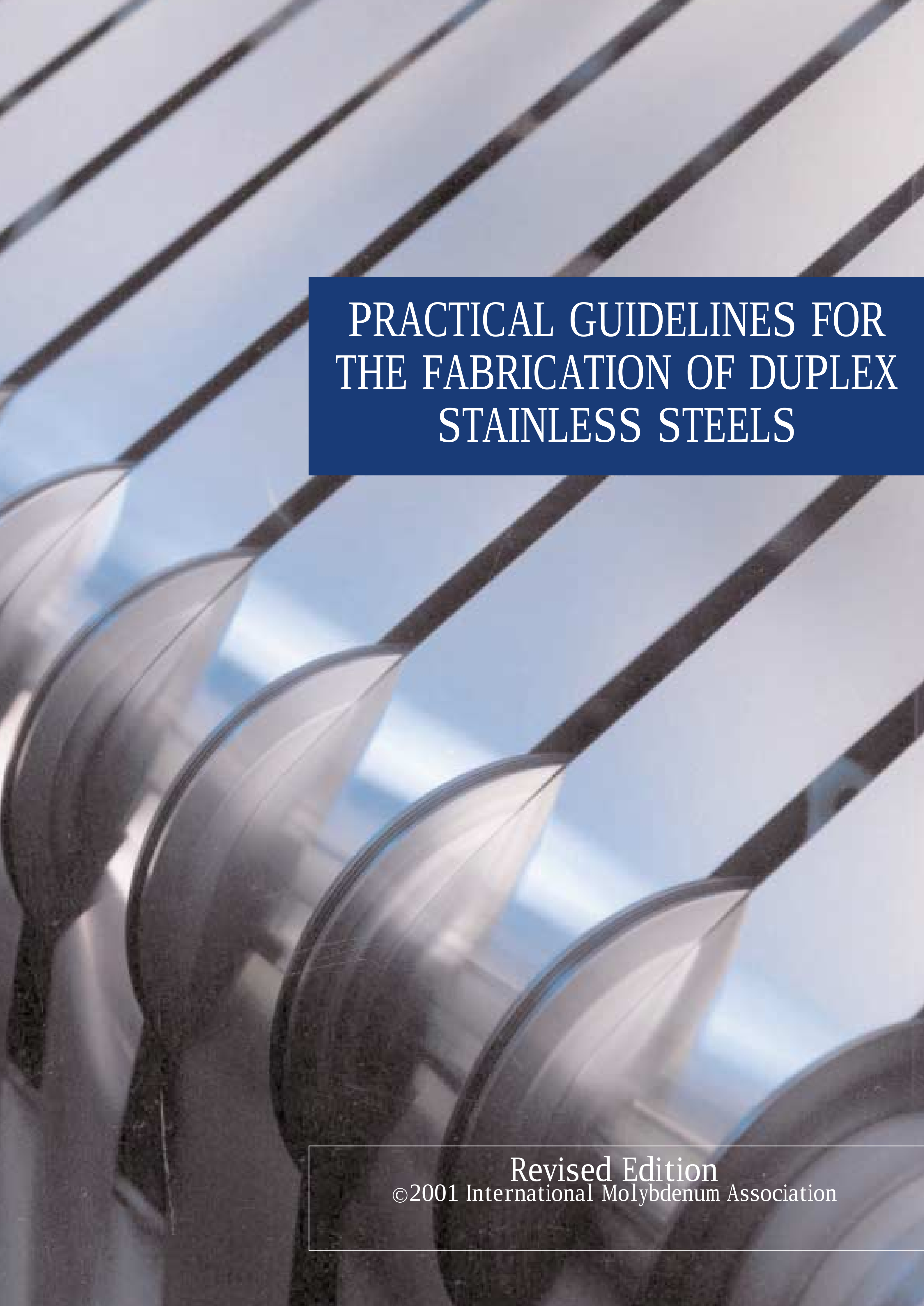

PRACTICAL GUIDELINES FOR THE FABRICATION OF DUPLEX STAINLESS STEELS

Revised Edition

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Front cover picture: Slitting of Duplex Stainless Steel (Source: Krupp Thyssen Nirosta)

1. INTRODUCTION

Duplex stainless steels are a family of grades combining good corrosion resistance with high strength and ease of fabrication. Their physical properties are between those of the austenitic and ferritic stainless steels but tend to be closer to those of the ferritics and to carbon steel. The chloride pitting and crevice corrosion resistance of the duplex stainless steels is a function of chromium, molybdenum, and nitrogen content. It may be similar to that of Type 316 or range up to that of the sea water stainless steels such as the 6% Mo austenitics. All the duplex stainless steels have chloride stress corrosion cracking resistance significantly greater than that of the 300-series austenitics. They all provide significantly greater strength than the austenitic grades while exhibiting good ductility and toughness.

There are many similarities in the fabrication of austenitic and duplex stainless steels but there are important differences. The high alloy content and the high strength of the duplex grades require some changes in fabrication practice. This brochure is for fabricators and for end users with fabrication responsibility. It presents, in a single source, practical information for the successful fabrication of duplex stainless steels. This brochure assumes the reader already has experience with the fabrication of stainless steels; therefore, it provides data comparing the properties and fabrication practices of duplex stainless steels to those of the 300-series austenitic stainless steels and to carbon steel.

The fabrication of duplex stainless steels is different but not difficult.

Chemical Processing Plant Using 2205 (Source: Krupp Thyssen Nirosta)

2. HISTORY OF DUPLEX STAINLESS STEELS

Duplex stainless steels, meaning those with a mixed microstructure of about equal proportions of austenite and ferrite, have existed for more than 60 years. The early grades were alloys of chromium, nickel, and molybdenum. The first wrought duplex stainless steels were produced in Sweden in 1930 and were used in the sulfite paper industry. These grades were developed to reduce the intergranular corrosion problems in the early, high-carbon austenitic stainless steels. Duplex castings were produced in Finland in 1930, and a patent was granted in France in 1936 for the forerunner of what would eventually be known as Uranus 50.[1] One of the first duplex grades developed specifically for improved resistance to chloride stress corrosion cracking (SCC) was 3RE60. AISI Type 329 became well established after World War II and was used extensively for heat exchanger tubing for nitric acid service. In subsequent years, both wrought and cast duplex grades have been used for a variety of process industry applications including vessels, heat exchangers and pumps.

These first-generation duplex stainless steels provided good performance characteristics but had limitations in the as-welded condition. The heat-affected zone (HAZ) of welds had low toughness because of excessive ferrite and significantly lower corrosion resistance than that of the base metal. These limitations confined the use of the first-generation duplex stainless steels, usually in the unwelded condition, to a few specific applications.

In 1968 the invention of the stainless steel refining process, argon oxygen decarburization (AOD), opened the possibility of a broad spectrum of new stainless steels. Among the advances made possible with the AOD was the deliberate addition of nitrogen as an alloying element. Nitrogen alloying of duplex stainless steels makes possible HAZ toughness and corrosion resistance which approaches that of the base metal in the as-welded condition. Nitrogen also reduces the rate at which detrimental intermetallic phases form.

The second-generation duplex stainless steels are defined by their nitrogen alloying. This new commercial development, which began in the late 1970s, coincided with the development of offshore gas and oil fields in the North Sea and the demand for stainless steels with excellent chloride corrosion resistance, good fabricability, and high strength. 2205 became the workhorse of the second-generation duplex grades and was used extensively for gas gathering line pipe and process applications on offshore platforms. The high strength of those steels allowed for reduced wall thickness and reduced weight on the platforms and provided considerable incentive to the use of these stainless steels.

Like the austenitic stainless steels, the duplex stainless steels are a family of grades, which range in corrosion performance depending on their alloy content. The development of duplex stainless steels has continued, and modern duplex stainless steels can be divided into four groups:

- lean duplex such as 2304, which contains no deliberate Mo addition;
- 2205, the work-horse grade accounting for more than 80% of duplex use;
- 25 Cr duplex such as Alloy 255 and DP-3;
- superduplex, with 25-26 Cr and increased Mo and N compared with the 25 Cr grades, including grades such as 2507, Zeron 100, UR 52N+, and DP-3W.

Table 1 lists the chemical compositions of the second-generation wrought duplex stainless steels and of the cast duplex stainless steels. The first-generation duplex grades and the common austenitic stainless steels are included for comparison.

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[1] Each stainless steel referenced by name or by industry designation in the text may be found in Table 1 or Appendix 1.

Table 1. Chemical Composition (wt. pct.) of Wrought and Cast Duplex Stainless Steels* (austenitic grades shown for comparison)

Name	UNS No.	EN	C	Cr	Ni	Mo	N	Cu	W
Wrought Duplex Stainless Steels									
First-Generation Duplex Grades									
329	S32900	1.4460	0.08	23.0-28.0	2.5-5.0	1.0-2.0	**	–	–
3RE60 ***	S31500	1.4417	0.030	18.0-19.0	4.3-5.2	2.50-3.00	0.05-0.1	–	–
Uranus 50	S32404		0.04	20.5-22.5	5.5-8.5	2.0-3.0	–	1.00-2.00	–
Second-Generation Duplex Grades									
2304	S32304	1.4362	0.030	21.5-24.5	3.0-5.5	0.05-0.60	0.05-0.20	–	–
2205	S31803	1.4462	0.030	21.0-23.0	4.5-6.5	2.5-3.5	0.08-0.20	–	–
2205	S32205	1.4462	0.030	22.0-23.0	4.5-6.5	3.0-3.5	0.14-0.20	–	–
DP-3	S31260		0.03	24.0-26.0	5.5-7.5	5.5-7.5	0.10-0.30	0.20-0.80	0.10-0.50
UR 52N+	S32520	1.4507	0.030	24.0-26.0	5.5-8.0	3.0-5.0	0.20-0.35	0.50-3.00	–
255	S32550	1.4507	0.04	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.50-2.50	–
DP-3W	S39274		0.03	24.0-26.0	6.8-8.0	2.5-3.5	0.24-0.32	0.20-0.80	1.50-2.50
2507	S32750	1.4410	0.030	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32	0.50	–
Zeron 100	S32760	1.4501	0.030	24.0-26.0	6.0-8.0	3.0-4.0	0.20-0.30	0.50-1.00	0.50-1.00
Wrought Austenitic Stainless Steels									
304L	S30403	1.4307	0.030	18.0-20.0	8.0-12.0	–	0.10	–	–
316L	S31603	1.4404	0.030	16.0-18.0	10.0-14.0	2.0-3.0	0.10	–	–
317L	S31703	1.4438	0.030	18.0-20.0	11.0-15.0	3.0-4.0	0.10	–	–
317LMN	S31726	1.4439	0.030	17.0-20.0	13.5-17.5	4.0-5.0	0.10-0.20	–	–
904L	N08904	1.4539	0.020	19.0-23.0	23.0-28.0	4.0-5.0	0.10	1.0-2.0	–
254 SMO	S31254	1.4547	0.020	19.5-20.5	17.5-18.5	6.0-6.5	0.18-0.22	0.50-1.00	–
6%Mo	Various	Various	0.030	19.5-22.0	17.5-25.5	6.0-7.0	0.18-0.25	1.00	–
Cast Duplex Stainless Steels									
CD4MCuN Grade 1B	J93372		0.04	24.5-26.5	4.4-6.0	1.7-2.3	0.10-0.25	2.7-3.3	–
CD3MN Cast 2205 Grade 4A	J92205		0.03	21.0-23.5	4.5-6.5	2.5-3.5	0.10-0.30	–	–
CE3MN Atlas 958 Cast 2507 Grade 5A	J93404	1.4463	0.03	24.0-26.0	6.0-8.0	4.0-5.0	0.10-0.30	–	–
CD3MWCuN Cast Zeron 100 Grade 6A	J93380		0.03	24.0-26.0	6.5-8.5	3.0-4.0	0.20-0.30	0.5-1.0	0.5-1.0
Cast Austenitic Stainless Steels									
CF3 (cast 304L)	J92500	1.4306	0.03	17.0-21.0	8.0-12.0	–	–	–	–
CF3M (cast 316L)	J92800	1.4404	0.03	17.0-21.0	9.0-13.0	2.0-3.0	–	–	–

* Maximum, unless range or minimum is indicated. Significant figures shown in accordance with ASTM A 751.

** Not defined in the specifications.

*** This grade was originally made without a deliberate nitrogen addition; without such an addition, it would be considered a first-generation duplex.

2205 Continuous Sulphate Pulp Digester and Impregnation Tower, Sodra Cell Mönsteras, Sweden (Source: Kvaerner Pulping)

3. CHEMICAL COMPOSITION & ROLE OF ALLOYING ELEMENTS

3.1 *Chemical Composition of Duplex Stainless Steels*

It is generally accepted that the favorable properties of the duplex stainless steels can be achieved for phase balances in the range of 30 to 70% ferrite and austenite. However, duplex stainless steels are most commonly considered to have roughly equal amounts of ferrite and austenite, with current commercial production just slightly favouring the austenite for best toughness and processing characteristics. The interactions of the major alloying elements, particularly the chromium, molybdenum, nitrogen, and nickel, are quite complex. To achieve a stable duplex structure that responds well to processing and fabrication, care must be taken to obtain the correct level of each of these elements.

Besides the phase balance, there is a second major concern with duplex stainless steels and their chemical composition: the formation of detrimental intermetallic phases at elevated temperatures. Sigma and chi phases form in high chromium, high molybdenum stainless steels and precipitate preferentially in the ferrite. The addition of nitrogen significantly delays formation of these phases. Therefore, it is critical that sufficient nitrogen be present in solid solution. The importance of narrow composition limits has become apparent as experience with the duplex stainless steels has increased. The composition range that was originally set for 2205 (UNS S31803, Table 1) is too broad. Experience has shown that for optimum corrosion resistance and to avoid intermetallic phases, the chromium, molybdenum and nitrogen levels should be kept in the higher half of their ranges for S31803. Therefore, a modified 2205 with a narrower composition range was introduced with the UNS number S32205 (Table 1). The composition of S32205 is typical of today's commercial production of 2205. Unless otherwise stated in this publication, a reference to 2205 means the S32205 chemistry.

3.2 *The Role of the Alloying Elements in Duplex Stainless Steels*

The following is a brief review of the effect of the most important alloying elements on the mechanical, physical and corrosion properties of duplex stainless steels.

Chromium: A minimum of about 10.5% chromium is necessary to form a stable chromium passive film that is sufficient to protect a steel against mild atmospheric corrosion. The corrosion resistance of a stainless steel increases with increasing chromium content. Chromium is a ferrite former, meaning that the addition of chromium stabilizes the body-centered cubic structure of iron. At higher chromium content, more nickel is necessary to form an austenitic or duplex (austenitic-ferritic) structure. Higher chromium also promotes the formation of intermetallic phases. There is usually at least 18% Cr in austenitic stainless steels and at least 22% in second-generation duplex stainless steels. Chromium also increases the oxidation resistance at elevated temperatures. This chromium effect is important because of its influence on the formation and removal of oxide scale or heat tint resulting from heat treatment or welding. Duplex stainless steels are more difficult to pickle and heat tint removal is more difficult than with austenitic stainless steels.

Molybdenum: Molybdenum acts to support chromium in providing chloride corrosion resistance to stainless steels. When the chromium content of a stainless steel is at least 18%, additions of molybdenum become about three times as effective as chromium additions against pitting and crevice corrosion in chloride-containing environments (see Page 12). Molybdenum is a ferrite former and also increases the tendency of a stainless steel to form detrimental intermetallic phases. Therefore, it is usually restricted to less than about 7.5% in austenitic stainless steels and 4% in duplex stainless steels.

Nitrogen: Nitrogen increases the pitting and crevice corrosion resistance of austenitic and duplex stainless steels. It also substantially

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[2] While several intermetallic phases can form in duplex stainless steels, sigma phase is the most frequent. In the discussions within the producer and user industries, it is common to refer to all such precipitation as "sigma phase". Because all intermetallic phase formation is harmful, it really does not matter so much which phase is present. The terms "intermetallic phase" and "sigma phase" are used interchangeably in practical discussions.

increases their strength and, in fact, it is the most effective solid solution strengthening element. Because of their higher strength, the nitrogen-enhanced austenitic and duplex stainless steels also have increased toughness. Nitrogen delays the formation of intermetallic phases enough to permit processing and fabrication of the duplex grades. Nitrogen is added to highly corrosion resistant austenitic and duplex stainless steels that contain high chromium and molybdenum contents to offset their tendency to form sigma phase.

Nitrogen is a strong austenite former and can replace some nickel in the austenitic stainless steels. In duplex stainless steels, nitrogen is typically added almost to its solubility limit, and the amount of nickel is adjusted to achieve the desired phase balance. The ferrite formers, chromium and molybdenum, are balanced by the austenite formers, nickel and nitrogen, to obtain the duplex structure.

Nickel: Nickel is an austenite stabilizer. That means that the addition of nickel to iron-based alloys promotes a change of the crystal structure of stainless steel from body-centered cubic (ferritic) to face-centered cubic (austenitic). Ferritic stainless steels contain little or no nickel, duplex stainless steels contain an intermediate amount of nickel such as 4 to 7%, and the 300-series austenitic stainless steels, contain at least 8% nickel (see Figures 1, 2). The addition of nickel delays the formation of detrimental intermetallic phases in austenitic stainless steels but is far less effective than nitrogen in delaying their formation in duplex stainless steels. The face-centered cubic structure is responsible for the excellent toughness of the austenitic stainless steels. Its presence in about half of the microstructure of duplex grades greatly increases their toughness relative to ferritic stainless steels.

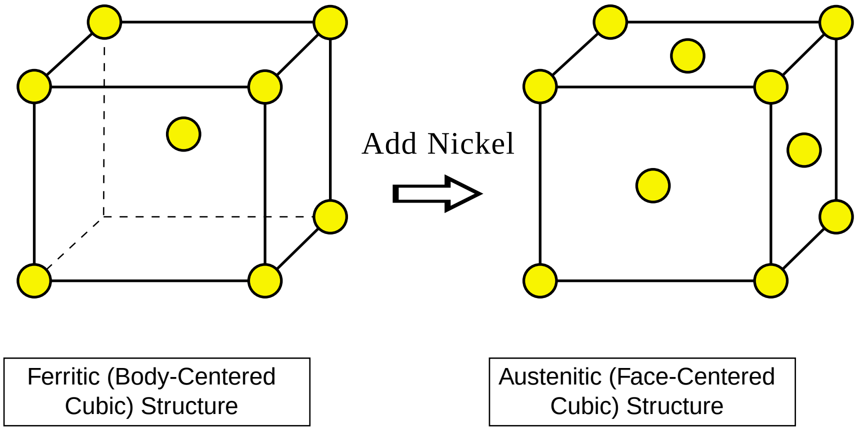
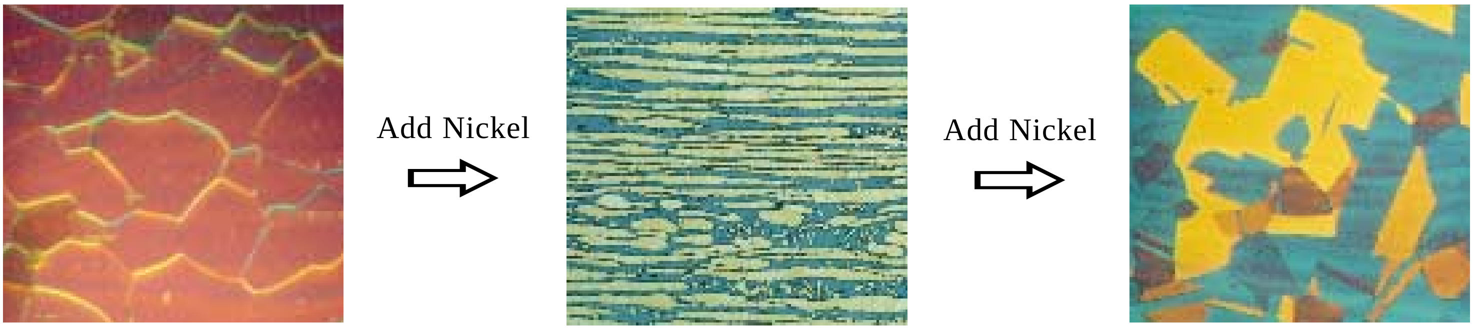


Figure 1. By Adding Nickel, the Crystallographic Structure Changes from Body-Centered Cubic (little or no nickel) to Face-Centered Cubic (at least 8% nickel). The Duplex Stainless Steels, with their Intermediate Nickel Content, have a Microstructure in which some Grains are Ferritic and some are Austenitic, Ideally, about Equal Amounts of Each (Figure 2).



Ferritic Structure **Duplex Structure** **Austenitic Structure**

Figure 2. Increasing the Nickel Content Changes the Microstructure of a Stainless Steel from Ferritic (left) to Duplex (middle) to Austenitic (right) (These pictures, courtesy of AvestaPolarit, show polished and etched samples, enlarged under a light microscope. In the duplex structure, the ferrite has been stained so that it appears as the darker phase.)

4. METALLURGY OF DUPLEX STAINLESS STEELS

The iron-chromium-nickel ternary phase diagram is a roadmap of the metallurgical behavior of the duplex stainless steels. A section through the ternary at 68% iron (Figure 3) illustrates that these alloys solidify as ferrite, some of which then transforms to austenite as the temperature falls to about 1000°C (1832°F) depending on alloy composition. There is little further change in the equilibrium ferrite–austenite balance at lower temperatures. The effect of increasing nitrogen is also shown in Figure 3 (Ref. 1). Thermodynamically, because the austenite is forming from the ferrite, it is impossible for the alloy to go past the equilibrium level of austenite. However, as cooling proceeds to lower temperatures, carbides, nitrides, sigma and other intermetallic phases are all possible microstructural constituents.

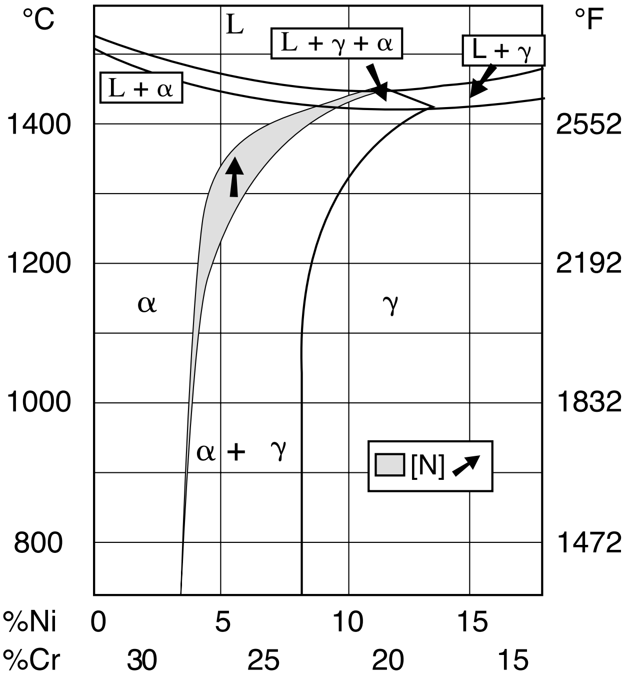


Figure 3. Section Through the Fe-Cr-Ni Ternary Phase Diagram at 68% Iron (Small changes in the nickel and chromium content have a large influence on the amount of austenite and ferrite in duplex stainless steels.)

The relative amounts of ferrite and austenite that are present in a mill product or fabrication depend on the composition and thermal history of the steel. Small changes in composition can have a large effect on the relative volume fraction of these two phases as the phase diagram indicates.

The tendencies of individual elements to promote the formation of austenite or ferrite apply reasonably well to the duplex grades. Work is underway to develop ferrite number relationships as a function of composition for duplex grades, similar to those that exist for austenitic stainless steel weldments. The goal of maintaining the desired phase balance in a duplex stainless steel is achieved primarily by adjusting chromium, molybdenum, nickel, and nitrogen contents, and then by control of thermal history. However, because the cooling rate determines the amount of ferrite that can transform to austenite, cooling rates following high temperature exposures influence the phase balance. Because fast cooling rates favor retention of ferrite, it is possible to have more than the equilibrium amount of ferrite. For example, low heat input welding of a heavy section might result in excessive ferrite in the HAZ.

Another beneficial effect of nitrogen is that it raises the temperature at which the austenite begins to form from the ferrite. Therefore, even at relatively rapid cooling rates, the equilibrium level of austenite can almost be reached. In the second-generation duplex stainless steels, this effect reduces the problem of excess ferrite in the HAZ.

Because sigma phase forms at temperatures below which austenite begins to re-form from the ferrite on cooling, the goal of avoiding sigma phase in mill products is achieved by selecting an appropriate intermediate cooling rate that favors austenite re-formation at high temperature and retards sigma formation at lower temperature. Fortunately, this intermediate cooling rate is quite rapid, allowing the use of water quenching. Only when welding widely differing section sizes or when welding heavy sections with very low heat inputs may the problem of too rapid quenching be observed in actual fabrication.

Alpha prime is also a stable phase in duplex alloys, forming in the ferrite phase below about 525°C (950°F) in the same manner it forms in fully ferritic alloys. Alpha prime causes the loss of ambient temperature toughness in ferritic stainless steel after extended exposure to temperatures centered in the range of 475°C (885°F); this behavior is known as 475C / 885F embrittlement.

The use of nitrogen as an alloying element in these stainless steels means that chromium nitrides may be present on ferrite-ferrite grain boundaries and on austenite-ferrite boundaries in the heat-affected zone of welds. If formed in large quantity and under conditions in which the chromium-depleted areas do not have time to repair themselves during annealing, these chromium nitrides may adversely affect corrosion resistance. However, because higher nitrogen promotes austenite, which has a high solubility for nitrogen, the second-generation duplex stainless steels seldom contain significant amounts of chromium nitrides. Furthermore, the second-generation duplex stainless steels are made with very low carbon content so that carbide formation to a detrimental extent is not usually a practical concern.

Detrimental sigma, alpha prime, and carbides and nitrides can form in a matter of minutes at certain temperatures. Consequently, the thermal treatments required for processing and fabrication, as well as the service cycles, must take reaction kinetics of phase formation into account to ensure that desired corrosion resistance and mechanical properties are obtained. These grades have been developed to maximize corrosion resistance and retard precipitation reactions sufficiently to allow successful fabrication.

An isothermal precipitation diagram for 2304, 2205, and 2507 duplex stainless steels is shown in Figure 4 (Ref. 2,3,4,5). The start of chromium carbide and nitride precipitation begins at the relatively “slow” time of 1-2 minutes at temperature. This is slower than in the ferritic grades or the highly alloyed austenitic grades, and is due, in part, to the high solubility of carbon and nitrogen in the low nickel austenite phase and possibly to a retardation effect of nitrogen on the carbide precipitation. As a result, the duplex grades are relatively resistant to sensitization on cooling. The carbide and nitride formation kinetics are only marginally affected by chromium, molybdenum, and nickel in these grades, so all the nitrogen-alloyed duplex stainless steel grades have kinetics similar to 2205 in regard to these precipitates. Sigma and chi precipitation occurs at slightly higher temperatures but in approximately the same time as the carbide and nitride precipitation. Duplex grades that are more highly alloyed in chromium, molybdenum, and nickel will have more rapid sigma and chi kinetics than 2205; those with lower alloy content are slower. This is illustrated by the dashed curves in Figure 4 showing an earlier start of sigma and chi formation in the more highly alloyed 2507 and a slower start for 2304.

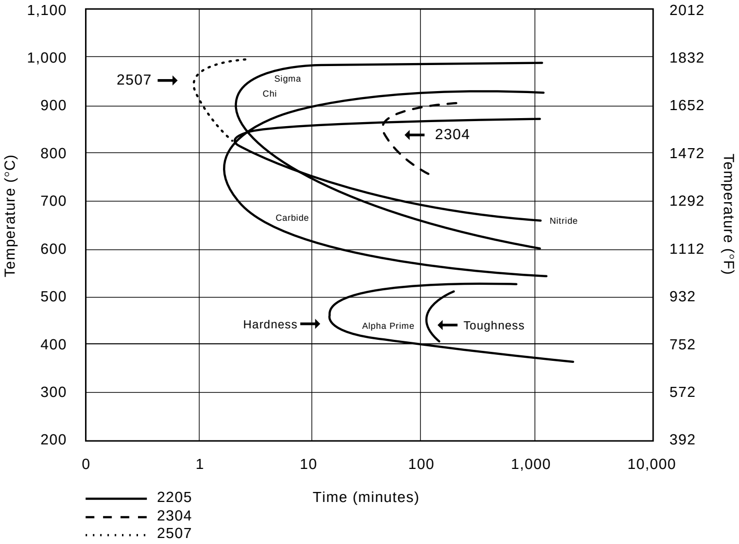


Figure 4. Isothermal Precipitation Diagram for 2205 Duplex Stainless Steel, Annealed at 1050˚C (1920˚ F). (Duplex grades 2304 and 2507 are shown for comparison)

2205 Flanges (Source: Arco Exploration and Production Technology)

Alpha prime precipitates within the ferrite phase, and its effects are to harden and embrittle the ferrite. Fortunately, because duplex stainless steels contain 50% austenite, this hardening and embrittling effect is not nearly as detrimental as it is in fully ferritic steels. The loss of toughness (embrittlement) due to alpha prime precipitation is slower than the rate of hardening (Figure 4). As a result, alpha prime embrittlement is rarely a matter of concern during fabrication. However, the upper temperature limit for service is controlled by alpha prime formation.

Because long-term, elevated temperature exposure can result in loss of ambient temperature toughness, pressure vessel design codes have established upper temperature limits for the maximum allowable design stresses. The German TüV code distinguishes between welded and unwelded constructions and is more conservative in its upper temperature limits than the ASME Boiler and Pressure Vessel Code. The temperature limits for these pressure vessel design codes for various duplex stainless steels are summarized in Table 2.

Table 3 summarizes a number of important precipitation reactions and temperature limitations for duplex stainless steels.

5. CORROSION RESISTANCE

Duplex stainless steels exhibit a high level of corrosion resistance in most environments where the standard austenitic grades are useful. However, there are some notable exceptions where they are decidedly superior. This results from their high chromium content, which is beneficial in oxidizing acids, along with sufficient molybdenum and nickel to provide resistance in mildly reducing acid environments. The relatively high chromium, molybdenum and nitrogen also give them very good resistance to chloride pitting and crevice corrosion. Their duplex structure is an advantage in potential chloride stress corrosion cracking environments. If the microstructure contains at least twenty-five or thirty percent ferrite, duplex stainless steels are far more resistant to chloride stress corrosion cracking than Types 304 or 316. Ferrite is, however, susceptible to hydrogen embrittlement; thus, the duplex stainless steels do not have high resistance in environments or applications where hydrogen may be charged into the metal.

5.1 Resistance to Acids

To illustrate the corrosion resistance of duplex stainless steels in strong acids, Figure 5 provides corrosion data for sulfuric acid solutions. This environment ranges from oxidizing at low acid

Grade	Condition	ASME		TüV	
		°C	°F	°C	°F
2304	Unwelded	315	600	300	570
2304	Welded, matching filler	315	600	300	570
2304	Welded with 2205/2209	315	600	250	480
2205	Unwelded	315	600	280	535
2205	Welded	315	600	250	480
2507	Seamless tubes	315	600	250	480
Alloy 255	Welded or unwelded	315	600	–	–

Table 2. Upper Temperature Limits for Duplex Stainless Steel for Maximum Allowable Stress Values in Pressure Vessel Design Codes

	2205		Superduplex	
	°C	°F	°C	°F
Solidification range	1445 to 1385	2630 to 2525	1450 to 1390	2640 to 2535
Scaling temperature in air	1000	1830	1000	1830
Sigma phase formation	700 to 975	1300 to 1800	700 to 975	1300 to 1800
Carbide precipitation	450 to 800	840 to 1470	450 to 800	840 to 1470
475C/885F embrittlement	350 to 525	650 to 980	350 to 525	650 to 980

Table 3. Typical Temperatures for Precipitation Reactions and Other Characteristic Reactions in Duplex Stainless Steels

concentrations, to mildly reducing at high concentrations, with a strongly reducing middle composition range in warm and hot solutions. Both 2205 and 2507 duplex stainless steels outperform many high nickel austenitic stainless steels in solutions containing up to about 15% acid. They are better than Types 316 or 317 through at least 40% acid. The duplex grades can also be very useful in acids of this kind containing chlorides or oxidizing constituents. The duplex stainless steels do not have sufficient nickel to resist the strong reducing conditions of mid-concentration sulfuric acid solutions, or hydrochloric acid. If there is an opportunity for concentration of the acid, as happens at the "waterline" or in splash zones, corrosion, especially of the ferrite, may be activated and may proceed rapidly. Their resistance to oxidizing conditions makes duplex stainless steels good candidates for nitric acid service and the strong organic acids; this is illustrated in Figure 6 for solutions containing 50% acetic acid and varying amounts of formic acid at their boiling temperatures. Although Types 304 and 316 will handle these strong organic acids at ambient and moderate temperatures, 2205 and other duplex grades are superior in many processes involving organic acids at high temperature. The duplex stainless steels are also used in processes involving halogenated hydrocarbons because of their resistance to pitting and stress corrosion.

5.2 *Resistance to Caustics*

The high chromium content and presence of ferrite provides for good performance of duplex stainless steels in caustic environments. At moderate temperatures, corrosion rates are lower than those of the standard austenitic grades.

5.3 *Pitting and Crevice Corrosion Resistance*

To discuss pitting and crevice corrosion resistance of stainless steels, it is useful to introduce the concept of critical temperatures for corrosion. For a particular chloride environment, each stainless steel can be characterized by a temperature above which pitting corrosion will initiate and propagate to a visibly detectable extent within about 24 hours. Below this temperature, pitting initiation will not occur in indefinitely long times. This temperature is known as the critical pitting temperature (CPT). It is a characteristic of the particular piece of stainless steel and the specific environment. Because pitting initiation is statistically random, and because of the sensitivity of the CPT to minor within-grade variations or within-product variations, the CPT is typically expressed for various grades as a range of temperatures. However, with a new research tool described in ASTM G 150, it is possible to determine the CPT by electropotential measurements. CPT can now be accurately and reliably measured.

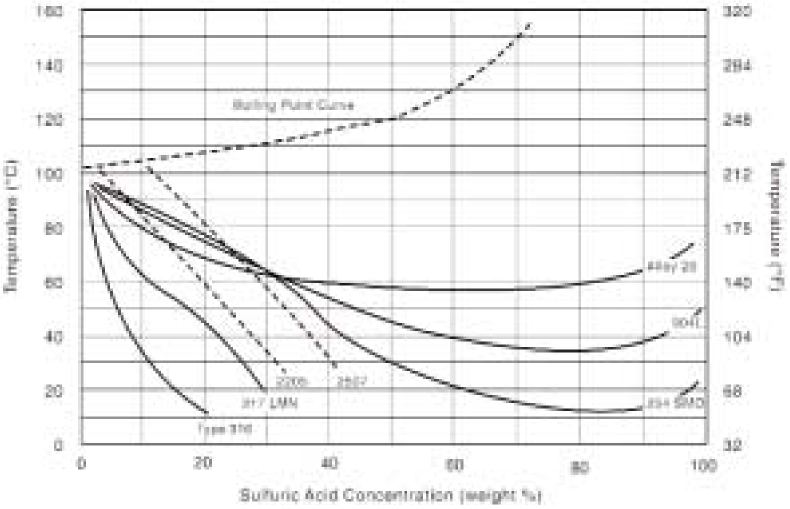


Figure 5. Corrosion in Non-aerated Sulfuric Acid, 0.1 mm/yr (0.004 inch/yr) Corrosion Curves (laboratory tests using reagent grade sulfuric acid)(Source: Producer Data Sheets, 254 SMO is a trademark of AvestaPolarit)

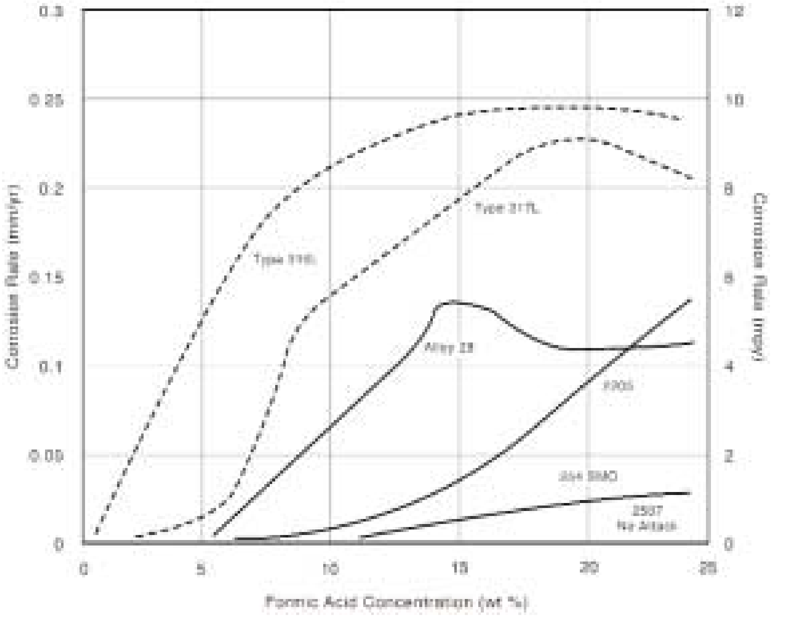


Figure 6. Corrosion of Duplex and Austenitic Stainless Steels in Boiling Mixtures of 50% Acetic Acid and Varying Proportions of Formic Acid (Source: Sandvik Steel)

There is a similar critical temperature for crevice corrosion, called the critical crevice temperature (CCT). The CCT is dependent on the individual sample of stainless steel, the chloride environment, and the nature (tightness, length, etc.) of the crevice. Because of the dependence on the geometry of the crevice and the difficulty of achieving reproducible crevices in practice, there is more scatter for the measurement of CCT than for the CPT. Typically, the CCT will be 15 to 20°C (27 to 36°F) lower than the CPT for the same steel and same corrosion environment.

The high chromium, molybdenum and nitrogen contents in duplex grades provide very good resistance to chloride-induced localized corrosion in aqueous environments. All but the very lowest alloyed duplex stainless steels are far superior to Type 316 in this respect. Depending on the alloy content, some duplex grades are among the best performing stainless steels. Because they contain relatively high chromium content, duplex stainless steels provide a high level of corrosion resistance very economically. A comparison of pitting and crevice corrosion resistance for a number of stainless steels in the solution annealed condition as measured by the ASTM G 48 procedures (10% ferric chloride) is given in Figure 7. Critical temperatures for materials in the as-welded condition would be expected to be somewhat lower. Higher critical pitting or crevice corrosion temperatures indicate greater resistance to the initiation of these forms of corrosion. The CPT and CCT of 2205 are well above those of Type 316. This makes 2205 a versatile material in applications where chlorides are concentrated by evaporation, as in the vapor spaces of heat exchangers or beneath insulation. The CPT of 2205 indicates that it can handle many brackish waters and deaerated brines. It has been successfully used in seawater applications where the surface has been maintained free of deposits through high flow rates or other means. 2205 does not have enough crevice corrosion resistance to withstand seawater in critical applications such as thin wall heat exchanger tubes, or where deposits or crevices exist. However, the more highly alloyed duplex stainless steels with higher CCT than 2205, for example, the superduplex grades, have been used in many critical seawater handling situations where both strength and chloride resistance are needed.

Because the CPT is a function of the material and the particular environment, it is possible to study the effect of individual elements. Using the CPT as determined by ASTM G 48 Practice A, statistical regression analysis was applied to the compositions of the steels (each element considered as an independent variable) and the measured CPT (the dependent variable). The result was that only chromium, molybdenum, and nitrogen showed consistent measurable effect on the CPT according to the relationship:

CPT = constant + %Cr + 3.3x%Mo + 16x%N.

In this relationship, the sum of the three alloy element variables multiplied by their regression constants is commonly called the Pitting Resistance Equivalent (PRE). It is useful for ranking grades within a single family of steels. However, care must be taken to avoid inappropriate over-reliance on this relationship. The “independent variables” were not truly independent because the steels tested were balanced compositions. The relationships are not linear, and cross relationships, such as the synergies of chromium and molybdenum, were ignored. The relationship assumes an ideally processed material, but does not address

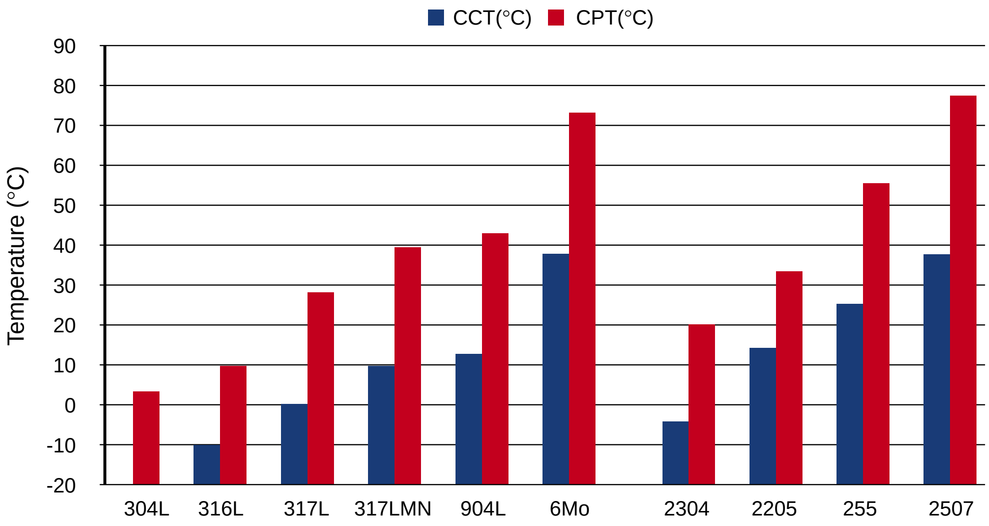


Figure 7. Critical Pitting and Crevice Corrosion Temperatures for Unwelded Stainless Steels in the Solution Annealed Condition (evaluated in 10% ferric chloride by ASTM G 48)

Name	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
Type 304L and Type 316L	■	■	■	■	■	■	■	■	■	■	■
3RE60	■	■	■	🟦	🟨	🟨	🟨	■	■	🟪	■
2205	■	■	■	🟨	🟨	🟨	🟨	🟦	■	🟪	■
25 Cr Duplex	■	■	■	🟨	🟨	🟨	🟨	🟨	■	🟪	🟪
Superduplex	■	■	■	🟨	🟨	🟨	🟨	🟨	🟨	🟪	🟪

■ Cracking Anticipated

🟦 Cracking Possible

🟨 Cracking Not Anticipated

🟪 Insufficient Data

Table 4. Comparative Stress Corrosion Cracking Resistance of Unwelded Duplex and Austenitic Stainless Steels in Accelerated Laboratory Tests (Source: Various Literature Sources)

the effect of intermetallic phases, non-metallic phases, or improper heat treatment that can adversely affect corrosion resistance.

5.4 *Stress Corrosion Cracking Resistance*

Some of the earliest uses of duplex stainless steels were based on their resistance to chloride stress corrosion cracking (SCC). Compared with austenitic stainless steels with similar chloride pitting and crevice corrosion resistance, the duplex stainless steels exhibit significantly better SCC resistance. Many of the uses of duplex stainless steels in the chemical process industries are replacements for austenitic grades in applications with a significant risk of SCC. However, as with all materials, the duplex stainless steels may be susceptible to stress corrosion cracking under certain conditions. This may occur in high temperature, chloride-containing environments, or when conditions favor hydrogen-induced cracking. Examples of environments in which SCC of duplex stainless steels may be expected include the boiling 42% magnesium chloride test, drop evaporation when the metal temperature is high, and exposure to pressurized aqueous chloride systems in which the temperature is higher than what is possible at ambient pressure.

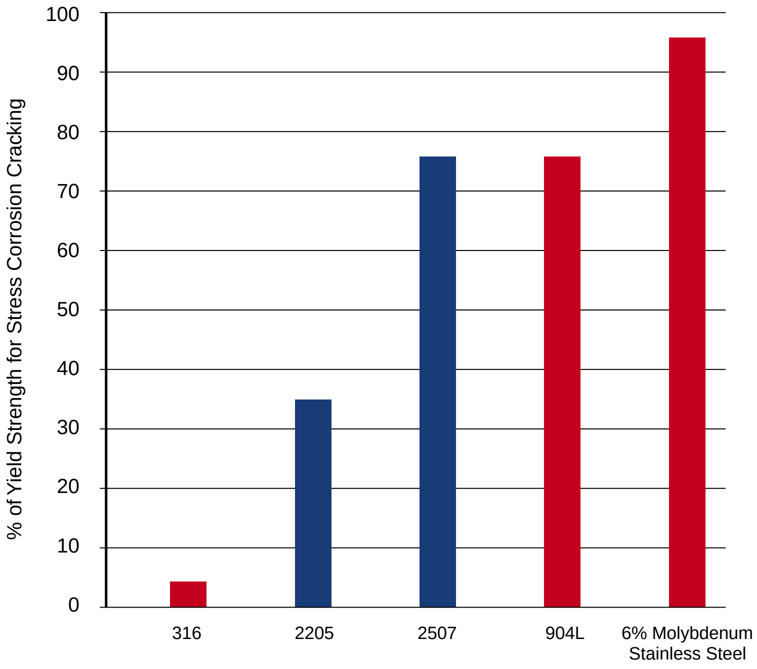


Figure 8. Stress Corrosion Cracking Resistance of Mill Annealed Austenitic and Duplex Stainless Steels in the Drop Evaporation Test with Sodium Chloride Solutions at 120°C (248°F) (stress that caused cracking shown as a percentage of yield strength) (Source: AvestaPolarit).

An illustration of relative chloride stress corrosion cracking resistance for a number of mill annealed duplex and austenitic stainless steels in a severe chloride environment is given in Figure 8 (Ref. 6). The drop evaporation test used to generate these data is very aggressive because it is conducted at a high temperature of 120°C (248°F) and the chloride solution is concentrated by evaporation. The two duplex steels shown, 2205 and 2507, will eventually crack at some fraction of their yield strength in this test, but that fraction is much higher than that of Type 316 stainless steel. Because of their resistance to SCC in aqueous chloride environments at ambient pressure, for example, under-insulation corrosion, the duplex stainless steels may be considered in chloride cracking environments where Types 304 and 316 have been known to crack. Table 4 summarizes

2304 Storage Tank for Forest Products, New Zealand (Source: Usinor Industeel)

chloride stress corrosion cracking behavior of different stainless steels in a variety of test environments with a range of severity. The environments on the left side of the table are severe because of their acid salts, while those on the right side are severe because of high temperatures. The environments in the center are less severe. The standard austenitic stainless steels, those with less than 4% Mo, undergo chloride stress corrosion cracking in all these environments, while the duplex stainless steels are resistant throughout the mid-range, moderate conditions of testing.

Resistance to hydrogen-induced stress corrosion is a complex function, not only of ferrite content, but also of strength, temperature, charging conditions, and the applied stress. In spite of their susceptibility to hydrogen cracking, the strength advantages of duplex stainless steels are used in hydrogen-containing environments provided the operating conditions are carefully evaluated and controlled. The most notable of these applications is high strength tubulars handling mixtures of slightly sour gas and brine. An illustration showing regimes of immunity and susceptibility for 2205 in sour environments containing sodium chloride is shown in Figure 9 (Ref. 7).

6. END USER SPECIFICATIONS AND QUALITY CONTROL

A critical practical issue in specification and quality control of duplex stainless steel fabrications is the retention of properties after welding. It is essential for the duplex stainless steel starting material to have the composition and processing that leads to good properties after welding by a qualified procedure.

6.1 *Standard Testing Requirements*

6.1.1 *Chemical Composition*

The ASTM specifications are the appropriate starting point for selecting a second-generation duplex stainless steel. Nitrogen is beneficial, both with respect to avoiding excessive ferrite in the HAZ and with respect to delaying the formation of sigma phase. The upper limit of nitrogen in a duplex stainless steel is the solubility of nitrogen in the melt, and that is reflected in the maximum of the specified nitrogen range in the standard specifications. However, the minimum nitrogen listed may or may not reflect the level needed to provide the best welding response. An example of this is S31803, the original specification for 2205.

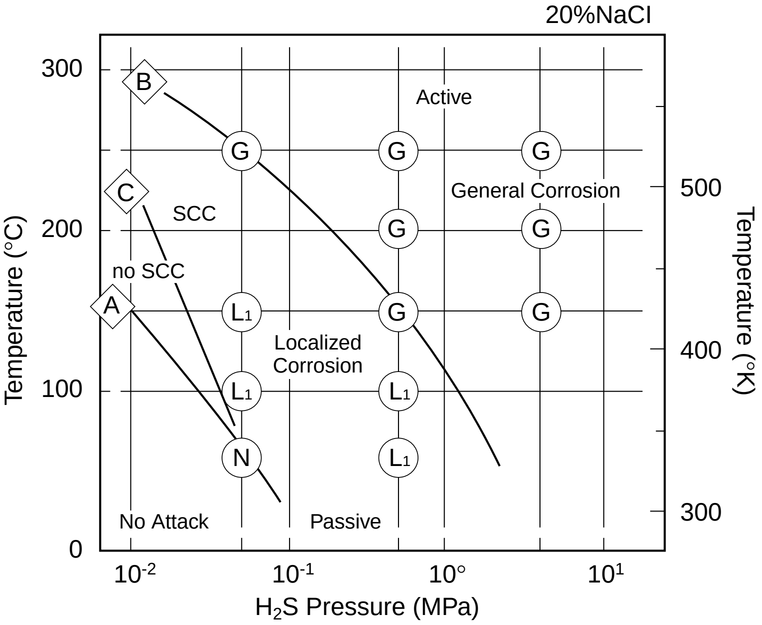


Figure 9. Corrosion of 2205 Duplex Stainless Steel in 20% Sodium Chloride-Hydrogen Sulfide Environments Based on Electrochemical Prediction and Experimental Results

At the lower end of the 0.08-0.20 N range permitted in S31803, 2205 had inconsistent response to heat treating and welding. Practical experience led to the recognition that "0.14 minimum nitrogen" is necessary for 2205 welded fabrications. Because this requirement was frequently specified, the S32205 version of 2205 was introduced into the specification for the convenience of the end users requiring welding. The superduplex stainless steels also have higher nitrogen ranges, reflecting the recognition of the importance of nitrogen.

There have been some end user duplex stainless steel specifications based on the "PRE" relationship. While a PRE value may be effective at ranking the corrosion resistance of various grades within a family of correctly balanced compositions, a composition modified to meet a specific PRE does not necessarily lead to correct metallurgical balance. The PRE may assist in selecting one of the listed grades, but when applied to variations within a grade, it suggests that chromium and molybdenum are substitutable with nitrogen. But metallurgically, chromium and molybdenum promote ferrite and intermetallic phases, while nitrogen promotes austenite and inhibits formation of intermetallic phases.

Therefore, the selection of composition for duplex grades is best based on the standard grades listed in the specification, possibly with restriction of nitrogen to the upper end of the solubility range for each grade. Whatever composition is specified, it should be the same material that is used in qualification of welding procedures, so that the qualifications are meaningful in terms of the results that may be expected in the fabrication.

6.1.2 *Solution Annealing and Quenching*

In addition to chemical composition, the actual annealed condition of mill products is also important for a consistent response to welding. In an austenitic stainless steel, the purpose of annealing is to recrystallize the metal and to put the carbon into solution. With the low carbon "L-grades", the stainless steel may be water quenched or air cooled relatively slowly because the time to re-form detrimental amounts of carbides is quite long. However, with the duplex stainless steels, even with the ideal nitrogen content, exposures of a few minutes in the critical temperature range are detrimental to corrosion and toughness (Ref. 8). When a mill product is slowly cooled, even by "rapid air cooling", the time that it takes the material to pass through the 700-980°C (1300-1800°F) range is no longer available for further thermal exposures, for example, welding. So the welder will have less time to make a weld that is free of intermetallic phases in the HAZ.

While specifications such as ASTM permit some duplex grades to be "water quenched or rapidly cooled by other means," the best metallurgical condition for welding is achieved by the most rapid quenching from the annealing temperature. In the case of sheet, air cooling is highly effective in modern coil processing lines; but for plate, water quenching produces the best metallurgical condition for welding. Allowing a plate or a fitting to cool into the 700-980°C (1300-1800°F) range prior to quenching may lead to the formation of intermetallic phases.

Another approach to assure an optimal starting condition is to require that mill products be tested for the absence of detrimental intermetallic phases. ASTM A 923 uses metallographic examination, impact testing, or corrosion testing to demonstrate the absence of a harmful level of intermetallic phases. This test assumes a rapidly cooled mill product and does not consider any early stages of precipitation, only whether harmful precipitation has already occurred. This testing is analogous to ASTM A 262 testing of austenitic stainless steels for sensitization due to chromium carbide precipitation. A 923 covers only wrought 2205 (S31803 and S32205) mill products, but other duplex grades may be added in the future. Although A 923 explicitly states that the tests are not applicable to welds without subsequent solution anneal, many fabricators have adopted these and similar tests, with lower test temperatures, reduced toughness or other changes in the acceptance criteria, as a part of their qualification for welding procedures.

6.2 *Special Testing Requirements*

6.2.1 *Tensile and Hardness Tests*

The duplex stainless steels have high strength relative to the austenitic stainless steels. However, there have been occasional end-user specifications in which a maximum has been imposed on either

Inside a 2205 (1.4462) Tank on a Marine Chemical Tanker (Source: Krupp Thyssen Nirosta)

the strength or hardness. Imposing maximums on strength or hardness is probably a carryover from experience with martensitic stainless steels where high strength or hardness is caused by untempered martensite. However, the duplex stainless steels will not form martensite. High strength and hardness in a duplex stainless steel are the result of high nitrogen content, the duplex structure itself, and work hardening that may occur in forming or straightening operations.

Hardness testing can be an effective means of demonstrating that there has not been excessive cold working in fabrication; but it is important that when the hardness test is being used for this purpose, the measurement is made at a location midway between the surface and center of the section and not on a surface that may have been locally and superficially hardened.

6.2.2 *Bend Tests*

Bend tests may demonstrate that mill products are free of cracking from rolling, but may be difficult for heavy sections, small pieces, or certain geometries. Bend tests are not a conservative indication of quality in duplex stainless steel because the point of bending may not coincide with the location of an unacceptable condition. Some conditions such as centerline intermetallic phase are unlikely to be detected because of the directionality of bending.

Bend tests are commonly used as part of the qualification of welding procedures for the austenitic stainless steels because there is a risk of hot cracking of the weld, especially for highly austenitic weld structures that are heavily constrained. The usefulness of bend tests for detecting problems of weld integrity is greatly reduced because of the ferritic solidification of the duplex stainless steel, as well as the higher thermal conductivity and lower thermal expansion. Bend tests might detect grossly excessive ferrite if the test location coincides precisely with the affected region, but bend tests are unlikely to detect the occurrence of intermetallic phases at the low levels known to be harmful to corrosion resistance and toughness of a fabrication.

6.2.3 *Impact Testing and Metallographic Examination for Intermetallic Phases*

There are two ways that an impact test can be used in specifying material or qualifying a procedure:

- test at conditions known to detect unacceptable material, for example, excessive ferrite or the presence of intermetallic phases;
- demonstrate that a fabrication has properties sufficient for the intended service.

For the first use, ASTM A 923 provides a test for 2205. The loss of toughness in a standard longitudinal Charpy test at -40°F/C to less that 54J (40 ft-lb.) is indicative of an unacceptable condition in a mill annealed product. To assure that the heat treatment and quenching are satisfactory, A 923 Method B (or Method C, the corrosion test) should be required for each heat lot of mill product as a production control measure. However, A 923 allows the use of metallographic examination (Method A), as a screening test for acceptance but not rejection. Because of the high level of metallographic skill required to perform Method A, it may be prudent for the end user to require the Charpy test rather than the metallographic examination. One way to state this is to require that the impact energies be reported.

One advantage of A 923 Method A is the identification of centerline intermetallic phase, as shown in Figure 4 of A 923. Centerline intermetallic phase will disqualify a material with respect to screening by Method A, but may not necessarily result in rejection of the material in A 923 Method B, impact testing. Because this centerline intermetallic phase may lead to delamination of the plate during forming, thermal cutting, or welding, the user should require that Method A be performed in addition to Method B or C, and that any material showing centerline intermetallic phase is rejected. Although A 923 states that Method A may not be used for rejection, an end user is permitted to impose more stringent requirements. Material that shows centerline intermetallic phase near mid-thickness as indicated by A 923 Figure 4 should be rejected.

The second use of impact testing, evaluating base metal, fusion zone and HAZ at more severe conditions than the intended service, may be cost effective and conservative. For weld evaluation, the test temperature and acceptance criterion must be specific to the type of weld and meaningfully related to the service conditions. The toughness will not be as high as that of a solution annealed duplex stainless steel mill product. Lower toughness in a weld metal is not necessarily indicative of intermetallic phases but is more frequently a result of increased oxygen content, especially for the flux-shielded welding procedures.

The ASME has issued new requirements applicable to duplex stainless steels with section thickness greater than 9.5 mm (0.375 inch) (Ref. 9). These requirements use Charpy impact tests at the minimum design metal temperature (MDMT), with acceptance criteria expressed in lateral expansion, to demonstrate that the starting material and production welds are tough enough for the intended service. The ASME test differs from the A 923 test in that the ASME test requires that the Charpy test consist of three specimens (the more common approach to measuring toughness for suitability for service) and requires reporting both minimum and average results.

For economy of testing with conservative results, it is possible to use the lower of the two testing temperatures (-40°C/F in ASTM A 923 or MDMT in ASME Code), and measure the toughness by both impact energy and lateral expansion for triplicate specimens.

6.2.4 *Phase Balance as Determined by Metallography or Magnetic Measurements*

The austenite-ferrite phase balance of duplex stainless steel mill products exhibits very little heat-to-heat or lot-to-lot variation because they are produced to very narrow chemical composition ranges and well defined annealing practices. Typically, 2205 contains 40-50% ferrite. For this reason, the determination of the phase balance in annealed mill products is of limited value.

However, a ferrite determination may be appropriate for qualification of welding procedures to guard against excessive ferrite in the HAZ. An accurate determination of phase balance for a duplex stainless steel usually requires a metallographic examination and point count, for example ASTM E 562 (manual) or E 1245 (automated). Because duplex stainless steels are ferromagnetic with an exceedingly fine spacing of austenite and ferrite, use of magnetic detection methods has limited reliability without reference standards of identical geometry and metallographically measured phase balance. AWS A4.2-91 and ISO 8249 describe procedures for calibrating magnetic instruments to measure ferrite in duplex stainless steel welds and reporting the results in Ferrite Number, FN. The range of phase balance acceptable for a weld is substantially wider than that for the base metal. If toughness and corrosion resistance of the weld and HAZ are acceptable, as demonstrated by tests such as those of A 923, then a range of 25-75% ferrite can provide the desired properties of the duplex stainless steel. Magnetic measurements in the range of FN 30-90 are considered acceptable.

Requiring determination of phase balance for material that is already in service center or stockist inventory is more expensive than imposing the same requirement on material as it is being produced at a mill. Obtaining the sample and performing a separate test may also reduce timely availability.

Because intermetallic phases are nonmagnetic, magnetic testing cannot be used to detect sigma and chi phases.

6.2.5 *Corrosion Testing*

Corrosion testing of solution annealed mill products, in accordance with A 923, is one of the most cost-effective testing methods for detection

Duplex Stainless Steel Pipes (Source: Butting)

of detrimental conditions. The precipitation of intermetallic phases, and possibly chromium nitride in an excessively ferritic phase balance, are detected as a loss of pitting resistance. These phases cause losses of 15°C, or more, from the CPT typically expected for the properly annealed material. Measurement of the actual critical pitting temperature for a specimen is relatively expensive because it requires multiple tests. However, performing a single corrosion test 10 to 15°C below the typical CPT for a duplex stainless steel will reveal the presence of detrimental phases. When using a corrosion test to detect the presence of harmful phases, any pitting on the faces or on the edges should be included as a basis for rejection. While the edge may not be exposed in actual service, this test is intended to detect intermetallic phases, and these are more likely to be present at the centerline, which is evaluated when edge attack is included.

Prior to the development of ASTM A 923, the corrosion test was generally called out by referencing the “modified G 48 test.” However, G 48 is a description of laboratory research procedure, rather than a material acceptance test. A requirement for testing by G 48 is not complete without a determination of which G 48 Practice is to be performed, and statement of other testing variables including:

- surface preparation,
- test temperature,
- test duration,
- inclusion or exclusion of edge corrosion,
- definition of an acceptance criterion.

A 923 is an acceptance test designed to demonstrate the absence of detrimental intermetallic phases in mill products in a cost effective and relatively rapid way. A 923, Method C, expresses the acceptance criterion as a corrosion rate. That may seem surprising when the issue is the detection of pitting corrosion; however, this approach was used for two reasons:

1. By basing the acceptance on weight loss, the burdensome and potentially subjective issue of what is a pit on the metal surface is eliminated. The weight loss required for rejection is large enough to be readily measured, but small enough to easily detect the kind of pitting associated with the presence of intermetallic phases in a 24-hour test.
2. By using a corrosion rate, almost any specimen size or shape can be tested provided that the total surface area can be determined.

The corrosion test is conservative and not sensitive to specimen geometry and location, in contrast to a Charpy test, which is sensitive to orientation and notch location. The corrosion test is appropriate as part of the qualification of weld procedures, and as a cost effective quality control test applied to samples of production welds when they can be obtained. However, allowance must be made for the difference in corrosion resistance of annealed mill products and an as-welded joint. Even a properly made weld may exhibit a CPT 5 to 15°C lower than that of the base metal depending on the welding procedure, shielding gas and the grade of duplex stainless steel being welded.

6.2.6 *Production Welding and Inspection*

The problems that might occur with duplex stainless steel are not readily apparent to the welder, nor are they detectable by non-destructive testing. The welder must appreciate that the total quality of the weld, as measured by its toughness and corrosion resistance in service, depends on strictly following the welding procedure. Deviations from the qualified procedure will not necessarily be detectable in the shop, but every deviation represents a risk to safe and economical service.

7. MECHANICAL PROPERTIES

Duplex stainless steels have exceptional mechanical properties. Their room temperature yield strength in the solution-annealed condition is more than double that of standard austenitic stainless steels not alloyed with nitrogen. This may allow the design engineer to decrease the wall thickness in some applications. The typical yield strengths of several duplex stainless steels are compared with that of 316L austenitic stainless steel between room temperature and 300°C (570°F) in Figure 10. Because of the danger of 475°C (885°F) embrittlement of the ferritic phase, duplex stainless steels should not be used in service at temperatures above those allowed by the applicable pressure vessel design code for prolonged periods of time (see Table 2).

The mechanical properties of wrought duplex stainless steels are highly anisotropic, that is, they may vary depending on the orientation. This anisotropy is caused by the elongated grains and the crystallographic texture that results from hot or cold rolling (see Figure 2). While the solidification structure of duplex stainless steel is typically isotropic, it is rolled or forged and subsequently annealed with both phases present. The appearance of the two phases in the final product reveals the directionality of the processing. The strength is higher perpendicular to the rolling direction than in the rolling direction. The impact toughness is higher when the crack propagates perpendicularly to the rolling direction than in the rolling direction. The measured toughness will be higher for a “longitudinal” (L-T) Charpy test specimen than for other test directions. The impact energy of a transverse specimen from a duplex stainless steel plate will typically be 1/2 to 2/3 that of a longitudinal specimen.

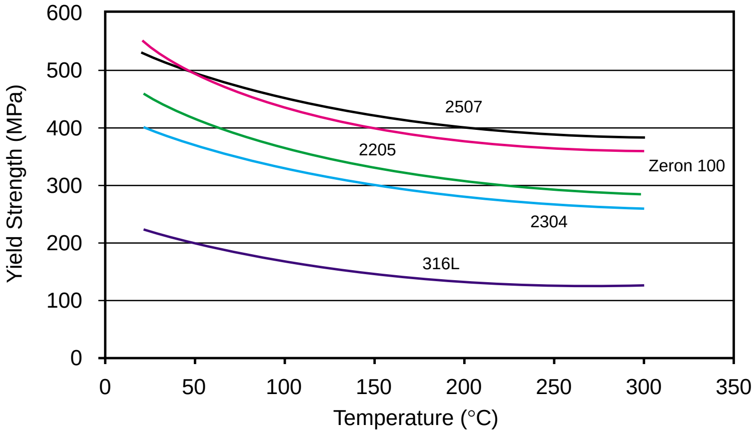


Figure 10. Comparison of Typical Yield Strength of Duplex Stainless Steels and Type 316L Between Room Temperature and 300°C (572°F) (Source: Producer Data Sheets)

Grade	Min. Elongation (Pct.)
2304	25
2205	25
25 Cr Duplex	15
Superduplex	15
304/304L	40
316/316L	40

Table 5. Comparison of the Ductility of Duplex and Austenitic Stainless Steels According to the Requirements of ASTM A 240

Despite the high strength of duplex stainless steels, they exhibit good ductility and toughness. Compared with carbon steel or ferritic stainless steels, the ductile-to-brittle transition is more gradual. Duplex stainless steels retain good toughness even to low ambient temperatures, for example, -40°C/F; however, ductility and toughness of duplex stainless steels are lower than those of

Installation of Insulated 24 inch 2205 Pipe on Vertical Support Members in Prudhoe Bay, Alaska (Source: Arco Exploration and Production Technology)

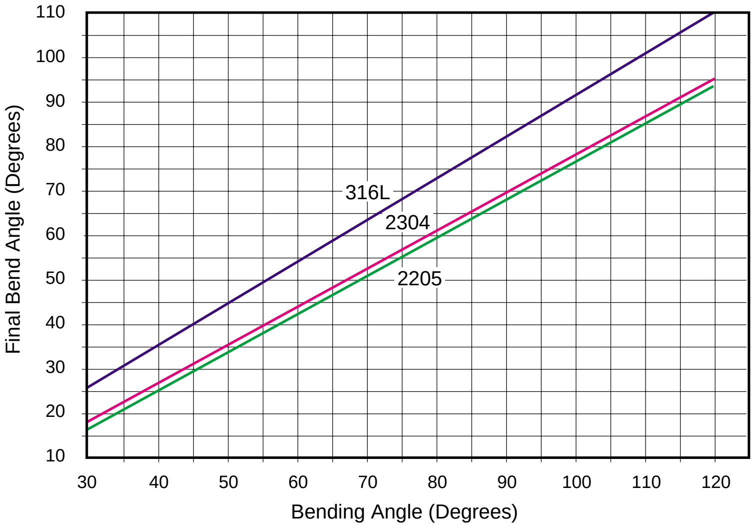


Figure 11. Comparison of Springback of Duplex Stainless Steels and Type 316L for 2 mm (0.079 inch) Thick Sheet (Source: AvestaPolarit)

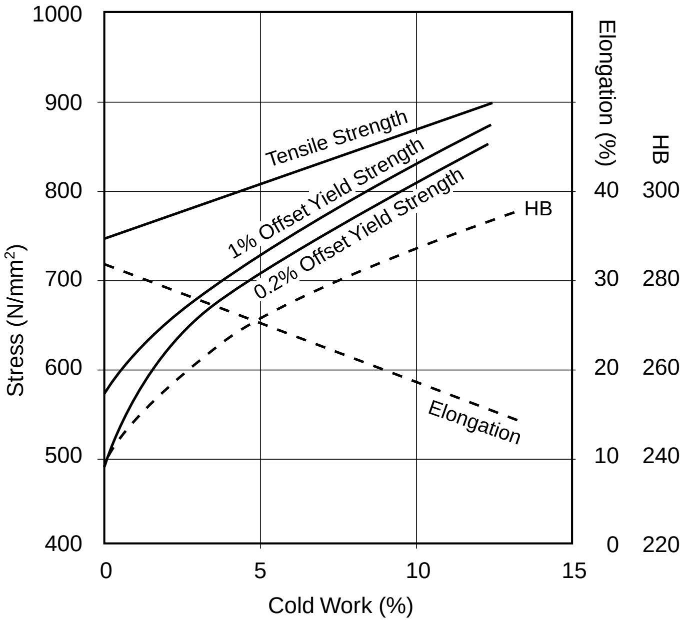


Figure 12. Effect of Cold Work on the Mechanical Properties of 2205 Duplex Stainless Steel (Source: AvestaPolarit)

austenitic stainless steels. Austenitic stainless steels typically do not show a ductile-to-brittle transition and maintain excellent toughness down to cryogenic temperatures. A comparison of minimum elongation in the tensile test for the standard austenitic and the duplex stainless steels is given in Table 5.

While the high yield strength of duplex stainless steel can be used to an advantage in lighter gauge designs, it can also pose challenges during fabrication. Because of their higher strength, plastic deformation requires higher forces. The springback in bending operations is larger than with austenitic stainless steels because of the higher bending forces required for duplex stainless steels. A springback comparison of two duplex stainless steels and Type 316L austenitic stainless steel is shown in Figure 11.

Because of their higher hardness and the high work hardening rate, duplex stainless steels reduce the tool life in machining operations or require increased machining times compared with standard austenitic grades. Annealing cycles may be needed between forming or bending operations because the ductility of duplex stainless steels is more quickly exhausted than that of austenitic stainless steels. The effect of cold work on the mechanical properties of 2205 is shown in Figure 12.

8. PHYSICAL PROPERTIES

Ambient temperature physical properties for a selection of duplex stainless steels are given in Table 6, and selected elevated temperature values are given in Table 7. Data are included for carbon steel and austenitic stainless steels for comparison.

Name	UNS No.	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	x10⁶ psi
Carbon Steel	G10200	7.64	0.278	447	0.107	0.10	3.9	207	30.0
Type 304	S30400	7.98	0.290	502	0.120	0.73	28.7	193	28.0
Type 316	S31600	7.98	0.290	502	0.120	0.75	29.5	193	28.0
Type 329	S32900	7.70	0.280	460	0.110	0.80	31.5	200	29.0
3RE60	S31500	7.75	0.280	482	0.115	–	–	200	29.0
2304	S32304	7.75	0.280	482	0.115	0.80	31.5	200	29.0
2205	S31803	7.85	0.285	482	0.115	0.80	31.5	200	29.0
DP-3	S31260	7.80	0.281	502	0.120	–	–	200	29.0
UR 47N	S32750	7.85	0.285	480	0.114	0.80	31.5	205	29.7
Ferralium 255	S32550	7.81	0.282	488	0.116	0.84	33.1	210	30.5
DP-3W	S39274	7.80	0.281	502	0.120	–	–	200	29.0
Zeron 100	S32760	7.84	0.281	–	–	0.85	33.5	190	27.6
52N+	S32520	7.85	0.280	450	0.108	0.85	33.5	205	29.7
2507	S32750	7.79	0.280	485	0.115	0.80	31.5	200	29.0

Table 6. Ambient Temperature Physical Properties of Duplex Stainless Steels Compared with Carbon Steel and Austenitic Stainless Steels (Source: Producer Data Sheets)

Name	UNS No.	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 as a Function of Temperature in Units of GPa (ksi x 1,000)							
Carbon steel	G10200	207(30.0)	–	–	–	–	–
Type 304	S30400	193(28.0)	192(27.9)	183(26.6)	177(25.7)	168(24.4)	159(23.0)
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	S32750	205 (29.7)	194 (28.1)	181 (26.2)	170 (24.7)	–	–
Ferralium 255	S32550	210 (30.5)	200 (29.9)	198 (28.7)	192 (27.8)	182 (26.4)	170 (24.7)
UR 52N+	S32520	205	185	185	1700	-–	–
2507	S32750	200 (29.0)	190 (27.6)	180 (26.1)	170 (24.7)	160 (23.2)	150 (21.8)
Coefficient of Thermal Expansion – From 20°C (68°F) to T in Units of /°C x 10^{-6} (°F x 10^{-6})							
Carbon steel	G10200	NA	12.1(6.70)	13.0 (7.22)	–	14 (7.78)	–
Type 304	S30400	NA	16.4(9.10)	16.9(9.40)	17.3(9.60)	17.6(9.80)	18.0(10.0)
Type 329	S32900	NA	10.9(6.10)	11.0(6.30)	11.6(6.40)	12.1(6.70)	12.3(6.80)
3RE60	S31500	NA	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
2304	S32304	NA	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
2205	S31803	NA	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
UR 47N	S32750	NA	12.5 (6.94)	13.0 (7.22)	13.5 (7.50)	–	–
Ferralium 255	S32550	NA	12.1 (6.72)	12.6 (7.00)	13.0 (7.22)	13.3 (7.39)	13.6 (7.56)
UR 52N+	S32520	NA	12.5 (6.94)	13.0 (7.22)	13.5 (7.50)	–	–
2507	S32750	NA	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)	14.5 (8.06)	15.0 (8.33)
Thermal Conductivity as a Function of Temperature in Units of W/m °C (Btu in/hr ft^2 °F)							
Carbon Steel	G10200	52 (360)	51 (354)	49 (340)	–	43 (298)	–
Type 304	S30400	14.5(100)	16.2(112)	17.8(123)	19.6(135)	20.3(140)	22.5(155)
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)
UR 47N	S32750	17.0 (118)	18.0 (124)	19.0 (132)	20.0(138)	–	–
Ferralium 255	S 32550	13.5 (94)	15.1 (105)	17.2 (119)	19.1 (133)	20.9 (145)	22.5 (156)
UR 52N+	S32520	17.0 (118)	18.0 (124)	19.0 (132)	20.0 (138)	–	–
2507	S32750	16.0 (110)	17.0 (118)	19.0 (132)	20.0 (138)	21.0 (147	22.0 (153)

Table 7. Elevated Temperature Physical Properties of Duplex Stainless Steels Compared with Carbon Steel and Austenitic Stainless Steels (Source: Producer Data Sheets)

In all cases, differences in physical property values among the duplex grades are very slight and probably reflect differences in test procedures. The physical properties of the duplex grades all fall between those of the austenitic stainless steels and carbon steels, but tend to be closer to those of the stainless steels.

9. CUTTING

The same processes typically applied to austenitic stainless steels and to carbon steels may be used to cut duplex stainless steels, but some adjustments in parameters will be necessary to accommodate the differences in mechanical properties and thermal response.

9.1 Sawing

Because of their high strength, high work hardening rate, and the virtual absence of inclusions that would serve as chipbreakers, the duplex stainless steels are more difficult to saw than carbon steels. Best results are achieved with powerful machines, strong blade alignment systems, coarse-toothed blades, slow-to-moderate cutting speeds, heavy feeds, and a generous flow of coolant, ideally a synthetic emulsion which provides lubrication as well as cooling, delivered so that the blade carries the coolant into the work piece. The cutting speeds and feeds should be similar to those used for Type 316 austenitic stainless steel.

9.2 Shearing

Duplex stainless steels are sheared on the same equipment used to shear Types 304 and 316, usually with no special adjustments. However, because of the greater shear strength of the duplex stainless steels, the power of the shear must be greater or the sheared thickness reduced.

The shear strength of stainless steels equals 0.577 times ultimate tensile strength for both hot rolled plate and for cold rolled sheet. Duplex stainless steels behave in the way that would be expected of a thicker piece of Type 316 stainless steel depending on the ratio of their actual shear strengths. Therefore, the maximum thickness of 2304 or 2205 duplex stainless steel that can be cut on a particular shear is about 85% of that for Type 304 or 316. The maximum thickness of super duplex stainless steels that can be cut on a particular shear is about 65% of that for these common austenitic grades.

9.3 Punching

Punching may be viewed as a difficult form of shearing. The high strength, rapid work hardening, and resistance to tearing make duplex stainless steels relatively difficult to punch and abrasive to the tooling. Experience in this operation is limited, but the guideline that the duplex stainless steel will behave as an austenitic stainless steel of twice the thickness provides a good starting point for this operation. The higher alloyed duplex stainless steels with the higher levels of nitrogen are disproportionately more difficult.

9.4 *Plasma and Laser Cutting*

The duplex stainless steels are routinely processed with the same plasma cutting and laser cutting equipment used for processing austenitic stainless steels. The slightly higher thermal conductivity and the typically low sulfur content in duplex stainless steels may slightly affect the optimal parameters, but acceptable results can be achieved without special adjustment.

The HAZ of the plasma cutting process is typically narrow, about 0.25 mm (0.010 inch) because the cut is made rapidly with one pass with rapid cooling from the plate or sheet. The normal machining of a weld preparation and the melting of adjacent base metal during welding will remove the HAZ of the plasma cutting process.

10. FORMING

10.1 *Hot Forming*

Duplex stainless steels show excellent hot formability with relatively low forming loads up to at least 1230°C (2250°F). However, if hot forming takes place at too low a temperature, deformation accumulates in the weaker but less ductile ferrite, which can result in cracking of the ferrite in the deformed region. Additionally, a large amount of sigma phase can be precipitated when the hot working temperature drops too low.

Most producers recommend a maximum hot forming temperature between 1100°C (2010°F) and 1150°C (2100°F). This upper temperature limit is suggested because of the effect of high temperatures on the dimensional stability of a part and the increased tendency to scale formation with increasing temperature. At high temperatures, duplex stainless steel becomes soft and fabricated pieces such as vessel heads or piping warp or sag in the furnace if they are not supported. At these temperatures the steel may also become too soft for certain hot forming operations. Table 8 summarizes the suggested temperature ranges for hot forming and the minimum soaking temperatures. It is not necessary or always advisable, to start hot working at the highest temperature in the range. However, the steel should reach at least the minimum soaking temperature before hot working. The furnace should be charged hot, to avoid slow heating through the temperature range where sigma phase is formed.

Grade	Suggested Hot Forming Temperature Range		Minimum Soaking Temperature	
	°C	°F	°C	°F
Lean Duplex (2304)	1150 to 950	2100 to 1740	980	1800
2205	1230 to 950	2250 to 1740	1040	1900
25 Cr Duplex	1230 to 980	2250 to 1795	1040	1900
UR 52N+	1230 to 1000	2250 to 1830	1080	1975
Zeron 100	1230 to 1000	2250 to 1830	1100	2010
2507	1230 to 1025	2250 to 1875	1050	1920
Types 304/316	1205 to 925	2200 to 1700	1040	1900

Table 8. Hot Forming Range and Minimum Soaking Temperature for Duplex Stainless Steels (common austenitic grades are included for comparison) (Source: Producer Data Sheets)

Temperature uniformity is important in successful hot forming of duplex stainless steel. If the shape of the workpiece is not compact, the edges may be significantly cooler than the bulk, and there is a risk of cracking in these cooler regions. To avoid this cracking, it is necessary to reheat the piece when these local regions are in danger of cooling below the minimum hot working temperature. The lower end of the suggested hot forming temperature range may be extended somewhat, but only if the temperature uniformity within the workpiece, especially the edges or thinner sections, is maintained.

With heavy sections, it is appropriate to consider whether water quenching is fast enough to prevent precipitation of intermetallic phases. For plate sections, this thickness limit is about 125 mm (5 inches) for 2205 plate in the high nitrogen S32205 version, and somewhat thinner cross sections for the lower nitrogen range permitted in S31803. For a simple cylindrical shape, the diameter limit is about 375 mm (15 inches). If the finished part is to have a through-penetrating inside diameter, the cooling of the part after final annealing is greatly improved when this opening is pierced or machined prior to the final heat treatment.

10.1.1 *Solution Annealing*

After hot forming, it is necssary to perform a full solution anneal followed by a rapid quench to fully restore the mechanical properties and corrosion resistance. The workpiece should be brought above the minimum solution annealing temperature and heldlong enough to dissolve any intermetallic precipitates. A conservative guideline is that the holding time should be comparable to the total time that the piece was held in the 650-980°C (1200-1800°F) temperature range subsequent to the previous full anneal. The part should be water quenched from the solution temperature. It should not be allowed to spend several minutes in the 818-1040°C (1500-1900°F) range while being transferred to the quench location after this final anneal. Minimum solution annealing temperatures for duplex stainless steels are summarized in Table 9.

Grade	Minimum Annealing Temperature	
	°C	°F
Lean Duplex (2304)	980	1800
2205	1040	1900
25 Cr Duplex	1040	1900
Superduplex (depending on grade)	1050 to 1100	1925 to 2010

Table 9. Minimum Solution Annealing Temperatures for Duplex Stainless Steels (Source: Producer Data Sheets and ASTM A 480)

At solution annealing temperatures, duplex stainless steels are quite soft, and warping and distortion are likely if the work piece is not adequately supported. This can be a significant problem in tubular products, especially those with large diameters and thin walls. Re-forming or straightening warped duplex products is more difficult than austenitic stainless steels because of the high ambient temperature strength of duplex stainless steels. Attempts to minimize this distortion by short annealing times, slow heating into the annealing temperature range, or use of a lower than recommended annealing temperature may not dissolve intermetallic phases or may cause the formation of additional amounts of intermetallic phases. This will lower corrosion resistance and reduce toughness.

Slitting of Duplex Stainless Steel (Source: Krupp Thyssen Nirosta)

The use of stress relief treatments to reduce the cold work of forming or straightening operations is not advisable. The duplex stainless steels inherently have very good chloride stress corrosion cracking resistance and this can be only marginally improved by reducing residual cold work. There is no satisfactory temperature below the solution annealing temperature at which stress relief can be employed without the danger of formation of intermetallic phases which will lower corrosion resistance and reduce toughness.

10.2 *Warm Forming*

It is sometimes useful to mildly warm a steel piece to aid forming operations. However, prolonged heating of duplex stainless steels above 315°C (600°F) may result in some loss of ambient temperature toughness or corrosion resistance due to 475°C (885°F) embrittlement (see Figure 4). At higher temperatures, there is the risk of a more rapid and detrimental effect from precipitation of intermetallic phases. Because these phases do not interfere with the forming process, it is possible to warm the duplex stainless steels for forming. However, when the working temperature exceeds about 300°C (570°F), warm forming should be followed by a full solution anneal and rapid quench (see Table 9).

10.3 *Cold Forming*

Duplex stainless steels have shown good formability in a variety of fabrications. Most applications of duplex stainless steels require relatively simple forming, such as the rolling of cylindrical sections, press forming, and vessel and tank head forming by pressing or rolling. In most of these applications, a primary concern is the high strength of duplex stainless steel and the power of the forming equipment. A typical first estimate is that a duplex stainless steel will respond to forming similar to a 300-series

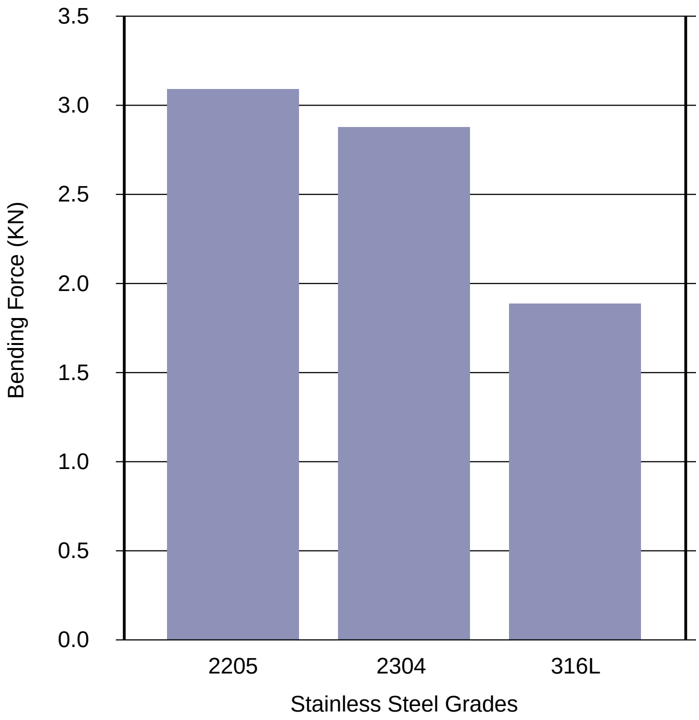


Figure 13. Minimum Force Required to Begin Plastic Deformation in Bending of 2304, 2205, and 316L Test Samples 50 mm (1.97 inch) Wide and 2 mm (0.079 inch) Thick (Source: AvestaPolarit)

austenitic grade at twice the thickness. A comparison of the minimum force required to begin plastic deformation in bending is shown in Figure 13 for several stainless steels.

The high strength of the duplex stainless steels can still pose problems. Even when the equipment has sufficient power, allowance must be made for the higher springback caused by the high strength of the duplex grades (see Figure 11).

The lower ductility of duplex stainless steels compared with austenitic stainless steel must also be taken into account. Duplex grades have a minimum required elongation in most specifications of 15 to 25% in comparison with the 40% minimum elongation required for many austenitic grades. While actual elongations may be somewhat greater, the relationship suggested by these minimums is appropriate and is a good guide for cold forming operations. The duplex grades require a more generous bend radius than austenitic grades or need intermediate anneals in severe or complex forming because of their lower ductility.

10.4 Press Forming

Duplex stainless steels are readily press formed. However, in many cases the duplex stainless steel is a replacement for a part that has been optimized for an austenitic stainless steel, carbon steel, or a ferritic stainless steel. The first trial is often made without a change of thickness. While the higher strength of the duplex grade would justify a reduction of thickness, the cost of redesign may postpone taking advantage of the cost and weight savings. In most cases, reducing the thickness would actually facilitate forming. Nevertheless, in the initial forming trials of a duplex stainless steel, it is often regarded as being somewhat “difficult”.

When the comparison is made with forming of carbon steel or ferritic stainless steel, the problems relate almost entirely to strength and springback. The duplex stainless steels are about 30 to 50% higher in yield strength. The ferritic steels show only limited work hardening and the running load can be relatively low. The duplex stainless steels start strong and get stronger, so springback will be a problem. On the other hand, the ductility of the duplex stainless steels is greater, and overbending will compensate for the springback. Also, in comparison with ferritic steels, the duplex stainless steels are less sensitive to the direction of bending relative to the rolling direction. The duplex stainless steels show some anisotropy of mechanical properties because of the rolling of the duplex structure, but its practical effect is smaller than with ferritic steels because of the greater ductility of the duplex.

The forming of ferritic stainless steel sheet often takes advantage of deep drawing. In this operation the sheet deforms in the plane of the sheet with minimal thinning as the sheet is drawn into the die. In ferritic stainless steels, this type of formability is greatly enhanced by metallographic texture development. Little attention has been given to this behavior in duplex stainless steel sheet, but it seems unlikely that the same degree of favorable behavior can be achieved in the duplex structure. The technology of deep drawability for duplex stainless steel is likely to be significantly different from either ferritic or austenitic stainless steel practices.

In the more frequent case, where duplex stainless steels are compared with austenitic stainless steels, adjustments must deal with both the higher strength and lower ductility of the duplex grades. The duplex stainless steel properties may be estimated as the average of the properties of the ferritic and austenitic phases. So while the duplex steel is more ductile than a ferritic stainless steel, it lacks the “top-end” ductility and work hardening that permits austenitic stainless steels to be stretchformed so extensively.

It has not been common to introduce duplex grades into applications requiring severe sheet forming, but an example of the limitation of duplex stainless formability is useful. One manufacturer encountered significant breakage when stamping duplex stainless steel for a flat plate heat exchanger using the same dies used for austenitic stainless steel sheet. The duplex stainless steel split at the high point of the pattern where deformation was greatest.

10.5 Spinforming

The strength and corrosion resistance of duplex stainless steels, especially their chloride stress corrosion cracking resistance, make them candidates for applications in rotating parts such as centrifuges. Spinforming is an economical and frequently used method to make these parts.

Spinforming is a complex operation with significant dependence on equipment and the skills of the operator. Austenitic stainless steels are regularly spinformed, but they often require multiple intermediate anneals to restore ductility during the forming sequence. The limited experience in spinforming of duplex stainless steels indicates that the forming loads are very high, especially when no reduction in thickness is made relative to austenitic stainless steel. With sufficient power and strength in the equipment, the duplex grades spinform well, but their lower ductility may require more frequent intermediate anneals than austenitic grades. Flatness and minimizing the “crown” of the starting blank are important for spinning response. However, heavy mechanical flattening, for example, by roller leveling, may exhaust a portion of the ductility for the first stage of spinforming. Some duplex stainless steel components have been spinformed at temperatures above 650°C (1200°F) followed by full solution annealing.

Turning Operation on a 2205 Enhanced Machining Grade (Source: AB Sandvik)

11. MACHINING DUPLEX STAINLESS STEELS

The duplex stainless steels have yield strengths typically about twice that of the non-nitrogen alloyed austenitic grades, and their initial work hardening rate is at least comparable to that of the common austenitic grades. The chip formed when machining duplex stainless steel is strong and abrasive to tooling, and especially so for the more highly alloyed duplex grades. Because the duplex stainless steels are produced with as low a sulfur content as possible, there is little to aid chip breaking.

For these reasons duplex stainless steels are somewhat more difficult to machine than the 300-series austenitic stainless steels of similar corrosion resistance. Higher cutting forces are required and more rapid tool wear is typical of duplex stainless steel machining. The more difficult machinability compared to austenitics is most noticeable when using carbide tooling. This is illustrated in Figure 14

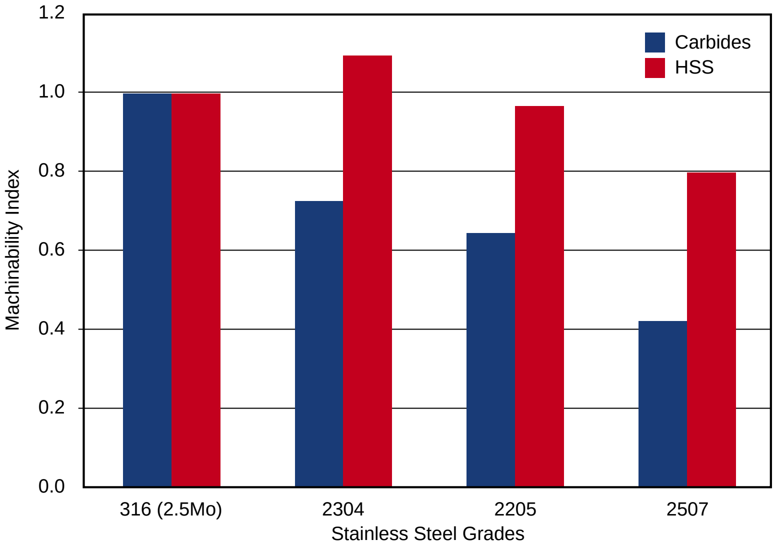


Figure 14. Relative Machinability of Duplex Stainless Steels Compared with Type 316 (2.5Mo) for Cemented Carbide Tooling and for High Speed Steel Tooling (Source: AvestaPolarit)

with a relative machinability index comparison for some duplex stainless steels and Type 316.

11.1 General Guidelines for Machining Duplex Stainless Steels

The following guidelines for machining are generally applicable to all stainless steels. However, it is appropriate to emphasize the importance of these guidelines even more strongly for duplex stainless steels.

- Use powerful, rigid machines with extremely strong, rigid mounting of the tools and work piece. (Cutting forces for similar cuts will typically be much higher for duplex stainless steels than for corresponding austenitic stainless steels.)
- Minimize vibration by keeping the tool extension as short as possible.
- Use a nose radius on the tool no larger than necessary.
- Favor an edge geometry for carbides that provides a “sharp” edge while still providing adequate strength.
- Design machining sequences to always provide for a depth of cut below the work hardened layer resulting from prior passes.
- Use adequate but not excessive speed to avoid built-up edge and rapid wear.
- Change tooling inserts or re-grind at scheduled intervals to insure sharp cutting edges.
- Use generous flows of coolant/ lubricant using cutting oils or emulsions with extreme pressure (EP) additives.
- Use coated carbide inserts with positive chipbreaker geometry.

11.2 Turning and Facing

Guidelines for turning and cutting are provided in Figure 15 and Table 10.

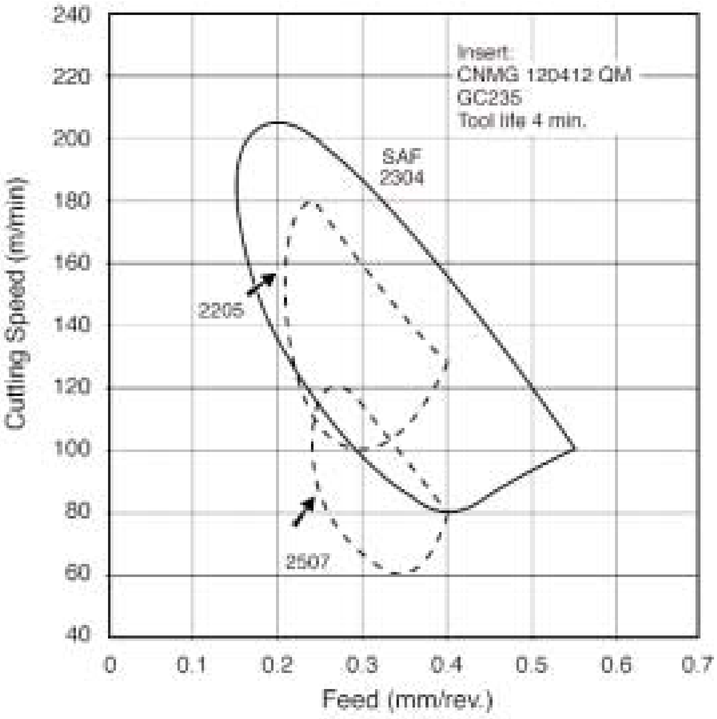


Figure 15. Comparison of Machining Parameters for Turning Duplex Stainless Steels with a Cemented Carbide Insert with a Tool Life of Four Minutes (Source: Sandvik Steel)

Table 10. Machining Guidelines for Face Turning Duplex Stainless Steels (Source: AvestaPolarit)

Stainless Steel (or machining data)	Carbides				High Speed Steel Tools	
	Roughing		Finishing			
	Speed (m/min)	Speed (sfm)	Speed (m/min)	Speed (sfm)	Speed (m/min)	Speed (sfm)
Lean duplex (2304)	120-160	400-525	150-210	500-680	150-210	500-680
2205	90-120	300-400	120-160	400-525	120-160	400-525
Superduplex	50-70	165-230	70-105	230-350	70-105	230-350
Feed (per turn)	0.3-0.6mm	0.012-0.024 in	0.3-0.6mm	0.002-0.012 in.	0.3-0.6mm	0.002-0.012
Depth of cut	2-5 mm	0.080-0.200 in.	2-5 mm	0.020-0.080	2-5 mm	0.020-0.080
Grade	2304, 2205: ISO P20-P35 (C5) Superduplex: ISO P30-P50		2304,2205: ISO P10-P15 (C6 - C7) Superduplex: ISO P25-P35		High Quality	

11.3 *Face Milling with Cemented Carbides*

Guidelines for face milling duplex stainless steels with cemented carbides are provided in Table 11.

- Use coated inserts or a tough grade of insert for roughing. A harder insert may be used for finishing when finer finish is required.
- Use climb milling with an average chip thickness of at least 0.1 mm (0.004 inch). Adjust feed by a proportional factor of 1.0 to 0.7 as the entering angle is increased from 45° to 90°.
- Use no coolant, particularly during roughing, to obtain good chip ejection from the tool.

11.4 *Twist Drilling with High Speed Steel Drills*

Guidelines for twist drilling duplex stainless steels with HSS drills are provided in Tables 12 and 13.

- Drill geometry: point angle 130°; self-centering drill point geometry is recommended; web thinning for large diameter drills is recommended.
- Coolant: 10% emulsion with ample flow to tool point; for depth greater than 2x diameter, remove chips by periodic withdrawal with flooding of coolant in hole.
- Increased speeds: TiN coating permits 10% increase; through drill coolant permits 10-20% increase.

Stainless Steel	**Roughing**		**Finishing**	
(or machining data)	**Speed (m/min)**	**Speed (sfm)**	**Speed (m/min)**	**Speed (sfm)**
Lean duplex (2304)	100-130	330-425	130-150	425-525
2205	50-80	165-260	80-110	260-360
Superduplex	30-50	100-165	50-70	165-230
Feed (per tooth)	0.2-0.4 mm	0.008-0.075 in.	0.1-0.2 mm	0.004-0.008 in.
Depth of cut	2-5 mm	0.080-0.200 in.	1-2 mm	0.040-0.080 in.
Carbide Grade	2304, 2205: ISO P20-P40 Superduplex: ISO P25-P40		2304, 2204: ISO P10-P25 Superduplex: P20-P30	

Table 11. Machining Guidelines for Face Milling Duplex Stainless Steels with Cemented Carbides (Source: AvestaPolarit)

Drill Diameter (mm)	**Speed (m/min)**			**Feed (mm/rev)**	
	Lean duplex (2304)	**2205**	**Superduplex**	**2304 / 2205**	**Superduplex**
1-3	6-10	6-8	5-9	0.05	0.04
5	6-10	10-12	9-11	0.10	0.08
10	12-15	10-12	9-11	0.20	0.15
15	12-15	10-12	9-11	0.25	0.20
20	12-15	10-12	9-11	0.30	0.25
30	12-15	10-12	9-11	0.35	0.30
40	12-15	10-12	9-11	0.40	0.35

Table 12. High Speed Steel Twist Drilling Parameters for Duplex Stainless Steels in SI Units (Source: AvestaPolarit)

Drill Diameter (in.)	**Speed (sfm)**			**Feed (in./rev)**	
	Lean duplex (2304)	**2205**	**Superduplex**	**2304 / 2205**	**Superduplex**
0.040-0.120	20-33	20-25	16-25	0.002	0.0015
0.20	33-40	33-40	30-36	0.004	0.003
0.40	40-50	33-40	30-36	0.008	0.006
0.60	40-50	33-40	30-36	0.010	0.008
0.80	40-50	33-40	30-36	0.012	0.010
1.20	40-50	33-40	30-36	0.014	0.012
1.60	40-50	33-40	30-36	0.016	0.014

Table 13. High Speed Steel Twist Drilling Parameters for Duplex Stainless Steels in English Units (Source: AvestaPolarit)

12. WELDING DUPLEX STAINLESS STEELS

12.1 General Welding Guidelines

12.1.1 Differences Between Duplex and Austenitic Stainless Steels

When there are problems with welding of austenitic stainless steels, the problems are most frequently associated with the weld metal itself, especially the tendency for hot cracking in a fully or predominantly austenitic solidification. For the more common austenitic stainless steels, adjusting the composition of the filler metal to provide a significant ferrite content minimizes these problems. For the more highly alloyed austenitic stainless steels where the use of a nickel-base filler metal is necessary and austenitic solidification is unavoidable, the problem is managed by low heat input, often requiring many passes to build up the weld.

Because duplex stainless steels have very good hot cracking resistance, hot cracking is rarely a consideration when welding these steels. The problems of most concern in duplex stainless steels are associated with the HAZ, not with the weld metal. The HAZ problems are loss of corrosion resistance, toughness, or post-weld cracking. To avoid these problems, the welding procedure should focus on minimizing total time at temperature in the “red hot” range rather than managing the heat input for any one pass. Experience has shown that this approach can lead to procedures that are both technically and economically optimal.

With this introduction in mind, it is possible to give some general guidelines for welding of duplex stainless steels and then to apply this background and those guidelines to specific welding methods.

12.1.2 Selection of Starting Material

The response of duplex stainless steels to welding may be substantially changed by variations in chemistry or processing. The importance of the base metal containing sufficient nitrogen has been repeatedly emphasized. If the starting material is cooled slowly through the 705 to 980°C (1300 to 1800°F) range, or if it is allowed to air cool into this range for a minute or so prior to water quenching, then those actions have used up some of the “time on the clock” for the welder to complete the weld without any detrimental precipitation reactions occurring. It is important that the metallurgical condition of the material used in actual fabrication is the same quality, with regard to composition and production practice, as the material used to qualify the welding procedure. The selection by composition and the specification of appropriate tests for the starting material were presented in the section on end line specification and quality control (Page 14).

12.1.3 Cleaning Before Welding

The admonition to clean all regions that are to be heated prior to welding applies not just to duplex stainless steels, but to all stainless steels. The chemistries of the base metal and the filler metal have been developed assuming that there are no additional sources of contamination. Dirt, grease, oil, paint, and sources of moisture of any sort will interfere with welding operations and adversely affect the corrosion resistance and mechanical properties of the weldment. No amount of procedure qualification is effective if the material is not thoroughly cleaned before the weld.

12.1.4 Joint Design

For duplex stainless steels, a weld joint design must facilitate full penetration and avoid undiluted base metal in the solidifying weld metal. It is best to machine rather than grind the weld edge preparation to provide uniformity of the land thickness or gap. When grinding must be done, special attention should be given of uniformity of

2205 Oxygen Delignification Reactor, Enterprise Steel Fab, Kalowna, Prince George, British Columbia, Canada (Source: AvestaPolarit) the weld preparation and the fit-up. Any grinding burr should be removed to maintain complete fusion and penetration. For an austenitic stainless steel, a skilled welder can overcome some deficiencies in joint preparation by manipulation of the torch. For a duplex stainless steel, some of these techniques may cause a longer than expected exposure in the harmful temperature range, leading to results outside of those of the qualified procedure.

Some joint designs used with duplex stainless steels are described in Figure 16. Other designs are possible provided they assure full penetration welds and minimize the risk of burn-through.

12.1.5 *Preheating*

As a general rule, preheating is not recommended because it may be detrimental. It should not be a part of a procedure unless there is a specific justification. Preheating may be beneficial when used to eliminate moisture from the steel as may occur in cold ambient conditions or from overnight condensation. When preheating to deal with moisture, the steel should be heated to about 95°C (200°F) uniformly and only after the weld preparation has been cleaned. Preheating may also be beneficial if the weld is one of those exceptional cases where there is a risk for forming a highly ferritic HAZ because of very rapid quenching. These cases are relatively rare but may involve heavy section plate.

12.1.6 *Heat Input and Interpass Temperature*

Duplex stainless steels can tolerate relatively high heat inputs. The duplex solidification structure of the weld metal is resistant to hot cracking, much more so than that of austenitic weld metals. Duplex stainless steels, with higher thermal conductivity and lower coefficient of thermal expansion, do not have the same high intensity of local thermal stresses at the welds as austenitic stainless steels. While it is necessary to limit the severity of restraint on the weld, hot cracking is not a common problem.

Exceedingly low heat input may result in fusion zones and HAZ which are excessively ferritic with a corresponding loss of toughness and corrosion resistance. Exceedingly high heat input increases the danger of forming intermetallic phases.

To avoid problems in the HAZ, the weld procedure should allow rapid cooling of this region after welding. The temperature of the work piece is important because it provides the largest effect on cooling of the HAZ. As a general guideline, the maximum interpass temperature is limited to 150°C (300°F). That limitation should be imposed when qualifying the weld procedure, and the production welding should be monitored to assure that the interpass temperature is no higher than that used for the qualification. Electronic temperature probes and thermocouples are the preferred instruments for monitoring the interpass temperature. It would not be conservative in the welding procedure qualification to allow the trial piece for a multipass weld to come to a lower interpass temperature than can be reasonably or economically achieved during actual fabrication. When a large amount of welding is to be performed, planning the welding so there is enough time for cooling between passes is good, economical practice.

12.1.7 *Postweld Heat Treatment*

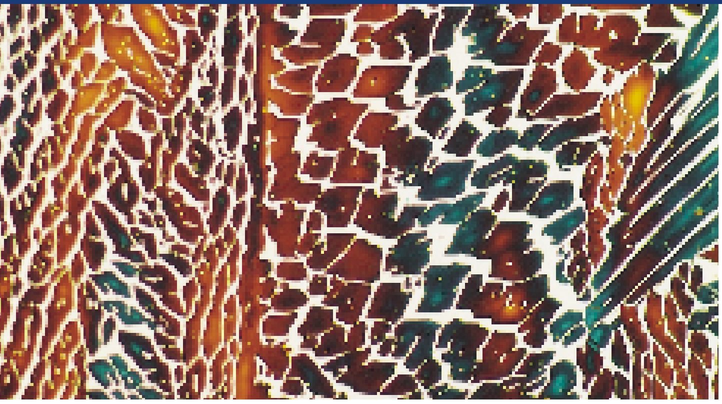
Postweld stress relief is not needed for duplex stainless steels and is likely to be harmful because the heat treatment may precipitate intermetallic phases or alpha prime (475°C/885°F) embrittlement causing a loss of toughness and corrosion resistance.

Any postweld heat treatment should be a full solution anneal followed by water quenching (see Table 9).

If there is to be a full solution anneal and quench subsequent to welding, for example in the manufacturing of a fitting, then that heat treatment should be considered a part of the welding procedure. The anneal can eliminate the problems associated with excessive ferrite and intermetallic phases, and the manufacturing process can tolerate some of these less desirable conditions as an intermediate state prior to the final anneal.

12.1.8 *Desired Phase Balance*

The phase balance of duplex stainless steels is often said to be “50-50”, equal amounts of austenite and ferrite. However, that is not strictly true because modern duplex stainless steels are balanced to have 40-50% ferrite with the balance being austenite. It is generally agreed that thec-



Metallographic Structure of 2205 Duplex Weld Metal, 500x (Source: Lincoln Smitweld bv)

chacteristic benefits of duplex stainless steels are achieved when there is at least 25% ferrite with the balance austenite. In some of the welding methods, particularly those relying upon flux shielding, the phase balance has been adjusted toward more austenite to provide improved toughness, offsetting the loss of toughness associated with oxygen pickup from the flux. The toughness of these filler metals is well below the high values that are possible for an annealed plate or pipe, but the toughness of the weld metal can still be adequate for the intended service. None of the welding methods will produce toughness as high as that achieved in the fully annealed wrought product. Restricting weld metal ferrite content to greater than the minimum required for mill annealed duplex stainless steel may result in an unnecessary limitation on applicable welding methods.

The phase balance in the HAZ, being the original wrought plate or pipe plus an additional thermal cycle, is usually slightly more ferritic than the original material. Accurate metallographic determination of the phase balance in the HAZ is nearly impossible. If this region is highly ferritic, it may be indicative of the unusual case of extremely rapid quenching leading to excessive ferrite and loss of toughness.

12.1.9 Dissimilar Metal Welds

Duplex stainless steels can be welded to other duplex stainless steels, to austenitic stainless steels, and to carbon and low alloy steels.

Duplex stainless steel filler metals with increased nickel content relative to the base metal are most frequently used to weld duplex stainless steels to other duplex grades.

When welding to austenitic grades, the austenitic filler metals with low carbon and a molybdenum content intermediate between the two steels are typically used; AWS E309MoL/ER309LMo is frequently used for these joints. The same filler metal, or AWS E309L/ER309L, is commonly used to join duplex stainless steels to carbon and low alloy steels. If nickel-base filler metals are used, they should be free of niobium (columbium). Because austenitic stainless steels have lower strength than duplex grades, welded joints made with austenitic filler metals will not be as strong as the duplex base metal.

Table 14 summarizes filler metals frequently used to weld duplex stainless steels to dissimilar metals. These examples show the AWS electrode designation (E), but depending on the process, joint geometry and other considerations, bare wire (AWS designation ER) and flux cored wire may be considered.

	2304	**2205**	**25 Cr**	**Superduplex**
2304	2304 E2209 E309L	E2209	E2209	E2209
2205	E2209	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
25 Cr	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
Superduplex	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
304	E309L E309MoL E2209	E309MoL, E2209	E309MoL, E2209	E309MoL
316	E309MoL E2209	E309MoL, E2209	E309MoL, E2209	E309MoL, E2209
Carbon steel **Low alloy steel**	E309L E309MoL	E309L, E309MoL	E309L, E309MoL	E309L, E309MoL

Table 14. Welding Consumables Used for Dissimilar Metal Welding

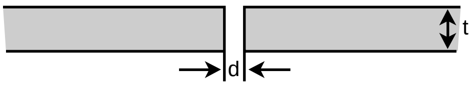
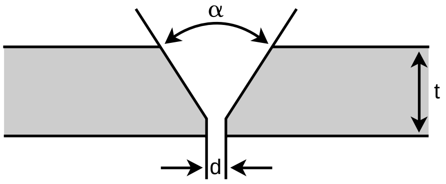
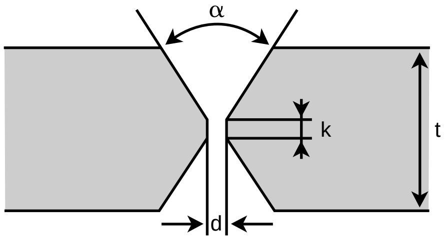
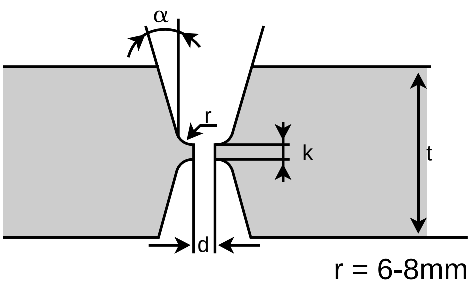
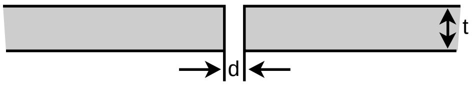
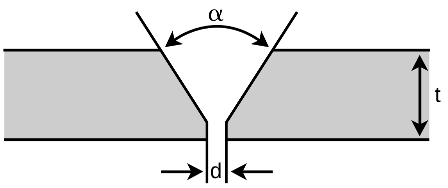
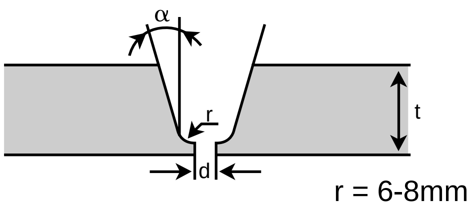
GROOVE	Process	Thickn. th(mm)	GAP d (mm)	ROOT K (mm)	BEVEL α(°)
	GTAW	3 - 5	1 - 3	-	-
	GMAW	3 - 6	1 - 3	-	-
	SMAW	3 - 4	1 - 3	-	-
	SMAW	4 - 15	1 - 3	1 - 2	55 - 65
	GTAW	3 - 8	1 - 3	1 - 2	60 - 70
	GMAW	5 - 12	1 - 3	1 - 2	60 - 70
	SAW	9 - 12	0	5	80
	SMAW	> 10	1.5 - 3	1 - 3	55 - 65
	GMAW	> 10	1.5 - 3	1 - 3	60 - 70
	SAW	> 10	0	3 - 5	90
	SMAW	> 25	1 - 3	1 - 3	10 - 15
	GMAW	> 25	1 - 3	1 - 3	10 - 15
	SAW	> 25	0	3 - 5	10 - 15
	GTAW	> 3	0 - 2	-	-
	GMAW	> 3	0 - 2	-	-
	SMAW	> 3	0 - 2	-	-
	SMAW	3 - 15	2 - 3	1 - 2	60 - 70
	GTAW	2.5 - 8	2 - 3	1 - 2	60 - 70
	GMAW	3 - 12	2 - 3	1 - 2	60 - 70
	SAW	4 - 12	2 - 3	1 - 2	70 - 80
	SMAW	12 - 60	1 - 2	2 - 3	10 - 15
	GTAW	> 8	1 - 2	1 - 2	10 - 15
	GMAW	> 12	1 - 2	2 - 3	10 - 15
	SAW	> 10	1 - 2	1 - 3	10 - 15

Figure 16. Examples of Weld Joint Designs Used with Duplex Stainless Steels. (Source: Usinor Industeel)

12.2 Welding Procedure Qualification

With other stainless steels, the usual qualification testing for weld procedures are fairly simple, with only a limited amount of testing to qualify a material, filler metal, and weld method. With hardness tests and bend tests (looking for martensite and hot cracking, respectively), these qualification tests reflect long experience for what can go wrong with ferritic, martensitic or austenitic steels. Duplex stainless steels are unlikely to have difficulty with these requirements, but these tests are unlikely to find intermetallic phases or excessive ferrite that are possible problems with duplex stainless steels. Also, because of the need to limit the total time at temperature for the HAZ, the properties of duplex grades will be sensitive to section thickness and details of actual welding practice. Therefore, "qualification" must be considered in a broader sense, that is, a demonstration that the welding procedures that will be applied during fabrication will not produce an unacceptable loss of engineering properties, especially toughness and corrosion resistance.

It would be conservative to qualify the welding procedure at every thickness and geometry of welding because the minor differences in setup may be significant in the results achieved in production. However, the complex nature of actual constructions makes such testing costly. Savings are achieved by qualifying the procedures (defined by section, filler, and method) determined to be the most demanding on the duplex stainless steel.

12.3 Welding Methods

The second-generation duplex stainless steels saw significant commercial development beginning in the early 1980s. With only limited understanding of the role of nitrogen in delaying the formation of intermetallic phases, the early views of welding focused on limiting heat input. With such severe limitations on heat input, many of the more economical welding methods with high deposition rates, such as submerged arc welding, were thought to be inappropriate for the duplex stainless steels. However, the properties of the duplex stainless steels are so desirable that much effort was directed to learning how to use the more economical processes. The result has been that virtually all welding processes, except for oxyacetylene because of the associated carbon contamination of the weld, are now applicable to duplex stainless steels.

2205 Pressurized Peroxide Reactor, Assi Domaen, Vallvik, (Source: AvestaPolarit)

12.3.1 Gas Tungsten Arc Welding (GTAW/TIG)

Gas tungsten arc welding (GTAW), sometimes referred to as tungsten inert gas (TIG) welding, is especially useful for short runs of manual welding. It may be automated for simple geometries, but generally it is not economical as the primary procedure for large amounts of welding on large equipment. Because many fabrications will require some GTA welds even when another procedure is the primary welding method, it is generally appropriate to qualify GTAW procedures for repairs or local finishing.

Equipment

GTAW is best performed with a constant current power supply, with a high-frequency circuit to aid in starting the arc. GTA welding should be performed with direct current straight polarity (DCSP), electrode negative. Use of direct current reverse polarity (DCRP) will lead to electrode deterioration.

The electrode should be a 2% thoriated tungsten electrode (AWS specification 5.12 Classification EWTh-2). Arc control is aided by grinding the electrode to a conical point with a vertex angle of 30 to 60 degrees, and with a small flat at the point. The ideal vertex angle for achieving penetration in automatic GTAW should be determined by a few tests in actual production.

Filler Metals

Most filler metals for duplex stainless steel welding are described as "matching", but typically they are overalloyed in nickel with respect to the wrought products that they are said to match. Usually there is about 2-4% more nickel than in the wrought product. The nitrogen content is typically slightly lower in the filler metal than in the base metal. It is generally accepted that the more highly alloyed duplex stainless steel weld fillers are suitable for welding the lower alloyed duplex stainless steel products. The "matching" fillers have been reported to give acceptable results when joining duplex stainless steels to austenitic stainless steels or to carbon and alloy steels.

Mechanized Welding of Large Diameters Duplex Stainless Steel Inside Welding Shack on Cross-Country Pipeline (Source: Arco Exploration and Production Technology)

Shielding

It is essential in GTAW, as in all gas shielded welding processes, that the weld pool be protected from atmospheric oxidation and contamination. Most typically this protection is achieved with the inert gas, argon, a dry welding grade with purity of 99.95% argon or better. It is important that the gas handling system be clean, dry, and free from leaks, and that flow conditions be adjusted to provide adequate coverage, as well as to prevent turbulence and aspiration of air into the shielding gas. Gas flow should be initiated several seconds ahead of striking the arc, and it should be maintained for several seconds after the arc is extinguished, ideally long enough for the weld and HAZ to cool below the oxidation range of the stainless steel. For electrode coverage, suggested flow rates are 12-18 l/min (0.4-0.6 cfm) when using a normal gas diffuser screen (gas lens), and with half that rate required for a normal gas nozzle.

Backing gas (also pure argon) flow rates depend on the root volume, but should be sufficient to assure complete flushing of air and full protection of the weld as indicated by the absence of heat tint. Because argon is heavier than air, the feed should be from the bottom to the top of the enclosed volume, with purging by a minimum of seven times the volume.

Satisfactory welds have been obtained with pure argon, but further improvements are possible. The addition of up to 3% dry nitrogen will aid in retention of nitrogen in the weld metal, particularly of the more highly alloyed duplex stainless steels. While, the nitrogen addition has been found to increase electrode wear, the addition of helium partially offsets this effect.

Additions of oxygen and carbon dioxide to the shielding gas should be avoided because they will reduce the corrosion resistance of the weld. Hydrogen should not be used in the shielding or backing gas because of the possibility of hydrogen embrittlement or hydrogen cracking of the ferrite phase in duplex stainless steels.

The gas handling system and the water cooling system, if the torch is so equipped, should be regularly inspected to ensure that the dry, clean nature of the gas is preserved.

Technique and Parameters

With duplex stainless steels, it is especially important to establish good consistent edge preparation, alignment, and root land or spacing. While austenitic stainless steels may accept some use of welding technique to overcome deficiencies in these areas, the duplex stainless steels risk extended time at temperature when these techniques are used. It is recommended that copper backing bars be avoided if possible, because the duplex stainless steels are sensitive to copper surface contamination.

Any arc strikes outside of the welding zone will create local points of autogenous welding with very high quench rates, resulting in locally high ferrite content and possible loss of corrosion resistance at those points. Arc strikes should be made in the weld joint itself to avoid this problem.

Tacking welds should be made with full gas shielding. There should be no tack weld at the starting point of the root pass. Ideally, to avoid cracking of the root pass associated with tack welds, the root pass weld should be interrupted and the tack weld ground away, or the tack may be partially ground before the root pass. The width of the root gap should be carefully maintained to ensure consistent heat input and dilution in the root pass. The start and finish of the root pass should be ground before the start of filler passes. The work piece should be allowed to cool below 150°C (300°F) between passes to provide for adequate cooling of the HAZ in subsequent passes.

2205 Spool Pieces (Source: Arco Exploration and Production Technology)

For GTAW, the filler metal most commonly used in joining duplex stainless steel is the “matching” filler, somewhat overalloyed with nickel. The matching fillers for the more highly alloyed duplex stainless steels, for example, the superduplex filler for 2205 base metal welds, have been used successfully. Wire sizes of 1.6, 2.4, and 3.2 mm (1/16, 3/32, and 1/8 inch) diameter are commonly used. Filler wire should be clean and dry, and should be stored in a covered container until use. Best results are obtained when the welding is done in the flat position. The torch should be maintained as near as possible to vertical to minimize aspiration of air into the shielding gas.

There is substantial freedom in the selection of heat input to deal with a wide range of material thickness and joint design. The heat input is typically in the range of 0.5-2.5 kJ/mm (15 to 65 kJ/inch) as calculated by the following formula:

Heat input = (V x A x 60) / (S x 1000)

where V = voltage (volts)

A = current (amperes)

S = travel speed (in./min)

GTAW, when made with good shielding and appropriate management of time at temperature, provides a weld of good toughness and corrosion resistance, and is versatile in the range of situations in which it can be used. GTAW is often used to supplement and finish larger constructions assembled using other welding methods. It is important that the GTAW procedures be qualified to deal with the variety of situations in which it may be employed.

12.3.2 Gas Metal Arc Welding (GMAW/MIG)

Gas metal arc welding (GMAW), sometimes referred to as metal inert gas (MIG) welding, is especially useful for longer runs of welding requiring economical deposition of relatively large volumes of weld metal. It may be automated for simple geometries. GMAW is often used for longer weld runs and then supplemented with GTAW for best control during complex finishing operations.

Equipment

GMAW requires specialized equipment including a constant voltage supply with variable slope and variable inductance control or with pulsed arc current capability. GMAW should be done with direct current reverse polarity (DCRP), electrode positive. There are three arc transfer modes possible with GMAW.

Short-Circuiting Transfer

This mode, requiring separate slope and secondary inductance controls, is useful for material up to about 3 mm (1/8 inch) thickness. This mode gives the lowest heat input for GMAW and is especially useful for thin sections where there is a risk of distortion with higher heat input. It can be used for out-of-position welding.

Pulsed Arc Transfer

This mode requires two power sources to provide the two ranges of output, with the switching of sources providing the pulse. Metal transfer is high during the spray transfer range, but lower in the globular range. This combination provides the benefit of higher metal deposition rates while still restraining the heat input.

Spray Transfer

This mode provides rapid deposition rates with a stable arc, but it also occurs with high heat input. It is generally limited to flat position welding. It is economical when making long, straight welding runs with moderately large welds.

Filler Metals

GMAW uses a consumable electrode in the form of a continuous wire that is fed through the torch by an automatic feeding system. The filler metals for GMAW of duplex stainless steels are “matching” compositions overalloyed with nickel to achieve the desired phase balance and properties in the as-welded condition.

Shielding

Selection of shielding gas for GMAW is somewhat more complex than for GTAW, and depends to a significant extent on whether the fabricator is relying upon purchased gas mixtures or has on-site gas mixing capability. The GMAW shielding gasses range from pure argon to about 80% argon with additions of helium, nitrogen, and oxygen selected to enhance weldability and final properties of the welded structure. Flow rates depend on the transfer mode, travel speed, and wire diameter, but are typically in the range of 12-16 l/min (0.4-0.6 cfm) for 1 to 1.6 mm (0.035 to 0.063 inch) diameter wire. As noted for GTAW, the integrity of the gas handling system is critical, and precautions should be taken against aspiration of air into the shielding gas. Because the welding is done over longer runs, shielding from drafts is important to maintain weld quality. Hydrogen should not be used in the shielding or backing gas because of the possibility of hydrogen embrittlement or hydrogen cracking of the ferrite phase in duplex stainless steels.

Technique and Parameters

Typical welding parameters for short-circuiting arc transfer and for spray arc transfer are summarized in Table 15.

As with GTAW of duplex stainless steels, GMAW requires good, consistent edge preparation, alignment, and root land or spacing. Copper backing bars should be avoided if possible because the duplex stainless steels are sensitive to copper surface contamination and copper backing bars may cause too rapid quenching in some situations.

Short-Circuiting Arc Transfer			
Weld Wire Diameter		**Current**	**Voltage**
mm	**inch**	**ampere**	**volts**
1.0	0.035	90-120	19-21
1.2	0.045	110-140	20-22
Spray Arc Transfer			
1.0	0.035	170-200	26
1.2	0.045	210-280	29
1.6	0.063	270-330	30

Table 15. Typical Gas-Metal Arc Welding (GMAW) Parameters for Short-Circuiting Arc Transfer and for Spray Arc Transfer for Welding Duplex Stainless Steels with Various Wire Sizes (Source: AvestaPolarit)

Any arc strikes outside of the welding zone will create local points of autogenous welding with very high quench rates, resulting in locally high ferrite content and possible loss of corrosion resistance at those points. Arc strikes should be made in the weld joint itself to avoid this problem. Any arc strikes outside of the weld zone should be removed by fine grinding.

2205 Flanged T-piece (Source: Arco Exploration and Production Technology)

Tacking welds should be made with full gas shielding. There should be no tack weld at the starting point of the root pass. Ideally, to avoid cracking of the root pass associated with tack welds, the root pass weld should be interrupted and the tack weld ground away, or the tack may be partially ground before the root pass. The width of the root gap should be carefully maintained to ensure consistent heat input and dilution in the root pass. The start and finish of the root pass should be ground before the start of filler passes. The work piece should be allowed to cool below 150°C (300°F) between passes to provide for adequate cooling of the HAZ in subsequent passes.

Mechanized Welding of Large Diameter Duplex Stainless Steel Pipeline on Alaska’s North Slope (Source: Arco Exploration and Production Technology)

Wire sizes of 1.6, 2.4, and 3.2 mm (1/16, 3/32, and 1/8 inch) are commonly used. Filler wire should be clean and dry, and should be stored in a covered container until used. The guide tube should be kept clean and dry. Best results are obtained when the work is done in the flat position. The torch should be maintained as near as possible to vertical to minimize aspiration of air into the shielding gas.

12.3.3 *Flux Core Wire Arc Welding (FCW)*

Flux core wire arc welding is one of the latest commercial developments for the duplex stainless steels. Its success demonstrates just how far and how rapidly the technology of the duplex stainless steels has developed. In FCW, the flux-filled wire is fed automatically through the torch, using the same equipment typically used for GMAW. The flux inside the wire provides a slag that protects the weld from the atmosphere, supplementing the gas shielding provided through the torch to protect the HAZ. FCW is economical because it provides high deposition rates. It is suitable for out-of-position welding and for a wide range of metal thicknesses.

Equipment

Flux core wire arc welding is performed using the same equipment used for GMAW.

Filler Metals

Because the flux-shielded welding methods tend to produce welds of somewhat reduced toughness, probably resulting from the increased oxygen content in the weld metal, the FCW filler metal is overalloyed with nickel so that the weld metal is more austenitic than the nearly balanced structure of the base metal. Because the composition of fluxes and the production of FCW wire are proprietary, there may be significant differences among the FCW fillers from different suppliers. It is important that production welding by FCW use wire from the same source as used in qualification of procedures to avoid variations in production.

Shielding

The shielding gases most typically used for FCW are 75% argon-25% carbon dioxide and 100% carbon dioxide for flat and vertical welding positions, respectively. The flow rate for either gas or position is 20-25 l/min (0.7-0.9 cfm).

Technique and Parameters

For 1.2 mm (0.045 inch) diameter wire, the typical current and voltage settings are 150-200 amps at 22-38 volts and 60-110 amps at 20-24 volts, for horizontal and vertical welding, respectively. Otherwise, the advice on technique of welding for FCW is identical to that for GMAW.

12.3.4 Shielded Metal Arc Welding (SMAW/stick electrode)

Shielded metal arc welding, sometimes called stick or covered electrode welding, is a highly versatile method of welding complex geometries in situations with relatively difficult positions or possibilities for protection. While it is possible to rely upon SMAW for whole structures, particularly for smaller and more complex structures, SMAW is most frequently used in combination with more cost efficient welding methods for large structures.

Equipment

The equipment required for SMAW is a constant current power supply. SMAW is done using direct current reverse polarity (DCRP), electrode positive.

Filler Metals

The SMAW electrode consists of a consumable electrode with a flux coating. The coating may or may not contain additional alloy elements that will carry into the weld. The coating is a complex proprietary mixture that provides arc stability, shielding of the metal during transfer, and protection of the weld from the atmosphere during and after solidification. Because of the proprietary nature of the coating, there can be substantial differences among nominally similar products from different suppliers. The coatings may emphasize improved weld toughness or physical appearance, and they may be specially engineered for best performance in a specific position such as flat, out-of-position, or vertical.

The coatings of SMAW electrodes are hygroscopic, and the presence of water will substantially degrade their performance. The electrodes should be kept in their factory-sealed container until ready for use. Once the package is opened, the electrodes should be stored in an oven heated to 95°C (200°F) or more to prevent accumulation of moisture that may lead to weld porosity or cracking.

Because the flux increases the oxygen content of the weld and, thereby, reduces toughness, it is common for the SMAW electrodes to be balanced near the maximum level of austenite at which the metal will still have the beneficial effects of the duplex structure. The toughness of the weld is well below that of the base metal, but generally it is well above the levels of toughness considered adequate for carbon and alloy steels. An error that has sometimes been made in qualification of the SMAW welds is the use of the ASTM A 923 testing without appropriate adjustment of the acceptance criterion. The lower toughness observed for the SMAW welds is not indicative of intermetallic phases, but is attributed to the oxygen from the flux shielding. Requiring the 40 ft-lb. at –40°C/F, which is required for the base metal, leads to inappropriate disqualification of this highly versatile procedure that has been used for years with excellent practical results.

Shielding

Shielding is not usually an issue in SMAW because this method relies upon the protective flux and gasses created by the covering on the electrodes.

Technique and Parameters

Welding parameters for SMAW are largely a function of electrode diameter as shown in Table 16.

To maximize the protection provided by the flux, the welder should maintain as short an arc as possible. Too wide a gap, called “long arc”, may introduce weld porosity, excessive oxidation, excessive heat inputs, and reduced mechanical properties.

Electrode Diameter		Current	Voltage
mm	**inch**	**ampere**	**volt**
2.0	0.078	35-60	22-28
2.5	0.094	60-80	22-28
3.25	0.125	80-120	22-28
4.0	0.156	100-160	22-28

Table 16. Typical Shield-Metal Arc Welding (SMAW) Parameters for Welding Duplex Stainless Steels with Various Size Electrodes (Source: AvestaPolarit)

2205 Manifold (Source: Arco Exploration and Production Technology)

The root pass should be made with one of the smaller sizes of electrodes, with the larger electrodes being used for the filler passes. The arc should always be struck within the weld zone itself. Any other arc strikes or spatter should be removed by fine grinding.

SMAW should not be used on duplex stainless steels of less than 2 mm (0.08 inch) thickness. The work piece should be flat if possible, but SMAW electrodes may be chosen to enable welding in virtually any position. The electrode should be held at a 20° angle (the drag angle) to the work piece, with the electrode grip inclined forward to the direction of travel. The metal should be deposited in a straight stringer bead with minimal weave. Current should be set only high enough to provide a smooth arc and good fusion of the weld and the base metal.

12.3.5 Submerged Arc Welding (SAW)

Submerged Arc Welding allows the deposition of relatively large welds with less total time at temperature for the HAZ than would be possible for a large number of passes with less deposition per pass. Because of the ferritic solidification and duplex transformation of the weld metal, the duplex stainless steels can be SAW with minimal risk of hot cracking. However, it is necessary to make some adjustment of joint design or welding parameters relative to austenitic stainless steels to obtain full penetration welds. For large constructions and for large straight runs of weld, SAW is a cost efficient and technically satisfactory approach to welding duplex stainless steels. SAW is commonly used to manufacture heavy wall duplex stainless steel pipe.

Filler Metals and Shielding

For SAW, the usual matching duplex filler metal is appropriate. However, it is important to select a correct flux to achieve the desired properties. It is reported that highly basic fluxes give the best impact toughness for the duplex stainless steels.

Technique and Parameters

Typical parameters for SAW duplex stainless steel are summarized in Table 17.

Electrode Diameter		Current	Voltage
mm	**inch**	**ampere**	**volt**
2.5	0.094	250-450	28-32
3.25	0.125	300-500	29-34
4.0	0.156	400-600	30-35
5.0	0.203	500-700	30-35

Table 17. Typical Submerged Arc Welding (SAW) Parameters for Welding Duplex Stainless Steels with Various Size Wire (Source: AvestaPolarit)

12.3.6 *Electron Beam and Laser Welding*

The experience with these newer welding methods as applied to duplex stainless steels is limited. However, there have been a few successful applications and there is every reason to expect that procedures will be developed more fully. It is unlikely that these procedures will involve times at temperature that will cause intermetallic phase formation. However, the qualification of the procedure must be alert to the possibility of excessive ferrite in the HAZ and even in the weld when the high speed welding capabilities of these methods are considered.

12.3.7 *Resistance Welding*

When single-pulse resistance welding is used for spot welds, the HAZ is very rapidly quenched. This quench is even more rapid for duplex stainless steels than for austenitic stainless steels because of the higher thermal conductivity of the duplex steel. In this situation, there will be a thin layer of material immediately adjacent to the fusion line that reaches the temperature range where the duplex structure is converted entirely to ferrite. The cooling is so rapid that even the higher nitrogen duplex stainless steels are unlikely to re-form austenite in this region. It is then possible to have a tough base material and a weld with an intervening continuous layer of ferrite of limited toughness.

With a programmable resistance welder, it may be possible to develop a two-pulse welding cycle that will slow the cooling sufficiently to prevent this continuous ferrite layer. Again, it may be necessary to qualify different section thicknesses.

A resistance seam welder is less likely to have this same problem, and very unlikely to have exposure times long enough for formation of intermetallic phases, but the welding qualification should particularly address the potential for excessive ferrite.

13. OTHER JOINING TECHNIQUES

The advantages of joining techniques other then welding (where the base material is melted to produce a joint) include minimum warpage and low residual stresses. The joints can be leak-tight and quite strong. However, the bond never comes close in its properties to a welded bond where the weld metal corrosion resistance and the strength are as high, or nearly as high, as in the base material. This is an important consideration for the duplex stainless steels, which are superior to the 300-series austenitic stainless steels in strength as well as corrosion resistance.

Offshore Oil Platform, Statfjord B (Source: Krupp, Thyssen Nirosta)

13.1 *Joint Preparation*

For all joining operations, it is very important to thoroughly clean the stainless steel before joining the parts. The surfaces should be free of oil, grease, dirt, dust or fingerprints. A solvent should be used to remove those surface contaminants. Oil or grease can prevent the flux from removing the oxide layer in soldering and brazing. Loose surface contaminants reduce the effective joint surface area. Often a slightly rough surface produces better joints than smooth surfaces. Sometimes roughening with a fine abrasive can help to increase the wetability of a surface, which is critical for a good bond.

13.2 *Adhesives*

A wide variety of commercial adhesives for the joining of metal surfaces is available. Duplex stainless steels are treated in the same way as any

Flue Gas Desulfurization Unit “Chemische Werke Hüls, Germany” (Source: Krupp, Thyssen Nirosta)

other metal for the purpose of joining with adhesives. The adhesives manufacturers can assist in the selection of the proper adhesive for a specific joint strength, service temperature, and service environment.

13.3 Soldering

Soldering is distinguished from brazing by the melting temperature of the filler material. The soldering temperature is usually below 450°C (840°F). In general, soldered joints are not as strong and their service temperature is lower than for brazed joints.

Typical soldering filler materials include tin-lead, tin-antimony, tin-silver, and tin-lead-bismuth alloys. These low-melting filler materials produce joints of different strength and corrosion resistance and with varying color match.

To produce a good solder joint, the surface oxide layer of stainless steel must be removed with a flux before the soldering takes place. The high stability of the protective oxide layer in stainless steels and, especially molybdenum-alloyed duplex stainless steels, can make proper fluxing very difficult. Typical acid-type fluxes can contain chlorides. If chloride-containing fluxes are used, they must be cleaned with water washing and/or a neutralizer, immediately after the soldering. Failure to completely remove the flux is likely to produce pitting corrosion, possibly even before the equipment is placed in service.

13.4 Brazing

Brazing filler material has a melting point above 450°C (840°F). The two most important types of brazing filler metals are silver brazing alloys and nickel brazing alloys. The silver brazing alloys are lower-melting, between 618 to 705°C (1145 and 1300°F), and the nickel brazing alloys are higher-melting, up to 1175°C (2150°F). The nickel brazed joints can withstand a higher service temperature than the silver brazed joints.

The temperature range between 705 and 980°C (1300 and 1800°F) should be avoided with duplex stainless steels. It is, therefore, important to braze at a temperature above 1040°C (1900°F) or below 705°C (1300°F). Nickel brazed joints can be water quenched from the brazing temperature.

The proper brazing material should be chosen according to required corrosion resistance, service temperature and joint strength. Nickel brazing materials contain up to 25% chromium which makes them somewhat corrosion resistant, although not quite as resistant as the duplex stainless steel, 2205.

It has been reported that nitrogen-containing stainless steels are difficult to braze. This could affect the second-generation duplex stainless steels that contain increased levels of nitrogen. Few data are available on the brazing of duplex stainless steels, so the fabricator should experiment to find the ideal brazing parameters.

As with soldering, the oxide layer must be removed prior to and during the brazing operation to create a sound brazed joint. Again, this is accomplished with a flux that must be removed after the brazing. The procedure is similar to the clean-up after soldering and includes scrubbing with hot water or a neutralizing chemical.

14.POST FABRICATION CLEAN-UP

The post fabrication clean-up of duplex stainless steels is not different from the clean-up required on other stainless steels. The post fabrication clean-up is very important, as important as the control of interpass temperature or the use of shielding gas during welding. A stainless steel that has not been properly cleaned after fabrication can fail at much lower temperatures or in a much less aggressive environment than the parent material would. This means that the extra cost of a more corrosion resistant material is wasted unless the material has been fabricated so that an optimum surface is maintained or restored. Weld spatter, weld heat tint, crayon marks, arc strikes, and undercuts can all serve as crevices in an aqueous environment. At the same time, they can also have a different potential than the stainless steel surface, so galvanic interactions may occur. It is important to remove these disruptions of the protective passive film. Figure 17 shows a summary of these disruptions that may occur during fabrication and that should be removed before putting any stainless steel in service.

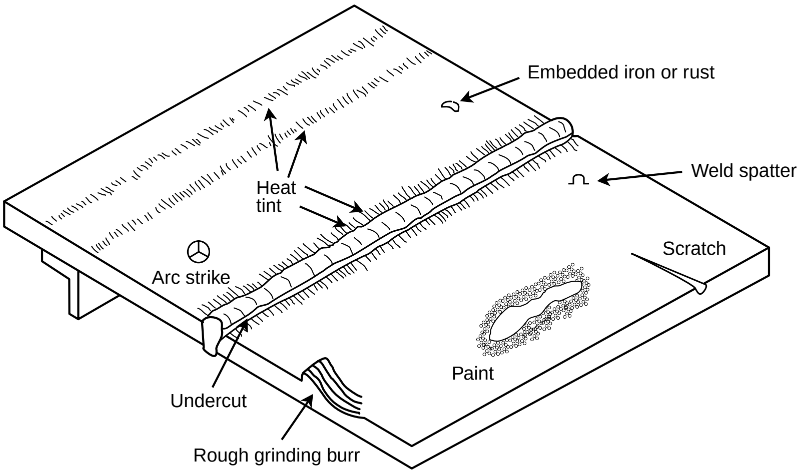


Figure 17. Typical Fabrication Defects Or Surface Conditions Which May Be Encountered (Source: NiDI Publication 10 026)

14.1 *Crayon Marks, Paint, Dirt, Oil*

All these surface contaminants can act as crevices and can be initiation sites for pitting or crevice corrosion of a stainless steel. They should be removed with solvents before embedded iron is removed.

14.2 *Embedded Iron*

Embedded iron, or free iron, results from fabrication or transportation of stainless steel with carbon steel tools. If steel tools are used on stainless steels or if carbon steel is fabricated near where stainless steel is stored, iron can be transferred to the surface of the stainless steel. The iron subsequently rusts in a moist or humid environment and can initiate corrosion on the stainless steel surface. One approach is to avoid all contact between stainless steel and carbon steel. Only stainless steel tools, stainless steel wire brushes, stainless steel clamps, and new, uncontaminated grinding wheels should be used on stainless. Often the tools are color coded in the shop.

It is often impractical and uneconomical to completely avoid the use of carbon steel tooling and to prevent the settling of iron contamination from the shop environment. In this approach, one accepts that there will be iron transfer but undertakes to ensure that it is removed before the stainless steel is put in service. The method of removing the iron may involve mechanical cleaning, chemical cleaning, or a combination of mechanical and chemical cleaning. The best cleaning method depends on the size and shape of the equipment, the anticipated service, and certain practical issues including disposal of the cleaning wastes. One common cleaning method has been a chemical treatment with nitric acid, which dissolves the free iron on the stainless steel surface but does not attack the stainless steel or the protective passive film layer. But there are many different chemical cleaning approaches that can achieve the desired results. Details of cleaning methods are thoroughly discussed in ASTM A 380. It is especially important that the user be familiar with the safety issues discussed in A 380.

ASTM A 967 (replacing US Federal Specification QQP-35c) provides information on the selection of appropriate testing to demonstrate that the cleaning of the steel (often called “passivation” in the common but imprecise jargon of the industry) has been effective. In this specification, it is expected that the purchaser will define the level of surface cleanliness to be achieved and permit the agency performing the cleaning to select the cleaning procedure that is economical and effective.

14.3 *Weld Spatter, Heat Tint, Flux, Slag, Arc Strikes*

All these defects may occur during welding. They can act as crevices and initiate crevice corrosion in chloride-containing environments and should be avoided or removed after welding. Weld spatter can be avoided during fabrication by using an anti-spatter compound. Heavy weld discolouration or heat tint should be avoided by inert gas shielding and by purging the back side of welds with an inert gas. Often, however, heat tint cannot be totally avoided and must be removed during postweld clean-up. Flux and slag inclusions as well as arc strikes should also be removed before putting equipment in service. Weld spatter, weld heat tint, flux, slag, arc strikes, and weld undercuts can all be removed by mechanical cleaning such as fine abrasive grinding, or with a stainless steel wire wheel or brush. It is important that a fine grinding wheel is used, as coarse grinding marks can themselves cause corrosion in service by allowing deposits to stick and crevices to form.

The one distinctive feature of duplex stainless steel is that the weld heat tint tends to be thin, adherent, and more resistant to chemical removal than for austenitic stainless steels of comparable corrosion resistance. Weld heat tint can be removed chemically by pickling; for example, pickle 2205 with a 20% nitric–5% hydrofluoric acid solution. This solution dissolves the chromium oxide and also attacks the stainless steel so that the chromium-depleted layer is removed. Similar in their effect, but easier to handle for large pieces, pickling pastes can be used in place of the acid solution. However, it should be recognized that the pickle paste will produce a hazardous solution when rinsed, and appropriate safety, handling, and disposal procedures are the responsibility of the user. Depending on the corrosion resistance of the duplex stainless steel, a less or more aggressive acid can be required to remove the heat tint.

Research has shown that the best corrosion resistance after welding is obtained by using chemical cleaning after mechanical cleaning.

Marine Chemical Tanker with 2205 Tanks (Source: Krupp, Thyssen Nirosta)

NOTES

ACKNOWLEDGEMENTS

Extensive technical information on the fabrication of duplex stainless steels is available from the duplex stainless steel producers. IMOA is especially grateful to AvestaPolarit, Usinor Industeel, and AB Sandvik Steel for their contribution to this brochure.

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APPENDIX 1. Duplex Stainless Steel Names, Trademarks and Associated Stainless Steel Producers

Category	UNS No.	Names	Producers
Wrought Duplex Stainless Steels			
Lean Duplex	S32304	2304	Common designation, many producers
		SAF 2304	AvestaPolarit
		SAF 2304	Sandvik
		UR 35 N	Usinor Industeel
2205	S31803	2205	Common designation, many producers
		SAF 2205	Sandvik
		UR 45N	Usinor Industeel
		Nirosta 4462	KTN
		Remanit 4462	Edelstahlwerk Witten Krefeld
		AL 2205	Allegheny Ludlum
		DMV 22-5	DMV
	S32205	2205	Common designation, many producers
		2205 Code Plus Two	AvestaPolarit
		UR 45N +	Usinor Industeel
		UR 45N Mo	Usinor Industeel
		Nirosta 4462	KTN
25 Cr Duplex	S31260	DP-3	Sumitomo
	S32550	Alloy 255	Common designation, many producers
		UR 52N	Usinor Industeel
		Ferralium 255	Langley Alloys, Meighs Ltd.
		DMV 25-7	DMV
Superduplex	S32520	UR 52N+	Usinor Industeel
	S39274	DP-3W	Sumitomo
	S32750	2507	Common designation, many producers
		SAF 2507	AvestaPolarit
		SAF 2507	Sandvik
		UR 47N	Usinor Industeel
	S32760	Zeron 100	Weir Materials
		UR 76N	Usinor Industeel
		Nirosta 4501	KTN
Cast Duplex Stainless Steels	J93372	CD4MCuN	ACI designation, common designation, many producers
		Grade 1B	ASTM A 890 designation
	J92205	CD3MN	ACI designation
		Grade 4A	ASTM A 890 designation
		Cast 2205	Common designation, many producers
	J93404	CE3MN	ACI designation
		Grade 5A	ASTM A 890 designation
		Atlas 958	Atlas Foundry
		Cast 2507	Common designation, many producers
	J93380	CD3MWCuN	ACI designation
		Grade 6A	ASTM A 890 designation
		Cast Zeron 100	Weir Materials

APPENDIX 2. Summary of ASTM Specifications

UNS No.	ASTM Specification
Wrought Duplex Stainless Steels	
S31500	A 789, A 790, A 959
S32404	None
S32900	A 240, A 268, A 789, A 790, A 959
S31260	A 240, A 480, A 789, A 790, A959
S31803	A 182, A 240, A 276, A 479, A 480, A 789, A 790, A 815, A 923, A 928, A 959, A 988
S32205	A 182, A 240, A 276, A 479, A 480, A 789, A 790, A 815, A 928, A 959, A 988
S32304	A 240, A 276, A 480, A 789, A 790, A 959
S32520	A182, A 240, A 480, A 928, A 959
S32550	A 240, A 479, A 480, A 789, A 790
S32750	A 182, A 240, A 479, A 480, A 789, A 790, A 959, A 988
S32760	A 182, A 240, A 276, A 479, A 480, A 789, A 790, A 959, A 988
S39274	A 789, A 790, A 815, A 988
Cast Duplex Stainless Steels	
J92205	A 890, A 995
J93372	A 890, A 995
J93380	A 890, A 995
J93404	A 890, A 995
Specification Titles	
A 182/ A 182M	Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service
A 240/ A 240M	Heat-Resisting Cr and Cr-Ni Stainless Steel Plate, Sheet, and Strip for Pressure Vessels
A 276	Stainless Steel Bars and Shapes
A 479/A 479M	Stainless Steel Bars and Shapes for Use in Boilers and Other Pressure Vessels
A 480/A 480M	General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip
A 789/ A 789M	Seamless and Welded Ferritic/Austenitic Stainless Steel Tubing for General Service
A 790/ A 790M	Seamless and Welded Ferritic/Austenitic Stainless Steel Pipe
A 815/A 815M	Wrought Ferritic, Ferritic/Austenitic, and Martensitic Stainless Steel Fittings
A 890/A 890M	Castings, Fe-Cr-Ni-Mo Corrosion-Resistant, Duplex for General Application
A 923	Detecting Detrimental Intermetallic Phase in Wrought Duplex Stainless Steels
A 928/A 928M	Ferritic/Austenitic Stainless Steel Pipe Electric Fusion Welded with Addition of Filler Metal
A 959	Harmonized Standard Grade Compositions for Wrought Stainless Steels
A 988/A 988M	Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves and Parts for High Temperature Service
A995	Castings, Austenitic-Ferritic (Duplex) Stainless Steels for Pressure-Containing Parts

Back cover picture: 2205 Transport Pipe at NAM Natural Gas Underground Storage in the Netherlands (Source: Lincoln Smitweld bv and NAM; Photographer: Rolf Goossen, Haaren)

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