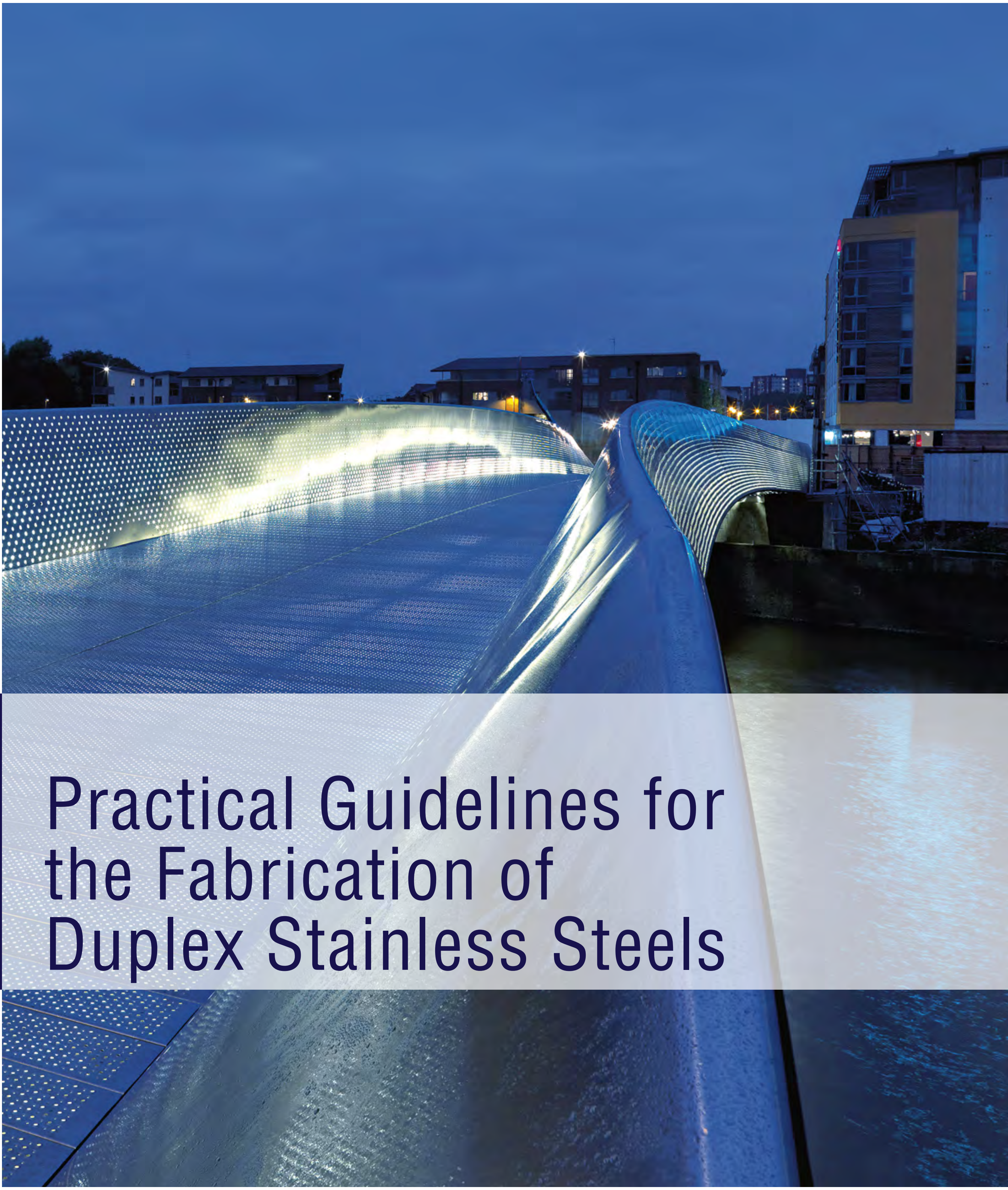
INTERNATIONAL MOLYBDENUM ASSOCIATION
THE VOICE OF THE MOLYBDENUM INDUSTRY



Practical Guidelines for the Fabrication of Duplex Stainless Steels

www.imoa.info

Practical Guidelines for the Fabrication of Duplex Stainless Steel

Third edition 2014

ISBN 978-1-907470-09-7

Published by the International Molybdenum
Association (IMOA), London, UK
www.imoa.info
info@imoa.info

Prepared by TMR Stainless, Pittsburgh, PA, USA
Designed by circa drei, Munich, Germany

Acknowledgement:
IMOA is grateful to the International Stainless Steel Forum and Euro Inox for their support and review of this handbook. We furthermore thank the following companies for their detailed feedback and contributions: Acerinox, Allegheny Ludlum, Aperam, Aquatech, ArcelorMittal, Baosteel, Columbus Stainless, JSL Limited, Nippon Yakin Kogyo, North American Stainless, Outokumpu Stainless, Sandvik, Swagelok, and Yieh United Steel Corporation.

The International Molybdenum Association (IMOA) has made every effort to ensure that the information presented is technically correct. However, IMOA does not represent or warrant the accuracy of the information contained in this handbook or its suitability for any general or specific use. The reader is advised that the material contained herein is for information purposes only; it is not intended as a substitute for any person's procedures, and should not be used or relied upon for any specific or general application without first obtaining competent advice. IMOA, its members, staff and consultants specifically disclaim any and all liability or responsibility of any kind for loss, damage, or injury resulting from the use of the information contained in this publication. ASTM's and EN international specifications were used predominantly in this publication; however, material specifications may vary among countries.

Cover photo: Meads Reach, Temple Quai, Bristol, UK.
© www.m-tec.uk.com (fabricator), www.photo-genics.com (photo)

Contents

1 Introduction 4

2 History of duplex stainless steels 5

3 Chemical composition and role of alloying elements 8
3.1 Chemical composition of duplex stainless steels 8
3.2 The role of the alloying elements in duplex stainless steels 8

4 Metallurgy of duplex stainless steels 10
4.1 Austenite-ferrite phase balance 10
4.2 Precipitates 11

5 Corrosion resistance 14
5.1 Resistance to acids 14
5.2 Resistance to caustics 15
5.3 Pitting and crevice corrosion resistance 15
5.4 Stress corrosion cracking resistance 17

6 End user specifications and quality control 20
6.1 Standard testing requirements 20
6.1.1 Chemical composition 20
6.1.2 Solution annealing and quenching 20
6.2 Special testing requirements 21
6.2.1 Tensile and hardness tests 21
6.2.2 Bend tests 22
6.2.3 Impact testing and metallographic examination for detrimental phases 22
6.2.4 Phase balance as determined by metallography or magnetic measurements 23
6.2.5 Corrosion testing 24
6.2.6 Production welding and inspection 25

7 Mechanical properties 26

8 Physical properties 29

9 Cutting 31
9.1 Sawing 31
9.2 Shearing 31
9.3 Slitting 31
9.4 Punching 31
9.5 Plasma and laser cutting 31

10 Forming 32
10.1 Hot-forming 32
10.1.1 Solution annealing 33
10.2 Warm forming 34
10.3 Cold forming 34
10.4 Press forming 35
10.5 Spinforming 35

11 Machining duplex stainless steels 36
11.1 General guidelines for machining duplex stainless steels 36
11.2 Turning and facing 37
11.3 Face milling with cemented carbides 38
11.4 Twist drilling with high-speed steel drills 39

12 Welding duplex stainless steels 40
12.1 General welding guidelines 40
12.1.1 Differences between duplex and austenitic stainless steels 40
12.1.2 Selection of starting material 40
12.1.3 Cleaning before welding 40
12.1.4 Joint design 40
12.1.5 Preheating 42
12.1.6 Heat input and interpass temperature 42
12.1.7 Postweld heat treatment 42
12.1.8 Desired phase balance 42
12.1.9 Dissimilar metal welds 43
12.2 Welding procedure qualifications 44
12.3 Welding methods 44
12.3.1 Gas tungsten arc welding (GTAW/TIG) 44
12.3.2 Gas metal arc welding (GMAW/MIG) 46
12.3.3 Flux core wire arc welding (FCW) 48
12.3.4 Shielded metal arc welding (SMAW/stick electrode) 44
12.3.5 Submerged arc welding (SAW) 50
12.3.6 Weld overlay – electro-slag welding (ESW) 50
12.3.7 Electron beam and laser welding 51
12.3.8 Resistance welding 51

13 Other joining techniques 52
13.1 Joint preparation 52
13.2 Adhesives 52
13.3 Soldering 52
13.4 Brazing 52

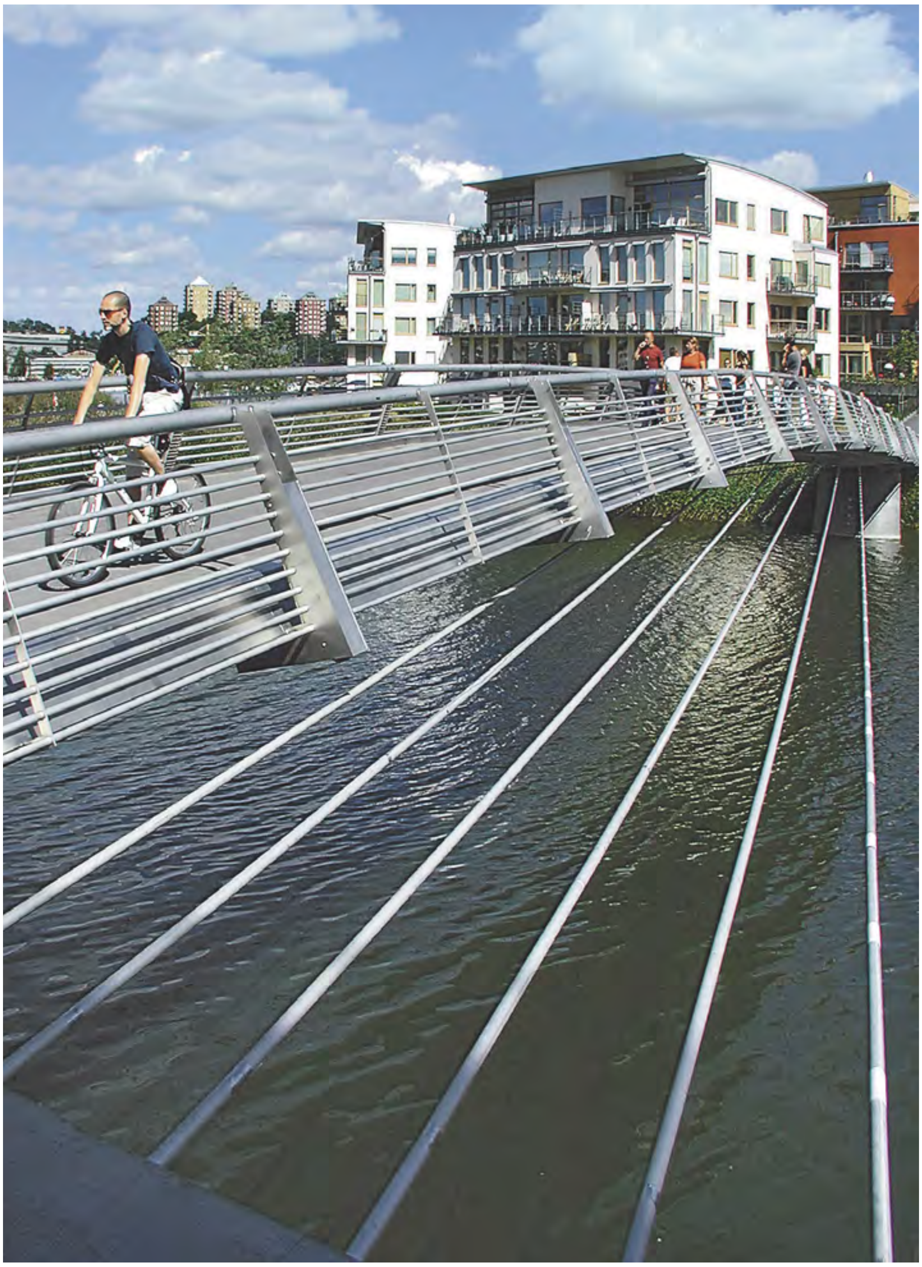
14 Post-fabrication cleanup 53
14.1 Crayon marks, paint, dirt, oil 53
14.2 Embedded iron 53
14.3 Weld spatter, weld discoloration, flux, slag, arc strikes 54

15 Duplex stainless steel applications 55

Suggested additional reading 58
References 61
Appendix 1: Duplex stainless steel designations and product names 62
Appendix 2: Summary of specifications 64

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 are a function of chromium, molybdenum, tungsten, and nitrogen content. They may be similar to those of Type 316 or range above that of the sea water stainless steels such as the 6% Mo austenitic stainless steels. All 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. © 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 of carbon steel.

We hope this brochure will give the reader both an understanding of the fabrication of structures and components made from duplex stainless steel, and knowledge that 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 in 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. 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 approaching 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.

Like the austenitic stainless steels, the duplex stainless steels are a family of grades ranging in their corrosion performance depending on the alloy content. The development of duplex stainless steels has continued, and modern duplex stainless steels have been divided into five groups in this brochure, according to their corrosion resistance. Other ways to group these steels have been proposed, but no consensus has been reached on the definition of these groups.

- **Lean duplex** without deliberate Mo addition, such as 2304;
- **Molybdenum-containing lean duplex**, such as S32003;
- **Standard duplex** with around 22% Cr and 3% Mo, such as 2205, the workhorse grade accounting for nearly 60% of duplex use;
- **Super duplex** with approximately 25% Cr and 3% Mo, with PREN of 40 to 45, such as 2507;
- **Hyper duplex** with higher Cr and Mo contents than super duplex grades and PREN above 45, such as S32707.

The resistance of a stainless steel to localized corrosion is strongly related to its alloy content. The primary elements that contribute to the pitting corrosion resistance are Cr, Mo, and N. W, although not commonly used, is about half as effective on a weight percent basis as Mo. An empirical relationship called the Pitting Resistance Equivalent Number (PREN) has been developed to relate a stainless steel's composition to its relative pitting resistance in chloride containing solutions. The PREN relationship for austenitic and duplex stainless steels is given as follows:

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

where Cr, Mo, W, and N represent the chromium , molybdenum, tungsten, and nitrogen contents of the alloy, respectively, in weight %.

Table 1 lists the chemical compositions and typical PREN range of the second-generation wrought duplex stainless steels and of the cast duplex stainless steels. The first-generation duplex grades and the most 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 (weight %) and PREN range 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	PREN
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	–	–	30–31
	S31500	1.4424	0.03	18.0–19.0	4.3–5.2	2.5–3.0	0.05–0.10	–	–	–	28–29
	S32404		0.04	20.5–22.5	5.5–8.5	2.0–3.0	0.20	2.00	1.00–2.00	–	29–30
Second-generation duplex grades											
Lean duplex											
	S32001	1.4482	0.03	19.5–21.5	1.00–3.00	0.6	0.05–0.17	4.00–6.00	1.00	–	21–23
	S32101	1.4162	0.04	21.0–22.0	1.35–1.70	0.1–0.8	0.20–0.25	4.00–6.00	0.10–0.80	–	25–27
	S32202	1.4062	0.03	21.5–24.0	1.00–2.80	0.45	0.18–0.26	2.00	–	–	25–28
2304	S32304	1.4362	0.03	21.5–24.5	3.0–5.5	0.05–0.60	0.05–0.20	2.50	0.05–0.60	–	25–28
	S82011		0.03	20.5–23.5	1.0–2.0	0.1–1.0	0.15–0.27	2.00–3.00	0.50	–	25–27
	S82012	1.4635	0.05	19.0–20.5	0.8–1.5	0.10–0.60	0.16–0.26	2.00–4.00	1.00	–	24–26
	S82122		0.03	20.5–21.5	1.5–2.5	0.60	0.15–0.20	2.00–4.00	0.50–1.50	–	24–26
		1.4655	0.03	22.0–24.0	3.5–5.5	0.1–0.6	0.05–0.20	2.00	1.00–3.00	–	25–27
		1.4669	0.045	21.5–24.0	1.0–3.0	0.5	0.12–0.20	1.00–3.00	1.60–3.00	–	25–27
Molybdenum-containing lean duplex											
	S32003		0.03	19.5–22.5	3.0–4.0	1.50–2.00	0.14–0.20	2.00	–	–	30–31
	S81921		0.03	19.0–22.0	2.0–4.0	1.00–2.00	0.14–0.20	2.00–4.00	–	–	27–28
	S82031	1.4637	0.05	19.0–22.0	2.0–4.0	0.60–1.40	0.14–0.24	2.50	1.00	–	27–28
	S82121		0.035	21.0–23.0	2.0–4.0	0.30–1.30	0.15–0.25	1.00–2.5	0.20–1.20	–	27–28
	S82441	1.4662	0.03	23.0–25.0	3.0–4.5	1.00–2.00	0.20–0.30	2.50–4.00	0.10–0.80	–	33–34
Standard duplex											
2205	S31803	1.4462	0.03	21.0–23.0	4.5–6.5	2.5–3.5	0.08–0.20	2.00	–	–	33–35
2205	S32205	1.4462	0.03	22.0–23.0	4.5–6.5	3.0–3.5	0.14–0.20	2.00	–	–	35–36
	S32950		0.03	26.0–29.0	3.5–5.2	1.0–2.5	0.15–0.35	2.00	–	–	36–38
	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	36–38
Super duplex											
	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	40–42
	S32520	1.4507	0.03	24.0–26.0	5.5–8.0	3.0–4.0	0.20–0.35	1.50	0.50–2.00	–	40–43
255	S32550	1.4507	0.04	24.0–27.0	4.4–6.5	2.9–3.9	0.10–0.25	1.50	1.50–2.50	–	38–41
2507	S32750	1.4410	0.03	24.0–26.0	6.0–8.0	3.0–5.0	0.24–0.32	1.20	0.50	–	40–43

Table 1 (continued): Chemical composition (weight %) and PREN range 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	PREN
Super duplex (continued)											
	S32760	1.4501	0.03	24.0–26.0	6.0–8.0	3.0–4.0	0.20–0.30	1.00	0.50–1.00	0.5–1.0	40–43
	S32906	1.4477	0.03	28.0–30.0	5.8–7.5	1.5–2.6	0.30–0.40	0.80–1.50	0.80	–	41–43
	S39274		0.03	24.0–26.0	6.8–8.0	2.5–3.5	0.24–0.32	1.00	0.20–0.80	1.50–2.50	40–42
	S39277		0.025	24.0–26.0	6.5–8.0	3.0–4.0	0.23–0.33	0.80	1.20–2.00	0.8–1.2	40–42
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	–	49–50
	S33207		0.03	29.0–33.0	6.0–9.0	3.0–5.0	0.40–0.60	1.50	1.0	–	52–53
Wrought austenitic stainless steels											
304L	S30403	1.4307	0.03	17.5–19.5	8.0–12.0	–	0.10	2.00	–	–	18–19
316L	S31603	1.4404	0.03	16.0–18.0	10.0–14.0	2.0–3.0	0.10	2.00	–	–	24–25
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	–	32–33
CD4MCuN Grade 1B	J93372		0.04	24.5–26.5	4.7–6.0	1.7–2.3	0.10–0.25	1.00	2.70–3.30	–	34–36
CD3MCuN Grade 1C	J93373		0.03	24.0–26.7	5.6–6.7	2.9–3.8	0.22–0.33	1.20	1.40–1.90	–	40–42
CE8MN Grade 2A	J93345		0.08	22.5–25.5	8.0–11.0	3.0–4.5	0.10–0.30	1.00	–	–	38–40
CD6MN Grade 3A	J93371		0.06	24.0–27.0	4.0–6.0	1.75–2.5	0.15–0.25	1.00	–	–	35–37
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	–	–	35–37
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	–	–	43–45
CD3MWCuN Grade 6A	J93380		0.03	24.0–26.0	6.5–8.5	3.0–4.0	0.20–0.30	1.00	0.50–1.00	0.5–1.0	40–42
Cast austenitic stainless steels											
CF3 (cast 304L)	J92500	1.4306	0.03	17.0–21.0	8.0–12.0	–	–	1.50	–	–	18–19
CF3M (cast 316L)	J92800	1.4404	0.03	17.0–21.0	9.0–13.0	2.0–3.0	–	1.50	–	–	24–25

* Maximum, unless range or minimum is indicated.
– Not defined in the specifications.

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 duplex stainless steels can be achieved if ferrite and austenite phases are both in the 30 to 70% range, including in welded structures. However, duplex stainless steels are most commonly considered to have roughly equal amounts of ferrite and austenite, with current commercial production just slightly favoring the austenite for best toughness and processing characteristics. The interactions of the major alloying elements, particularly 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, precipitating 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 the 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 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% Cr 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 enhances the pitting corrosion resistance of stainless steel. When the chromium content of a stainless steel is at least 18%, additions of molybdenum become about three times as effective as chromium additions in improving pitting and crevice corrosion resistance 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% 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. It is a low cost alloying element and a strong austenite former, able to replace some of the nickel content for austenite stabilization. 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 increases the strength of the austenite phase by solid solution strengthening and also increases its work hardening rate. 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 from 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 compared to ferritic stainless steels.

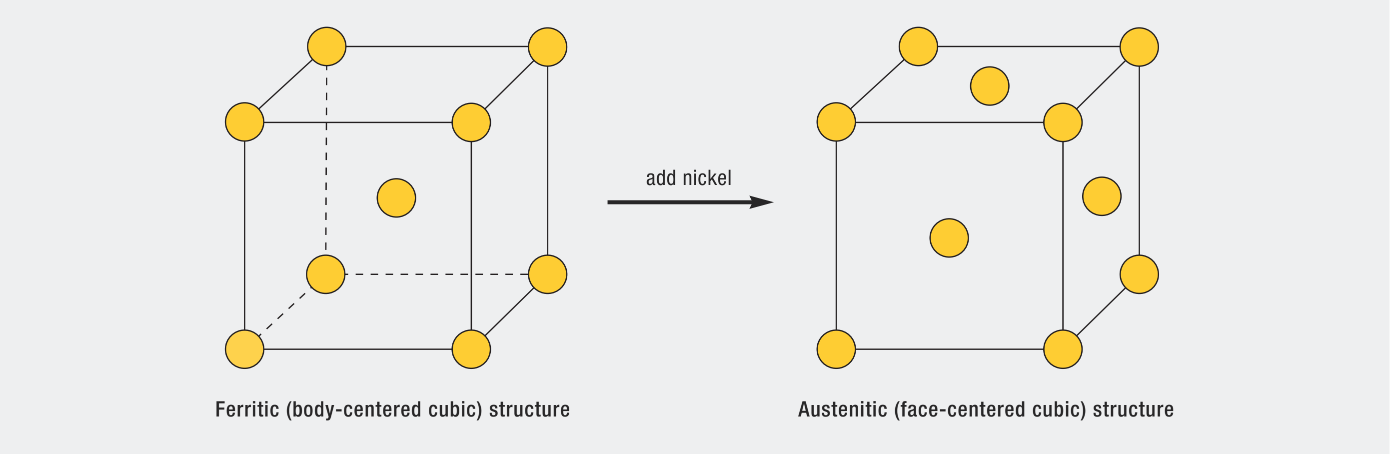
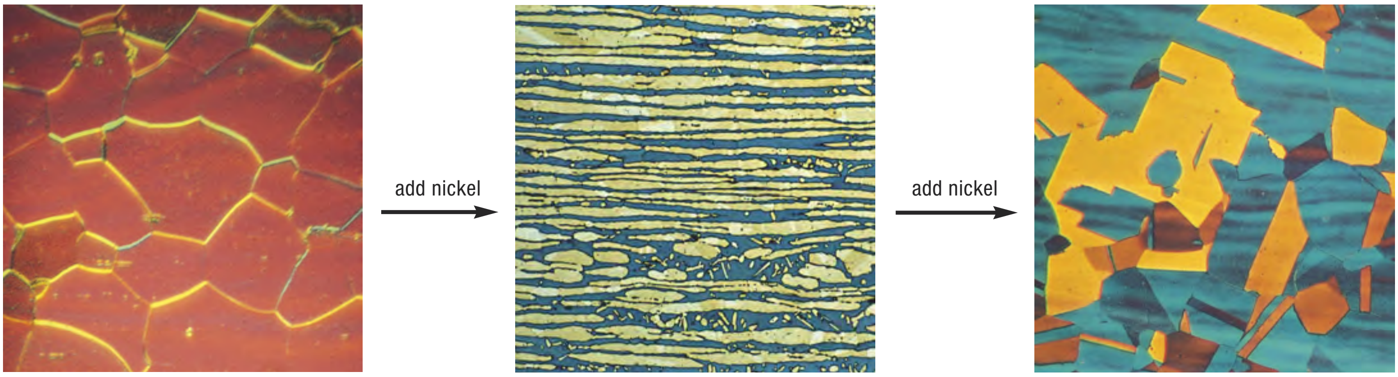


Figure 1: By adding nickel, the crystallographic structure changes from body-centered cubic (little or no nickel) to face-centered cubic (at least 6% nickel – 300 series). The duplex stainless steels, with their intermediate nickel content, have a microstructure in which some grains are ferritic and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

4.1 Austenite-ferrite phase balance

The iron-chromium-nickel ternary phase diagram is a roadmap of the metallurgical behavior of the duplex stainless steels. A section through the ternary diagram at 68% iron **(Figure 3)** illustrates that these alloys solidify as ferrite (α), which then partially transforms to austenite (γ) as the temperature falls, depending on alloy composition. When water quenching from the solution annealing temperature, a microstructure of roughly 50% austenite and 50% ferrite can be achieved at room temperature. Increasing the nitrogen content increases the ferrite to austenite transformation start temperature (Ref. 1) and improves the structural stability of the grade particularly in the HAZ.

The relative amounts of ferrite and austenite that are present in a mill product or fabrication of a given duplex grade depend on the chemical composition and thermal history of the steel. Minor changes in composition can have a significant effect on the relative volume fraction of these two phases, as the phase diagram indicates. Individual alloying elements tend to promote either the formation of austenite or ferrite. 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 °C) is the annealing temperature ranging from 1050–1150°C and the elemental compositions are in weight% (Ref. 2).

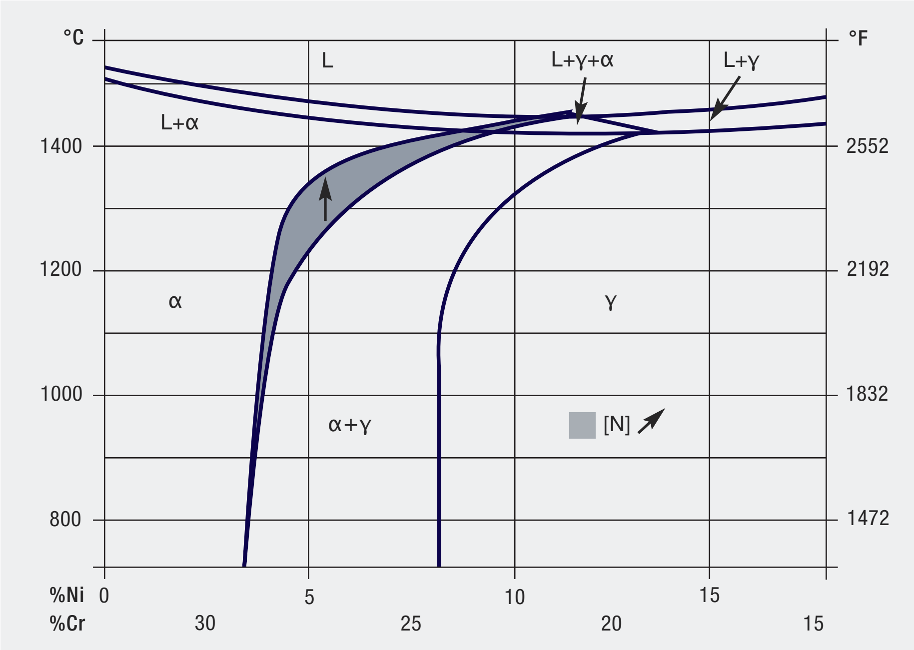


Figure 3: Section through the Fe-Cr-Ni ternary phase diagram at 68% iron (small changes in the nickel and chromium content have a large influence on the amount of austenite and ferrite in duplex stainless steels.)

The goal of obtaining the desired phase balance of close to 45 to 50 % ferrite with the remainder austenite, is achieved primarily by adjusting chromium, molybdenum, nickel and nitrogen contents, and then by controlling the thermal history.

For mill products, solution annealing at an appropriate solution annealing temperature followed by immediate water quenching gives the best results. It is important to keep the time between exiting the furnace and water quenching as short as possible. This is to minimize heat loss of the product which could lead to detrimental phase precipitation before water quenching to room temperature.

For welded structures, the heat input has to be optimized for each grade and weld configuration so that the cooling rate will be quick enough to avoid detrimental phases but not so fast that there remains excessive ferrite in the vicinity of the fusion line. In practice this situation may occur when welding widely differing section sizes or when welding heavy sections with very low heat inputs during fabrication. In these cases the thick metal section can quench the thin weld so rapidly that there is insufficient time for enough of the ferrite to transform to austenite, leading to excessive amounts of ferrite, particularly in the HAZ.

Because nitrogen increases the temperature at which the austenite begins to form from the ferrite, as illustrated in Figure 3, it also increases the rate of the ferrite to austenite transformation. Therefore, even at relatively rapid cooling rates, the equilibrium level of austenite can nearly be reached if the grade has sufficient nitrogen. In the second-generation duplex stainless steels, this effect reduces the potential of excess ferrite in the HAZ.

4.2 Precipitates

Detrimental phases can form in a matter of minutes at the critical temperature, as can be seen in the isothermal precipitation diagram for 2507 and 2205 duplex stainless steels in **Figure 4** (Ref. 4, 5, 6, 7). They can reduce corrosion resistance and toughness significantly. Therefore, the cumulative time in the temperature range where they can form, especially during welding and cooling after annealing, has to be minimized. Modern duplex grades have been developed to maximize corrosion resistance and retard precipitation of these phases, allowing successful fabrication. However, once formed, they can only be removed by full solution annealing and subsequent water quenching.

Sigma phase (Figure 5) and other intermetallic phases such as chi can precipitate from the ferrite at temperatures below austenite formation on cooling too slowly through the temperature range of 700–1000˚C (1300–1830˚F). Sigma phase formation in mill products can, therefore, be avoided by water quenching the steel as rapidly as possible from the solution annealing temperature and avoiding the sigma phase field **(Figure 6)**.

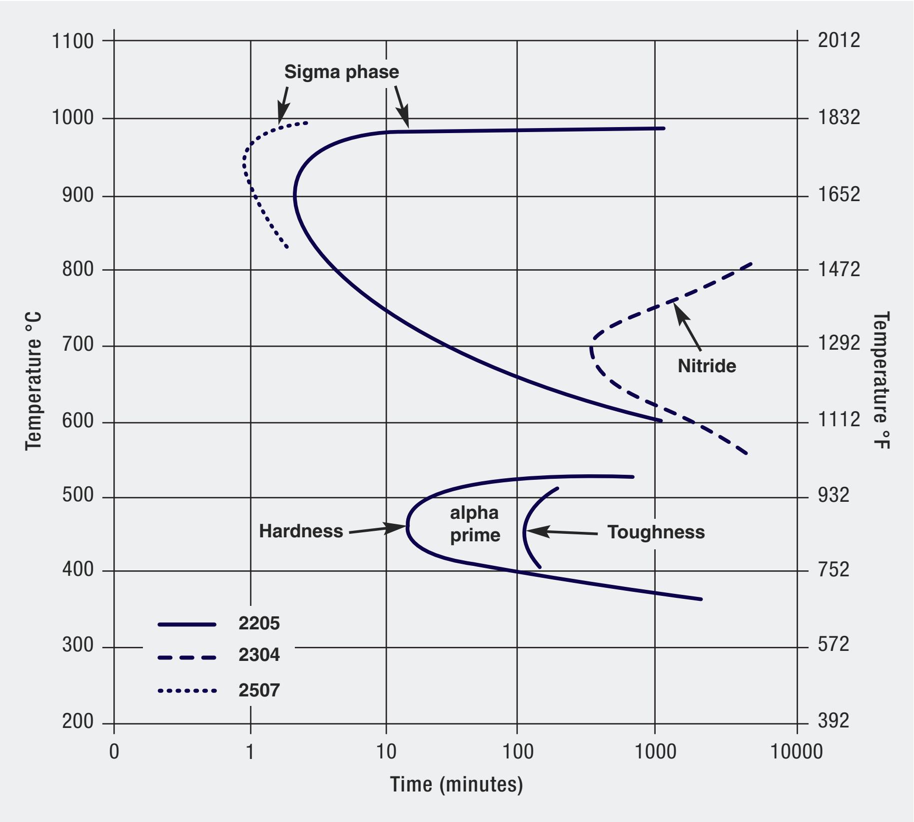


Figure 4: Isothermal precipitation diagram for 2205 duplex stainless steel, annealed at 1050˚C (1920˚F). (The sigma phase and nitride precipitation curves for 2507 and 2304, respectively, are shown for comparison)

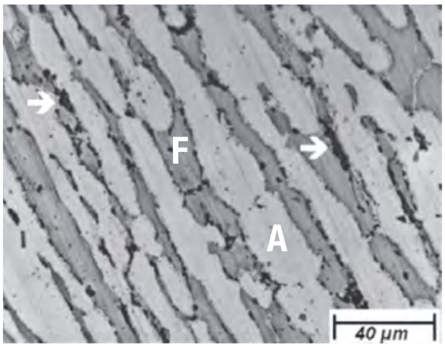


Figure 5: Microstructure of a 2205 sample aged at 850°C (1560°F) for 40 minutes showing sigma phase precipitation (arrows) on the austenite/ferrite grain boundaries. The ferrite (F) phase appears darker than the austenite (A) phase in the micrograph (Ref. 3).

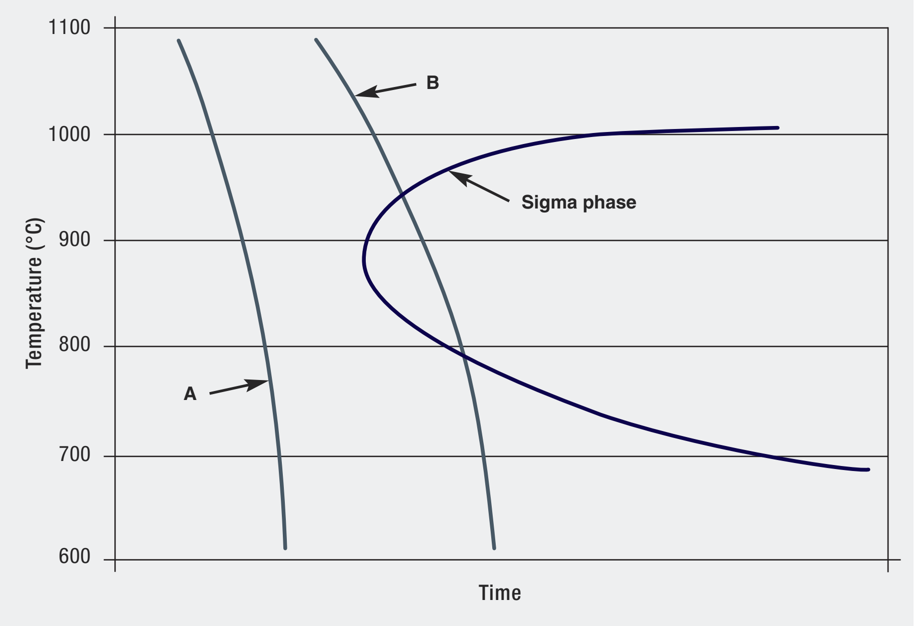
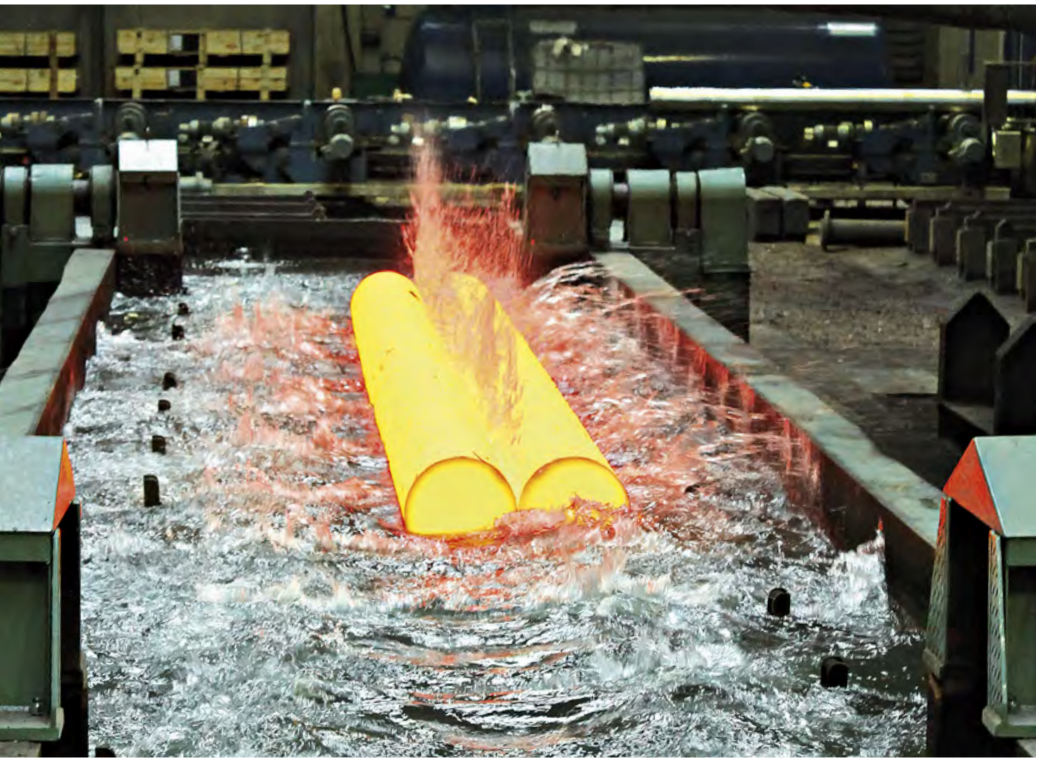


Figure 6: Cooling from the solution annealing temperature should be fast enough (cooling curve A) to avoid the sigma phase field (cooling curve B).



Duplex stainless steel has to be water quenched immediately after solution annealing.
© Bosch-Gotthard-Hütte

The driving force for sigma phase formation increases with increasing molybdenum and chromium content. The more highly alloyed grades, from 2205 on up are therefore most affected. Precipitates tend to form quicker with increasing alloy content as shown in Figure 4 where the start curve for 2507 is to the left (shorter time) of the one for 2205. Lean duplex grades such as 2304 do not readily form intermetallic phases and nitride precipitation is more likely as shown in Figure 4.

The presence of sigma phase decreases the pitting resistance of duplex stainless steels, due to the depletion of chromium and molybdenum in surrounding areas. This depletion leads to a local reduction of the corrosion resistance next to the precipitates. Toughness and ductility are also sharply reduced when intermetallic phase precipitation occurs.

Chromium nitride precipitation can for some grades start in only 1–2 minutes at the critical temperature. It can occur in the grain or phase boundaries as a result of too slow cooling through the temperature range of 600–900°C (1100–1650˚F). Nitride formation is not very common in most duplex grades, but it can be an issue with some lean duplex stainless steels, due to relatively high nitrogen content and reduced nitrogen solubility compared to higher alloyed grades. Similar to sigma phase, it can largely be avoided in the steel mill by water quenching from an adequate solution annealing temperature.

Chromium nitride can, however, also precipitate in the HAZ and weld metal in welded fabrications. A high ferrite content in the vicinity of the fusion line, due to very rapid cooling in this area, can lead to nitrogen oversaturation. Ferrite in general has very low solubility for nitrogen which decreases further as the temperature decreases. So if nitrogen is ‘caught’ in the ferrite phase it might precipitate as chromium nitride upon cooling. A slower cooling rate will result in a competition between nitride precipitation and an increase of austenite re-transformation. More austenite allows more nitrogen to dissolve in the austenite grains, reducing the nitrogen oversaturation of the ferritic grains and the amount of chromium nitride. The precipitation of chromium nitrides in welds can therefore be decreased by increasing the austenite level through higher heat input (slower cooling) or through additions of austenite-promoting elements such as nickel in the weld metal or nitrogen in the shielding gas.

If formed in large volume, chromium nitrides may adversely affect corrosion resistance and toughness properties.

Alpha prime can form in the ferrite phase of duplex stainless steels below about 525°C (950°F). It takes significantly longer to form than the other phases discussed above and is first noticed as an increase in hardness and only later as a loss in toughness (Figure 4).

In ferritic stainless steels alpha prime causes the loss of ambient temperature toughness after extended exposure to temperatures around 475°C (885°F); this behavior is known as 475°C/885°F embrittlement. 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. It does affect all duplex stainless steel grades, but is most pronounced in the molybdenum-containing grades and much less in the lean duplex grades.

Alpha prime embrittlement is rarely a concern during fabrication because of the long times required for embrittlement to occur. One exception, which has to be carefully evaluated, is stress relief treatment of duplex-clad carbon steel constructions. Any heat treatment in the critical temperature range for alpha prime formation of 300–525°C (575–980°F) (or for intermetallic phase formation of 700–950°C (1300–2515°F), for 2205) has to be avoided. If a stress relief treatment is required, it is best to consult the clad plate producer for advice.

However, the upper temperature limit for duplex stainless steel service is controlled by alpha prime formation. Pressure vessel design codes have therefore 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**.

The second generation duplex stainless steels are produced with very low carbon content so that **carbide** formation to a detrimental extent is typically not a concern.

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	1470–1380	2680–2515	1450–1350	2640–2460
Scaling temperature in air	1000	1830	1000	1830
Sigma phase formation	700–950	1300–1740	700–1000	1300–1830
Nitride, carbide precipitation	450–800	840–1470	450–800	840–1470
475°C/885°F embrittlement	300–525	575–980	300–525	575–980

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. The duplex structure is an advantage in potential chloride stress corrosion cracking environments. If the microstructure contains at least 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 7** 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,

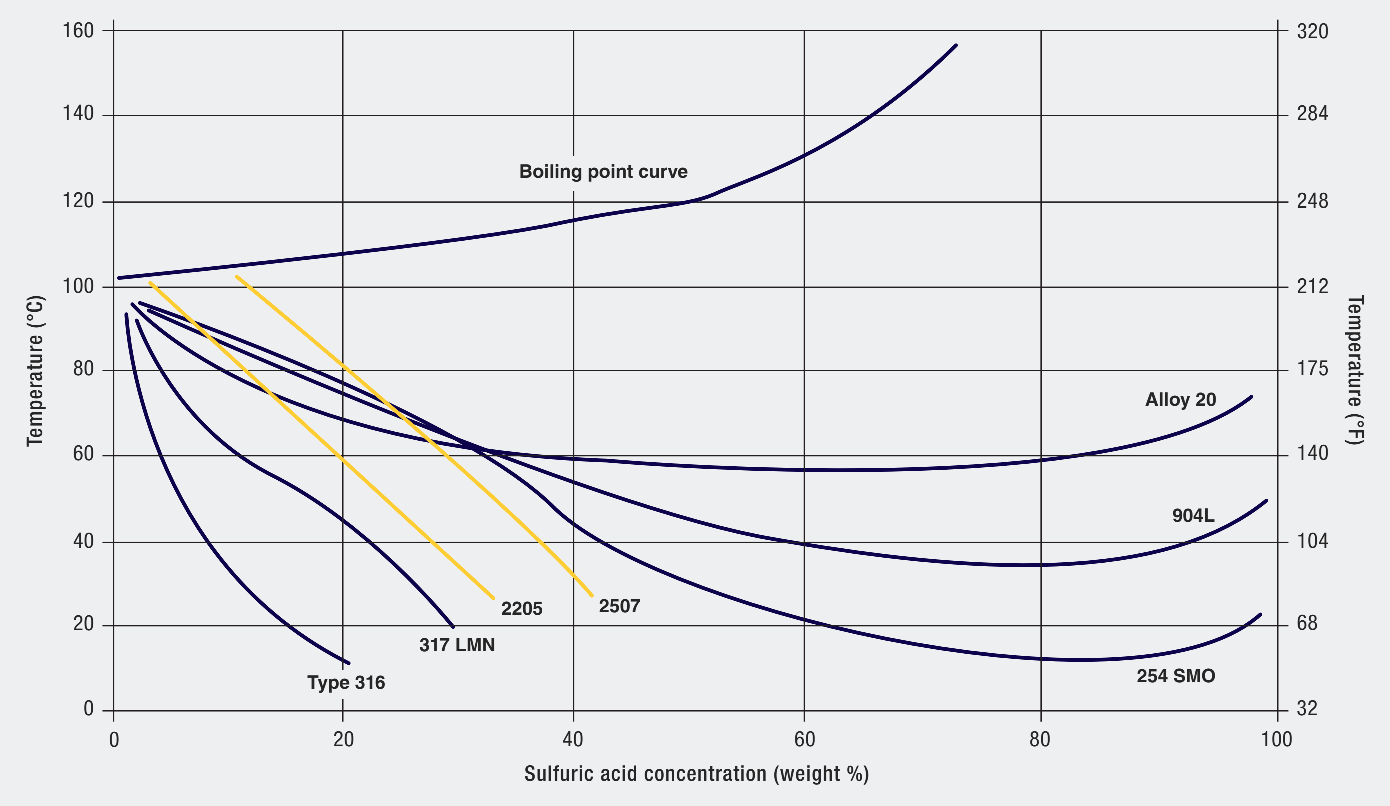


Figure 7: Corrosion in non-aerated sulfuric acid, 0.1 mm/yr (0.004 inch/yr) isocorrosion diagram (laboratory tests using reagent grade sulfuric acid). Source: Producer data sheets, 254 SMO is a trademark of Outokumpu

especially of the ferrite, may be activated and proceed rapidly. Their resistance to oxidizing conditions makes duplex stainless steels good candidates for nitric acid service and the strong organic acids. This is illustrated in **Figure 8** 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.

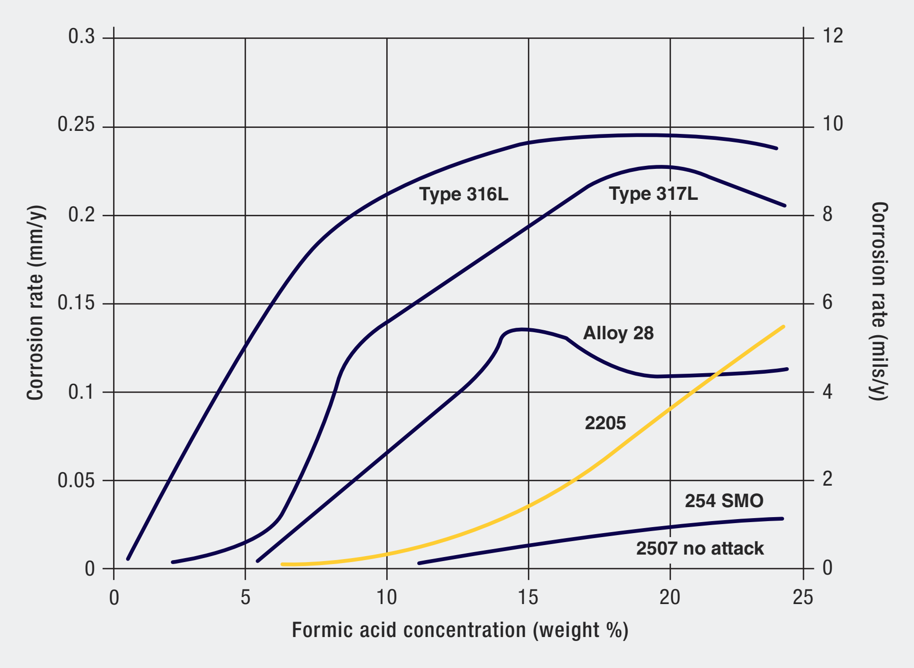


Figure 8: Corrosion of duplex and austenitic stainless steels in boiling mixtures of 50% acetic acid and varying proportions of formic acid. Source: Sandvik

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.

2205 continuous sulphate pulp digester and impregnation tower, Sodra Cell Mönsteras, Sweden. © Kvaerner Pulping

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. 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.

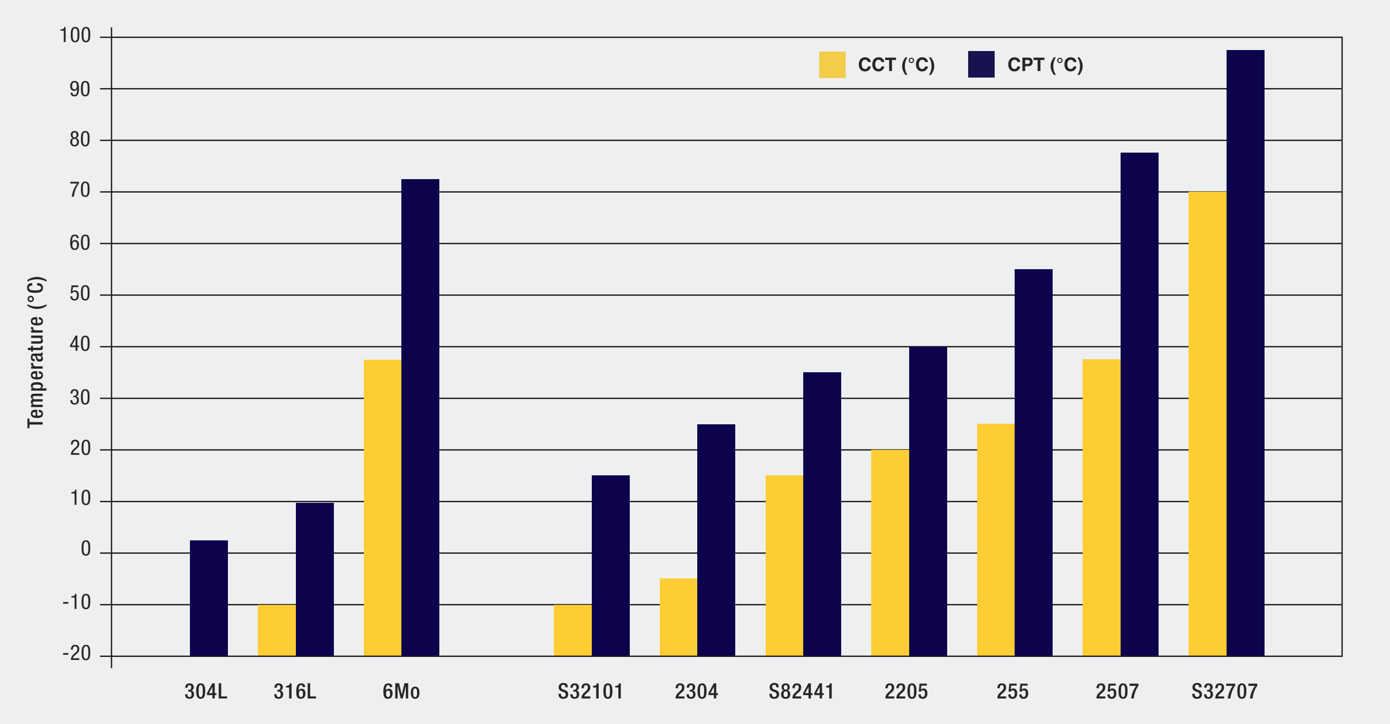


Figure 9: Critical pitting and crevice corrosion temperatures for unwelded austenitic stainless steels (left side) and duplex stainless steels (right side) in the solution annealed condition (evaluated in 6% ferric chloride by ASTM G 48).

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 temperature for crevice corrosion, which occurs in gasket joints, under deposits and in bolted joints where a crevice is formed in fabricated products. The critical crevice temperature (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 9**. 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 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 super duplex and hyper

[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

duplex grades, have been used in many critical seawater handling situations where both strength and chloride resistance are needed. Although the super duplex grades do not corrode in lower temperature seawater, they have limits in higher temperature service. The improved corrosion resistance of hyper duplex stainless steels extends their use to aggressive chloride environments, such as in hot tropical seawater, especially when there are crevices.

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 + 0.5W) + 16N.

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 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 alloys, the duplex stainless steels may be susceptible to SCC under certain conditions. This may occur in high temperature, chloride-containing environments, or when conditions favor hydrogen-induced cracking. Examples of environments in which SCC of duplex stainless steels may be expected include the boiling 42% magnesium chloride test, drop evaporation when the metal temperature is high, and exposure to pressurized aqueous chloride systems in which the temperature is higher than what is possible at ambient pressure.

An illustration of relative chloride SCC resistance for a number of mill annealed duplex and austenitic stainless steels in a severe chloride environment is given in **Figure 10** (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 three duplex steels shown, UNS S32101, 2205 and 2507, will

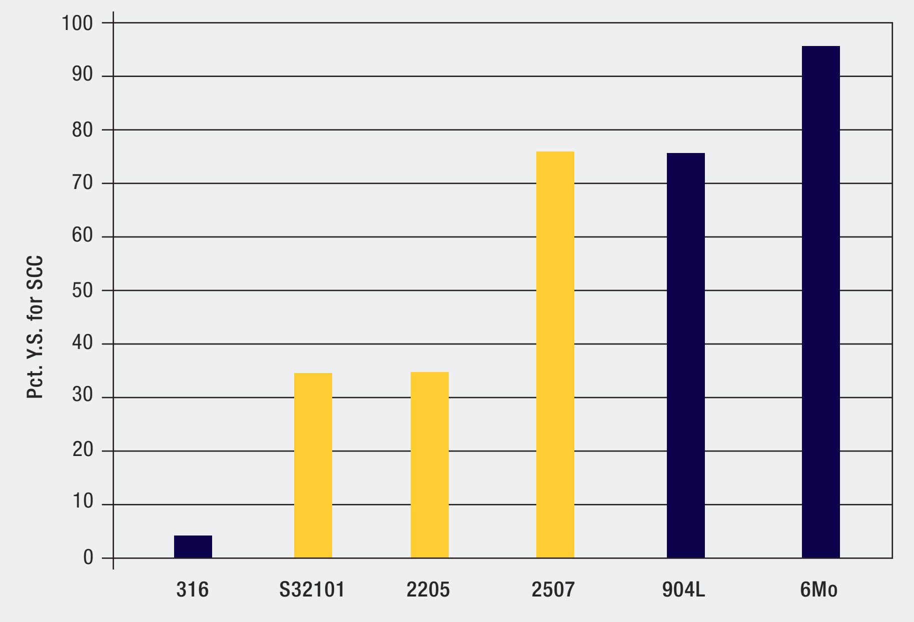


Figure 10: Stress corrosion cracking resistance of mill annealed austenitic and duplex stainless steels in the drop evaporation test with sodium chloride solutions at 120°C (248°F) (stress that caused cracking shown as a percentage of yield strength). Source: Outokumpu

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, 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 SCC behavior of different stainless steels in a variety of test environments with a range of severities. The environments listed near the top of the table are severe because of their acid salts, while those near the bottom 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 SCC in all these environments, while the duplex stainless steels are resistant throughout the mid-range, moderate conditions of testing.

Resistance to hydrogen-induced SCC 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

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

Grade	Type 304L Type 316L	3RE60	S32101 S32202	2205	Super duplex	Hyper duplex
42% $MgCl_2$, boiling, 154°C, U-bend	█	█	█	█	█	█
35% $MgCl_2$, boiling, 125°C, U-bend	█	█	█	█	█	█
Drop evap.,0.1M NaCl, 120°C, 0.9 x Y.S.	█	█	█	█	█	░
Wick test 1500 ppm Cl as NaCl 100°C	█	▓	▒	▒	▒	░
33% $LiCl_2$, boiling, 120°C, U-bend	█	▒	▒	▒	▒	░
40% $CaCl_2$, 100°C, 0.9 x Y.S.	█	▒	▒	▒	▒	▒
25–28% NaCl, boiling, 106°C, U-bend	█	▒	▒	▒	▒	▒
26% NaCl, autoclave, 155°C, U-bend	█	█	█	▓	▒	░
26% NaCl, autoclave, 200°C, U-bend	█	█	█	█	░	░
600 ppm Cl (NaCl), autoclave, 300°C, U-bend	█	░	░	░	░	▒
100 ppm Cl (sea salt + O_2), autoclave, 230°C, U-bend	█	█	█	█	░	░

█ Cracking anticipated ▓ Cracking possible ▒ Cracking not anticipated ░ Insufficient data can be 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 11** (Ref. 10).

Duplex stainless steel pipes. © Butting

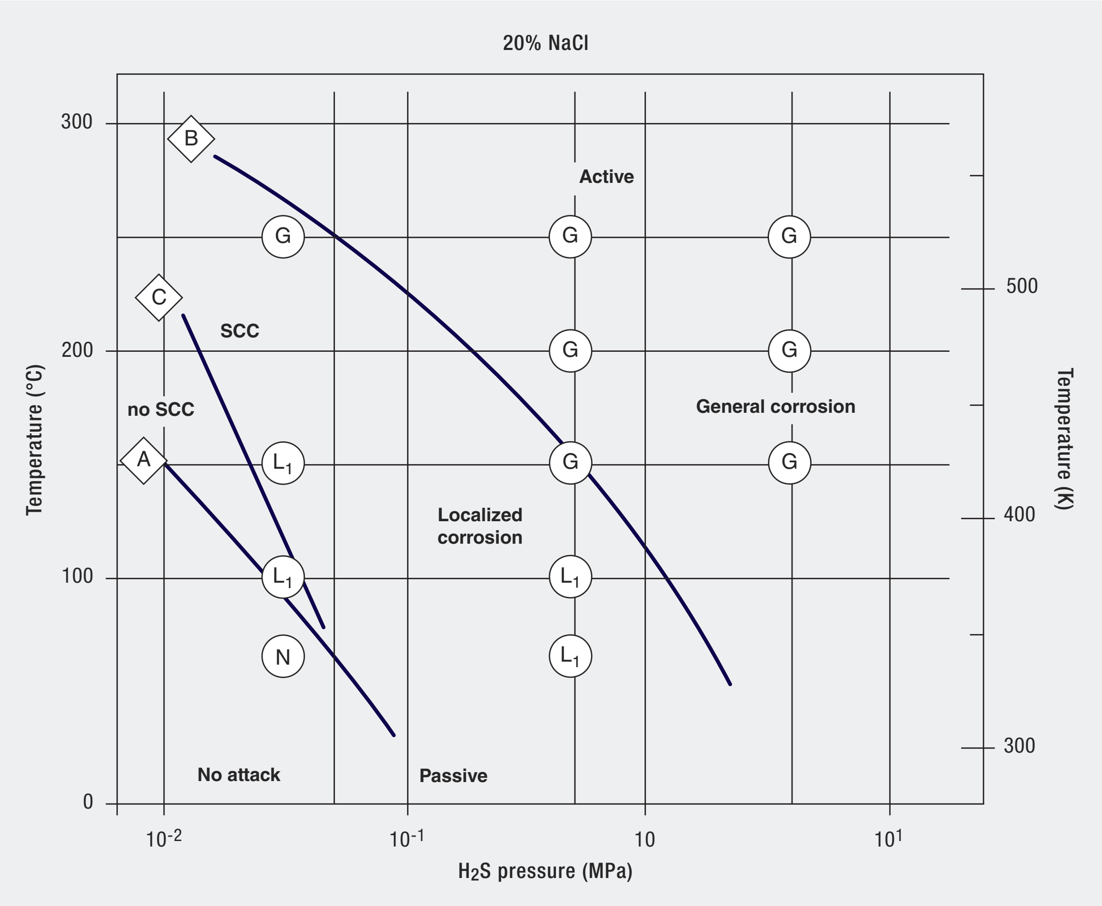


Figure 11: Corrosion of 2205 duplex stainless steel in 20% sodium chloride-hydrogen sulfide environments based on electrochemical prediction and experimental results.

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 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 super duplex 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 dissolve any carbides. 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 resistance and toughness (Ref. 12). When a mill product is slowly cooled in the steel mill, 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 in that temperature range, for example, when welding. So the welder will have less time to make a weld that is free of intermetallic phases in the HAZ.

While specifications such as ASTM permit some duplex grades to be ‘water quenched or rapidly cooled by other means,’ the best metallurgical condition for welding is achieved by the most rapid quenching from the annealing temperature. 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 and thicker section products, 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] and ASTM A 1084[4] use metallographic examination, impact testing, or corrosion testing to demonstrate the absence of a harmful level of detrimental phases. This test considers only whether harmful precipitation has already occurred and not the amount or degree of detrimental precipitation. With this type of testing the mill procedure is verified to ensure that harmful phases have not been formed during mill processing. This testing is analogous to ASTM A 262[5] or EN ISO 3651-2[6] testing of austenitic stainless steels for sensitization due to chromium carbide precipitation. ASTM A 923 covers 2205, 2507, 255 and S32520, and ASTM A 1084 covers the lean duplex grades S32101 and S32304. Many fabricators have adopted these and similar tests or other acceptance criteria, as a part of their qualification for welding procedures of fabricated products.

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.

Inside a 2205 tank on a marine chemical tanker. © Outokumpu

---

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

[4] ASTM A 1084 – Standard test method for detecting detrimental phases in lean duplex austenitic/ferritic stainless steels

[5] ASTM A 262 – Standard practices for detecting susceptibility to intergranular attack in austenitic stainless steels

[6] 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

6.2.2 Bend tests

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

Bend tests are commonly used as part of the qualification of welding procedures for the austenitic stainless steels because there is a risk of hot cracking of the weld, especially for highly austenitic weld structures that are heavily constrained. The usefulness of bend tests for detecting problems of weld integrity is greatly reduced in duplex stainless steel because they have no tendency for hot cracking. 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.

6.2.3 Impact testing and metallographic examination for detrimental phases

There are two ways that an impact test can be used to specify material or qualify a procedure:

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

For the first way to use impact testing, ASTM A 923 provides acceptance criteria for duplex and super duplex stainless steels and ASTM A 1084 for lean duplex stainless steels. For example, the loss of toughness described in ASTM A 923, Method B, in a standard longitudinal Charpy test at -40°C/F 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 also 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 implement Method A, it may be prudent for the end user to require the Method B Charpy impact test in addition to the metallographic examination.

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 way to use impact testing, evaluating base metal, fusion zone and HAZ at lower temperatures 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 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.

2507 stainless steel falling film evaporator. © Gary Carinci, TMR Stainless

Installation of duplex stainless steel rebar on a large bridge deck. © Hardesty & Hanover, LLP

ASME 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 the ASME test requires that the Charpy test consists of three specimens and requires reporting both minimum and average results. ASME requires testing of base metal, weld metal and HAZ (nine samples total) 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 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[7] (manual) or ASTM E 1245[8] (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

---

[7] ASTM E 562 – Standard test method for determining volume fraction by systematic manual point count

[8] ASTM E 1245 – Standard practice for determining the inclusion or second-phase constituent content of metals by automatic image analysis

measured phase balance. AWS A4.2[9] and EN ISO 8249[10] 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.

Table 5: Corrosion test temperature for different duplex grades according to ASTM A 1084C and ASTM A 923C. The maximum acceptable corrosion rate is 10 mg/dm^2 day.

Grade	Location	Test	Testing temperature °C (°F)
S32101	Base metal	ASTM A 1084C	25 (77)
S32304	Base metal	ASTM A 1084C	25 (77)
S31803	Base metal	ASTM A 923C	25 (77)
S31803	Weld metal	ASTM A 923C	22 (72)
S32205	Base metal	ASTM A 923C	25 (77)
S32205	Weld metal	ASTM A 923C	22 (72)
S32750	Base metal	ASTM A 923C	40 (104)
S32550	Base metal	ASTM A 923C	40 (104)
S32520	Base metal	ASTM A 923C	40 (104)

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 non-magnetic, magnetic testing cannot be used to directly detect sigma and chi phases. However, low-magnetic ferrite readings on a duplex stainless steel may be an indication that the ferrite has been transformed to an intermetallic phase. Duplex stainless steels exposed to the intermetallic precipitation temperature range for an extended period of time during heat treating or cooling may exhibit low ferrite contents.

Installation of hyper duplex stainless steel bolts to preserve the historic wooden Vasa ship in Sweden.
© Anneli Karlsson, the Swedish National Maritime Museums

6.2.5 Corrosion testing

Corrosion testing of solution annealed mill products, in accordance with ASTM A 923/A 1084 Method C, is one of the most cost-effective testing methods for detection of detrimental conditions. The presence of intermetallic phases, and chromium nitride, in an excessively ferritic phase balance, are detected as a loss of pitting resistance. These phases cause losses of 15°C, or more, from the CPT typically expected for the properly annealed material. Measurement of the actual critical pitting temperature for a specimen is relatively expensive because it requires multiple tests per ASTM G 48 or ASTM G 150 testing of a single specimen. However, performing a single corrosion

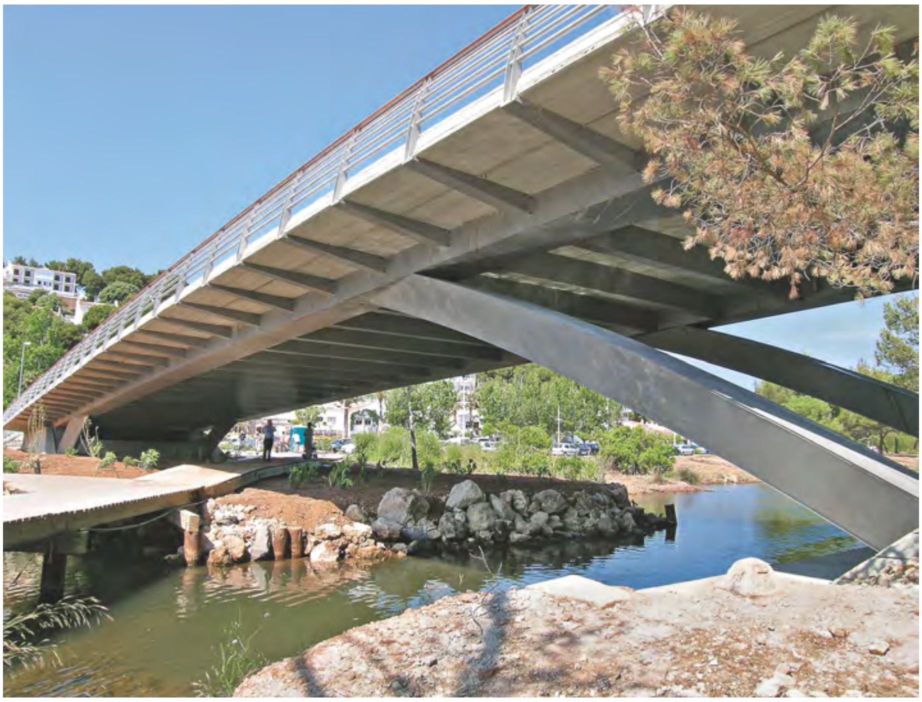
---

[9] AWS A4.2 – Standard procedure for calibrating magnetic instruments to measure delta ferrite content of austenitic and duplex ferritic-austenitic stainless steel weld metal

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

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.

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 a 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 a statement of other testing variables including:



Bridge in Cala Galdana on Menorca fabricated using 2205 duplex stainless steel. © PEDELTA

- 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 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 6**. 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 12**. 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).

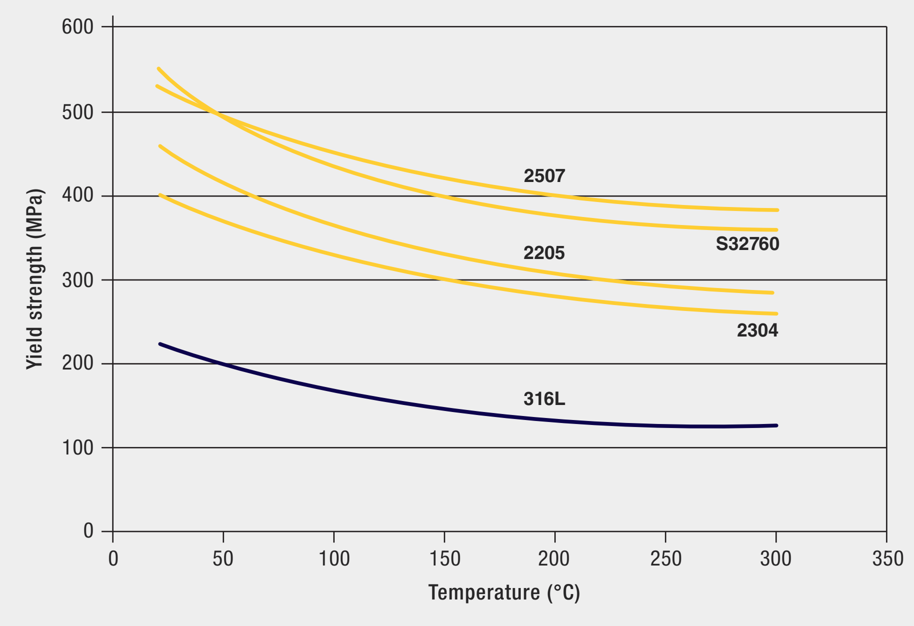


Figure 12: Comparison of typical yield strength of duplex stainless steels and Type 316L between room temperature and 300°C (572°F). Source: producer data sheets

The mechanical properties of wrought duplex stainless steels are highly anisotropic, that is, they may vary depending on the orientation of the test sample. 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

Table 6: 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 $R_{p0.2}$ 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

Table 7: 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			
Grade	UNS No.	Elongation, min. (%)	EN No.	Elongation, min. (%)*		
				P	H	C
	S32101	30	1.4162			
	S32202	30	1.4062			
2304	S32304	25	1.4362	25	20	20
	S32003	25				
2205	S32205	25	1.4462	25	25	20
2507	S32750	15	1.4410	20	15	15
304L	S30403	40	1.4307	45	45	45
316L	S31603	40	1.4404	45	40	40

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

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.

Despite their high strength, duplex stainless steels 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 7**.

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 the higher strength of duplex stainless steels, higher forces are required to deform them. As a result, their springback in bending operations is larger than that of austenitic stainless steels. A springback comparison of two duplex stainless

Installation of insulated 24 inch 2205 pipe on vertical support members in Prudhoe Bay.
© Arco Exploration and Production Technology

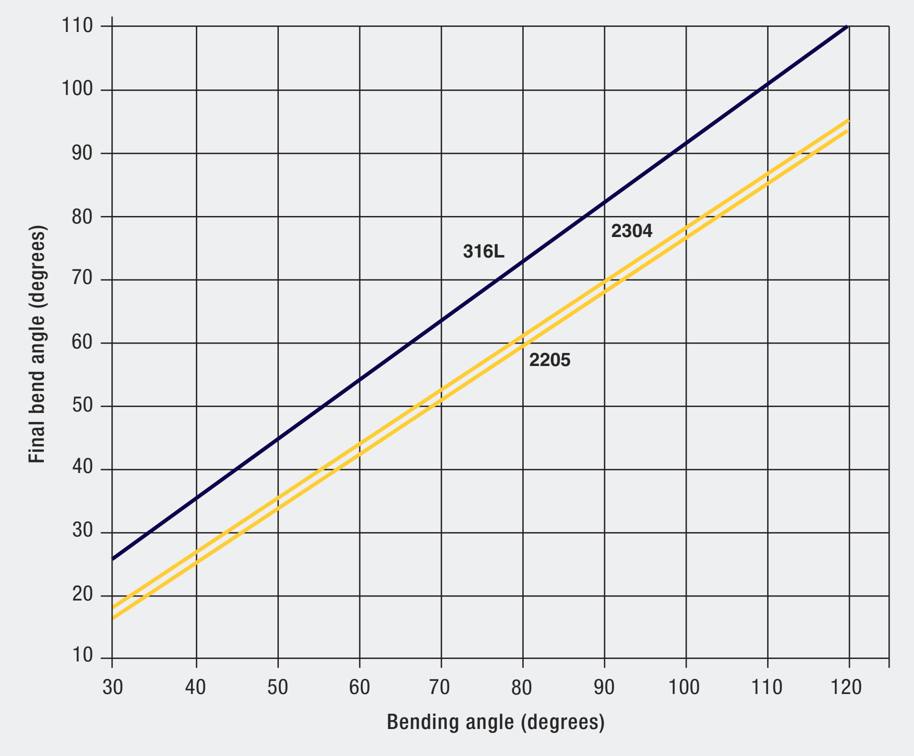


Figure 13: Comparison of springback of duplex stainless steels and Type 316L for 2 mm (0.08 inch) thick sheet. Source: Outokumpu

steels and Type 316L austenitic stainless steel is shown in **Figure 13**. 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 tool life in machining operations or increase 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 that of the austenitic stainless steels. The effect of cold work on the mechanical properties of 2205 is shown in **Figure 14**.

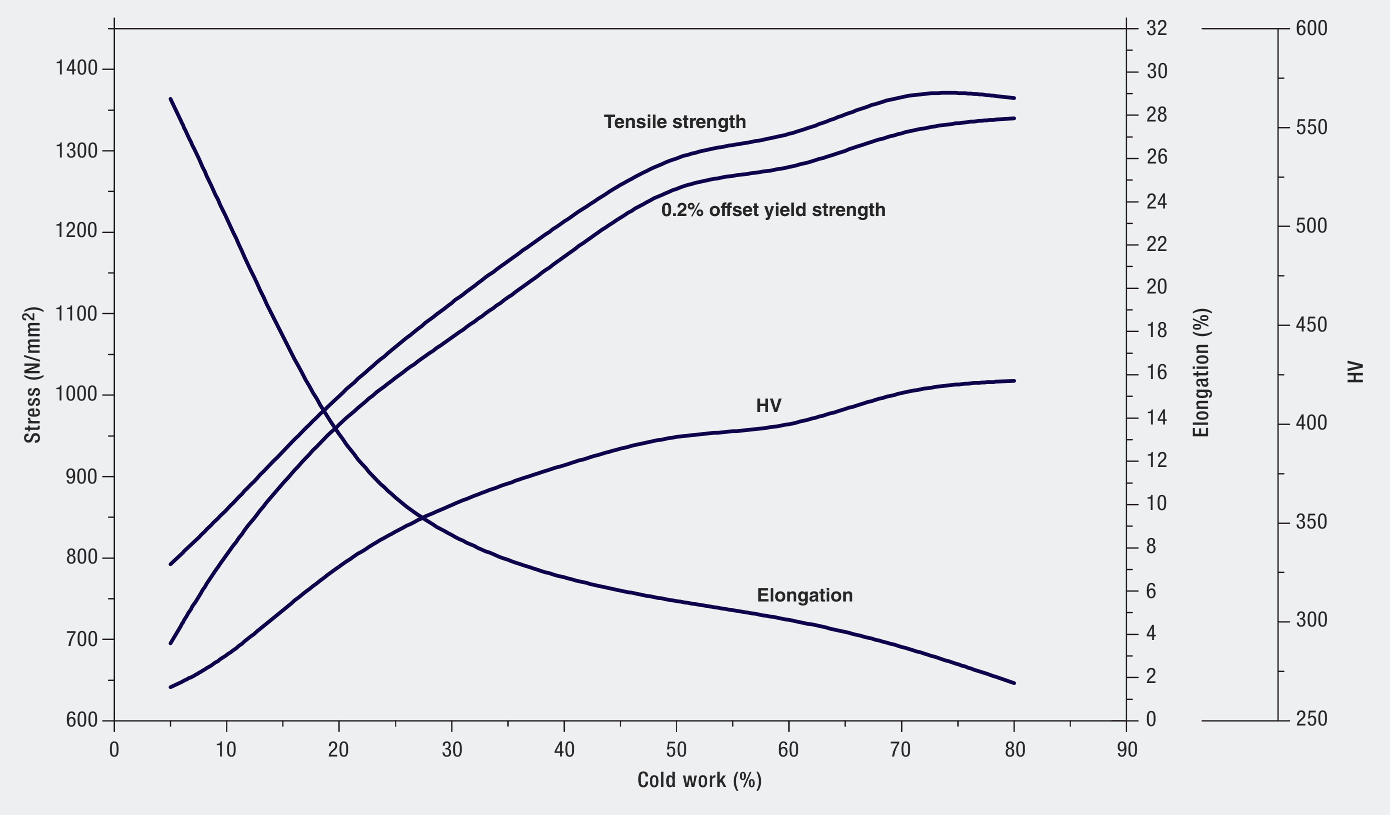


Figure 14: Effect of cold work on the mechanical properties of 2205 duplex stainless steel. Source: Baosteel

8 Physical properties

Ambient-temperature physical properties for a selection of duplex stainless steels are given in **Table 8**, and selected elevated temperature values are given in **Table 9**. 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 austenitic stainless steels and carbon steels, but tend to be closer to those of the stainless steels.

Table 8: 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	7.75	0.280	460	0.110	0.80	31.5	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
255	S32550	7.82	0.282	488	0.116	0.84	33.1	210	30.5
	S39274	7.80	0.281	502	0.120			200	29.0
	S32520	7.75	0.280	450	0.108	0.85	33.5	205	29.7
2507	S32750	7.75	0.280	485	0.115	0.80	31.5	200	29.0
	S32760	7.80	0.281			0.85	33.5	190	27.6
	S32707	7.80	0.281	470	0.112	0.75	29.5	197	28.5

Table 9: 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)			
	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)
	S32707	197 (28.5)	189 (27.5)	178 (25.7)	168 (24.2)		
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)
	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)
	S32707	NA	12.5 (6.94)	12.5 (6.94)	13.0 (7.22)	13.5 (7.50)	14.0 (7.78)
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)
	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	14.3 (98.5)	16.4 (113)	18.6 (128)	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)
	S32707	12.0 (84)	14.0 (96)	16.0 (110)	18.0 (124)	19.0 (132)	

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.

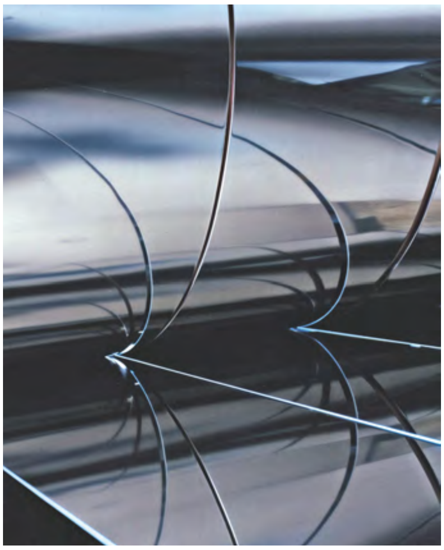
9.1 Sawing

Because of their high strength, high work hardening rate, and the virtual absence of inclusions that would serve as chip-breakers, 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 workpiece. 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 the same as would be expected of a thicker piece of Type 316 stainless steel. Therefore, the maximum thickness of 2304 or 2205 duplex stainless steel that can be cut on a particular shear is about 75% 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 the common austenitic grades.



Slitting of duplex stainless steel. © Outokumpu

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.

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. A good starting point and guideline is to assume that duplex stainless steel will behave similarly to an austenitic stainless steel twice its thickness. The more highly alloyed duplex stainless steels with higher levels of nitrogen are disproportionately more difficult.

9.5 Plasma and laser cutting

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 affect the optimal parameters marginally, but acceptable results can be achieved without special adjustment. The HAZ of the plasma cutting process is typically narrow, about 0.25 mm (0.010 inch) because the cut is made rapidly in 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.

Hot roller bending of duplex stainless steel plate. © Outokumpu

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 form scale above 1150°C (2100°F). At these 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 10** 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 super duplex plate, the exact limits vary with the composition of the duplex stainless steel and the efficiency of the quenching equipment. For a simple 2205 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.

Table 10: 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	1100–900	2000–1650	950	1750
2304	S32304	1.4362	1150–950	2100–1740	980	1800
2205	S32205	1.4462	1230–950	2250–1740	1040	1900
2507	S32750	1.4410	1230–1025	2250–1875	1050	1920
	S32520	1.4507	1230–1000	2250–1830	1080	1975
	S32760	1.4501	1230–1000	2250–1830	1100	2010
304	S30400	1.4301	1205–925	2200–1700	1040	1900
316	S31600	1.4401	1205–925	2200–1700	1040	1900

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 workpiece 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 annealing temperature. It should not be allowed to spend several minutes 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 11**.

Duplex stainless steels are quite soft at solution annealing temperatures, and warping and distortion are likely if the workpiece is not adequately supported. This can be a significant problem in tubular products, especially those with large diameters and thin walls. Reforming 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 best option may be the use of temporary supports to maintain the geometry of the product during annealing of thin sections.

Hot duplex stainless steel is removed from the heat treating furnace after solution annealing.
© Bosch-Gotthard-Hütte

Table 11: Minimum solution annealing temperatures for duplex stainless steels.
Source: producer data sheets and ASTM A 480

Grade	UNS No.	Minimum annealing temperature	
		°C	°F
	S32001	1040	1900
	S32101	1020	1870
	S32202	980	1800
2304	S32304	980	1800
	S82011	1010	1850
	S32003	1010	1850
	S82441	1000	1830
2205	S32205	1040	1900
	S32506	1020–1120	1870–2050
	S32520	1080–1120	1975–2050
255	S32550	1040	1900
2507	S32750	1025–1125	1880–2060
	S32760	1100	2010
	S32707	1080–1120	1975–2050

The use of stress relief treatments to reduce the cold work of forming or straightening operations is not advisable. 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 detrimental phases which will lower corrosion resistance and reduce toughness.

10.2 Warm forming

It is sometimes useful to slightly warm a steel piece to aid forming operations. However, prolonged heating of duplex stainless steels above 315°C (600°F) may result in some loss of ambient temperature toughness or corrosion resistance due to 475°C (885°F) embrittlement (see Figure 4). At higher temperatures, there is the risk of a more rapid and detrimental effect from precipitation of intermetallic phases. Because these phases do not interfere with the forming process, it is possible to warm the duplex stainless steels for forming. However, when the working temperature exceeds about 300°C (570°F), warm forming should be followed by a full solution anneal and rapid quench (see Table 11).

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 similarly 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 15** for several stainless steels. In addition to the higher initial bending forces, duplex stainless steels also strongly work harden as they are deformed. This rapid increase in strength during deformation also has to be taken into account when determining the maximum material thickness that can be formed on a press. 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 13).

The lower ductility of duplex stainless steels compared with austenitic stainless steels must also be taken into account. Duplex grades have a minimum required elongation of 15 to 30% in most specifications, in comparison with the 40% minimum elongation required for many austenitic grades. While actual

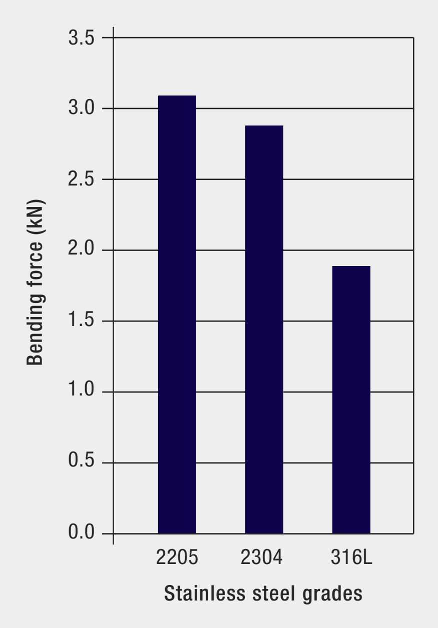
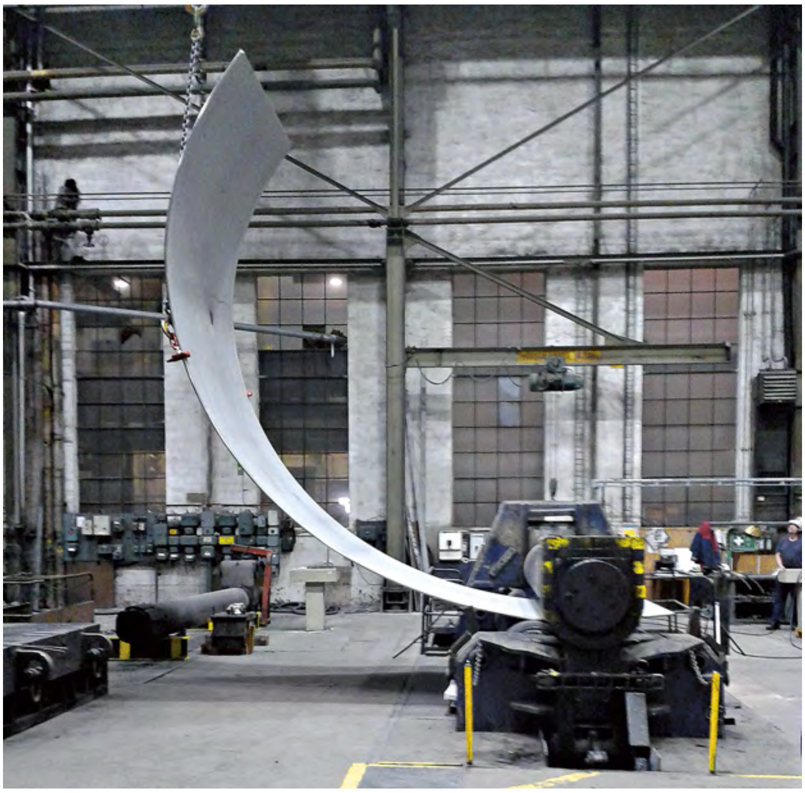


Figure 15: Minimum force required to begin plastic deformation in bending of 2304, 2205, and 316L test samples 50 mm (2 inch) wide and 2 mm (0.08 inch) thick. Source: Outokumpu



Roller bending of 28 mm thick duplex stainless steel plate. © Outokumpu 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 perceived 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. Duplex stainless steels are about 30 to 50% higher in yield strength, whereas ferritic steels show only limited work hardening and the running load can be relatively low. 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. 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 structure.

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.

In duplex stainless steels this strategy has not yet proven useful. However, a new type of duplex stainless steel has been developed to address this drawback. The formable duplex stainless steels exhibit a unique combination of high strength and substantially improved formability utilizing Transformation Induced Plasticity (TRIP). Characteristic properties are higher mechanical strength and increased formability compared to other duplex grades through a TRIP effect rather than through a preferred crystallographic texture.

For the formable duplex grades, UNS S82012 and S82031, the composition is balanced to give optimal austenite stability. During cold forming operations this leads to a controlled transformation of austenite to martensite (TRIP effect). Typically, the austenite content in the solution-annealed condition is slightly higher for the formable duplex grades than for other duplex grades.

The improved formability of these grades is similar to that of standard austenitic stainless steels during stretch forming processes. The TRIP effect results in enhanced uniform elongation and higher work hardening rates with greater plastic deformation in comparison to other duplex grades. These unique mechanical properties result in enhanced stretch formability, while deep drawing characteristics are similar to other duplex stainless steel grades.

Stamping trials have verified that the formable duplex grades are suitable for forming difficult components such as plate frame heat exchanger plates, flexible tubing, pump components, and domestic water heater and automotive components.

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 operator skills. 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 part thickness is not reduced 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 needed for 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, especially 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 16** 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 Type 316 stainless steel.

11.1 General guidelines for machining duplex stainless steels

The guidelines for machining below are generally applicable to all stainless steels, but following them is especially important for duplex stainless steels.

- Use powerful, rigid machines with extremely strong, rigid mounting of the tools and workpiece. (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 carbide tooling that provides a ‘sharp’ edge while still providing adequate strength.
- Design machining sequences to always provide for a depth of cut below the work hardened layer resulting from prior passes.
- Use adequate but not excessive speed to avoid built-up edge and rapid wear.
- Change tooling inserts or re-grind at scheduled intervals to ensure 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.

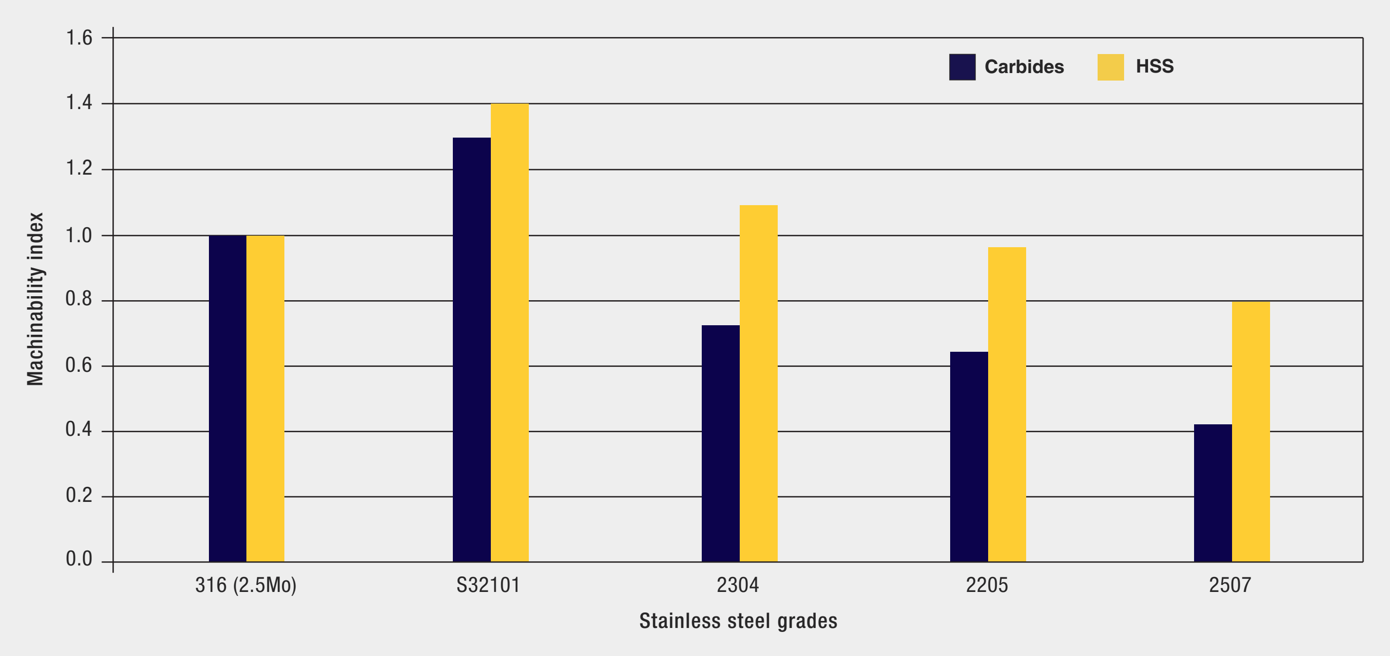


Figure 16: Relative machinability of duplex stainless steels compared with Type 316 (2.5Mo) for cemented carbide tooling and for high-speed steel (HSS) tooling. Source: Outokumpu

11.2 Turning and face turning

Turning and face turning 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 17** and **Table 12**. 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.

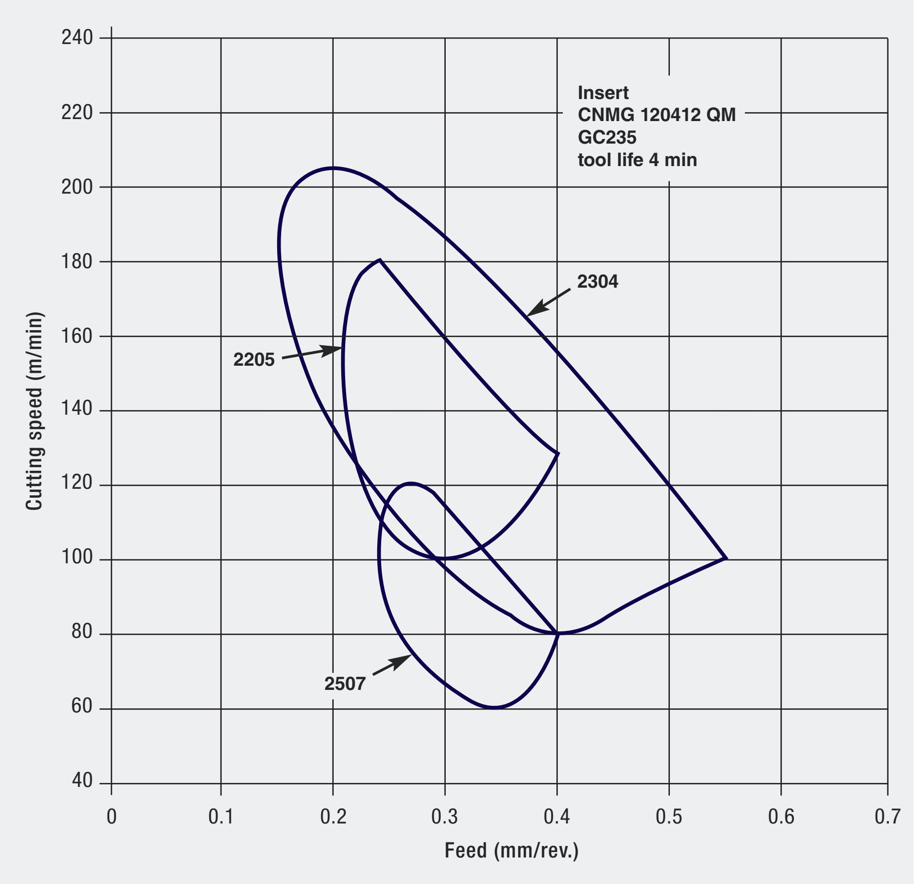


Figure 17: Comparison of machining parameters for turning duplex stainless steels with a cemented carbide insert with a tool life of four minutes. Source: Sandvik

Table 12: Machining guidelines for face turning duplex stainless steels. Source: Outokumpu

Stainless steel (or machining data)	Carbides				High-speed steel	
	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
2507	50–70	165–230	70–105	230–350	10–15	35–50
Feed (per turn)	0.3–0.6mm	0.012–0.024 in.	0.05–0.3mm	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	S32101, 2304, 2205: ISO P20-P35 (C5) Super duplex: ISO P30-P50		S32101, 2304,2205: ISO P10-P15 (C6-C7) Super duplex: ISO P25-P35		High quality	

Face milling operation. © AB Sandvik Coromant

11.3 Face milling with cemented carbides

Guidelines for face milling duplex stainless steels with cemented carbides are provided in **Table 13**.

- Use coated inserts or a tough grade of insert for roughing. A harder insert may be used for finishing when a 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.

Table 13: 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	S32101, 2304, 2205: ISO P20-P40 Super duplex: ISO P25-P40		S32101, 2304, 2204: ISO P10-P25 Super duplex: P20-P30	

11.4 Twist drilling with high-speed steel drills

Guidelines for twist drilling duplex stainless steels with HSS drills are provided in **Tables 14** and **15**.

- 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.

Twist drilling operation. © Sandvik

Table 14: 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	2507	S32101, 2304, 2205	2507
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 15: 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	2507	S32101, 2304, 2205	2507
0.040–0.120	40–120	20–33	20–25	16–25	0.002	0.0015
0.20	40–120	33–40	33–40	30–36	0.004	0.003
0.40	40–120	40–50	33–40	30–36	0.008	0.006
0.60	40–120	40–50	33–40	30–36	0.010	0.008
0.80	40–120	40–50	33–40	30–36	0.012	0.010
1.20	40–120	40–50	33–40	30–36	0.014	0.012
1.60	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 HAZ, not with the weld metal. The HAZ problems can be loss of corrosion resistance, toughness, or post-weld cracking. To avoid these problems, the welding procedure should focus on minimizing total time at temperature in the 'red hot' range rather than managing the heat input for any one pass. Experience has shown that this approach can lead to procedures that are both technically and economically optimal.

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

12.1.2 Selection of starting material

The response of duplex stainless steels to welding may be substantially changed by variations in chemistry or processing. The importance of the base metal containing sufficient nitrogen has been repeatedly emphasized. If the starting material is cooled slowly through the 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

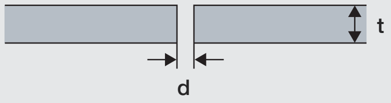
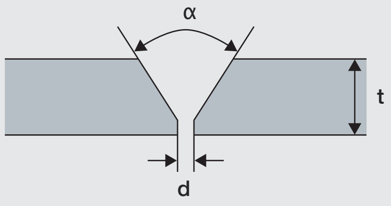
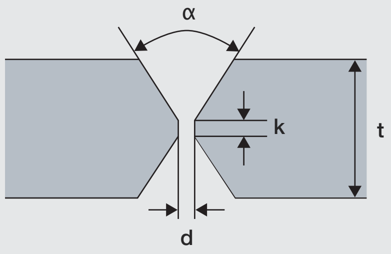
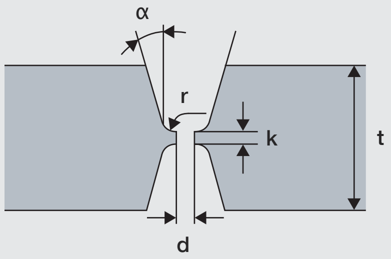
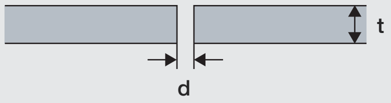
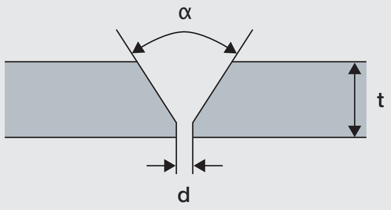
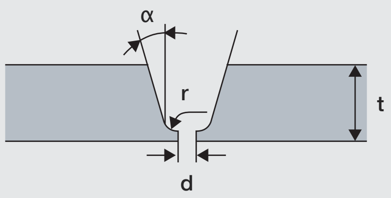
The admonition to clean all regions that are to be heated prior to welding applies not just to duplex stainless steels, but to all stainless steels. The chemistries of the base metal and the filler metal have been developed assuming that there are no additional sources of contamination. Dirt, grease, 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 welding.

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 and 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, for example weaving, 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 18**. Other designs are possible provided they assure full-penetration welds and minimize the risk of burn-through.

Figure 18: Examples of weld joint designs used with duplex stainless steels. Source: ArcelorMittal

Groove	Process	Thickness 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

2205 oxygen delignification reactor, Enterprise Steel Fab, Kalowna, Prince George, British Columbia, Canada. © Outokumpu

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 (210°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 workpiece 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 super duplex 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 (700–1000°C/1300–1830°F) or alpha prime (475°C/885°F), causing a loss of toughness and corrosion resistance. Postweld heat treating temperatures in excess of 315°C (600°F) can result in detrimental phase precipitation.

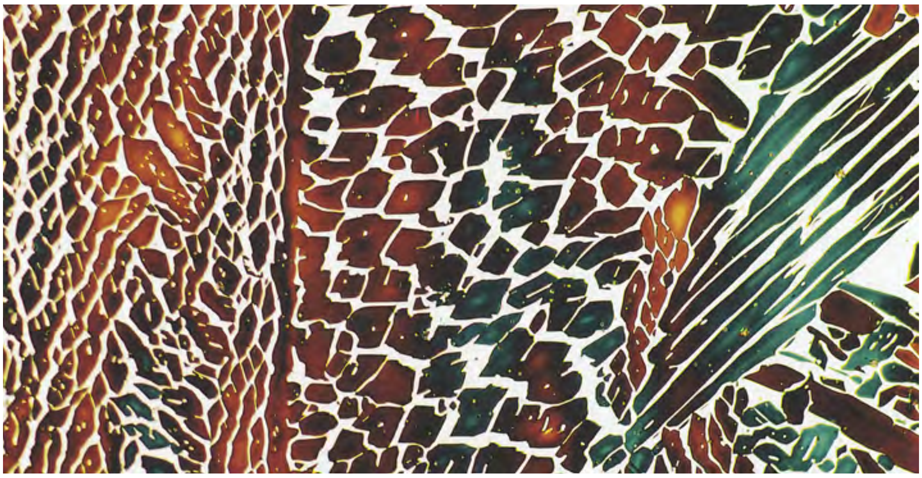
Postweld heat treatment should include full solution annealing followed by water quenching (see Table 11). Full solution annealing should also be considered after autogenous welding, since the microstructure will be highly ferritic if an overalloyed filler metal is not used during welding.

If a full solution anneal and quench is planned 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 25–30% 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. © 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 16 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 16: Welding consumables used for dissimilar metal welding

	Lean duplex	**Standard duplex**	**Super duplex**
Lean duplex	E2307 E2209 E309L	E2209	E2209
Standard duplex	E2209	E2209	E2594
Super duplex	E2209	E2594	E2594
304	E2209 E309L E309LMo	E2209 E309LMo	E2209 E309LMo
316	E2209 E309LMo	E2209 E309LMo	E2209 E309LMo
Carbon steel **Low alloy steel**	E2209 E309L E309LMo	E2209 E309L E309LMo	E2209 E309L 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 thickest section for each of the welding methods to be used for production.

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.

Gas tungsten arc welding. © Sandvik

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.

Duplex stainless steel can be welded using 2% thoriated (AWS EW-Th2), 2% ceriated (EW-Ce2), or 2% lanthanated (EWG-La2) tungsten electrodes. 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.
© 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 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 workpiece should be allowed to cool below 150°C (300°F) for standard duplex stainless steels and below 100°C (210°F) for super duplex 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 super duplex 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:
0.5–1.5 kJ/mm (15–38 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.

Lean duplex stainless steel asphalt hauling tanker. © Outokumpu

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

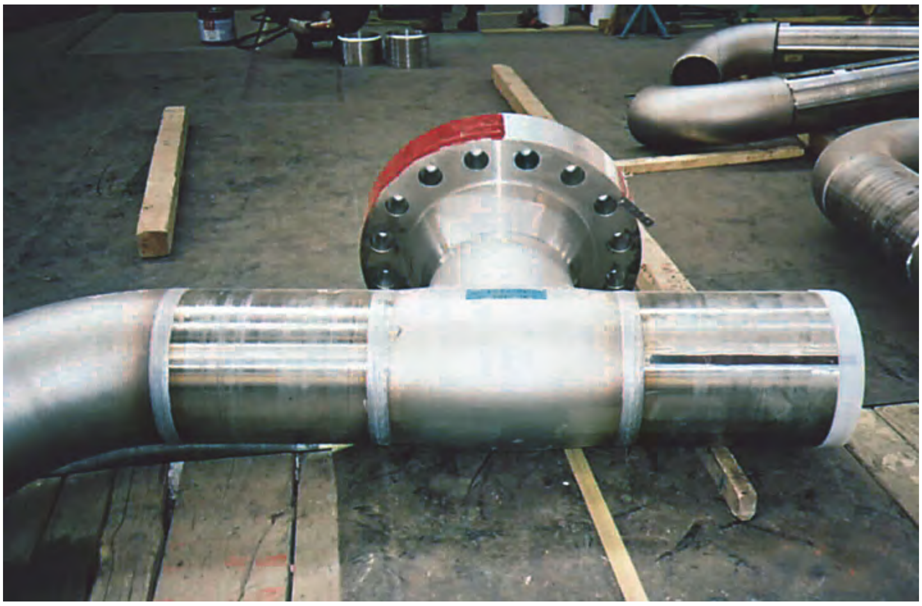
Selection of shielding gas for GMAW is somewhat more complex than for GTAW, and depends to a significant extent on whether the fabricator is relying upon purchased gas mixtures or has on-site gas mixing capability. The GMAW shielding gasses range from pure argon to about 70% argon with additions of helium, nitrogen, oxygen, and carbon dioxide, 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 17**.

Table 17: 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

Short-circuiting arc transfer			
Weld wire diameter		Current	Voltage
mm	Inch	A	V
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



2205 Flanged T-piece. © Arco Exploration and Production Technology

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.

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 workpiece should be allowed to cool below 150°C (300°F) between passes to provide for adequate cooling of the HAZ in subsequent passes.

Mechanized welding of large diameter duplex stainless steel pipeline on Alaska's north slope. © Arco Exploration and Production Technology

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

Table 18: 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	5/64	35–60	22–28
2.5	3/32	60–80	22–28
3.25	1/8	80–120	22–28
4.0	5/32	100–160	22–28

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 2205 welds, is the use of the ASTM A 923 Method B 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 acceptable 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 Method B.

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 18**.

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.

2507 stainless steel enhanced oil recovery equipment. © Aquatech

SMAW should not be used on duplex stainless steels of less than 2 mm (0.08 inch) thickness. The workpiece 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 workpiece, with the electrode grip inclined forward to the direction of travel. The metal should be deposited in a straight stringer bead with minimal weave. Current should be set only high enough to provide a smooth arc and good fusion of the weld and the base metal.

12.3.5 Submerged arc welding (SAW)

Submerged Arc Welding allows the deposition of relatively large welds with less total time at temperature for the HAZ than would be possible for a large number of passes with less deposition per pass. Because of the ferritic solidification and duplex transformation of the weld metal, the duplex stainless steels can be SAW with minimal risk of hot cracking. However, it is necessary to make some 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 and can be used for strip overlay welding.

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.

Table 19: 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	3/32	250–450	28–32
3.25	1/8	300–500	29–34
4.0	5/32	400–600	30–35
5.0	11/64	500–700	30–35

Note: Travel Speed is typically 30–60 cm/minute (12-24 in/minute)

Submerged arc welding. © Outokumpu

Technique and parameters

Typical parameters for SAW duplex stainless steel are summarized in **Table 19**.

12.3.6 Weld overlay – electro-slag welding (ESW)

Surface weld overlaying of low alloyed base metals with strip electrodes by Submerged Arc Welding (SAW) or Electro-Slag Welding (ESW) is a method to obtain an economical, corrosion resistant material in applications where strength requirements necessitate relatively thick and high strength construction materials.

Compared to other weld surfacing processes the total heat-input is higher for SAW and ESW strip welding. ESW strip weld overlay resembles the SAW strip welding process by utilization of the same type of equipment but operates with electrically conductive molten flux and ohmic heating instead of an electrical arc. In ESW no arc is found except at the start of welding in order to initially melt the flux. The molten flux is electro-conductive and by means of resistance heating provides enough heat to melt both the strip and the base metal. Dilution levels in the range of 10–15% are commonly observed. The deposition rate is around 50–60% higher than SAW for the same size of strip electrode. The ESW process has the advantage over SAW welding of enabling higher weld speed, smoother weld beads and cleaner weld beads because of melting by ohmic heating of the strip with slag refining of the fused metal.

Duplex steels are particularly suitable for surface alloying because the thermal expansion coefficient is similar to that of carbon or low-alloyed steel base metal, in comparison to austenitic stainless steels that have a higher thermal expansion coefficient. Therefore, with duplex stainless steel surface alloying, the welded components exhibit lower stresses and display a lower probability of welding related problems.

Filler metals and shielding

The ESW electrodes are in the form of continuous strip that is fed through a weld head by an automatic feeding system. The weld flux is fed to cover the strip and weld pool and is fused creating a molten slag, in which ohmic resistance between the workpiece and the strip generates heat to fuse the strip. The molten strip metal is refined through the slag, which solidifies on top of the weld bead and thereby creates an effective shielding from the surrounding atmosphere. The filler metals for ESW of duplex and super duplex stainless steels are 'matching' compositions overalloyed with nickel to achieve the desired phase balance and properties in the as-welded condition.

Technique and parameters

The strip is deposited as a weld bead that is typically 4–5 mm thick in a single layer. Typical parameters for duplex and super duplex stainless steels are summarized in **Table 20.**

Table 20: Typical ESW welding parameters for duplex and super duplex stainless steels. Source: Sandvik

Strip dimension (width x thickness)		Current	Voltage
mm	Inch	A	V
30 x 0.5	1.181 x 0.020	550–700	23–26
60 x 0.5	2.362 x 0.020	1100–1400	23–26
90 x 0.5	3.543 x 0.020	1650–2100	23–26

Note: Travel speed is typically 13–22 cm/minute (5–9 in/minute)

Electro-slag weld strip overlay. © Sandvik

12.3.7 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.

12.3.8 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 steels. 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.

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 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 off 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. Except for 2205, limited data is 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 cleanup after soldering and includes scrubbing with hot water or a neutralizing chemical.

14 Post fabrication cleanup

The post fabrication cleanup of duplex stainless steels is not different from the cleanup required on other stainless steels. The post fabrication cleanup 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 corrosion potential than the stainless steel surface, so galvanic interactions may occur. It is important to remove these disruptions of the protective passive film. **Figure 19** shows a summary of disruptions that may occur during fabrication and that should be removed before putting any stainless steel in service.

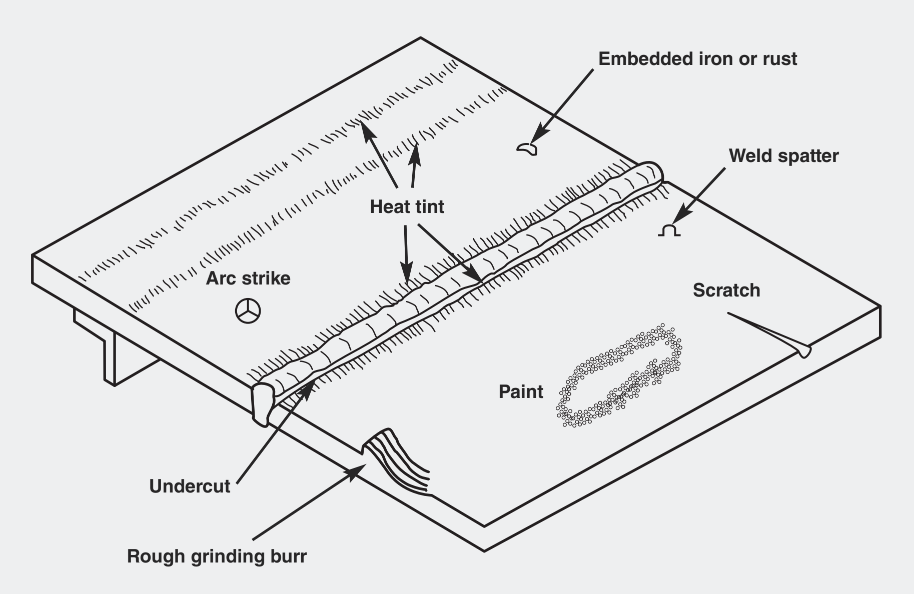


Figure 19: Typical fabrication defects or surface conditions which may be encountered. Source: Nickel Institute Publication 10 026

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 steel. Often the tools are color coded in the shop.

Embedded iron in roll formed duplex stainless steel plate fabrication. © Gary Carinci, TMR Stainless

However, it may be 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 another approach, one accepts that there will be iron transfer but undertakes to ensure that it is removed before the stainless steel is put in service. The method of removing the iron may involve mechanical cleaning, chemical cleaning, or a combination of mechanical and chemical cleaning. The best cleaning method depends on the size and shape of the equipment, the anticipated service, and certain practical issues including disposal of the cleaning wastes. One common cleaning method has been a chemical treatment with nitric acid, which dissolves the free iron on the stainless steel surface but does not attack the stainless steel or the protective passive film layer. However, there are many different chemical cleaning approaches that can achieve the desired results. Details of cleaning methods are thoroughly discussed in ASTM A 380[11]. It is especially important that the user be familiar with the safety issues discussed in ASTM A 380.

ASTM A 967[12] (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 standard, 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.

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 discoloration 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 cleanup. 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. 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 may be required to remove the heat tint.

Research has shown that chemical cleaning after welding results in the optimum level of corrosion resistance.

Marine chemical tanker with 2205 tanks. © ArcelorMittal

---

[11] ASTM A 380 – Standard practice for cleaning, descaling and passivation of stainless steel parts, equipment, and systems

[12] ASTM A 967 – Standard specification for chemical passivation treatments for stainless steel parts

15 Duplex stainless steel applications

Pulp and Paper

One of the first applications to use duplex stainless steels in the 1930's was the sulfite paper industry. Duplex stainless steel is used currently by the pulp and paper industry for bleaching equipment, digesters, chip storage tanks, black and white liquor storage tanks, and suction roll shells. Duplex stainless steel has replaced austenitic stainless steel and carbon steel as the higher strength and superior corrosion resistance of duplex stainless steel allows for thinner plate to be used for the same pressure rating. Fabrication with thinner plate results in lower overall material costs and less welding time, along with lower shipping and handling costs.

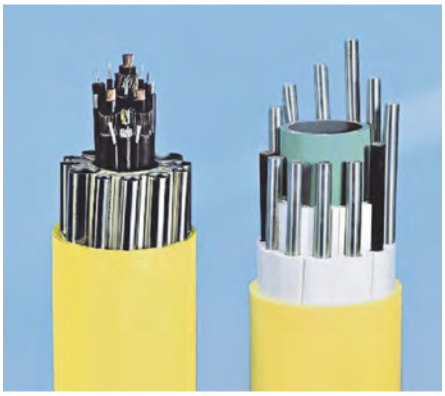
Multi stage flash seawater desalination unit constructed of S32101 and 2205 duplex stainless steels. © Outokumpu

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 equipment suppliers and 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 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 was selected for solid-duplex evaporators to be installed in the Melittah MSF plant and the Zuara MED plant in Libya.



2507 umbilical tubing for offshore oil and gas applications. © Sandvik

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 for parts exposed to less hostile conditions.

Three MSF plants were constructed using this dual duplex concept, with a combination of 2205 and UNS S32101: Taweelah B (Abu Dhabi, 69.2 MIGD capacity), Jebel Ali L2 (Dubai, 55 MIGD) and Ras Abu Fontas B2 (Qatar, 30 MIGD).

Oil and gas

In oil and gas, duplex stainless steel has played a crucial role in helping to withstand aggressive conditions. This is due to its strength and pitting and crevice corrosion resistance, which is superior to that of standard austenitic alloys, with PREN often exceeding 40.

Part of a 31 m (102 ft) tall 2205 duplex stainless steel tank. © Outokumpu

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. Super duplex (25% chromium) stainless steels are used for their high strength, so they are often used for bar, forgings, castings, sheet, plate, tube, and fasteners. Super duplex 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. Umbilcals are now being used in warmer water, and new concepts are developing where a riser is introduced in the umbilical. These trends demand increased corrosion resistance and mechanical strength. New hyper duplex stainless steels with better corrosion resistance and higher strength than super duplex stainless steel have been developed for use in umbilicals.

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 Types EN 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 Types 304/304L.

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 Helix 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. © Ove Arup & Partners

In addition, the Helix 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 the double-helix and support structures 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 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 salt corrosion. Other factors in the selection included cost and a favorable strength-to-weight ratio for duplex stainless steel compared to other grades.

The Helix Bridge, Singapore, made of 2205 duplex stainless steel.

Hamad International Airport in Doha, Qatar has a duplex stainless steel roof. © Hamad International Airport

Suggested additional reading

General information

P. Johansson, M. Liljas, A New Lean Duplex Stainless Steel for Construction Purposes, Proceedings of 4th European Stainless Steel Conference Science and Market, Paris 2002.

M. Liljas, J.Y. Jonsson, S.Wessman, Stress Relief Treatment of 22Cr Duplex Stainless Steel EN 1.4462, Proceedings of Stainless Steel World Conference, Maastricht, Netherlands, 2005

M. Liljas, 80 Years with Duplex Steel, a Historic Review and Prospects for the Future,
Proceedings of 6th European Stainless Steel Conference Science and Market, Helsinki, Finland 2008

H. Liu, P.Johansson, M.Liljas , Structural Evolution of LDX 2101 During Isothermal Ageing at 600–850°C,
Proceedings of 6th European Stainless Steel Conference Science and Market, Helsinki, Finland 2008

Z. Wei, J. Laizhu, H. Jincheng, S. Hongmei, Study of Mechanical and Corrosion Properties of a Fe-21.4Cr-6Mn-1.5Ni-0.24N-0.6Mo Duplex Stainless Steel, Materials Science and Engineering A, 2008, 497: 501–504

J. Charles, Why and Where Duplex Stainless Steels, Proceedings of the 5th World Conference on Duplex Stainless Steels,
KCI Publishing, Zutphen, The Netherlands, 1997, p. 29.

M.G. Mecozzi, M. Barteri, Effect of Alloying Elements and Impurity on Hot Ductility of 23% Cr 4% Ni Stainless Steel,
5th World Conference Duplex Stainless Steels, Conference Proceedings, KCI Publishing, 1997, p. 1011–1016.

J. Charles, Super Duplex Stainless Steels: Structure and Properties, Proceedings of Duplex Stainless Steels ’91,
Les Editions de Physique, F-91944 Les Ulis Cedex, France, 1991, p. 3 and p. 151.

F. Dupoiron, S. Faucheur, and G. Varvat, Fabrications of Process Equipment in Duplex Stainless Steels,
Proceedings of Duplex Stainless Steels ’91, Les Editions de Physique, F-91944 Les Ulis Cedex, France, 1991, p. 621.

C. W. Kovach, High-Performance Stainless Steels, Nickel Development Institute Reference Book Series No 11021,Toronto, Canada, 2000

Physical metallurgy

R. Sanchez, I. Moreno, J. Amagro, J. Botella, Effects of Composition and Thermal History on the Phase Balance and Elements Distribution of Standard and Modified Duplex Stainless Steel, 4th Stainless Steel Science and Market Congress,
Conference Proceedings, Paris 2002, p. 108–113.

J.-O. Nilsson, The Physical Metallurgy of Duplex Stainless Steels, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 73.

J.-O. Nilsson, The Use of Modern Physical Metallurgy in the Development and Characterization of Special Stainless Steels, Journal de Physique, 4, 1993, Vol. 3, Number 7/V1, p. C7-67–C76.

B. Josefsson, J.-O. Nilsson and A. Wilson, Phase Transformations in Duplex Steels and the Relation Between Continuous Cooling and Isothermal Heat Treatment, Proceedings of Duplex Stainless Steels ’91, Les Editions de Physique, F-91944 Les Ulis Cedex, France, 1991, p. 67.

Machining

C. Bergqvist, J. Olsson, Machining in the New Duplex Grade LDX 2101-Easier Than Expected. Proceedings of Duplex 2007, Grado, Italy 2007.

B. Pellegrini, B.N. Di Caprio and R. Pacagnella, Tool Performance in Continuous Cutting of Duplex Stainless Steel, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 175.

C.G. Carlborg, Å. Nilsson and P-Å. Frandlind, Machinability of Duplex Stainless Steel, Proceedings of Duplex Stainless Steels ’91, Les Editions de Physique, F-91944 Les Ulis Cedex, France, 1991, p. 685.

Welding

F. Hägg, M.Liljas, B.Holmberg, The welding consequences of replacing austenitic with duplex stainless steel. Proceedings of Stainless Steel World Conference, Maastricht, Netherlands, 2007

C. Baxter, M.Young, Practical aspects for production welding and control of duplex stainless steel pressure and process plants. Proceedings of Duplex America, Houston, TX, 2000

C. Baxter, N.A McPherson, High-productivity welding of duplex stainless steel. Proceedings of Duplex America, Houston, TX, 2000

B. Holmberg, M.Larén, Welding and applications of the new lean duplex steel LDX 2101. IIW Annual meeting, Prague, Czech Republic, 2005.

C. Eriksson, P.Johansson, M.Liljas, E.M. Westin, Mechanical properties of welds in the new lean duplex stainless steel LDX 2101. Proceedings of Stainless Steel World Conference, Maastricht, Netherlands, 2003

L. Duprez, B. De Cooman, N. Akudt, Microstructure Evolution During Isothermal Annealing of a Standard Duplex Stainless Steel Type 1.4462, Steel Research, 71, 2000, No.10, p. 417–422

L. van Nassau, H. Meelker, F. Neessen and J. Hilkes, Welding duplex and super duplex stainless steel, an update of the guide for industry, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 17.

L. Karlssson, Duplex stainless steel weld metal – effects of secondary phases, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 43.

C. Baxter, L. Tuveson-Carlström, L. Svensson and A. Brorson, The significance of filler metal type on the stress corrosion cracking and fracture toughness of welded 2205 duplex stainless steel, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 279.

B. Holmberg, How to Perform Welding in Duplex Stainless Steels to Obtain Optimum Weld Metal Properties, Stainless Steel World, March 1997, p. 28.

P. Rouault and C. Bonnet, A new shielding gas range for the TIG, plasma and MIG welding of duplex and super duplex stainless steels, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 289.

R.N. Gunn, Intermetallic formation in super duplex stainless steel heat affected zone, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 335.

L. Karlsson, S.L. Andersson and S. Rigdal, Welding super duplex stainless steels with Ni-base consumables, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 433.

B. Bonnefois, J. Charles, A. Bruyere, and R. Cozar, Welding of super duplex steels: new efficient solutions for joining using Ni alloys filler materials, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 499.

D.N. Noble, W. A. Bruce, and R.N. Gunn, Hot tapping 22% Cr duplex stainless steel, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 471.

K. Yasuda, R.N. Gunn, and T.G. Gooch, Prediction of austenite content in duplex stainless steels weld metals, Paper 26, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

L. Odegard, C-O Pettersson and S-A Fager, The selection of welding consumables and properties of dissimilar welded joints in the super duplex stainless steel Sandvik SAF 2507 to carbon steel and highly alloyed austenitic and duplex stainless steels, Paper 94, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

V. van der Mee, H. Meelker, and L. van Nassau, How to avoid hydrogen cracking in (super) duplex stainless steel weldments, Paper 119, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

M. Liljas, The welding metallurgy of duplex stainless steels, Paper KV, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

D.J. Kotecki and J.L. P. Hilkes, Welding processes for duplex stainless steels, Paper KVI, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

Inspection

F.H. Dijkstra and J.A. de Raad, Non-destructive testing of duplex welds, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 509.

D.J. Kotecki, Ferrite measurement in duplex stainless steel, Proceedings of the 5th World Conference on Duplex Stainless Steels, KCI Publishing, Zutphen, The Netherlands, 1997, p. 957.

C.I.K. Sinclair and B.W.O. Shepherd, Non-destructive testing of welds in duplex stainless steels, Paper 63, Proceedings of 4th International Conference Duplex Stainless Steels, TWI, Abington Hall, Abington, Cambridge, UK, 1994.

J.D. Redmond and R.M. Davison, Critical Review of Testing Methods Applied to Duplex Stainless Steels, Stainless Steel World, April 1998, p. 37–45

References

1 J. Charles, Super duplex stainless steels: structure and properties, Proceedings of Duplex Stainless Steels '91, Les Editions de Physique, F-91944 Les Ulis Cedex, France, p. 3, 1991.

2 R. Sánchez, I. Moreno, J. Almagro, J. Botella, X. Llovet, Effects of Composition and Thermal History on the Phase Balance and Elements Distribution of Standard and Modified Duplex Stainless, Fourth Stainless Steel Science and Market Congress, Paris 2002, Conference Proceedings

3 I. Zucato, M. C. Moreira, I. F. Machado and S. M. Giampietri Lebrão, Microstructural Characterization and the Effect of Phase Transformations on Toughness of the UNS S31803 Duplex Stainless Steel Aged Treated at 850 °C, Materials Research Print version ISSN 1516-1439, Mat. Res. vol.5 no.3 São Carlos July/Sept. 2002

4 B. Josefsson, J.-O. Nilsson and A. Wilson, Phase Transformations in duplex steels and the relation between continuous cooling and isothermal heat treatment, Proceedings of Duplex Stainless Steels '91, Les Editions de Physique, F-91944 Les Ulis Cedex, France, 1991, p. 67.

5 C. Hounglu and S. Hertzman, Kinetics of Intermetallic Phase Formation in Duplex Stainless Steel and Their Influence on Corrosion Resistance, Report IM-2689, Swedish Institute of Metals Research, Stockholm, Sweden.

6 G. Herbsleb and P. Schwaab, Precipitation of Intermetallic Compounds, Nitrides and Carbides in AF 22 Duplex Steel and their Influence on Corrosion Behavior in Acids, Proceedings of Duplex Stainless Steels Conference, ASM, Metals Park, Ohio, 1983, p.15

7 L. Iturgoyen and M. Anglada, The Influence of Aging at 475°C on the Fatigue Crack Propagation of a Duplex Stainless Steel, Proceedings of Stainless Steels '91, The Iron and Steel Institute of Japan, Tokyo, Japan, Vol. 2, p. 746, 1991.

8 D. Bauernfeind and G. Mori, Corrosion of Superaustenitic Stainless Steels in Chloride- and Sulfate-Containing Media-Influence of Alloying Elements Cr, Mo, N, and Cu, Proceedings of NACE Corrosion 2003 Conference, Paper 03-257

9 P.-E. Arnvig, and W. Wasielewska, Stress Corrosion Behaviour of Highly Alloyed Stainless Steels under Severe Evaporative Conditions, ACOM 3-1993, Avesta Sheffield AB, 1993.

10 A. Miyasaka, K. Denpo and H Ogawa, Prediction of Application Limits of Stainless Steels in Oilfield Equipment, Proceedings of Stainless Steels '91, The Iron and Steel Institute of Japan, Tokyo, Japan, Vol. 1, p. 241, 1991.

11 J.J. Eckenrod, et al, "Effects of Chemical Composition and Thermal History on the properties of Alloy 2205 Duplex Stainless Steel", New Developments in Stainless Steel Technology, R. A Lula, Ed., ASM 1985.

12 R.M. Davison and J.D. Redmond, Paper No. 302, CORROSION/91, NACE International, Houston, Texas, 1991.

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 DP12
S31500		1.4424	X2CrNiMoSi 18-5-3				3RE60
S32001		1.4482	X2CrMnNiMoN21-5-3				Nitronic 19D
S32003							ATI 2003
S32101		1.4162	X2CrMnNiN21-5-1				LDX 2101 B2101
S32202							UR 2202
S31803 S32205	2205*	1.4462	X2CrNiMoN22-5-3	SUS 329 J3L	022Cr22Ni5Mo3N	STS 329J3L	SAF 2205 UR 2205 UR 2205+ UR 2205Mo DMV 22-5 ATI 2205 2205 Code Plus Two NAS 329J3L NSSC DX1 DP8 B2205
S32304	2304*	1.4362	X2CrNiN23-4		022Cr23Ni5Mo3N		SAF 2304 UR 2304 B2304
S32506							NAS 64
S32520		1.4507	X2CrNiMoCuN25-6-3				UR 2507Cu
S32550	255*				03Cr25Ni6Mo3Cu2N		Ferralium 255 UR 2507Cu
S32707							SAF 2707 HD
S32750	2507*	1.4410	X2CrNiMoN25-7-4	SUS 329 J4L	022Cr25Ni7Mo4N	STS 329 J4L	AF 2507 UR 2507 NAS 74N SAF 2507
S32760		1.4501	X2CrNiMoCuWN25-7-4				Zeron 100 UR 2507W 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	X2CrNiCuN23-4				
		1.4477	X2CrNiMoN29-7-2				SAF 2906
S82012		1.4635					FDX 25
S82121							329LA
S82122							NSSC 2120
S81921							329LD
S82031		1.4637					FDX 27
S82441		1.4662					LDX 2404

* 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 182	A 240/M SA 240	A 270	A 276 SA 276	A 314	A 479/M SA 479	A 480/M SA 480	A 484/M SA 484
S31200		X	X					X	
S31260			X					X	
S31803		X	X	X	X	X	X	X	X
S32001			X					X	
S32003			X	X		X		X	
S32101			X		X	X	X	X	X
S32202		X	X		X	X	X	X	X
S32205	2205	X	X	X	X	X	X	X	X
S32304	2304		X		X	X		X	X
S32506			X		X		X	X	X
S32520		X	X					X	
S32550	255	X	X		X		X	X	X
S32707									
S32750	2507	X	X	X	X		X	X	X
S32760		X	X		X	X	X	X	X
S32900	329		X					X	X
S32906		X	X				X	X	X
S32950		X	X			X	X	X	X
S33207									
S39274		X	X					X	
S39277		X					X		X
S82011			X					X	
S82012			X					X	
S82031			X					X	
S82121			X					X	
S82122			X					X	
S82441			X		X	X	X	X	X

EN specifications

EN No.	EN Name	EN 10028-7	EN 10088-2	EN 10088-3	EN 10088-4	EN 10088-5	EN 10095	EN 10216-5
1.4362	X2CrNiN23-4	X	X	X	X	X	X	X
1.4655	X2CrNiCuN23-4		X					
1.4460	X3CrNiMoN27-5-2			X		X		
1.4477	X2CrNiMoN29-7-2		X	X	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
1.4424	X2CrNiMoSi18-5-3		X	X	X	X		X
1.4062	X2CrNiN22-2							
1.4162	X2CrMnNiN21-5-1				X	X		

	A 580/M	A 790/M SA 790	A 789/M SA 789	A 815	A 923	A 928/M	A 959	A 1082	A 1084	API 650	NSF/ ANSI 61
		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	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 10217-7	EN 10222-5	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	X	
	X		X		X		X	
							X	

Cast duplex stainless steels

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

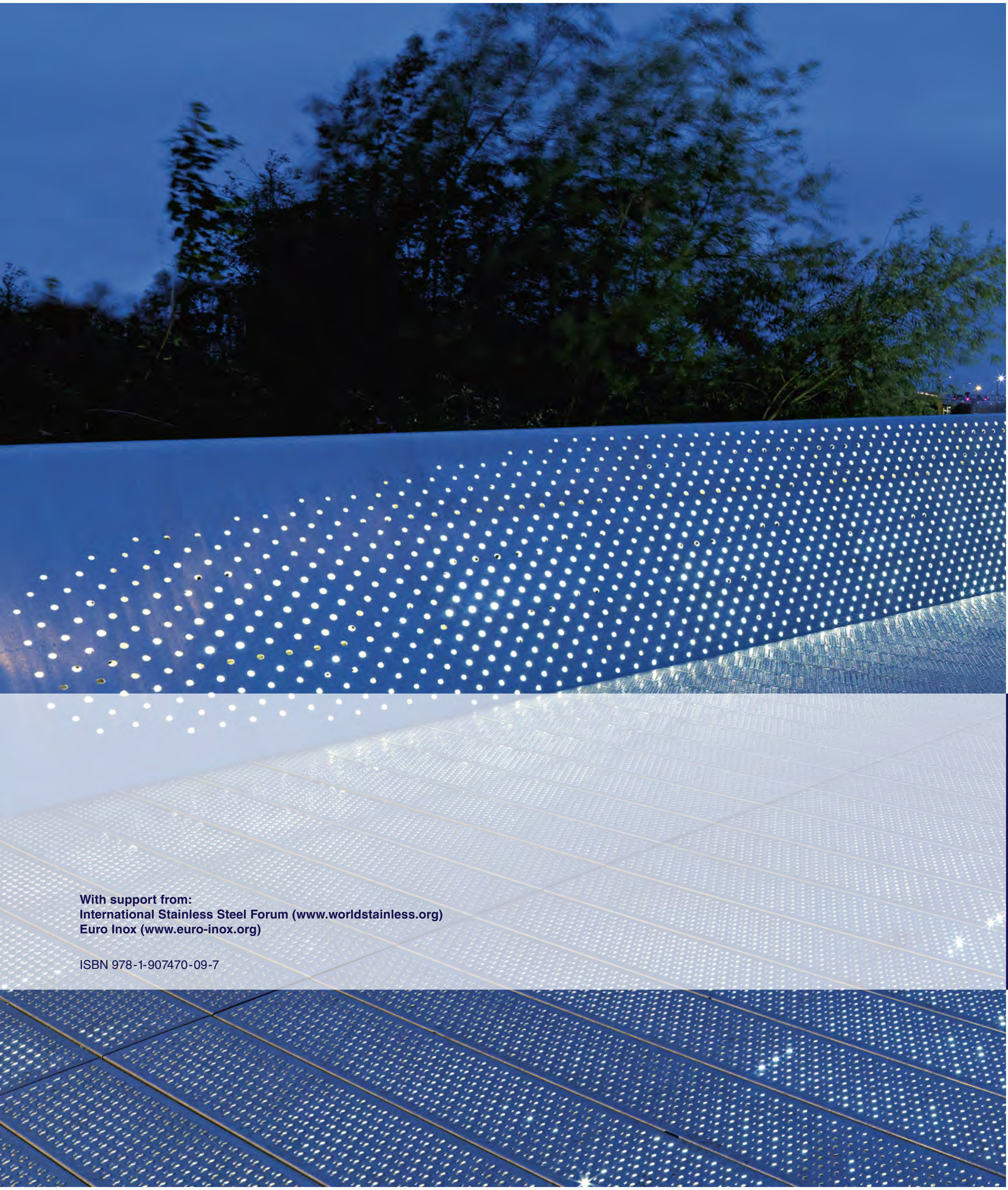
Specification titles US

Specification titles	
A 182/A 182M	Standard Specification for Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service
A 240/A 240M	Standard Specification for Heat-Resisting Cr and Cr-Ni Stainless Steel Plate, Sheet, and Strip for General Applications
A 270/A 270M	Standard Specification for Seamless and Welded Austenitic and Ferritic/Austenitic Stainless Steel Sanitary Tubing
A 276	Standard Specification for Stainless Steel Bars and Shapes
A 314	Stainless Steel Billets and Bars for Forging
A 479/A 479M	Standard Specification for Stainless Steel Bars and Shapes for Use in Boilers and Other Pressure Vessels
A 480/A 480M	Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip
A 484/A 484M	Standard Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings
A 580/A 580M	Standard Specification for Stainless Steel Wire
A 789/A 789M	Standard Specification for Seamless and Welded Ferritic/Austenitic Stainless Steel Tubing for General Service
A 790/A 790M	Standard Specification for Seamless and Welded Ferritic/Austenitic Stainless Steel Pipe
A 815/A 815M	Standard Specification for Wrought Ferritic, Ferritic/Austenitic, and Martensitic Stainless Steel Piping Fittings
A 890/A 890M	Standard Specification for Castings, Fe-Cr-Ni-Mo Corrosion-Resistant, Duplex (Austenitic/Ferritic) for General Application
A 923	Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels
A 928/A 928M	Standard Specification for Ferritic/Austenitic (Duplex) Stainless Steel Pipe Electric Fusion Welded with Addition of Filler Metal
A 959	Standard Guide for Specifying Harmonized Standard Grade Compositions for Wrought Stainless Steels
A 988/A 988M	Standard Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service
A 995/A 995M	Standard Specification for Castings, Austenitic-Ferritic (Duplex) Stainless Steel, for Pressure-Containing Parts
A 1082/A 1082M	Standard specification for high strength precipitation hardening and duplex stainless steel bolting for special purpose applications
A 1084	Standard test method for detecting detrimental phases in lean duplex austenitic/ferritic stainless steels
API 650	Welded Tanks for Oil Storage
NSF/ANSI 61	Drinking Water System Components Health Effects
NACE MR0175	Petroleum and natural gas industries – Materials for use in H_2S-containing environments in oil and gas production

Specification titles Europe

Specification titles	
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
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 10088-4	Stainless steels – Part 4: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes
EN 10088-5	Stainless steels – Part 5: Technical delivery conditions for bars, rods, wire, sections and bright products of corrosion resisting steels for construction 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

INTERNATIONAL MOLYBDENUM ASSOCIATION
THE VOICE OF THE MOLYBDENUM INDUSTRY



With support from:
International Stainless Steel Forum (www.worldstainless.org)
Euro Inox (www.euro-inox.org)

ISBN 978-1-907470-09-7

www.imoa.info