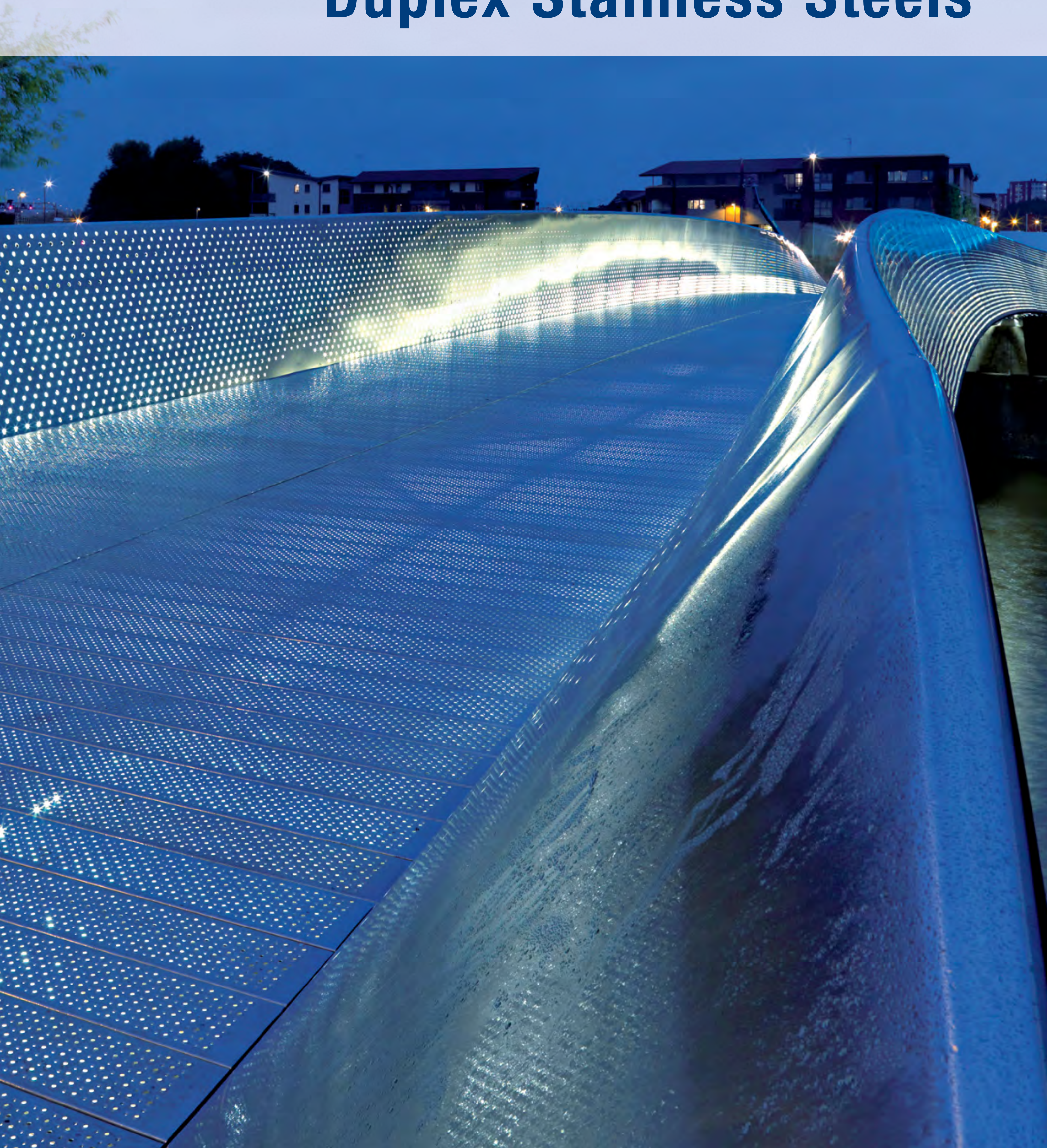
# Practical Guidelines for the Fabrication of Duplex Stainless Steels



**Practical Guidelines for the Fabrication of Duplex Stainless Steel**
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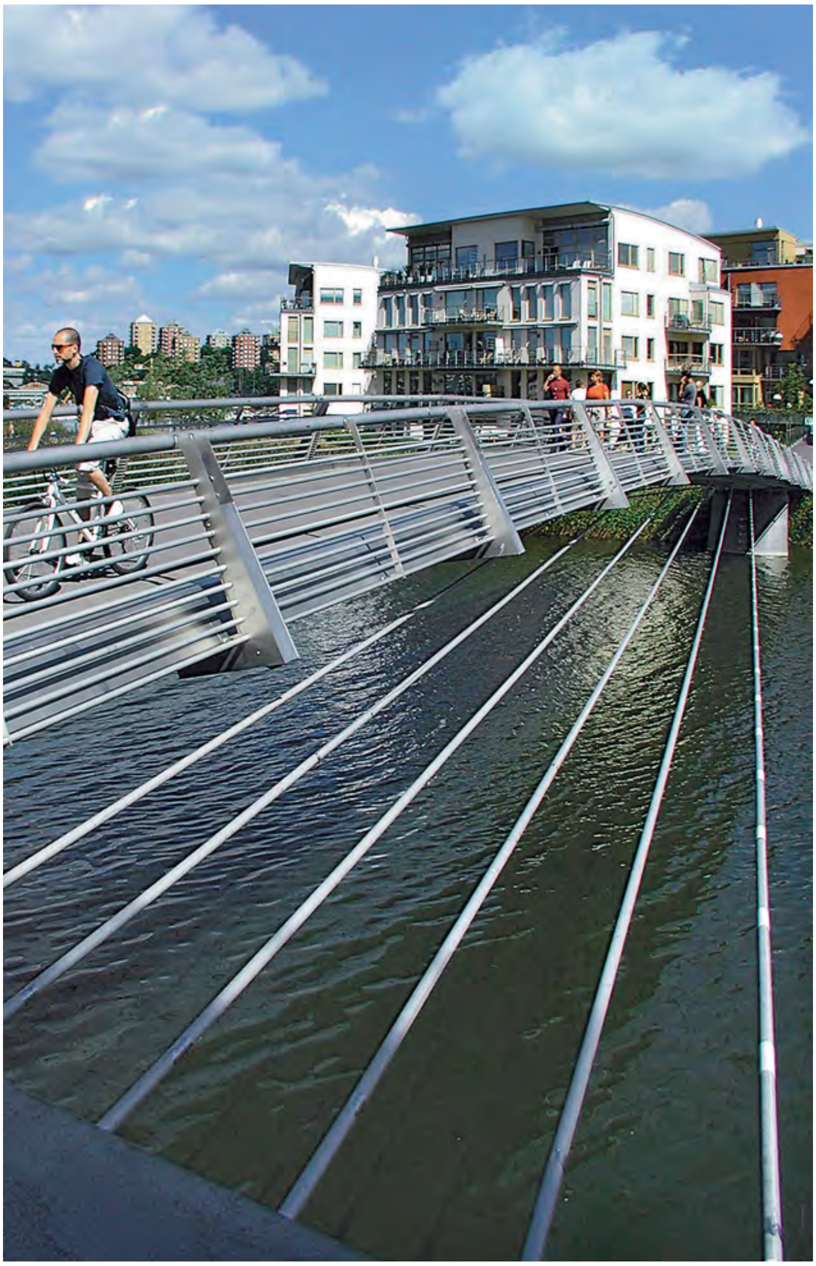
# 1 Introduction

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, tungsten, and nitrogen content. It may be similar to that of Type 316 or range above that of the sea water stainless steels such as the 6% Mo austenitic stainless steels. All the duplex stainless steels have chloride stress corrosion cracking resistance significantly greater than that of the 300-series austenitic stainless steels. They all provide significantly greater strength than the austenitic grades while exhibiting good ductility and toughness.



**Duplex stainless steel bridge in Stockholm, Sweden (Source: Outokumpu)**

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 manual 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 publication 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.

# 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 nearly 80 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. AISI Type 329 became well established after World War II and was used extensively for heat exchanger tubing for nitric acid service. One of the first duplex grades developed specifically for improved resistance to chloride stress corrosion cracking (SCC) was 3RE60. 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. With increased austenite stability, 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 these steels allowed for reduced wall thickness and reduced weight on the platforms and provided considerable incentive for their use.

**2205 continuous sulphate pulp digester and impregnation tower, Sodra Cell Mönsteras, Sweden (Source: Kvaerner Pulping)**

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 five groups:

- lean duplex such as 2304, which contains no deliberate Mo addition;
- standard duplex such as 2205, the work-horse grade accounting for more than 80% of duplex use;
- 25 Cr duplex such as Alloy 255 with PREN* less than 40
- super duplex (PREN 40-45), with 25-26 Cr and increased Mo and N compared with the 25 Cr grades, such as 2507;
- hyper duplex, defined as a highly alloyed duplex stainless steel with PREN in excess of 45.

*PREN = Pitting Resistance Equivalent Number
= %Cr + 3.3(%Mo + 0.5%W) + 16%N

**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.

Note: 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)**

| Grade | UNS No. | EN No. | C | Cr | Ni | Mo | N | Mn | 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 | – | 1.00 | – | – |
| ** | S31500 | 1.4424 | 0.03 | 18.0–19.0 | 4.3–5.2 | 2.5–3.0 | 0.05–0.1 | | – | – |
| | S32404 | | 0.04 | 20.5–22.5 | 5.5–8.5 | 2.0–3.0 | 0.20 | 2.00 | 1.0–2.0 | – |
| Second-generation duplex grades | | | | | | | | | | |
| Lean | | | | | | | | | | |
| | S32001 | 1.4482 | 0.03 | 19.5–21.5 | 1.0–3.0 | 0.6 | 0.05–0.17 | 4.0–6.0 | 1.0 | – |
| | S32101 | 1.4162 | 0.04 | 21.0–22.0 | 1.35–1.7 | 0.1–0.8 | 0.20–0.25 | 4.0–6.0 | 0.1-0.8 | – |
| | S32202 | 1.4062 | 0.03 | 21.5–24.0 | 1.0–2.8 | 0.45 | 0.18–0.26 | 2.00 | – | – |
| | S82011 | | 0.03 | 20.5–23.5 | 1.0–2.0 | 0.1–1.0 | 0.15–0.27 | 2.0–3.0 | 0.5 | – |
| **2304** | S32304 | 1.4362 | 0.03 | 21.5–24.5 | 3.0–5.5 | 0.05–0.6 | 0.05–0.20 | 2.50 | 0.05–0.60 | – |
| | | 1.4655 | 0.03 | 22.0–24.0 | 3.5–5.5 | 0.1–0.6 | 0.05–0.20 | 2.00 | 1.0–3.0 | – |
| Standard | | | | | | | | | | |
| | S32003 | | 0.03 | 19.5–22.5 | 3.0–4.0 | 1.5–2.0 | 0.14–0.20 | 2.00 | – | – |
| **2205** | S31803 | 1.4462 | 0.03 | 21.0–23.0 | 4.5–6.5 | 2.5–3.5 | 0.08–0.20 | 2.00 | – | – |
| **2205** | S32205 | 1.4462 | 0.03 | 22.0–23.0 | 4.5–6.5 | 3.0–3.5 | 0.14–0.20 | 2.00 | – | – |
| 25 Cr | | | | | | | | | | |
| | S31200 | | 0.03 | 24.0–26.0 | 5.5–6.5 | 1.2–2.0 | 0.14–0.20 | 2.00 | – | – |
| | S31260 | | 0.03 | 24.0–26.0 | 5.5–7.5 | 2.5–3.5 | 0.10–0.30 | 1.00 | 0.2–0.8 | 0.1–0.5 |
| | S32506 | | 0.03 | 24.0–26.0 | 5.5–7.2 | 3.0–3.5 | 0.08–0.20 | 1.00 | – | 0.05–0.30 |
| | S32520 | 1.4507 | 0.03 | 24.0–26.0 | 5.5–8.0 | 3.0–4.0 | 0.20–0.35 | 1.50 | 0.5–2.0 | – |
| **255** | S32550 | 1.4507 | 0.04 | 24.0–27.0 | 4.5–6.5 | 2.9–3.9 | 0.10–0.25 | 1.50 | 1.5–2.5 | – |
| Super duplex | | | | | | | | | | |
| **2507** | S32750 | 1.4410 | 0.03 | 24.0–26.0 | 6.0–8.0 | 3.0–5.0 | 0.24–0.32 | 1.20 | 0.5 | – |
| | S32760 | 1.4501 | 0.03 | 24.0–26.0 | 6.0–8.0 | 3.0–4.0 | 0.20–0.30 | 1.00 | 0.5–1.0 | 0.5–1.0 |
| | S32808 | | 0.03 | 27.0–27.9 | 7.0–8.2 | 0.8–1.2 | 0.30–0.40 | 1.10 | – | 2.1–2.5 |
| | S32906 | | 0.03 | 28.0–30.0 | 5.8–7.5 | 1.5–2.6 | 0.30–0.40 | 0.80–1.5 | 0.8 | – |
| | S32950 | | 0.03 | 26.0–29.0 | 3.5–5.2 | 1.0–2.5 | 0.15–0.35 | 2.00 | – | – |
| | S39274 | | 0.03 | 24.0–26.0 | 6.8–8.0 | 2.5–3.5 | 0.24–0.32 | 1.0 | 0.2–0.8 | 1.5–2.5 |
| | S39277 | | 0.025 | 24.0–26.0 | 6.5–8.0 | 3.0–4.0 | 0.23–0.33 | 0.80 | 1.2–2.0 | 0.8–1.2 |
| | | 1.4477 | 0.03 | 28.0–30.0 | 5.8–7.5 | 1.5–2.6 | 0.30–0.40 | 0.80–1.50 | ≤0.8 | – |
| Hyper duplex | | | | | | | | | | |
| | S32707 | | 0.03 | 26.0–29.0 | 5.5–9.5 | 4.0–5.0 | 0.30–0.50 | 1.50 | 1.0 | – |
| | S33207 | | 0.03 | 29.0–33.0 | 6.0–9.0 | 3.0–5.0 | 0.40–0.60 | 1.50 | 1.0 | – |

| Grade | UNS No. | EN No. | C | Cr | Ni | Mo | N | Mn | Cu | W |
|---|---|---|---|---|---|---|---|---|---|---|
| Wrought austenitic stainless steels | | | | | | | | | | |
| **304L** | S30403 | 1.4307 | 0.03 | 17.5–19.5 | 8.0–12.0 | – | 0.10 | 2.00 | – | – |
| **316L** | S31603 | 1.4404 | 0.03 | 16.0–18.0 | 10.0–14.0 | 2.0–3.0 | 0.10 | 2.00 | – | – |
| **317L** | S31703 | 1.4438 | 0.03 | 18.0–20.0 | 11.0–15.0 | 3.0–4.0 | 0.10 | 2.00 | – | – |
| **317LMN** | S31726 | 1.4439 | 0.03 | 17.0–20.0 | 13.5–17.5 | 4.0–5.0 | 0.10–0.20 | 2.00 | – | – |
| **904L** | N08904 | 1.4539 | 0.02 | 19.0–23.0 | 23.0–28.0 | 4.0–5.0 | 0.10 | 2.00 | 1.0–2.0 | – |
| Cast duplex stainless steels | | | | | | | | | | |
| **CD4MCu** Grade 1A | J93370 | | 0.04 | 24.5–26.5 | 4.75–6.0 | 1.75–2.25 | – | 1.00 | 2.75–3.25 | – |
| **CD4MCuN** Grade 1B | J93372 | | 0.04 | 24.5–26.5 | 4.7–6.0 | 1.7–2.3 | 0.10–0.25 | 1.00 | 2.7-3.3 | – |
| **CD3MCuN** Grade 1C | J93373 | | 0.03 | 24.0–26.7 | 5.6–6.7 | 2.9–3.8 | 0.22–0.33 | 1.20 | 1.4–1.9 | – |
| **CE8MN** Grade 2A | J93345 | | 0.08 | 22.5–25.5 | 8.0–11.0 | 3.0–4.5 | 0.10–0.30 | 1.00 | – | – |
| **CD6MN** Grade 3A | J93371 | | 0.06 | 24.0–27.0 | 4.0–6.0 | 1.75–2.5 | 0.15–0.25 | 1.00 | – | – |
| **CD3MN** Cast 2205 Grade 4A | J92205 | | 0.03 | 21.0–23.5 | 4.5–6.5 | 2.5–3.5 | 0.10–0.30 | 1.50 | – | – |
| **CE3MN** 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 | 1.50 | – | – |
| **CD3MWCuN** Grade 6A | J93380 | | 0.03 | 24.0–26.0 | 6.5–8.5 | 3.0–4.0 | 0.20–0.30 | 1.00 | 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 | – | – | 1.50 | – | – |
| **CF3M** (cast 316L) | J92800 | 1.4404 | 0.03 | 17.0–21.0 | 9.0–13.0 | 2.0–3.0 | – | 1.50 | – | – |

* Maximum, unless range or minimum is indicated.

– 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.

# 3 Chemical Composition and 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) was 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, 2205 refers to the S32205 composition.

## 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 promotes the body-centered cubic structure of iron. At higher chromium contents, 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 16% Cr in austenitic stainless steels and at least 20% of chromium in duplex grades. 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 pitting 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. 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 increases their strength and, in fact, it is the most effective solid solution strengthening element and a low-cost alloying element. The improved toughness of nitrogen bearing duplex stainless steels is due to their greater austenite content and reduced intermetallic content. Nitrogen does not prevent the precipitation of intermetallic phases but delays the formation of intermetallics 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. Nitrogen reduces the stacking fault energy and increases the work hardening rate of the austenite. It also increases the strength of austenite by solid solution strengthening. In duplex stainless steels, nitrogen is typically added 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 develop the duplex structure.

**Nickel**: Nickel is an austenite stabilizer, which 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 low to intermediate amount of nickel such as 1.5 to 7%, and the 300-series austenitic stainless steels, contain at least 6% 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.

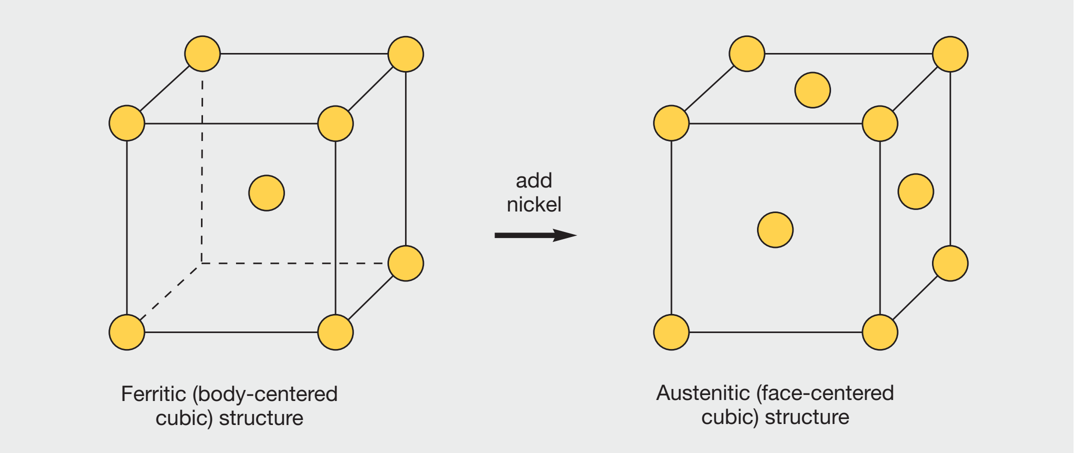
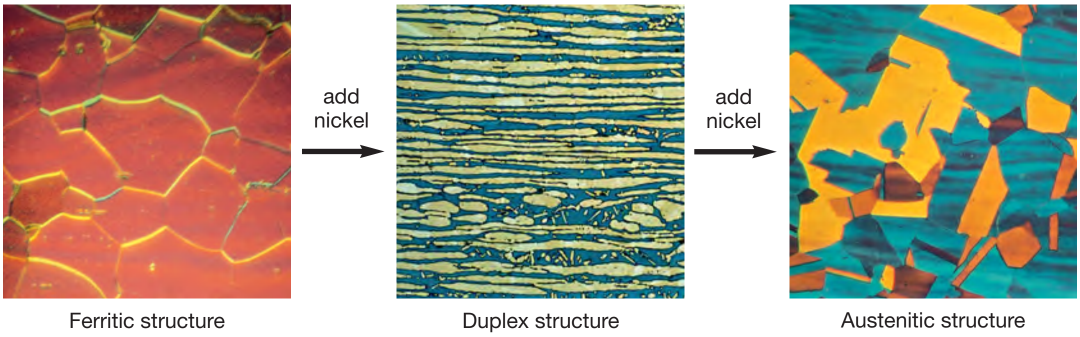


**Figure 1: By adding nickel, the crystallographic structure changes from body-centered cubic (little or no nickel) to face-centered cubic (at least 6% nickel – 300 series). The duplex stainless steels, with their intermediate nickel content, have a microstructure in which some grains are ferritic and 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 Outokumpu, 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 (α), some of which then transforms to austenite (γ) 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.

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. The ferrite/austenite phase balance in the microstructure can be predicted with multivariable linear regression as follows:

$$\mathrm{Cr_{eq}} = \%\mathrm{Cr} + 1.73\ \%\mathrm{Si} + 0.88\ \%\mathrm{Mo}$$

$$\mathrm{Ni_{eq}} = \%\mathrm{Ni} + 24.55\ \%\mathrm{C} + 21.75\ \%\mathrm{N} + 0.4\ \%\mathrm{Cu}$$

$$\%\ \mathrm{Ferrite} = -20.93 + 4.01\ \mathrm{Cr_{eq}} - 5.6\ \mathrm{Ni_{eq}} + 0.016\ T$$

where T (in degrees Celsius) is the annealing temperature ranging from 1050–1150°C and the elemental compositions are in wt.% (Ref. 2). 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 the 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 Heat Affected Zone (HAZ).

Another beneficial effect of nitrogen, evidenced in Figure 3, is that it raises the temperature at which the austenite begins to form from the ferrite. This increases the rate of the ferrite to austenite transformation. 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 precipitates at temperatures below austenite formation from the ferrite on cooling (**Figure 4**), the goal of avoiding sigma phase in mill products is achieved by controlling the annealing temperature and ensuring that the steel is quenched as rapidly as possible from the annealing temperature to prevent sigma formation during cooling. The required 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 excessive cooling rates be encountered during 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 as it forms in fully ferritic alloys. Alpha prime causes the loss of ambient temperature toughness in ferritic stainless steel after extended exposure to temperatures around 475°C (885°F); this behavior is known as 475°C / 885°F embrittlement.

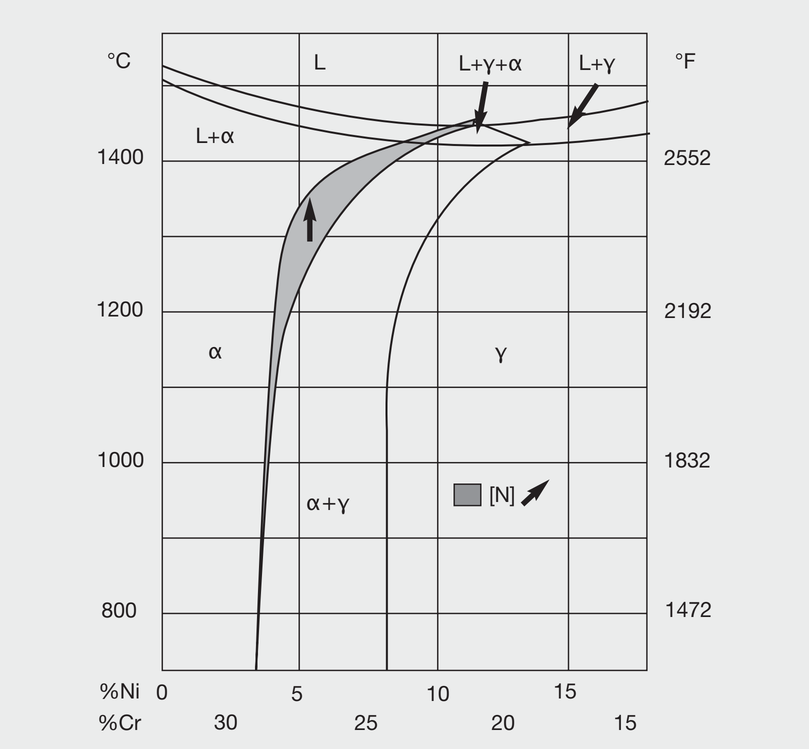


**Figure 3: Section through the Fe-Cr-Ni ternary phase diagram at 68% iron (small changes in the nickel and chromium content have a large influence on the amount of austenite and ferrite in duplex stainless steels.)**

The 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 volume fraction and under conditions in which the chromium-depleted areas do not have time to homogenize 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 duplex grades have been developed to maximize corrosion resistance and retard precipitation reactions sufficiently to allow successful fabrication.

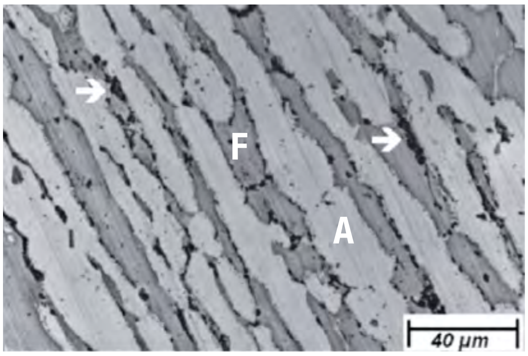


**Figure 4: Microstructure of a 2205 sample aged at 850°C (1560°F) for 40 minutes showing sigma phase precipitation (arrows) on the austenite/ferrite grain boundaries. The ferrite (F) phase appears darker than the austenite (A) phase in the micrograph (Ref. 3).**

An isothermal precipitation diagram for 2304, 2205, and 2507 duplex stainless steels is shown in **Figure 5** (Ref. 4, 5, 6, 7). 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

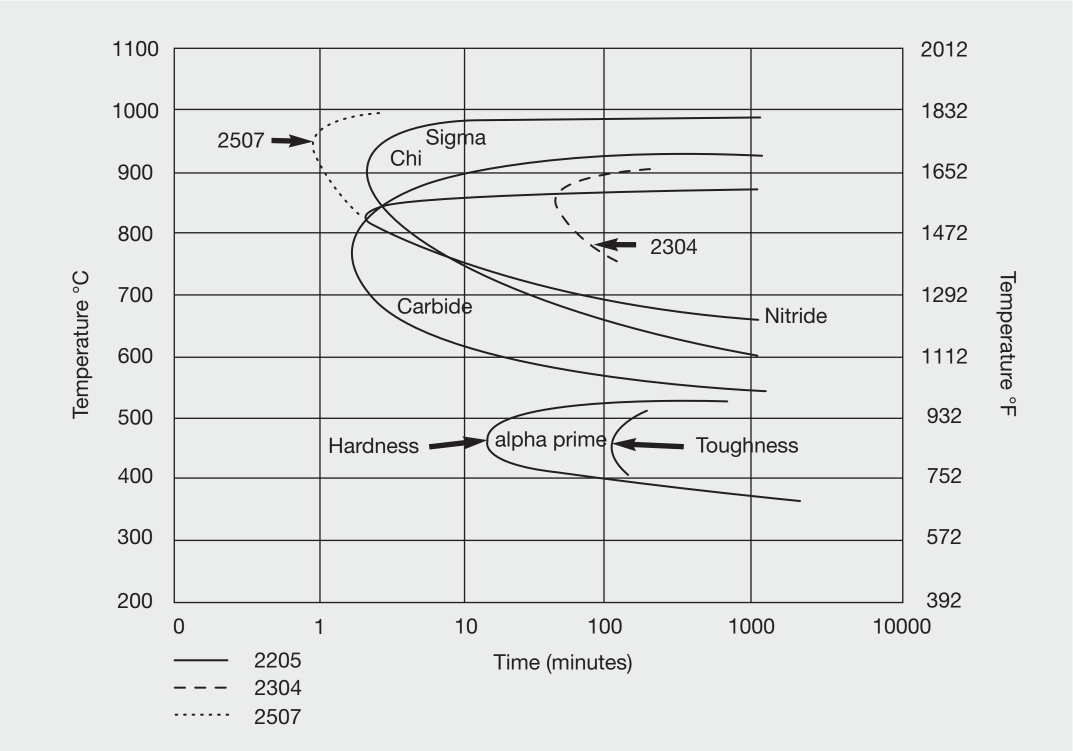


**Figure 5: Isothermal precipitation diagram for 2205 duplex stainless steel, annealed at 1050˚C (1920˚F). (Duplex grades 2304 and 2507 are shown for comparison)**

**2507 Duplex Stainless Steel Fittings (Source: Swagelok)**

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 5 showing an earlier start of sigma and chi formation in the more highly alloyed 2507 and a slower start for 2304.

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 5). Alpha prime embrittlement is rarely a concern during fabrication because of the long times required for embrittlement to occur. 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.

**Table 2. Upper temperature limits for duplex stainless steel for maximum allowable stress values in pressure vessel design codes**

| 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 3: Typical temperatures for precipitation reactions and other characteristic reactions in duplex stainless steels**

| | 2205 | | 2507 | |
|---|---|---|---|---|
| | °C | °F | °C | °F |
| Solidification range | 1470 to 1380 | 2680 to 2515 | 1450 to 1350 | 2640 to 2460 |
| Scaling temperature in air | 1000 | 1830 | 1000 | 1830 |
| Sigma phase formation | 700 to 950 | 1300 to 1740 | 700 to 1000 | 1300 to 1830 |
| Carbide precipitation | 450 to 800 | 840 to 1470 | 450 to 800 | 840 to 1470 |
| 475°C/885°F embrittlement | 300 to 525 | 575 to 980 | 300 to 525 | 575 to 980 |

# 5 Corrosion Resistance

Duplex stainless steels exhibit a high level of corrosion resistance in most environments where the standard austenitic grades are used. 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 induced 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 to thirty percent ferrite, duplex stainless steels are far more resistant to chloride stress corrosion cracking than austenitic stainless steel 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 and cause hydrogen embrittlement.

## 5.1 Resistance to acids

To illustrate the corrosion resistance of duplex stainless steels in strong acids, **Figure 6** provides corrosion data for sulfuric acid solutions. This environment ranges from mildly reducing at low acid concentrations, to oxidizing 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 oxidizing acids of this kind containing chlorides. The duplex stainless steels do not have sufficient nickel to resist the strong reducing conditions of mid-concentration sulfuric acid solutions, or hydrochloric acid. At wet/dry intefaces in reducing environments where there is concentration of the acid, corrosion, especially of the ferrite, may be activated and proceed rapidly. Their resistance to oxidizing conditions makes duplex stainless

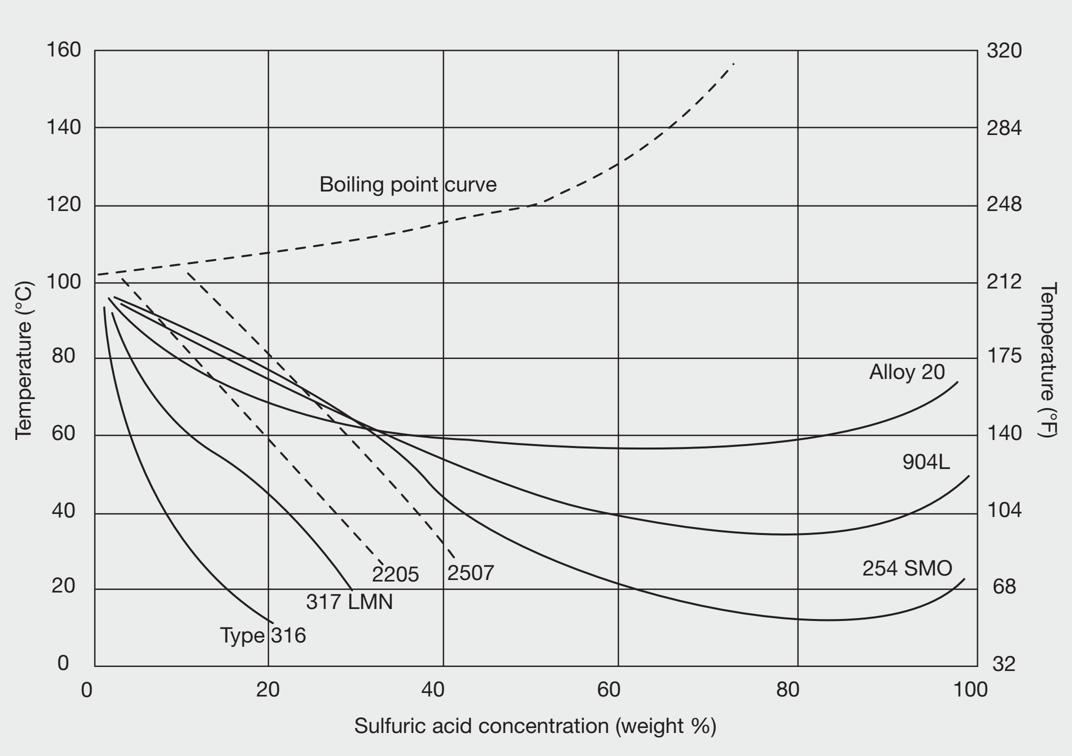


**Figure 6: Corrosion in non-aerated sulfuric acid, 0.1 mm/yr (0.004 inch/yr) isocorrosion diagram (laboratory tests using reagent grade sulfuric acid). (Source: Producer data sheets, 254 SMO is a trademark of Outokumpu)**

steels good candidates for nitric acid service and the strong organic acids. This is illustrated in **Figure 7** 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 pitting 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 stainless steel grade 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 the research tool described in ASTM G 150[1], it is possible to determine the CPT accurately and reliably by electrochemical measurements.

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. 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 [2] procedures (6% ferric chloride) is given in **Figure 8**. 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 deaerated seawater applications where the surface has been maintained free of deposits

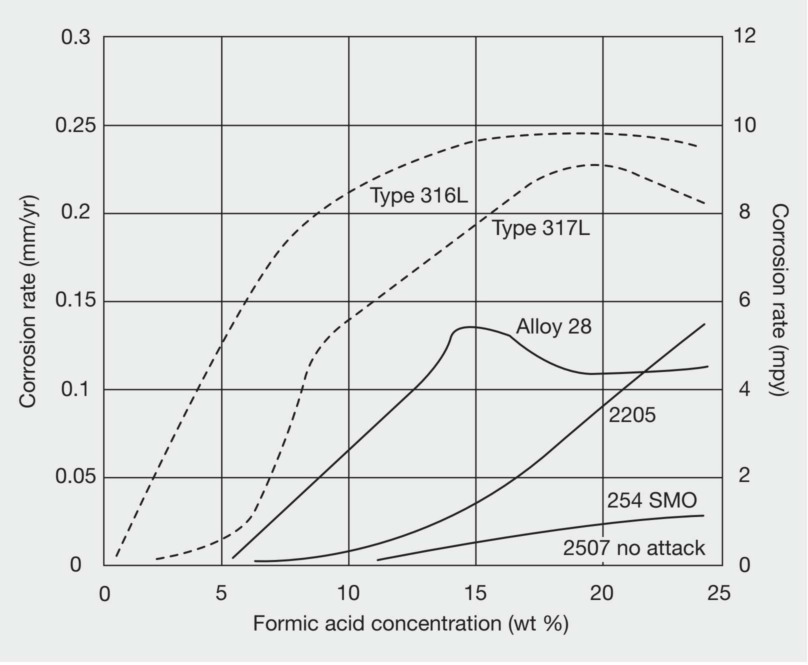


**Figure 7: Corrosion of duplex and austenitic stainless steels in boiling mixtures of 50% acetic acid and varying proportions of formic acid (Source: Sandvik)**

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1 ASTM G 150 standard test method for electrochemical critical pitting temperature testing of stainless steels

2 ASTM G 48 standard test method for pitting and crevice corrosion resistance of stainless steels and related alloys by ferric chloride solution

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, tungsten, and nitrogen showed consistent measurable effect on the CPT according to the relationship:

**CPT = constant + %Cr + 3.3 (%Mo + 0.5%W) + 16%N.**

In this relationship, the sum of the four alloy element variables multiplied by their regression constants is commonly called the Pitting Resistance Equivalent Number (PREN). The coefficient for nitrogen varies among investigators and 16, 22, and 30 are commonly used (Ref. 8). The PREN 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 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 many 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

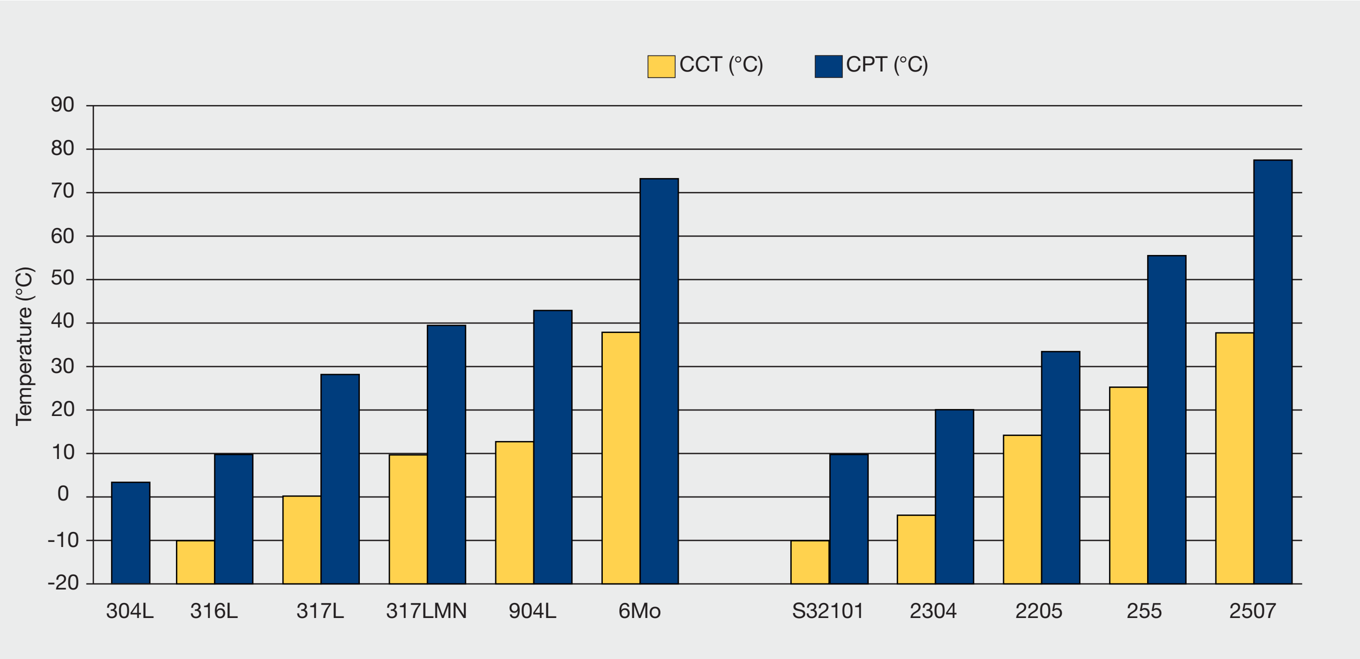

**Figure 8: Critical pitting and crevice corrosion temperatures for unwelded austenitic stainless steels (left side) and duplex stainless steels (right side) in the solution annealed condition (evaluated in 6% ferric chloride by ASTM G 48)**

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.

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 9** (Ref. 9). 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 chloride stress corrosion cracking behavior of different stainless steels in a variety of test environments with a range of severities. 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.

**Duplex stainless steel pipes (Source: Butting)**

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 10** (Ref. 10).

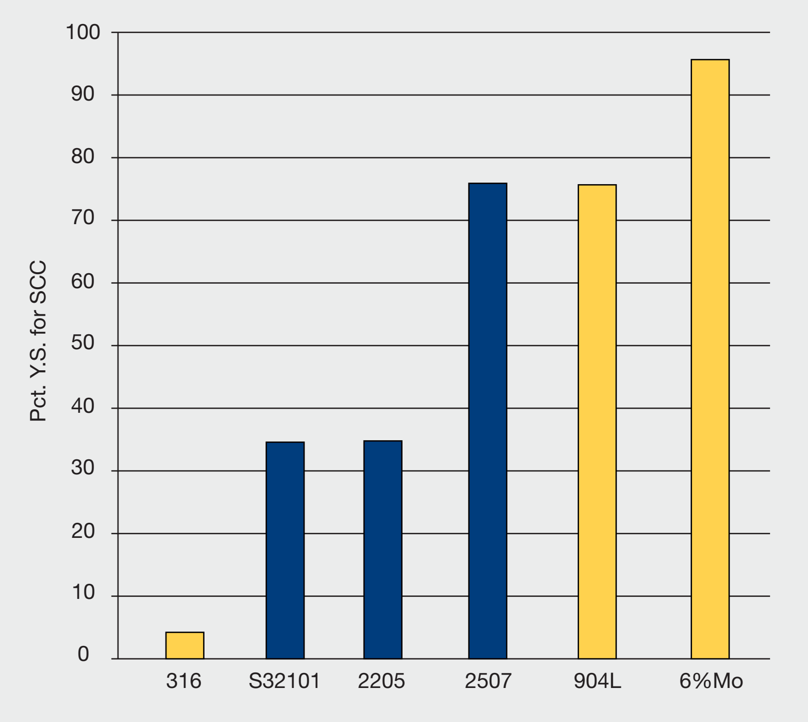

**Figure 9: Stress corrosion cracking resistance of mill annealed austenitic and duplex stainless steels in the drop evaporation test with sodium chloride solutions at 120°C (248°F) (stress that caused cracking shown as a percentage of yield strength) (Source: Outokumpu).**

**Table 4: Comparative stress corrosion cracking resistance of unwelded duplex and austenitic stainless steels in accelerated laboratory tests (Source: various literature sources)**

| Grade | 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 auto-clave 155°C U-bend | 26% NaCl auto-clave 200°C U-bend | 600 ppm Cl(NaCl) auto-clave 300°C U-bend | 100 ppm Cl(sea salt+$O_2$) auto-clave 230°C U-bend |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Type 304L<br>Type 316L | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 3RE60 | ▨ | ▨ | ▨ | ▦ | ▧ | ▧ | ▧ | ▨ | ▨ | □ | ▨ |
| S32101<br>S32202 | ▨ | ▨ | ▨ | ▧ | ▧ | ▧ | ▧ | ▨ | ▨ | □ | ▨ |
| 2205 | ▨ | ▨ | ▨ | ▧ | ▧ | ▧ | ▧ | ▦ | ▨ | □ | ▨ |
| 25 Cr Duplex | ▨ | ▨ | ▨ | ▧ | ▧ | ▧ | ▧ | ▧ | ▨ | □ | □ |
| Superduplex | ▨ | ▨ | ▨ | ▧ | ▧ | ▧ | ▧ | ▧ | □ | □ | □ |

▨ Cracking anticipated ▦ Cracking possible ▧ Cracking not anticipated □ Insufficient data

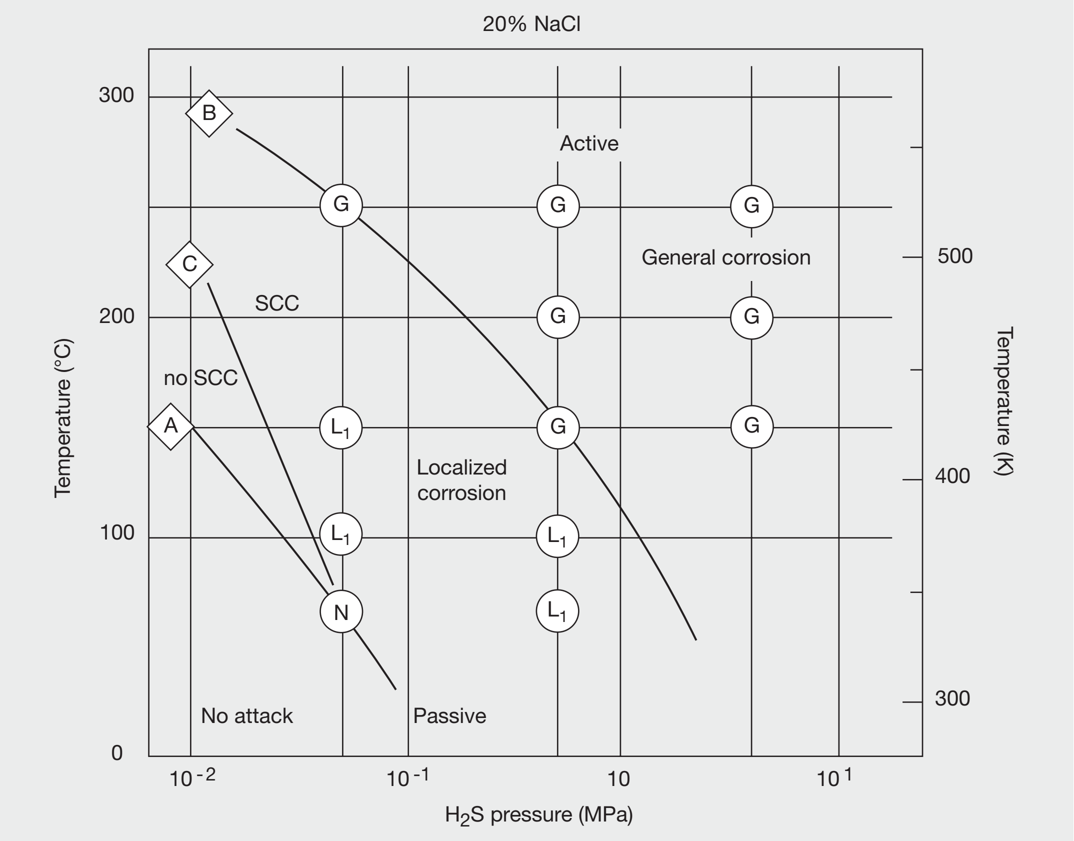

**Figure 10: Corrosion of 2205 duplex stainless steel in 20% sodium chloride-hydrogen sulfide environments based on electrochemical prediction and experimental results.**

# 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 or EN 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 Heat Affected Zone (HAZ) and with respect to greater metallurgical stability. 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 (Ref. 11).

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 "PREN" relationship. While a PREN 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 PREN does not necessarily lead to correct metallurgical balance. The PREN 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 specification 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. 12). When a mill product is slowly cooled, 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 Heat Affected Zone (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. However, this ignores the distortion and increased residual stresses induced by water quenching. In the case of sheet product, 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[3] uses metallographic examination, impact testing, or corrosion testing to demonstrate the absence of a harmful level of intermetallic phases.

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[3] ASTM A 923 standard test methods for detecting detrimental intermetallic phases in duplex austenitic/ferritic stainless steels

This test considers only whether harmful precipitation has already occurred. No similar testing procedure is included in the EN standards. With this type of testing the mill procedure is verified to ensure that harmful intermetallic phases are not formed during processing. This testing is analogous to ASTM A 262[4] or EN ISO 3651-2[5] testing of austenitic stainless steels for sensitization due to chromium carbide precipitation. ASTM A 923 covers only 2205 (S31803 and S32205), 2507, 255, and S32520, but other duplex grades may be added in the future. Many fabricators have adopted these and similar tests or other acceptance criteria, as a part of their qualification for welding procedures.

## 6.2 Special testing requirements

### 6.2.1 Tensile and hardness tests

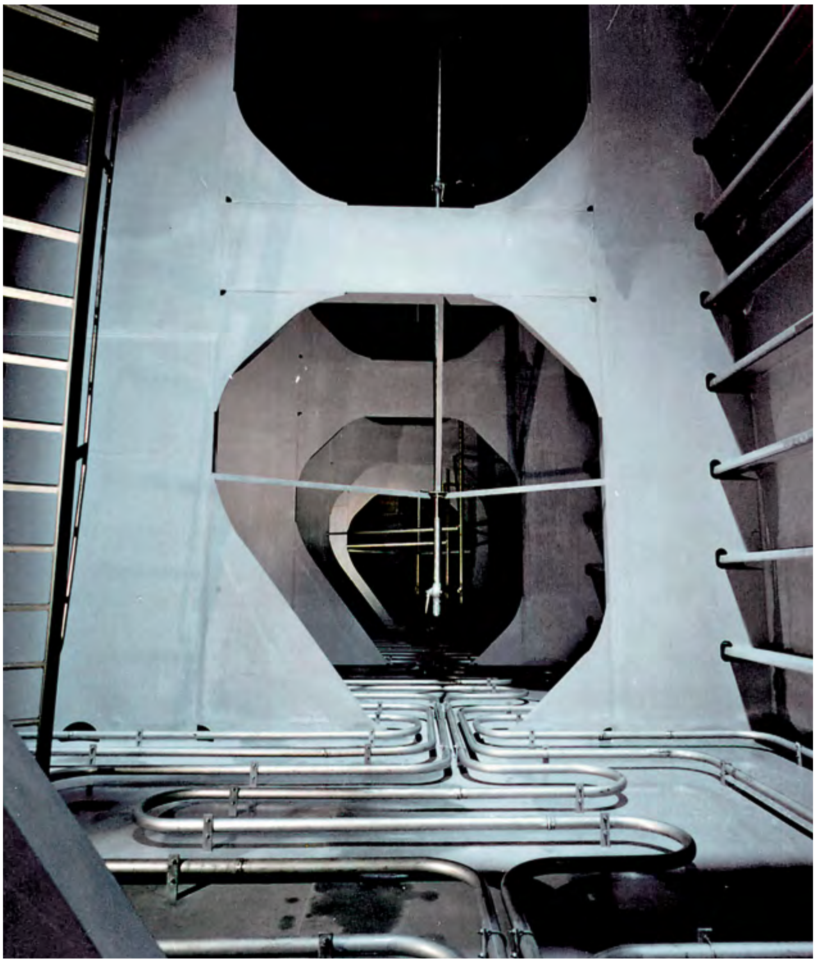
The duplex stainless steels have high strength relative to the austenitic stainless steels. However, there have been occasional end-user specifications in which a maximum has been imposed on either the strength or hardness. Imposing maximums on strength or hardness is probably a carryover from experience with martensitic stainless steels where high strength or hardness is caused by untempered martensite. However, the duplex stainless steels will not form martensite during cooling. 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



**Inside a 2205 (1.4462) tank on a marine chemical tanker (Source: ThyssenKrupp Nirosta)**

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[4] ASTM A 262 standard practices for detecting susceptibility to intergranular attack in austenitic stainless steels

[5] EN ISO 3651-2 Determination of resistance to intergranular corrosion of stainless steels – Part 2: Ferritic, austenitic and ferritic-austenitic (duplex) stainless steels – corrosion test in media containing sulfuric acid

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 described in ASTM A 923, Method B, in a standard longitudinal Charpy test at -40°F/C to less than 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, ASTM 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, ASTM 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 Method C corrosion test rather than the metallographic examination. One way to state this is to require that the corrosion rate be reported.

One advantage of ASTM A 923 Method A is the identification of centerline intermetallic phase, as shown in Figure 7 of ASTM 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 ASTM 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 should be rejected. Although ASTM 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 ASTM A 923 Figure 7 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.

ASME has issued new requirements applicable to duplex stainless steels with section thickness greater than 9.5 mm (0.375 inch) (Ref. 13). These requirements use Charpy impact tests at or below 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 ASTM A 923 test in that 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. ASME requires testing of base metal, weld metal and HAZ for each heat of base material and each lot of filler.

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 the 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 Heat Affected Zone (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 EN ISO 8249[6] 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 ASTM 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 ASTM A 923 Method C, is one of the most cost-effective testing methods for detection 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 critical pitting temperature (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 per ASTM G 48 or ASTM G 150 testing of a single specimen. However, performing a single corrosion test (ASTM A 923 Method C) 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.


**Installation of duplex stainless steel rebar on a large bridge deck (Source: Hardesty & Hanover, LLP)**

Prior to the development of ASTM A 923, the corrosion test was generally called out by referencing the “modified ASTM 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.

ASTM 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. ASTM A 923, Method C, expresses

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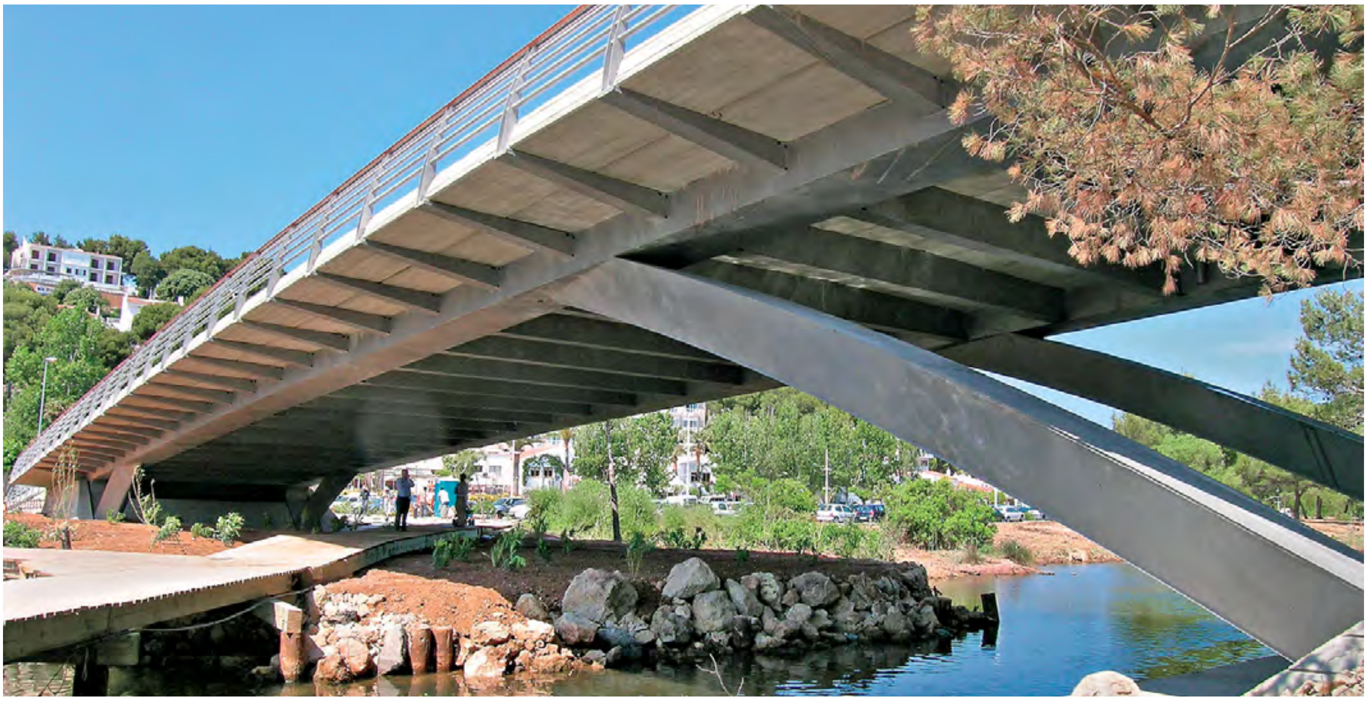
[6] EN ISO 8249 Welding – determination of ferrite number (FN) in austenitic and duplex ferritic-austenitic Cr-Ni stainless steel weld materials



**Bridge in Cala Galdana on Menorca fabricated using 2205 duplex stainless steel (Source: PEDELTA)**

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. They are listed for the standard duplex grades in **Table 5**. 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 11**. 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 notch is positioned perpendicular 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.

**Table 5. Minimum ASTM and EN mechanical property limits for duplex stainless steel plate**

| | ASTM | | | | EN | | | |
|---|---|---|---|---|---|---|---|---|
| Grade | UNS No. | Yield strength 0.2% MPa (ksi) | Tensile strength MPa (ksi) | Elongation in 2" % | EN No. | Proof strength $Rp_{0.2}$ MPa (ksi) | Tensile strength $R_m$ MPa (ksi) | Elongation $A_5$ % |
| **2304** | S32304 | 400 (58) | 600 (87) | 25 | 1.4362 | 400 (58) | 630 (91) | 25 |
| **2205** | S32205 | 450 (65) | 655 (95) | 25 | 1.4462 | 460 (67) | 640 (93) | 25 |
| **2507** | S32750 | 550 (80) | 795 (116) | 15 | 1.4410 | 530 (77) | 730 (106) | 20 |

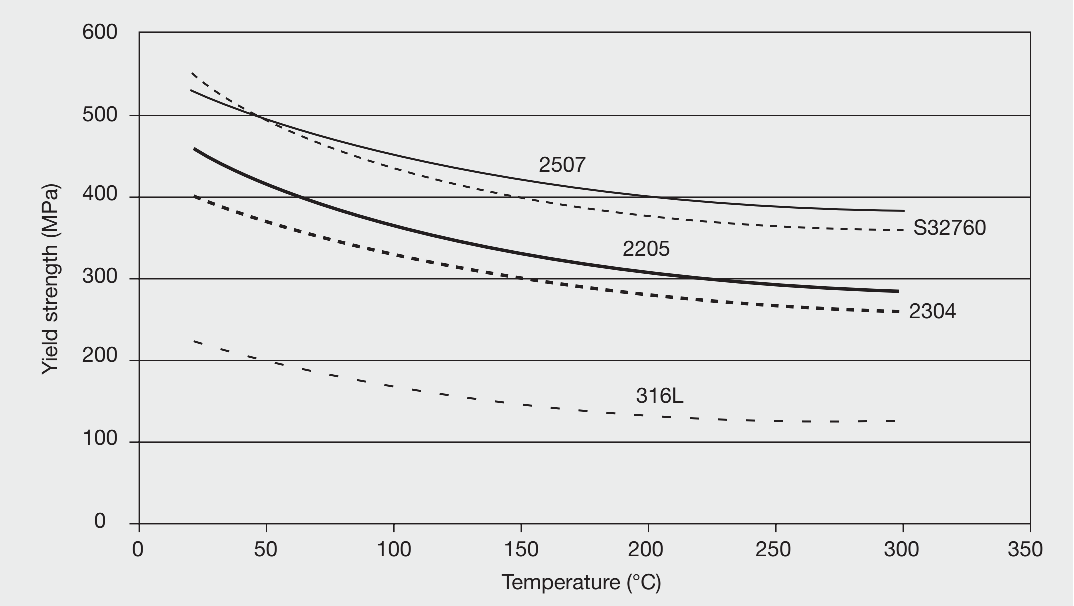


**Figure 11: Comparison of typical yield strength of duplex stainless steels and Type 316L between room temperature and 300°C (572°F) (Source: producer data sheets)**

**Table 6. Comparison of the ductility of duplex and austenitic stainless steels according to the requirements of ASTM A 240 and EN 10088-2**

| ASTM A 240 | | | EN 10088-2 | | | |
|---|---|---|---|---|---|---|
| **UNS No.** | **Grade** | **Elongation, min. (%)** | **EN No.** | **Elongation, min. (%)*** | | |
| | | | | P | H | C |
| **S32003** | | 25 | | | | |
| **S32101** | | 30 | 1.4162 | 30 | 30 | 30 |
| **S32202** | | 30 | 1.4062 | | | |
| **S32304** | 2304 | 25 | 1.4362 | 25 | 20 | 20 |
| **S32205** | 2205 | 25 | 1.4462 | 25 | 25 | 20 |
| **S32750** | 2507 | 15 | 1.4410 | 20 | 15 | 15 |
| **S30403** | 304L | 40 | 1.4307 | 45 | 45 | 45 |
| **S31603** | 316L | 40 | 1.4404 | 45 | 40 | 40 |

P = hot rolled plate H = hot rolled coil C = cold rolled coil and sheet * transverse direction

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 in general lower than those of 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 6**.

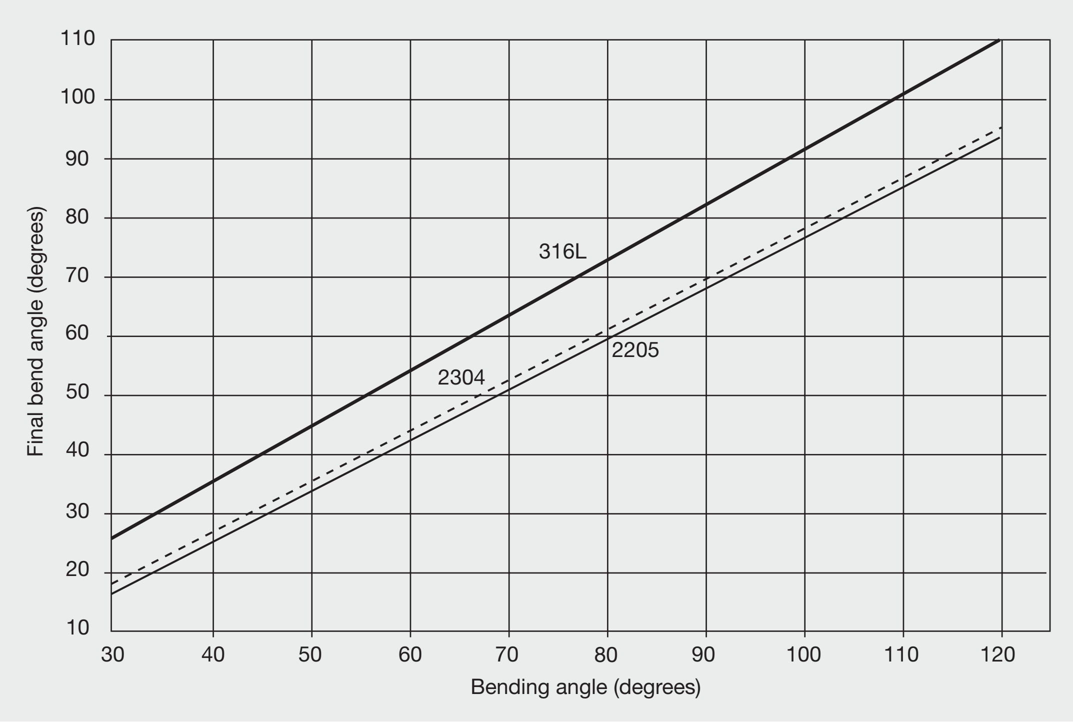


**Figure 12. Comparison of springback of duplex stainless steels and type 316L for 2 mm (0.08 inch) thick sheet (Source: Outokumpu)**

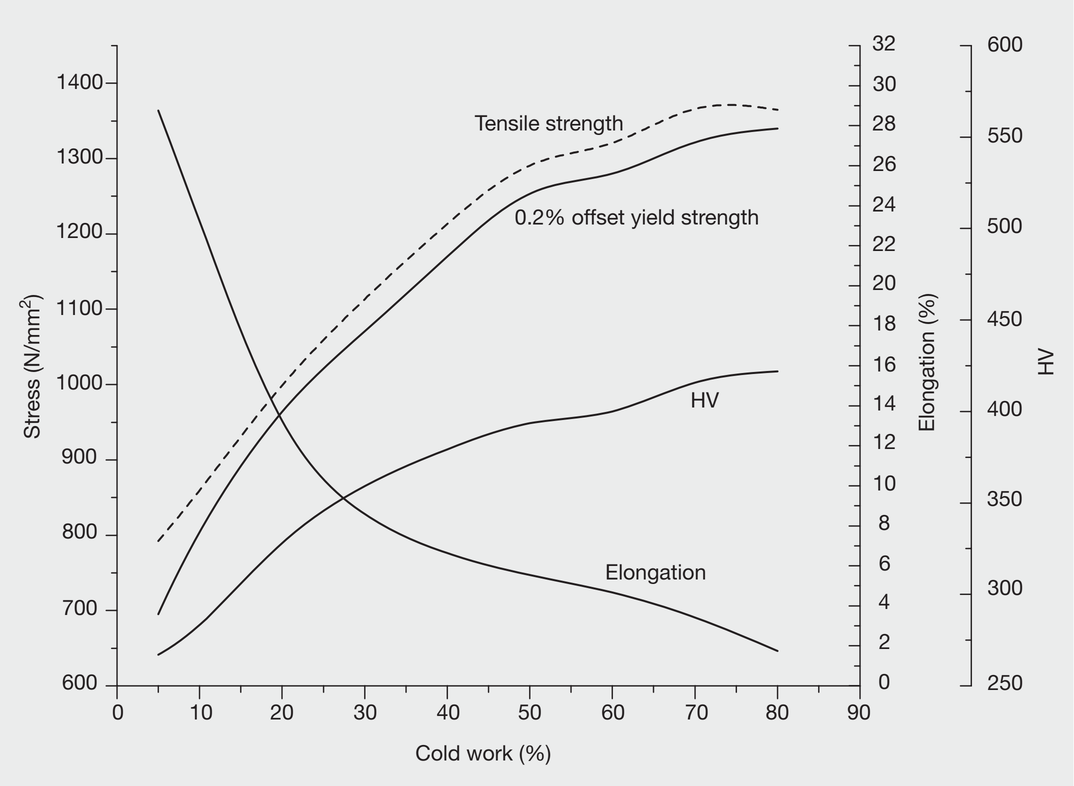


**Figure 13. Effect of cold work on the mechanical properties of 2205 duplex stainless steel (Source: Baosteel)**

While the high yield strength of duplex stainless steel can allow down gauging, depending on buckling and Young's Modulus limitations, 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 12**. Duplex stainless steels have less ductility than austenitic stainless steels and increased bend radii may be required to avoid cracking.

Because of their higher hardness and the high work hardening rate, duplex stainless steels typically reduce the tool life in machining operations or typically 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 approximately half of the austenitic stainless steels. The effect of cold work on the mechanical properties of 2205 is shown in **Figure 13**.

**Installation of insulated 24 inch 2205 pipe on vertical support members in Prudhoe Bay (Source: Arco Exploration and Production Technology)**

# 8 Physical Properties

Ambient temperature physical properties for a selection of duplex stainless steels are given in **Table 7**, and selected elevated temperature values are given in **Table 8**. Data are included for carbon steel and austenitic stainless steels for comparison.

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.

**Table 7: Ambient temperature physical properties of duplex stainless steels compared with carbon steel and austenitic stainless steels (Source: producer data sheets)**

| Grade | UNS No. | Density | | Specific heat | | Electrical resistivity | | Young's modulus | |
|---|---|---|---|---|---|---|---|---|---|
| | | g/cm$^3$ | lb./in$^3$ | J/kg K | Btu/lb./°F | micro Ω m | micro Ω in. | GPa | x10$^6$ 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 |
| | S31500 | 7.75 | 0.280 | 482 | 0.115 | | | 200 | 29.0 |
| | S32101 | 7.80 | 0.281 | 500 | 0.119 | 0.80 | 31.5 | 200 | 29.0 |
| **2304** | S32304 | 7.75 | 0.280 | 482 | 0.115 | 0.80 | 31.5 | 200 | 29.0 |
| | S31803 | 7.80 | 0.281 | 500 | 0.119 | 0.80 | 31.5 | 200 | 29.0 |
| **2205** | S32205 | 7.80 | 0.281 | 500 | 0.119 | 0.80 | 31.5 | 200 | 29.0 |
| | S31260 | 7.80 | 0.281 | 502 | 0.120 | | | 200 | 29.0 |
| | S32750 | 7.85 | 0.285 | 480 | 0.114 | 0.80 | 31.5 | 205 | 29.7 |
| **255** | S32550 | 7.81 | 0.282 | 488 | 0.116 | 0.84 | 33.1 | 210 | 30.5 |
| | S39274 | 7.80 | 0.281 | 502 | 0.120 | | | 200 | 29.0 |
| | S32760 | 7.84 | 0.281 | | | 0.85 | 33.5 | 190 | 27.6 |
| | 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 8: Elevated temperature physical properties of duplex stainless steels compared with carbon steel and austenitic stainless steels (Source: producer data sheets)**

| Grade | 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) | | | |
| | S31500 | 200 (29.0) | 190 (27.6) | 180 (26.1) | 170 (24.7) | 160 (23.2) | 150 (21.8) |
| | S32101 | 200 (29.0) | 194 (28.0) | 186 (27.0) | 180 (26.1) | | |
| **2304** | S32304 | 200 (29.0) | 190 (27.6) | 180 (26.1) | 170 (24.7) | 160 (23.2) | 150 (21.8) |
| | S31803 | 200 (29.0) | 190 (27.6) | 180 (26.1) | 170 (24.7) | 160 (23.2) | 150 (21.8) |
| **2205** | S32205 | 200 (29.0) | 190 (27.6) | 180 (26.1) | 170 (24.7) | 160 (23.2) | 150 (21.8) |
| **255** | S32550 | 210 (30.5) | 200 (29.9) | 198 (28.7) | 192 (27.8) | 182 (26.4) | 170 (24.7) |
| | S32520 | 205 (29.7) | 185 (26.8) | 185 (26.8) | 170 (24.7) | | |
| **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 $10^{-6}$/K ($10^{-6}$/°F) | | | | | | | |
| **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) |
| | S31500 | NA | 13.0 (7.22) | 13.5 (7.50) | 14.0 (7.78) | 14.5 (8.06) | 15.0 (8.33) |
| | S32101 | NA | 13.0 (7.22) | 13.5 (7.50) | 14.0 (7.78) | | |
| **2304** | S32304 | NA | 13.0 (7.22) | 13.5 (7.50) | 14.0 (7.78) | 14.5 (8.06) | 15.0 (8.33) |
| | S31803 | NA | 13.0 (7.22) | 13.5 (7.50) | 14.0 (7.78) | 14.5 (8.06) | 15.0 (8.33) |
| **2205** | S32205 | NA | 13.0 (7.22) | 13.5 (7.50) | 14.0 (7.78) | 14.5 (8.06) | 15.0 (8.33) |
| **255** | S32550 | NA | 12.1 (6.72) | 12.6 (7.00) | 13.0 (7.22) | 13.3 (7.39) | 13.6 (7.56) |
| | 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 K (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 | | | | | | |
| | S31500 | 16.0 (110) | 17.0 (118) | 19.0 (132) | 20.0 (138) | 21.0 (147) | 22.0 (153) |
| | S32101 | 15.0 (105) | 16.0 (110) | 17.0 (118) | 18.0 (124) | | |
| **2304** | S32304 | 16.0 (110) | 17.0 (118) | 19.0 (132) | 20.0 (138) | 21.0 (147) | 22.0 (153) |
| | S31803 | 16.0 (110) | 17.0 (118) | 19.0 (132) | 20.0 (138) | 21.0 (147) | 22.0 (153) |
| **2205** | S32205 | 16.0 (110) | 17.0 (118) | 19.0 (132) | 20.0 (138) | 21.0 (147) | 22.0 (153) |
| **255** | S32550 | 13.5 (94) | 15.1 (105) | 17.2 (119) | 19.1 (133) | 20.9 (145) | 22.5 (156) |
| | 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) |

# 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.

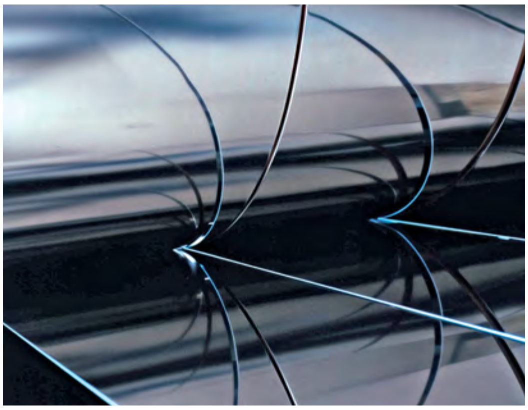
## 9.2 Shearing

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 is about 58% of the 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 Slitting

Conventional coil slitters are used to shear coiled duplex stainless steel sheet or strip. The coiled stainless steel feeds off from a payoff reel and through an upper and lower arbor on the slitting line that contains circular slitting knives, and a take-up reel recoils the slit width coils. The position of the slitting knives can be adjusted based on the desired slit mult width of the coil product. Because of the higher strength of duplex stainless steels compared to austenitic stainless steels, slitter knife tool wear and slit edge consistency are more difficult to control. Maintaining good slit edge quality of duplex stainless steel coils requires the use of tool steel or carbide slitter knifes.



**Slitting of duplex stainless steel (Source: ThyssenKrupp Nirosta)**

## 9.4 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.

## 9.5 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 Heat Affected Zone (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 (2000°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 9** 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.

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 150 mm to 200 mm (6–8 inches) for wrought 2205 plate and 75 mm to 125 mm (3–5 inches) for wrought superduplex plate, the exact limits vary with the composition of the duplex stainless steel and the efficiency of the quenching equipment. 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 necessary to perform a full solution anneal followed by a rapid quench to fully restore the mechanical properties and corrosion resistance. The work piece should be brought above the minimum solution annealing temperature and held long enough to dissolve any intermetallic precipitates. A conservative guideline is that the holding time at temperature 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

**Table 9: Hot forming temperature range and minimum soaking temperature for duplex stainless steels (common austenitic grades are included for comparison) (Source: producer data sheets)**

| Grade | UNS No. | EN No. | Hot forming temperature range | | Minimum soaking temperature | |
|---|---|---|---|---|---|---|
| | | | °C | °F | °C | °F |
| | S32101 | 1.4162 | 1100 to 900 | 2000 to 1650 | 950 | 1750 |
| **2304** | S32304 | 1.4362 | 1150 to 950 | 2100 to 1740 | 980 | 1800 |
| **2205** | S32205 | 1.4462 | 1230 to 950 | 2250 to 1740 | 1040 | 1900 |
| **2507** | S32750 | 1.4410 | 1230 to 1025 | 2250 to 1875 | 1050 | 1920 |
| | S32520 | 1.4507 | 1230 to 1000 | 2250 to 1830 | 1080 | 1975 |
| | S32760 | 1.4501 | 1230 to 1000 | 2250 to 1830 | 1100 | 2010 |
| **304** | S30400 | 1.4301 | 1205 to 925 | 2200 to 1700 | 1040 | 1900 |
| **316** | S31600 | 1.4401 | 1205 to 925 | 2200 to 1700 | 1040 | 1900 |

in the 700–1000°C (1300–1830°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 10**.

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 the 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.

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.

**Table 10: Minimum solution annealing temperatures for duplex stainless steels (Source: producer data sheets and ASTM A 480)**

| Grade | UNS No. | Minimum annealing temperature | |
|---|---|---|---|
| | | °C | °F |
| **2304** | S32304 | 980 | 1800 |
| | S32003 | 1010 | 1850 |
| | S32001 | 1040 | 1900 |
| | S32101 | 1020 | 1870 |
| | S32202 | 980 | 1800 |
| | S82011 | 1010 | 1850 |
| **2205** | S32205 | 1040 | 1900 |
| | S32506 | 1020 to 1120 | 1870 to 2050 |
| | S32520 | 1080 to 1120 | 1975 to 2050 |
| **255** | S32550 | 1040 | 1900 |
| **2507** | S32750 | 1025 to 1125 | 1880 to 2060 |
| | S32760 | 1100 | 2010 |

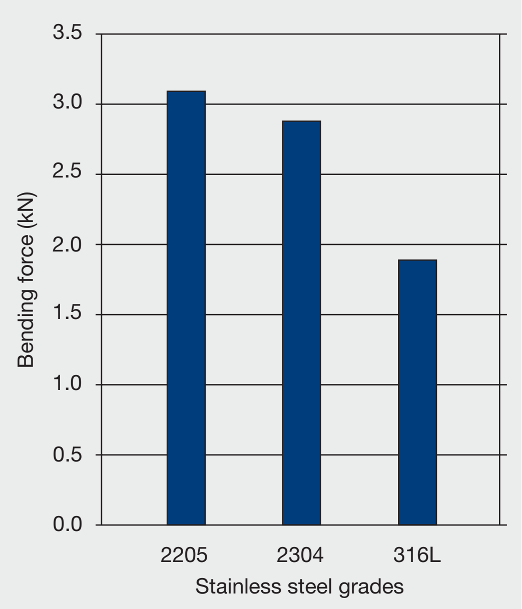


**Figure 14: Minimum force required to begin plastic deformation in bending of 2304, 2205, and 316L test samples 50 mm (2 inch) wide and 2 mm (0.08 inch) thick (Source: Outokumpu)**

## 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 5). 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 10).

## 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 austenitic grade at twice the thickness. A comparison of the minimum force required to begin plastic deformation in bending is shown in **Figure 14** for several stainless steels. Thickness reductions are possible using duplex stainless steels, but the reductions will be less than anticipated from the increase in yield strength. 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 12).

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 30% 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 annealing 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 stretch forming properties are limited by the ferrite phase, and they do not possess the high work hardening that permits austenitic stainless steels to be stretch formed so extensively.

## 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 annealing treatments 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.

# 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 typically 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 15** with a relative machinability index comparison for some duplex stainless steels and Type 316. Note, the higher machinability rating of the lean duplex stainless steel S32101 compared to 316 stainless steel.

## 11.1 General guidelines for machining duplex stainless steels

The following guidelines for machining are generally applicable to all stainless steels, but the importance of these guidelines apply 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.

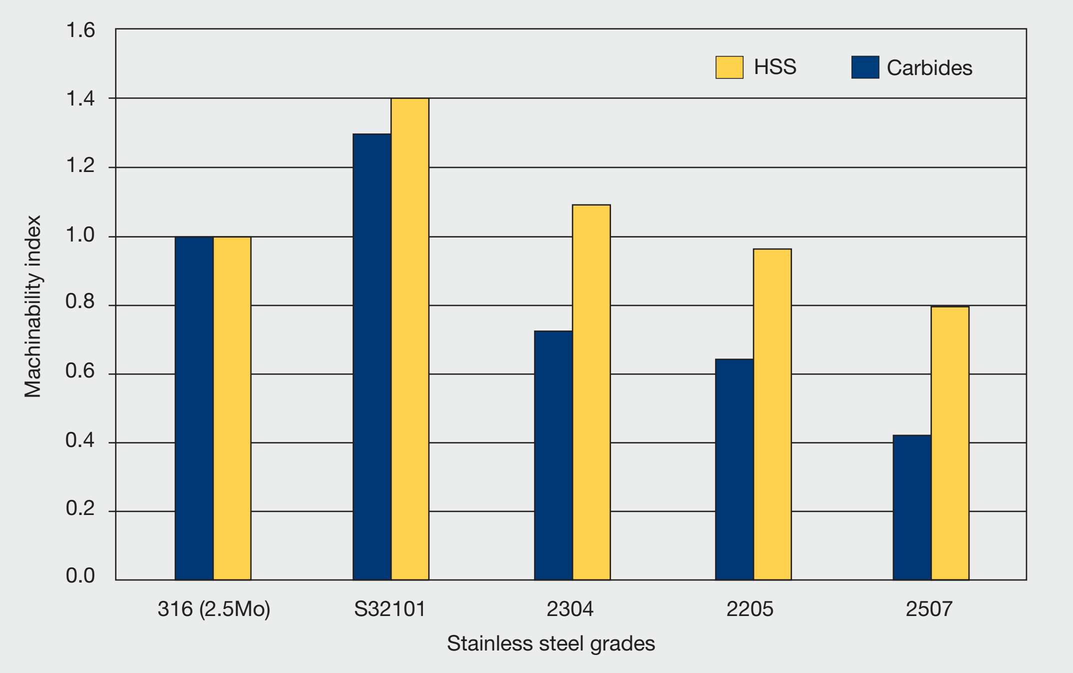


**Figure 15. Relative machinability of duplex stainless steels compared with Type 316 (2.5Mo) for cemented carbide tooling and for high speed steel tooling (Source: Outokumpu)**

- 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 chip-breaker geometry.

## 11.2 Turning and facing

Turning and facing operations involve so many variables that it is impossible to make specific recommendations that would apply to all conditions. The general guidelines for turning and cutting are provided in **Figure 16** and **Table 11**. Carbide tools can be used in turning operations and will allow higher speeds than high-speed tool steels. However, carbide tooling requires even greater attention to the rigidity of the tooling and the workpiece, and interrupted cuts should be avoided.

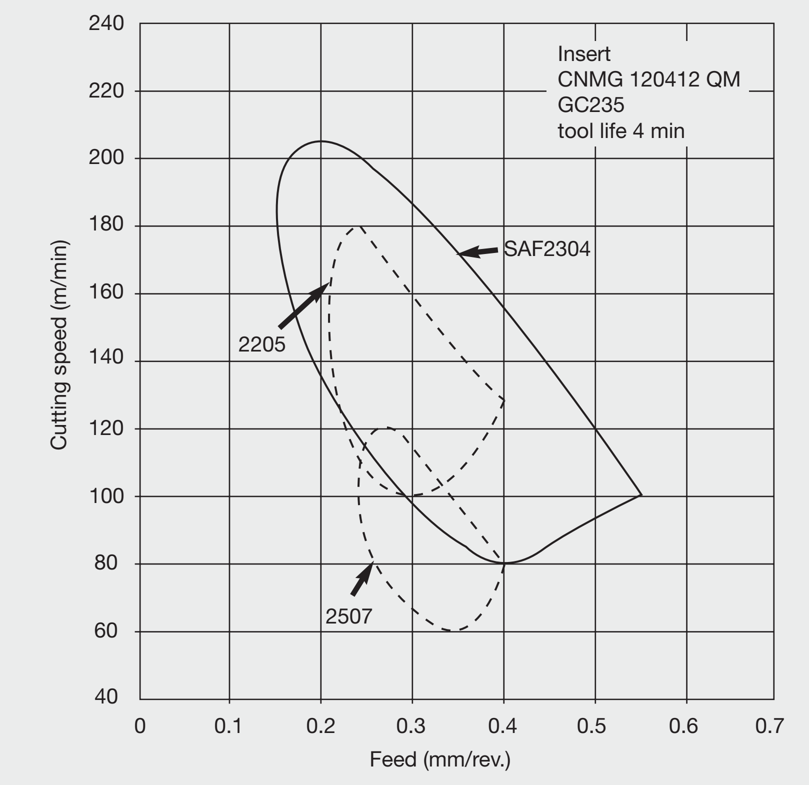
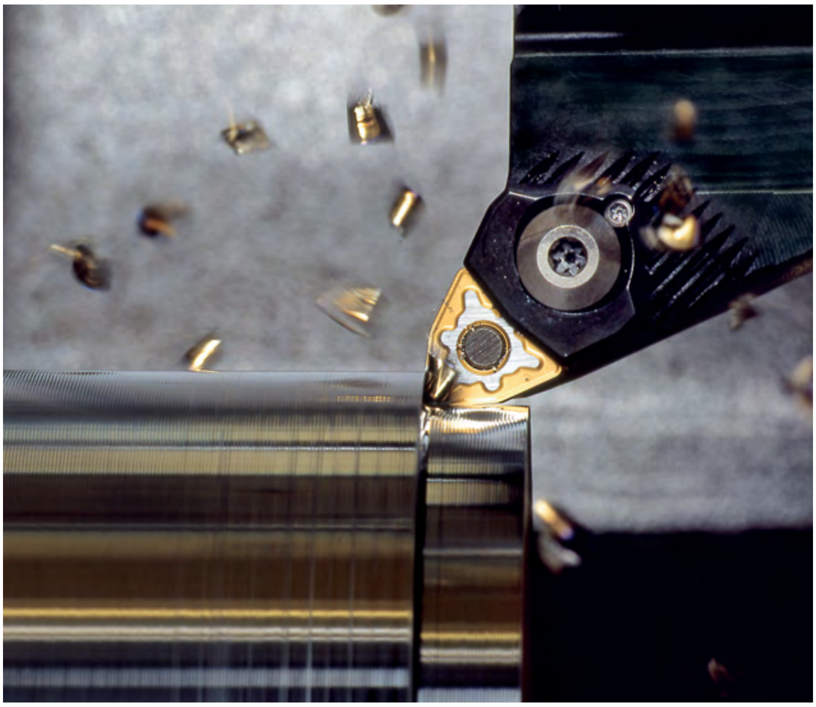


**Figure 16: Comparison of machining parameters for turning duplex stainless steels with a cemented carbide insert with a tool life of four minutes (Source: Sandvik)**

**Table 11: Machining guidelines for face turning duplex stainless steels (Source: Outokumpu)**

| 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) |
| **S32101** | 170–240 | 560–790 | 200–280 | 660–925 | 20–30 | 65–100 |
| **2304** | 120–160 | 400–525 | 150–210 | 500–680 | 18–25 | 60–85 |
| **2205** | 90–120 | 300–400 | 120–160 | 400–525 | 15–20 | 50–65 |
| **Superduplex** | 50–70 | 165–230 | 70–105 | 230–350 | 10–15 | 35–50 |
| **Feed (per turn)** | 0.3–0.6mm | 0.012–0.024 in. | 0.05–0.3 mm | 0.002–0.012 in. | 0.05–0.2mm | 0.002–0.008 |
| **Depth of cut** | 2–5 mm | 0.080–0.200 in. | 0.5–2 mm | 0.020–0.080 | 0.5–2 mm | 0.020–0.080 |
| **Grade** | 2101, 2304, 2205:<br>ISO P20–P35 (C5)<br>Superduplex: ISO P30–P50 | | 2101, 2304, 2205:<br>ISO P10–P15 (C6–C7)<br>Superduplex: ISO P25–P35 | | High quality | |



**Turning operation (Source: Seco Tools)**

## 11.3 Face milling with cemented carbides

Guidelines for face milling duplex stainless steels with cemented carbides are provided in **Table 12**.

- 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 13** and **14**.

- 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.

**Table 12: Machining guidelines for face milling duplex stainless steels with cemented carbides (Source: Outokumpu)**

| Stainless steel (or machining data) | Roughing | | Finishing | |
|---|---|---|---|---|
| | Speed (m/min) | Speed (sfm) | Speed (m/min) | Speed (sfm) |
| S32101 | 180–230 | 595–760 | 200–250 | 660–825 |
| 2304 | 100–130 | 330–425 | 130–150 | 425–525 |
| 2205 | 50–80 | 165–260 | 80–110 | 260–360 |
| 2507 | 30–50 | 100–165 | 50–70 | 165–230 |
| Feed (per tooth) | 0.2–0.4 mm | 0.008–0.016 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 | 2101, 2304, 2205: ISO P20–P40<br>Superduplex: ISO P25–P40 | | 2101, 2304, 2205: ISO P10–P25<br>Superduplex: ISO P20–P30 | |

**Table 13: High speed steel twist drilling parameters for duplex stainless steels in SI units (Source: Outokumpu)**

| Drill diameter (mm) | Speed (m/min) | | | | Feed (mm/rev) | |
|---|---|---|---|---|---|---|
| | S32101 | 2304 | 2205 | Superduplex | S32101, 2304, 2205 | Superduplex |
| 1–3 | 12–37 | 6–10 | 6–8 | 5–8 | 0.05 | 0.04 |
| 5 | 12–37 | 10–12 | 10–12 | 9–11 | 0.10 | 0.08 |
| 10 | 12–37 | 12–15 | 10–12 | 9–11 | 0.20 | 0.15 |
| 15 | 12–37 | 12–15 | 10–12 | 9–11 | 0.25 | 0.20 |
| 20 | 12–37 | 12–15 | 10–12 | 9–11 | 0.30 | 0.25 |
| 30 | 12–37 | 12–15 | 10–12 | 9–11 | 0.35 | 0.30 |
| 40 | 12–37 | 12–15 | 10–12 | 9–11 | 0.41 | 0.35 |

**Table 14: High speed steel twist drilling parameters for duplex stainless steels in English units (Source: Outokumpu)**

| Drill diameter (in.) | Speed (sfm) | | | | Feed (in./rev) | |
|---|---|---|---|---|---|---|
| | S32101 | 2304 | 2205 | Superduplex | S32101, 2304, 2205 | Superduplex |
| 0.040-0.120 | 40–120 | 20–33 | 20–25 | 16–25 | 0.002 | 0.0015 |
| 0.2 | 40–120 | 33–40 | 33–40 | 30–36 | 0.004 | 0.003 |
| 0.4 | 40–120 | 40–50 | 33–40 | 30–36 | 0.008 | 0.006 |
| 0.6 | 40–120 | 40–50 | 33–40 | 30–36 | 0.01 | 0.008 |
| 0.8 | 40–120 | 40–50 | 33–40 | 30–36 | 0.012 | 0.01 |
| 1.2 | 40–120 | 40–50 | 33–40 | 30–36 | 0.014 | 0.012 |
| 1.6 | 40–120 | 40–50 | 33–40 | 30–36 | 0.016 | 0.014 |

# 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 due to the high ferrite content, hot cracking is rarely a consideration when welding these steels. The problems of most concern in duplex stainless steels are associated with the Heat Affected Zone (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.

**2205 oxygen delignification reactor, Enterprise Steel Fab, Kalowna, Prince George, British Columbia, Canada (Source: Outokumpu)**

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 700 to 1000°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 user specification and quality control (Section 6).

### 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 to the uniformity of 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 illustrated in **Figure 17**. Other designs are possible provided they assure full penetration welds and minimize the risk of burn-through.

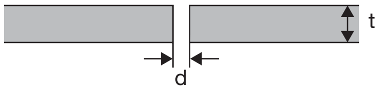
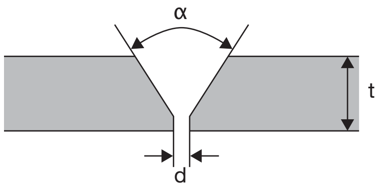
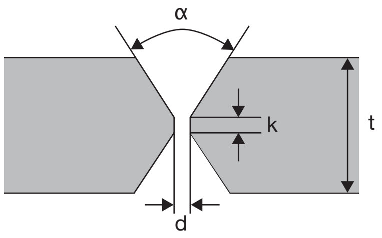
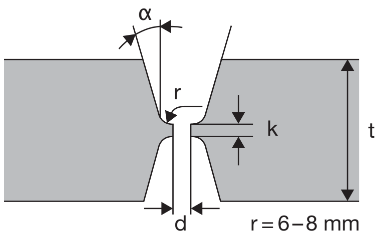
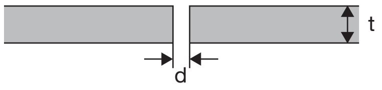
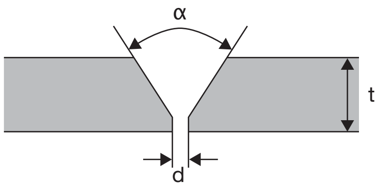
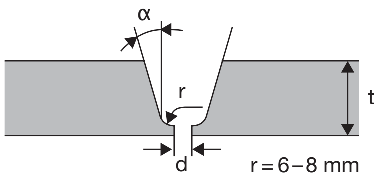
| Groove | Process | Thickn. t (mm) | Gap d (mm) | Root k (mm) | Bevel α (°) |
|---|---|---|---|---|---|
|  | GTAW | 3–5 | 1–3 | – | – |
| | GMAW | 3–6 | 1–3 | – | – |
| | SMAW | 3–4 | 1–3 | – | – |
|  | SMAW | 4–15 | 1–3 | 1–2 | 55–65 |
| | GTAW | 3–8 | 1–3 | 1–2 | 60–70 |
| | GMAW | 5–12 | 1–3 | 1–2 | 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 17: Examples of weld joint designs used with duplex stainless steels (Source: ArcelorMittal)**

### 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 100°C (200°F) uniformly and only after the weld preparation has been cleaned.

### 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) for lean and standard duplex stainless steels and 100°C (210°F) for superduplex stainless steels. 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. Postweld heat treating temperatures in excess of 315°C (600°F) can adversely affect the toughness and corrosion resistance of duplex stainless steels.

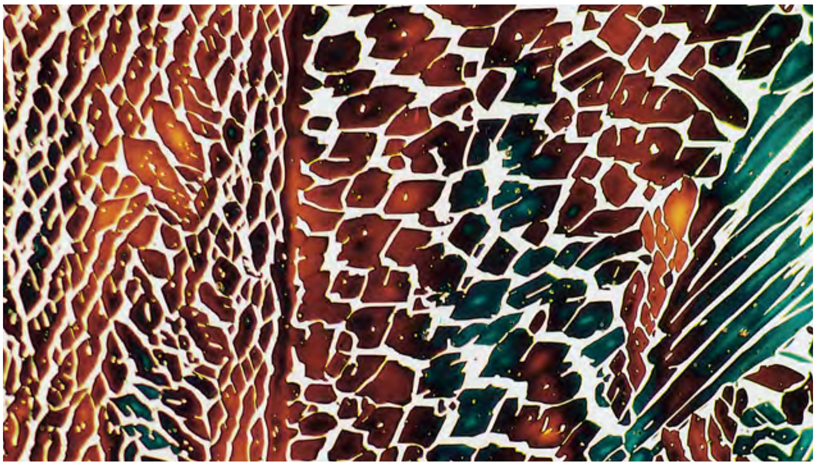
Any postweld heat treatment should include full solution annealing followed by water quenching (see Table 10). Full solution annealing should be considered after autogenous welding, since the microstructure will be highly ferritic if an overalloyed filler metal is not used during welding.

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 annealing treatment 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 the 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.



**Metallographic structure of 2205 duplex weld metal, 500x (Source: Lincoln Smitweld bv)**

## 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. The elevated nickel content of the filler metal ensures that an adequate level of austenite is formed in the weld during cooling.

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 E309LMo/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 15** 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.

**Table 15: Welding consumables used for dissimilar metal welding**

| | **2304, S32101<br>S32202, S82011** | **2205<br>S32003** | **25 Cr duplex<br>Superduplex** |
|---|---|---|---|
| **2304<br>S32101<br>S32202<br>S82011** | 23Cr-7Ni-N<br>E2209<br>E309L | E2209 | E2209 |
| **2205<br>S32003** | E2209 | E2209 | 25Cr-10Ni-4Mo-N |
| **25 Cr duplex<br>Superduplex** | E2209 | 25Cr-10Ni-4Mo-N | 25Cr-10Ni-4Mo-N |
| **304** | E2209<br>E309L<br>E309LMo | E2209<br>E309LMo | E2209<br>E309LMo |
| **316** | E2209<br>E309LMo | E2209<br>E309LMo | E2209<br>E309LMo |
| **Carbon steel<br>Low alloy steel** | E2209<br>E309L<br>E309LMo | E2209<br>E309L<br>E309LMo | E2209<br>E309L<br>E309LMo |

## 12.2 Welding procedure qualification

With standard austenitic 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 thickness, filler, and welding method) determined to be the most demanding on the duplex stainless steel.

**2507 stainless steel enhanced oil recovery equipment (Source: Aquatech)**

## 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 controlling phase stability, 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.

### 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.

**Mechanized welding of large diameter duplex stainless steel cross-country pipeline (Source: Arco Exploration and Production Technology)**

### 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.

### 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

**Lean duplex stainless steel asphalt hauling tanker (Source: Outokumpu)**

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) for standard duplex stainless steels and below 100°C (210°F) for superduplex stainless steels between welding passes to provide for adequate cooling of the HAZ in subsequent passes.

For GTAW, the filler metal most commonly used in joining duplex stainless steel is the "matching" filler, somewhat overalloyed with nickel. The superduplex filler metals have also been used successfully to weld 2205 stainless steel. 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 (kJ/mm) = (V x A )/(S x 1000)**
where V = voltage (volt)
A = current (ampere)
S = travel speed (mm/s)
or
**Heat input (kJ/inch) = (V x A x 6)/(S x 100)**
where V = voltage (volt)
A = current (ampere)
S = travel speed (in/min)

General heat input recommendations:

| | |
|---|---|
| 2304 or lean duplex | 0.5–2.0 kJ/mm (15–50 kJ/in) |
| 2205 | 0.5–2.5 kJ/mm (15–65 kJ/in) |
| 2507 | 0.3–1.5 kJ/mm (8–38 kJ/in) |

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

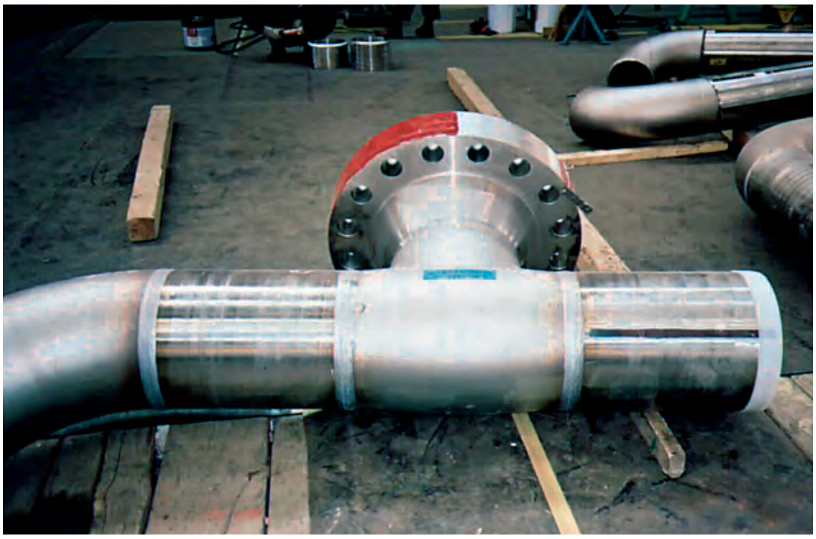
Selection of shielding gas for GMAW is somewhat more complex than for GTAW, and depends to a significant extent on whether the fabricator is relying upon purchased gas mixtures or has on-site gas mixing capability. The GMAW shielding gasses range from pure argon to about 80% argon with additions of helium, 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. Excessive wire stickout should be avoided to allow shielding to be maintained during welding. 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 16**.

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.

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)**

**Table 16: 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: Avesta Welding)**

| Weld wire diameter | | Current | Voltage |
|---|---|---|---|
| mm | inch | A | V |
| **Short-circuiting arc transfer** | | | |
| 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 | 25–28 |
| 1.2 | 0.045 | 210–280 | 26–29 |
| 1.6 | 0.063 | 270–330 | 27–30 |

**Mechanized welding of large diameter duplex stainless steel pipeline on Alaska's north slope (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.

Wire sizes of 1.0, 1.2, and 1.6 mm (1/32, 3/64, and 1/16 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 powder inside the wire provides some of the weld metal alloying elements and the 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 and is suitable for out-of-position welding and for a wide range of 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 80% argon-20% 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). Control of wire stickout is important in limiting carbon pickup, especially if 100% carbon dioxide is used.

### Technique and parameters

For 1.2 mm (0.045 inch) diameter wire, the typical current and voltage settings are 150–200 A at 22–38 V and 60–110 A at 20–24 V, 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 minimum 54 J/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. The minimum impact energy for the weld metal is 34 J/ 25 ft lb and 54 J/ 40 ft lb for the heat affected zone according to ASTM A 923.

### Shielding

Shielding is not usually an issue in SMAW because this method relies upon the protective flux and gases 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 17**.

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.

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.

**Table 17: Typical shielded metal arc welding (SMAW) parameters for welding duplex stainless steels with various size electrodes (Source: Outokumpu)**

| Electrode diameter | | | |
|---|---|---|---|
| Weld wire diameter | | Current | Voltage |
| mm | inch | A | V |
| 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 |

**2205 manifold (Source: Arco Exploration and Production Technology)**

### 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 adjustments of joint design or welding parameters relative to austenitic stainless steels to obtain full penetration welds. SAW welds made at very fast travel speeds combined with unfavorable groove designs may lead to centerline cracks, but lowering the travel speed normally solves the cracking problem. 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 18**.

**Table 18: Typical submerged arc welding (SAW) parameters for welding duplex stainless steels with various size wire (Source: Outokumpu)**

| Weld wire diameter | | Current | Voltage |
|---|---|---|---|
| mm | inch | A | V |
| 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 |

Note: Travel speed is typically 30–60 cm/minute

### 12.3.6 Electron beam and laser welding

The experience with these welding methods as applied to duplex stainless steels has been positive. These procedures produce very limited heat affected zones and rapid cooling that prevents intermetallic phase formation. However, the high cooling rate associated with these techniques can result in excessive ferrite formation in the weld so weld qualification of the procedure is critical when using these methods. Solution annealing after welding with these techniques reduces the ferrite level and improves the austenite/ferrite phase ratio of the weld.

### 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.

**2507 stainless steel falling film evaporator (Source: Gary Carinci, TMR Stainless)**

## 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 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). Types of brazing filler metals include silver brazing alloys, nickel brazing alloys, and copper brazing alloys. The silver brazing alloys are lower-melting and brazed at 618–705°C (1145–1300°F), and the copper alloys are brazed at 1100–1150˚C (2000–2100˚F), while nickel brazing alloys are higher-melting, up to 1175°C (2150°F). The nickel brazed joints can withstand a higher service temperature than the copper and silver brazed joints.

The temperature range 705–980°C (1300–1800°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). Brazed joints can be quenched from brazing temperatures in excess of 1040°C (1900°F).

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.

**Flue gas desulfurization unit fabricated using 2205 stainless steel (Source: ArcelorMittal)**

# 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 18** shows a summary of these disruptions that may occur during fabrication and that should be removed before putting any stainless steel in service.

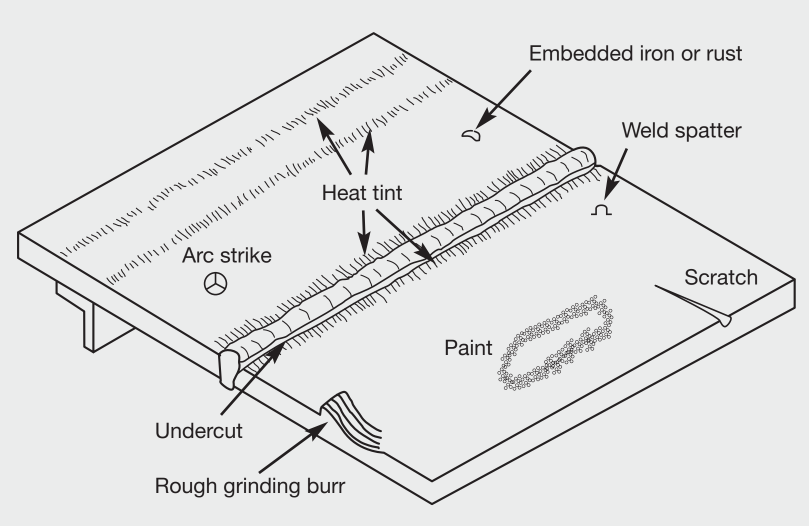


**Figure 18. Typical fabrication defects or surface conditions which may be encountered (Source: Nickel Institute Publication 10 026)**

## 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. In addition, they can lead to carbonaceous contamination. If further welding takes place, carbide precipitation can occur. The steel can then be sensitized and intergranular corrosion can occur in service. The contamination should be removed with solvents.

## 14.2 Embedded iron (ferrous contamination)

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

**Embedded iron in roll formed duplex stainless steel plate fabrication (Source: Gary Carinci, TMR Stainless)**

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[7]. It is especially important that the user be familiar with the safety issues discussed in ASTM A 380.

ASTM A 967[8] (replacing US Federal Specification QQP-35c) provides information on the selection of appropriate testing to demonstrate that the passivation treatment of the stainless steel has been effective. In this specification, it is expected that the purchaser will define the level of passivation to be achieved and permit the agency performing the surface treatment to select the appropriate procedure that is economical and effective.

**Marine chemical tanker with 2205 tanks (Source: ArcelorMittal)**

## 14.3 Weld spatter, weld discoloration, 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. Weld discoloration causes a loss of corrosion resistance due to the destruction of the passive layer. 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 discoloration 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 pickling 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 passivation after mechanical cleaning.

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[7] ASTM A 380 standard practice for cleaning, descaling and passivation of stainless steel parts, equipment, and systems

[8] ASTM A 967 standard specification for chemical passivation treatments for stainless steel parts

# 15 Duplex Stainless Steel Applications

## Flue gas desulfurization

Coal-fired electric utilities face an uncertain future with respect to air quality planning around the world. Further reductions in $SO_2$ emissions will be required, and flue gas desulfurization (FGD) is one method for achieving these low sulfur dioxide emissions. The use of lime or limestone slurries for "wet scrubbing" sulfur dioxide from a flue gas is a mature technology, as the basic system has been applied to utility boiler systems since the 1970s. Modern scrubbers are now capable of removing over 90% of the $SO_2$ from the exhaust gas. Modern FGD units are comprised of several zones that have different temperatures, chloride concentrations, and pH. Type 2205 stainless steel, S32205, has been used for FGD applications in Europe and Asia because of their lower cost and enhanced corrosion resistance when compared to the austenitic stainless steels. Recently, the use of the duplex stainless steel has gained acceptance in North America, and this grade has become the most popular choice for FGD absorbers because of its high strength, good corrosion resistance, and high toughness properties after welding.

**Multi stage flash seawater desalination unit constructed of S32101 and S32205 duplex stainless steels (Source: Outokumpu)**

## Desalination

Desalination presents one of the most severe tests to materials owing to the high-chloride, high-temperature corrosive process environment. The history of desalination is largely a history of materials development, as desalination customers seek to balance the needs for corrosion resistance with needs to keep investment costs under control to make desalination projects affordable. In the early days of desalination, the evaporators of both multi-stage flash (MSF) and multi-effect (MED) desalination plants were manufactured using mild steel. At a later stage, MSF evaporators were typically clad with 316L (EN 1.4404) austenitic stainless steel. MED chambers were first coated with epoxy and next clad with stainless.

The benefits of duplex stainless steel for this application are high strength – double that of conventional austenitic grades – combined with high corrosion resistance. As a result, duplex stainless steel evaporators can be built with thinner plates, requiring less material and less welding. Further benefits include easier handling and less overall environmental impact.

The breakthrough for the duplex stainless steel concept came in 2003, when grade 2205 duplex stainless steel (EN 1.4462) was selected for solid-duplex evaporators to be installed in the Melittah MSF plant and the Zuara MED plant in Libya. The plant with 4 million gallons per day (MIGD) capacity was commissioned in 2004.

The next stage in the duplex stainless steel desalination evolution was initiated in 2004 when two different types of duplex stainless steel were used in the structures of evaporators – applying the highly corrosion resistant 2205 for parts exposed to the most hostile conditions, and 2304 (EN 1.4362) for parts exposed to less hostile conditions.

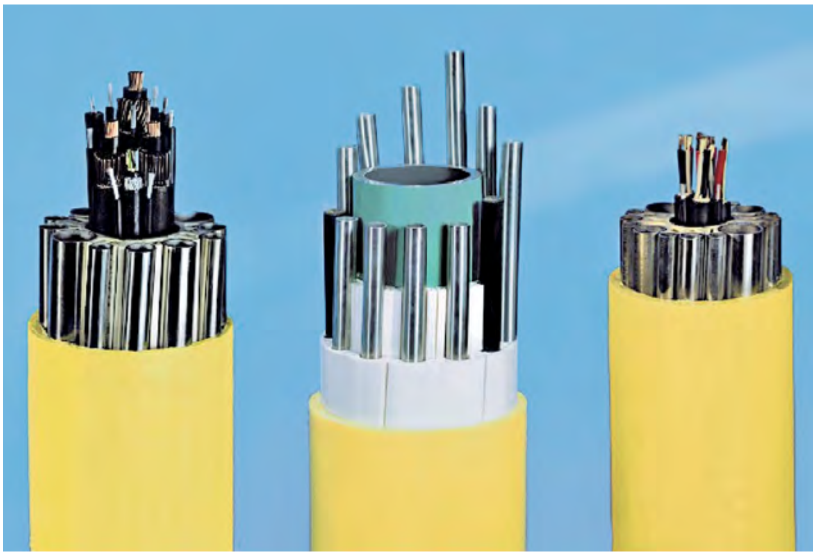
Three MSF plants were recently constructed using this concept, with a combination of 2205 and UNS S32101 (EN 1.4162): Taweelah B (Abu Dhabi, 69.2 MIGD capacity), Jebel Ali L2 (Dubai, 55 MIGD) and Ras Abu Fontas B2 (Qatar, 30 MIGD). This concept using 2304 and 2205 was applied since 2003 in MED plants and more recently to the construction of the world's largest MED plant to date, Al Hidd in Bahrain with 60 MIGD capacity.

## Oil and gas

In oil and gas, duplex has played a crucial role in helping to withstand tough conditions. This is due not only to its corrosion resistance and mechanical strength, but also because its pitting and crevice corrosion resistance is superior to that of standard austenitic alloys, with pitting resistance equivalent numbers (PREN) often exceeding 40.

The main applications for duplex stainless steels are flow lines, process piping systems and equipment like separators, scrubbers and pumps. Subsea the materials are used in downhole production tubing, piping and manifolds, Christmas tree components, flowlines and pipelines transporting corrosive oil and gas. Superduplex (25% chromium) stainless steels are useful for their resistance to design stress, so they are often used on such items as bar, forgings, castings, sheet, plate, tube, and fasteners. Superduplex stainless steels also have excellent fatigue resistance and galvanic compatibility with other high alloy stainless steels.

Umbilicals are used for controlling wellhead functions using hydraulic lines and can also be used for chemical injection. Since steel umbilicals were introduced to the market, duplex stainless steels have been the most commonly used material. In recent years there has been a trend to explore fields at deeper sea depths and longer umbilicals are required. Increasing the strength of the material decreases the weight of the umbilical, which enables longer lengths. The trend is also that umbilcals are used in warmer water and developing concepts where a riser is introduced in the umbilical. Hence, the demand on the corrosion resistance and mechanical strength is increased. New hyper duplex stainless steels have been developed for use in umbilicals with better corrosion resistance and higher strength than super duplex stainless steel.



**2507 umbilical tubing for offshore oil and gas applications (Source: Sandvik)**

## Biofuels

On land, biofuels (especially ethanol) are a sector in which use of duplex grades is growing. 2205 stainless steel has been used for the biomass to liquid NExBTL plant in Singapore, and S32101 was selected by Dutch tank builder Oostwouder Tank- & Silobouw BV for its tank farm for Noba Vetveredeling BV in a large-scale biofuel project in the Port of Amsterdam. S32101 was also specified for the vessels and pipes of Agroetanol's expanded ethanol plant on the island of Händelö in Sweden. The lean duplex stainless steel grades have been used to replace the 300-series austenitic stainless steels for many ethanol service applications.

## Food and drink

In the food and drink industries too, lean duplex stainless steel is proving its worth. The material is being used for two projects in Spain, a food storage depot and a wine storage depot. In the Port of Barcelona Emypro SA constructed food storage tanks entirely from S32101 as a replacement for EN 1.4301/1.4307 (304/304L). The wine storage depot, built by Spanish tank builder Martinez Sole for Garcia Carrión in Daimiel in the south of Spain, is the first to use duplex stainless steel: S32101 and 2304 were used in the construction of the roof and uppermost level of all new tanks, as a lower cost alternative to 1.4301/1.4404 (304/316L).

## Architecture

Duplex stainless steel continues to play an important role in the construction of bridges, wherever corrosion and saline conditions combine with the need for high load-bearing strength. Two recent examples, both from Asia, are Hong Kong's Stonecutters Bridge and Singapore's Marina Bay Pedestrian Bridge, both of which use duplex grade 2205 stainless steel. For the Stonecutters Bridge, 2000 tons of 2205 duplex plate and pipe were used in 2006. The skin segments were finished by a fabricator in China from customized plates. The plates were polished and shot-peened to provide the optimum level of reflection during both day and night.

**Stonecutters Bridge, Hong Kong (Source: Ove Arup & Partners)**

In addition, the Marina Bay Pedestrian Bridge uses 570 tons of duplex stainless steel. The bridge's stunning design comprises two spiralling tubular stainless steel members resembling the structure of DNA, and it is the double-helix and support structures that use duplex 2205 pipes and plates respectively. The stainless steel surfaces provide night time illumination by reflecting lights programmed to enhance the design.

The world's largest stainless steel roof at the New Doha International Airport in Qatar is constructed of a molybdenum grade lean duplex stainless steel (S32003). The terminal's most striking feature is its undulating roof, said to be the largest stainless steel roof in the world. The area of the terminal roof is approximately 195,000 square meters (2.1 million square feet) and used approximately 1600 metric tonnes (3.5 million pounds) of duplex stainless steel. Several factors had to be taken into account when selecting the the stainless steel grade. The most important of these was the airport's close proximity to the sea. The roof had to resist not only the heat and humidity found in the Middle East, but it also had to withstand the salt corrosion. Other factors in the selection included cost and a favorable strength-to-weight ratio for duplex stainless steel compared to other grades.

**New Doha International Airport with a duplex stainless steel roof (Source: Qatar Airways)**

**2304 duplex stainless steel bridge arches in construction near Padova, Italy (Source: ArcelorMittal)**

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13 ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, Paragraph UHA 51.

# Appendix 1: Duplex Stainless Steel Designations and Product Names

| UNS No. | Grade | EN No. | EN Name | JIS/Japan | GB/PR China | KS/Korea | Product name |
|---|---|---|---|---|---|---|---|
| S31200 | | | | | 022Cr25Ni6Mo2N | | 44LN |
| S31260 | | | | | 022Cr25Ni7Mo3 WCuN | | DP3<br>DP12 |
| S31500 | | | | | | | 3RE60 |
| S32001 | | 1.4482 | X2CrMnNiMoN21-5-3 | | | | Nitronic 19D |
| S32003 | | | | | | | ATI 2003 |
| S32101 | | 1.4162 | | | | | LDX 2101<br>B2101 |
| S32202 | | | | | | | UR 2202 |
| S31803<br>S32205 | 2205* | 1.4462 | X2CrNiMoN 22-5-3 | SUS 329 J3L | 022Cr22Ni5Mo3N | STS 329J3L | SAF 2205<br>UR 2205<br>UR 2205+<br>UR 2205Mo<br>DMV 22-5<br>ATI 2205<br>2205 Code Plus Two<br>NAS 329J3L<br>NSSC DX1<br>DP8<br>B2205 |
| S32304 | 2304* | 1.4362 | X2CrNiN 23-4 | | 022Cr23Ni5Mo3N | | SAF 2304<br>UR 2304<br>B2304 |
| S32506 | | | | | | | NAS 64 |
| S32520 | | 1.4507 | X2CrNiMoCuN 25-6-3 | | | | UR 2507Cu |
| S32550 | 255* | | | | 03Cr25Ni6Mo3Cu2N | | Ferralium 255<br>UR 2507Cu |
| S32707 | | | | | | | SAF 2707 HD |
| S32750 | 2507* | 1.4410 | X2CrNiMoN 25-7-4 | SUS 329 J4L | 022Cr25Ni7Mo4N | STS 329 J4L | AF 2507<br>UR 2507<br>NAS 74N<br>SAF 2507 |
| S32760 | | 1.4501 | X2CrNiMoCuWN25-7-4 | | | | Zeron 100<br>UR 2507W<br>NAS 75N |
| S32808 | | | | | | | DP28W |
| S32900 | 329 | 1.4460 | X3CrNiMoN27-5-2 | SUS 329 J1 | 0Cr26Ni5Mo2 | STS 329 J1 | |
| S32906 | | | | | | | SAF 2906 |

| UNS No. | Grade | EN No. | EN Name | JIS/Japan | GB/PR China | KS/Korea | Product name |
|---|---|---|---|---|---|---|---|
| S32950 | | | | | | | 7-Mo Plus |
| S32960 | | | | | | | |
| S33207 | | | | | | | SAF 3207 HD |
| S39274 | | | | | | | DP-3W |
| S39277 | | | | | | | AF918 |
| S82011 | | | | | | | ATI 2102 |
| – | | 1.4655 | X2CrNiCuN 23-4 | | | | |
| – | | 1.4477 | X2CrNiMoN 29-7-2 | | | | |
| – | | 1.4424 | X2CrNiMoSi 18-5-3 | | | | |

* Common name, not a trademark, widely used, not associated with any one producer

# Appendix 2: Summary of Specifications

## ASTM/ASME Specifications

| UNS No. | Grade | A 815 | A 959 | A 480/M SA 480 | A 314 | A 240/M SA 240 | A 484/M SA 484 | A 276 SA 276 | A 479/M SA 479 |
|---|---|---|---|---|---|---|---|---|---|
| | | Pipe fittings | Wrought grades | General requirements | Billets | Flat Roll | General requirements | Bar, shapes | Bar, shapes |
| S31200 | | | X | X | | X | | | |
| S31260 | | | X | X | | X | | | |
| S31803 | | X | X | X | | X | X | X | X |
| S32001 | | | X | X | | X | | | |
| S32003 | | | X | X | | X | | | |
| S32101 | | X | X | X | | X | X | X | X |
| S32202 | | X | | X | X | X | X | X | X |
| S32205 | 2205 | X | X | X | | X | X | X | X |
| S32304 | 2304 | | X | X | | X | X | X | |
| S32506 | | | X | X | | X | X | X | X |
| S32520 | | | X | X | | X | | | |
| S32550 | 255 | X | X | X | | X | X | X | X |
| S32707 | | | | | | | | | |
| S32750 | 2507 | X | X | X | | X | X | X | X |
| S32760 | | X | X | X | X | X | X | X | X |
| S32900 | 329 | | X | X | | X | X | | |
| S32906 | | | X | X | | X | X | | X |
| S32950 | | X | X | X | X | X | X | | X |
| S39274 | | X | X | X | | X | | | |
| S39277 | | | X | | | | X | | X |
| S33207 | | | | | | | | | |
| S82011 | | | | X | | X | | | |

## EN Specifications

| EN No. | EN Name | EN 10028-7 | EN 10088-2 | EN 10088-3 | EN 10095 | EN 10216-5 | EN 10217-7 | EN 10222-5 |
|---|---|---|---|---|---|---|---|---|
| 1.4362 | X2CrNiN23-4 | X | X | X | X | X | X | |
| 1.4655 | X2CrNiCuN23-4 | | X | | | | | |
| 1.4460 | X3CrNiMoN27-5-2 | | | X | | | | |
| 1.4477 | X2CrNiMoN29-7-2 | | X | X | | | | |
| 1.4462 | X2CrNiMoN22-5-3 | X | X | X | | X | X | X |
| 1.4507 | X2CrNiMoCuN25-6-3 | X | X | X | | X | | |
| 1.4410 | X2CrNiMoN25-7-4 | X | X | X | | X | X | X |
| 1.4501 | X2CrNiMoCuWN25-7-4 | X | X | X | | X | X | |
| 1.4424 | X2CrNiMoSi18-5-3 | | X | X | | X | | |
| 1.4062 | X2CrNiN22-2 | | | | | | | |

| A 580/M | A 270 | A 789/M SA 789 | A 790/M SA 790 | A 928/M | A 923 | A 182 | API 650 | NSF/ANSI 61 |
|---|---|---|---|---|---|---|---|---|
| Wire rod | Sanitary tubing | Tubing, seamless & welded without filler | Pipe, seamless & welded without filler | Welded with filler | Duplex testing | Fittings |  | Potable water |
|  |  | X | X | X |  | X |  |  |
|  |  | X | X | X |  |  |  |  |
|  | X | X | X | X | X | X | X | X |
|  |  | X |  |  |  |  |  |  |
|  | X | X | X | X |  |  | X | X |
|  |  | X | X |  |  |  | X | X |
| X |  | X | X | X |  | X |  |  |
|  | X | X | X | X | X | X | X | X |
|  |  | X | X | X |  |  | X | X |
|  |  | X | X | X |  |  |  |  |
|  |  | X | X |  | X | X | X |  |
|  |  | X | X | X | X | X | X |  |
|  |  | X | X |  |  |  |  |  |
|  | X | X | X | X | X | X | X |  |
|  |  | X | X | X |  | X | X |  |
|  |  | X | X | X |  |  |  |  |
|  |  | X | X |  |  | X |  |  |
|  |  | X | X | X |  | X |  |  |
|  |  | X | X |  |  | X |  |  |
|  |  | X | X |  |  | X |  |  |
|  |  | X | X |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |

| EN 10250-4 | EN 10263-5 | EN 10272 | EN 10296-2 | EN 10297-2 | EN 10312 |
|---|---|---|---|---|---|
| X |  | X | X | X |  |
|  |  |  |  |  |  |
| X |  |  |  | X |  |
|  |  |  |  |  |  |
| X | X | X | X | X | X |
| X |  | X |  | X |  |
| X |  | X | X | X |  |
| X |  | X |  | X |  |
|  |  |  |  | X |  |
|  |  |  |  |  |  |

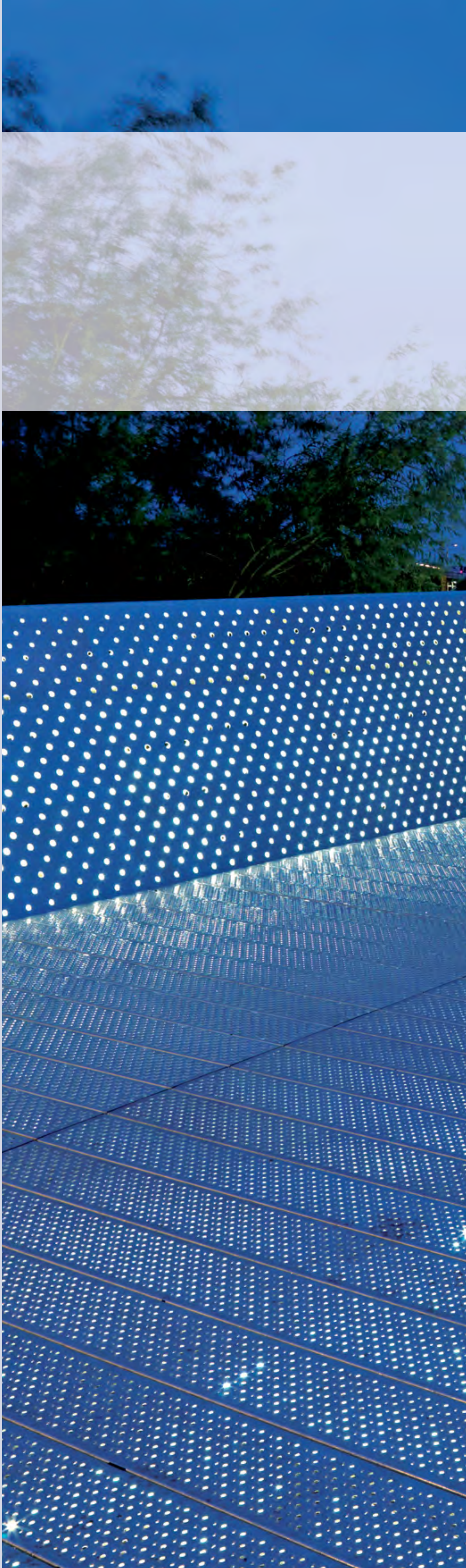
## Cast duplex stainless steels

| UNS No. | ASTM 890 castings, general | ASTM A 995 castings, pressure parts |
|---|---|---|
| J93370 | X | |
| J93372 | X | X |
| J93373 | X | |
| J93345 | X | X |
| J93371 | X | X |
| J92205 | X | X |
| J93404 | X | X |
| J93380 | X | X |

## Summary of specification titles

| 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 270 | Seamless and Welded Austenitic and Ferritic / Austenitic Stainless Steel Sanitary Tubing |
| A 314 | Stainless Steel Billets and Bars for Forging |
| 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 484 / A 484M | General Requirements for Stainless Steel Bars, Billets, and Forgings |
| A 580 / A 580M | Stainless Steel Wire |
| 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 |
| A 995 / A 995M | Castings, Austenitic-Ferritic (Duplex) Stainless Steels for Pressure-Containing Parts |
| API 650 | Welded Steel Tanks for Oil Storage |
| NSF / ANSI 61 | Drinking Water System Components |
| NACE MR0175 | Sulphide stress cracking resistant material for oil field equipment |
| EN 10028-7 | Flat products made of steels for pressure purposes - Part 7: Stainless steels |
| EN 10088-2 | Stainless steels – Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes |

| **Specification titles** | |
|---|---|
| **EN 10088-3** | Stainless steels – Part 3: Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes |
| **EN 10095** | Heat resisting steels and nickel alloys |
| **EN 10216-5** | Seamless steel tubes for pressure purposes – Technical delivery conditions – Part 5: Stainless steel tubes |
| **EN 10217-7** | Welded steel tubes for pressure purposes – Technical delivery conditions – Part 7: Stainless steel tubes |
| **EN 10222-5** | Steel forgings for pressure purposes – Part 5: Martensitic, austenitic and austenitic-ferritic stainless steels |
| **EN 10250-4** | Open die steel forgings for general engineering purposes – Part 4: Stainless steels |
| **EN 10263-5** | Steel rod, bars and steel wire for cold heading and cold extrusion – Part 5: Technical delivery conditions for stainless steels |
| **EN 10272** | Stainless steel bars for pressure purposes |
| **EN 10296-2** | Welded circular steel tubes for mechanical and general engineering purposes – Technical delivery conditions – Part 2: Stainless steel |
| **EN 10297-2** | Seamless circular steel tubes for mechanical and general engineering purposes – Technical delivery conditions – Part 2: Stainless steel |
| **EN 10312** | Welded stainless steel tubes for the conveyance of aqueous liquids including water for human consumption – Technical delivery conditions |
| **EN ISO 8249** | Welding – Determination of Ferrite Number (FN) in austenitic and duplex ferritic-austenitic Cr-Ni stainless steel-weld metals |
| **VdTÜV WB 418** | Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4462 |
| **VdTÜV WB 496** | Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4362 |
| **VdTÜV WB 508** | Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4410 |



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