE) number, for example, PRE = %Cr + 3.3%Mo + 16%N, where the percentage of these elements in the steel is expressed in weight percent.

Some typical correlations of the PRE number with several critical temperature indices (*Figure 46*) show the strong alloying effects of

Figure 46 Critical pitting and crevice corrosion temperatures for austenitic stainless steel related to PRE numbers

- Critical temperatures evaluated in 6% ferric chloride per ASTM G48 and in 1M NaCl in the Avesta cell[30,31]

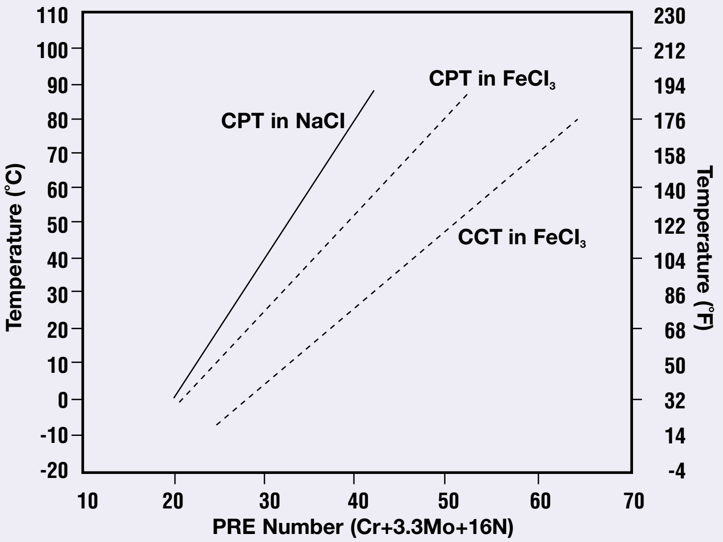
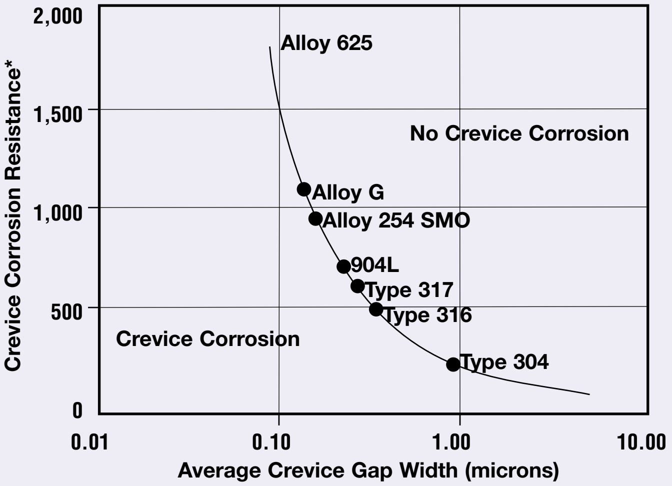


Figure 47 Effect of crevice gap width on the initiation of crevice corrosion in ambient temperature seawater[33]



**Dimensionless units based on the critical crevice solution*

Table 23 Crevice corrosion initiation for various alloys related to their critical crevice solutions[33]

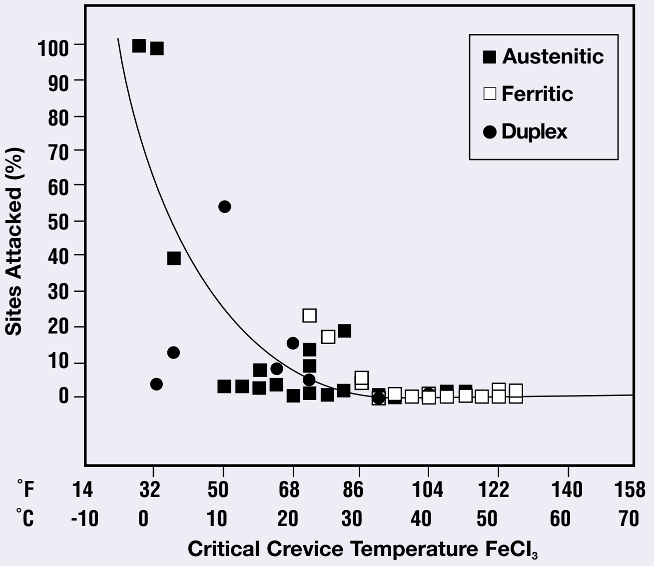
			Chloride Concentration		
Name	UNS Number	pH	Molar	ppm	Ratio to Seawater
430	S43000	2.9	1.0	35,000	1.84
Type 304	S30400	2.1	2.5	88,750	4.68
Type 316	S31600	1.65	4.0	142,000	7.48
904L	N08904	1.25	4.0	142,000	7.48
AL-6XN	N08367	<1.0	6.0	213,000	11.22
Alloy 625	N06625	0.0	6.0	213,000	11.22

chromium, molybdenum, and nitrogen on pitting resistance. The fact that a different test method will give a different critical temperature is also demonstrated by the NaCl CPT curve being higher than the $FeCl_3$ CPT curve. ASTM Standard Test Method G 150 evaluates the CPT in 1M NaCl using a device commonly called the Avesta Cell. This electrochemical test is a less severe method of evaluation than the ferric chloride test because the natural pH of sodium chloride solutions is near neutral, while that of the highly oxidizing ferric chloride solution is about 1.6.

Another method of evaluating and ranking these alloys uses the 2% $KMnO_4$ - 2% NaCl test which simulates the highly oxidizing conditions of chlorinated manganese-containing cooling waters. Streicher[24] used this test to show that alloys which do not pit at 90°C (194°F) would be resistant in severe heat exchanger applications.

Newer methods being used to evaluate resistance to localized corrosion are beginning to provide quantitative predictions of initiation based on solution chemistry within crevices and the crevice gap width. Some representative work, shown in *Table 23* and *Figure 47*, shows that the 4.5% and 6% molybdenum high-performance austenitic stainless steels can function with much higher acidity and chloride ion concentrations within crevices before corrosion initiates, as compared with lower

Figure 48 Crevice sites attacked in seawater exposure at 35°C for a number of standard and high-performance stainless steels having different CCT temperatures[31]



alloyed stainless steel grades. Likewise, these grades can withstand a much tighter crevice gap. This consideration is especially important for systems that produce very tight, severe crevices such as threaded connections and compression fittings.

NEAR NEUTRAL ENVIRONMENTS – NATURAL WATERS AND BRINES

Much of the available crevice corrosion information on the high-performance stainless steels comes from a considerable body of seawater crevice corrosion exposure tests conducted by many investigators. These exposure data are based on coupon exposures using controlled crevices, with the results correlated in some way with grade composition or a laboratory parameter such as the CCT. This testing has shown that in seawater at ambient temperatures crevice attack will not initiate in grades having a CCT (G 48) of about 35°C (94°F) or higher. *Figure 48* illustrates CCT temperature versus crevice corrosion initiation as determined in ambient seawater exposures. The 35°C (94°F) CCT (G 48) temperature criterion appears to hold, regardless of whether the grade is austenitic, ferritic, or duplex. It also seems to relate well to service experience where the subgroups A-4 and A-6 austenitic grades, which have CCT (G 48) temperatures above 35°C (94°F), are all considered suitable for handling seawater at near ambient temperatures in applications such as condenser tubing and piping. This suitability appears to be limited to pitting resistance on clean surfaces and moderate natural crevice situations such as fouling. With very severe crevices such as under gaskets, or at higher temperatures, more resistant materials may be required. To illustrate this point, crevice corrosion data for a large number of alloys evaluated in filtered seawater are given in *Table 24*. In these tests, only some nickel-base alloys and high-purity ferritic stainless steels were completely resistant.

Based on service experience in brackish and fresh waters, chloride ion levels of about 1,000 and 5,000 ppm maximum, for Types 316 and 904L respectively, are reasonable limits for cooling water in conventional heat exchanger applications. These limits and the 35°C CPT criterion can be used to develop a serviceability guide for other high-performance stainless steels by relating anticipated water chloride limits to the CCT. *Figure 49* shows that a broad range in resistance to natural waters of varying chloride content results from the relatively small range of CCT (G 48) values existing among the various high-performance stainless steels. Because of their low molybdenum content, the subgroup A-1 acid-resistant grades are only marginally better than Type 316 in resistance to crevice corrosion. Most of the other grades, however, are far superior to Type 316 in their capability to resist crevice corrosion in high chloride waters.

There are applications involving heavy sections where some localized corrosion initiation may be acceptable. In these circumstances it is useful to have some estimate of the rate of

Table 24 Crevice corrosion ranking of alloys evaluated for 30 days in filtered seawater at 30°C[34]

Rank	Alloy	Composition (wt.%)						Number of sides (S) attacked	Maximum depth (D) of attack (mm)	CCI (S x D)
		Cr	Ni	Mo	Mn	Cu	Other			
1	Hastelloy C-276	15.5	54.7	15.5	0.5	0.1	3.8 W	0	0.00	0.00
	Inconel 625	22.3	61.0	8.5	0.1	—	3.6 Nb	0	0.00	0.00
	29-4	29.6	0.1	4.0	—	—	—	0	0.00	0.00
	29-4-2	29.5	2.2	4.0	—	—	—	0	0.00	0.00
	29-4C(1)	28.8	0.8	3.8	0.2	—	0.6Ti	0	0.00	0.00
	MONIT	25.3	4.1	3.8	0.4	0.4	—	0	0.00	0.00
2	Crucible SC-1	25.6	2.1	2.9	0.2	—	0.5Ti	1	0.05	0.05
3	Ferralium 255	26.2	5.6	3.2	0.8	1.8	0.19 N	2	0.08	0.16
4	Hastelloy G-3	22.8	43.7	7.0	0.8	1.8	3.5 Co	1	0.21	0.21
5	Haynes 20 Mod	21.6	25.5	5.0	0.9	—	0.5 Co	2	0.46	0.92
6	26-1S	25.0	0.2	1.0	0.2	—	1.1 Ti	4	0.30	1.2
7	20Mo-6	23.9	33.4	5.6	0.4	3.3	—	3	0.53	1.6
8	EB 26-1 (A.L.)	25.9	0.1	1.0	—	—	0.1 Nb	4	0.46	1.8
9	AL 4X	20.2	24.4	4.4	1.4	1.5	0.019 P	4	0.50	2.0
10	AL 6X	20.4	24.6	6.4	1.4	—	—	4	0.62	2.5
11	254 SMO	20.0	17.9	6.1	0.5	0.8	0.2 N	5	0.51	2.6
12	Hastelloy G	22.2	46.8	5.8	1.5	1.8	3.5 Co	4	0.87	3.5
13	904L (Uddeholm)	20.5	24.7	4.7	1.5	1.6	—	5	0.74	3.7
14	AISI 216	20.0	6.0	2.5	8.0	—	0.35 N	6	0.64	3.8
15	254SFER	29.4	22.2	2.1	1.7	0.1	0.15 N	5	0.90	4.5
16	254 SLX	19.9	25.0	4.7	1.6	1.7	0.04 N	6	0.92	5.5
17	Rex 734	21.3	9.4	2.7	3.8	—	0.42N	6	1.00	6.0
18	Type 317 LM	19.5	14.5	4.1	1.3	0.2	0.056 N	6	1.07	6.4
19	Nitronic 50	21.1	13.7	2.3	4.8	—	0.26 N	6	1.10	6.6
20	Jessop 700	20.7	25.2	4.4	1.6	0.2	0.28 Nb	5	2.00	10
21	Type 316	17.5	10.7	2.4	1.6	0.3	—	6	1.93	12
22	Carpenter 20 Cb-3	19.4	33.2	2.2	0.4	3.2	0.51 Nb	6	3.10	16
23	Jessop 777	20.8	25.6	4.5	1.4	2.2	0.24 Nb	6	2.90	17
24	44 LN	25.0	5.9	1 .5	1.8	0.1	0.2 N	6	3.35	20
Perforated										
	AISI 444	18.9	0.1	2 0	0.4	—	0.4 Nb	6	1.21	7.2
	AISI 329	27.0	4.2	1.4	0.3	0.1	—	6	1.29	7.7
	34 LN	16.8	13.8	4.2	1.6	—	0.14 N	6	1.04	6.2
Attack Outside Crevice Areas										
	AISI 439	17.7	0.3	—	0.3	—	0.4 Ti	6	0.72	4.3
	AISI 317L	18.9	12.2	3.6	1.7	—	0.056 N	6	1.92	12
	AISI 317L+	18.3	15.8	4.2	1.5	0.2	0.16 Co	6	1.09	6.5
	Incoloy 825	22.0	44.0	2.7	0.4	1.7	0.7 Ti	6	2.42	15

(1) Three additional panels were tested for 82 days with the same results.

Figure 49 Cooling water serviceability guidelines for stainless steel heat exchanger tubing based on alloy CCT temperature[31]

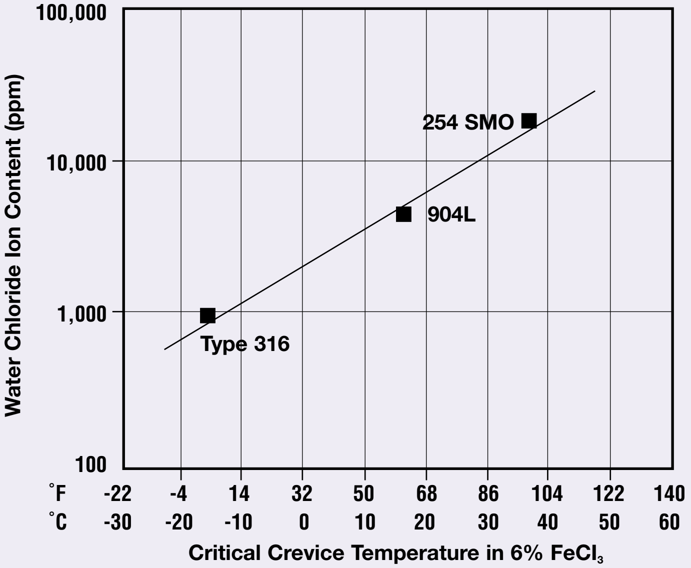
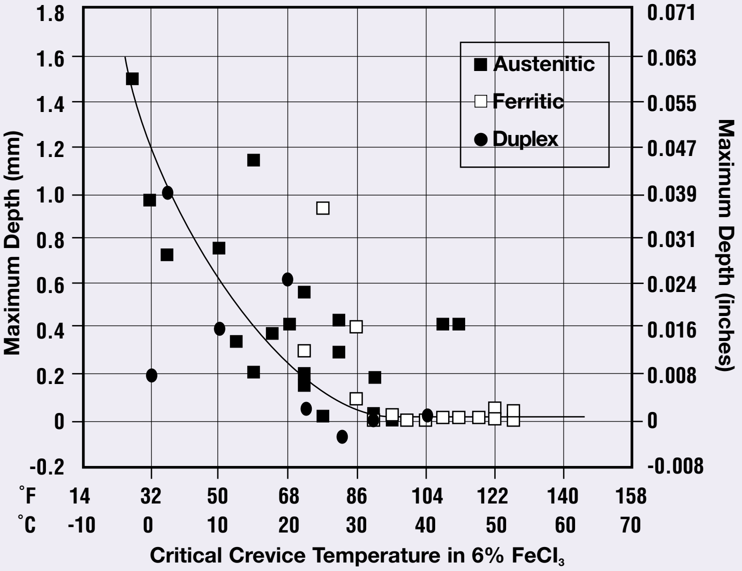


Figure 50 Depth of crevice attack in seawater exposure at 35°C for stainless steels having different critical crevice temperatures[31]

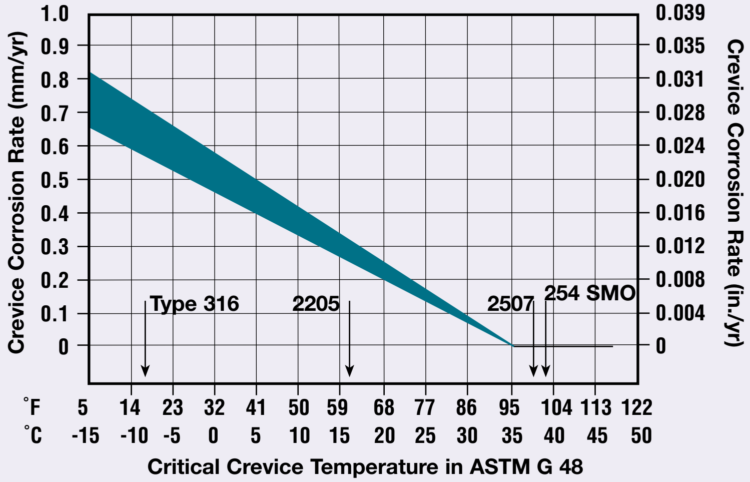


pitting or crevice corrosion that might be anticipated. These propagation rates are very hard to predict because of geometry and other variables. However, available data suggest that those grades with a high CCT will have a relatively low corrosion propagation rate even if localized corrosion initiates. The initiation of crevice corrosion versus CCT correlation in *Figure 48* also suggests the existence of such a relationship. The existence of a relationship is demonstrated when crevice depth data are plotted versus the CCT as in *Figure 50*. Other studies have shown similar effects that correspond to the data of *Figure 50* when the crevice depth data are also rationalized in terms of time. *Figure 51* provides data from various sources with test durations from several months to several years. When evaluated in terms of rate, most of the data fall within a band that provides an order of magnitude estimation of crevice corrosion rates as a function of CCT (G 48). This also shows that stainless steel grades with a higher CCT (G 48) will have lower rates of crevice corrosion if corrosion does initiate.

Another approach to grade selection when some localized corrosion can be tolerated is based upon mathematical model predictions for corrosion in waters of various chloride concentrations[32]. The guidelines shown in *Figure 52* also incorporate the concept of criticality of service and the fact that the

Figure 51 Estimated crevice corrosion rates for stainless steels in near ambient temperature seawater

(based on long-term crevice corrosion tests from various sources)[35,36,37,38]



Courtesy Carpenter Technology Corp.

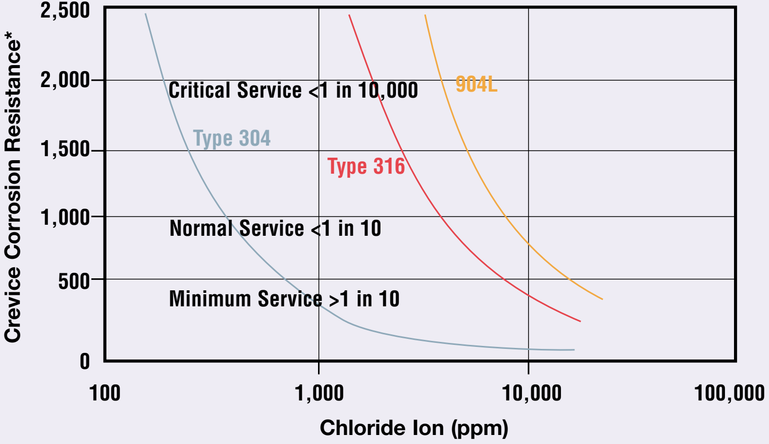
Carpenter alloy 20Cb-3® (right) displays very high resistance to hot sulphuric acid compared to Type 316 stainless steel

probability of failure is less than the probability of attack. An example of critical service would be thin wall tubing, where the available distance for propagation would be small; normal service would be heavier sections of material for which the propagation rate will determine the time of useful service. With this approach, Type 316 can provide useful service under some circumstances at moderate chloride levels, but a high-performance stainless steel such as 904L is necessary for critical service. However, at high chloride levels such as seawater, a grade more resistant than 904L is necessary for critical service, for example, grades in subgroups A-4, A-6, F-2, F-3, and D-3.

As temperature increases above ambient, the aggressivity of most pitting and crevice corrosion environments increases for all stainless steels. This effect will be tempered by the declining solubility of oxygen in water at higher temperature, by a peak in polarization

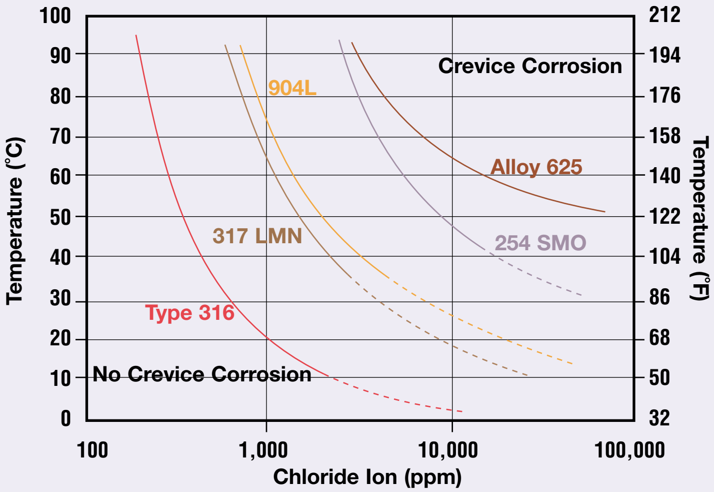
Figure 52 Guidelines for selection of stainless steels for water service based on mathematical modelling of corrosion rates and criticality of service[39,40]

Ratios relate to probability of crevice initiation in severe crevices



**Dimensionless units based on the critical crevice solution*

Figure 53 Effect of temperature and chloride on the initiation of crevice corrosion on austenitic alloys in aerated synthetic sea salt solutions at pH 2[41]



due to a peak in biological activity, or by oxygen solubility product-temperature relations for other water constituents. Additionally, corrosivity in seawater passes through a maximum at approximately 40°C, then decreases as biofouling is reduced. For applications involving cooling with clean seawater with metal temperatures near ambient, such as condensers, it is generally accepted that the subgroups A-4, D-4, F-2, and F-3 high performance stainless steels will resist pitting and crevice attack with moderate crevices such as fouling, and they can be used in thin wall tube applications. These same grade subgroups will become susceptible to localized corrosion in seawater at higher temperatures, as crevice severity increases, or with increasing chlorination. For example, these grades have been found not suitable for plate heat exchangers handling fresh seawater because this type of heat exchanger often operates at high temperature and the gaskets required in their design create very severe crevices. The subgroup A-6 high performance austenitic stainless steels are candidate materials for these severe applications.

The effect of temperature and chloride concentration on crevice corrosion initiation for several austenitic stainless steels is shown in *Figure 53*. This figure is based on one-year laboratory tests in oxygenated synthetic sea salt solutions that were acidified to pH 2.0 to simulate the corrosivity of natural seawater. A strong temperature effect is clearly indicated, but the superiority of high performance stainless steels is also evident. Many of these grades can extend useful service temperatures to levels well above that of Type 316 in a variety of cooling waters and other aqueous environments. The very highly alloyed subgroup A-6 austenitic stainless steels are useful well above ambient temperature in seawater and brines, even when gaskets or other severe crevices are employed. This is illustrated in *Table 25* which gives data for several brines and stainless steel grades ranging from Type 316 to 654 SMO. 654 SMO stainless

**Table 25 Localized corrosion of stainless steels in 90°C (194°F) sodium chloride solutions[42]
Effect of alloy, pH and aeration**

Name	UNS Number	20,000 Cl, pH 4, Aeration					100,000 Cl, pH 4, Aeration				
		C	P	W	S	E	C	P	W	S	E
Type 316	S31600	–	X	X	–	0	–	X	X	–	X
2205	S31803	X	0	0	0	0	X	0	0	0	X
904L	N08904	X	0	0	–	X	X	0	X	–	X
254 SMO	S31254	X	0	0	–	0	X	0	0	–	X
654 SMO	S32654	0	0	0	–	0	X	0	0	–	0
		100,000 Cl, pH 8, Aeration									
Type 316	S31600	–	X	0	–	X					
2205	S31803	X	0	X	0	X					
904L	N08904	X	0	X	–	X					
254 SMO	S31254	X	0	0	–	0					
654 SMO	S32654	0	0	0	–	0					
		100,000 Cl, pH 4, N_2 Purge					100,000 Cl, pH 8, N_2 Purge				
Type 316	S31600	–	0	X	–	0	–	X	X	–	X
2205	S31803	X	0	0	0	X	X	0	X	0	0
904L	N08904	X	0	X	–	0	X	0	X	–	0
254 SMO	S31254	0	0	0	–	0	0	0	0	–	0
654 SMO	S32654	0	0	0	–	0	0	0	0	–	0

C = Crevice Corrosion
P = Pitting Corrosion
W = Weld Pitting
S = Stress Corrosion Cracking
E = Attack on Cut Edges
0 = No Visible Attack
X = Attack
– = Not Tested

steel is the only grade which exhibits no pitting or crevice attack to the maximum test temperature of 90°C, regardless of whether the brines are aerated or not. The effect of oxygen is also shown in *Table 25*; corrosion performance is improved when the brines have been deaerated with nitrogen. For a detailed discussion on the selection of stainless steels for service in these environments, see the NiDI publication No. 11 003, “Guidelines for Selection of Nickel Stainless Steels for Marine Environments, Natural Waters and Brines”.

INFLUENCE OF MICROBIAL ACTIVITY

There are circumstances where microbial activity can influence the corrosion process. This usually involves microbes which metabolize sulphur compounds, producing an aggressive acidic hydrogen sulphide-containing localized environment. Less frequently it involves a combination of microbes and a unique chlorine-containing environment which oxidizes certain cations, including iron and manganese, producing a localized environment having a highly oxidizing corrosion potential relative to stainless steels. In some situations where this microbial activity is present, the standard stainless steel grades will undergo localized corrosion that would not have occurred otherwise. This is known as microbiologically influenced corrosion (MIC). MIC is most likely to occur in environments having high microbial population of the required species and relatively stagnant conditions at near ambient temperatures. Metallurgically, welds are most susceptible, especially poorly cleaned weld and heat-affected zone surfaces. This form of corrosion is known to occur in Types 304 and 316 stainless steels.

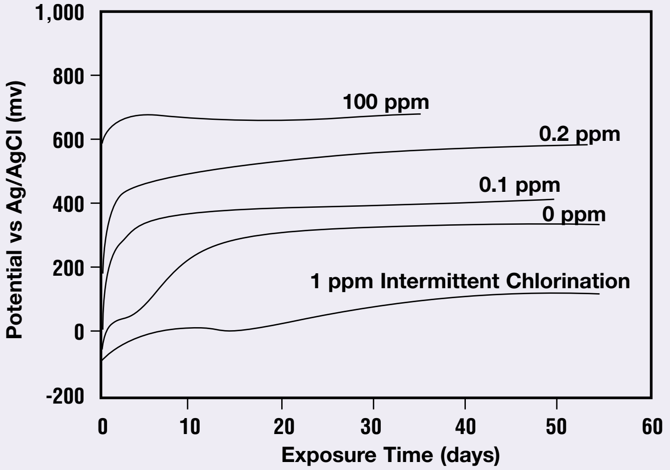
It is natural to expect that those stainless steels that have greater intrinsic resistance to localized corrosion will have greater resistance to MIC, and this is indeed the case. A review of reported incidences of MIC in stainless steels has identified no service failure of any high-performance stainless steel grade where microbial activity was conclusively demonstrated to have been present[43]. While it is difficult to produce this corrosion in the laboratory, this review also showed that laboratory studies centering mostly on the subgroup A-4 6% molybdenum austenitic stainless steel grades have not produced any convincing data to suggest that MIC represents a threat to the serviceability of these stainless steels. One would expect that resistance to MIC would improve with grades that have a higher critical pitting or crevice temperature; so interest in dealing with this problem has emphasized the subgroup A-4 austenitic stainless steels. They have been used extensively in nuclear power plant service water and emergency cooling systems where stagnant conditions have produced MIC-related failure in coated carbon steel or Type 304 and Type 316 piping.

OXIDIZING HALIDE ENVIRONMENTS – CHLORINATED COOLING WATERS AND BLEACH SOLUTIONS

The aggressivity of environments containing halides, in terms of localized corrosion, depends on the halide, pH, temperature, and the oxidizing power of the oxidant. Bromide is the most aggressive halide in near neutral solutions, followed by chloride; iodide and fluoride are relatively innocuous. In acid solutions, fluoride can be very aggressive. Strong oxidizers can act to raise the stainless steel corrosion potential above its pitting or crevice corrosion potential for any given halide. High temperature and low pH will also contribute toward producing very corrosive conditions. Examples of situations where such environments are encountered include chlorination for fouling control in seawater-cooled heat exchangers, and especially in the pulp bleaching step in paper production where a variety of strong oxidants are used.

The effect of chlorination on the corrosion potential is illustrated in *Figure 54* for the case of 254 SMO exposed in natural seawater with different chlorine concentrations. As little as 0.1 ppm continuous chlorination will produce a positive shift in the corrosion potential, significantly greater than the normal shift that occurs even in the absence of chlorination. Fortunately, chlorination also reduces the cathodic current density in seawater, and so the effect on corrosion is not as serious as might be expected. Because stainless steel pitting and crevice corrosion initiation potentials increase with increasing chromium and molybdenum, and because of the cathode effect, the high-performance stainless steels can give good service where chlorination is necessary in high chloride cooling waters. Experience has indicated that the subgroup A-4 6% molybdenum austenitic grades and the subgroups F-2 and F-3 ferritic grades can be used with continuous chlorination in ambient temperature seawater at chlorine levels at least as high as 1 ppm[45]. The duplex grades generally seem to provide lower performance within similar PRE ranges. Intermittent or targeted

***Figure 54* Effect of chlorination on the open circuit potential of 254 SMO stainless steel exposed in natural seawater with and without continuous chlorination**[44]



chlorination will allow the use of considerably higher chlorine levels[46]. High temperature and severe crevices, such as those found at flanges, will limit the use of all but the most resistant grades. *Table 26* compares 1 ppm chlorination exposures at 15°C (59°F) and 40°C (104°F). For severe service involving any of these variables, the subgroup A-6, 654 SMO stainless steel equals the performance of the best nickel-base alloys and has seen extensive service as flange connections in critical seawater handling systems.

Chlorine and chlorine dioxide produce highly oxidizing conditions in some stages of the paper pulp bleaching and washing process. Highly corrosive conditions are produced by these oxidants acting in combination with high chloride ion residual, low pH, and high temperatures. Traditionally, Type 316 stainless steel had been used in some of the milder corrosive environments in the bleach plant. However, trends toward waste stream closure and more advanced bleach and environmentally friendly bleaching practices have produced more corrosive conditions. These include higher chloride ion residuals and higher temperatures. Conditions are most severe in the D-stage, probably because it generally operates at the highest temperature. Corrosivity is also severe in the C- and C/D-stages because these stages carry the highest

Courtesy Avesta Sheffield AB

Condenser tubes in 654 SMO® stainless steel being installed in a nuclear power plant.

Table 26 Corrosion after 40 days' chlorination in recirculating seawater test rigs[47]

		Temperature 15°C (59°F)				Temperature 40°C (104°F)			
		No Chlorine		Chlorination - 1mg/l		No Chlorine		Chlorination - 1 mg/l	
Name	UNS Number	No. Sites Attacked	Max. Depth mm (in.)	No. Sites Attacked	Max. Depth mm (in.)	No. Sites Attacked	Max. Depth mm (in.)	No. Sites Attacked	Max. Depth mm (in.)
Type 316	S31600	3	0.24 (0.010)	2	0.32 (0.013)	7	0.92 (0.036)	5	1.04 (0.041)
		3	0.12 (0.005)	6	0.68 (0.027)	7	0.60 (0.024)	1	0.47 (0.018)
255	S32550	0	0 (0.0)	2	0.10 (0.004)	1	0.12 (0.005)	1	0.11 (0.004)
		1	0.04 (0.002)	2	0.06 (0.002)	1	0.02 (0.001)	1	0.15 (0.006)
254 SMO	S31254	0	0	0	0	2	0.04 (0.002)	5	0.14 (0.006)
		0	0	0	0	1	0.02 (0.001)	5	0.12 (0.005)

Figure 55 Corrosion after six months of exposure in chlorination stage washers at ten Canadian pulp mill bleach plants[48]

Plant:	D	G	K	B	F	H	C	E	A	J
Type 316	🟦	🟦	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Type 317L	🟦	🟦	🟦	🟪	🟪	🟪	🟪	🟪	🟪	🟪
904L	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟪	🟪	🟪
254 SMO	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Alloy G	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟥	🟥	🟥
C 276	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Titanium	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

🟥 Low Corrosion 🟦 Moderate Corrosion 🟪 High Corrosion

acidity and chloride ion residual. In recent years, many of the high-performance stainless steels have been evaluated in extensive field test programs. While conditions vary greatly from mill to mill, the testing programs have demonstrated the limitations of Types 316L and 317L in these stages and a general suitability of the subgroup A-4 austenitic grades for many sections of the bleach washers. The results of an extensive test program conducted in C-stage washer incoming stock are given in *Figure 55*. The 254 SMO stainless steel, in subgroup A-4, was the only stainless steel exhibiting acceptable resistance to localized corrosion in all ten Canadian pulp mill bleach plants involved in the test program. However, under very severe conditions, as might occur in the vapour phase or when chlorine residual exceeds 50 ppm with high chloride ion residuals, even 6% Mo grades may not be resistant.

In the D-stage, the recent substitution of more chlorine dioxide for chlorine has produced conditions where general attack may occur on nickel-base alloys that had been used because of their superior localized corrosion resistance compared with the 6% molybdenum austenitic stainless steels. The subgroup A-6 austenitic stainless steel grades appear to meet the requirements of both localized and general corrosion in this instance. Data illustrating this superior performance in a simulated D-stage environment is given in *Table 27*.

ACIDIC ENVIRONMENTS CONTAINING HALIDES – FLUE GAS CONDENSATES

Mildly acid aqueous environments containing halides but not strong oxidants can be handled by many of the high-performance stainless steels, provided the temperature and halide concentrations remain relatively low. The likelihood of pitting and crevice corrosion increases with acidity, temperature, halide content and, especially, with reducing conditions which could lead to general corrosion. Conditions found in flue gas desulphurization (FGD) and cleaning equipment produce these kinds of environments.

Fuels that contain sulphur or chlorine produce the most corrosive combustion products, the most common examples being high sulphur coals and fuel oils and municipal waste.

Table 27 Weld corrosion in a simulated D-stage paper bleach environment[49]

20–hour tests with 600 ppm chloride at 70°C (158°F) and 900 mv-SCE potential.

Name	UNS Number	Weld Parameters Method	 Filler	Corrosion Rate mm/yr (mpy) pH 6.5	 pH 2.0
254 SMO	S31254	–	–	0.01 (0.4)	0.24 (9.0)
254 SMO	S31254	SMAW	P12	0.10 (4.0)*	0.32 (13.0)**
654 SMO	S32654	–	–	<0.01 (0.4)	0.24 (9.0)
654 SMO	S32654	GTAW	–	<0.01 (0.4)	0.25 (10.0)
654 SMO	S32654	GTAW	P16	0.01 (0.4)	0.25 (10.0)
654 SMO	S32654	SMAW	P16	0.04 (2.0)	–
Alloy C–276	N10276	–	–	0.53 (21.0)	0.44 (17.0)
Alloy C–276	N10276	GTAW	C–276	0.53 (21.0)	0.44 (17.0)

** Pitting on edge in fusion zone, max. 0.4 mm (0.016 in.)*
*** Pitting in weld metal, max. 1.0 mm (0.039 in.)*

Condensate and scrubbing liquor will become acidic with the SO_2 and also reducing with SO_3 and HCl. The design and method of operation of the gas-handling system will also contribute greatly to the severity of corrosive conditions that may develop. In general, raw condensate and recycling will produce the most corrosive conditions, while washed walls and absorbent-treated liquors represent less corrosive conditions. The "generic FGD system" defined in ASTM STP 837[50] describes the layout of a generic flue gas desulphurization system which defines various system locations in terms of relative potential for corrosion. This system is illustrated in *Figure 56*, where zones having different degrees of corrosivity are indicated by the letter symbols A through H. Each zone is defined in terms of both qualitative and quantitative severity in *Tables 28* and *29*, respectively. From the standpoint of metallic corrosion, the most severe zones all involve ductwork and stacks or wet/dry conditions where the pH can be <0.1 and temperatures can be as high as 182°C (360°F). Locations that are washed or that handle absorbent are mild or moderately corrosive.

The generic FGD system does not account for chloride and fluoride levels, or any operating variables such as deposit buildup or drains; so further information is needed in order to make

Figure 56 Operating zones in a generic FGD system as defined in ASTM STP 837[50]

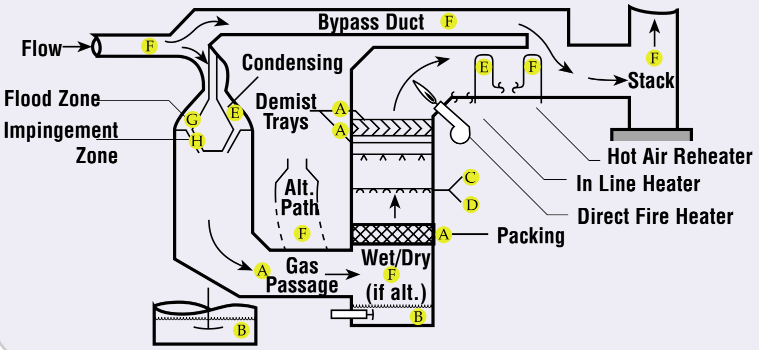


Table 28 Qualitative description of scrubber operating zones[50]

Code	Chemistry	Mechanical Environment	Temperature
A	Mild Corrosive (vapour)	Mild	Mild
B	Moderate (Immersion)	Mild	Mild
C	Moderate	Moderate	Mild
D	Moderate	Severe	Mild
E	Severe	Mild	Moderate
F	Severe	Mild	Severe
G	Severe	Severe	Severe
H	Moderate	Severe	Moderate

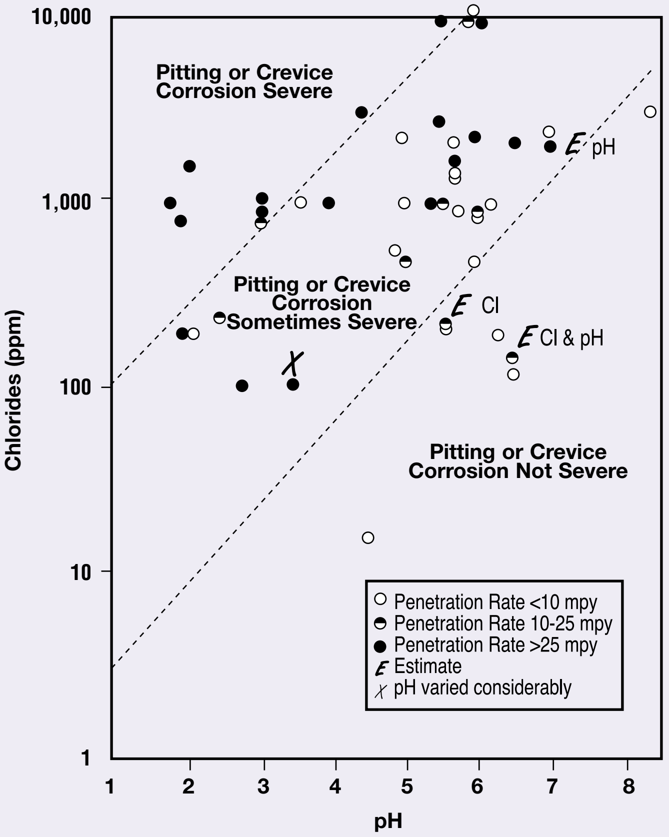
Table 29 Quantitative description of scrubber operating zones[50]

Severity	Chemical Environment	Mechanical Environment (Abrasion Level)	Temperature
Mild	pH 3.8 H_2SO_4	Agitated Tk. Ducts, Thickener	Ambient to 66°C (150°F)
Moderate	pH 0.1-3, 8-13.9 H_2SO_4 0-15%	Spray Zone Tank Bottoms	Ambient to 93°C (200°F)
Severe	pH <0.1, >13.9 H_2SO_4 15%	Hi Energy Venturi Impingement- Turning Vanes Targets	Ambient to 182°C (360°F)

judgments on materials selection. One of the first and most broadly based studies on stainless steel performance in FGD was a test rack exposure program conducted by the International Nickel Company[51]. In this program, Types 316L and 317L were exposed in a large number of commercial SO_2 scrubbing environments, with the results shown in *Figures 57* and *58*. This work clearly showed the strong detrimental effect of high chloride and acidity, primarily in terms of increasing the tendency for localized pitting or crevice corrosion. Nevertheless, in the early years of FGD construction in the U.S.A., a considerable number of absorbers and other "moderate" severity locations were constructed using either Type 317L or a high molybdenum version of Type 316L stainless steel. The aim was to operate these units at pH levels above 4 and chloride levels of not more than a few thousand ppm. A summary of operating experience with these U.S. and European units was reported by NiDI in 1989 in publication No. 10 024, "The Use of Nickel Stainless Steels and Nickel Alloys in Flue Gas Desulphurization Systems in the United States" and No. 10 025, "Flue Gas Desulphurization; the European Scene". While many of these installations were successful, operating experience showed that more highly alloyed stainless steels are needed in moderate severity locations where chloride plus fluoride levels could sometimes range upward of 5,000 ppm, and nickel-base alloys would be necessary for those severe locations handling raw condensate at high temperature.

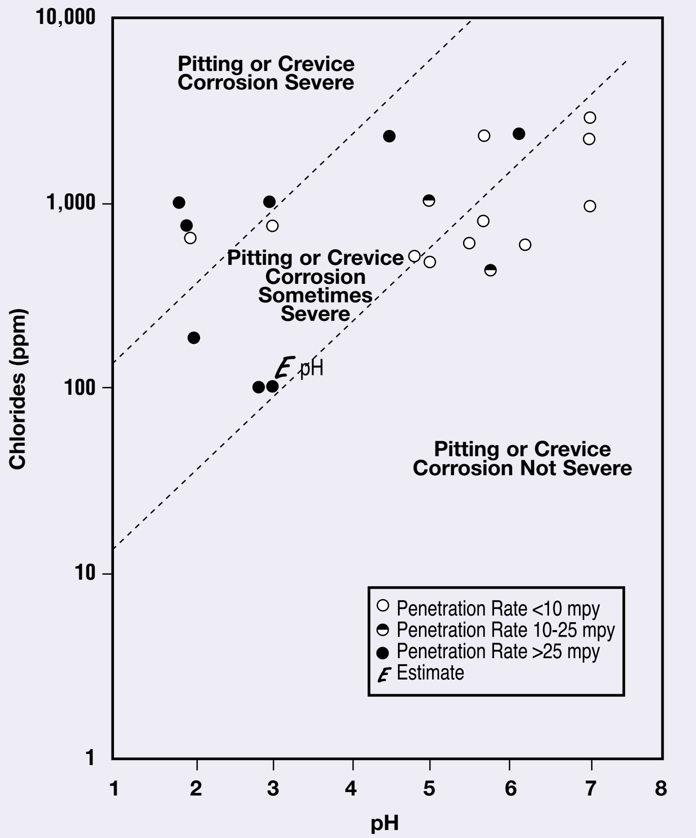
The high-performance stainless steels as a whole have not been as extensively evaluated as Types 316L and 317L, but they have become preferred over high molybdenum Type 316L and have been extensively used for the "moderate severity" locations in many recent FGD installations. Investigators have attempted to quantify the performance of the high-performance grades based on the behaviour of Types 316L and 317L with respect to chloride and pH, and on relative pitting or crevice resistance as reflected by the PRE number or CCT. The approximate behaviour of representative grades is presented in *Figure 59*. The exact position of each curve for an individual grade is yet to be confirmed by field experience, but there is no question that a wide range in performance and cost-effectiveness is available. A large number of

Figure 57 Effect of pH and Cl ions on the localized attack of Type 316L stainless steel in SO_2 scrubber environments[51]



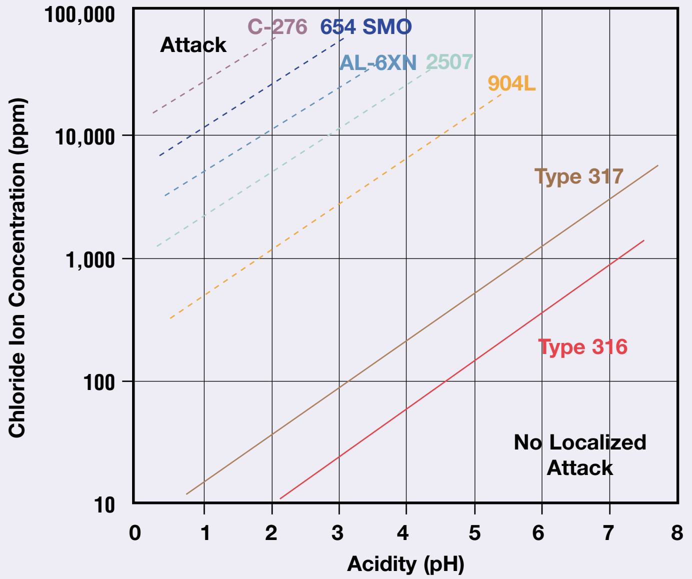
Dashed lines approximate attack. Some points represent as many as 5 tests.

Figure 58 Effect of pH and Cl ions on the localized attack of Type 317L stainless steel in SO_2 scrubber environments[51]



Dashed lines approximate attack. Some points represent as many as 5 tests.

Figure 59 Approximate service limits for stainless steels and nickel-base alloys in flue gas condensates and acid brines at moderate temperatures [60-80°C (140-176°F)][51,52,53]

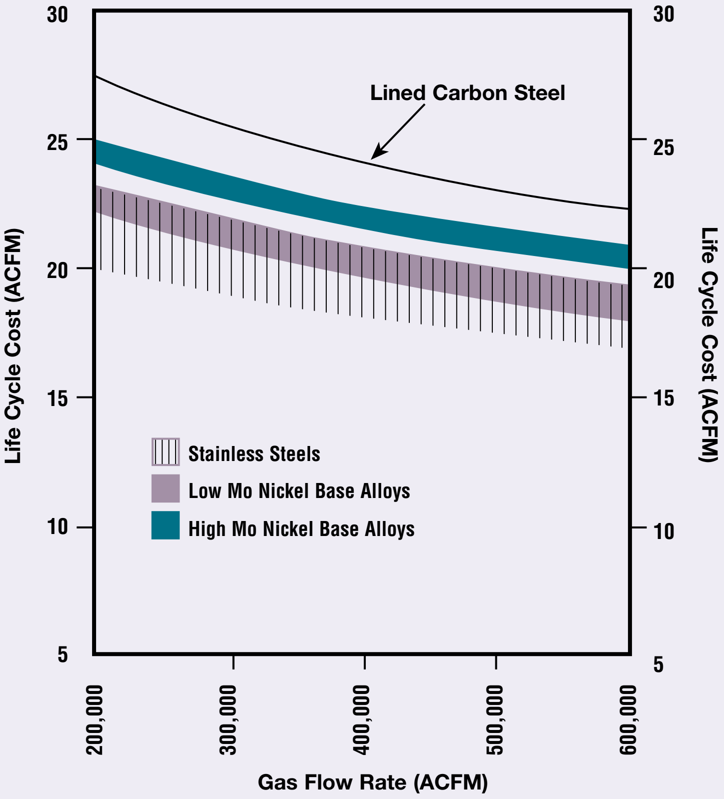


317LM and 317LMN absorber installations with pH of about 4 and chloride up to several thousand ppm were made beginning in the 1980s. These two grades appear to be performing well under these moderate conditions and have the advantage of adding a relatively small cost premium over the standard stainless steel grades.

When chloride levels in the absorber begin to exceed about 5,000 ppm, concern arises over the suitability of 317LMN in this kind of application. In such cases, the subgroups A-4, A-6, D-3, and D-4 austenitic and duplex stainless steels are good candidates and have been used in a limited number of cases. A disadvantage of these grades, as well as nickel-base alloys, for these more severe applications is their relatively high cost compared with nonmetallic lining, FRP, or acid-resistant brick. However, these grades have been very successfully used in the form of clad plate or wallpaper construction. Life cycle cost comparisons show that this type of construction can provide substantially lower overall costs than rubber-lined carbon steel for absorber applications without the maintenance patching and repair inherent with rubber linings. The result of a typical life cycle cost analysis is shown in *Figure 60*. Methods for the quality fabrication of clad plate and wallpaper designs have been developed and are available from such sources as the Nickel Development Institute and NACE International (see Appendix 1).

The localized corrosion predictions as a function of chloride and pH in *Figure 59* should not be used to estimate performance for the very severe condition of raw acid condensate that may occur in ducting and stacks. When the pH begins to fall below about 1.0, the corrosion mode for most stainless steels, including the high-performance grades, begins to shift toward general attack. Corrosion data for acid solutions are more applicable for these conditions. General experience has indicated that only the most highly alloyed nickel-base

Figure 60 ***Life cycle cost comparisons for alloy clad and lined carbon steel absorbers***[54]



alloys will be useful in ducting or stacks where raw acid condensate is likely to form. An exception may be the newest subgroup A-6, the austenitic high-performance stainless steels which have outstanding resistance to strong acids containing chloride. An example of this performance is provided in *Table 30* which gives the results of test rack exposure in the quench section of a municipal waste incinerator where quench liquor pH was 0.5-1.0 and contained very high levels of chloride and fluoride ions. The 654 SMO stainless steel in subgroup A-6 performed at least as well as several nickel-base alloys tested at the same time. The disadvantage of titanium in strong fluoride-containing acids was also confirmed by these tests.

STRESS CORROSION CRACKING

Stress corrosion cracking in stainless steels, when it occurs, usually involves either anodically controlled cracking in the presence of a specific ion, usually chloride, or cathodically controlled hydrogen cracking. Halides other than chloride will also produce cracking, but they are less often encountered and their effect will depend on other solution variables such as acidity and oxidizing potential, just as with pitting and crevice corrosion. The influence of cations in halogen salts is primarily through their effect on the pH of hydrolization, the more acid salts being more aggressive. Sodium chloride, although by far the most commonly encountered salt, is fairly neutral; thus, it will generally be less aggressive than salts containing calcium and magnesium ions. Hydrogen cracking usually requires high hydrogen partial pressures and is confined primarily to the ferritic phase found in the duplex and ferritic grades.

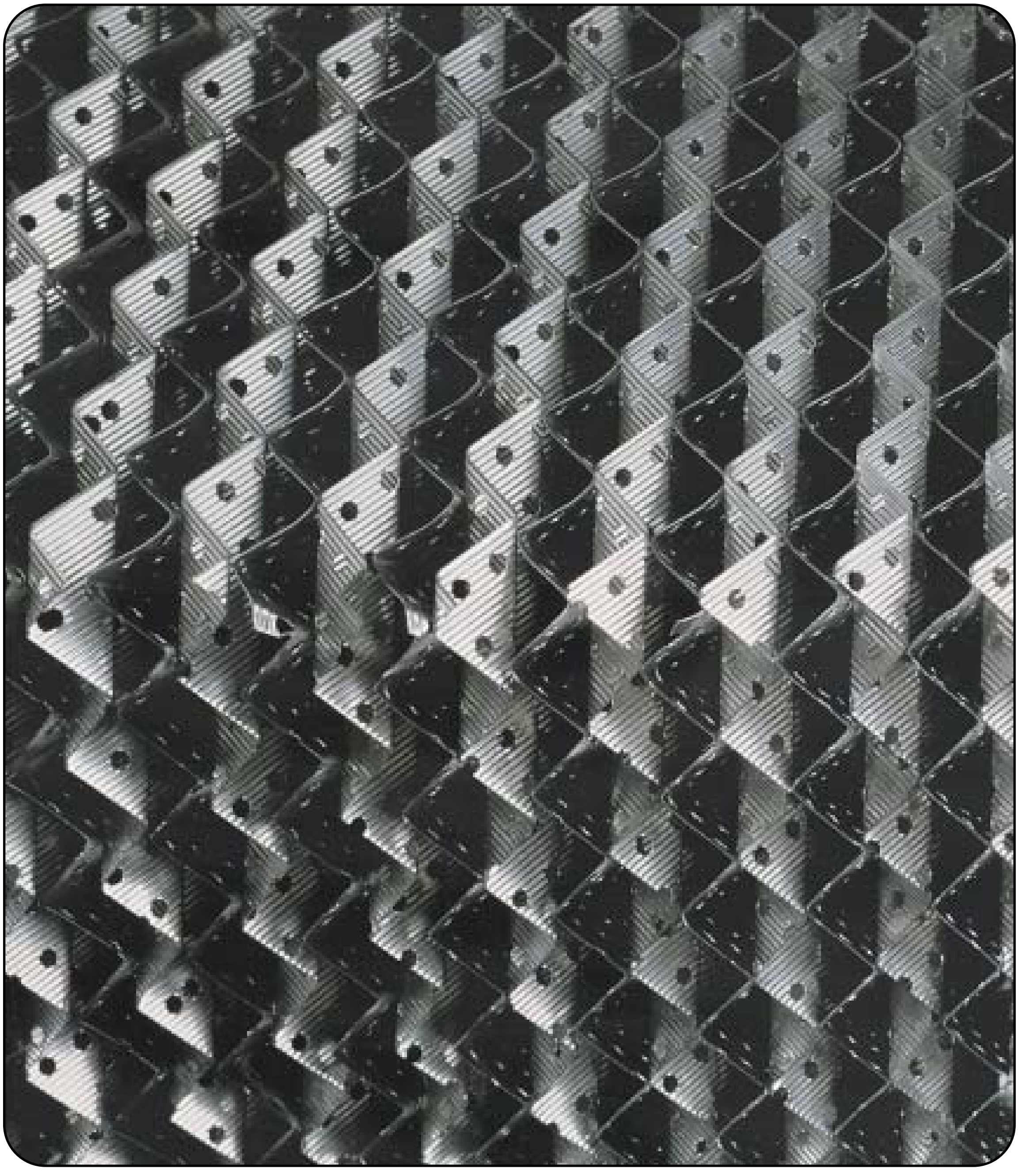
As a family, the high-performance stainless steels, regardless of structure type, generally offer better stress corrosion cracking resistance than the standard austenitic stainless steels. The reason for this is that the 8 to 12 percent nickel in Types 304 and 316 stainless steel is at an inopportune level from the standpoint of stress corrosion cracking; this was demonstrated many years ago by Copson[56], using the boiling 45% $MgCl_2$ solution. Higher nickel, chromium, and molybdenum increase the stress corrosion cracking resistance of austenite, thereby improving resistance in the high-performance grades. The ferrite phase further improves the resistance of the duplex grades, and provides very good resistance for the ferritic grades in the commonly encountered chloride environments. Furthermore, it has recently become clear that the boiling 45% $MgCl_2$ solution, while clearly showing alloying effects, is an extremely

Table 30 Corrosion of welded coupons in a waste incineration plant flue gas quencher[55]

3.5 months at pH 0.5-1.0, Cl 4-20 g/l, Fl 0.01-0.07 g/l, SO_4 0.05-0.15 g/l, T 60°C (140°F)

Name	UNS Number	Weight Loss mg/m2hr (mg/ft2hr)	Crevice Corrosion mm (in.)	Pitting Corrosion
904	N08904	58 (5.39)	40 sites - 0.65 (0.026)	in weld - 0.75 (0.030)
2507	S32750	3 (0.28)	10 sites - 0.22 (0.009)	in weld - 0.60 (0.024)
254 SMO	S31254	1 (0.09)	5 sites - 0.37 (0.015)	0
654 SMO	S32654	0	0	0
625	N06625	0	2 sites - 0.01 (0.0004)	0
Alloy C-276	N10276	0	4 sites - <0.01 (0.0004)	0
Alloy C-22	N06022	0	3 sites - <0.01 (0.0004)	0
Titanium Gr 2	R50400	892 (83)	0	severe uniform corrosion

Courtesy Koch Engineering



AL-6XN® tower packing in a distillation column

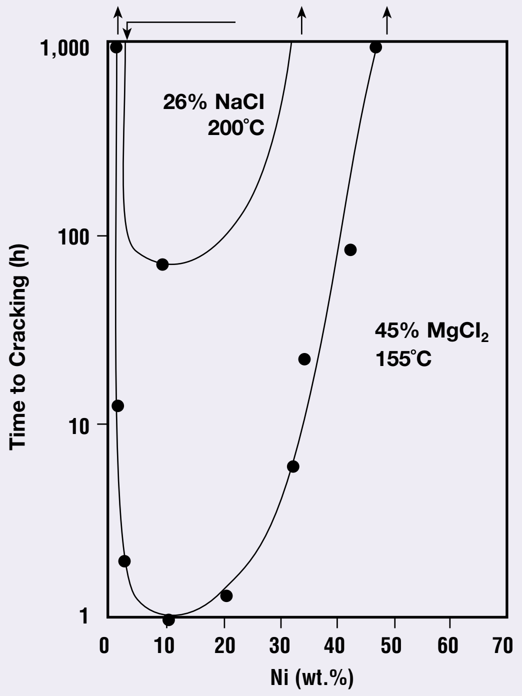
aggressive environment that is not necessarily useful in defining areas of applicability. Present research has placed emphasis on procedures that come closer to simulating real conditions. When testing in sodium chloride environments, established alloying effects are verified; in addition, the possibility of obtaining useful resistance from the high-performance stainless steels in aggressive environments is indicated. This is illustrated in *Figure 61* where very long failure times, or immunity, are demonstrated for alloys within the austenitic high-performance stainless steel nickel content range in 26% NaCl at 200°C (392°F).

WATER AND BRINE ENVIRONMENTS

The high-performance stainless steels have been evaluated for stress corrosion cracking resistance in a large variety of laboratory tests involving the chloride ion. Many of these tests were originally developed to apply to severe conditions in cooling waters or brines that could lead to stress corrosion cracking in the standard stainless steels. By variation in test conditions, these produce a range in test severity that allows comparisons among the different high performance stainless steel subgroups and the standard stainless steel grades. The performance of the stainless steels in these tests is summarized qualitatively in *Table 31*. The tests listed in this table have been arranged with the more severe high temperature acid chloride environments on the left side; the severe, high oxygen, high temperature environments on the right side; and the more moderate, low temperature environments in the centre. The grade subgroups are listed in order of increasing resistance in these environments from top to bottom in each section of the table. The standard austenitic grades, as exemplified by Type 316, will develop stress corrosion cracking in all these tests. The most severe test, boiling 45% $MgCl_2$ will produce stress corrosion cracking in all of the high-performance grades except the low nickel ferritic grades. In between these extremes of grade sensitivity and test severity, there exists a wide range in alloy performance.

Of the high performance austenitic grades, the stainless steels in subgroup A-2 show stress cracking susceptibility in all of these tests, and the subgroup A-5 stainless steels are only marginally better. While both of these subgroups would probably perform somewhat better than Type 316 in less severe tests, they should not be considered as solutions to stress cracking problems encountered with Type 316 because their nickel content is only slightly higher than that of Type 316. It is with the remaining austenitic subgroups, which have nickel contents above 18 percent, that stress corrosion cracking resistance is dramatically improved. This improvement increases with increasing nickel content and with increasing chromium and molybdenum. For example, of the high performance austenitic stainless steels, 904L and 20Cb-3 have frequently been used in applications where Type 316 would be considered inadequate from the standpoint of stress corrosion cracking, and they have given good service in these instances. *Table 31* suggests that the A-4 and A-6 grades should be useful in even more aggressive environments. The duplex high-performance stainless steels are superior in stress corrosion cracking resistance compared with Types 304 and 316 because they contain the ferrite phase, but they do not have the ability to resist extremely aggressive environments as do the most highly alloyed austenitic and ferritic alloys. This is

***Figure 61 Relative severity of the NaCl and $MgCl_2$ tests in evaluating the effect of nickel on the stress corrosion resistance of stainless steels*[57]**



Source: Various Literature Sources

Table 31 Comparison of stress corrosion cracking resistance of stainless steel groups in accelerated laboratory tests

Typical Grade Name	Alloy Content	42% $MgCl_2$ boiling 154°C U-Bend	35% $MgCl_2$ boiling 125°C U-Bend	Drop Evap. 0.1M NaCl 120°C 0.9xY.S.	Wick Test 1500 ppm Cl as NaCl 100°C	33% $LiCl_2$ boiling 120°C U-Bend	40% $CaCl_2$ 100°C 0.9xY.S.	25-28% NaCl boiling 106°C U-Bend	26% NaCl autoclave 155°C U-Bend	26% NaCl autoclave 200°C U-Bend	600 ppm Cl (NaCl) autoclave 300°C U-Bend	100 ppm Cl (sea salt+O_2) autoclave 230°C U-Bend	Group No.
AUSTENITIC STAINLESS STEELS													
Type 316L	16 - 20 Cr 10 -15 Ni 2 - 4 Mo	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
317LMN	17 - 20 Cr 11 - 17 Ni 3 - 5 Mo	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	A - 2
Mn-N Alloys	23 - 26 Cr 12 - 18 Ni 3 - 5 Mo	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟪	🟪	▒	🟦	A - 5
904L	19 - 26 Cr 21 - 30 Ni 3 - 5 Mo	🟦	🟦	🟦	🟪	🟪	▒	▒	▒	▒	▒	🟦	A - 3
Alloy 20	19 - 26 Cr 32 - 46 Ni 2 - 4 Mo	🟦	🟦	🟦	🟪	▒	▒	▒	▒	▒	▒	🟦	A - 1
6Mo Alloys	19 - 25 Cr 17 - 26 Ni 5 - 7 Mo	🟦	🟦	🟪	▒	▒	▒	▒	▒	▒	▒	🟦	A - 4
654 SMO	24 - 28 Cr 21 - 32 Ni 6 - 8 Mo	🟦	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	A - 6
DUPLEX STAINLESS STEELS													
3RE60	18 - 26 Cr 3 - 5 Ni 0 - 3 Mo	🟦	🟦	🟦	🟪	▒	▒	▒	🟦	🟦	☐	🟦	
2205	21 - 26 Cr 2 - 7 Ni 2 - 4 Mo	🟦	🟦	🟦	▒	▒	▒	▒	🟪	🟦	☐	🟦	D - 2
255	24 - 27 Cr 4 - 8 Ni 3 - 4 Mo	🟦	🟦	🟦	▒	▒	▒	▒	🟦	🟦	☐	☐	D - 3
2507	24 - 26 Cr 6 - 8 Ni 3 - 5 Mo	🟦	🟦	🟦	▒	▒	▒	▒	▒	▒	☐	☐	D - 4
FERRITIC STAINLESS STEELS													
444	18-20 Cr 0-0.5 Ni 1-3 Mo	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	
E-BRITE 26-1	25-27 Cr 0-0.3 Ni 0.75-1.5 Mo	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	F - 1
SEA-CURE	25-30 Cr 1-4 Ni 3-4.5 Mo	🟦	▒	▒	▒	▒	▒	▒	▒	▒	🟪	🟦	F - 3
AL 29-4-2	28-30 Cr 2-2.5 Ni 3.5-4.2 Mo	🟦	▒	▒	▒	▒	▒	▒	▒	▒	🟪	🟪	F - 4

🟦 Cracking Anticipated 🟪 Cracking Possible ▒ Cracking Not Anticipated ☐ Insufficient Data probably because their nickel contents, at 2 to 8 percent, are at about the same level that is highly detrimental in the austenite phase. The ferritic grades all have good chloride stress corrosion cracking resistance. Those that contain no nickel do not show susceptibility in any of the test environments shown in *Table 31*, while the 1 to 4 percent nickel found in the more highly alloyed F-2 and F-3 grades causes susceptibility in the more severe environments.

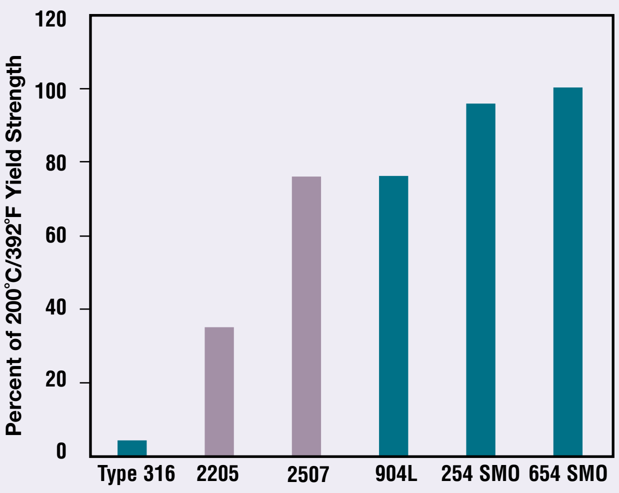
The application of laboratory stress corrosion cracking data to engineering design is very difficult because many system variables other than alloy content are involved. These include the actual stress pattern; the possibility of evaporation and localized ion concentration; and the potential, which is determined by the amount of oxygen available. Heat exchangers subject to localized boiling and hot surfaces covered with insulation are widely encountered situations involving these factors. The limitations of the standard stainless steel grades may indicate the need for high-performance stainless steel in these instances. The Wick Test and Drop Evaporation Test both attempt to simulate these situations[58, 59]. The Drop Evaporation Test is perhaps the more severe of the two tests and is often conducted over a range of stress levels. This test can provide guidance for grade selection in many cases. *Figure 62* gives data for a representative group of high-performance stainless steels evaluated by the Drop Evaporation Test; all tests were conducted at the same laboratory under exactly the same test conditions. These data suggest that the ferritic grades, as well as the higher alloyed austenitic and duplex high-performance stainless steel subgroups, should perform well in situations of localized boiling and evaporation that are encountered in many cooling water applications with boiling temperatures associated with near-ambient pressures.

Actual field experience supports these conclusions. There have been many instances of the successful use of high-performance stainless steels to replace Types 304 and 316 heat exchanger tubing, piping, and vessels that failed due to stress corrosion cracking. Incidents of stress corrosion cracking with these replacement grades have been exceedingly rare. Although limits of usefulness are difficult to define, the laboratory and field data provide some guidance for the case of oxygen-containing cooling waters as shown in *Figure 63*. The solid curve for Types 304 and 316 is based on a survey of operating heat exchangers and describes the temperature and chloride limits for useful service extending to about six years. This curve will shift slightly depending on variables such as the type of heat exchanger and the process fluid temperature, but it provides a guide for Types 304 and 316 and emphasizes that stress corrosion cracking, while it can occur at lower temperatures, becomes quite likely at temperatures above about 50°C (120°F) if evaporation occurs even at very low water chloride contents. The curves for the high-performance stainless steels are based on the laboratory test data from *Figure 62* and field experience. These curves show that the high-performance stainless steels are useful at significantly higher water chloride concentrations and temperatures.

SOUR OIL AND GAS ENVIRONMENTS

The presence of hydrogen sulphide adds to the corrosiveness of high chloride waters often involved with oil and gas production, and the presence of carbon dioxide or intentionally added acidifiers increases the aggressiveness of these environments. This increases the likelihood for pitting or crevice corrosion, stress corrosion cracking, and even general corrosion as the severity of the environment increases. At relatively low levels of H_2S, the standard grades of all three structure types can provide useful resistance and many are included in the NACE Standard MR0175, “Sulphide Stress Cracking Resistant Metallic Materials for Oilfield Equipment.” However, as H_2S partial pressure, chloride concentration, temperature, and acidity increase, the high-performance austenitic and duplex stainless steels are necessary to provide useful resistance. The high performance austenitic grades will generally outperform the duplex grades from the standpoint of H_2S-assisted stress corrosion cracking while the ferritic grades would be vastly inferior to both. Because many of these applications require high-strength, the duplex grades are often prime

***Figure 62* Stress corrosion in the drop evaporation test with sodium chloride solution at 120°C (248°F) showing the stress at which cracking will initiate**[59]

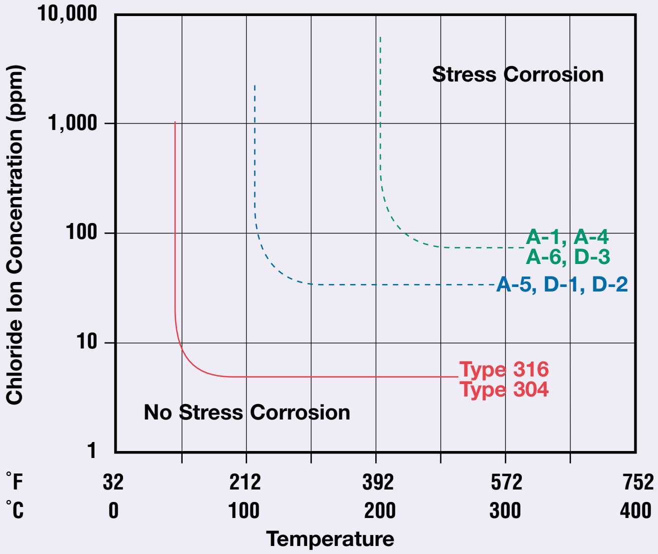


candidates for applications involving environments of moderate severity and they have been studied extensively to define their limits of serviceability in these circumstances.

The resistance of duplex stainless steels to sour environments is a very complex subject because resistance depends on interrelationships between metallurgical, environmental, and stress factors. In the presence of H_2S, the primary failure mode is hydrogen stress cracking of the ferrite phase. Low pH and high chloride contents seem to accelerate this process. However, the effect of temperature is such that susceptibility increases as temperature increases from ambient to about 100°C (210°F) and then declines at higher temperatures. The anodic stress corrosion cracking mechanism or general corrosion can take over at higher temperatures, especially if the chloride concentration is high. From a metallurgical standpoint, hydrogen cracking will be favoured if the structure is high in ferrite, while excessive austenite will promote the anodic form of cracking. Cold work will promote both forms of cracking, but some degree of cold work is often employed to provide higher strength. In addition to the environmental factors already mentioned, the presence of oil, which coats metallic surfaces, can provide an inhibiting effect; and certain ions, such as bicarbonate in seawater and produced water, raise the pH and produce less severe conditions than those in a laboratory using unbuffered sodium chloride. The method of stressing specimens in laboratory tests also produces differing test results that must be interpreted for applicability to engineering situations.

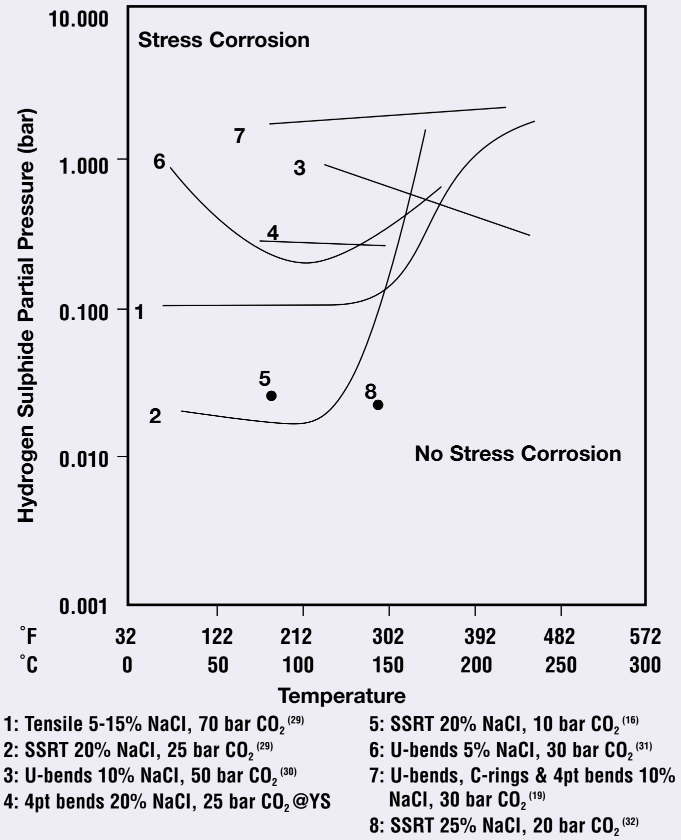
Many laboratory test programs seem to have produced overly conservative results in comparison to service experience. For example, stress corrosion cracking evaluations conducted with the slow strain rate test (SSRT) generally define lower acceptable H_2S levels than tests conducted using other methods. This difference and the influence of H_2S and temperature on stress corrosion cracking are illustrated in *Figure 64*. The SSRT test usually produces cracking at the lowest H_2S partial pressures and a maximum in stress corrosion cracking susceptibility at about 100°C (210°F) is

***Figure 63* Stress corrosion in cooling waters based on actual experience with Type 304 and Type 316 and predictions for high-performance stainless steels based on laboratory tests**[60]



indicated. Efforts have been made to define the H_2S and temperature regimes in which the various failure modes will be operative. An example for 2205 is given in *Figure 65*. Above some minimum combination of H_2S and temperature, localized pitting becomes a possibility followed by stress corrosion cracking. At the highest combinations of H_2S and temperature, general corrosion is encountered. These regimes will shift with other environmental factors as well as alloy composition and grade. This is shown for martensitic, duplex, and austenitic grades in *Figure 66*. Duplex stainless steels perform well at intermediate conditions, but the high-performance austenitic stainless steels or nickel-base alloys are required for severe service.

Figure 64 Hydrogen stress corrosion of duplex stainless steels showing variability in test results for different test methods in NaCl-CO_2-H_2S[61]



HYDROGEN ENVIRONMENTS

The standard and high-performance austenitic stainless steels are very resistant to environments having high hydrogen partial pressures and are often specified for handling hydrogen over a wide range of temperatures and pressures. The ferrite phase is susceptible to hydrogen damage, reflected in poorer performance in the duplex and especially the ferritic stainless steels. The duplex grades can retain some ductility and toughness under moderate hydrogen charging conditions because the austenite will provide residual ductility even if the ferrite is severely embrittled.

This beneficial effect of austenite is not available in the ferritic grades; therefore, caution must be exercised when considering them for applications involving hydrogen. For example, ferritic grades can develop voids and cracks when exposed to hydrogen-containing annealing atmospheres. Hydrogen charging is also a possibility at the more moderate temperatures involved in hydrocarbon processing, especially if a hydrogen charging catalyst such as cyanide is present. With heat exchangers handling cooling waters, it is possible to charge hydrogen and produce severe embrittlement if the surface is maintained cathodic by galvanic coupling or cathodic protection. The potential at which charging begins to become significant is about -800 mV compared with the standard calomel electrode. Water chloride concentration, biological activity, potential, temperature, and time all affect the severity of hydrogen charging. The effect of chloride on the loss of ductility of a subgroup F-2 ferritic grade due to hydrogen embrittlement is shown in *Figure 67*. Hydrogen embrittlement reduces ductility and toughness. Fracture is usually by cleavage, but severe embrittlement will even produce grain boundary fracture. Stabilization with titanium or alloying with nickel seem to aggravate the effect. High-purity E-BRITE 26-1 is probably the most resistant of the high-performance ferritic grades and has given good service in many refinery applications involving both hydrogen and cyanides.

Figure 65 Corrosion of duplex stainless steels in 20% NaCl-H_2S environments based on electrochemical prediction and experimental results[62]

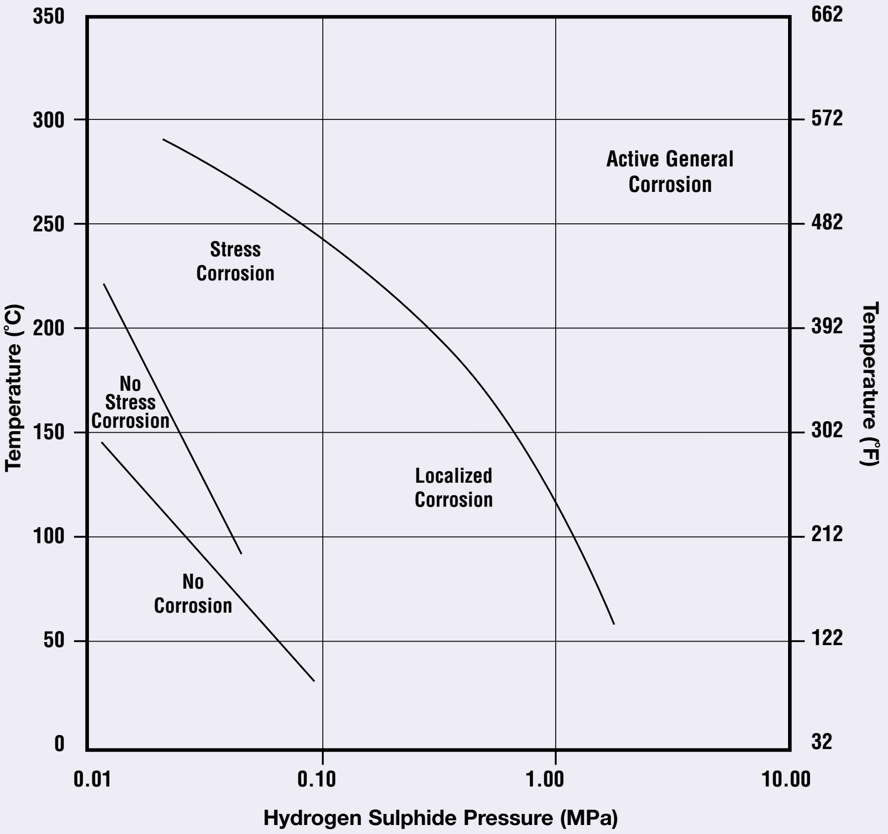


Figure 66 Proposed applicability range for corrosion resistant stainless steels in sour environments containing 50 g/l NaCl[63]

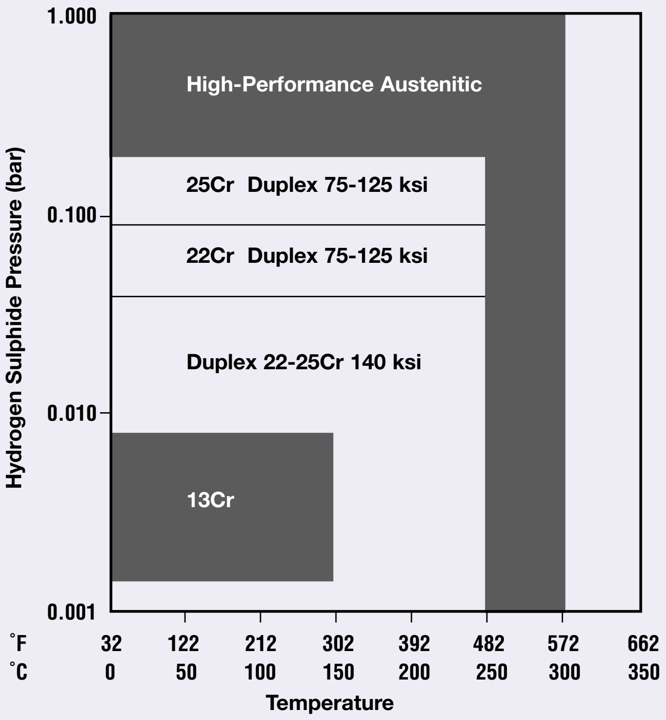
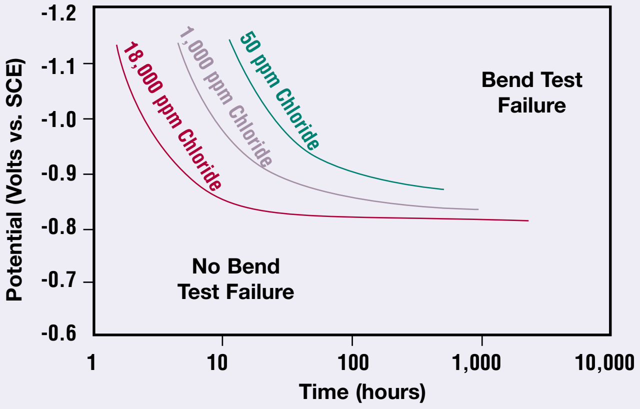


Figure 67 Loss of bend ductility from hydrogen after cathodic charging in sodium chloride solutions for S44660 high-performance ferritic stainless steel[64]



CORROSION ACCEPTANCE TESTS

The concept of using corrosion tests to verify a given particular property of a stainless steel is well established as a useful tool for the evaluation of mill products and for evaluating equipment after fabrication. In most cases, the test demonstrates the absence of a particular problem such as grain boundary carbides or intermetallic phases. A number of tests have become standardized, the best known being ASTM A 262 for detecting susceptibility to intergranular attack in the standard austenitic grades; A 763, for detecting intergranular attack in the ferritic grades; and more recently, A 923, which is concerned with detrimental intermetallic phases in duplex stainless steels. ASTM G 48, which measures pitting and crevice corrosion resistance, differs from these tests because it describes only the laboratory procedures without defining the acceptance criteria. Even more recently, G 150 has described electropotential measuring procedures for determining critical pitting temperature, but again without defining acceptance criteria for various grades.

It is reasonable that corrosion acceptance tests should also be useful for the high-performance stainless steels. However, it cannot be assumed that metallurgical factors controlling performance, or the acceptance tests, will be the same as for the standard grades. For example, ASTM Standard A 262 is designed primarily to evaluate intergranular attack associated with chromium carbides. However, intergranular attack, when it occurs in the high-performance stainless steels, is more likely to be associated with sigma and other intermetallic phases, and chromium nitride; and, more aggressive test environments might be required for these more corrosion resistant steels. The test procedures applicable to the relatively low-alloyed common austenitic stainless steels may not be appropriate for the highly alloyed high-performance grades. For example, the “sensitizing treatment” required for a sample of low carbon 304L or 316L may itself introduce intermetallic phases in the very highly alloyed grades, all of which have such low carbon contents that carbide sensitization is unlikely. As indicated in ASTM Standard Specification A 480, even 317L may demonstrate this problem. The usefulness of A 262 for high-performance grades, even when testing in the mill condition or the welded condition, has not been demonstrated.

Fortunately, G 48, in its focus on chloride-induced localized corrosion, is directed toward the corrosion quality criterion of most importance to the high-performance stainless steels. The test method is also extremely sensitive to the effects of intermetallic phases and is applicable to all alloy types – austenitic, ferritic, and duplex. Therefore, producers and users often use it as a corrosion acceptance test for these alloys when localized corrosion is a consideration. It is important to recognize that G 48 does not define acceptance criteria for given alloys because any criterion will depend on factors such as the application, method of fabrication, etc., and mutual agreement among parties involved.

A broad based, generally accepted corrosion acceptance test has not yet been developed for the high-performance austenitic grades. ASTM A 262 specifically limits itself to grades of lesser alloy content than Type 317L inclusive, and so it is not intended to apply to the high-performance austenitic grades even though some of the individual test methods might be of use in certain instances. Some feel that ASTM G 48 is useful for detecting the potential for intergranular, as well as localized attack susceptibility, in these austenitic grades because of its sensitivity to intermetallic phases. Therefore, ASTM G 48 is sometimes used as an overall corrosion acceptance test. A general applicability to intergranular attack, however, has not been demonstrated through detailed testing. ASTM Standard Test Method G 28

254 SMO® high-performance austenitic stainless steel is used extensively for high pressure piping in reverse osmosis seawater desalination systems

does deal specifically with intergranular attack. This standard was originally designed to evaluate susceptibility to intergranular attack of nickel-rich, chromium-bearing alloys, but now it includes a limited number of the high-performance austenitic grades. Whether it is broadly applicable to all of these grades is unknown, and there is the possibility that the G 28, Method A may not be adequately sensitive to intergranular attack susceptibility as has been reported by Qvarfort[8]. He has proposed that a constant-potential etching method (CPE) will have very high sensitivity for detecting sensitization and might be useful for acceptance testing.

The evaluation of susceptibility to intergranular attack has received serious attention only for the high-performance ferritic grades. This is undoubtedly due to the fact that some of these steels are extremely sensitive to the effect of cooling rate on intergranular attack. ASTM A 763 addresses intergranular attack and includes most of the high-performance ferritic grades, and it provides for detecting the effects of carbide, nitride and intermetallic phases, depending on which test method is used.

Containing both ferrite and austenite, the duplex alloys present a challenge for any

Courtesy Avesta Sheffield AB

single approach to an acceptance test, and so the new ASTM Standard Test Method A 923 has been created. It uses three distinctly different tests as a basis for determining acceptability, which is defined as the absence of detrimental intermetallic phases:

1. Test Method A - Sodium Hydroxide Etch Test of the Classification of Etch Structures
2. Test Method B - Charpy Impact Test for Classification of Structures
3. Test Method C - Ferric Chloride Corrosion Test for Classification of Structures.

ASTM A 923 is based on the proposition that intermetallic phases have an effect on corrosion resistance and toughness; and that detection of these phases above some limit can provide for distinguishing acceptable material. Although not stated explicitly, the intermetallic phase involved is primarily sigma phase, and possibly chi or laves phase for Methods B and C. None of the methods has been demonstrated to detect small amounts of carbide or nitride that could have an effect on intergranular attack. ASTM A 923 is intended specifically for mill products and is not a fitness-for-service test. Use of this or any other standardized acceptance test as a fitness-for-service test may be possible, but only after the test environment has been shown to correlate with intended service conditions. Use of its test procedures for qualification of welds may be possible, but the acceptance criteria in A 923, developed to be applicable to annealed mill products, are not applicable to weldments. At the time of this writing (2000), A 923 includes only duplex grades S31803 and S32205 and provides acceptance criteria for both. It is anticipated that other high performance duplex stainless steels will be added because of the interest in having some acceptance criteria for this alloy family.

FABRICATION

Well-established principles which apply to the fabrication of the standard stainless steel grades apply equally to the high-performance grades and provide a good starting point for understanding their special requirements. Virtually all fabrication techniques applied to the standard grades also apply to the high-performance grades. Differences include:

1. more critical hot working and annealing temperature ranges associated with secondary phase formation
2. more critical cooling rate requirements associated with secondary phase precipitation kinetics
3. maintenance of structure and corrosion balance after welding
4. higher strengths which affect many cold working and machining operations
5. avoidance of surface contamination through all stages of fabrication.

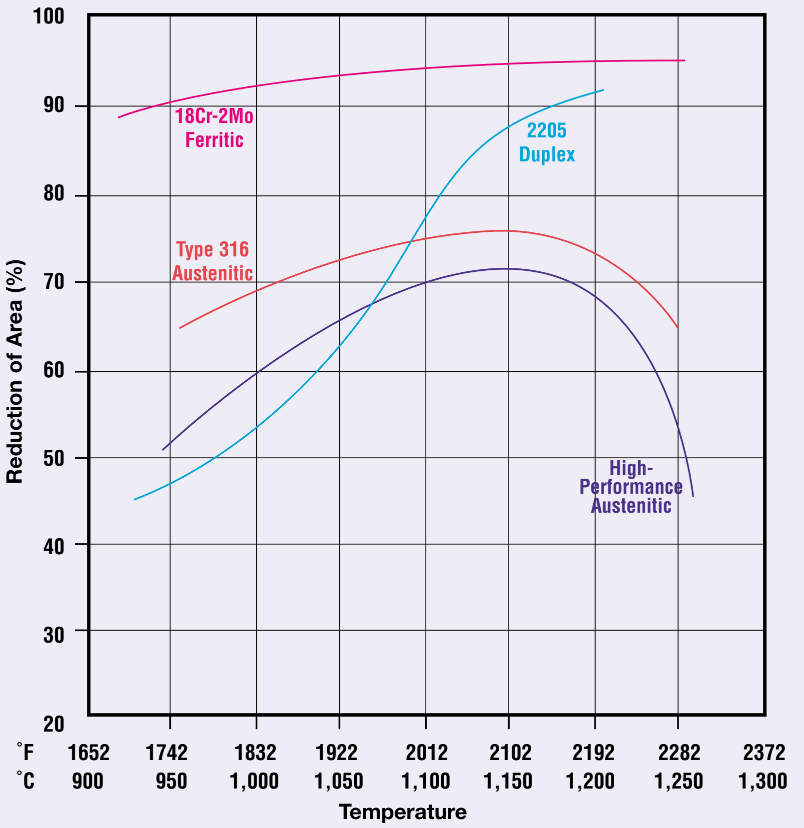
Successful fabrication requires a good metallurgical understanding of the specific grade of stainless steel and close attention to all details of fabrication, especially for the duplex stainless steels. The best information and guidance on fabrication of individual grades are obtained from the producer. The broad overview discussed here highlights the most important principles and considerations of fabrication of the high-performance stainless steels.

HOT WORKING

The three high performance stainless steel families display distinct differences in hot working behaviour which result directly from the different characteristics of the ferrite and austenite.

The austenitic high-performance stainless steels display good hot ductility, but over a fairly narrow temperature range (*Figure 68*). The rapid reduction of ductility above about 1200°C (2200°F) results from the deleterious grain boundary effects of sulphur, oxygen, and phosphorous. Producers make special efforts to minimize and neutralize these impurities during melting and refining of the steel; while helpful, this does not completely compensate for these effects. Increased nitrogen content and low self-diffusion rates of the austenite also reduce high strain rate ductility at lower temperatures. Because they are prone to segregation and sigma phase formation in the as-cast condition, it is desirable to work the austenitic stainless steels above the upper sigma phase solvus temperature. Therefore, hot working must be conducted over a rather narrow temperature range. These grades also oxidize rapidly at high temperatures. Increasing molybdenum increases this oxidation tendency;

Figure 68 ***Hot ductility of wrought standard and high-performance stainless steels by structure type***



so the upper temperature and time limit for heating and hot working is a compromise between excessive oxidation and the time needed to accomplish homogenization.

Ferrite is relatively weak, has high self-diffusion rates, and has a high solubility for such impurities as sulphur and phosphorus. Thus, the ferritic grades have very good hot workability over a wider temperature range than the austenitic grades (*Figure 68*). The lower-temperature working limit is determined primarily by the upper temperature of sigma phase formation, while excessive scaling determines the upper temperature limit. The ferritic stainless steels have little tendency for as-cast segregation; so there usually is little need for the long soaking time that is required with the austenitic grades to minimize segregation.

The duplex stainless steels combine the best and the worst of the hot workability characteristics of their component phases. Unlike the single phase grades, the relative ferrite-austenite balance of the duplex stainless steels changes dramatically as temperature increases above about 1100°C (2000°F). Hot workability is poor at low temperatures because the steel contains the maximum proportion of austenite. This austenite is much stronger than ferrite at these temperatures; so most of the hot working deformation is absorbed by the ferrite, which cannot accommodate it on a macroscopic level. At high temperatures, the structure becomes predominately ferritic and the steel displays workability similar to that of the ferritic grades. Therefore, high working temperatures are preferred, and temperature is limited only by the point at which oxidation becomes excessive.

COLD WORKING

The main consideration when cold working the high-performance stainless steels is their higher strengths compared with the standard stainless steel grades. This will have an effect on forming equipment loading, power, and lubrication requirements. These grades can be successfully cold worked by all conventional methods, but demands on equipment will be substantial. The three families of stainless steels behave somewhat differently because the ferrite phase has an initial high yield strength and initial high work hardening rate, while the austenite phase displays greater ductility and develops greater work hardening with heavy cold reductions. These differences among grades are illustrated in *Figure 69*, where yield strength and ductility are shown as a function of cold reduction. The duplex grades exhibit the initial high strength and work hardening characteristics of the ferrite phase, which makes them very stiff when rolling or bending. This effect is not as noticeable with the austenitic grades until very heavy cold reductions are encountered. Because the ductility of the high-performance ferritic and duplex grades is less than that of the austenitic grades, it can become a limiting factor at heavy reductions. With cutting operations such as shearing and blanking, the usual requirement for sharp blades and proper clearances is especially important with these stainless steels. Also, because of their high strengths, more springback will often be encountered in operations such as bending. Detailed information on the cold working of stainless steels can be found in the NiDI publication No. 428, "Fabrication of Chromium-Nickel Stainless Steel (300 Series)".

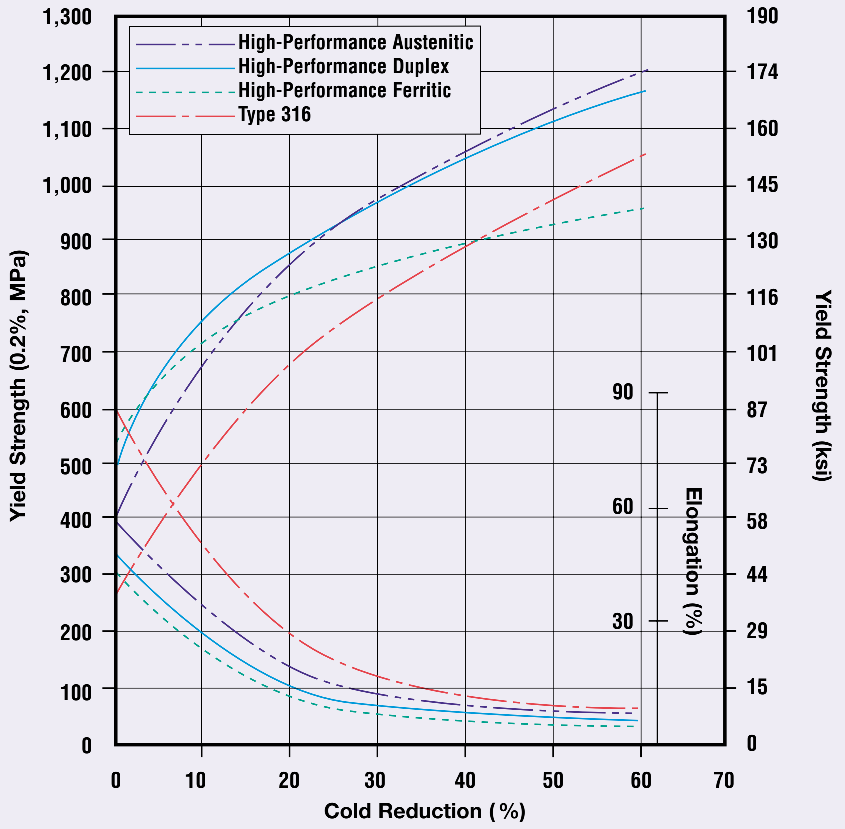
ANNEALING

The most important considerations when annealing the high performance stainless steels are:

1. furnace atmospheres and possible surface contamination
2. avoiding secondary phase formation
3. re-solutionizing precipitates and reducing segregation
4. cooling rate
5. potential loss of chromium from surfaces.

Transformation diagrams should be consulted when selecting temperatures and cooling rates. While most diagrams are based on isothermal transformation kinetics, experience has shown that continuous cooling results in slower kinetics. Therefore, time limits based on isothermal diagrams are usually somewhat conservative when defining the minimum allowable cooling rate to avoid secondary phase formation. While intermetallic compounds must be avoided because of their adverse effects on mechanical and corrosion properties, carbide and nitride precipitation can be very rapid, significantly reducing corrosion resistance but producing no noticeable effect on mechanical properties. As with heating for hot working, there are significant differences in annealing principles and concerns among the three families of high-performance stainless steel.

Figure 69 Effect of cold work on the strength and ductility of high-performance stainless steel families compared with Type 316 stainless steel



The austenitic stainless steels are tolerant of nitrogen-containing annealing atmospheres, but not of atmospheres having carburizing potential because it is desirable to maintain the carbon content at less than 0.02 percent in these materials. These grades require higher annealing temperatures than the ferritic and duplex stainless steels because of their high sigma and chi phase solvus temperatures. It is desirable to anneal at high temperatures to minimize segregation, but this increases the likelihood of rapid oxidation and loss of chromium from surfaces. The annealing temperature range is relatively narrow and represents a compromise among competing factors. All the austenitic grades require rapid cooling after annealing to avoid a loss in corrosion resistance associated with secondary phase precipitation.

The annealing atmosphere is extremely important with the ferritic grades. They have high solubility and diffusivity for such impurities as carbon, nitrogen, and hydrogen. Atmospheres should be as neutral as possible with regard to these elements, and surfaces must be degreased before furnace charging, especially in the case of tubes which may have residues of drawing lubricants. Air, argon, or vacuum atmospheres are preferred for the ferritic alloys. They do not require excessively high temperatures or long annealing times because all reactions are very rapid at high temperature. With the exception of AL 29-4-2, the ferritic grades all use stabilizing elements such as titanium or niobium for carbon and nitrogen. Annealing should be carried out at a low enough temperature to ensure that carbon is effectively stabilized by combining with these elements. As with all the high-performance stainless steels, annealing conditions and cooling rates after annealing should take into consideration whether the material being annealed has been welded, or is merely being annealed to remove the effects of cold work. Ferritic alloys are produced in thin sections; so air or fan cooling can be adequate when not dealing with welds. Welds usually will deliver adequate performance in the as-welded condition; however, cooling rates must be very rapid if they are annealed.

The annealing atmospheres used with duplex stainless steels can have some nitriding potential, but they should not be carburizing or capable of hydriding. There usually is little need to use extremely high temperatures to dissolve precipitates or remove segregation, and extremely high temperatures should be avoided to limit excessive ferrite in the final structure and loss of chromium from the surface. The annealing temperature range usually begins above the carbide and sigma solvus temperatures and extends upward to the temperature that produces a maximum of about 60 percent ferrite. Because these grades are not stabilized with respect to carbon and nitrogen, cooling rates must be rapid enough to avoid sensitization by these elements. The possibility of sensitization increases as the amount of ferrite increases; therefore, the anticipated amount of ferrite existing over the carbide precipitation range should be considered when determining the cooling rate. Rapid sigma precipitation over the temperature region near the nose of the transformation curve is usually the most troublesome aspect of cooling after annealing or welding. Heat compositions having high nitrogen are preferred where heavy sections or other difficult circumstances exist because nitrogen significantly delays the start of this transformation.

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Vent piping for pharmaceutical manufacturing in 654 SMO®

MACHINING

When appropriate consideration is given to the special characteristics of the high-performance stainless steels, they can be machined successfully by all the methods commonly used to machine the standard stainless steel and nickel-base alloys. Compared to the 300-series austenitic grades, the high-performance stainless steels have:

1. higher room temperature and elevated temperature strength
2. higher work hardening rates
3. similar galling characteristics
4. extremely low sulphur contents.

As a result, machining will be more difficult than with the standard grades, and careful attention must be given to detail to ensure success.

The basic machining principles that apply to the standard stainless steel grades and nickel-base alloys are a good starting point for machining the high-performance stainless steels. These include sharp tools, rigid setups, positive feeds, adequate depths of cut, positive cutting geometries where possible, and quality tooling and coolant designed for stainless steels. Feed rate and depth of cut are very important if there will be a subsequent finishing operation because prior surface work hardening effects must be removed as much as possible before attempting shallower finishing passes. Finishing passes should be as deep as possible to cut below the work hardened surface layer. High cutting tool toughness is helpful because of the high strength of the stainless steel. High machine power is also important because of the high strength and high work hardening behaviour of these stainless steels. The machining parameters given in the NiDI publication No. 11 008, “Machining Nickel Alloys,” for the Group C nickel-base alloys in the annealed condition provide a good starting point for the high-performance stainless steels. *Table 32*, based on the above publication, gives machining parameters for some basic operations.

Of the three stainless steel families, the austenitic stainless steels are the most difficult to machine. These grades, especially the more highly alloyed subgroups, have machining characteristics similar to the corrosion resistant nickel-base grades in the solution annealed condition. The ferritic grades are the easiest to machine. Machining parameters that would usually be used for Type 316 stainless steel can provide a starting point for working with the high-performance ferritic stainless steels. The duplex grades are about halfway between Type 316 and the high-performance austenitic grades.

Table 32 Machining parameters for high-performance austenitic stainless steels[65]

OPERATION	HIGH SPEED TOOLING				CARBIDE TOOLING			
	Speed		Feed		Speed		Feed	
	(sfm)	(m/min.)	(ipr)	(mm/rev.)	(sfm)	(m/min.)	(ipr)	(mm/rev.)
TURNING - Rough	25	8	0.030	0.75	200	65	0.015	0.40
TURNING - Finish	35	15	0.008	0.20	290	95	0.004	0.10
DRILLING - 1/4 in. HSS, 3/4 in. C-2	25	8	0.004	0.10	70	25	0.006	0.15
DRILLING - 1/2 in. HSS, 1-1/2 in. C-6	30	10	0.015	0.40	100	35	0.009	0.25
TAPPING	15	5	–	–	–	–	–	–
THREADING	20	7	–	–	290	95	–	–
BAND AND HACK SAWING - <1/2 in. thick	90	30	12 t/in.	0.50 t/mm	–	–	–	–
BAND AND HACK SAWING - >1/2 in. thick	60	20	8 t/in.	0.30 t/mm	–	–	–	–
			in./tooth	mm/tooth			in./tooth	mm/tooth
MILLING - Face and Side - Rough	30	10	0.004	0.10	60	20	0.008	0.20
MILLING - Face and Side - Finish	70	25	0.002	0.20	90	30	0.004	0.10
MILLING - End - Rough	20	7	0.002	0.20	30	10	0.003	0.08
MILLING - End - Finish	60	20	0.002	0.20	80	25	0.002	0.05

WELDING

The high-performance stainless steels are weldable by most processes normally used for the standard grades; however, much greater attention to detail is needed to achieve acceptable results. The high-performance stainless steels are much more sensitive to small metallurgical variables and their typical severe applications put high demands on the corrosion and mechanical properties of the welds. Successful welding demands a good metallurgical understanding of the material and of the additional requirements of welding. An excellent guide for the welding of all stainless steels is NiDI publication No. 11 007, "Guidelines for the Welded Fabrication of Nickel-Containing Stainless Steels for Corrosion Resistant Services". Literature provided by manufacturers is the best source of detailed welding information and should always be consulted once a decision is made to work with a specific grade. The following guidelines provide an overview of considerations that apply to all the high-performance stainless steels.

Most of the requirements that apply to welding the standard grades also apply to the high-performance stainless steels. These include:

1. avoidance of oxidation during welding
2. avoidance of contamination by carbon and sulphur and, in some cases, by nitrogen
3. post-weld removal of weld oxide and heat tint.

These requirements are stricter than they are for the standard grades. Primary additional requirements relate to the thermal cycle because of the possibility of secondary phase formation, and the choice of filler metal because of its influence on corrosion resistance and mechanical properties. Control of weld metal ferrite is less important in the high-performance grades than in the standard austenitic grades. The high-performance austenitic stainless steels and their filler metals are designed to be fully austenitic at all temperatures beginning just below the solidus temperature. While not helpful to hot cracking resistance, the fully austenitic structure reduces the formation of sigma phase, which can form rapidly within ferrite. Guidelines on filler metals for use with austenitic stainless steels are given in *Table 33*, and for ferritic and duplex stainless steels in *Table 34*. Additional special requirements for welding of the three families of high-performance stainless steels are discussed below.

AUSTENITIC STAINLESS STEEL GRADES

The high-performance austenitic stainless steels are successfully welded if the following issues are addressed:

1. susceptibility to hot cracking
2. effect of carbon and oxygen contamination on corrosion resistance
3. microsegregation in the fusion zone
4. avoidance of intermetallic precipitation in the HAZ
5. precipitation of chromium carbides and nitrides in the heat-affected zones, sensitization or susceptibility to intergranular attack.

Techniques have been developed to deal with these issues; so these grades are readily weldable using all conventional stainless steel processes under all conditions encountered in the fabrication shop and the field.

Many of these grades solidify with a fully austenitic structure; therefore, delta ferrite is not available to absorb impurities and avoid hot cracking as it is in the standard grades. The high-performance austenitic grades behave like nickel-base alloys with regard to hot cracking; so techniques used with nickel-base alloys to avoid this problem also apply here. Contaminants that are known to cause hot cracking, such as sulphur, phosphorus, oxygen, copper, and zinc, must be rigorously excluded from the weld zone. This is accomplished by scrupulous cleaning of the weld area to a distance several centimetres (one inch) from the

Table 33 Filler metals for welding austenitic stainless steels

Alloy Class	UNS Number	AWS Designation	Consumable Type	C	Si	Mn	Cr	Ni	Mo	N	Other	Supplier Designations
A-1	N08020	ER320LR	wire	0.015	0.2	2.0	20	34	2.5	–	Cu	–
A-1	N08825	ERNiFeCr-1	wire	–	–	–	21	42	3	–	Cu, Ti	65
A-1	N06625	ERNiCrMo-3	wire	0.015	–	–	21.5	61	9	–	Cb, Ta	625
A-1	W88022	E320LR	coated electrode	0.020	0.2	2.0	20	34	2.5	–	Cu	–
A-1	–	ERNiFeCr-1	coated electrode	–	–	–	21	42	3	–	Cu,Ti	–
A-1	W86112	ENiCrMo-3	coated electrode	0.020	–	0.3	21.5	61	9	–	Cb, Ta	112
A-2	S31783	ER317L	wire	0.015	0.5	1.7	19.5	14	3.5	–	–	–
A-2	W31713	E317L	coated electrode	0.020	0.5	1.5	19.5	13	3.5	–	–	–
A-2	W31735/7	E317LT	flux core	0.020	0.5	1.5	19.5	13	3.5	–	–	–
A-2	–	–	coated electrode	0.020	0.8	1.5	18.5	17.5	4.5	0.15	–	SLR-NF
A-2	S30986	ER309LMo	wire	0.015	0.5	1.8	24	13	2.5	–	–	–
A-2	W30923	E309MoL	coated electrode	0.020	0.5	1.5	23.5	13	2.5	–	–	–
A-2	W30938	E309LMoT	flux core	0.020	0.5	1.5	23	14	2.5	–	–	–
A-2	W30936	309LNiMoT	flux core	0.020	0.5	1.5	22	16	3	–	–	–
A-3	N08904	ER385	wire	0.013	0.3	1.8	20.5	25	4.7	–	Cu	904L
A-3	W88904	E385	coated electrode	0.015	0.4	1.8	20.5	25	4.7	–	Cu	904L
A-3	N08028	ER383	wire	0.013	0.3	1.8	27.5	32	3.7	–	Cu	28
A-3	W88028	E383	coated electrode	0.015	0.5	1.5	27.8	32	3.7	–	Cu	28
A-3	N06625	ERNiCrMo-3	wire	0.015	–	–	21.5	61	9	–	Cb, Ta	625, P12
A-3	W86112	ENiCrMo-3	coated electrode	0.020	–	0.3	21.5	61	9	–	Cb, Ta	112, P12
A-4	N06625	ERNiCrMo-3	wire	0.015	0.3	0.2	21.5	61	9	–	Cb, Ta	625, P12
A-4	N10276	ERNiCrMo-4	wire	0.015	0.1	0.4	15.5	63	16	–	W	C276
A-4	N06022	ERNiCrMo-10	wire	0.015	0.1	0.5	21.8	62	13.5	–	W	C-22
A-4	W86112	ENiCrMo-3	coated electrode	0.020	0.5	0.3	21.5	61	9	–	Cb, Ta	112, P12
A-4	W80276	ENiCrMo-4	coated electrode	0.015	0.1	0.5	15.5	63	16	–	W	C276
A-4	W86022	ENiCrMo-10	coated electrode	0.015	0.1	0.5	21.3	–	13.5	–	W	C-22
A-6	–	–	wire	0.015	0.1	0.4	23	60	16	–	–	P16
A-6	–	–	coated electrode	0.020	0.3	0.7	25	60	14	–	–	P16

Table 34 Filler metals for welding ferritic and duplex stainless steels

Alloy Class	UNS Number	AWS Designation	Consumable Type	C	Si	Mn	Cr	Ni	Mo	N	Other	Supplier Designations
FERRITIC STAINLESS STEELS												
F-1	S44687	ER446LMo	wire	0.015	0.3	0.3	26.7	–	1.2	–	Nb	–
DUPLEX STAINLESS STEELS												
D-1	S32304	–	wire	0.020	0.4	1.5	23	7	–	0.14	–	2304
D-1	–	–	coated electrode	0.030	0.9	0.5	25	9	–	0.12	–	2304
D-2	S39209	ER2209	wire	0.015	0.5	1.3	22.5	8.5	3	0.14	–	2205
D-2	W39209	E2209	coated electrode	0.020	0.5	1.3	22.5	9.5	3	0.12	–	2205–PW
D-2	W39239	W2209T	flux core	0.020	0.5	1.5	22.5	9.5	3.3	0.14	–	FCW 2205
D-3	S39553	ER2553	wire	0.020	0.5	0.8	25.5	5.5	3.4	0.17	Cu	–
D-3	W39553	E2553	coated electrode	0.030	0.5	1.0	25.5	7.5	3.4	0.17	Cu	–
D-3	W39533	E2553T	flux core	0.020	0.4	1.0	25.5	9.5	3.4	0.15	Cu	–
D-4	S32750	–	wire	0.020	0.3	0.4	25	9.5	4	0.25	–	2507/P100
D-4	–	–	coated electrode	0.030	0.5	0.7	25	10	4	0.25	–	2507/P100

joint. In addition, heat input must be minimized by techniques such as weld beads employing no weaving and a low interpass temperature. Joint designs that minimize stresses should be used wherever possible.

Corrosion resistance is reduced if welds are contaminated with carbon or if the surface is oxidized in the weld or heat-affected zone. Careful pre-weld cleaning and subsequent avoidance of contamination is essential. Gas tungsten arc (GTA) welding and carefully designed, non-copper alloy backing bars are recommended for good inert gas coverage of root passes where the backside is not accessible. A gas diffuser screen should be used to minimize turbulence in the GTA shielding gas. Strong drafts should be avoided during welding to minimize air entrainment in shielding atmospheres. All starts and stops should be ground out before continuing welding, and all slag should be removed between passes when using coated electrodes or welding processes incorporating fluxes. The optimum corrosion resistance is restored when the weld heat tint is removed; and, in critical applications, it is imperative that tint is removed.

The austenitic stainless steels are prone to chromium and molybdenum micro-segregation within the weld metal. This reduces weld metal corrosion resistance to less than that of the base metal when welding autogenously or with matching filler metal. This effect becomes more severe as the alloying

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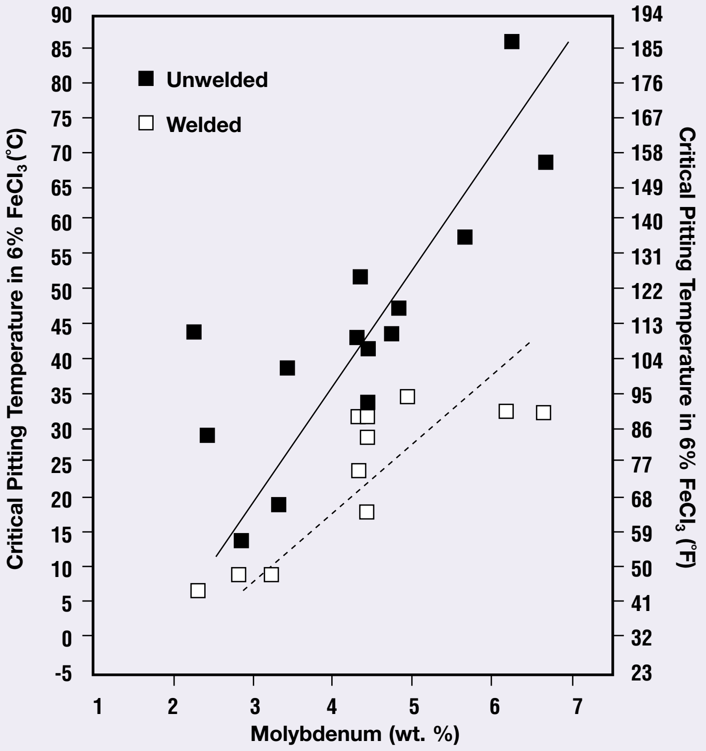
The world's first paper continuous digester built entirely of 2205 duplex stainless steel

content, especially molybdenum, increases. The resultant reduction in pitting resistance in a ferric chloride environment is illustrated in *Figure 70*. The effect also becomes more severe as section size and heat input increase, and the loss in corrosion resistance is enough to require that the welding consumable be more highly alloyed than the base metal. Over alloying in the filler is intended to give weld metal corrosion resistance that matches that of the base metal. Many of the fillers designed for the most highly alloyed stainless steels in subgroups A-4 and A-6 are modifications of corrosion resistant nickel-base alloys. In addition to the weld metal itself, the unmixed fusion zone may be susceptible to this same micro-segregation effect. Using sufficient heat input to ensure maximum weld pool mixing may minimize this.

Carbide and nitride sensitization, and loss of corrosion resistance from heat-affected zone intermetallic phase precipitation, are possible occurrences that may result from excessive heat input or inadequate cooling rates. Heat inputs are generally limited to less than about 16 kJ/mm (400 kJ/inch), but should still be high enough to provide fusion zone mixing. Interpass temperature limits of 100°C (212°F) help ensure rapid cooling rates between passes.

The goal behind the principles of joint design and welding practice for the austenitic stainless steels is avoidance of excessive heat input and excessive dilution from the base metal, while ensuring complete penetration and freedom from oxidation and slag. This requires generous groove angles and gap widths, well-designed backing bars, and the use of diffuser screens. Tack and stringer bead starts and stops should be ground out and all weld slag removed before subsequent passes when using coated electrodes or welding processes involving fluxes. The finished weld should be thoroughly cleaned of all spatter and oxide as discussed in the "Surface Condition" section.

Figure 70 Effect of welding and molybdenum content on weld corrosion resistance of austenitic stainless steels when welded by the GTA process without filler metal[66]



FERRITIC STAINLESS STEEL GRADES

The ferritic stainless steels are perhaps the most complex from the standpoint of weldability and are seldom welded in anything but thin sections because of their toughness limitations. These grades will be discussed only in terms of tube-to-tubesheet welding and the welding of thin sheet. In all cases, thorough degreasing is mandatory to avoid carburization of the weld and heat-affected zone. Very good inert argon or helium shielding and backing gas protection are also necessary to avoid oxidation, nitriding or hydriding. Rapid cooling after welding is necessary to avoid a sensitized structure with both the high-purity and stabilized grades. GTA welding without filler is usually used for seal welding and other thin section applications. In seal welding, the tubesheet provides a sufficient heat sink to achieve an adequate cooling rate. When welding thin sheet fabrications, water or another means of rapid cooling is required. Filler metals may be used, and matching metals for the high purity and stabilized versions have been developed. Austenitic stainless steels and nickel alloy consumables will produce sound welds. However, very low carbon is essential if sensitization in the fusion zone is to be avoided, and the effect of filler metal dilution on weld structure and corrosion resistance must be considered. Post-weld anneal or stress relief treatments are usually not recommended for these grades because cooling rates associated with post-weld heat treatments may actually be slower than from welding, increasing the likelihood of intermetallic phase precipitation and subsequent loss of corrosion resistance and toughness.

DUPLEX STAINLESS STEEL GRADES

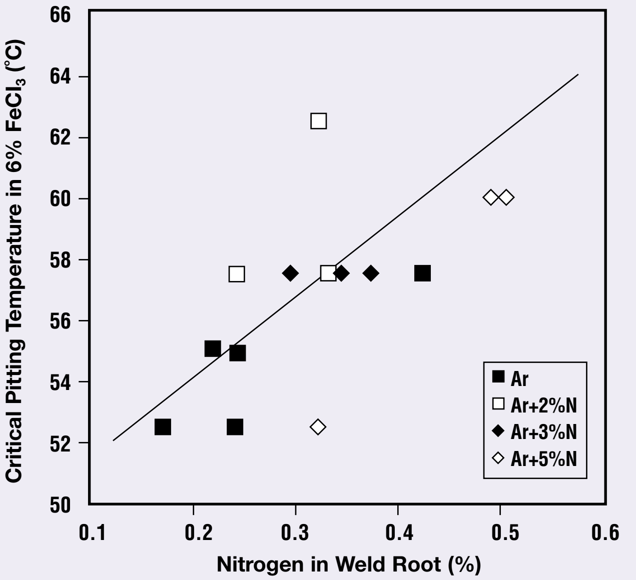
These grades have good weldability in terms of fluidity and resistance to hot cracking and delayed weld hydrogen cracking; thus, sound welds can be made from the standpoint of the weld fabricator. The key to successful welding lies with the control of weld microstructure and composition to obtain acceptable weld mechanical and corrosion properties. This is achieved through control of the thermal cycle and choice of filler metal, if one is used. The objectives are:

1. obtain a desirable austenite-ferrite balance in the weld metal and heat-affected zone
2. ensure adequate nitrogen in the weld metal
3. minimize weld metal oxygen
4. avoid the formation of deleterious secondary phases.

Excessive ferrite will lower toughness and increase the possibility of sensitization, while excessive austenite reduces strength and stress corrosion cracking resistance. While the optimum balance is half austentite and half ferrite, a range must be established that is practical for both steel production and welding. The latitude and aim point of this range may vary with the application, for example, the relative importance of strength versus toughness. Quite good properties are generally obtained over a relatively broad range of about 30 to 70% ferrite, but narrower ranges are necessary for many applications.

Control of the desired structural balance is relatively simple when post-weld annealing can be employed. If welding is without filler metal, nitrogen in the shielding and backing gases can minimize nitrogen loss. The benefit of nitrogen-containing backing gas in GTA welding of root passes is illustrated in *Figure 71*. When the backing gas was 100% argon, the root weld metal was depleted in nitrogen, with a resultant lowering of the critical temperature. Adding nitrogen to the backing gas increased the nitrogen content and restored the corrosion resistance. Filler metals are also available which will produce weld metal having the desired phase balance with less need for nitrogen control by the welding gases. Welds in the as-welded

Figure 71 Effect of shielding gas nitrogen content on the weld pitting resistance of S32760 high-performance duplex stainless steel[67]



condition generally have more than the optimal amount of ferrite. Post-weld annealing converts some of the high temperature ferrite produced by welding back to austenite. Annealing conditions for these weldments, including the need for rapid cooling, follow the same principles as discussed previously for base metal.

When post-weld annealing is not employed, a filler metal over-balanced with austenite formers is usually used. This provides the required austenite-ferrite balance in the high temperature regime just below the solidus temperature, and this balance is retained in the weld metal by the relatively fast cooling rates associated with welding. The thermal cycle is designed to promote the reversion of the heat-affected zone (HAZ) from ferrite to austenite. A rapidly cooled, single-pass weld may have as much as 90% ferrite in the HAZ. The optimum thermal cycle accounts for section thickness and the number of passes to allow for adequate reversion of this ferrite back to austenite. In thin sections with few passes and at cold ambient temperatures, some preheating and relatively high heat input may be necessary to assist with adequate weld annealing of the prior passes. As section size and the number of passes increase, the need for preheat and high heat input diminishes until the other extreme is reached. Interpass temperature limits are imposed to minimize nitride, carbide, sigma, and alpha prime precipitation resulting from the cumulative heat input of many passes. The effect of heat input on optimizing corrosion resistance for 2205 stainless steel is illustrated in *Figure 72*. The detrimental effect of high heat input becomes larger with the more highly alloyed grades because of their more rapid intermetallic phase precipitation kinetics.

Oxidation of the weld metal has an adverse effect on corrosion resistance and mechanical properties. This is especially important in welding processes that use fluxes for weld protection. Increasing weld metal oxygen content reduces the critical pitting temperature as shown in *Figure 73* for both duplex and austenitic welds. Toughness is also reduced significantly in the duplex grades with welding processes that impart high oxygen or slag content. This is shown in *Figure 74*, where the submerged arc weld with rutile flux, known for delivering high oxygen weld metal, is inferior to the other welding processes. Toughness increases with processes capable of maintaining good weld metal purity.

Figure 72 Effect of weld arc energy on the weld corrosion resistance of 2205 duplex stainless steel evaluated in 6% ferric chloride[68]

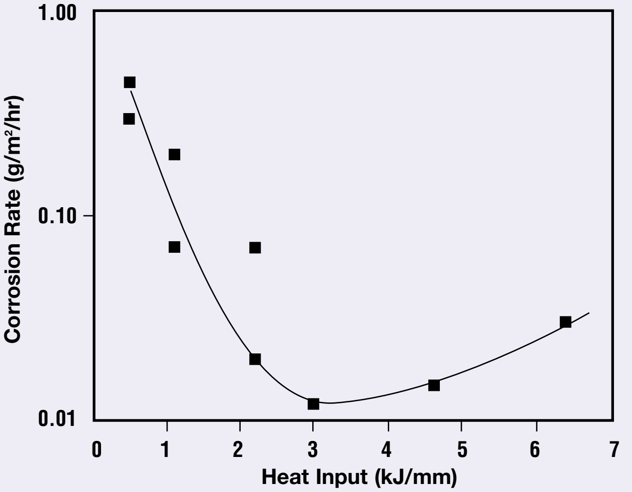
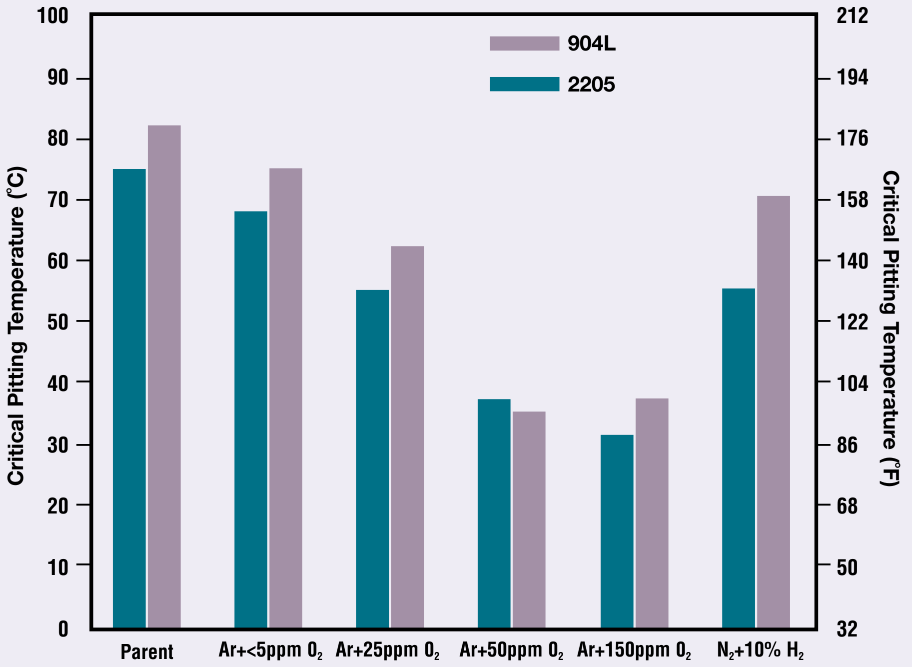
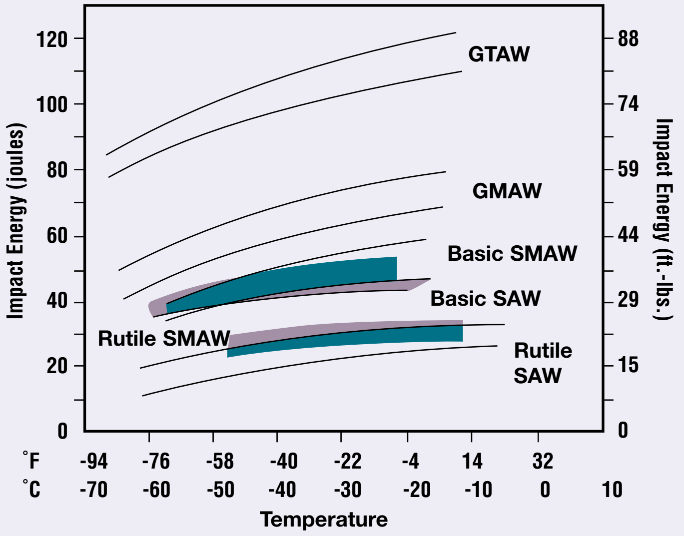


Figure 73 ***Effect of backing gas oxygen content on the weld corrosion of 904L austenitic and 2205 duplex stainless steels evaluated in 3% NaCl at 300 mV, SCE***[69]



Some principles of joint design and welding practice are of special importance to the duplex grades. The joint geometry should be wide enough to easily allow full penetration. Arc strikes should be made within the joint. Consideration should be given to GTA welding for the root pass if the root is exposed to the critical environment. Adequate backing and shielding gas should be available and the welder should be able to observe the weld pool and any slag formation. Excessive weaving should be avoided to prevent excessive heat input and consequent intermetallic phase formation, and extremely low heat input should be avoided to prevent ferrite-rich heat-affected zones. An excellent discussion on the welding of duplex stainless steels is provided in the NiDI reprint No. 14 036, "Welding Duplex and Super-Duplex Stainless Steels".

Figure 74 ***Effect of weld practice on the toughness of 2205 duplex stainless steel weld metal***[70]

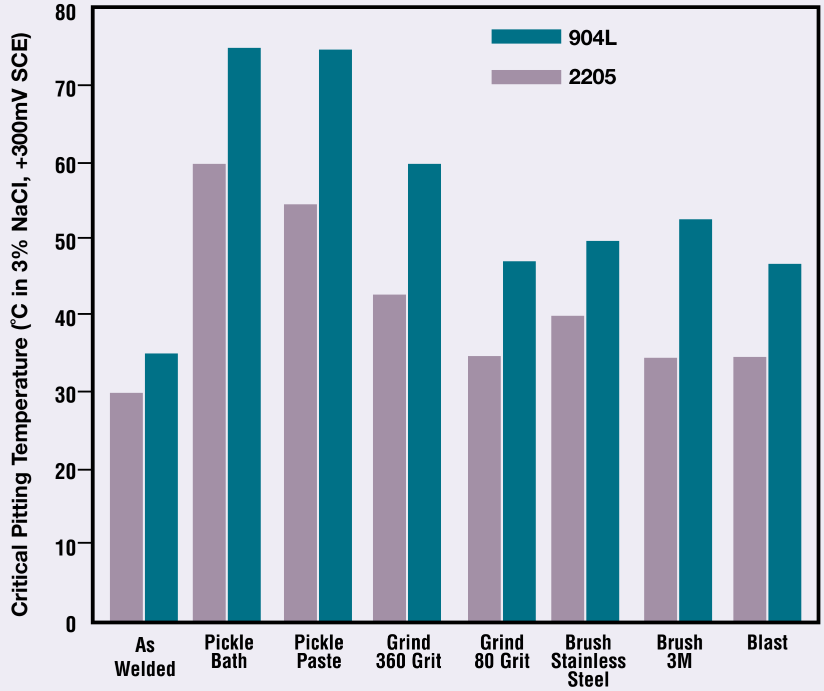


SURFACE CONDITION

Two important considerations in the use of the high-performance stainless steels are the need to avoid surface contamination and to provide for clean surfaces both during fabrication and service. Both must be considered when planning the fabrication of stainless steel equipment. Any high temperature operation must avoid the introduction of carbon and sulphur into the surface. The surface must be free of any detrimental contaminants before annealing or welding, and the atmosphere itself must not introduce contaminants. Surface oxide or heat tint produced during welding is undoubtedly the most frequently encountered condition that can lead to corrosion problems. While detrimental to all stainless steels, unremoved surface oxide is especially harmful to the high-performance stainless steels because the surface oxide is accompanied by underlying chromium depletion. Because corrosion resistance depends strongly on the chromium content, any lowering of chromium at the surface reduces corrosion resistance. The chromium depletion, if not removed, is a likely source of corrosion initiation in the severe environments in which the high-performance stainless steels are typically used.

It is not sufficient to merely specify "slag, oxide, and heat tint removal" following welding operations because the method of removal may strongly influence the ultimate corrosion resistance of the material. Some removal methods generate heat or leave disturbed metal that is still not in an ideal condition to resist corrosion. A number of studies have examined the effectiveness of various oxide removal methods; an example of typical results is provided in *Figure 75*. Acid pickling, either by immersion or with pickling paste, is the most effective method; it will remove the chromium-depleted layer as well as the surface oxide. Specially formulated, strong pickling acids are required because of the high corrosion resistance of the high performance stainless steels. On the other hand, coarse grit grinding has little benefit and has been shown to be detrimental in some cases. The heat generated by coarse grit grinding can easily produce heat tint on the ground surface which then recreates the initial condition. NiDI publications No. 10 004, "Fabrication and Post-Fabrication Cleanup of Stainless Steels" and No. 10 068, "Specifying Stainless Steel Surface Treatment", provide excellent discussions on all aspects of this important topic.

Figure 75 Effect of post weld surface cleaning methods on the corrosion resistance of 2205 and 904L stainless steel welds

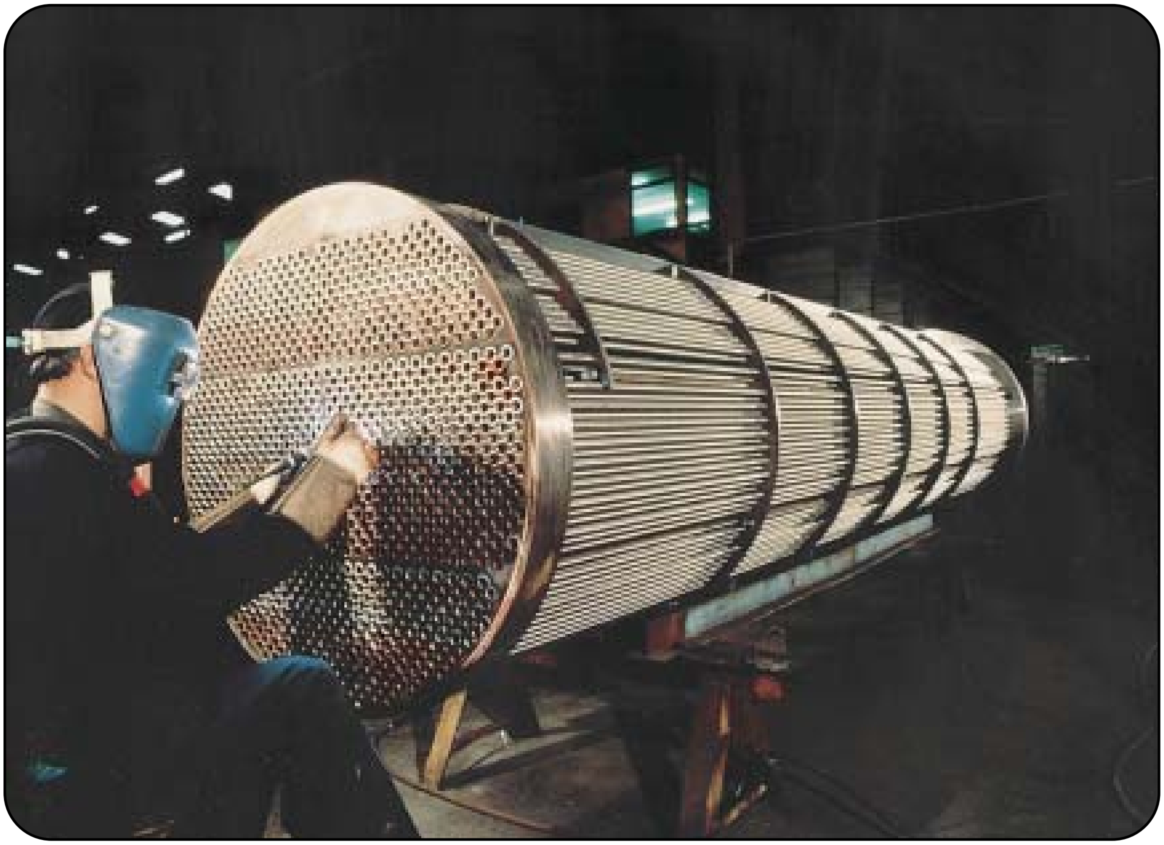


APPLICATIONS

The high-performance stainless steels collectively offer a great variety in mechanical, physical, metallurgical, and corrosion properties, with the common theme being that they are very resistant to strong chloride and oxidizing to reducing acid environments. Thus, the applications in which they are used are extremely varied and usually much more corrosive than would be suitable for the standard stainless steel grades. The high-performance stainless steels are being used in literally thousands of different applications in many areas of the process, energy, paper, transportation, and other industries. They are available in essentially all product forms and are covered by many industry specifications.

To assist the designer with grade selection, a summary of the stainless steel subgroups in terms of their general characteristics and areas of application is provided in *Table 35*. The illustrations of applications used throughout this book are only a small sampling of this wide experience and show some of the unique and demanding applications where high performance stainless steels are successfully used. In some cases, the application might be based on extending the service life over what might be obtained with Type 316 stainless steel; in other cases, it may represent a unique need that can only be filled by one of these truly remarkable grades. The high-performance stainless steels provide a cost-effective solution to many demanding application problems.

Courtesy Sandvik Steel



Heat exchanger with SAF 2507® tubes for aggressive chloride service

Table 35 Representative corrosion characteristics and applications for high-performance stainless steels

Alloy Group	PRE Number	Description	Applications
AUSTENITIC ALLOYS			
A-1	26-28	Resistant to mid-concentration sulphuric and other strong, mildly reducing or oxidizing acids. Resistant to stress corrosion and pitting (at high PRE number)	Process equipment handling sulphuric acid solutions; condensers and coolers handling acid-chloride condensates where stress corrosion is a problem
A-2	30-32	Good resistance to mildly acidic, moderate chloride aqueous environments while providing a moderate strength advantage	FGD absorbers and piping operating under mild conditions, paper bleach equipment requiring improved performance compared to Type 316
A-3	32-36	Good general and stress corrosion resistance in strong acids at moderate temperatures and in organic acids at high temperatures	General process equipment
A-4	40-43	Very good chloride pitting and stress corrosion resistance; resists seawater and many saline acidic waters, and many acids and caustics; provides a substantial strength advantage	Process equipment for all but strong reducing and hot sulphuric acids; piping and heat exchangers handling ambient seawater; FGD absorbers and paper bleach equipment operating at moderate Cl-pH-T conditions
A-5	29-41	Very high strength and good general corrosion and pitting resistance	Where high strength is important
A-6	45-54	Very high strength with excellent chloride pitting and stress corrosion resistance, resists warm seawater and high chloride, acidic and oxidizing waters and brines; excellent resistance to a wide variety of acids and caustics	Process equipment for all but strong reducing and hot sulphuric acids; piping and heat exchangers/evaporators handling hot seawater and brines; FGD absorbers and piping operating at high chloride levels; highly oxidizing paper bleach applications
FERRITIC ALLOYS			
F-1	27	Excellent chloride stress corrosion cracking resistance with good resistance to pitting; excellent resistance to hot organic acids and caustics	Heat exchanger tubing handling fresh water, organic acid condensers, caustic evaporator tubing
F-4	34-40	Resistant to pitting and crevice corrosion in ambient temperature seawater; good stress corrosion resistance in high temperature water; good strength	Seawater-cooled condenser tubing; heat exchanger tubing handling fresh and brackish water and organic acids
DUPLEX ALLOYS			
D-1	22	Good stress corrosion resistance in cooling waters and under evaporative conditions; high strength	Equipment handling water, foods, and pharmaceuticals where better strength or stress corrosion resistance is needed compared to Type 304
D-2	30-34	Good pitting and stress corrosion resistance; good resistance to oxidizing acids and caustics; high strength	Pressure vessels, piping, pumps and valves where strength and weight are factors along with resistance to stress corrosion and fatigue; general purpose heat exchanger tubing
D-3	32-39	Very good pitting and stress corrosion resistance, good resistance to mildly reducing and oxidizing acids and caustics; high strength	Where better pitting and crevice corrosion resistance is needed compared to the D-2 alloys
D-4	36-38	Resistant to seawater pitting and crevice corrosion; very good stress corrosion resistance; good resistance to mildly reducing acids and oxidizing acids and caustics; high strength	Pumps, valves, and high pressure piping and pressure tubing handling seawater or chloride containing waters

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APPENDIX 1

ADDITIONAL READING

The following publications can be obtained from:
Nickel Development Institute
214 King Street West, Suite 510
Toronto, Ontario M5H 3S6
Canada
Phone: 416-591-7999
Fax: 416-591-7987
www.nidi.org

428	Fabrication of Chromium-Nickel Stainless Steel (300 series)
10 002	Evaluating Installed Cost of Corrosion-Resistant Piping
10 004	Fabrication and Post-Fabrication Cleanup of Stainless Steels
10 006	High-Performance Austenitic Stainless Steels in the Pulp Industry
10 017	Stainless Steel Is Cost-Equivalent to FRP for Use in the Bleach Plant
10 023	Life Cycle Cost Comparison of Alternative Alloys for FGD Components
10 024	The Use of Nickel Stainless Steels and Nickel Alloys in Flue Gas Desulphurization Systems in the United States
10 025	Flue Gas Desulphurization; the European Scene
10 032	Practical Guide to Using 6Mo Austenitic Stainless Steel
10 039	Stainless Steel Sheet Lining of Steel Tanks and Pressure Vessels
10 043	Design, Water Factors Affect Service-Water Piping Materials
10 044	Practical Guide to Using Duplex Stainless Steel
10 068	Specifying Stainless Steel Surface Treatments
11 003	Guidelines for Selection of Nickel Stainless Steels for Marine Environments, Natural Waters and Brines
11 007	Guidelines for the Welded Fabrication of Nickel-Containing Stainless Steels for Corrosion-Resistant Services
11 008	Machining Nickel Alloys
12 001	Life Cycle Cost Benefits of Constructing an FGD System with Selected Stainless Steels and Nickel-Base Alloys
12 002	Performance of Tubular Alloy Heat Exchanges in Seawater Service in the Chemical Process Industries
13 007	Flue Gas Desulphurization in Japan
14 013	Corrosion of Metallic and Nonmetallic Piping for Bleach Plant D Stage Filtrate
14 014	Performance of Highly-Alloyed Materials in Chlorine Dioxide Bleaching
14 020	Weld Fabrication of a 6% Molybdenum Alloy to Avoid Corrosion in Bleach Plant Service.

ADDITIONAL READING (continued)

14 023	Performance of Highly Alloyed Materials in Chlorination Bleaching
14 026	Corrosion Behaviour of Stainless Steel, Nickel-Base Alloy and Titanium Weldments in Chlorination and Chlorine Dioxide Bleaching
14 029	Fabrication Options for Nickel Containing Alloys in FGD Service: Guidelines for Users
14 036	Welding Duplex and Super-Duplex Stainless Steels
15 001	Nuclear Service Water Piping
15 002	Nuclear Service Water Piping

The following publications can be obtained from:
NACE International
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1. NACE Standard RP0292-92. Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment

2. NACE Standard MR0175. Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment

3. NACE Report 1F192. Use of Corrosion Resistant Alloys in Oilfield Environments (1993 Revision)

APPENDIX 2 (A)

AUSTENITIC HIGH-PERFORMANCE STAINLESS STEEL PRODUCER NAMES

Name	UNS Number	Class	Producer Names
Alloy 20	N08020		Carpenter 20Cb-3, Nicrofer 3620 Cb, VLX 920, DMV 920, AL 20,
			INCO alloy 020, NAR-20-3, Sumitomo HR10, NTK 30A, NTK 30AC
		A-1	
Alloy 825	N08825		INCOLOY alloy 825, AL 825, Sandvik Sanicro 41, L 314, UR 825,
			VLX 825, DMV 825, Nicrofer 4221, NAR-825, Sumitomo HR11
317LN	S31753		CLI 168 HE, YUS 317LN
260			YUS 260, R 315CX
		A-2	
317LM	S31725		CLI 68 BC, NTK M5
317LMN	S31726		Cronifer 1713 LCN, Sandvik 3R68,
			CLI 170 HE, NIROSTA 4439
204X	NAS 204X		
310MoLN	S31050		Sandvik 2RE69, Sumitomo HR3 ELM
700	N08700		JS 700
904L	N08904		URANUS B6, Sandvik 2RK65, AL 904L, NAR-20-25LMCu
			VLX 904L, DMV 904L, Cronifer 1925 LCN, POLARIT 774,
			Sumitomo HR8C, Avesta Sheffield 904L
		A-3	
904LN	URB6N,		NIROSTA 4539
20Mo-4	N08024		20Mo-4
20 Mod	N08320		NAR-20-25MTI, Sumitomo HR8
Alloy 28	N08028		Sandvik Sanicro 28, VEW A958, A958, VLX 928, DMV 928,
			Nicrofer 3127 LC, URANUS B28, Sumitomo HR21
20Mo-6	N08026		Carpenter 20Mo-6
25-6MO1925 hMo	N08925 / N08926		INCO alloy 25-6MO, NAR-AC-3, NTK M6, NAR-AC-3,
			Sumitomo HR8N, Cronifer 1925 hMo, URANUS B26, NTK M6
254N			NAS 254N
		A-4	
SB8	N08932		URANUS SB8
254 SMO	S31254		Avesta Sheffield 254 SMO, Sandvik 254 SMO, Sumitomo HR254,
			POLARIT 778, YUS 270, VLX 954, DMV 954, VEW A965, A965
AL-6XN	N08367		
AL-6XN			YUS 170
YUS 170			
2419 MoN		A-5	Cronifer 2419 MoN
4565S			
S34565			NIROSTA 4565S
B66	S31266		URANUS B66
3127 hMo	N08031	A-6	Nicrofer 3127 hMo
654 SMO	S32654		Avesta Sheffield 654 SMO

APPENDIX 2 (B)

FERRITIC HIGH-PERFORMANCE STAINLESS STEEL PRODUCER NAMES

Name	UNS Number	Class	Producer Names
26-1S	S44626		26-1S, Sumitomo FS3Ti, R24-2
		F - 1	
E-BRITE 26-1	S44627		E-BRITE 26-1, R26-1
MONIT	S44635		MONIT
		F - 2	
SEA-CURE	S44660		SEA-CURE
AL 29-4C	S44735		AL 29-4C, NTK U-20
AL 29-4-2	S44800	F - 3	AL 29-4-2, Sumitomo FS10

APPENDIX 2 (C)

DUPLEX HIGH-PERFORMANCE STAINLESS STEEL PRODUCER NAMES

Name	UNS Number	Class	Producer Names
2304	S32304	D - 1	URANUS 35N, Sandvik SAF 2304, Avesta Sheffield SAF 2304
45M			NAS 45M
44LN	S31200		Avesta Sheffield 44LN, VLX547, NTK R-5
2205	S31803	D - 2	DMV 22-5, Sandvik SAF 2205, Avesta Sheffield 2205, AL 2205, NAR-DP-8,VS22, VLX562, A903, URANUS 45N, URANUS 45N+, URANUS 45N Mo, YUS DX1, NTK R-8, NIROSTA 4462, VM 22, AB 318, V225MN, 329 A, 4462
2205	S32205		Avesta Sheffield 2205 Code Plus Two, Sandvik SAF 2205, URANUS 45N+, URANUS 45N Mo, A903
7-Mo PLUS	S32950		7-Mo PLUS
DP3	S31260		NAR- DP3, Sumitomo DP3
47N		D-3	URANUS 47N, VS25, VM 25
64			NAS 64
255	S32550		FERRALIUM alloy 255, URANUS 52N, DMV 25-7, DMV 25-7 Cu, 4507, AL 255
DP3W	S39274		NAR- DP3W, Sumitomo DP3W
100	S32760		ZERON 100, A911, DMV 25-7 N, DMV 25-7 NCu, URANUS 76N, NIROSTA 4501, AB 327 U, V257MWU, 329 S
		D - 4	
2507	S32750		2507, SAF 2507, Sandvik SAF 2507, Avesta Sheffield SAF 2507, CLI SAF 2507, AB 327, V257M, 329 S/1
52N+	S32520		URANUS 52N+

APPENDIX 3

REPRESENTATIVE CHEMICAL COMPOSITIONS OF CORROSION RESISTANT NICKEL-BASE ALLOYS REFERENCED IN THIS REPORT

Name	UNS No.	Ni	Co	Fe	Cr	Mo	W	Si	Mn	C	Cb+Ta
Alloy 625	N06625	62	1.0*	5.0*	21.5	9.0		0.50*	0.5*	0.10*	3.6Cb+Ta
Alloy C-4	N06455	65	2.0*	3.0*	16.0	15.5		0.08*	1.0*	0.01*	0.7Ti
Alloy C-22	N26022	56	2.5*	3.0	22.0	13.0		0.08*	0.5*	0.01*	0.35V*
Alloy C-276	N10276	57	2.5*	5.5	15.5	16.0	3.8	0.08*	1.0*	0.01*	0.35V*
Alloy B-2	N10665	69	1.0*	2.0*	1.0*	28.0		0.10*	1.0*	0.01*	
Alloy B-3	N10675	65	3.0*	1.5	1.5	28.5	3.0*	0.10*	3.0*	0.01*	0.2*Ti
Alloy G-3	N06985	44	5.0*	19.5	22.8	7.0	1.5*	0.40	0.8	0.015*	
Alloy G-30	N06030	43	5.0*	15.0	30.0	5.5	2.5	1.0*	1.5*	0.03*	1.5Cb+Ta* 2.0Cu

** Maximum allowed in typical industry specifications*

APPENDIX 4

PRODUCER-REGISTERED TRADEMARKS AND TRADE NAMES

ACCEAIERIE DI BOLZANO

AB 318, AB 327 U, AB 327

ACCEAIERIE VALBRUNA

V225MN, V257MWU, V257M

ATI PROPERTIES, INC.

AL 825, AL 904L™, AL-6XN®, JS 700®, AL 20™
E-BRITE 26-1®, AL 29-4C®, AL 29-4-2®
AL 255™, AL 2205™

AVESTA SHEFFIELD AB

Avesta Sheffield 254 SMO®, Avesta Sheffield 654 SMO®, Avesta Sheffield 904L
MONIT®
Avesta Sheffield 2205, Avesta Sheffield 2205 Code Plus Two®, Avesta Sheffield SAF 2507®, Avesta Sheffield 2304™, Avesta Sheffield 44LN

BÖHLER EDELSTAHL GmbH

A958, A965, L 314
A903, A911

CARPENTER TECHNOLOGY CORPORATION

20Cb-3®, 20Mo-4®, 20Mo-6®
7-Mo PLUS®

COGNE ACCIAI SPECIALI

329 A, 329 S, 329 S/1

CREUSOT-LOIRE INDUSTRIE

URANUS® SB8, URANUS® B26, URANUS® B66, URANUS® B28, URANUS® B6
CLI-68BC, UR 825, URB6N, CLI SAF 2507, CLI 170 HE®, CLI 168 HE®
URANUS® 35N, URANUS® 45N, URANUS® 45NMo, URANUS® 45N+, URANUS® 47N, URANUS® 52N,
URANUS® 52N+, URANUS® 76N

CRUCIBLE MATERIALS CORPORATION

26-1S, SEA-CURE®

DMV STAINLESS

DMV® 825, DMV® 904L, DMV® 920, DMV® 928, DMV® 954
DMV® 22-5, DMV® 25-7, DMV® 25-7N, DMV® 25-7Cu, DMV® 25-7NCu

KAWASAKI STEEL CORPORATION

R 315 CX
R24-2, R26-1

KRUPP THYSSEN NIROSTA GmbH

NIROSTA® 4439, NIROSTA® 4539,
NIROSTA® 4565S
NIROSTA® 4462, NIROSTA® 4501

KRUPP VDM

Nicrofer® 3620Cb, Nicrofer® 4221, Cronifer® 1713 LCN, Cronifer® 1925 hMo
Cronifer® 1925 LCN, Nicrofer® 3127LC, Cronifer® 2419 MoN, Nicrofer® 3127 hMo

MEIGHS LIMITED

FERRALIUM® alloy 255

NIPPON METAL INDUSTRY CO. LTD.

NTK 30A, NTK 30AC, NTK M5, NTK M6
NTK R-5, NTK R-8
NTK U-20

NIPPON YAKIN KOGYO CO. LTD.

NAS 204X, NAS 254N
NAS 64, NAS 45M

OUTOKUMPU POLARIT Oy

Polarit 777, Polarit 778, VEW A958,
VEW A965

SANDVIK AB

Sandvik Sanicro 41, Sandvik 2RE69, Sandvik 2RK65, Sandvik Sanicro 28, Sandvik 254 SMO
Sandvik SAF 2304®, Sandvik SAF 2205®, Sandvik SAF 2507®, Sandvik 3R68

SPECIAL METALS CORPORATION

INCOLOY® alloy 825

SUMITOMO METAL INDUSTRIES, LTD.

YUS 317LN, YUS 170, YUS 260, YUS 270, YUS DX1, NAR-825, NAR-20-3, NAR-AC-3,
NAR-20-25MTI, NAR-20-25LMCu, Sumitomo HR3 ELM, Sumitomo HR8, Sumitomo HR8C, Sumitomo HR8N, Sumitomo HR10, Sumitomo HR11, Sumitomo HR21, Sumitomo HR254
FS3Ti
NAR-DP3, NAR-DP3W, NAR-DP8,

SUMITOMO METAL TECHNOLOGY, INC.

Sumitomo FS10
Sumitomo DP3W

TRAFILERIE BEDINI

4462

UGINE SRL ITALIA

4462, 4507

VALLOUREC MANNESMANN TUBES

VM® 22, VM® 25

VALLOUREC WELDED

VLX® 920, VLX® 825, VLX® 904,
VLX® 928, VLX® 954
VLX® 547, VLX® 562, VS22, VS25

WEIR MATERIALS LIMITED

ZERON™ 100