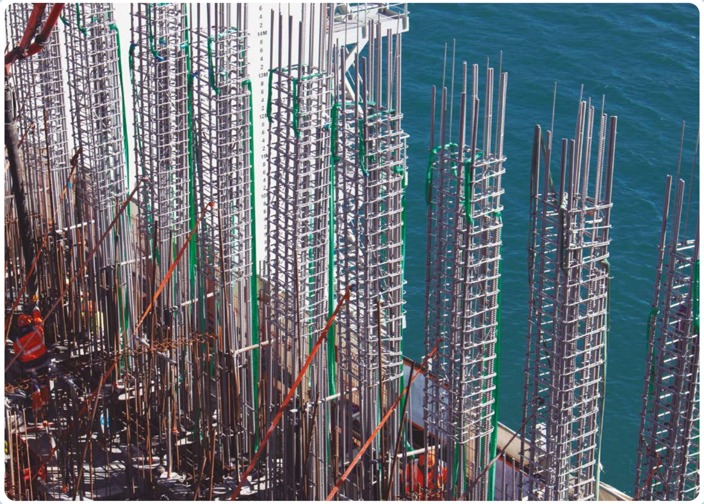
ISSF
INTERNATIONAL STAINLESS STEEL FORUM

Duplex Stainless Steels



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Foreword

The first experiments making duplex stainless steels were initiated in the early 1930s with Avesta AB in Sweden playing a significant role in this development. As we now approach the 90th anniversary of the development of duplex grades, it gives me great pleasure to provide the foreword for the ISSF's new brochure on this family of stainless steels. This brochure is an extremely useful reference document that will inform and guide readers in how to appropriately select the correct duplex stainless steel for specific projects. It will also provide sound guidance for the selection of duplex stainless steels, when this family of stainless steels may not have been otherwise considered.

This document covers an extensive range of helpful subject matter about duplex stainless steels. Furthermore a detailed walk through many applications where duplex stainless steels have been used provides inspiration for further usage possibilities. The brochure concludes with what will be an extremely helpful guide to the fabrication of duplex stainless steels which dispels many of the myths surrounding this branch of the stainless steels family.

It is fair to say that the uses of duplex stainless steels have not reached their full potential yet. Modern duplex grades combine high strength with good corrosion resistance and solid formability making this family of stainless steels an important group for material selection consideration in demanding applications in which maintenance-free longevity is also required.
I would like to thank both Bernard Heritier and Clara Herrera who are key members of the ISSF Long Products Committee for their dedication to this project. The detailed content and coherent structure of this publication is very much a result of their combined skills and expertise in this field. I would also like to thank Jo Claes of the ISSF for her design skills that brought this brochure to life.

We commend this brochure to producers, material specifiers, architects, OEMs and stockists, with the knowledge that they will all find this a helpful tool in their material selection decisions and market development activities.

Tim Collins
Secretary-General
International Stainless Steel Forum

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1 Introduction

Duplex stainless steels form the latest family of stainless steels, tested as early as in the 1930's and mass produced from the 1970's onwards (Refs: 1.1 to 1.6). Their excellent mechanical properties and their corrosion resistance have made them a first choice material for high-load applications in corrosive environments. The development of the modern duplex stainless steel family began with a few grades, the most representative being UNS S31803, later S32205, often referred to as 2205 (EN 1.4462). Then it went on in two opposite directions:

- More corrosion-resistant "Superduplex" and "Hyperduplex" stainless steel grades to meet the demands of very aggressive environments.
- "Lean Duplex" stainless steel grades for demands of higher strength but for less corrosive environments, typically for structural applications.

They offer low maintenance and low Life Cycle Costs, just like the other stainless steel families. Their high strength, high corrosion resistance, good processing properties – once their specifics are taken into account - have begun to be valued in a wide range of new applications such as long-lasting structures (bridges, floodgates...) and equipment (desalination plants, water and energy utilities...). Duplex stainless steels complement other stainless steel families, particularly austenitics. In some cases, duplex stainless steels should be the first choice, while in other cases, duplex stainless steels solve unexpected corrosion problems. Examples will be given in this brochure.

This brochure will hopefully help you to consider using duplex stainless steels for your projects.

Sluice gates at the Mont Saint Michel in France

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2 Standards and Chemical Compositions

Applicable Standards

Duplex stainless steel grades are covered by major standards, such as EN, ISO, ASTM for a number of products and/or applications (see Appendix 1). Although there is a fairly long list of UNS grades, only a few of them make the largest part of today's production.

Chemical compositions

Duplex stainless steels have a structure of about 50% ferrite (a body centered cubic crystallographic structure) and 50% austenite (a face centered cubic crystallographic structure). To achieve this, elements that stabilise the ferrite phase (Cr, Mo, Si, W ...) are balanced by elements that stabilise the austenite phase (Ni, N, Mn ...). The ferrite/austenite ratio depends not only on the alloying elements but also on heat treatments.

The classification of duplex stainless steels is done according to their corrosion resistance which depends on the alloying elements. It is customary to distinguish them according to their Pitting Resistance Equivalent Number (PREN). (Ref 2.1) The next section provides more information on PREN.

- Lean duplex grades (typefied by UNS S32304 -EN1.4362), PREN 22-27, with a lower Ni content, without or with some Mo, are best for less severe environments.
- Standard Duplex (typified by S32205 (EN 1.4462), PREN 28–38, with 22%Cr and 3%Mo, which is mid-range in terms of corrosion resistance.
- Super duplex (typically S32520 (EN 1.4507)), PREN 39–45, with 25%Cr, 3.5% Mo and 0.22-0.3%N.
- Hyper duplex with PREN >45 for very severe environments, usually in the oil and gas industry.

Note: PREN stands for Pitting Resistance Equivalent Number: PREN = Cr+3.3Mo + 16N where Cr, Mo and N are the contents expressed in weight percent of the three elements chromium, molybdenum and nitrogen respectively (Ref 2.2). See section 3.2

Many duplex stainless steel grades are offered today, partly as a result of patents, partly because new grades are needed to meet new requirements, particularly for use in the oil and gas industry.

A list of duplex grades is provided in Appendix 2 and the correspondence between standards is given in Appendix 3.

Champlain Bridge in Montreal, Canada. Picture courtesy of Infrastructure Canada

3 Corrosion resistance

Duplex stainless steels show high corrosion resistance in a variety of environments like oxidising industrial solutions, sulphuric acid containing solutions, organic acids, diluted mineral acids and hot alkaline solutions due to the high contents of Cr, Mo and N.
They show an exceptional combination of high strength and good corrosion resistance (Figure 3.1), making it possible to design lighter components and consequentially to decrease the materials and manufacturing costs. This led to the use of duplex stainless steel in applications such as oil and gas, reactors and tanks in the chemical industry, water treatment equipment, desalination plants and heat exchangers.

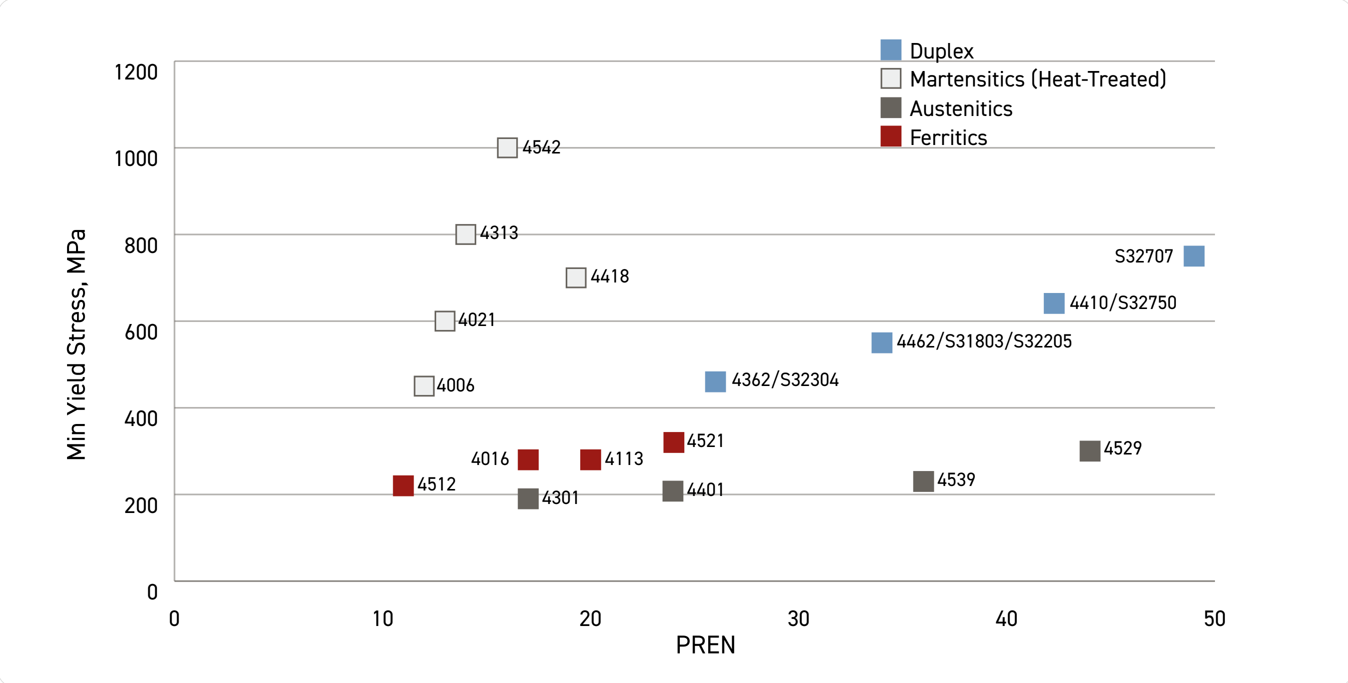


Figure 3.1 Minimum Yield Stress vs. Pitting Corrosion Resistance (section 3.2).
Note: Grade numbers refer to EN standards and for Duplex EN and UNS
Mechanical properties of stainless steels (martensitic are in the heat treated condition) are those of EN 10088-3 and 2 standards.

3.1 Uniform corrosion

Uniform corrosion or general corrosion is the uniform loss of metal over an entire surface area or a large fraction of the total area. It occurs when the material is exposed to strong acids (organic acids are less aggressive than inorganic acids), hot alkaline environments and many other media used in chemical engineering processes. Certain minor chemicals and impurities (such as chlorides and fluorides) and abrasive solids will increase corrosion rates. Conversely, some impurities will reduce the corrosion rate. In extremely aggressive media, the passive film may not able to prevent completely the onset of corrosion. Materials with very low corrosion rates, typically less than 0.1 mm/year are required. Corrosion Tables for stainless steels, covering a wide range of chemicals are available and provide a rough guide for alloy selection. Under real industrial conditions, other factors may contribute to corrosion: aeration, variations of temperature, stop/start conditions, flow rates, impurities, etc...

It must be pointed out that the PREN should NOT be used to predict or to rank stainless steels when uniform corrosion occurs. For instance, in media with a high pH, molybdenum does not contribute to the corrosion resistance.
Sulphuric acid content solutions are used in several industrial processes. Duplex grades must be selected

to withstand the acidity and the temperature of the medium. Lean duplex can be used in less aggressive conditions. With increasing acidity and temperature standard duplex (S32205) may be the best option, in some case better than austenitic grades 316LN or 317LM. For harsher environments, super duplex stainless steels are recommended (Figure 3.2).
For specific media, lab tests and industrial experience are necessary to refine

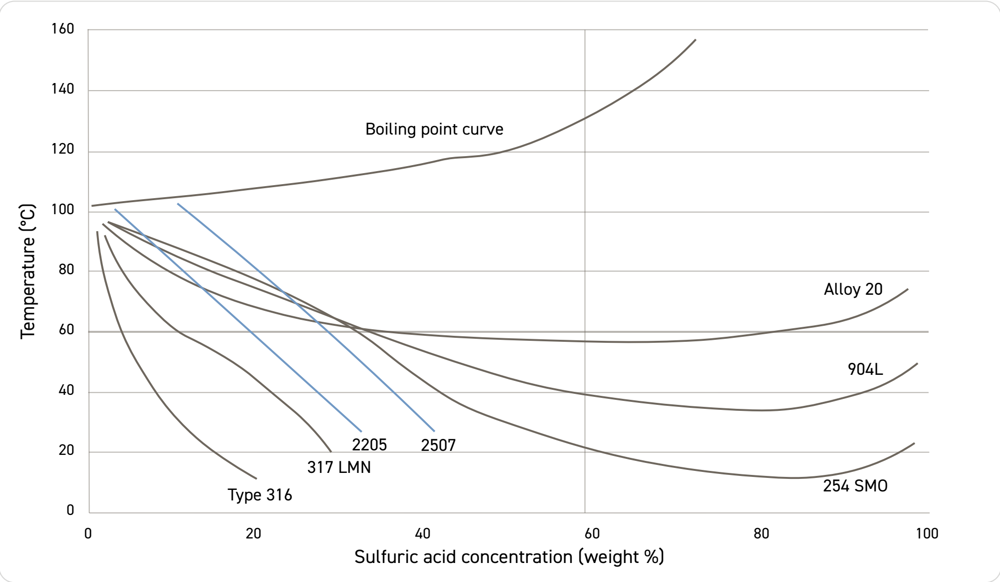


Figure 3.2 Corrosion in non-aerated sulphuric acid, 0.1 mm/yr (0.004 inch/yr) isocorrosion diagram (laboratory tests using reagent grade sulphuric acid).
Source: Producer data sheets, 254 SMO is a trademark of Outokumpu.

the relative performance of grades. For example different materials, like carbon steels, stainless steels and nickel-based alloys have been used for batch and continuous digesters in the pulp and paper production. The maximum corrosion rates that have been measured in laboratory corrosion testing of metals in batch and continuous digester liquors at 170°C are shown in Figure 3.3.
Duplex grades present excellent uniform corrosion resistance even superior to some Ni-base alloys for this application.
Strong alcalis like caustic soda (NaOH) or caustic potash solutions (KOH) are not very corrosive, independently of their concentrations, when the temperature is below 100°C. At higher temperatures, where the risk of corrosion cracking is high, duplex stainless steels, UNS S32205 (EN 1.4462) or lean duplex, are recommended. Super Duplex stainless steels are used at temperatures up to about 150°C. These high-temperature caustic environments are found in the fabrication of alkalis, in oil refineries, in pulp and paper manufacturing and in the

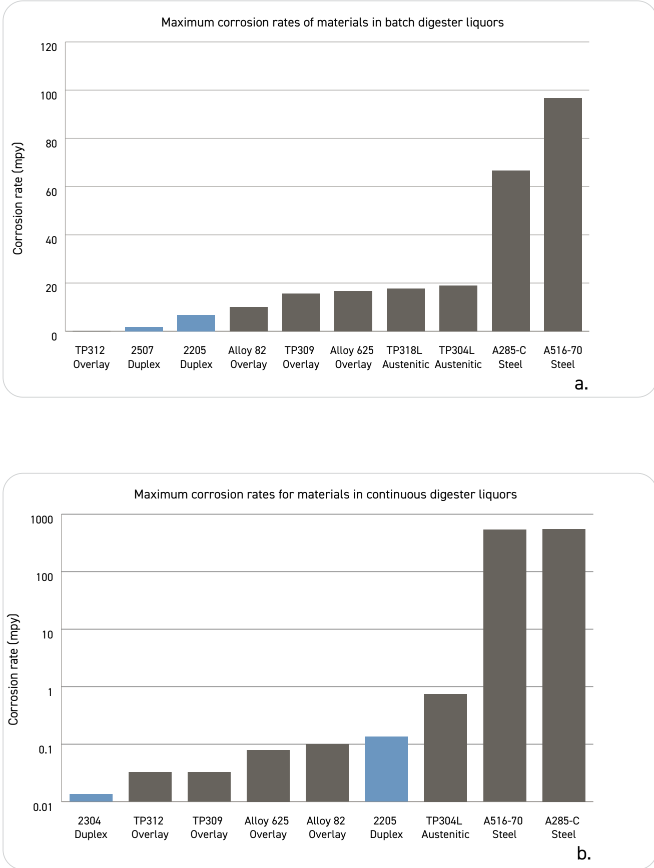


Figure 3.3 Maximum corrosion rates measured in laboratory corrosion testing of metals and alloys in (a) batch digester liquors and (b) continuous digester extraction liquors at 170°C. (Ref. 3.5). Note the log scale.

processing of alumina. The uniform corrosion in duplex grades is lower than 0.3 mm/year in caustic soda and sulphide-containing caustic solution (white liquor) even at 170°C. However, sulphide additions increase the corrosion rate in duplex stainless steels, especially in grades containing Mo like UNS S32205 (EN 1.4462) (Figure 3.4 and 3.5).

In paper manufacturing, sulphides are a corrosion aggravating factor (Figure 3.6).

The processes used to manufacture cellulose from wood (kraft process) involve cooking the wood chips at 170°C, under pressure, with liquor composed of 20 % soda, to which sodium sulphide Na_2S, sodium carbonate Na_2CO_3 and traces of sodium thiosulphate $Na_2S_2O_3$ have been added.

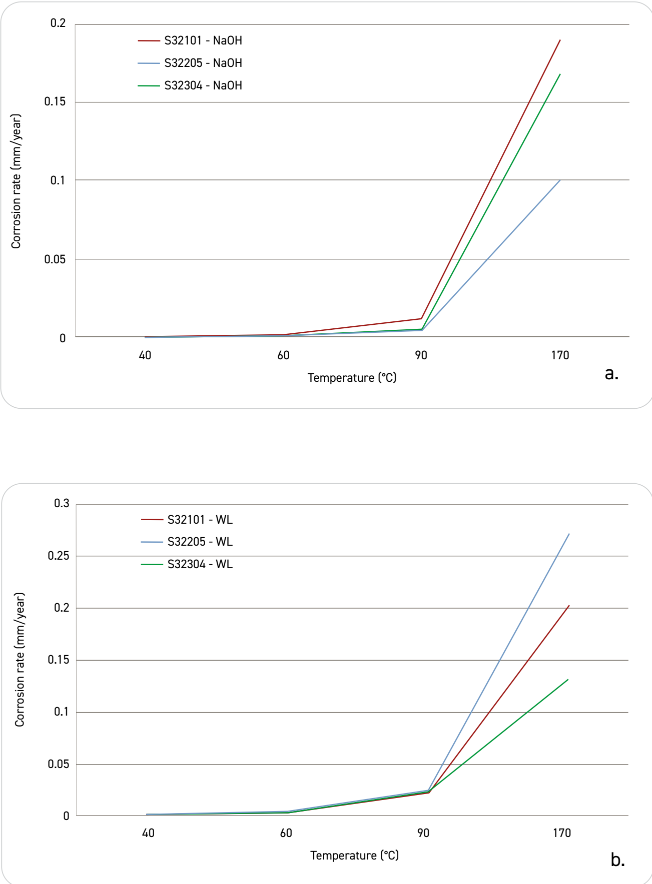


Figure 3.4 Corrosion rates of some duplex grades in (a) 3.75M NaOH and (b) 3.75M NaOH + 0.64M Na_2S (White Liquor) solutions at different test temperatures. (Ref 3.12)

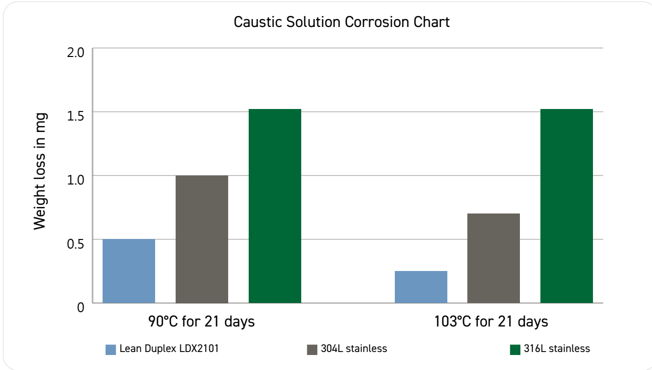


Figure 3.5 Corrosion rate in white liquor (Ref 3.13)

During curing cycles at a temperature between 70°C and 170°C, there is a change in the chemical composition of the environment, which then contains organic impurities in addition to polysulphides. The duplex family presents good resistance against uniform corrosion and stress corrosion cracking in white liquor environments with 20 % caustic soda, chlorides and sulphur contents.

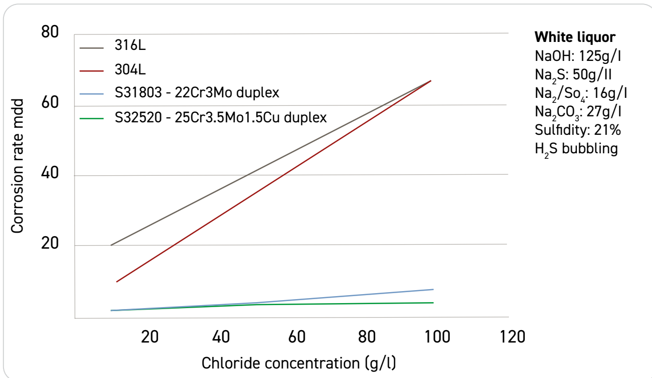


Figure 3.6 Corrosion rates in white liquor - kraft process (Ref 2.2)
Uniform corrosion tests in the pulp and paper industry. Samples are submitted to hot plate boiling effects. The samples are 140°C and the liquor 80°C.

3.2 Pitting and Crevice corrosion

Pitting corrosion is a localised corrosion that produces holes or cavities in the metal. Pitting corrosion can be more destructive than uniform corrosion because it is difficult to predict, detect and design against.
The pitting resistance depends strongly on the chemical composition of the steel and is affected by different parameters like temperature, Cl^- content, pH value and the presence of an oxidising agent.
The elements which have an important effect on the pitting corrosion resistance are chromium, molybdenum and nitrogen. The following empirical formula is widely used:

PREN = %Cr + 3.3 × %Mo + 16 × %N

Percentages are expressed in weight percent.
The PREN describes the resistance of stainless steels to localised corrosion in a chloride-containing environment.
Other formulas have been developed taking into account other elements like W and Mn. W has a positive effect on the pitting resistance, while Mn decreases it.

PRENW = %Cr + 3.3 × (%Mo+ 0.5%W) + 16 × %N
PRENMn = %Cr + 3.3 × %Mo + 16 × %N - %Mn

Increasing Cr and Mo, which have a positive effect on pitting corrosion resistance, requires a corresponding increase of austenite stabiliser elements to maintain the 50% ferrite / 50% austenite ratio. An unwanted consequence is that some intermetallic phases, very detrimental to the mechanical properties, may form in a short time in some temperature ranges (Figures 5.2 and 5.3). Avoiding them puts some additional constraints on the processing, heat treatment and welding of the high alloyed grades i.e. super duplex and hyper duplex. They are, however,

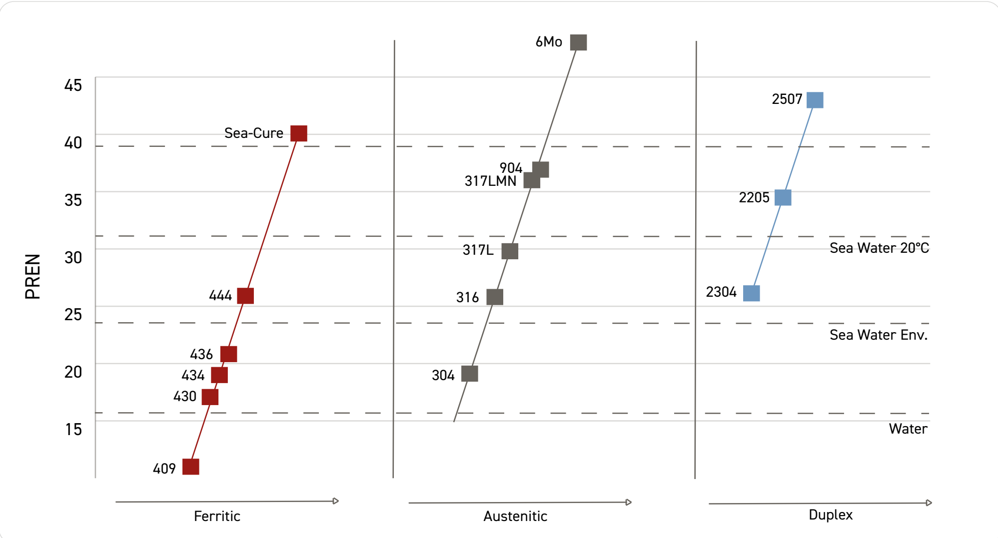


Figure 3.7 PREN Ranking (Ref 3.1 and 3.14)

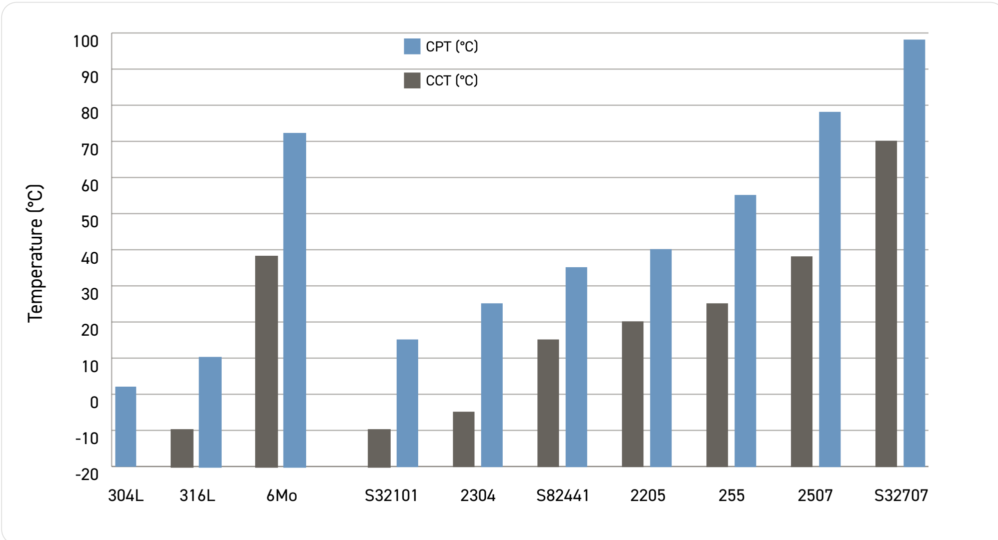


Figure 3.8 CPT and CCT* for austenitic and duplex stainless steel (Evaluated in 6% ferric chloride by ASTM G48). (Ref 2.1)*
** definitions on the page 10*

well worth the effort as they normally cost much less than super austenitics or Ni-based alloys. A PREN ranking of several stainless steel families is presented in Figure 3.7.
Pitting corrosion can be quantified by determining the Critical Pitting Temperature (CPT) according to different standards such as ASTM G48 method E, or ASTM G150. CPT is the lowest temperature (°C) at which pitting occurs. Stainless steels with higher CPT are more resistant to pitting corrosion.

Crevice corrosion is another type of localised corrosion. It occurs in confined spaces, gaps or crevices, where access to the surrounding environment is restrained. These confined spaces can occur between two metals or a metal and non-metallic material, i.e. gaskets, washers, couplings, fastener heads, lap joints and clamps. Critical Crevice Temperature (CCT) can be determined according to ASTM G48 method F or ASTM G78.
Figure 3.8 shows CPT and CCT for various austenitic and duplex stainless steels measured in 6 % ferric chloride. Lean duplex grades show a better corrosion resistance than EN 1.4301/1.4307 (304/304L) austenitic grade, than most ferritic grades and are better or equivalent to EN 1.4044 (316L) for some environmental conditions. For harsher conditions like marine environments or high temperature oxidising and chloride-containing solutions, duplex S32205 (EN 1.4462) or super duplex grades can be used, replacing highly alloyed austenitic grades. Hyper duplex steels combine high strength with higher CCT and CPT compared to nickel alloys and high-alloy austenitic stainless steels, making them suitable for aggressive environments and critical applications such as oil refineries, deep water umbilicals, petrochemical and chemical plants, tropical seawater or urea production (Ref 2.1 and 2.2).

3.3 Environmentally-assisted cracking

Environmentally assisted cracking (EAC) is a general term that includes processes such as stress corrosion cracking (SCC), hydrogen embrittlement (HE), sulphide stress cracking (SSC), liquid metal embrittlement (LME), and fatigue corrosion (FC). EAC can be tested using the NACE standard TM0177.

Stress corrosion cracking (SCC)

Stress corrosion cracking (SCC) is a form of localised failure due to a combination of tensile stress, corrosive environments and susceptible materials (Figure 3.9). This combination leads to a component failure by initiation and propagation of a crack. SCC occurs not only in chloride-containing environments at temperatures above 60°C but also in concentrated alkali solutions at temperatures higher than 100°C.
Ferritic and duplex stainless steel show a high resistance to SCC in chloride-containing environments. Duplex stainless steels have better SCC resistance

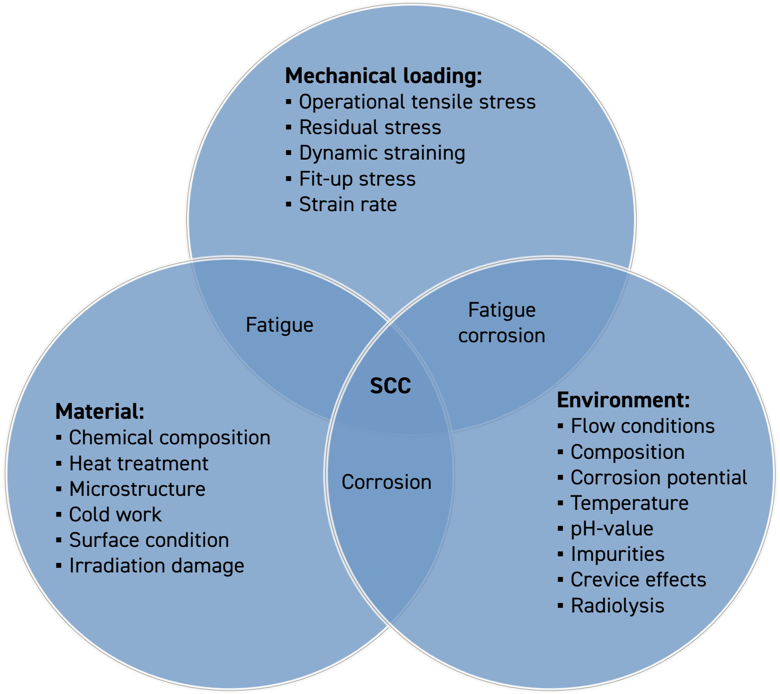


Figure 3.9 Factors effecting Stress Corrosion Cracking. (Ref 3.15)

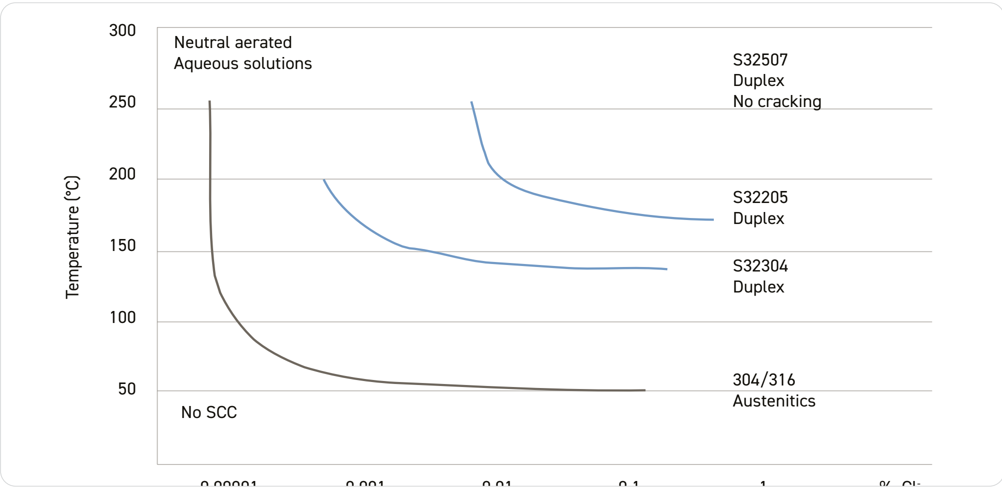


Figure 3.10 Effect of chloride content and temperature on the SCC resistance of different austenitic and duplex stainless steels. (Ref 2.2)

than austenitics; they can replace austenitics in the oil and gas, chemical or pulp and paper processes where the risk of chloride SCC is significant. Figure 3.10 shows the effect of chloride content and temperature on the resistance to stress corrosion cracking of different austenitic and duplex stainless steels. Appendix 4 presents some data of stress corrosion cracking resistance of duplex and austenitic stainless steels in different environments. Figure 3.11 gives the limiting conditions, temperature and chloride concentration, in terms of pitting and crevice corrosion and stress corrosion cracking at unadjusted pH (~5.5) for EN 1.4404 (316L) and S32750 (EN 1.4410) respectively. Super duplex S32750 shows higher CPT, and CCT than EN 1.4404. Additionally, S32750 presents a better SCC resistance at higher temperatures and higher chloride content than EN 1.4404. No cracking appears in 10M chloride at temperatures lower than 85°C for S32750, while the temperature for EN 1.4404 is lower than 60°C. (Ref 3.16)

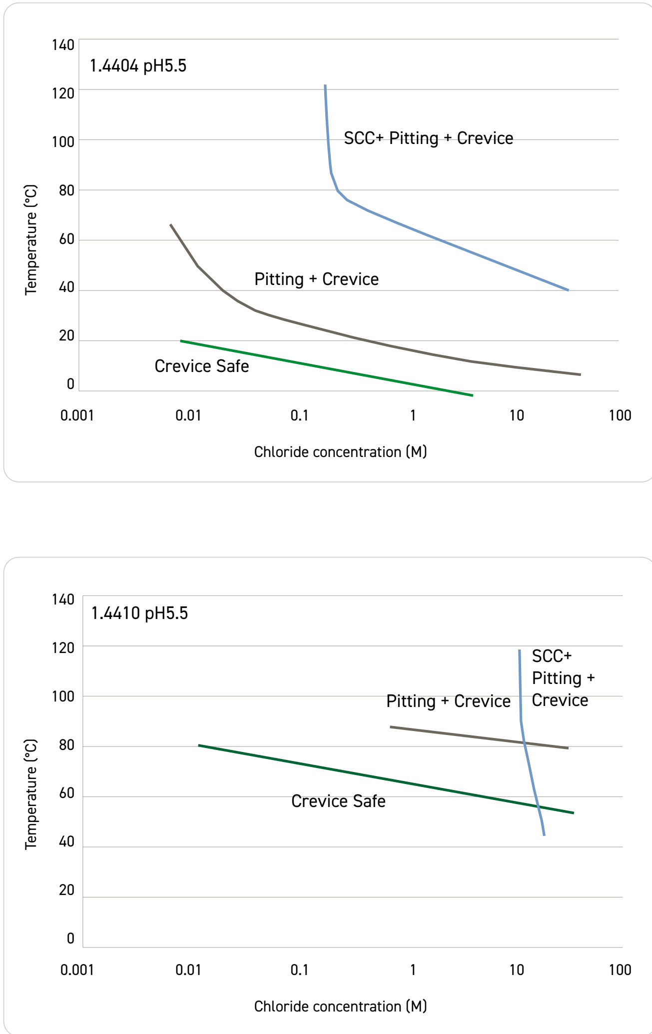


Figure 3.11 Comparison of chloride SCC and crevice behaviour of austenitic grade EN 14404 (316L) and super duplex EN 1.4410 (S32750) (Ref 3.16)

Sulphide stress cracking (SSC)

Sulphide stress cracking (SSC) is defined by NACE as the "Cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and sulphides (H_2S), a form of hydrogen stress cracking." The variables involved in SSC are susceptible material, tensile stress, hydrogen sulphide and water. SSC is very important in the oil and gas industry because the media contains chloride and sulphides (sour service). The NACE standard MR0175/ ISO 15156:3 2015 provides guidance for the selection, specification and application limits of SSC-resistance materials used in H_2S-containing environments in oil and gas production. Figure 3.12 shows the performance of duplex stainless steels compared to austenitic, martensitic and nickel alloys.

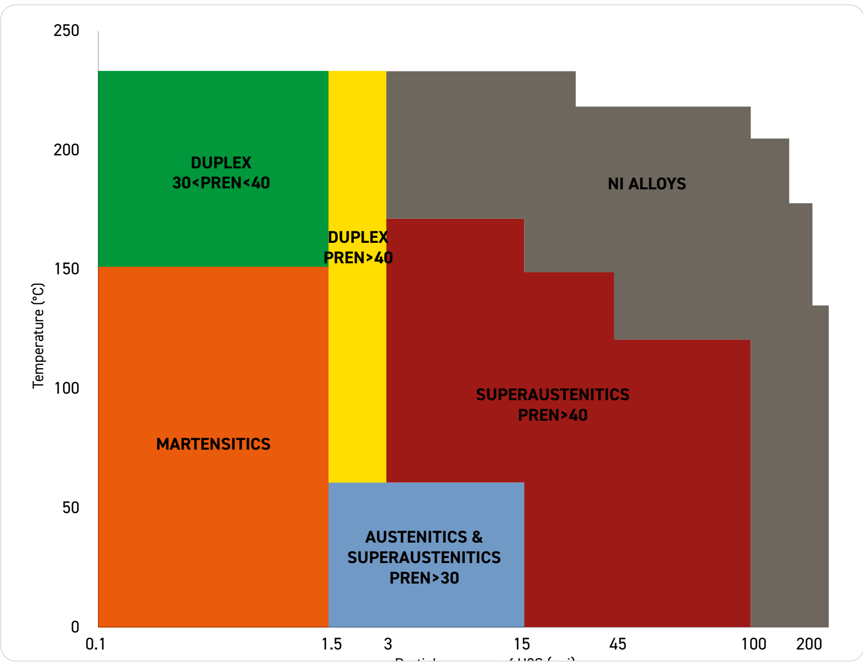


Figure 3.12 Limit of uses of stainless steel and nickel alloys in H_2S-containing environments. (Ref 3.17)

3.4 Fatigue corrosion (FC)

Fatigue corrosion (FC) may take place when materials are exposed to alternating or cyclic stress in a corrosive environment. Fatigue corrosion resistance decreases when duplex stainless steels are subjected to high temperatures and high loads, low pH value and chlorides, sulphide or CO_2. Figure 3.13 shows

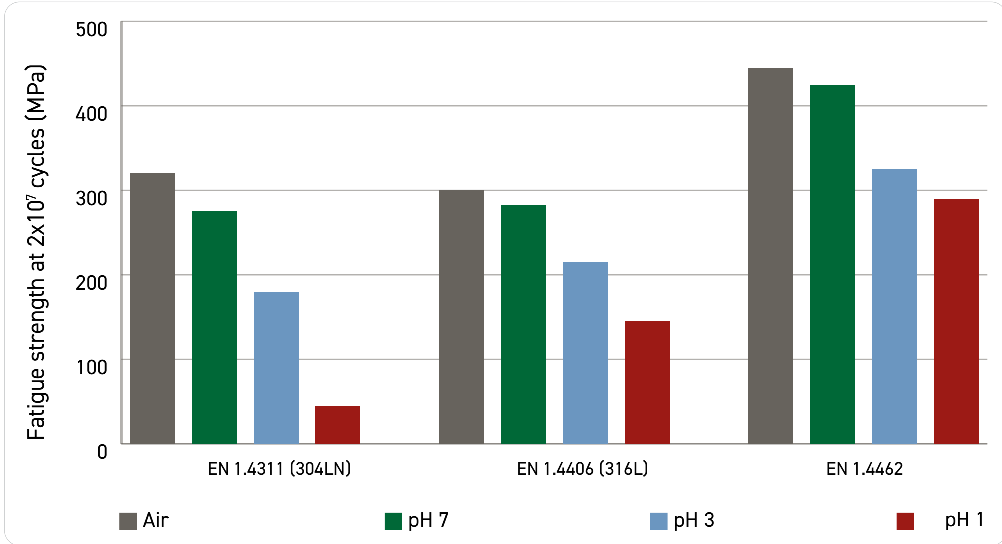


Figure 3.13 Fatigue strength of some stainless steels obtained by rotating bending at 40°C, 100Hz, in air and in 3%NaCl solutions at different pH (Ref 3.18)

the behaviour of the duplex stainless steel S32205 (EN 1.4462) and standard austenitic grades in fatigue–corrosion tests performed in air and environments with different pH, from neutral to very acid. S32205 shows a better performance than austenitic grades. In seawater conditions, duplex stainless steels (S32205 and S32304) perform very well compared with austenitic grades (Figure 3.14). FC is an issue in the pulp & paper and oil & gas industries which is another reason for using duplex grades.

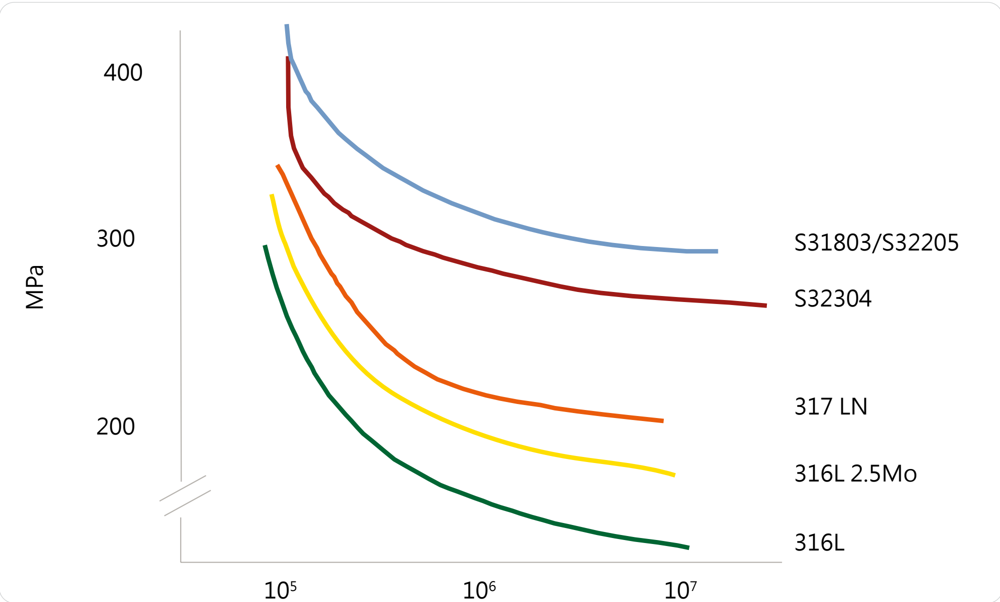


Figure 3.14 Fatigue Corrosion resistance of some stainless steels. Tested in synthetic seawater and rotating beam. (Ref 3.8)

The fatigue limit in air is approximately 50 % of UTS for most of the stainless steels. On the other hand, in seawater, martensitic and austenitic grades present a marked decrease of fatigue limit, while duplex grades show a similar ratio compared to the one determined in air, i.e. close to 40 % of the UTS (Ref 3.20).

3.5 Abrasion-Corrosion

Abrasion-corrosion is a well-known cause of damage to materials in many industries, particularly mining, hydrometallurgy, oil sands and water treatment.
The results of abrasion-corrosion tests on wear resistant steels (WRS), duplex stainless steels and on the ferritic-martensitic grade S41003 (EN 1.4003) are shown Figures 3.15 a and b. (Ref 3.21).
The two media, one acidic and the other basic, both containing abrasive particles, are representative of the conditions encountered in the above-mentioned industries.
Duplex stainless steels are the best performers in abrasion-corrosion when corrosion is the leading damage mechanism.

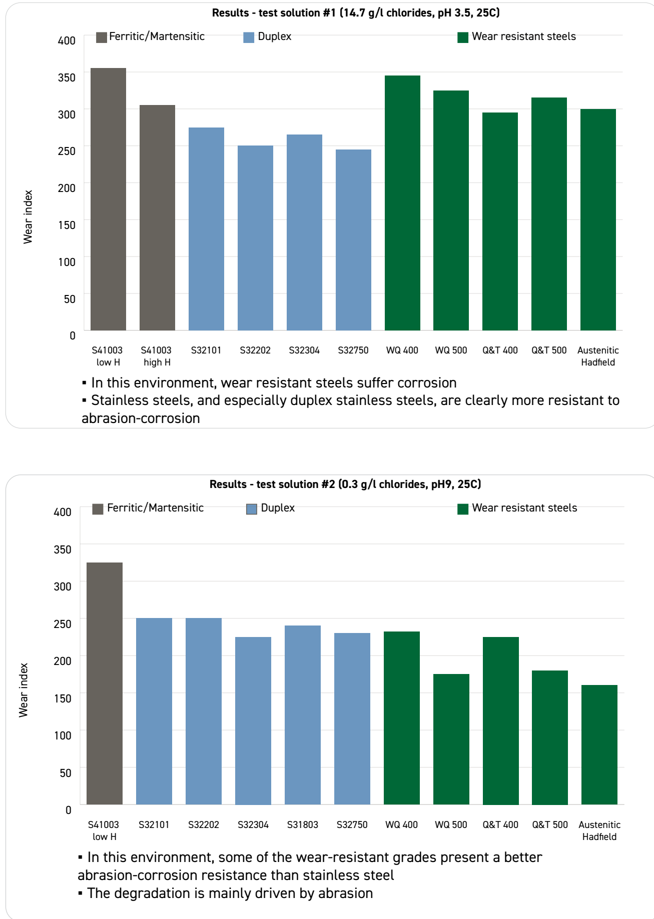
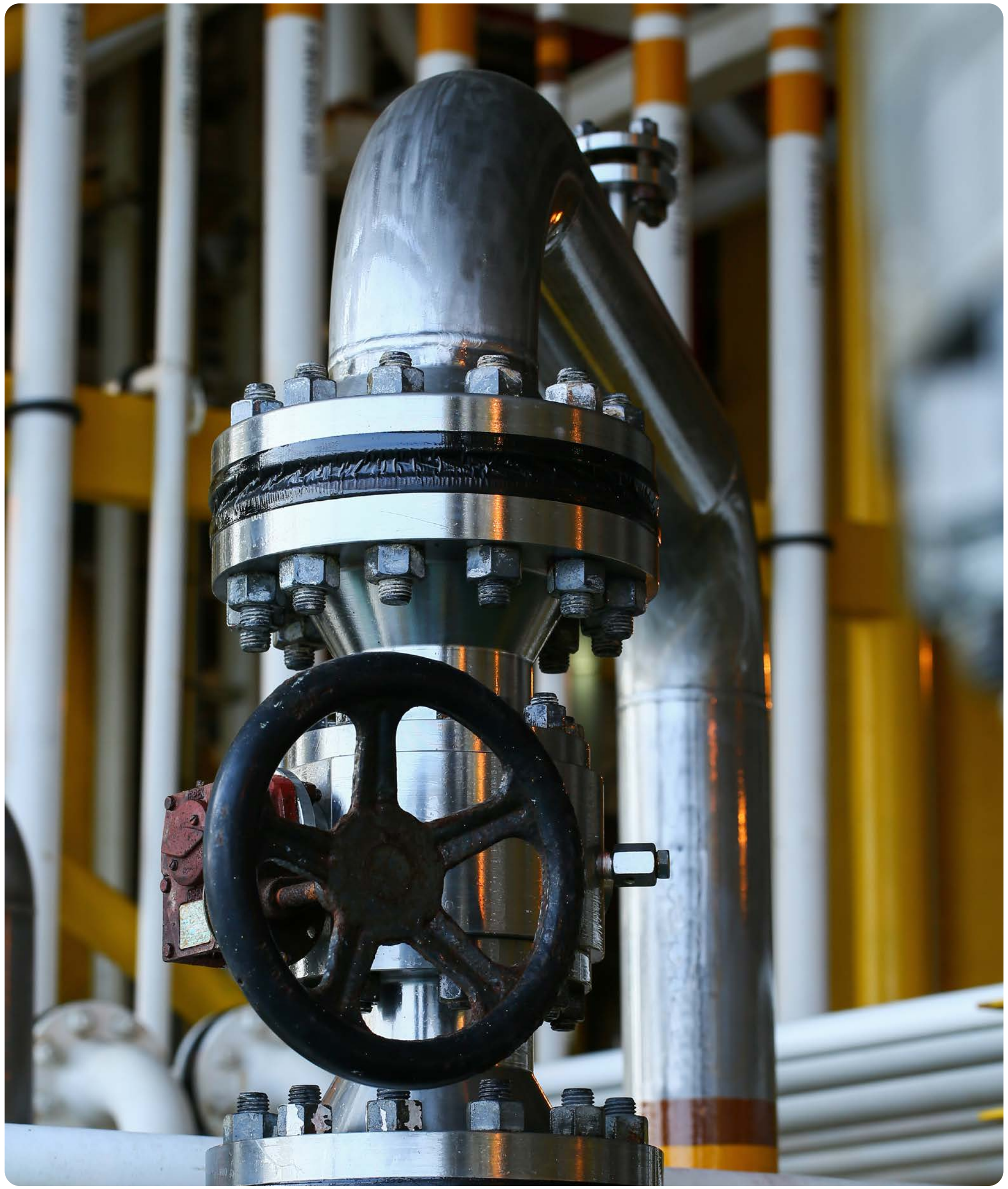


Figure 3.15 Wear resistance of Duplex vs Wear resistant Steels
Note: The higher the wear index, the higher the abrasion-corrosion
WQ400: Martensitic 0.19%C-steel Water quenched to a Hardness of 400HV
WQ500: Martensitic 0.30%C-steel Water quenched to a Hardness of 500HV
Q&T 400: Martensitic/bainitic low C-steel Quenched and Tempered to a Hardness of 400HV
Q&T 500: Martensitic/bainitic low C-steel Quenched and Tempered to a Hardness of 500HV



Duplex stainless steel manual valve in the oil and gas production process

4 Physical properties (Ref 4.1)

The physical properties are as one might expect somewhere in between those of the austenitic and of the ferritic alloys.
They are presented in Appendix 5.

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5 Mechanical Properties

5.1 Tensile properties

The stress-strain curves of austenitic, ferritic and duplex stainless steels, along with that of that of S355 (a common structural steel with 355 MPa yield strength) are shown in Figure 5.1.

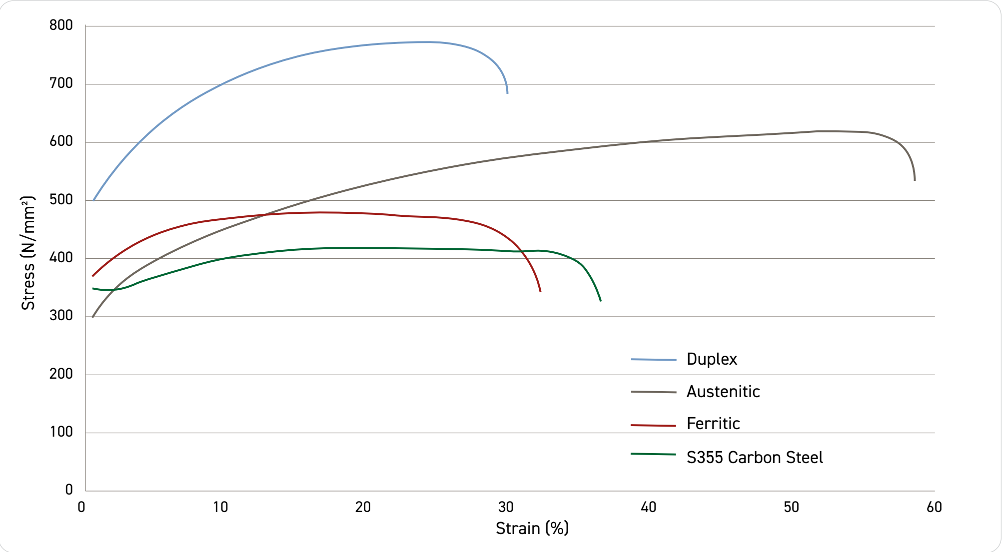


Figure 5.1 Typical stress strain curves of stainless steels (Ref 5.1)

Duplex stainless steels exhibit a much higher yield strength and work-hardening while retaining an elongation in excess of 25%. Standards guarantee minimum values of tensile properties. Values for both EN and ASTM standards are given in

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

Table 5.1 Minimum ASTM and EN mechanical properties for duplex stainless steel plates (Ref 3.2)

Table 5.1 for three typical grades.
These values are quite conservative, as a higher strength level can be achieved by chemical composition adjustments and/or by a suitable thermomechanical processing. Higher values are usually offered by suppliers. An important case is duplex stainless steel rebar which must meet a minimum Yield Strength value of 500 MPa (Ref 5.2). Building codes take into consideration load supporting members obtained by cold forming by allowing larger permissible stress levels (Ref 5.1).
More details on mechanical properties for long products are given in Appendix 6 and for flat products in Appendix 7.

5.2 Range of Service Temperatures

5.2.1 Elevated temperatures (Ref 5.3 to 5.6)

At temperatures above ~350°C up to ~1000°C, precipitation of intermetallic phases occurs as shown Figure 5.2, causing brittleness at room temperature.

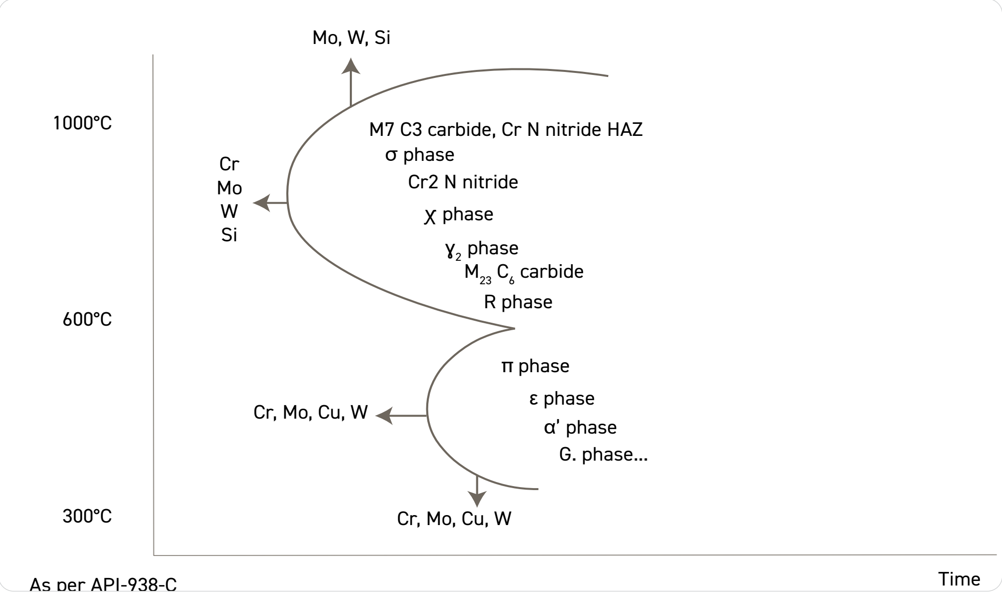


Figure 5.2 Influence of the alloying elements on the kinetics of precipitation of intermetallic phases (Ref 3.8)

Precipitation in the high temperature range (~600-1000°C) can be avoided by fast cooling.
By contrast, precipitation in the lower temperature range (~350-600°C) is much slower and is not usually a problem for metal processing (welding, heat treatment...). However, the situation is different for operating temperatures in the 250-350°C range, typically in chemical engineering. Over thousands of hours at this temperature, plus transients, low temperature precipitation can occur and limits must be known to designers. As shown Figure 5.2, higher contents of Cr, Mo, Cu and W accelerate the precipitation kinetics. Lean duplex stainless steels are therefore expected to be much less prone to low temperature precipitation than super and hyper duplex grades. This is shown in Figure 5.3 for a few common duplex grades.
Suppliers are usually able to provide advice.

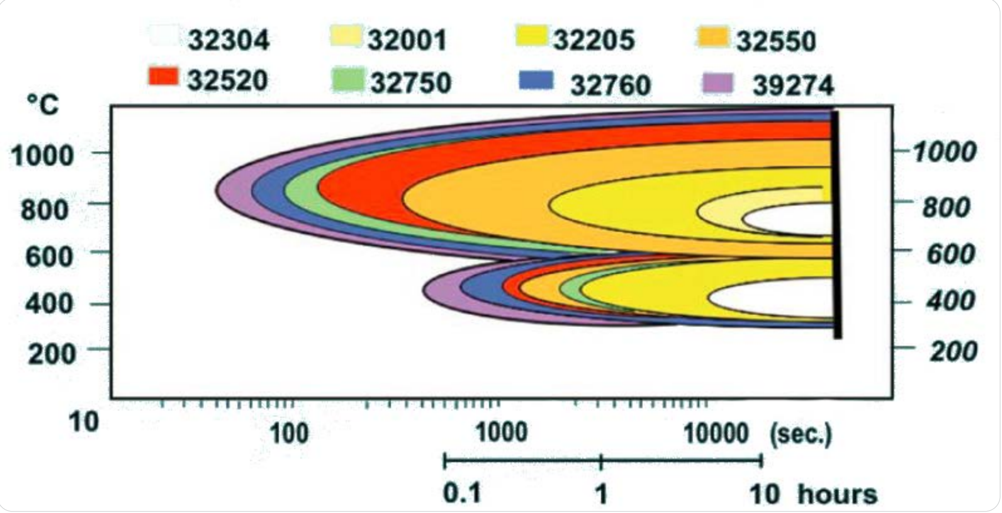


Figure 5.3 Temperature/Time/Transformation kinetics of some Duplex stainless steels (UNS designations) (Ref 2.2)

Pressure vessel codes have set up maximum service temperatures as follows:

- European Code EN 13455 restricts the maximum service temperature to 250°C. This is a quite conservative approach.
- ASME VIII div 1 limits the temperature to 316°C for most grades. They all have a warning note that embrittlement may occur above 260°C.

No provision has been made so far to distinguish between lean and standard duplex grades, but this may change in the future.

5.2.2 Low Temperatures (Ref 5.7 to 5.9)

Duplex stainless steels, unlike austenitic grades, exhibit a ductile to brittle transition as the temperature decreases, evidenced by the decrease of impact resistance (usually measured by Charpy impact values). This limits the use of duplex grades for cryogenic applications. The minimum temperature at which duplex grades can be used is set by the minimum impact values required. However, the impact resistance at low temperatures can be improved by a number of adjustments:

- lowering somewhat the ferrite content by chemical composition adjustment
- optimising forging/hot rolling
- optimising heat treatments

Duplex grades meet the requirements of the international standards (such as ASTM, NACE and Norsok), which set minimum Charpy KV impact values of 45J at -46°C.

More recently, requirements for arctic service conditions down to -80°C have led to the optimisation of grades that meet impact values of 200J at -100°C (Figure 5.4). It is usually the properties of the welds that determine the lowest temperature of usage.

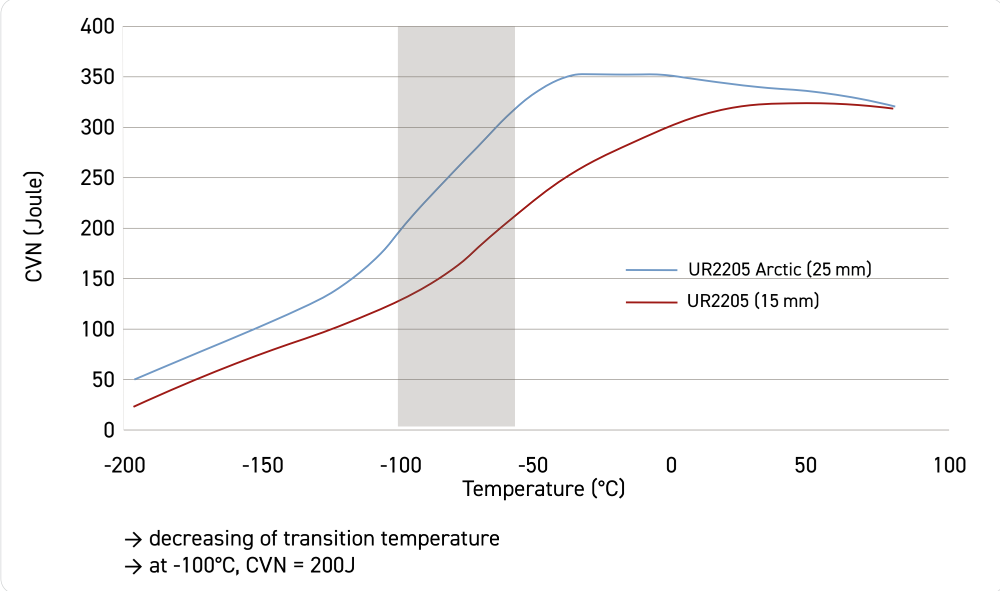


Figure 5.4 Impact resistance vs temperature of EN 1.4462 duplex grades optimized for low temperature service (Ref 5.7)

5.3 Work hardening (Ref 5.10 to 5.15)

Work-hardening, i.e. the increase of strength by cold deformation, is a well-known process. It is widely used in wire products to tailor the mechanical properties to the application.

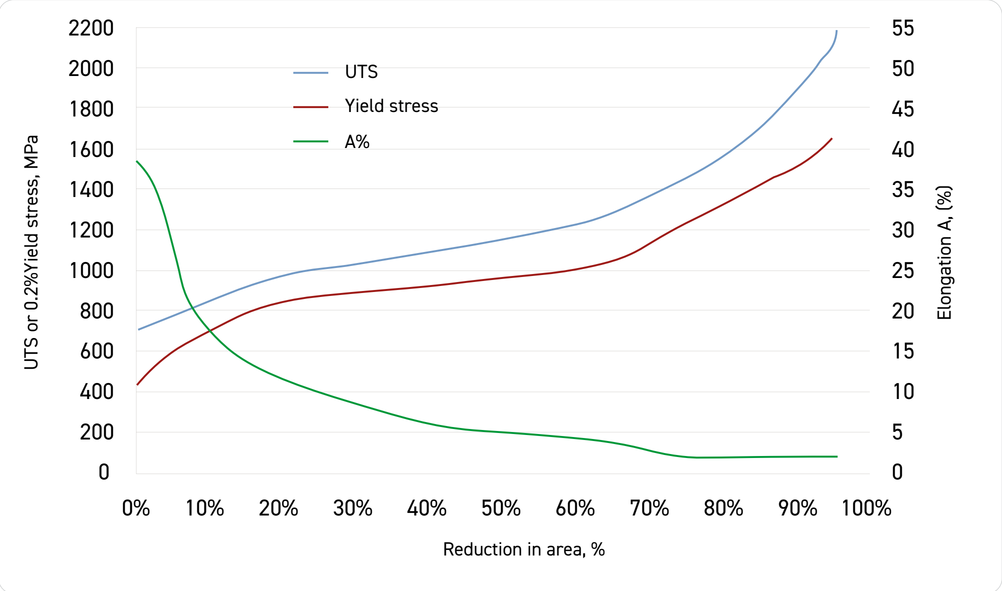


Figure 5.5a Work hardening curve of lean duplex grade S32202 (EN 1.4062) (Ref 5.10)

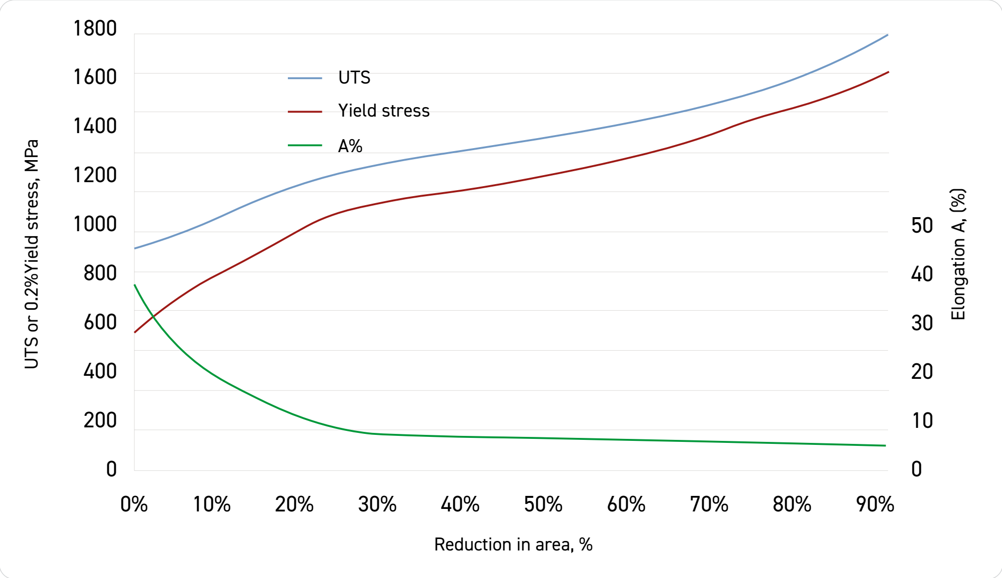


Figure 5.5b Work hardening curve of super duplex grade S32750 (EN 1.4410) (Ref 5.10)

Figures 5.5a and 5.5b show the work-hardening curves of a lean duplex and of a super duplex stainless steel respectively. As expected, strength increases steadily with deformation while residual elongation decreases. Super duplex grades achieve higher tensile strength levels than lean duplex grades.
A comparison of the work hardening behaviour of austenitic grades (304 and 316), semi-austenitic precipitation hardening grade (631 a.k.a 17-7PH) and duplex stainless grades (S32101, S32304 and S32205) is shown Figure 5.6.
Duplex grades do not reach the strength level of the austenitic spring grade 302 (EN 1.4310), but they will be adequate for applications demanding both high strength and high corrosion resistance, especially to SCC.
The load relaxation vs time of duplex grades is shown Figure 5.7. Treatment refers to an in-line induction heating in the 380-400°C temperature range for less than one minute. This relaxation treatment is typical of carbon steel. It must be noted that induction heating is more efficient on partly ferromagnetic duplex grades than on paramagnetic austenitic ones.
The performance of cold-worked duplex grades for pre and/or post stressing of

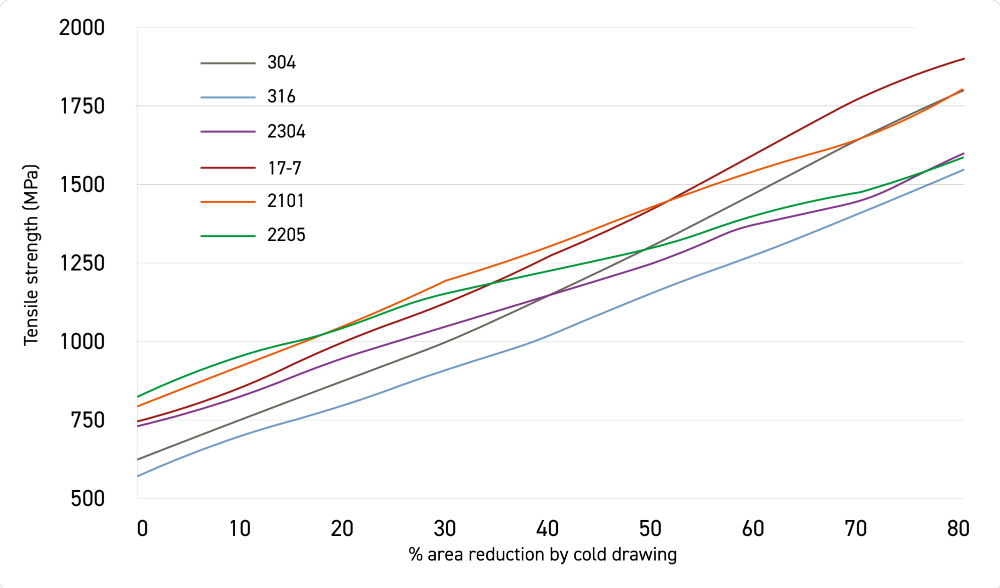


Figure 5.6 Comparison of UTS values of some stainless steels (Ref 5.12)

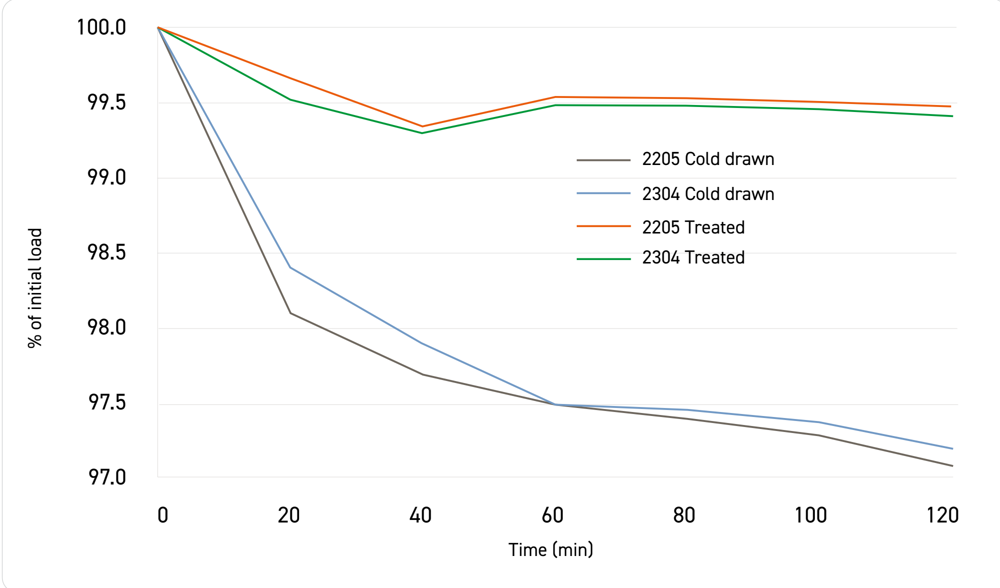


Figure 5.7 Load relaxation of duplex stainless steels (Ref 5.12)

concrete has been investigated (Ref 5.12 to 5.15). The results show that precast pre-stressed concrete piles may be constructed with S32205 duplex stainless steel with 250 ksi (1720MPa) low-relaxation strand, using the same procedures as used for conventional pre-stressing and wire reinforcement.
Cost considerations have not so far led to the development of this application, although problems with the long-term performance of carbon steel pre- and post-stressed concrete, and with cable-stayed bridges have been reported.
Cold worked duplex stainless steel is now used in various applications: 10.9 class fasteners (UTS≥ 1000 MPa and Yield Stress≥ 900 MPa), erosion-corrosion resistant profiles, load-bearing members (profiles), high strength rebar (Yield stress ≥ 700 Mpa), etc.

5.4 Fire resistance (Refs 5.16 to 5.18)

Building codes include fire resistance requirements, typically R120, meaning that the structure must be able to withstand at least 120 minutes before collapsing when subjected to a "standardised" thermal load such as the one defined by ISO 843 , which is typical of cellulosic fire.
The variation of the yield strength of carbon steel, of austenitic and of duplex stainless steels with temperature, Figure 5.8, shows that in the 400-700°C range duplex stainless steels retain the highest strength level, expressed in MPa, although the decrease is important relative to the strength at room temperature.
Duplex stainless steels offer higher strength than carbon steels at all temperatures with grade S32205 (EN 1.4462) retaining the highest strength up to 800°C.

Duplex stainless steels, particularly lean grades, are now the preferred grades for stainless rebar, for strength and corrosion resistance including SCC. They offer in addition an improved fire resistance.

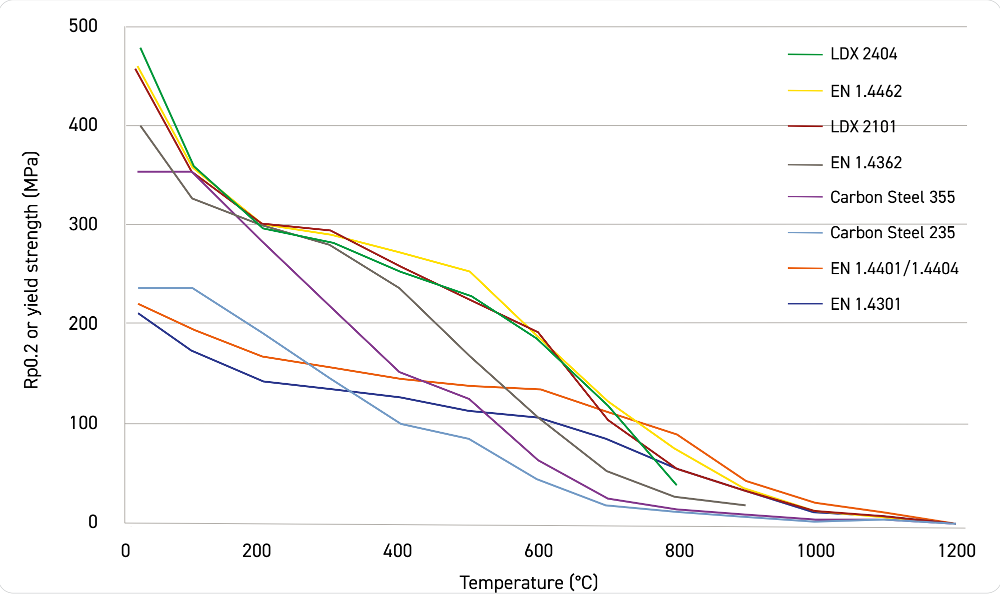


Figure 5.8 Yield strength vs Temperature of austenitic stainless, duplex stainless and carbon steels (Ref 5.17)

Fire resistance requirements are not limited to commercial, office and residential buildings. Industries handling flammable liquids and gases or hazardous chemicals are required to meet stringent requirements. Stainless steels, particularly duplex grades, can be very useful in this respect. A well-known case is that of blast walls on oil&gas platforms (see section on oil&gas).

5.5 Seismic resistance (Ref 5.19)

The damage caused by earthquakes results from 3 effects:

- a lateral force exerted on the foundations of the structure, directly proportional to the acceleration measured by the seismographs (can exceed 1g). The structure then may collapse.
- a torsion torque on asymmetrical buildings for which the center of gravity is not located on the axis of symmetry of the building
- for very tall buildings, a resonance effect.

As it is not practical and probably impossible to design buildings that would deform only in an elastic manner, priority is given to a design that allows damage but keeps the structure standing and functional as much as possible. One of the key considerations is to have structural components that can absorb as much energy as possible, i.e. strength and high deformability without breaking. Austenitic and duplex stainless steels are very good in this respect.
While buildings are of course the main concern, the consequences for industrial equipment can be very serious as well. The analysis of the seismic resistance of a large storage tank has been published (Ref 5.19).

6 Applications

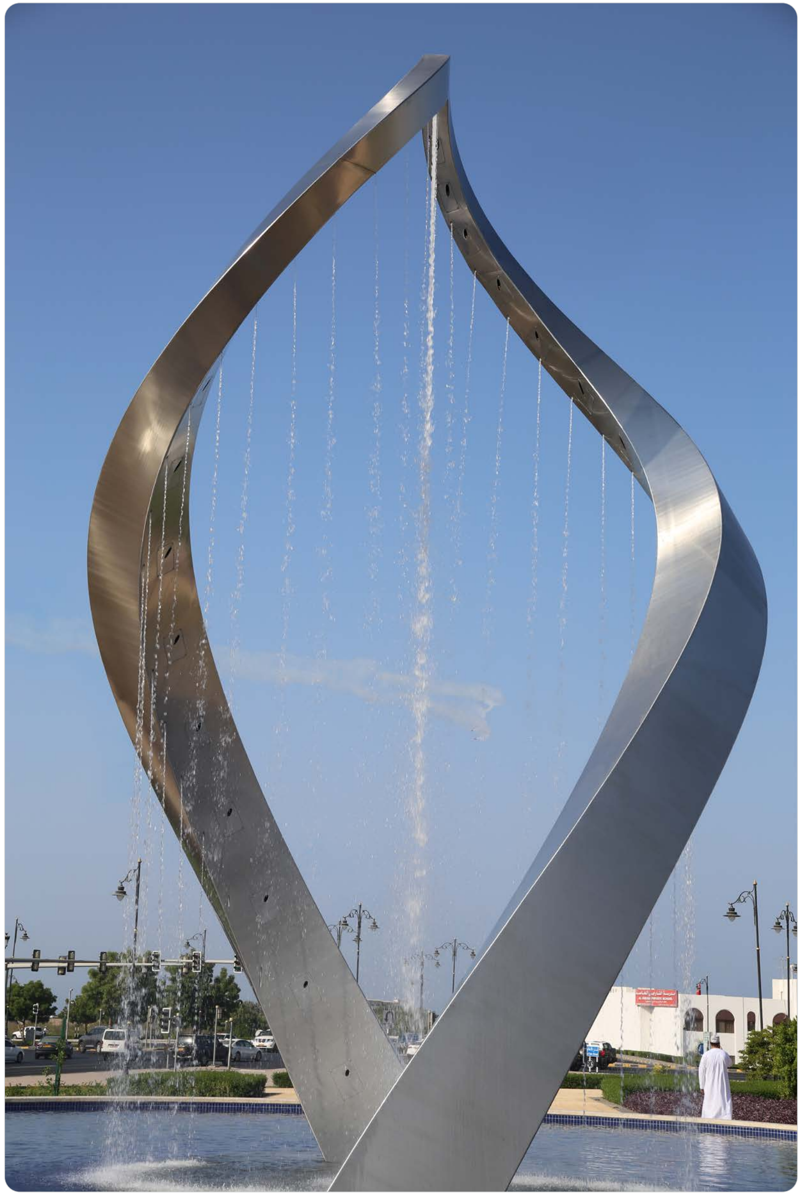
This section reviews some of the applications of duplex stainless steels today.
Artists, architects, designers, industrial engineers have seen and taken advantage of the benefits of duplex stainless steels. Building codes and regulations include them now for structural applications. Duplex offer usually a better alternative to coated carbon steels, starting from the installation costs.

6.1 Art

Duplex stainless steel is increasingly used by artists when they look for strength and durability. Three cases of art are presented briefly below.

The sculpture "**Arches of Oman**" (Ref 6.1.1) by Giles Rayner is formed of two entwined polished stainless steel tusks that flow around one another, connected by the flowing curtain of water that streams from their inner surfaces. The sculpture reaches 12 m in height above a 60 m wide oval pool. Water from 77 vertical jets suggest a stringed instrument. The sculpture is located in the private gardens outside The Royal Opera House Muscat, Oman. It is made of Duplex stainless steel grade S32205 (EN 1.4462) for strength, surface finish and corrosion resistance in this hot coastal environment.

It should be pointed out again that duplex grades are generally not competing with other stainless steel families. If anything, they tend to complement them and it is not rare to see them associated in an application. Some examples will be given later.



Arches of Oman by Giles Raynet in Muscat, Oman.
Picture courtesy of archesoman.com

BACK ? ☰ ← →

Venus Rising by Ross Wolfgang Buttress in Brisbane.
Picture courtesy of David Sandison

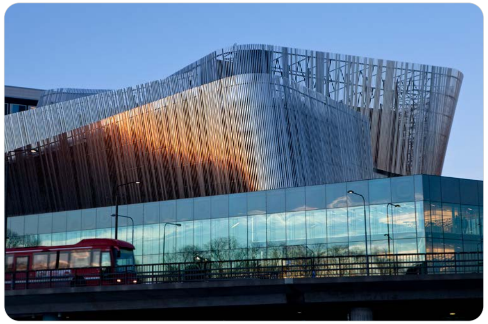
"**Venus rising**" (Ref 6.1.2) by artist Ross Wolfgang Buttress was inspired by the Fibonacci series and by the intersecting spines of nautilus shell. This slender structure, 23 m high, is located in Kangaroo Point Park in Brisbane, Australia. Made of stainless steel 316 (EN 1.4404) and Duplex S32205 (EN 1.4462) tubes and bars, is designed to look as good as new in 50 years.

The runners by Dr. T. Papagiannis in Chicago.
Picture courtesy of CS Associates Inc.

"**The Runners**" (Ref 6.1.3) This 4.9 m high, 12 m long sculpture, by Dr. T. Papagiannis is located near intersecting highways close to Chicago O'Hare Airport. It represents five runners emerging from antiquity into the modern world, represented by Chicago, "a city on the move". It is made of Duplex stainless S32205 (EN 1.4462) plate, 2.25" (57 mm) thick, cut by water jet. Each of the five runners weighs about 3 tons. The sculpture, exposed to the harsh Chicago winter with its road salt, is expected to last over 1000 years!

6.2 Architecture

Duplex stainless steels have expanded the potential of stainless steel in architecture by offering higher strength and higher corrosion resistance. Design manuals and guides for stainless steels which include high strength duplex grades have been published (Refs 6.2.1 to 6.2.8).
A few remarkable projects involving duplex grades are presented in this section.



Waterfront Building in Stockholm.
Picture courtesy of Outokumpu Oyj

Stockholm's waterfront building (Ref 6.2.1)
This congress center in Stockholm displays a duplex stainless steel façade, grade S32205 (EN 1.4462), 2E finish, made from 3500 Z-shaped louvres. Apart from providing a dynamic wave effect and an outstanding appearance, the louvres are positioned to reduce solar gain in summer and to allow sunlight to penetrate and provide passive heating in winter. The building earned a Gold LEED status.

Louvre Abu Dhabi, a rain of light (Ref 6.2.2)
The Louvre Abu Dhabi Museum by Architect Jean Nouvel features a woven double

Louvre by Jean Nouvel in Abu Dhabi.
Picture courtesy of Liz Coughlan

dome, 150 m in diameter, that creates an interior skin of dappled light. The water pools, the apertures and the dome create an interior micro climate full of light, shadows and movement. The roof is made of 8 interlocking layers of Aluminium and Duplex stainless steel. Approximately 300 tonnes of stainless were used for the roof. In addition, 250 tonnes of stainless rebar were used for the structure.

Roof of Doha airport (Ref 6.2.3)

The Doha airport, in Qatar, sets new standards in elegance, comfort and smart technology. One of its most striking characteristics is its undulating stainless steel roof (350,000 m²). It has to resist heat and humidity, salt corrosion and possess a low reflectance to protect pilots from glare. A duplex stainless steel (21.5%Cr, 3.7%Ni, 1.8%Mo, 0.17%N) was selected for the roof as it met the corrosion requirements and offered a favourable strength to weight ratio. A proprietary surface finish achieved a low gloss, a uniformly textured appearance, and a low reflectance.

Roof of Doha Airport in Qatar.
Picture courtesy of Hamad International Airport

La Sagrada Familia by Antoni Gaudí in Barcelona. Picture courtesy of Outokumpu Oyj.

La Sagrada Familia
(Ref 6.2.4 and 6.2.5)

The construction of the world-famous Basilica de la Sagrada Familia in Barcelona, designed by Gaudí, began in 1882. This huge project now nears completion, scheduled for 2026, thanks to the possibilities offered by new technologies and materials, of which stainless steel is one. Duplex grade S32205 (EN 1.4462) was selected for its high corrosion resistance and strength which will ensure a long life and a large decrease in the weight of the upper levels of the towers. Rebar, plates and profiles were used for prefabricated elements that were then easy to assemble and allowing a reduction in cost.
Gaudi's masterpiece will be completed with materials and technologies that did not exist in his lifetime. Who knows what he might have designed with them?

Louis Vuitton Foundation (Ref 6.2.6 to 6.2.8)

Architect Frank Gehry's remarkable structure for the Louis Vuitton foundation, a museum in Paris, involves 12 spectacular glass sails supported by an entanglement of steel columns, beams, tension rods, etc. Overall, approximately 1500 tons of duplex stainless were used for nodes, inserts, mullions transoms and gutters.

Fondation Louis Vuitton by Frank Gehry in Paris.
Picture courtesy of Daniel Rodet.

6.3 Bridges (Ref 6.3.1 to 6.3.14)

There are hundreds of thousands of bridges in the world, over 600,000 in the USA alone. More and more are being built. They provide essential links between regions and countries. The costs of maintenance or/and replacement amount to huge figures over time.
Life Cycle Cost (LCC) evaluations consistently show the benefits of providing operation with as little maintenance as possible over a lifetime exceeding a century. Duplex stainless steels offer an extremely attractive way of providing structural integrity over unlimited time, thanks to their high strength and their corrosion resistance that meets all climates and weather conditions. The extra cost over a cheap short-term solution is less than 10% when just used in the critical areas.
The few cases below illustrate the use of duplex stainless steel for road, pedestrian, rail, mixed rail/road/cycles traffic. They are located in hot and cold climates, inland and on the seaside.
Various product forms, tubes, tie rods, rebar, plates, fasteners, etc... have been used, demonstrating the wide range of options available to the architects and civil engineers.

6.3.1 Road and Rail Bridges

Stonecutter's bridge in Hong Kong (Ref 6.3.6 to 6.3.8).
This heavily-trafficked iconic bridge is located in an urban area, and has been designed to withstand tropical weather conditions, urban pollution, sea mist, wind, typhoons, accidental loads due to ship impacts and seismic loading. It was at the time (2009) the first cable-stayed bridge exceeding a 1 km span and has an expected lifetime of 120 years. Duplex stainless steel plate grade UNS S32205 (EN 1.4462) was used as skin around concrete for the upper part of the towers, for the cable-stay anchorage and for reinforcing bar of the foundations and lower parts of the towers.

*Stonecutter's bridge in Hong Kong.
Picture courtesy of Outokumpu Oyj*

*Champlain Bridge in Montreal, Canada.
Picture courtesy of Infrastructure Canada*

Champlain bridge, Montreal (Ref 6.3.9 and 6.3.10).
The new bridge (2019), which replaces the old one that was failing due to corrosion, will resist severe freeze-thaw cycles with temperatures as low as -25°C to up to 30°C. It is 3.4 km long, spans over the St. Lawrence river and the seaway and will carry over 50 million vehicles per year. The elegant structure features innovations such as construction largely from prefabricated elements and a provision for the mobility of the future with a commuter rail line, a 4-lane highway, bicycle tracks and lookouts for sightseeing. Over 15,000 ton of duplex stainless steel S32304 (EN 1.4362) rebar was used in the critical parts of the structure.

Hong-Kong - Zhuhai - Macau Bridge (Ref 6.3.11 and 6.3.12).
The bridge is a part of a 50 km link consisting of a series of three cable-stayed bridges, one 6.7 km under-sea tunnel, and 3 artificial islands. The bridge was constructed over 9 years, at an estimated cost of $20 billion for a lifetime of 100 years and was completed in 2018. Over 10,000 ton of duplex stainless steel was used in the critical areas.

Hong Kong - Zhuhai - Macau bridge

Cala Galdana bridge in Menorca
Picture courtesy of Pedelta

specified value for Carbon steel was only 355 MPa. The stainless structure was assembled on site from 8 sections and the whole construction time lasted from October 2004 to June 2005.

In India, future railway bridges built in corrosive environments (e.g. seaside...) are likely to rely on duplex stainless steels (Ref 6.3.15)

Bridge at Fort Worth, Texas (Ref 6.3.13)

Fort Worth bridge in Texas

This is the world's first arch bridge made of precast elements, 12 in total. It was completed in 2013. The innovative feature is the load-bearing angled hanger bars that connect the top and the bottom of the arch bridge. They provide stability and structural performance. They are made of duplex stainless steel grade S32205 (EN 1.4462). The overall design is structurally very efficient, very elegant and ensures long-term durability.

Cala Galdana bridge, Menorca (Ref 6.3.14).
This is a case of the replacement of a carbon steel reinforced concrete structure by a stainless one. Duplex grade S32205 (EN 1.4462) was selected over carbon steel for its higher mechanical properties and corrosion resistance. The minimum Yield strength specified was 460 MPa, for a measured value of 535 MPa, while the

6.3.2 Foot bridges

Helix bridge in Singapore (Ref 6.3.16)
Its unique double helix structure, 280 m long, supporting a walkway is made of tubes and plates of duplex S32205 (EN 1.4462). This grade has been selected for its strength and corrosion resistance in a tropical maritime environment. The life cycle cost of the bridge will be lower than that of a carbon steel solution. The white light at night is particularly beautiful, enhanced by the surface finish of the stainless steel.

Helix Bridge in Singapore
Picture courtesy of Christopher Fredrick Jones

Bascule Pedestrian Bridge
Picture courtesy of Industeel

Bascule pedestrian bridge, Lyon, France (Ref 6.3.17)
Located in an area that underwent a major upgrading and close to the new Musée des Confluences, this duplex stainless steel bridge opens up to allow the passage of ships entering the docks. It is elegant, aesthetic and requires no maintenance.

Footbridge of Trumpf, Ditzingen, Germany (Ref 6.3.18)
This footbridge over the heavily trafficked Gerlinger Strasse connects two work sites at the TRUMPF Headquarters in Ditzingen, Germany. Made of thin, strong, corrosion-resistant duplex grades S32205 (EN 1.4462) cut with TRUMPF laser technology.
It has a very original shape that everyone remembers and demonstrates that duplex is not for very large structures only.

Footbridge of Trumpf, Ditzingen, Germany
Picture courtesy of Schlaich Bergermann Partner

San Diego Harbor Bridge, California
Picture courtesy of Sherry V. Smith

San Diego Harbor Bridge (Ref 6.3.19)
This self-anchored suspension structure, 168 m long, is strikingly beautiful. The curved deck is supported by stay cables attached to a single inclined pylon, resulting in a very simple and attractive design. Duplex stainless steel grade S31803 and austenitic 317L have been selected for structural parts, railings, cables and connectors. The expected life time will exceed 100 years in this marine environment.

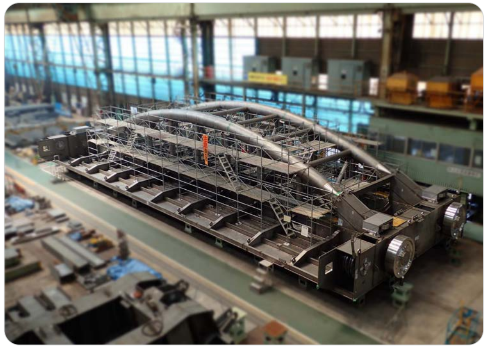
6.4 Coastal Works

Sea Wall at Cromer, United Kingdom (Ref 6.4.1)
Cromer is a beautiful North Norfolk seaside resort from the Victorian times. Protection against the sea is achieved by a concrete sea wall and by timber groynes. Following a major storm in 2013, large and expensive repairs had to be carried out, not only to maintain the actual level of defense, but also to anticipate 100 years of predicted sea level rise. In this project, over 300 MT of S32304 (EN 1.4362) duplex stainless steel rebar were used.

Sea wall at Cromer, UK
Picture courtesy of Archant/Anthony Kelly

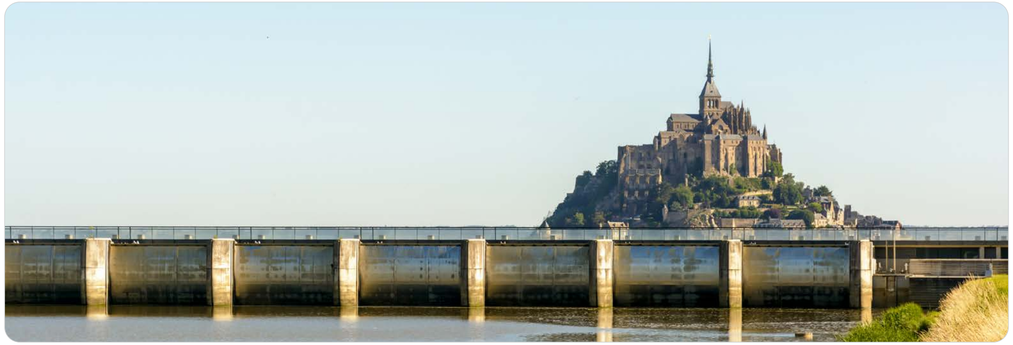
Breakwater in Bayonne, France
Picture courtesy of Ugitech S.A.

Breakwater at Bayonne, France (Ref 6.4.2)
The breakwater, built in the 1960s, protects the entrance of the Bayonne harbour against storms. It features a wall and a platform wide and strong enough to bear a heavy duty crane. This crane replaces the 40 ton concrete blocks that dissipate the energy of the incoming waves on the sea side as they wear out. As the platform itself eventually started to show cracks, it has been repaired using high strength S32205 (EN 1.4462) duplex stainless steel rebar (Yield stress min 750 MPa), allowing a significant reduction of tonnage. In the end only 130 tons of rebar were needed.



Kamihirai Floodgate in Japan
Picture courtesy of NIPPON STEEL Stainless Steel Corporation

Tsunami-proof floodgates in Japan (Ref 6.4.3)
Japan has paid a huge price to disasters caused by tsunamis. The Fukushima nuclear accident was the last major disaster caused by a tsunami. Under the national Earthquake reconstruction project, aiming at safety and resilience, over 50 dams and floodgates have been built. The new floodgates are huge structures. For instance, the Kamihirai gate is 11 m high, 2 m higher than the previous one. The use of duplex stainless steel grades SUS323L (S32304 / EN 1.4362) and SUS821L1 (21%Cr, 2%NI, 3%Mn, 1%Cu, 0.17%N) allowed the increase of height without the corresponding increase in weight.

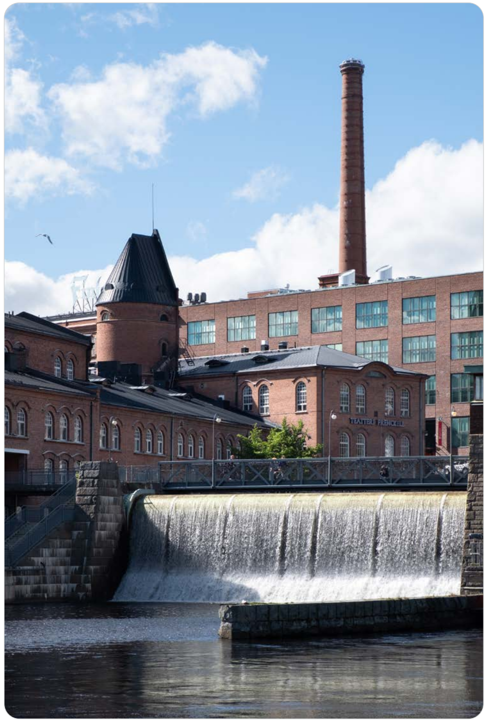


Sluice gates and Mont Saint Michel, France.

Sluice Gates at Mont Saint Michel, France (Ref 6.4.4)
Mont Saint Michel is one of the most visited tourist spots of France. The tiny

island with its cloister and with an angel on top is located in a bay. Over time, stilting of the bay was slowly taking place, changing the landscape. Gates were built to store the water of the incoming stream during the incoming tides and release it at low tides, thereby taking away some sediments back to the sea twice per day. The eight sets of sluice gates were built using for each 24 tons of carbon steel and 6 tons of S32205 (EN 1.4462) duplex stainless steel, selected for its good corrosion and abrasion resistance.
Mont Saint Michel now returns to the sea.

River floodgates at Tampere, Finland (Ref 6.4.5)

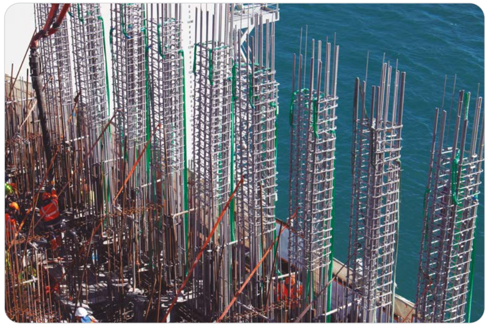


Floodgate at the Tammerkoski rapids, Finland

The Tammerkoski rapids flow through the center of the Finnish city of Tampere, running four hydroelectric power plants. An ongoing rehabilitation project will bring the rapids' two channels to the highest standards and worthy of the culturally and historically valuable site. For the past one hundred years, the water flow in the channels has been controlled by structures and equipment that have reached the end of their service lives. The old floodgates were largely built from wood and would take hours to open.
The design life of the rebuilt channels is 200 years. Duplex S32101 (EN 1.4162) stainless steel was preferred over coated carbon steel for all the main structural parts of the gates.

Monaco extension on the sea
(Ref 6.4.6)
The Principauté (principalty) de Monaco, on the mediteranean coast, is expanding its tiny territory (2 km²) over the sea to build a huge 600 000 m² new city development, residential and commercial, for an estimated cost of 2 billion Euros. The technical challenges are huge: creating a temporary dam to build the enclosure; erecting the concrete wall capable of lasting at least 100 years, filling up the new space gained over the sea and preparing it for multi storey residential buildings, minimising the impact on marine life, etc. Over 4000 metric tons of duplex S32304 (EN 1.4362) stainless steel rebar will be used to reinforce the concrete walls and protect them against the corrosion by sea water.

Monaco Extension on the sea
Picture courtesy of Bouygues TP



Monaco Extension on the sea
Picture courtesy of Cedinox

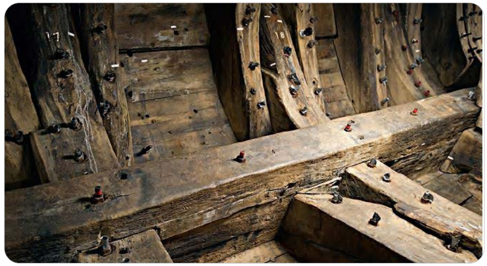
6.5 Restoration

Duplex stainless steels are now part of the solution for restoration when strength and corrosion resistance are needed. Here are some examples:

The iconic **Statue of Liberty**, (Ref 6.5.1) installed in New York in 1886, was repaired in 1981 using austenitic stainless steel 316L secondary armature to replace the original iron one. This one, in turn, is supported by a high strength, highly corrosion-resistant duplex stainless steel (UNS S32550). Austenitic and duplex grades complement each other and provide a solution to corrosion conditions involving chlorides, some pollution and galvanic coupling.

The great **Warship Vasa** (Ref 6.5.2) was launched on August 10, 1628 and sank immediately on her maiden voyage. After sitting some 300 years at the bottom of the sea, she was raised in the 1950's and sits now in the Vasa Museum in Stockholm. Among the necessary repairs was the replacement of the iron bolts that held the beams together. Epoxy-coated galvanized bolts corroded and had to be replaced by super and hyper duplex, spring-loaded, hollow bolts. The latter allowed a weight reduction from 16 down to 5 tons.

Statue of Liberty, New York
Picture courtesy Maurice LE BAIL from Pixabay



Partial view of the Vasa ship
Picture courtesy of Anneli Karlsson of the Swedish National Maritime Museum

Churches
Less visible but essential restorations have been carried out in other heritage buildings such as the churches of Santa Catalina (Ref 6.5.3) and San Antonio in Spain, (Ref 6.5.4). There, duplex stainless steel rebar reinforces the structure.

Reinforcing stainless bar in the floor of the Santa Catalina church in Spain
Picture courtesy of Cedinox

6.6 Tunnels

Road tunnels are subjected to very aggressive environments caused by heat, humidity, pollutants from exhaust gases and chlorides brought in by incoming traffic when the tunnel is close to the sea or when roads leading to it are de-iced. Tunnels must resist fire, be open at all times and no lifetime limit has been set for them. Therefore long lasting, maintenance-free, fire resistant solutions are needed. (Ref 6.6.1)

In the refurbishment of the Queensway tunnel, connecting Liverpool and Birkenhead under the Mersey river, new cladding panels on the tunnel sides are supported by a stainless steel framework of both austenitic EN 1.4301 strip and Duplex EN 1.4462 hooks. The duplex grade complements the austenitic grade and

Lining of the Queensway tunnel in Liverpool
Picture courtesy of Ancon Ltd

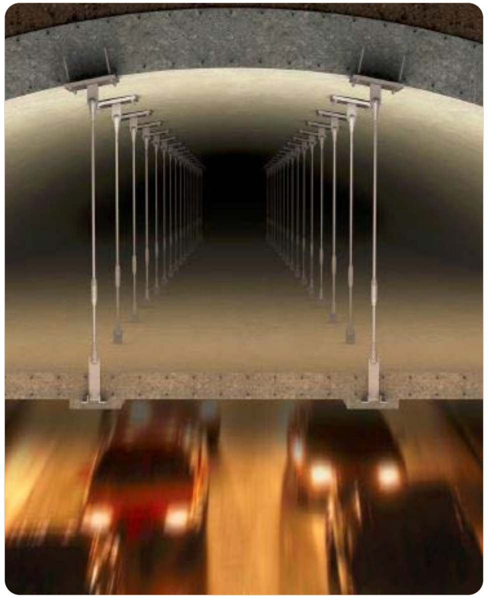
has been selected for its higher yield strength (Ref 6.6.2).

In the North/South bypass in Brisbane, Australia, the ventilation system is supported by duplex stainless steel suspension tie-bars. With as many as 100 jet fans installed, smoke can be quickly flushed out in the event of a fire. (Ref 6.6.3)

Railway Tunnels

Dynamic Hangers

The underground Holmestrand train station in Norway is part of the high speed train system that is being built. As high speed trains generate high forces of pressure, vibration, noise and winds even in open railway stations, new problems had to be solved.



Road Tunnel ceiling hangers
Picture courtesy of Ancon Ltd

Dynamic hangers in Holmestrand train tunnel
Picture courtesy of Sandvik Materials Technology

The station ceiling is supported by dynamic hangers made of duplex stainless steel hollow bars. These hangers are dynamic, i.e. they are able to accommodate pressure waves and vibrations beside the design load and provide damping. They are designed for a life of 100 years (Ref 6.6.4 and 6.6.5).

6.7 Transportation (Ref 6.7.1 to 6.7.7)

Marine chemical tankers (Ref 6.7.1 to 6.7.4)

The use of high strength duplex stainless steels allows a 10 % reduction of tank weight, decreases the initial cost of the tank, and increases the useful payload. In addition, their coefficient of expansion, close to that of carbon steel, facilitates the welding to surrounding steel structures.

Chemical tankers are equipped with large corrosion-resistant tanks or double hulls. Transporting large quantities of corrosive chemicals in rough seas without risk of spills and of harm for the crew puts additional constraints on the tanks'

Bow Sagami chemical tanker
Picture courtesy of Manuel Hernandez Lafuente

design and materials. Duplex stainless steels are increasingly used although they are not suitable for all chemicals (see the corrosion resistance section).

Flue Gas Desulphurization equipment (FGD) (Ref 6.7.5)

The combustion of crude oil releases harmful SO_2, a pollutant that has been drastically reduced years ago in most countries. Accordingly, FGD equipment has been installed years ago, chiefly in power plants. These regulations were not applicable to ships. The International Maritime Organization has caught up and similar regulations are applicable to ships as of 2020.

Duplex tank on truck
Picture courtesy of Technoimpianti A.P.M.

Ship owners must comply and install FGD systems in ships, where space is limited and ship stability must be taken into account. The alternative today is to use LNG (liquid natural gas), but soon (green) hydrogen may take over.

Materials used for FGD must resist the very aggressive environment of hot combustion gases containing ash, CO_2, SO_2 and often hot seawater. Super duplex stainless steels and Ni-base alloys are required.

Tank trucks

Duplex stainless steels are used for tank trucks for the same reasons as for chemical tankers. The payload increase reduces the transportation cost to a greater extent than for chemical tankers.

Railway Wagon (Ref 6.7.6)

Wagons for the transportation of iron ore in Kiruna (Sweden) are now built using duplex stainless steel (S32101 – EN 1.4162). The cost increase is offset by the following advantages:

- the stainless surface allows good discharge properties of the basket in the long term – also for materials that can be hard to release.
- the thickness and therefore the weight can be reduced compared to carbon steel, a cost-effective option for mining transportation
- weldability and formability are good, making it ideal as part of a construction.
- there is a good compatibility of welds with C-steel used in all the outside reinforcements, bars and in the bottom section or ‘skirt’ of the basket.

Iron ore wagon
Picture courtesy of Kiruna Wagon

Public transportation (Ref 6.7.7)

High strength duplex stainless steel has been selected by Stadler, a Swiss company, for light, corrosion-resistant tramlink cars, such as the pictured one for Transportes Urbanos de São Paulo, Brazil. Such cars will provide a long service life with minimal maintenance.

Tramcar with duplex stainless frame
Picture courtesy of Stadler SA

6.8 Chemical engineering (Ref 6.8.1 to 6.8.3)

Duplex stainless steels are used along with other stainless steels to process/produce a wide variety of chemicals: fertilisers, polymers, pharmaceuticals, etc. Their corrosion resistance and high strength make them particularly valuable for key process equipment such as

- pressure vessels,
- heat exchangers,
- condensers,
- storage tanks,
- distillation columns,
- and all the ancillary equipment: tubes, pumps, valves, fittings, filters, fasteners, agitators, ...

A list of chemicals with the corresponding corrosion resistance can be found in Ref 3.3.
Presence of impurities such as chlorides or fluorides, abrasive solids and of course elevated temperature increase the aggressiveness of the medium.

Heat Exchanger
Picture courtesy of Titan Metal Fabricators

Pressure vessel

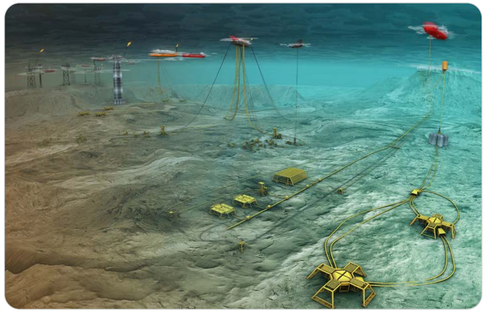
6.9 Pulp and paper (Ref 6.9.1 to 6.9.4)

Batch Digester
Picture courtesy of Metso Paper Pori Oyj

The Pulp and Paper industry is very competitive, and reducing costs a priority. In spite of it, or because of it, this industry has been one of the earliest ones to recognise the value of duplex stainless steels.
For example, S32205 (EN 1.4462), S32304 (EN 1.4362) and S32101 (EN 1.4162) can be used in digesters, pressure vessels and liquor tanks as well as in paper machines. For more aggressive environments, such as bleaching, super duplex S32750 (EN 1.4410) is needed.
The properties that led to this development are the overall low life cycle costs, the high strength (reduction of weight), the increased corrosion resistance (particularly to SCC) and the higher surface hardness. The latter property is important to resist the abrasion of wood chips and pulp (particularly in digesters).
The optimum material choice today is a selection of austenitic, duplex and super-austenitic stainless steels that complement each other.

6.10 Oil and gas (Refs 6.10.1 to 6.10.9)

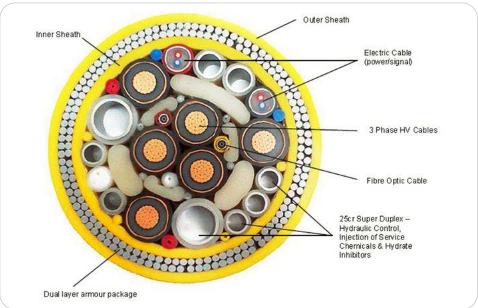
The oil and gas industry remains by far the largest user of duplex stainless steels. Standards such as Norsok and NACE (Appendix 1) provide detailed instructions for the selection of materials. They range from carbon steels, stainless steels (martensitic, austenitic, duplex, super austenitic) to nickel-base alloys depending upon pressure, temperature, chloride concentration and H_2S content (Figure 3.12)
Duplex are generally used in an intermediate position between martensitics and super-austenitics / Ni-base alloys. Their high strength is an asset when it comes to high pressures at great depths.



Oil and gas field layout
Picture courtesy of the Photothèque Technip FMC – All rights reserved

Blast wall
Picture courtesy of Mech Tool Engineering

As oil exploration offshore moved to greater depths, involving higher pressures and harsher environments, demands for higher corrosion resistance, particularly to chloride SCC, and higher mechanical properties emerged. They led to the development of super and hyper duplex grades that offer the lowest life-cycle-cost including that of the risk of a component failure. The latter is critical in subsea operations.
Duplex grades are specified in a wide range of components in the oil&gas industry as shown in Figures 6.10.1 and 6.10.2.
Besides the ancillary equipment (pumps, valves, fittings, filters) not listed in the table, armouring of umbilicals (for wear and damage resistance) and blast walls designed to contain fire and explosions on oil and gas platforms (see picture) are examples of other applications.



Area	Application	Alloy
Topside	Process piping Process pumps Injection pumps Process valves Separator vessels Manifolds	2205 / Superduplex
	Seawater/ waste water piping Seawater pumps Seawater valves Seawater filter vessels	Superduplex
Subsea	Flexibles	2003 / 2205
	Flowlines Gathering lines Manifolds Valves Hub connectors	2205 / Superduplex
	Risers	Superduplex
Downhole	OCTG Wireline Valves	2205 / Superduplex

Figure 6.10.1 Examples of the uses of duplex stainless steels in oil and gas recovery (Ref 6.10.8)

Oil and Gas service conditions are pushing materials to their limits in corrosion resistance, service temperatures, both high and low, and mechanical properties. The wide use of duplex stainless steels demonstrates their remarkable capabilities.

Area	Application	Alloy
Refinery	Crude desalters Amine towers lean/rich H/Ex Amine reclaimer units with caustic Filter drums (at risk of SCC) Fresh and brackish water coolers	2205 & Superduplex 2205 2205 2205 2205
Steam Cracker	Freshwater cooling towers/Coolers Dilution steam generators Spent caustic oxidation vessels/piping Coolers for acidic process condensate	2101/2102/2205 2205 2205 & Superduplex 2205 & Superduplex
Aromatics	Feed fraction tower airfins/piping/vessels Aromatics/HC separation units, reboilers, H/Ex tubing	2205 2205
Polymers	Polypropylene piping, drums, dust collectors, dryers and rotating equipment Elastomer slurry tanks, vessels, piping and rotating equipment LLPDE extruder feed shafts LDPE co-polymer piping Elastomer extruders barrels and screws	2205 2205 2205 2205 2205
Intermediates and other fluids	Corrosive service with organic acids, sulfuric acid, nitric acid, phosphoric acid, caustic, carbonyls etc. at high temperature and pressure Intermediate storage tanks	2205 2101/2102

Figure 6.10.2 Typical uses of duplex stainless steels in refineries and chemical plants (Ref 6.10.8)

6.11 Nuclear Energy (Refs 6.11.1 to 6.11.6)

In this industry with very high safety standards, any change in materials specifications takes a very long time. Nevertheless, duplex stainless steels are being specified in some new build and in decommissioning uses.
Their high SCC corrosion resistance ensures long term safety (up to 150 years), while the high strength allows a simpler design. In addition, a better thermal performance is obtained thanks to a relatively low thermal expansion and higher thermal conductivity compared to austenitic stainless steels. In new built plants, duplex stainless steels are used in the piping of the secondary water cooling circuit of the power plants.
In decommissioning, they are now one of the preferred materials for boxes in which slow-decaying radioactive materials are placed for geological storage. An example is provided by the Pile Fuel Cladding Silo at Sellafield, one of the world's oldest nuclear storage sites, which will need a total of 2200 duplex stainless containers, weighing 1.3 tons each, to keep the nuclear waste for at least 500 years. Other applications are canisters for transport and storage of nuclear fuel.

Nuclear waste container
Picture courtesy of Sellafield

6.12 Renewable Energy (Refs 6.12.1 to 6.12.10)

As mitigation of climate change is now recognised as one the most urgent problems the world must deal with, renewable energy production is set to increase drastically. Duplex stainless steels are increasingly relied on wherever strength and high corrosion resistance are required.

Biogas

Biogas, produced by the anaerobic digestion by bacteria of biomass, is a very attractive process as it produces energy from organic waste. Farms, restaurants, waste water treatment plants and others industries generating suitable organic waste can produce biogas that can be converted into electricity, used locally or sold to an energy utility. Heat is used onsite for drying or for heating purposes. (Ref 6.12.2)
While austenitic grades are usually specified for most of the equipment, duplex stainless steels provide the best solution for large digesters, where strength is

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Duplex stainless biogas tank
Picture courtesy of Börger GmbH

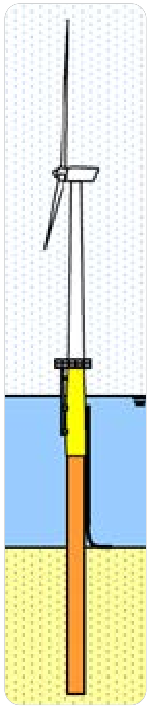
needed besides corrosion resistance. In addition, on-site construction from lighter prefabricated sections are less expensive.

Biofuels (Ref 6.12.3)
Reducing the dependence from fossil fuels has led to the development of bioethanol and biodiesel from energy crops, particularly in Brazil and in the USA.
While austenitic grades 304L/304 and 316L/316 are capable of resisting most of the corrosive conditions encountered in the production of biofuels, some parts of the cellulosic ethanol process such as the pretreatment phase of the bioethanol plants require a higher corrosion resistance. There, duplex S32205 and super duplex S32750 are used, along with super austenitic 904L, super austenitic 6 %Mo and nickel alloy C-276. In addition, duplex and super duplex are used when better erosion-corrosion properties are necessary, i.e pumps.
A similar situation occurs in biodiesel plants, where duplex UNS S32205 (EN 1.4462) and S32750 are used where weak hydrochloric or sulphuric acids are present in the pretreatment systems and in the washing and glycerin removal processes. Centrifuges can be made of 317L/317 and S32205. In both bioethanol and biodiesel plants, large tanks can be made of lean duplex S32101 (EN 1.4162) (Ref 6.12.4).

Solar panels supporting frames made of Duplex Grade SUS821L1
Picture Courtesy NIPPON STEEL Stainless Steel Corporation

Solar panel supporting frames (Ref 6.12.5)
In harsh environments duplex stainless steels offer a better performance than pre-painted and coated carbon steels for supporting frames. They provide the necessary corrosion resistance for no maintenance but in addition the higher strength allows the design of lighter structures that are both less expensive and easier to install.

Geothermal (Ref 6.12.6 and 6.12.7)
Wellheads can use duplex or super duplex as an alternative to nickel alloy 625 for the geothermal well heads carrying hot brine.



Windmill with monopile foundation (orange) and transition piece (yellow)

Offshore/onshore wind turbines (Ref 6.12.8 to 6.12.10)
Bolts are used to fasten turbine components not only for the excellent corrosion resistance in marine environments but also for the high mechanical properties that reduce weight, increase efficiency and guard against premature failure.
Duplex stainless steel grade UNS S32205 (EN 1.4462) is used in brackets that are used to connect the monopile foundations to the transition piece. It was chosen for its high mechanical properties (YS > 355MPa) and excellent corrosion resistance, in tough operational conditions that can include freezing temperatures, strong currents and winds, and marine environment. These properties have been considered for windmill tower tubular designs able to reach heights up to 160 m.

6.13 Water

Corrosion resistance has always been a requirement for any material in contact with water, whether drinking water, waste water or sea water. Duplex stainless steels are used for an increasing number of applications for strength and corrosion resistance:

Boats (Refs 6.13.1 to 6.13.4)

- Hulls, for high quality yachts, provide a long life without maintenance.
- Davits (onboard cranes): They are usually made from sheets bent into square sections and then laser-welded. The work-hardening associated with bending provides a beneficial increase in strength at no extra cost. As with other stainless steels, various surface finishes are available on demand.
- Propellers and boat shafts: Duplex stainless steels are now part of the materials available. Manufacturers value their high level of resistance to fatigue corrosion and their good resistance to abrasion and erosion at high flow rates.

Davit (Marine crane)
Picture courtesy of Stainless Structurals

Large storage tanks (Refs 6.13.5 to 13.6.9).
They may contain, besides water, a wide range of liquids and corrosive chemicals at various stages of processing, the end product before shipping, etc
A comparison of the Life Cycle Costs (LCC) of various options for a typical 20 m in diameter, 20 m high tank over a 30 years life is shown in Figures 6.1 and 6.2.
Duplex grade S32304 (EN 1.4362) offers the lowest LCC because:

- Carbon steels require an expensive coating, and an even more expensive re-coating after some years
- High strength duplex allows reductions in wall thickness and therefore weight compared to austenitic stainless steel grades. Less material is needed, transportation and assembly of lighter parts and welding is easier.

Similar results were obtained with different tank sizes and duplex grades (Ref 6.13.8)
Ferritic and/or austenitic stainless steel grades remain the preferred choice for small and medium-sized tanks, as the thickness reduction is much smaller.

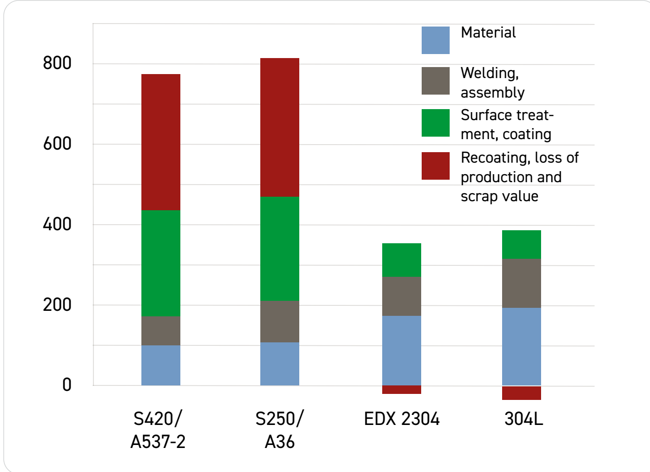
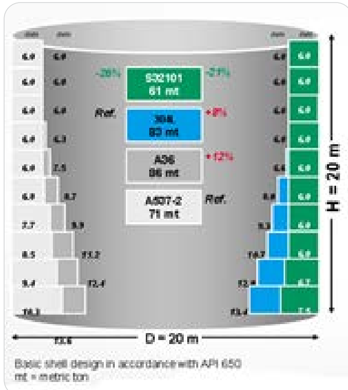


Figure 6.1 LCC of a duplex tank (Ref 6.13.6)



Duplex Stainless Steel in Storage tanks give the following structural efficiency:

- Stainless steel does not need any corrosion allowance
- In the lower part of the tank the minimum shell thickness corresponds to the design strength of the material
- In total this gives a significant weight saving by using the high strength of duplex stainless steel

Figure 6.2 Thickness reduction achieved by duplex stainless steels (Ref 6.13.7)

Wastewater tanks

(Ref 6.13.9 to 6.13.12)

Among the ongoing developments, the use of duplex grades for wastewater treatment tanks is receiving a lot of attention, for both the replacement of existing ones (often carbon steel reinforced concrete) or for new ones.

Waste water treatment plant
Picture courtesy of Institut de la Corrosion

Drinking water storage tanks

(Ref 6.13.13)

These storage tanks are much larger and have been for the most part made of reinforced concrete, with coatings. Deterioration over time requires expensive crack repairs and waterproofing, which only have a temporary effect. Microbial growth is always a concern and materials that do not favour it while remaining innocuous for human health are needed.

These considerations have led to the retrofitting of an existing water reservoir in Korea with duplex stainless steel lining, grades 329LD (20Cr-2.5Ni-1.4Mo-N) and 329J3L (22Cr-5Ni-3Mo-0.15N). The lining is assembled on-site by welding (which will be automated) and anchoring to the concrete, technologies which are also used with austenitic stainless steels. Duplex grades may well be the preferred material in the future.

Left: Water reservoir before repairs. Right: Same with duplex stainless steel lining
Pictures courtesy of Moonchang.

Desalination plants (Refs 6.13.14 to 6.13.17)

Water scarcity is a big problem in many countries. Desalination of sea water is an effective mitigation solution. Two processes are used:

- Multi-Stage Flash distillation (MSF) / Multi-effect Distillation (MED) in which the water is evaporated and then condensed, producing drinking water while the remaining water is a concentrated salt solution, a brine.
- Reverse osmosis (RO) and Brackish water reverse osmosis (BWRO) in which the water under pressure of about 60 bars is forced through a membrane that retains the salt ions. In this process even the salt-free water has some degree of corrosiveness.

In both processes the incoming sea water must be filtered to remove solids and the brine safely discharged into the sea to avoid harming the ecosystem.

Reverse Osmosis water desalination plant in Israel

All processes require very corrosion resistant materials. Super austenitics (such as 904L and 6 %Mo), duplex S32205 (EN 1.4462), super duplex grades (typically UNS S32750 (EN 1.4410)) and Titanium are used in various parts of the plants. High strength and high fatigue resistance are additional criteria for material selection.

Some of the plants that use duplex stainless steels are the Mellitah plant (2004) in Libya, the Skikda plant (2005) in Algeria, and Sing Spring desalination plant (2005) in Singapore.

Water heaters (Ref 6.13.18)

Hot water cylinders for domestic/institutions water heaters and boilers are increasingly made of lean and standard duplex, thanks to their lower weight and their excellent resistance to pitting, crevice corrosion and chloride SCC, making them competitive compared to coated carbon steels.

6.14 Multi markets (Refs 6.14.1 to 6.14.3)

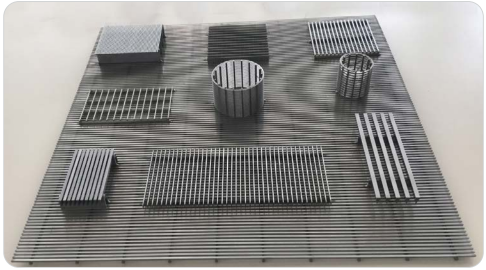
Besides market-specific applications, duplex stainless steels are used in less visible but essential components widespread in all industry sectors: pumps, valves, tie-bars, machined parts, fittings, fasteners, anchoring systems, filters, springs, structural profiles….

Duplex stainless steels are generally part of a range of available materials for these applications. They are preferred when high strength and high corrosion resistance, with occasional additional requirements such as resistance to erosion corrosion and to fatigue corrosion, are demanded.

Some of these components take advantage from the additional strengthening due to cold work: fasteners (with yield stress levels close to 1000 MPa), structural profiles obtained by the cold forming of sheets, cold drawn profiles, parts made from cold-drawn bars, rebar, … Higher strength without reduction of corrosion resistance reduces thickness, weight and therefore cost.

A more complex mix of properties may offer optimum solutions. For good heat transfer properties, very thin walls with a heat conductivity close to that of ferritic grades can be obtained by using thin gauge cold-worked sheets.

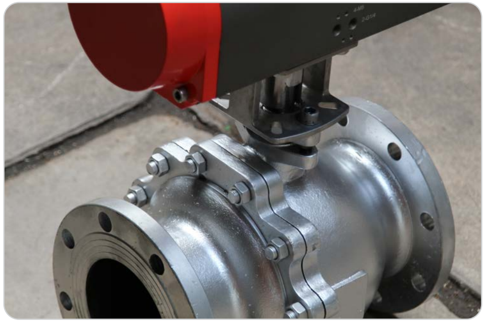
Balcony connector
Picture courtesy of Slabe



Profiles wire for filtration
Picture courtesy of Ugitech S.A.

Anchoring systems
Picture courtesy of Halfen

Fittings



Valve

Submerged pump

7 Fabrication

7.1 Forming (Refs 7.1.1 to 8)

Cold Forming

Duplex stainless steels can be cold-formed without any particular difficulty, as long as provisions are made for:

- a higher strength, requiring sturdier and more powerful machines
- a larger springback (Figure 7.1.1)
- a lower ductility than austenitics and ferritics, particularly for deep drawing operations.

Grades with improved cold formability are available today. They rely mostly on optimised compositions.

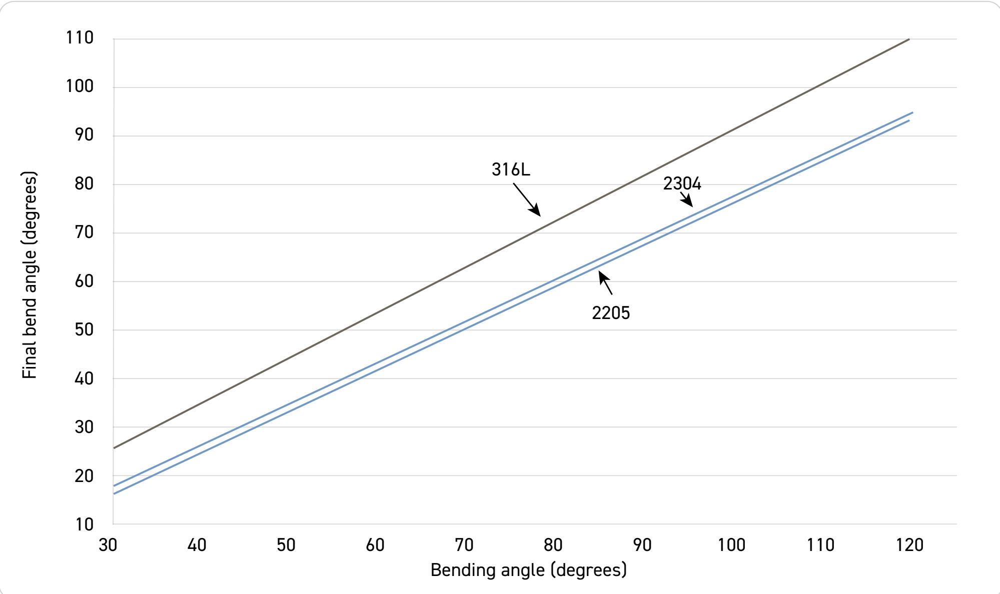


Figure 7.1.1 Comparison of springback of duplex stainless steels and Type 316L for 2 mm (0.08 inch) thick sheet (Ref 7.1.1)

Hot-forming/forging

Optimum hot working conditions require a good control of the temperature range (Table 7.1), as it affects:

- the austenite/ferrite phase balance
- the precipitation of nitrides
- the precipitation of intermetallic phases at temperatures below ~1050°C.

These conditions define an operating "window" shown in (Figure 7.1.2). Alloying elements, Cr and Mo in particular, accelerate the precipitation of intermetallic phases like sigma phase by low cooling rate and low temperatures, while N induces the precipitation of Cr nitrides inside the ferrite at very high temperatures and fast cooling rates. As a result, the operating window is widest for the lean duplex and narrowest for the super

UNS N°	EN N°	Hot forming temperature range °C	Minimum soaking temperature, °C
S32101	1.4162	1100-900	950
S32304	1.4362	1150-950	980
S32205	1.4462	1230-950	1040
S32750	1.4410	1230-1025	1050
S32520	1.4507	1230-1000	1080
S32760	1.4501	1230-1000	1100
S30400	1.4301	1205-925	1040
S31600	1.4401	1205-925	1040

Table 7.1 Recommended hot forming temperature range (Ref 7.1.2)

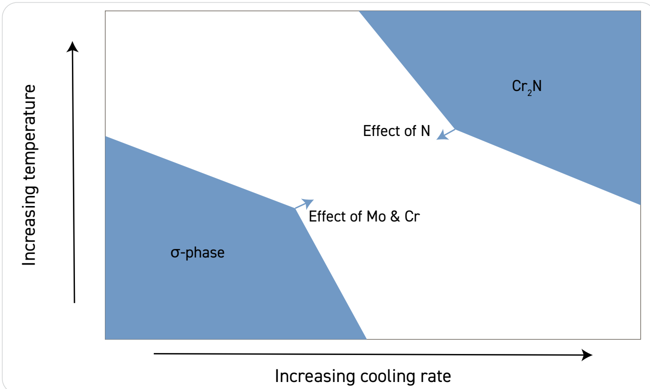


Figure 7.1.2 Schematic diagram of the production window of duplex stainless steels defined by temperature and cooling rate (Ref 7.1.6)

and hyper duplex grades.
In practice, attention must be paid to make sure that the temperature at the final stage of hot working (rolling or forging) is above the lower limit, and that a rapid cooling follows.

Special processes are known:

Transformation Induced Plasticity (TRIP effect), whereby the austenite phase transforms into martensite during cold work. This in turn increases the work hardening rate and prevents early rupture. For this to happen, the chemical composition of the grades must be carefully balanced. The TRIP effect in this material enhances strain hardening over a wide deformation regime hence the ductility of the steel. Duplex stainless steels that show TRIP effect present an excellent strength-ductility profile with an ultimate tensile strength above 1000MPa and an elongation to fracture of above 60%. These steels can be used in applications that require good formability and high energy absorption (Figure 7.1.3). Some applications that can profit from TRIP effect are forming-intensive components, components from automotive industry, heat exchangers, pump components, braiding and springs, etc.
Figure 7.1.4 shows the excellent behaviour of duplex TRIP steels compared to other non-stainless steels.

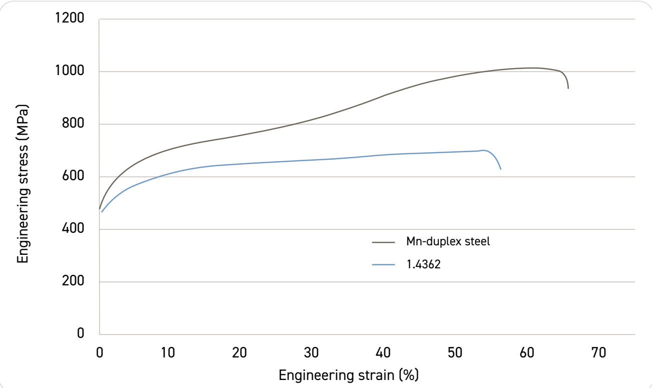


Figure 7.1.3 Stress strain curves of a standard duplex (1.4362) and of a TRIP modified grade (Ref 7.1.7)

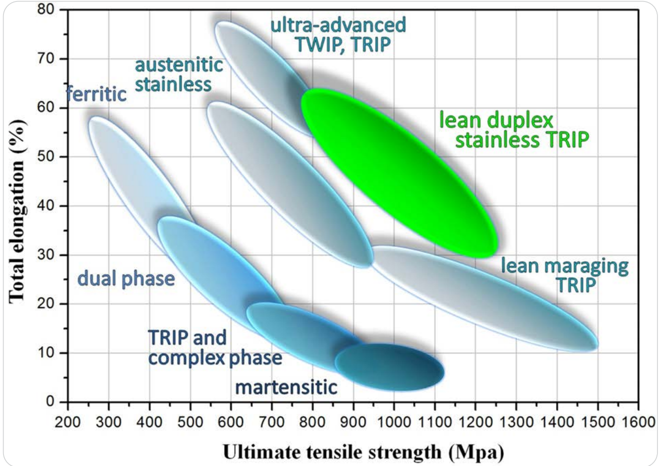


Figure 7.1.4 Overview of total elongation to fracture vs. ultimate tensile strength for different steel grades (Ref 7.1.7)

Superplasticity, a property known in many materials (such as glass), superplasticity has been evidenced in duplex stainless steels. It requires the right temperature and strain rate conditions. Figure 7.1.5 shows that elongations in excess of 1000% can be obtained in a lean duplex previously cold worked. The conditions required for superplastic behaviour, and in particular the low strain rates, have not allowed the development of this forming process.

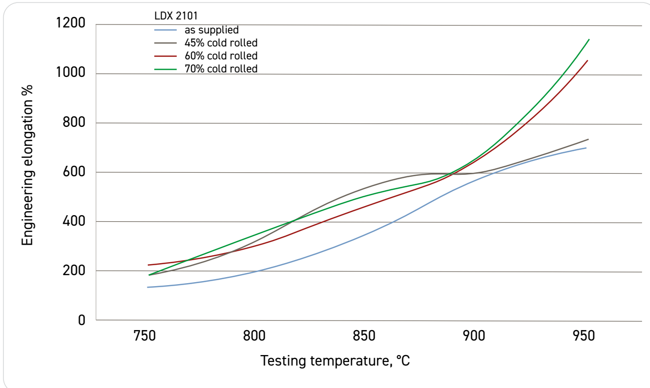


Figure 7.1.5 Superplastic elongation of a lean duplex (Ref 7.1.8)

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7.2 Machining (Refs 7.2.1 to 7.2.4)

All bar products are machined to produce parts. Plates are often drilled and milled to obtain the desired shape. Machining is therefore an important processing property as it can significantly increase the cost of the finished parts. Improved machinability grades are well known in engineering steels, in martensitic and austenitic stainless steels, but it is only recently that attention has been given to the machinability of duplex stainless steels.
The two most important parameters for machinability are tool wear and chip breaking behaviour. The high strength of the duplex grades leads to higher cutting forces and increased tool wear.
Improving machinability can be achieved in different ways

1. Adjusting the grade chemical composition to decrease strength and work-hardening without deteriorating the corrosion resistance. This can be achieved by increasing Ni and Cu and decreasing N, leaving the same austenite/ferrite balance, or increasing somewhat the ferrite content.
2. Optimizing the Sulphur Content. The EN 10088-1 standard sets a maximum S content of 150 ppm for most grades. Figure 7.2.1 (Ref 7.2.2) show large differences in good chip breakability exist (Blue area in the feed/depth-of-pass diagram with S content varying from 7 to 37 ppm. By contrast, there is no significant change in tool wear. Even at such low S contents, well below the limit of 150 ppm, a marked decrease of the pitting potential is observed (Figure 7.2.2). The higher the S, the lower the pitting resistance. Furthermore, increasing Sulphur contents deteriorates the impact properties, particularly at subzero temperatures, Figure 7.2.3. From these results, a very low sulphur content is required to ensure a good pitting corrosion resistance and good impact properties. As a result, the

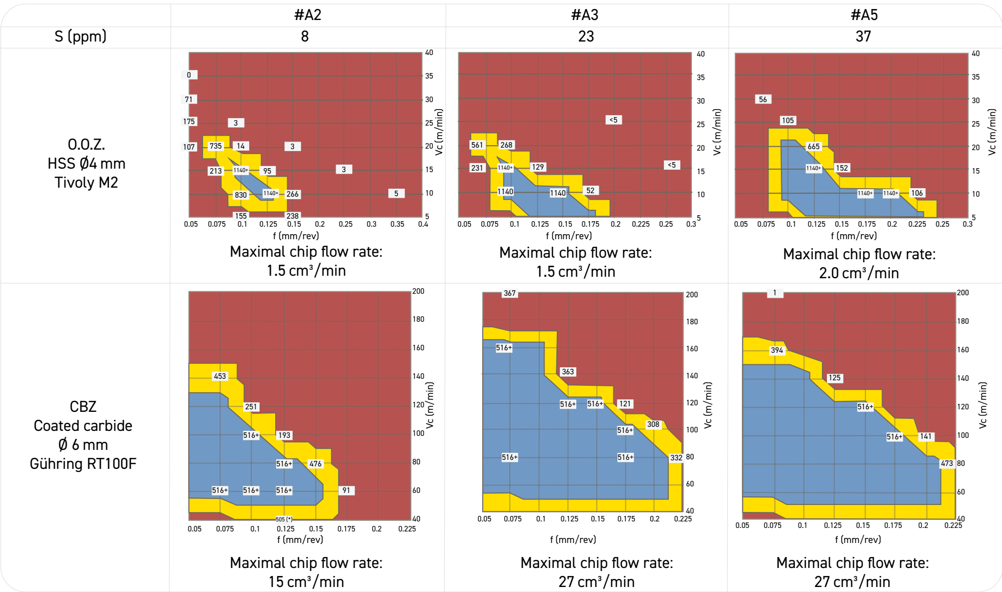

Figure 7.2.1 Optimum chip breakability vs Sulphur content for High Speed Steel and for Coated Carbide cutting tools (Ref 7.2.2)

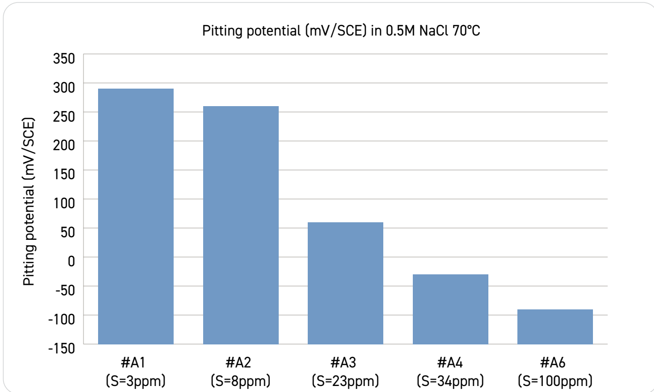

Figure 7.2.2 Pitting Corrosion resistance vs. S content

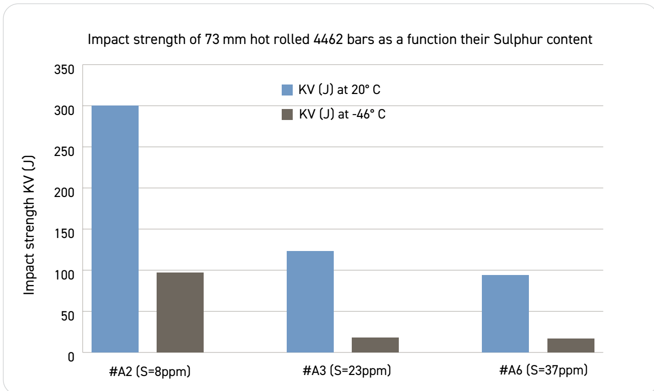

Figure 7.2.3 Impact strength vs. S content

improvement of machinability by Sulphur additions is not attractive.

3. Low melting point oxide inclusions, able to lubricate the carbide tool/ steel interface, are well known. Improved machinability grades based on such oxide inclusions have been developed for engineering steels, martensitic and austenitic stainless steels, but the "recipe" cannot be just copied for the duplex grades. Nevertheless, duplex stainless grades with controlled oxide inclusions have been developed. Fig 7.2.4 shows a significant machinability improvement achieved by oxide inclusion control of grade S32304 (EN 1.4362) in a turning operation with carbide tools. Similar results are reported for drilling. Chip breaking is also improved. Published data indicate that oxide inclusions do not deteriorate significantly the pitting corrosion resistance of lean duplex grades. Their main drawback, as of today, appears to be a large decrease of KV impact values below 0°C. It limits the applications for which duplex grades with an improved machinability by oxides can be used.

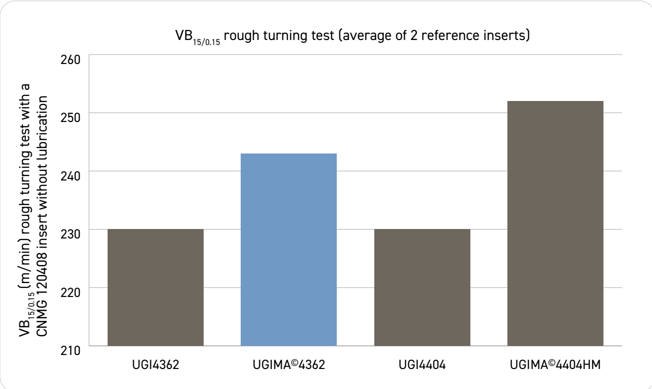

Figure 7.2.4 Improved machinability obtained by controlled oxide inclusions (Ref 7.2.4)

7.3 Welding (Ref 7.3.1 to 7.3.6)

Duplex stainless steels can be readily welded by most processes, the most frequent one being arc welding. Unlike austenitic grades, they are not sensitive to hot cracking and their coefficient of expansion is close to that of Carbon Steels. The welding recommendations presented below stem from the following metallurgical features of the duplex grades (Figure 7.3.1):

- Solidification of duplex takes place fully in the ferritic phase. Then, as the temperature drops, austenite forms. If the cooling rate is very high, there may be more ferrite phase than what the equilibrium phase balance would lead to. In addition, the solubility of N in ferrite decreases sharply with temperature, leading to the unwanted precipitation of chromium nitrides inside the ferrite phase unless nitrogen can migrate into the austenite. Increased transformation of ferrite to austenite can be obtained by proper choice of

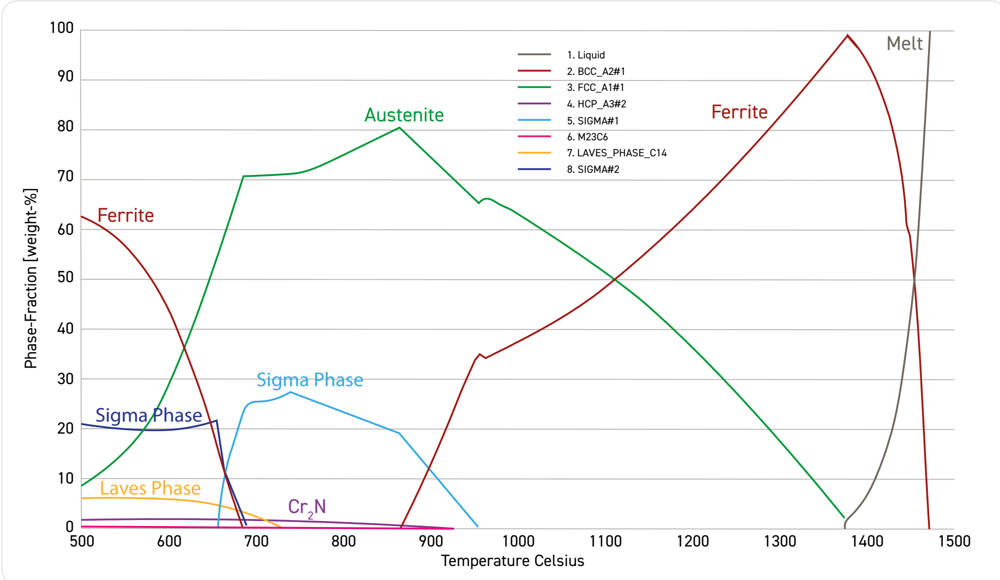

Figure 7.3.1 Equilibrium phases of a 22%Cr duplex stainless steel versus T° computed by Thermocalc (Version 2017a/TCFE 9)

shielding gas and filler metal.

- Cooling below ~1000°C must take place fairly quickly to avoid the precipitation of intermetallic phases, of nitrides and of carbides that are detrimental to both impact properties and corrosion resistance. Low temperature spinodal decomposition takes place too slowly to be a concern in welding.

The optimum welding conditions will therefore depend on the thickness of the plates to be welded and of their chemical composition. The welding parameters must be set accordingly, with the following rules:

- Heat input: An optimum value results from the compromise between the need for a rather slow cooling below the melting point and that of a fast cooling below ~1000°C
- Filler metal composition: It usually has a higher Ni content than the base metal, so that it helps the formation of austenite. The nitrogen content, on the other hand, may be lower than that of the base metal to reduce the potential for precipitation of chromium nitrides
- Shielding gas: It may contain some nitrogen to promote austenite formation as well. In all cases, moisture and hydrogen must be avoided
- Preheating should be avoided. When necessary, the temperature should be

Weld Process	Electrode/ Filler AWS Classification	Diameter (in)	Welding Position	Bead	Recommended current (A)	Voltage (V)	Travel speed (inch/min.)
SMAW	E-2209	3/32 & 1/8	3G-Up	Root Cap	50-60 80-95	20-24	4-6/7-9
GTAW	ER-2209	3/32	1G	Root	100-120	16-18	5-8
GTAW & FCAW	ER-2209 + E2209T1-4	3/32 & 1/16	1G	Root Cap	100-120 190-210	16-18 28-30	5-8 17-22
SAW	ER-2209+ P100 Flux	3/32	1G	Cap	350-400	30-32	30-40

Figure 7.3.2 Recommended welding parameters for different types of joints (Ref 7.3.1)

Welding Process	Shielding Gases	Remarks
GMAW	Ar+30 He+1 O_2	Short arc welding gives very convex beads
	Ar+30 He+1 O_2 (22Cr duplex) Ar+2 CO_2 (Super duplex)	Spray arc welding
	Ar+30 He+1 O_2 (22Cr duplex) Ar (99.996%) for super duplex	Pulsed arc welding
GTAW	■ Shielding - Ar+2% N_2 ■ Purging / Root Gas- Ar	■ Purge to maintain 0.5% oxygen max ■ Ar+ 2% N_2 shielding gas is recommended for the root run ■ For subsequent runs, Argon (Ar) may be used as shielding gas ■ Root is mandatory for first two runs Note: Per ASME section IX, a changing for purging gas is a non-essential variable. Formier gas (90% nitrogen and 10% hydrogen) is a cheaper and sometimes a tried alternative for root Pp. However, the acceptance is subject to satisfactory procedure qualification only
FCAW	■ Ar-20% CO_2 ■ Ar-18%CO_2-2%O_2	■ Typical gas flow rate 20-25 l/min ■ Wire stickout length 15-20 mm

Figure 7.3.3 Recommended welding parameters (Ref 7.3.1)

about 100°C.

- The requirement for maximum interpass temperature is usually at 150°C for lean and standard duplex, and at 100°C for super duplex.
- Stress relief treatment at low temperature (600-650°C) must be avoided.
- Postweld heat treatment should be a solution annealing followed by fast cooling.

Processes without filler metal such as spot welding should be avoided.

Note: The welding of dissimilar metals, usually austenitic stainless steels or carbon steel is commonly done. The most suitable filler metal will depend on the particular combination of alloys.

7.4 Quality control (Ref 7.4.1 and 7.4.2)

Duplex stainless steels are not significantly more difficult to process than martensitic or austenitic grades, but they require a closer control of fabrication parameters.

Specifications must include the necessary testing. They usually rely on standards (see Appendix 1). For instance, ISO 17781 and NACE MR0175/ISO 15156 provide and describe common test methods for quality control for oil and gas applications, which are among the most demanding ones. More specific standards can be demanded, an example being Norsok M-630 (for materials) and M-650 (for vendor approvals), also for oil and gas.
The usual quality control requirements are :

1. Chemical composition (ASTM or EN)
2. Heat treatment parameters
3. Mechanical properties: hardness, tensile test, impact test at room temperature and subzero if need be (i.e: Norsok at -46°C)
4. Metallography examination: ferrite between 40- 60%. No third phases such as Sigma phase, Chi phase, nitride or carbide (ASTM A923).
5. Corrosion test: corrosion pitting temperature (ASTM G48).

An example of additional requirement is Stress Corrosion Cracking test for oil and gas applications involving H_2S.

Qualification of operators

Fabrication must be carried out by operators with the required level of qualification. This is particularly important for welding. ISO and ASME specify qualification procedures. Similar qualifications requirements are demanded for non-destructive testing operators.

Detail of the Kwandong Ice Hockey Center in Korea, clad in lean duplex 329LD

8 Conclusions

Duplex stainless steels are now used in a wide variety of applications, but they are still far from having reached their full potential. In most uses they complement other stainless steel families, particularly austenitics.
While strength and corrosion resistance are their best-known advantage, recent developments are tailoring them to fit different requirements: arctic service, higher corrosion resistance, higher mechanical properties, better heat transfer (thinner gauges), improved machinability, better forming properties. Further developments will come out. The additive manufacturing (3D printing) process, for instance, may be able to produce duplex stainless parts with high strength and corrosion resistance. All this while offering the usual properties of stainless steels, i.e. durability, low life cycle cost, 100% recyclability, aesthetics, ...
Hopefully, this brochure will help you for your projects.

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10 Appendices

Appendix 1 Main standards

1. **ISO 15510** Stainless steels – chemical composition
2. **ISO 17781** Petroleum, petrochemical and natural gas industries - Test methods for quality control of microstructure of ferritic/austenitic (duplex) stainless steels
3. **ASTM A182** Standard specification for forged or rolled alloy or stainless steel pipe flanges, forged fittings and valves and parts for high temperature service
4. **ASTM A240** Standard specification for chromium and chromium nickel stainless steel plate, sheet and strip for pressure vessels and for general applications
5. **ASTM A270** Standard specification for seamless and welded austenitic and ferritic/austenitic stainless steel sanitary tubing
6. **ASTM A276** Standard specification for stainless steel bars and shapes
7. **ASTM A480** Standard specification for general requirements for flat-rolled stainless and heat resisting steel plate, sheet and strip
8. **ASTM A789** Standard specification for seamless and welded ferritic/austenitic stainless steel tubing for general service
9. **ASTM A790** Standard specification for seamless and welded ferritic/austenitic stainless steel pipe
10. **ASTM A815** Standard specification for wrought ferritic, ferritic/austenitic, martensitic stainless steel piping fittings
11. **ASTM A890** Standard specification for castings, iron-chromium-nickel-molybdenum corrosion-resistant, duplex (austenitic/ferritic) for general application
12. **ASTM A923** Standard test methods for detecting detrimental intermetallic phase in duplex (austenitic/ferritic) stainless steels
13. **ASTM A928** Standard specification for ferritic/austenitic (duplex) stainless steel pipe electric fusion welded with addition of filler metal
14. **ASTM A959** Standard guide for specifying harmonized standard grade compositions for wrought stainless steels
15. **ASTM A995** Standard specification for castings, austenitic/ferritic (duplex) stainless steel for pressure-containing parts
16. **BS 6744**: 2016 Stainless steel bars. Reinforcement of concrete. Requirements and test methods
17. **EN ISO 9445** Continuously cold-rolled stainless steel – Tolerances on dimensions and form Part 1: narrow strip and cut lengths Part 2: Wide strip and plate/sheet
18. **EN 10088-1** Stainless steels – list of stainless steels
19. **EN 10088-2** Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion-resisting steels for general purposes
20. **EN 10088-3** Stainless steels. Technical delivery conditions for semi-finished products, bars, rods, wire sections and bright products of corrosion-resisting steels for general purposes
21. **EN 10028-7** Flat products made of steels for pressure purposes. Stainless steels
22. **EN 10216-5** Seamless steel tubes for pressure purposes. Technical delivery conditions. Stainless steel tubes
23. **EN 10272** Stainless steel bars for pressure purposes
24. **EN 10296-2** Welded circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions. Stainless steel
25. **EN 10217-7** Welded steel tubes for pressure purposes. Technical delivery conditions. Stainless steel tubes
26. **EN 10253** Butt-welding pipe fittings. Wrought austenitic and austenitic-ferritic (duplex) stainless steels without specific inspection requirements
27. **EN 10297-2** Seamless circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions. Stainless steel
28. **Vd TüV WB418** Ferritisch-austenitischer Walz- und Schmiedestahl, X2CrNiMoN22-5-3, Werkstoff-Nr. 1.4462; Band, Blech, Flansch, Form- und Stabstahl, nahtloses Rohr, Schmiedestück
29. **Norsok Standard M630** Material data sheets and element data sheets for piping
30. **NACE MR0175/ISO15156-3** Petroleum and natural gas industries – materials for use in H2S containing environments in oil and gas production

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Appendix 2 Chemical compositions (typical analyses)

	Grade	Standards	C	Cr	Ni	Mo	N	Mn	Cu	W	PREN
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
	S82012	1.4635	0.05	19.0-20.5	0.80-1.50	0.10-0.60	0.16-0.26	2.00-4.00	1.00	-	24-26
	S82122		0.03	20.5-21.5	1.50-2.50	0.60	0.15-0.20	2.00-4.00	0.50-1.50	-	24-26
	S32101	1.4162	0.04	21.0-22.0	1.35-1.70	0.10-0.80	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
	S32304	1.4362	0.03	21.5-24.5	3.00-5.50	0.05-0.60	0.05-0.20	2.50	0.05-0.60	-	25-28
	S82011		0.03	20.5-23.5	1.00-2.00	0.10-1.00	0.15-0.27	2.00-3.00	0.50	-	25-27
		1.4655	0.03	22.0-24.0	3.50-5.50	0.10-0.60	0.05-0.20	2.00	1.00-3.00	-	25-27
		1.4669	0.045	21.5-24.0	1.00-3.00	0.50	0.12-0.20	1.00-3.00	1.60-3.00	-	25-27
	S81921		0.03	19.0-22.0	2.00-4.00	1.00-2.00	0.14-0.20	2.00-4.00	-	-	27-28
	S82031	1.4637	0.05	19.0-22.0	2.00-4.00	0.60-1.40	0.14-0.25	2.50	1.00	-	27-28
	S82121		0.035	21.0-23.0	2.00-4.00	0.30-1.30	0.15-0.25	1.00-2.50	0.20-1.20	-	27-28
	S31500	1.4424	0.03	18.0-19.0	4.30-5.20	2.50-3.00	0.05-0.10	-	-	-	28-29
	S32404		0.04	20.5-22.5	5.50-8.50	2.00-3.00	0.20	2.00	1.00-2.00	-	29-30
	S32900	1.4460	0.08	23.0-28.0	2.50-5.00	1.00-2.00	-	1.00	-	-	30-31
	S32003		0.03	19.5-22.5	3.00-4.00	1.50-2.00	0.14-0.20	2.00	-	-	30-31
	S82441	1.4662	0.03	23.0-25.0	3.00-4.50	1.00-2.00	0.20-0.30	2.50-4.00	0.10-0.80	-	33-34
Standard Duplex	S31803	1.4462	0.03	21.0-23.0	4.50-6.50	2.50-3.50	0.08-0.20	2.00	-	-	33-35
	S32205	1.4462	0.03	22.0-23.0	4.50-6.50	3.00-3.50	0.14-0.20	2.00	-	-	35-36
	S32950		0.03	26.0-29.0	3.50-5.20	1.00-2.50	0.15-0.35	2.00	-	-	36-38
	S32808		0.03	27.0-27.9	7.00-8.20	0.80-1.20	0.30-0.40	1.10	-	2.10-2.50	36-38
Super Duplex	S32506	-	0.03	24.0-26.0	5.50-7.20	3.00-3.50	0.08-0.20	1.00	-	0.05-0.30	40-42
	S32520	1.4507	0.03	24.0-26.0	5.50-8.00	3.00-4.00	0.20-0.35	1.50	0.50-2.00	-	40-43
	S32550	1.4507	0.04	24.0-27.0	4.40-6.50	2.90-3.90	0.10-0.25	1.50	1.50-2.50	-	38-41
	S32750	1.4410	0.03	24.0-26.0	6.00-8.00	3.00-5.00	0.24-0.32	1.20	0.50	-	40-43
	S32760	1.4501	0.03	24.0-26.0	6.00-8.00	3.00-4.00	0.20-0.30	1.00	0.50-1.00	0.50-1.00	40-43
	S32906	1.4477	0.03	28.0-30.0	5.80-7.50	1.50-2.60	0.30-0.40	0.80-1.50	0.80	-	41-43
	S39274	-	0.03	24.0-26.0	6.80-8.00	2.50-3.50	0.24-0.32	1.00	0.20-0.80	1.50-2.00	40-42
	S39277	-	0.025	24.0-26.0	6.50-8.00	3.00-4.00	0.23-0.33	0.80	1.20-2.00	0.80-1.20	40-42
Hyper Duplex	S32707	-	0.03	26.0-29.0	5.50-9.50	4.00-5.00	0.30-0.50	1.50	1.00	-	49-50
	S33207	-	0.03	29.0-33.0	6.00-9.00	3.00-5.00	0.40-0.60	1.50	1.00	-	52-53

Appendix 3 Equivalence between Duplex stainless steel grades listed in the international standard ISO 15510:2010

4460-312-00-I	X3CrNiMoN27-5-2	1.4460	S31200			S22553
4480-312-60-J	X2CrNiMoN25-7-3	1.4481	S31260		SUS329J4L	S22583
4424-315-00-I	X2CrNiMoSiMnN19-5-3-2-2	1.4424	S31500			
4462-318-03-I	X2CrNiMoN22-5-3	1.4462	S32205, S31803	F51, F60	SUS329J3L	S22053
4162-321-01-E	X2CrMnNiN21-5.1	1.4162	S32101			
4062-322-02-U	X2CrNiN22-2	1.4062	S32202			
4362-323-04-I	X2CrNiN23-4	1.4362	S32304			S23043
4507-325-50-X	X3CrNiMoCuN26-6-3-2	1.4507	S32550			S25554
4507325-20-I	X2CrNiMoCuN25-6-3	1.4507	S32520			
4501-327-60-I	X2CrNiMoCuWN25-7-4	1.4501	S32760			S27603
4410-327-50-E	X2CrNiMoN25-7-4	1.4410	S32750			S25073
4658-327-07-U	X2CrNiMoCoN28-8-5-1	1.4658	S32707			
4477-329-06-E	X2CrNiMoN29-7-2	1.4477	S32906			
4480-329-00-U	X6CrNiMo26-4-2	1.4480	S32900	329	SUS329J1	
4485-332-07-U	X2CrNiMoN31-8-4	1.4485	S33207			

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Appendix 4 Comparative Stress corrosion cracking resistance of unwelded duplex and austenitic stainless steels in accelerated laboratory tests (Ref 2.1)

Grade	Type 304L Type 316L	3RE60	S32101 S32202	2205	Super duplex	Hyper duplex
42% $MgCl_2$, boiling, 154°C, U-bend	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated
35% $MgCl_2$, boiling, 125°C, U-bend	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated
Drop evap., 0.1M NaCl, 120°C, 0.9 x Y.S.	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Insufficient data
Wick test 1500 ppm Cl as NaCl 100°C	Cracking anticipated	Cracking possible	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Insufficient data
33% $LiCl_2$, boiling, 120°C, U-bend	Cracking anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Insufficient data
40% CaCl2, 100°C, 0.9 x Y.S.	Cracking anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated
25-28% NaCl, boiling, 106°C, U-bend	Cracking anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated	Cracking not anticipated
26% NaCl, autoclave, 155°C, U-bend	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking possible	Cracking not anticipated	Insufficient data
26% NaCl, autoclave, 200°C, U-bend	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Insufficient data	Insufficient data
600 ppm Cl (NaCl) autoclave, 300°C, U-bend	Cracking anticipated	Insufficient data	Insufficient data	Insufficient data	Insufficient data	Cracking not anticipated
100 ppm Cl (sea salt + O_2), autoclave, 230°C, U-bend	Cracking anticipated	Cracking anticipated	Cracking anticipated	Cracking anticipated	Insufficient data	Insufficient data

Cracking anticipated · Cracking possible · Cracking not anticipated · Insufficient data

Appendix 5 Physical properties

from EN 10088-1:2014-12 standard

Steel designation		Density	Modulus of elasticity at				Mean coefficient of thermal expansion between 20° and			Thermal conductivity at 20°C	Specific thermal capacity at 20°C	Electrical resistivity at 20°C	Magnetisable
Name	Number	kg/dm^3	20°C	100°C	200°C	300°C	100°C	200°C	300°C	$\frac{W}{m . K}$	$\frac{J}{kg . K}$	$\frac{\Omega . mm^2}{m}$	
			GPa				10^{-6} x K^{-1}						
X2CrNiN22-2	1.4062	7.8	200	194	186	180	13.0	13.5	14.0	15	480	0.68	
X2CrCuNiN23-2-2	1.4669	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrNiMoSi18-5-3	1.4424	7.8	200	194	186	180	13.0	13.5	14.0	13	475	0.8	
X2CrNiN23-4	1.4362	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrMnNiN21-5-1	1.4162	7.7	205	200	190	180	13.0	14.0	14.5	15	500	0.75	
X2CrMnNiMoN21-5-3	1.4482	7.8	200	194	186	180	13.0	13.5	15.0	13	500	0.8	
X2CrNiMoN22-5-3	1.4462	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrNiMnMoCuN24-4-3-2	1.4662	7.7	205	200	190	180	13.0	13.5	14.0	15	500	0.8	yes
X2CrNiMoCuN25-6-3	1.4507	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X3CrNiMoN27-5-2	1.4460	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrNiMoN25-7-4	1.4410	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrNiMoCuWN25-7-4	1.4501	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	
X2CrNiMoN29-7-2	1.4477	7.7	200	194	186	180	11.5	12.0	12.5	13	470	0.8	
X2CrNiMoCoN28-8-5-1	1.4658	7.8	197	189	178	168	12.5	-	13.5	12	470	0.8	
unusual austenitic-ferritic corrosion resistant steels													
X2CrNiCuN23-4	1.4655	7.8	200	194	186	180	13.0	13.5	14.0	15	500	0.8	yes

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Appendix 6 Mechanical Properties, Long Products

EN 10088-3:2014 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

Steel designation		Thickness t or diameter d	Hardness	0.2% proof strength	Tensile strength	Elongation after fracture	Impact energy (ISO-V)	Resistance to intergranular corrosion	
Name	Number	mm	HBW max.	Mpa min.	R_m [d] MPa	% min. (long.)	KV_J min (long.)	in the delivery condition	in the sensitised condition
Standard grades									
X2CrNiN23-4	1.4362	≤160	260	400	600 to 830	25	100	yes	yes
X2CrNiMoN22-5-3	1.4462	≤160	270	450	650 to 880	25	100	yes	yes
X3CrNiMoN27-5-2	1.4460	≤160	260	450	620 to 880	20	85	yes	yes
Special grades									
X2CrNiN22-2	1.4062	≤160	290	380	650 to 900	30	40	yes	yes
X2CrCuNiN23-2-2	1.4669	≤160	300	400	650 to 900	25	100	yes	yes
X2CrNiMoSi18-5-3	1.4424	≤50	260	450	700 to 900	25	100	yes	yes
		50 < t ≤ 160	260	400	680 to 900	25	100	yes	yes
X2CrMnNiN21-5-1	1.4162	≤160	290	400	650 to 900	25	60	yes	yes
X2CrMnNiMoN21-5-3	1.4482	≤160	-	400	650 to 900	25	60	yes	yes
X2CrNiMnMoCuN24-4-3-2	1.4662	≤160	290	450	650 to 900	25	60	yes	yes
X2CrNiMoCuN25-6-3	1.4507	≤160	270	500	700 to 900	25	100	yes	yes
X2CrNiMoN25-7-4	1.4410	≤160	290	530	730 to 930	25	100	yes	yes
X2CrNiMoCuWN25-7-4	1.4501	≤160	290	530	730 to 930	25	100	yes	yes
X2CrNiMoN29-7-2	1.4477	≤10	310	650	800 to 1050	25	100	yes	yes
		10 < t ≤160	310	550	750 to 1000	25	100	yes	yes

Mechanical Properties, Flat Products - EN 10088-2:2014 Stainless Steels - Part 2: Technical Delivery Conditions For Sheet/Plate And Strip Of Corrosion Resisting Steels For General Purposes

Steel designation		Product form	Thickness	0.2% proof strength	Tensile strength	Elongation		Impact energy (ISO V) KV_2 >10 mm thick - J min		Resistance to intergranular corrosion	
Name	Number		mm max.	$R_{p0.2}$ Mpa min. (long)	R_m Mpa	A_{80} <3 mm thick % min. long.+transv.	A ≥ 3 mm thick % min. long.+transv.	long.	transv.	in the delivery condition	in the sensitised condition
Standard grades											
X2CrNiN23-4	1.4362	C	8	450	650 to 850	20	20	-	-	yes	yes
		H	13.5	400				100	60		
		P	75	400	630 to 800	25	25				
X2CrNiMoN22-5-3	1.4462	C	8	500	700 to 950	20	20	-	-	yes	yes
		H	13.5	460		25	25	100	60		
		P	75	460	640 to 840	25	25				
Special grades											
X2CrNiN22-2	1.4062	C	6.4	530	700 to 900	20	20	-	-	yes	yes
		H	10	480	680 to 900	30	30	80	80		
		P	75	450	650 to 850	30	30	80	60		
X2CrNiMoSi18-5-3	1.4424	C	8	450	700 to 900	25	25	100	60	yes	yes
		H	13.5								
		P	75	400	680 to 900						
X2CrNiCuN23-4	1.4655	C	8	420	600 to 850	20	20	-	-	yes	yes
		H	13.5	400				100	60		
		P	75	400	630 to 800	25	25				
X2CrMnNiN21-5-1	1.4162	C	6.4	530	700 to 900	20	30	-	-	yes	yes
		H	10	480	680 to 900	30	30	80	80		
		P	75	450	650 to 850	30	30	60	60		
X2CrMnNiMoN21-5-3	1.4482	C	6.4	500	700 to 900	20	30	-	-	yes	yes
		H	10	480	660 to 900	30	30	100	60		
		P	75	450	650 to 850	30	30	100	60		
X2CrNiMnMoCuN24-4-3-2	1.4662	C	6.4	550	750 to 900	20	25	-	-	yes	yes
		H	13	550	750 to 900	-	25	80	80		
		P	75	480	680 to 900	-	25	60	60		
X2CrNiMoCuN25-6-3	1.4507	C	8	550	750 to 1000	20	20	-	-	yes	yes
		H	13.5	530				100	60		
		P	75	530	730 to 930	25	25				
X2CrNiMoN25-7-4	1.4410	C	8	550	750 to 1000	20	20	-	-	yes	yes
		H	13.5	530				100	60		
		P	75	530	730 to 930	20	20				
X2CrNiMoCuWN25-7-4	1.4501	P	75	530	730 to 930	25	25	100	60	yes	yes
X2CrNiMoN29-7-2	1.4477	C	8	650	800 to 1050	20	20	-	-	yes	yes
		H	13.5	550	750 to 1000	20	20	100	60		
		P	75	550							

C: cold rolled steel; H: hot rolled steel; P: plate

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The International Stainless Steel Forum (ISSF) is a not-for-profit research and development organisation which was founded in 1996 and serves as the focal point for the global stainless steel industry.

Vision

Sustain our future with stainless steels

Membership of the ISSF

ISSF has two categories of membership namely:

a. **company members** who are producers of stainless steels (integrated mills and re-rollers)

b. **affiliated members** who are national or regional stainless steels industry associations.

The ISSF now has 57 members in 26 countries. Collectively they represent approximately 90% of the total production of stainless steels.

More information

For more information about ISSF, please consult our website worldstainless.org.

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