INFORMATION & GUIDANCE NOTE

UK Water Industry

APPLICATIONS FOR STAINLESS STEEL IN THE WATER INDUSTRY

FOREWORD

This guide was prepared originally in 1999 by The Steel Construction Institute (SCI), in association with Avesta Sheffield and the Nickel Development Institute (NiDI) under the guidance of an USWIG (Users of Steel in the Water Industry Group) Stainless Steel Working Group. The Working Group included representatives from Water Companies, plant manufacturers, fabricators and the steel industry. This update has been prepared by the British Stainless Steel Association, the Nickel Institute, the Steel Construction Institute and OSTP with the approval of Water UK. Their assistance is gratefully acknowledged.

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Technical enquiries relating to grade selection, corrosion resistance, product forms, applications and availability should be directed to either the British Stainless Steel Association or the Nickel Institute. Queries regarding the structural application of stainless steel should be addressed to The Steel Construction Institute.

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1 GENERAL SCOPE AND OBJECTIVES

The use of stainless steel can provide economic benefits to the water industry both through lower initial plant costs and lower plant operating costs. Stainless steels have long been used and have a good track record of successful applications in the water treatment industry. Stainless steels offer excellent corrosion resistance in many media, coupled with good strength, ductility and toughness. They are easily maintained to give an attractive hygienic, ‘high tech’ appearance. Standard grades are readily available in a wide variety of product forms.

The purpose of this Information and Guidance Note is to help plant designers and operators to recognise those applications where economic benefits can be realised from selecting an appropriate grade of stainless steel. Guidance is given on material selection for corrosion resistance, design of structural members, tanks and pipework systems, fabrication and installation. The factors are described which can enable stainless steel to make a contribution to sustainability in the water industry.

Standard austenitic stainless steels are capable of meeting most of the corrosion conditions encountered in water treatment and handling equipment. For higher strength, a duplex stainless steel may be suitable. A wide range of more highly alloyed, special stainless steels is available for applications where greater corrosion resistance is needed.

2 BACKGROUND

For many years stainless steels have been used in equipment for the UK water industry for applications where a significant corrosion risk is recognised, such as in pumps, valves and chemical treatment plant.

Because the raw material costs of stainless steels, weight for weight, are significantly higher than for other established materials, originally there was a perception that they are ‘expensive’ materials, confined to specialist plant items. However, the intrinsic advantages of stainless steels have allowed them to be used to economic advantage in a wide range of potable and waste water treatment and storage plant as well as remaining the material of first choice for many applications throughout Europe and the rest of the world

Table 2-1 lists some of these proven applications.

Table 2-1 Proven applications of stainless steels in the water industry

Mechanical Systems
- Screening systems, sieves
- Grit chambers
- Aeration trenches and tanks
- Inlet and outlet constructions for sedimentation tanks
- Scraper installations
- Screening drums
- Sludge/scrapers
- Pre-treatment tanks
- Syphons and lifting devices
- Weirs and overflows
- Slide gates
- Valves and pumps
- Bolting

Sludge Treatment
- Tanks, containers for mixing, thickening, dewatering sludge and digesters for processing sludge
- Sludge circulation installations
- Filter-presses
- Stop logs, valves, stop gates

Subsoil Water Technology
- Groundwater separation casings and membranes
- Pumps
- Agitators
- Supports for pipe-systems
- Clayware pipe separators

Biological and Oxidation Systems
- Sedimentation tanks
- Inlet and outlet construction
- Aeration installations
- Ozone treatment
- Sludge separator installations
- Anaerobic waste water treatment
- Disinfection – UV systems
- Tank covers

Pipe Systems
- Sewage water transportation
- Potable water mains and distribution systems
- Sludge transportation
- Gas transportation
- Desalination equipment
- Commercial/residential building pipework for low temperature hot water, chilled water, boosted cold water and condensers

Hardware and Miscellaneous
- Linings for concrete tanks
- Manholes and covers
- Shaft covers
- Climbing rungs
- Ladders
- Railing and platforms
- Fire doors, safety doors, pressure doors
- Wellheads
- Ventilation stacks

Table 2-2 summarises reasons for their adoption. Stainless steels are effectively inert under most of the conditions met in water handling and treatment - providing the correct grade is selected and simple design and fabrication rules are followed. They also have excellent mechanical properties offering a good combination of strength, ductility, ease of fabrication and toughness. These attributes result in the following advantages:

- There is no dependence upon applied coatings, (organic, polymeric, cementitious or metallic) for corrosion protection. Hence, no allowances for corrosion loss are required at the design stage, no constituents of the coatings are lost into the water and there is no coating maintenance.

- Their high strength and ductility mean that the weight of a component can be reduced in many cases, and resistance to impact damage during operations is enhanced.

Table 2-2 Relevant attributes of stainless steel for the water industry

Characteristics	Advantages conferred
High corrosion resistance	Long service life. No downtime for repair or replacement, consistent operation No dependence on applied coatings and their maintenance Tolerates repeated disinfecting Does not change with time
No corrosion or leached products, no organoleptic or turbidity problems	Clear and pure drinking water
Smooth surface	Less bacterial slime, low energy consumption, low cleaning costs, good for conveying wet solids
100% recyclable (and usually contains 80 – 90% recycled content. Dismountable and reusable.	Cost benefits and low environmental impact. A sustainable material.
Good ductility and weldability	Compatible with system construction
Low weight (for tubular components)	Simple construction and erection
Good mechanical properties	High material utilization factor. Potential for lightweight structures. Less fabrication consumables and energy usage. Properties do not change with time.
Good wear and fatigue resistance	Low maintenance, long life (even in installations subject to cyclic vibrations)
Materials covered by well-defined European standard specifications	Ready availability in most product forms
Attractive appearance	Clean, hygienic, 'high tech' image
Far easier to flush/clean pipework after installation	Greatly reduced delays in commissioning plant/services compared with more traditional materials, giving savings in initial cost

Corrosion and wear-resistant features are particularly important for mechanical systems, constructional hardware and sludge treatment plant. The low weight, high strength and flow-promoting properties are useful for pipework systems. Lack of toxicity of surfaces is essential for biological treatment plant and the supply of potable water.

In many cases, the life cycle cost of a plant item can be reduced by using stainless steels, arising from a combination of installation, reduced maintenance and extended life benefits.

This Information and Guidance Note aims to help plant designers and operators to recognise those applications where they can realise economic benefits from selecting stainless steel and to specify, design and fabricate stainless steel components correctly.

Originally published in 1999, this IGN has been revised to reflect updating of standards and recent operating experience.

3 INTRODUCTION TO STAINLESS STEELS

Stainless steels are alloys of iron containing a minimum of 10.5% chromium and usually at least 50% iron. With chromium contents above 10.5%, exposure to air or water results in the spontaneous formation of a thin, stable, chromium-rich oxide film. This film provides a high degree of protection and if damaged by abrasion, the film reforms rapidly. This mechanism of protection by a “passive film” also occurs with other metals, notably aluminium and titanium.

The stability of the oxide film and the resistance of the underlying metal to dissolution are both influenced by alloying additions, which in turn also control the mechanical and physical properties of the steels. The controlled addition of alloying elements results in a wide range of grades, each offering specific attributes in respect of strength and ability to resist certain chemical environments. Examples from within the major families of stainless steels, their compositions and attributes are shown in Table 3-1. The EN grade designations given in the table are explained in more detail in 4.1. The popular name originates from the (now superseded) British Standards and AISI systems.

Just as there is a range of structural and engineering carbon steels meeting different requirements of strength, weldability and toughness, so there is a range of stainless steels with progressively higher levels of corrosion resistance and strength. To achieve the optimum economic benefit from using stainless steel, it is important to select a grade of steel which is adequate for the application without being unnecessarily highly alloyed and costly.

The simplest stainless steels are based on 10.5% – 13% chromium additions, and although they have the lowest corrosion resistance within the family of stainless steels, they offer significant advantages over the conventional painted or galvanised carbon steels. The ***FERRITIC*** grades shown in Table 3-1 are generally restricted to use in sections below about 3 mm thickness because they have limited toughness when welded. Grade 1.4003 is compositionally balanced to give improved properties in the welded condition compared with the standard ferritic grades. It can be therefore be used at much greater thicknesses up to 50 mm.

The most widely used types of stainless steel are based on 17 – 18% chromium and 8 – 11% nickel additions. This combination of alloying elements results in a modification of the crystal structure of iron, compared with that of standard structural carbon steels. As a result, these ***AUSTENITIC*** stainless steels have, in addition to their corrosion resistance, different yielding and forming characteristics, together with significantly better toughness over a wide range of temperatures, compared with standard structural grades. Their corrosion performance can be further enhanced by additions of molybdenum.

The austenitic stainless steel grades in Table 3-1 are capable of meeting most of the corrosion conditions encountered in water treatment and handling equipment. The most widely used grades, commonly referred to as the standard austenitic grades, are the ‘304’ and ‘316’ types. The designation ‘L’ denotes lower carbon versions of the near-identical standard specifications. The grades 1.4301 (304) and 1.4401 or 1.4436 (316), were formerly made with significantly higher carbon levels than those shown in Table 3-1, with implications for corrosion behaviour[1]. Either the ‘L’ grade, or a stabilised steel such as 1.4541 (321), would have been used where there was concern about corrosion performance in the as-welded condition.

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[1] Carbon present in the steel reacts with chromium and precipitates chromium carbides on grain boundaries under certain thermal cycles, *e.g.* in weld heat affected zones (HAZ). The local loss of chromium from the boundary region into the carbide particles allows preferential, intercrystalline corrosion attack and the steel is said to be ‘sensitised’, or suffer from ‘weld decay’. To overcome this requires either a low carbon alloy, which reduces significantly the amount of the chromium combined as chromium carbides, or the use of ‘stabilised’ steels. These contain an addition of a strong carbide-forming agent such as titanium, which reacts preferentially with carbon and prevents formation of chromium carbides.

The presence of weld heat tint is more likely to be a cause of corrosion attack in the welded condition than any effect of the carbon content slightly exceeding that of the ‘L’ grades. However, the ‘L’ grades remain the preferred choice for optimum corrosion performance after welding. Today, commonly available 304 and 316 types are commercialized as "dual certified" 304/304L - 316/316L grades, except when a high carbon content is specifically sought after (the "H" grades from ASTM) in view of high temperature service. Also, stabilised stainless steels are primarily used in Germany and surrounding markets and for elevated temperature applications.

For simplicity, reference is made later in this IGN to the ‘304’ or ‘316’ types of stainless steel without quoting directly an EN designation. This means that the results quoted were obtained on steel grades containing about 18% chromium, 8% nickel, or 17% chromium, 10% nickel, 2% molybdenum. However, the terms ‘304’ or ‘316’ must not be used as steel specifications, unless quoted fully against a relevant national standard to define a specific steel. The presence of ‘316’ steel types with two levels of molybdenum in Table 3-1 illustrates the drawback of using this short notation.

Localised attack by chlorides, resulting from penetration of the passive oxide film by pitting or crevice corrosion, is an important consideration in most applications of stainless steels in aggressive environments. The influence of chemical composition on corrosion resistance can be shown numerically by means of the ‘Pitting Resistance Equivalent Number’ or ‘PREN’, which sums the effects of the alloying elements chromium, molybdenum, nitrogen and tungsten. The higher this number, the better the localized corrosion resistance, in principle. The ‘PREN’, which indicates the maximum obtainable pitting resistance of an alloy in the initial, correctly solution annealed condition, allows different steel compositions to be compared. It is defined more fully in Appendix A, which also describes briefly the nature of pitting and crevice corrosion.

More corrosion resistant, ***HIGHER ALLOY AUSTENITIC*** stainless steels, the *“**SUPER-AUSTENITIC**”* grades, are available, *e.g.* grade 1.4547 in Table 3-1. These materials may be required selectively to meet specific corrosion conditions encountered in chemicals handling and the treatment of certain industrial process and waste waters.

The ***DUPLEX*** (ferritic-austenitic) steels, typified by 1.4362 (2304) and 1.4462 (2205), offer the combination of relatively high strength and good corrosion performance. The 1.4362 (2304) grade has a resistance to pitting and crevice corrosion in water environments similar to that of 1.4401 (316). These grades have very good resistance to the form of corrosion known as chloride stress corrosion cracking (see section 5.3.5), compared with the standard austenitic grades. The 25% Cr duplex steels, sometimes known as “*SUPERDUPLEX*” are comparable to the *HIGHER ALLOY AUSTENITIC* grades in pitting and crevice corrosion resistance. Therefore, they can be used for the same special applications.

The high strength ***MARTENSITIC AND PRECIPITATION HARDENING*** steel shown in Table 3-1 illustrates the type of materials which offer a combination of high strength and good corrosion performance. They are likely to be encountered as highly loaded components such as pump shafts, valve spindles and special fasteners. Other martensitic steels with lower chromium content are also available: generally these have higher carbon contents and poorer corrosion resistance.

Table 3-1 Main alloying elements in selected grades of stainless steels in EN 10088-1

(The austenitic and duplex grades are those most likely to be encountered in the water industry)

Family	EN 10088 designation	Popular /Other name(1)	Content of alloying element (maximum or range permitted) weight %							Attributes
			C	Cr	Ni	Mo	Cu	N	Others	
Ferritic	1.4512	409	0.03	10.5–12.5	—	—	—	—	Ti(2)	Lower corrosion resistance than 1.4301 (304) and with more restricted fabrication properties. Grades 1.4512 (409) and 1.4016 (430) are welded only in sections thinner than 3 mm. Grade 1.4003 has better weldability and is suited to applications involving abrasion and wear.
	1.4003		0.03	10.5–12.5	0.3–1.0	—	—	0.030	—	
	1.4016	430	0.08	16.0–18.0	—	—	—	—	—	
Austenitic	1.4307	304L	0.03	17.5–19.5	8.0–10.5	—	—	0.10	—	This family of stainless steels meet most of the requirements in the water industries. Good combination of corrosion resistance, forming and fabrication properties; generally readily available. The principal difference between the standard and lower carbon 'L' grades is that the latter have greater resistance to sensitisation (reduction in corrosion resistance) in weld heat affected zones. The pitting and crevice corrosion resistance increases as the molybdenum content is raised from 1.4301, through 1.4401 to 1.4436 (304, through 316 to 316 high Mo)
	1.4301	304	0.07	17.0–19.5	8.0–10.5	—	—	0.10	—	
	1.4404	316L	0.03	16.5–18.5	10.0–13.0	2.0–2.5	—	0.10	—	
	1.4401	316	0.07	16.5–18.5	10.0–13.0	2.0–2.5	—	0.10	—	
	1.4432	316L	0.03	16.5–18.5	10.5–13.0	2.5–3.0	—	0.10	—	
	1.4436	316	0.05	16.5–18.5	10.5–13.0	2.5–3.0	—	0.10	—	
	1.4541	321	0.08	17.0–19.0	9.0–12.0	—	—	—	Ti(2)	
	1.4571	316Ti	0.08	16.5–18.5	10.5–13.5	2.0–2.5	—	—	Ti(2)	
Higher alloy austenitic	1.4539	904L	0.02	19.0–21.0	24.0–26.0	4.0–5.0	1.2-2.0	0.15	—	Often referred to as super-austenitic grades or 6%Mo-grades, they exhibit better corrosion resistance than simpler austenitic grades. Pitting and crevice corrosion resistance improves with increasing molybdenum and nitrogen content. 1.4547 and 1.4529 were specifically developed for use in saline conditions.
	1.4547	S31254	0.02	19.5–20.5	17.5–18.5	6.0–7.0	0.5-1.0	0.18–0.25	—	
	1.4529	N08926	0.02	19.0–21.0	24.0-26.0	6.0–7.0	0.5-1.5	0.15–0.25	—	
Lean Duplex	1.4482	S32001	0.030	19.5-21.5	1.5-3.5	0.10-0.60	—	0.05-0.20	Mn	High strength. Pitting and crevice corrosion resistance between that of 1.4301 (304) and 1.4401 (316). Good stress corrosion cracking resistance.
	1.4062	S32202	0.030	21.5-24.0	1.0-2.9	0.45	—	0.16-0.28		
	1.4162	S32101	0.040	21.0-22.0	1.35-1.90	0.10-0.80		0.20-0.25	Mn	
	1.4362	2304	0.03	22.0–24.0	3.5–5.5	0.10–0.60	0.10–0.60	0.5–0.20	—	High strength and wear resistance with very good resistance to stress corrosion cracking. 1.4462 (2205) has better corrosion resistance than 1.4362 (2304).
Standard Duplex	1.4462	2205	0.03	21.0–23.0	4.5–6.5	2.5–3.5	—	0.10–0.22	—	
Superduplex	1.4410	S32750	0.030	24.0-26.0	6.0-8.0	3.0-4.5		0.24-0.35		Comparable to the 6% Mo grades for pitting and crevice corrosion resistance and stress corrosion cracking resistance. Higher strength than lower alloy duplex grades
	1.4501	S32760	0.030	24.0-26.0	6.0-8.0	3.0-4.0	0.50-1.00	0.20-0.30	W	
	1.4507	S32550	0.030	24.0-26.0	6.0-8.0	3.0-4.0	1.00-2.50	0.20-0.30		
High strength martensitic & precipitation hardening (PH)	1.4418	248SV	0.06	15.0–17.0	4.0–6.0	0.8–1.5	—	0.020 minimum	—	Heat treatable higher strength stainless steels, Used for specific items of plant mechanisms where a combination of the corrosion resistance of a standard stainless steel and the strength of a conventional heat treated engineering steel is required.
	1.4542	17-4 PH	0.07	15.0–17.0	3.0–5.0	0.60	3.0–5.0	—	Nb	

Notes

(1) The popular name originates from the (now superseded) British Standards and AISI systems. Duplex grades are often referred to by their UNS Numbers

(2) Titanium and/or niobium are added to stabilise carbon and improve corrosion performance in the heat affected zones of welds. However, except for Germany and surrounding markets, the use of titanium stabilised austenitic steels has been superseded largely by the ready availability of the low carbon, or 'L' grades, in the table.

The standard austenitic stainless steels are readily welded. The duplex and higher alloy austenitic steels require care in the selection of welding consumables and good welding practice to realise their full corrosion resistance, see Section 7.

For further information, the *ASM Speciality Handbook on Stainless Steels* (1) may be consulted. This gives a comprehensive description of the metallurgy of stainless steels and describes in detail aspects such as forming, corrosion, fabrication and machining. Further useful texts are given in the Further Reading, Section 10.

Stainless steels are available in the following forms:

- Plate, sheet, strip (‘flat products’)
- Pipe, tube and fittings (welded and seamless)
- Flanges
- Bar, rod, wire and special wire sections (‘long products’)
- Cold formed structural sections (*e.g.* channels, angles, square and rectangular sections)
- Hot rolled sections (*e.g.* equal and unequal angles)
- Castings
- Fasteners, fixings and fittings.

Hot rolled sections are available, but generally structural sections are fabricated by either welding together cold formed plate, sheet and strip or by roll or press brake forming.

Appendix B lists some national, European and international standards relating to many of these product forms.

SUMMARY OF SECTION 3

Stainless steels derive their corrosion resistance from a thin, stable, protective surface oxide film which forms spontaneously in the presence of air or water. If the film is damaged by abrasion, it reforms rapidly.

Many grades of stainless steel are available, each with different mechanical, physical and corrosion properties. Generally, corrosion resistance improves with increased content of chromium, molybdenum, nickel and nitrogen. For optimum economic benefit, it is important to choose a grade with adequate properties without incurring unnecessary cost.

Austenitic stainless steels are the most widely used grades of stainless steel and are capable of meeting most of the corrosion conditions encountered in water treatment and handling equipment.

Duplex stainless steels are stronger, and have better resistance to stress corrosion cracking, than the standard austenitic stainless steels.

Stainless steels are available in a wide variety of product forms.

4 GRADES, PROPERTIES AND PRODUCT FORMS

4.1 Specifications and designation systems

Most product forms in stainless steel have a European Norm (EN). Those for flat products (sheet, strip, plate), long products (bar, rod and wire) and tubular products are summarised below.

4.1.1 Flat and Long Products

The material standard for these products is EN 10088, it comprises five parts:

- Part 1 *List of stainless steels.* This sets out the chemical compositions of particular grades of stainless steel and reference data on physical properties such as density, modulus of elasticity and thermal conductivity.
- Part 2, *Technical delivery conditions for sheet, plate and strip for general purposes*. This sets out the chemical compositions, surface finishes and mechanical properties such as proof strength for the materials used in flat products. It also provides references to the appropriate standards for dimensional tolerances, mechanical test methods and methods of non-destructive testing.
- Part 3, *Technical delivery conditions for semi-finished products, bars, rods and sections for general purposes*. This sets out the chemical compositions, surface finishes and mechanical properties such as proof strength for the materials used in long products. It also provides references to the appropriate standards for dimensional tolerances, mechanical test methods and methods of non-destructive testing.

Parts 4 and 5 cover the compliance of stainless steel flat and long products with the Construction Products Regulation. Broadly, these standards correspond to parts 2 and 3 respectively but with an Appendix ZA which covers CE Marked products. CE marking continues for products placed on the EU market, which includes the Republic of Ireland. However, now that the UK has left the EU, a new system of UK Conformity Assessed marking (UKCA marking) has been introduced. Further information on UKCA marking for steel construction is available from the BCSA (2).

Where an application demands conformance to the Pressure Equipment Directive (PED), the relevant standards for flat and long products are EN 10028-7 and EN 10272 respectively.

4.1.2 Tubular Products

There are a number of standards for tubes and fittings:

- EN 10296-2 Welded circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions - Stainless steel. This sets out the chemical compositions, mechanical properties, weld quality, inspection methods and dimensional tolerances.
- EN 10297-2 Seamless circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions - Stainless steel. This sets out the chemical compositions, mechanical properties, weld quality, inspection methods and dimensional tolerances.
- EN 10217-7 Welded steel tubes for pressure purposes. Technical delivery conditions - Stainless steel tubes This sets out the chemical compositions, mechanical properties, weld quality, inspection methods and dimensional tolerances.
- EN 10216-5 Seamless steel tubes for pressure purposes. Technical delivery conditions - Stainless steel tubes. This sets out the chemical compositions, mechanical properties, weld quality, inspection methods and dimensional tolerances.

- EN 10253-3 Butt-welding pipe fittings - Wrought austenitic and austenitic-ferritic (duplex) stainless steels without specific inspection requirements. This sets out the chemical compositions, mechanical properties, weld quality, inspection methods standard dimensions and dimensional tolerances.

- EN 10253-4 Butt-welding pipe fittings - Wrought austenitic and austenitic-ferritic (duplex) stainless steels with specific inspection requirements Similar to EN 10253-3 but with detailed guidance on calculating pressure factors

- EN 10312 Welded stainless steel tubes for the conveyance of aqueous liquids including water for human consumption. Technical delivery conditions.

4.1.3 Grade designations in the EN system

The designation systems adopted in the European standard use the **European material number** and a **material name.**

For example, grade 304L has a material number 1.4307, where:

1.	**43**	**07**
Denotes steel	Denotes one group of stainless steels	Individual grade identification

The material name system provides some understanding of the steel composition. The name of material number 1.4307 is X2CrNi18-9, where

X	**2**	**CrNi**	**18-9**
Denotes high alloy steel	100 × % of carbon	Chemical symbols of main alloying elements	% of main alloying elements

Each stainless steel material name has a unique corresponding material number. Note that whilst the German DIN designations are similar, those in the new EN standards are not fully compatible and the latter should be used.

In this IGN, the designation system adopted where appropriate is the European material number, followed in brackets by a ‘popular name’, *e.g*. 1.4307 (304L). This popular name originates from the (now superseded) British Standards and AISI system and is included here to help those familiar with the older naming convention.

Appendix B lists national, European and international standards covering other stainless steel product forms, *e.g*. castings, fasteners, piping, wire *etc*.

4.2 Mechanical properties

4.2.1 Strength and elongation

The mechanical properties of some widely used grades of stainless steel sheet, plate and strip are given in Table 4-1.

Stainless steel ‘yield’ strengths are generally quoted in terms of a proof strength defined for a particular offset permanent strain, conventionally the 0.2% strain. EN 10088 quotes 0.2% proof strengths of around 220 MPa for the standard grades of austenitic stainless steel. This strength relates to material in the annealed (softened) condition. In practice, these values will be exceeded if the material is cold worked. There is provision within EN 10088 for supply of certain steels, including austenitic steels 1.4301 (304) and 1.4401 (316), as cold rolled strip with 0.2% proof strengths up to four times those of the annealed material.

Duplex grades offer a minimum strength of 400 MPa for the lean duplex type and 530 MPa for the superduplex grades.

The martensitic and precipitation hardening grades shown in Table 3-1 can be heat treated to a range of 0.2% proof strength levels between 650 and 1150 MPa. Guidance should be sought from the steel supplier when using these higher strength materials.

Note that the minimum mechanical properties in Table 4-1 correspond to EN 10088-2 and refer to the transverse direction (i.e. perpendicular to the rolling direction). Other standards, such as ASTM A240, for stainless steel plate, sheet, and strip, specify longitudinal properties. The respective property ranges can be different for a number of reasons. One is that ASTM A240 is an older specification compared to EN 10088-2. Another is that the difference between transverse and longitudinal is affected by thermomechanical processing. Stockholders who mostly supply the oil and gas industry usually quote properties to ASTM, while the water industry tends to use EN standards. The two are not exclusive and material with properties to one standard will usually meet the requirements of the other.

The design implications of the stress-strain characteristics of stainless steels are discussed in Section 6.1.

4.2.2 Fatigue

Fatigue resistance is important in plant items such as aeration pipework. Stainless steels are markedly superior to plastics in this respect. Fatigue testing of a range of details in both austenitic and duplex stainless steel have demonstrated that the performance of stainless steel is equivalent to that of carbon steel and hence the Eurocode (3) covering the design of structural stainless steel refers to fatigue rules for carbon steel.

As with carbon steels, modification of the surface stress state by shot or roller peening can result in a significant improvement in the fatigue performance of stainless steels. (Such a treatment can also be beneficial in resisting stress corrosion in the austenitic steels.)

Table 4-1 Minimum specified mechanical properties to EN 10088-2

Steel number (popular name)	Product form[1]	Maximum thickness (mm)	Minimum 0.2% proof strength[2] (mm)	Minimum 1.0% proof strength[2] (mm)	Tensile strength (MPa)	Minimum elongation after fracture %	
						t < 3 mm	t ≥ 3 mm
Ferritic							
1.4512 (409)	C	8	210		380 – 560	25	
	H	13.5					
1.4003	C	8	280		450 – 650	20	
	H	13.5					
	P	25[3]	250			18	
1.4016 (430)	C	8	260		430 – 600	20	
	H	13.5	240			18	
	P	25[3]			430 – 630	20	
Austenitic							
1.4307 (304L)	C	8	220	250	520 – 700	45	
	H	13.5	200	240			
	P	75			500 – 700		
1.4301 (304)	C	8	230	260	540 – 750	45[4]	
	H	13.5	210	250	520 – 720		
	P	75				45	

Steel number (popular name)	Product form[1]	Maximum thickness (mm)	Minimum 0.2% proof strength[2] (mm)	Minimum 1.0% proof strength[2] (mm)	Tensile strength (MPa)	Minimum elongation after fracture %	
						t < 3 mm	t ≥ 3 mm
1.4404 (316L)	C	8	240	270	530 – 680	40	
	H	13.5	220	260			
	P	75			520 – 670	45	
1.4401 (316)	C	8	240	270	530 – 680	40	
	H	13.5	220	260			
	P	75			520 – 670	45	
1.4432 (316)	C	8	240	270	550 – 700	40	
	H	13.5	220	260			
	P	75			520 – 670	45	
Lean Duplex							
1.4482	C	6.4	500		700-900	20	30
	H	10	480		680-900	30	
	P	75	450		650-850	30	
1.4062	C	6.4	530		700-900	20	
	H	10	480		680-900	30	
	P	75	450		650-850	30	
1.4162	C	6.4	530		700-900	20	30
	H	10	480		680-900	30	
	P	75	450		650-850	30	
1.4362 (2304)	C	8	450		650 – 850	20	
	H	13.5	400				
	P	75			630 – 800	25	
Standard Duplex							
1.4462 (2205)	C	8	500		700 – 950	20	
	H	13.5	460			25	
	P	75			640 – 840	25	
Superduplex							
1.4410	C	8	550		750-1000	20	
	H	13.5	530		750-1000	20	
	P	75	530		730-930	20	
1.4507	C	8	550		750-1000	20	
	H	13.5	530		750-1000	20	
	P	75	530		730-930	25	
1.4501	P	75	530		730-930	25	

Notes:
(1) C = cold rolled strip, H = hot rolled strip, P = hot rolled plate
(2) transverse properties
(3) for thickness above 25 mm the mechanical properties can be agreed
(4) for stretcher levelled material, the minimum value is 5% lower

4.3 Physical properties

Table 4-2 gives some physical properties at room temperature, as quoted in EN 10088-1.

Compared with carbon steels, austenitic stainless steels have 30-50% greater thermal expansion and 30% lower thermal conductivity. Those differences are readily accommodated by appropriate welding practice (see Section 7) and by allowance for more expansion in long or restrained pipe runs.

Austenitic stainless steels are essentially non-magnetic whereas duplex, ferritic and martensitic grades are magnetic. Cold working of austenitic grades can lead to the formation of the magnetic martensitic phase, for the grades listed in the table below. If necessary, this effect can be reversed by re-solution annealing, where practical. There is a common perception that magnetic stainless steels grades are of lower corrosion resistance than non-magnetic grades. This is not true. Magnetism is a strictly physical property linked to the alloy's microstructure and hence composition. Corrosion resistance is not related to magnetism, but is based on the presence and amount of elements such as chromium, molybdenum and nitrogen. Provided that the right alloy is chosen, magnetic stainless steels show adequate corrosion resistance in a given environment.

Table 4-2 Room temperature physical properties to EN 10088-1 (annealed condition)

Steel designation	Density (g/cm^3)	Modulus of elasticity (kMPa)	Thermal expansion 20 – 100 °C (10^{-6}/°C)	Thermal conductivity at 20 °C (W/m°C)	Heat capacity at 20 °C (J/kg°C)
Ferritic					
1.4512 (409)	7.7	220	10.5	25	460
1.4003			10.4		430
1.4016 (430)			10.0		460
Austenitic					
1.4307 (304L)	7.9	200	16	15	500
1.4301 (304)					
1.4404 (316L)	8.0				
1.4401 (316)					
1.4436 (316)					
Lean Duplex					
1.4482	7.8	200	13	15	500
1.4062				13	480
1.4162				15	500
1.4362 (2304)					
Duplex					
1.4462 (2205)	7.8	200	13	15	500
Superduplex					
1.4410 (2507)	7.8	200	13	15	500
1.4501					
1.4507 (255)					

4.4 Finishes

Unless sold in the as-hot worked ('black') condition for subsequent machining or operations involving heat treatment, stainless steel products will usually have been given a pickling (chemical descaling) operation prior to despatch. Pickling removes all surface oxide formed during heat treatment to obtain optimum corrosion performance.

The standard finishes with EN 10088 and their designations are given in Table 4-3. Cold rolled products have smoother surface finishes and closer tolerances than hot rolled products of equivalent thickness.

The finishes designated as 1D or 2D (hot rolled or cold rolled, heat treated and descaled) and 2B (cold rolled, heat treated, descaled and lightly flattened by tension levelling or rolling) are most likely to be encountered in water industry plant items. They have properly descaled surfaces with a fully stable oxide film. Further pickling or acid cleaning will be required only to remove any oxide films formed during welding, or non-stainless metallic contamination.

The 2R, or Bright Annealed (BA), finish is highly reflective and usually would be encountered only on items such as laboratory test equipment.

A range of special finishes is also available. These include ground, brushed or polished surfaces and pattern rolled surfaces, for applications such as reduced reflectivity equipment enclosures and architectural applications. In addition, special polished 'hygienic' finishes are available for ease of cleaning tube and pipework. Further guidance on the selection of these is available from steel manufacturers.

Since the surface finish is a major determinant of corrosion performance, it is essential that any changes in surface condition, such as might result from site weld repairs of modifications, are made good following a suitable procedure. Guidance on surface rectification measures is given in Section 7.

Table 4-3 Selected standard surface finishes from EN 10088-2

Product form	Finish code	Process route	Surface finish	Notes	Typical applications
Hot rolled	1C	Heat treated, not descaled	Black, rolling scale	For items to be machined or descaled prior to use,	A surface finish for semi-finished items only.
	1D	Heat treated, pickled	Free of scale	Standard finish for entering service,	Plate for tanks, penstocks, chutes *etc.*
	1M	Patterned	Roll patterned on one side	Lower surface is flat,	Chequer and non-slip floor plate.
Cold rolled	2D	Heat treated, pickled	Smooth, free of scale	Finish for annealed, (softest) condition,	
	2B	Heat treated, pickled lightly cold rolled	Smoother than 2D	Standard cold rolled finish,	Strip for tube and pipe-making, general purposes.
	2R	Bright Annealed	Smooth, bright, reflective	Surface developed by annealing in a controlled atmosphere,	Possibly too reflective for general applications, may be used for enclosures *etc.* in clean environments.

SUMMARY OF SECTION 4

Stainless steel flat and long products for general purposes are covered by the material standard, EN 10088. For pressure purposes, the appropriate standards are EN 10028-7 and EN 10272. Stainless steel tubular products are covered by EN 10296-2, EN 10297-2, EN 10217-7 and EN 10216-5.

Design strengths are generally quoted in terms of a 0.2% proof strength; typical values for standard austenitic and duplex stainless steels are about 220 MPa and 460 MPa respectively.

Austenitic stainless steels are non-magnetic and have higher thermal expansion coefficients and lower thermal conductivities than structural carbon steels.

Stainless steels are available in a wide range of surface finishes, ranging from matt to highly reflective finishes and from smooth to roll patterned finishes.

5 MATERIALS SELECTION AND SYSTEM DESIGN FOR OPTIMUM CORROSION RESISTANCE

5.1 Basic issues

In order to achieve the full economic benefits, specifiers, designers and plant engineers need to understand the basis of stainless steels' corrosion resistance and to recognise that achieving maximum component life in water and waste water treatment plants depends on a combination of:

- correct understanding of any potentially corrosive conditions associated with the process stage,
- correct materials specification,
- good plant design,
- specification of, and adherence to, appropriate standards of fabrication,
- correct commissioning and operating procedures.

In most areas of water and waste water treatment plant, distribution as well as domestic plumbing systems the standard grades of stainless steels have excellent corrosion resistance. Under the normal conditions met in the water industries, stainless steels do not suffer from the general loss of section that is characteristic of rusting in non-alloyed irons and steels. However, certain chemical environments can lead to localised attack of the protective oxide film, and these conditions must be properly assessed, in order to select the correct grade of stainless steel. The assessment will usually concentrate on the following areas:

- unusual water conditions, such as strongly saline waters and certain industrial waste waters,
- process stages involving the introduction of chemicals, particularly strong oxidising agents such as chlorine solutions or hypochlorite,
- equipment for the handling, storage and dispensing of chemicals in their concentrated forms.

There are few concerns in freely flowing, non-brackish waters.

In general terms, the key parameters of the water which govern the performance of a grade of stainless steel are the chloride level, presence of oxidising agents and temperature. For most potable and fresh waters, variations in bulk pH do not have a significant effect on the behaviour of stainless steels, though localised effects, for example in crevices, can be important. When sulphate reducing bacteria are present, microbiological activity can also have an influence under stagnant conditions. In water and waste water treatment plants, water temperatures are usually well below 25 °C, and temperature variations are not a concern.

The corrosion engineer will always consider not only the basic process specification, but the detailed design of the plant components and the 'worst case' conditions which might be encountered. The aim is to assess the likelihood of significant excursions from the anticipated normal ranges of parameters such as temperature, salinity and presence of oxidising agents. A simple example associated with chlorination treatment would be the possibility of variation in pre-dilution levels of an addition such as hypochlorite.

Appraisal of a process stage may point to one or two critical areas which, if the conditions cannot be modified by design, justify the selection of a more corrosion resistant grade of stainless steel. Often specialist equipment suppliers have valuable experience in materials performance for individual environments and their advice can be sought.

For Reverse Osmosis (RO) desalination, high chloride waters such as brackish or sea water are often involved and at high pressure. Under these conditions higher grades of stainless steel are required.

For plant that handles process chemicals in bulk, there is a considerable body of data available from various industries on the performance of different grades of stainless steels in contact with specific chemicals. Examples of the use of such data are given in Section 5.5. Other information of this type may be accessed via reference books and databases (4). It is important to note that the corrosive nature of many chemicals depends upon their purity.

The following information explains the principal issues to be considered and demonstrates how performance can be influenced by the nature of operations.

5.2 Response to atmospheric exposure

When fabricated and finished to suitable standards, the standard austenitic grades such as 1.4301 (304) and 1.4401 (316) can provide excellent resistance to atmospheric corrosion over many years (4) (5), particularly when any surface deposits which build up in exposed or sheltered areas are removed by a periodic wash down (6). Stainless steels are widely used in the chemical and offshore industries as durable materials for the roofing and cladding of buildings and for structures such as walkways, ladders and cable trays. Where maximum life and good appearance are required in marine and moderate chloride-bearing or industrial atmospheres, 316 type grades are normally preferred.

Where aesthetic appearance is important, as may be the case outside normal engineering or structural requirements, surface finishes better than R_a<0.5 microns or electropolishing offer improved resistance to a brown cosmetic staining called “tea staining” (7) and also provide better overall corrosion resistance. Smoother surfaces can maintain brightness much longer for any given alloy since a coarse surface can more readily retain dirt, particles and corrosive chemicals.

The general engineering ferritic grades may develop continuous adherent surface rust staining, which makes them unsuitable for atmospheric exposure applications where appearance is important.

5.3 Behaviour of stainless steel in water

Because of the formation of a passive oxide surface film, freely exposed, correctly finished 304 and 316 types have such high corrosion resistance to water that they do not need a corrosion allowance (unlike ductile cast iron and carbon steel). In the event of mechanical damage to the oxide film, self-repair is rapid in water.

However, there are some situations and conditions where corrosion may occur and, when this happens, it is usually localised to crevice areas, or takes the form of surface pitting (these localised corrosion processes are described more fully in Appendix A). The following sections describe how stainless steels behave under various process conditions; they address the situations which can cause corrosion and how they can be avoided.

5.3.1 Flow

High velocities can limit the performance of other materials, such as ductile cast iron, carbon steel and copper alloys. However, stainless steels have excellent erosion-corrosion (impingement) characteristics, being able to handle turbulent flow and flow velocities up to 40 m/s (8).

Experience has shown that optimum performance of stainless steel is achieved when a minimum velocity of 0.5 m/s in clean water and 1 m/s in raw water is maintained.

5.3.2 Effects of aeration

Under normal conditions, variations in dissolved oxygen level do not have any significant effect. Increased oxygen levels, as in aeration processes, which can cause corrosion of carbon steels and cast iron, are not harmful to stainless steels.

5.3.3 Chloride level and resistance to crevice and pitting corrosion

The chloride level of the water is an important factor in determining the resistance of stainless steels to pitting and crevice corrosion. As a general guide in the pH range of 6 – 8.5 normally encountered in raw, natural and potable waters, 304 types are considered suitable for chloride levels up to about 200 mg/L and 316 types for chloride levels up to about 1000 mg/L (9) (10). At higher chloride levels, there is an increased risk of pitting or crevice corrosion in these alloys and more highly alloyed stainless steels are available. Information about materials selection for such environments, as well as seawater, is shown in Section 5.10.

It is important to note that pitting and crevice corrosion can occasionally occur at lower water chloride levels (11). This may be in local environments where the protective surface film is weakened, as could occur with low pH, high temperatures or under deposits in low flow rate conditions. They may also occur where chlorides can concentrate by drying out (as at ‘low spots’ in pipe runs which are used infrequently). A more conservative approach would be to consider 304 types for chloride levels up to 50 mg/L and 316 types for chloride levels up to 250 mg/L: for example, the use of 2–3% molybdenum 316 grades in preference to the 304 types has also been advocated for waste water treatment plant, where chloride levels run typically at 70 mg/L (12). Also 316 can be preferred for domestic piping systems (250 mg/L max chlorides in Europe) where hot waters are involved.

Figure 5-1 illustrates pitting on the upper surface of a 304L beam on a tank exposed to an aggressive marine atmosphere for 12 months. The corrosion products were wiped off to show the pitting.

Figure 5-1 Pitting of 304L

(© Roger Francis)

It is possible to use the alloys at higher chloride levels than the guidelines if other conditions apply to make this acceptable such as if the water is deaerated, or there is cathodic protection applied, or there is only short term, transient exposure above recommended chloride levels.

Closed or mixed metal piping systems also containing copper, aluminium or carbon steel may benefit from the addition of multi-metal inhibitor solutions. Specialised advice should be sought, including on conformity with water and environmental standards.

In plant equipment and pipe runs, attention to design, correct fabrication and operating conditions can minimise the incidence of crevices and drying-out.

Crevices are of two types:

- Natural – formed beneath sediment, deposits or sludges.
- Man-made – originating from design or construction, *e.g.* incomplete fusion welds, surface contamination or pipe flange faces.

Sedimentation can be reduced by sufficiently high flow rates. When design or operating conditions are such that sediment deposits may occur, a periodic flushing with a high pressure water stream should be employed. Design and fabrication practices should aim to limit man-made crevices. For example, in pipe welding, full penetration welds should be made, without excessive projection of the root bead. Also, where gaskets are used at flanged joints, a material which is inert, chloride-free, and accurately aligned will reduce crevice features and ensure least flow disturbance.

It is good practice to use materials of higher corrosion resistance in regions of plant where, locally, conditions are adverse. For example, flanges may be made of a stainless steel with a higher crevice corrosion resistance than that used in the pipe run.

Crevices can occur under black Fe-Mn rich deposits which form when an oxidant such as chlorine or potassium permanganate is added to precipitate iron and manganese out of raw waters. The precipitate is subsequently removed from the water by filters. This deposit is normally benign to 304 and 316 types, but has resulted in serious crevice corrosion near welds on these materials in waters with less than 50 mg/L chloride and where heat tint oxide scale from welding has not been removed (13) (14). To minimise the risk of this, heat tint scale should be prevented or removed (see Section 7). In addition, the chlorine or permanganate injection points should be located as close as possible to the sand filters, to reduce the length of pipe susceptible to Fe-Mn bearing deposits.

Figure 5-2 shows crevice corrosion of a 316L flange exposed in a brackish water.

Figure 5-2 Crevice corrosion of 316L
(© Roger Francis)

International experience has confirmed that in relation to water chloride levels there are three main potential corrosion areas in water treatment plants:

- crevices formed due to welds lacking penetration.

- pitting at unremoved weld heat tint, associated with microbiologically influenced corrosion (see Section 5.4.2), when water is left stagnant in pipe work for extended periods, *e.g.* after hydrotesting on commissioning.
- pitting associated with weld heat tint under Fe-Mn deposits, in the presence of chlorine or potassium permanganate oxidants.

Thus, attention to achieving full penetration welds, avoidance of stagnant or slow-drying conditions, attention to the removal of heat tint and the positioning of filters at Fe-Mn removal stages can greatly reduce the potential sites for localised corrosion.

5.3.4 Galvanic behaviour

When two different metals are in contact with each other in an environment containing water or another electrolyte, they form a galvanic couple in which the corrosion of the least noble metal is increased and the corrosion of the more noble is decreased. Such galvanic corrosion can be avoided by recognising where it may occur and taking suitable measures. Detailed practical guidance is given in (15), (16) and (17).

The extent of corrosion depends, among other things, on the conductivity of the water and the relative surface areas of the two metals exposed. If the more noble metal has the larger surface area, more corrosion of the less noble metal must be expected. Table 5-1 shows typical values of conductivity in different types of water. The higher the conductivity, the higher the risk of galvanic corrosion. Seawater has a higher conductivity than low chloride waters including drinking water and will more readily cause galvanic corrosion.

Table 5-1 Typical values of conductivity in different types of water (16)

Environment	Conductivity in S.cm^{-1}
Pure water	$5x10^{-8}$
Demineralised water	$2x10^{-6}$
Rain water	$5x10^{-5}$
Drinking Water	$2x10^{-4}$ to $1x10^{-3}$
Brackish river water	$5x10^{-3}$
Sea water	$3.5x10^{-2}$ to $5x10^{-2}$

Table 5-2 Grouping of compatible metals in fresh water at 25°C

GROUP	TYPE	ALLOYS
1	Passive	Austenitic Stainless Steels Duplex Stainless Steels
2	Good Corrosion Resistance	Copper Copper Alloys (Brasses and Bronzes) Silver Solder (Copper-Silver-Phosphorus) Soft Solder (Tin-Silver)
3	Moderate Corrosion Resistance	Cast Iron Carbon Steel
4	Low Corrosion Resistance	Aluminium and Its Alloys Zinc Galvanised Steel

It is well established that the alloys in each of the four groups shown in Table 5-2 can be connected together safely (15). If components from two different groups are connected together then the one in the lower group will suffer galvanic corrosion, *e.g.* stainless steel and carbon steel. Stainless steel and copper and its alloys may be connected together safely under some circumstances, as described below.

Of metals used in the water industry, stainless steels are nearly always the most noble in the system and are unlikely to be the items galvanically corroded. Galvanic attack of stainless steels has been experienced in chemical plant under crevice corrosion conditions created by the use of graphite gaskets at flange joints, and graphitised packing of pump shafts and valve spindles in saline waters. However, galvanic corrosion of this type has not been reported from water industry applications (17).

Figure 5-3 shows corrosion of non-pickled heat tint on a stainless steel pipe and galvanic corrosion of carbon steel bolts used with a stainless steel flange.

Figure 5-3 Heat tint and galvanic corrosion
(© Roger Francis)

Different types of stainless steels are generally compatible with each other in low chloride waters and also with copper alloys unless active localised corrosion of the stainless steel is occurring or the area ratios are particularly adverse. In domestic drinking water systems, copper alloy or gunmetal fittings, including valves, are successfully used with stainless steel tubing. However, less noble alloys, such as aluminium, steel, galvanised steel and zinc, can be prone to corrosion and precautionary measures may be required. In high conductivity waters such as sea water, contact with stainless steels may also cause galvanic corrosion of copper alloys (15). An example of galvanic corrosion risk is the use of carbon steel or galvanised steel fasteners in stainless steel flanges. Here the ratio of areas of the reactive material, the fasteners, to the noble material, the flange, is small. This serves to concentrate the attack on the fasteners. Conversely, attack on a carbon steel plate located by a stainless steel fastener would be dispersed over a wider area, making the effects less significant and in some cases negligible.

Methods of avoiding galvanic corrosion involve:

- careful design to ensure that the more noble area is small in comparison with the less noble area
- coating the joint region, ensuring adequate coverage either side. If this is difficult, then coat *only* the more noble metal. If the less noble material only is protected, then attack at any coating defects will be severe
- insulating the joint with electrically non-conducting gaskets, fastener sleeves and washers
- providing cathodic protection
- use of isolation spools.

One practical example of insulation is the use of fusion bonded epoxy (FBE) coated carbon steel flanges for thin walled stainless steel pipes with pressed or rolled collars. The coatings insulate the flange from the pipe and may allow the use of galvanised steel, rather than stainless steel bolting.

Galvanic behaviour can be used to provide protection against corrosion and is the basis of cathodic protection. Deliberate coupling of a protective ‘sacrificial anode’ material with adequate electrical driving force will result in preferential corrosion of the anode and protection of the more noble material, the cathode. For example, a carbon steel component coupled to stainless steel could be protected by a zinc or magnesium anode. In the case of stainless steels in seawater, zinc-aluminium alloy anodes have been used (see Section 5.8).

Codes of practice and other literature are available giving further guidance on avoiding galvanic corrosion (18) (19).

5.3.5 Stress corrosion cracking (SCC)

Most applications of stainless steel in the water industry present no risk of stress corrosion cracking because this type of corrosion usually occurs only at elevated temperatures. Chloride SCC is well understood in the chemical and process industries: it usually occurs at temperatures above 50 °C in 304 and 316 types of stainless steel where chlorides are present and the component is subject to tensile stress. The stress may arise in service or from bending and welding during fabrication.

Even in hot water pipework, experience has shown that SCC is unlikely to occur in 304 and 316 stainless steel where chloride levels are less than 250 mg/L (20). Where SCC does occur in hot water pipework, it is often on the outside of pipework exposed to salt water-bearing solutions which concentrate by evaporation. Leaching of chlorides from thermal insulation may also be a problem. Although insulation is available with a maximum of 10 ppm leachable chloride and the presence of a sodium silicate inhibitor, external contamination of the insulation may be more important. The guidance in BS 5970 (21) and BS 5422 (22) should be followed in respect of the external weatherproofing of insulation. Appropriate barrier paints can be used to protect stainless steels under insulation.

Where SCC is a possibility within a process stage, a stress relieving heat treatment or shot peening – where practical - can be used to alleviate this, although carbon steel shot should be avoided as it can cause iron pick-up on the surface. Alternatively, higher nickel austenitic or duplex stainless steels are available and do not usually develop chloride SCC below 100 °C (8). Ferritic grades with little or no nickel content have very high resistance to chloride SCC. Some hot water tanks have been made in duplex or ferritic types to provide extra protection against SCC. Specialist advice should be sought on their use.

5.3.6 Metal pick-up in potable water

The equilibrium transfer rate of metals from the oxide films on stainless steel into potable and non-aggressive waters is negligible.

Some transient pick-up of nickel has been observed when systems are operated for the first time (20) (23) (24). For example, when commissioning a hospital wing hot and cold water distribution system in a mix of 304 and 316 type steels, a maximum level of 15 μg/l nickel was reached after 20 days in the hot water system. This declined to very low levels thereafter, with chromium and molybdenum levels below 2 μg/l for most of the initial 1250 days of operation (20) .

Tested and approved grades of stainless steel are also listed in UK Drinking Water Inspectorate (DWI) Regulation 31 for product approval when used in accordance with the “Operational Guidelines and Code of Practice” (25). 304/304L and 316/316L, along with the duplex 2205 and proprietary lean duplex grades are also approved in the US under the ANSI/NSF61 regulations (26).

5.4 Response to contact with sludges, microbiologically influenced corrosion (MIC) and conditions involving hydrogen sulphide

5.4.1 Sludges

Under normal operating conditions, stainless steels can tolerate wet sludge contact. Free flow minimises deposit formation and sludge build-up, while aeration and agitation of sludges also reduce their tendency to adhere to stainless steel surfaces. Corrosion risks may increase under stagnant conditions when drying out, as a result of the formation of sludge poultices and concentration of salts in the water. Good housekeeping practices, involving the cleaning and removal of sludge residues from the surfaces of piping, aeration basins, other process tanks and vessels during downtime, will help avoid crevice corrosion risks.

5.4.2 Microbiologically influenced corrosion (MIC)

Bacteria themselves are not capable of attacking stainless steels. However, when present in biofilms and tubercles, the microbes, which can be either aerobic or anaerobic, may alter the chemistry locally, leading to attack of the stainless steel substrate, resulting in under-deposit corrosion and pitting. This can be further aggravated in areas where the chromium content of the metal surface has been lowered, such as at heat tint areas associated with welds.

MIC attack is unlikely to be found in potable waters which have supply levels of chlorine and other oxidants. It is rarely found on properly fabricated stainless steel components, free of crevices and heat tint, and where good housekeeping practices are maintained during operations. Also, flowing conditions are less conducive to this form of attack.

MIC is more likely to occur under stagnant conditions and where raw and untreated waters are involved (27), or potable water has suffered chlorine decay. This is especially the case when untreated waters are allowed to stand in vessels and piping. Leaving hydrotesting waters in lines prior to activating the system has resulted in failures of this nature. Such conditions additionally favour chloride pitting attack if any chloride ions present in stagnant waters are allowed to concentrate as evaporation occurs. Good practice dictates that good quality waters should be used for both factory and site hydrotesting, and systems should be drained thoroughly and dried within 24 to 48 hours of the test. If this is not practicable, then water should be circulated through the system on a regular basis for at least one hour per day, to avoid stagnation. Guidance on good practice in hydrostatic testing is published by the Institution of Chemical Engineers (28).

Although waste water treatment plants handle sludges and use bacteria for their decomposition, there has been a very low incidence of MIC. (Aeration, agitation and regular housekeeping practices all tend to reduce the risk of attack on exposed stainless steel surfaces.) However, in those areas where sludges can accumulate and are not removed, the possibility of MIC attack must be considered and, if necessary, a more highly alloyed steel grade should be used.

Figure 5-4 illustrates MIC of a 316L vessel after handling raw fresh water for several months. The photograph shows the preference for bacteria to attach at the rougher surfaces of welds.

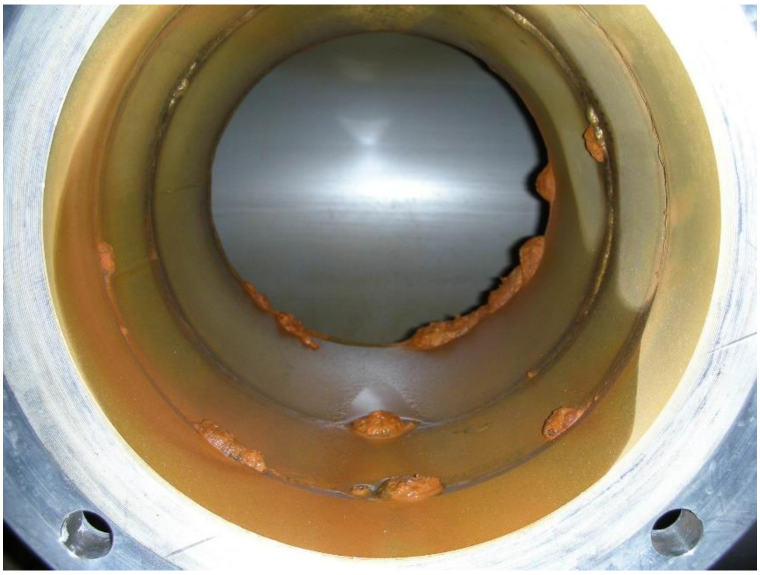


Figure 5-4 **MIC of 316L**
(© Roger Francis)

5.4.3 Hydrogen sulphide gas

Hydrogen sulphide gas is generated in the digesters and throughout much of a waste water treatment plant. It contributes to the corrosion that occurs in copper alloys, aluminium and carbon steel (29). The corrosion rate of 304 and 316 types in moist hydrogen sulphide is negligible at near ambient temperatures. A US survey of waste water treatment plants found minimal problems (30) due to hydrogen sulphide gas.

In closed systems there may be a propensity for localised pitting and crevice attack to occur in 304 and 316 types if moist hydrogen sulphide and chlorides are present together at elevated temperatures. The acidity of waste waters might also be raised if condensates containing dissolved sulphur dioxides are generated, forming sulphurous acids particularly under stagnant conditions and at deposits. For these more corrosive environments, avoiding stagnant areas and the use of higher molybdenum stainless steels such as 904L (1.4539) or duplex 2205 may be required.

5.5 Resistance to chemical additives

5.5.1 Oxidants (chlorine, ozone *etc.*)

Oxidants are often added to water for chemical reaction, such as iron and manganese precipitation, and for disinfection. The beneficial effect of low concentrations of these oxidants for stainless steels is that they control bacteria which under some circumstances can result in MIC (Section 5.4.2). However, because of the oxidising nature of chlorine and ozone, stainless steels can be more susceptible to the presence of any chlorides.

Chlorine

The presence of ‘free’ chlorine increases the risk of crevice and pitting corrosion of stainless steels by chlorides and this aspect has been studied extensively in the context of offshore seawater systems. In fresh waters, guidelines set by an early study (31) have withstood the test of time and have also been reconfirmed by a second, more recent study (32). They are shown in Table 5-3.

Table 5-3 Guidelines for long term exposure of stainless steel in chlorinated water environments (pH 6-8)

Alloy	Chloride Level mg/L Cl^-	Free Chlorine Level mg/L Cl_2
304	Up to 200	Up to 2
316	Up to 1000	Up to 5

However, stainless steel can tolerate considerably higher levels of chlorine for short periods of time, as would be the case during sterilisation treatments *e.g.* 25-50 mg/L for 24 hours. It is important however that such levels are well flushed through the system immediately afterwards or pitting can occur.

Experience suggests that both 304 and 316 types can behave well under flowing, submerged conditions at the chlorine levels found at the finishing stages of water treatment plant. However, the following potential problems have been identified:

a) over-chlorination for extended periods of time

b) excessive local concentrations of free chlorine, for example as a result of poorly set injection nozzles directing additions to pipe walls

c) collection and concentration of chlorine gas and water vapour on the walls in the air-space of unventilated tanks or pipes.

Good process control can prevent the incidence of over-chlorination and local concentrations in the water.

The third problem c) above can be avoided either by providing adequate ventilation and regular washing down to stop acid chlorides concentrating or, if necessary, by using a more corrosion resistant alloy grade at and above the water-line and in ductwork where the vapours condense. Care should also be taken in vent and stack design, to avoid local corrosion problems resulting from channelling and discharge of moist, chlorine-bearing vapours. As an example, one affected area was improved by sealing the ventilation/extraction systems and sealing off a number of access points where the chlorine-bearing vapour could seep out of underground treated water storage tanks causing corrosion of stainless steels in the plant room located above.

Experience in heated indoor swimming pools has shown that the atmosphere generated by the disinfectant reactions between chlorine or hypochlorite additions and body matter is corrosive to some stainless steels and a range of other building materials (33). Not only has this led to staining and surface micropitting, but cases of SCC of austenitic stainless steel wire and fasteners have been reported. These cases have all been found at temperatures below those at which SCC is normally encountered (see Section 5.3.4). Whilst no such cases of SCC have been reported from the water industry, more highly alloyed austenitic or duplex stainless steels are available to meet the conditions encountered in these environments.

It is advised that regions, where chlorine and the gaseous products of a chlorine reaction with ammonium compounds may be liberated, should be kept well ventilated and exposed stainless steel surfaces should be regularly washed down.

In addition to its use as a biocide, chlorine is also used to precipitate iron and manganese from raw waters (see Section 5.3.3). The resulting black Fe-Mn film formed on the surface of the pipe can be a site for corrosion at unremoved weld heat tint. Particular attention to removal or avoidance of heat tint in the zone between the injection point and the filter should be made.

Chlorine overdosing can be detrimental to all common materials used for pipework, tanks etc. and it is therefore important that the introduction of chlorine is carefully monitored and controlled.

Ozone, chlorine dioxide and other oxidants

At the dilutions normally encountered in finished potable water, ozone, potassium permanganate, chlorine dioxide and chloramines, like chlorine, do not present corrosion problems for immersed standard austenitic stainless steel components.

The main risks in oxidation stages appear to be close to the dosage point. In those areas and where high levels of oxidants are present and/or chloride levels of the water are close to maximum recommended levels, higher alloy grades provide higher resistance.

Stainless steels are commonly used in the construction of ozone generators. Because of the oxidising nature of ozone, as with chlorine, the tolerance of stainless steels to chlorides can be reduced, and the more resistant 316 types are normally preferred. However, passage of chlorinated water through either the pre- or post-ozonation tanks can produce offgases forming aggressive condensates which attack the vent ozone destruction (VOD) lines and the use of a more corrosion resistant grade than 316 may be necessary.

5.5.2 Other chemicals used within plants

The following general information on the rates of corrosion in commonly used treatment media is based on Reference (1) unless otherwise stated. It is important to emphasise that the risk of corrosion can be strongly influenced by the purity of the treatment chemicals; in particular, chloride level, oxidising potential and pH can affect risk of attack. Stainless steels can be safely used in all the following treatment media provided that a grade recommended for the solution concentration is selected.

Aluminium sulphate

Corrosion rates of less than 0.1 mm/year have been reported for 316 types for concentrations of aluminium sulphate up to 27% at room temperature. 304 types are less resistant. Both 304 and 316 types perform satisfactorily in a 10% solution at temperatures up to 50 °C.

Ferric chloride

Ferric chloride is sometimes used for flocculation in conditioning tanks where sludge is further concentrated and de-watered for incineration and disposal. Ferric chloride is highly aggressive to all standard grades of stainless steel, with significant corrosion reported at a concentration of 500 mg/L. Corrosion is a risk mainly at locations close to injection points or when subject to overdosing. Sludge piping from 304 types has performed well downstream of ferric chloride injection points where thorough mixing and lower chloride levels exist. Aluminium chloride is a far less aggressive flocculant.

Ferric sulphate

Low corrosion rates of below 0.1 mm/year have been observed for the standard austenitic stainless steel grades in 10% ferric sulphate solutions at ambient temperature. Similar low corrosion rates were measured in 316 types at the boiling point of this solution.

Fluorosilicic acid (H_2SiF_6)

Dilute solutions (up to about 7%) may be handled by 316 types at ambient temperatures. Higher alloy austenitic grades or duplex stainless steels are available for contact with more concentrated solutions.

Granular activated carbon (GAC)

Graphite, like stainless steel, is a noble material. Under normal conditions, carbon and graphite would be expected to be inert with respect to stainless steel, particularly in potable water treatment where high purity GAC is used. However, should localised corrosion initiate on stainless steel electrically coupled to carbon particles, then the ‘active’ steel surface would be less noble than the carbon surface and there would be a tendency for an increased rate of corrosion. To avoid initiation conditions, stainless steels for GAC containment should be used well within the chloride levels suggested in Sections 5.3.3 and 5.10.1 and preferably a molybdenum bearing grade used of type 316 or if necessary of higher resistance.

Phosphoric acid

The standard grades of austenitic stainless steel are resistant to pure phosphoric acid over a wide range of concentrations and temperatures. However, in the production of phosphoric acid via wet-process acid, which is contaminated with chlorides, fluorides and sulphuric acid standard grades can be aggressively attacked. Information is available to aid grade selection for specific types of phosphoric acid (4) (34).

Polyelectrolytes

Both anionic and cationic polyelectrolytes are used as flocculants and can be corrosive to unprotected and galvanised steels and aluminium. In general, standard grade stainless steels are suitable for the storage of both types, but guidance should be sought from the flocculant manufacturers.

Sodium hydroxide (caustic soda)

The standard grades of austenitic stainless steel and (lean) duplex grades are suitable for handling sodium hydroxide at ambient and near ambient temperatures up to a concentration of 30%. Sodium hydroxide is often supplied in totes at 50% concentration, and both 316L and 1.4462 (2205) have been used to handle this at ambient and near ambient temperatures.

Sulphuric acid

Guidelines for grade selection are given in (4). Type 304 austenitic stainless steel is susceptible to attack at ambient temperature at concentrations of sulphuric acid between approximately 5% and 85%; attack is increased significantly by the presence of chlorides. Type 316 is significantly more resistant (lower limit of 20%) and higher alloy stainless steels are available with enhanced performance, for example grade 1.4539 (904L) and 1.4507 (255) were specifically developed for sulphuric acid processes. Superduplex 1.4501 has been used for various applications in concentrated acid at elevated temperatures in sulphuric acid plants (35).

5.6 Resistance to abrasion and erosion

All austenitic and duplex stainless steels are ductile at ambient temperatures and are resistant to impact damage by solids onto screens and grids. Metal loss under continuous and intermittent flow of waters with suspended solids is generally lower than for unalloyed steels; penetration of the thin protective oxide film is restored rapidly and there is no loss as friable corrosion products.

The use of stainless steels for hoppers, launders and chutes handling damp solids has proved beneficial because of the smooth finish which is maintained, particularly where equipment operates intermittently. Hang ups and sticky flow as a result of friction between the medium and rusted carbon steel panels are avoided.

The resistance of stainless steels to cavitation erosion is significantly higher than that of unalloyed steels.

5.7 Response to contact with soils

External corrosion of buried stainless steel is dependent upon soil chemistry and resistivity. Soils differ in their corrosiveness depending on moisture level, pH, aeration, chloride level, presence of chemical contamination, microbiological activity and surface drainage. This is affected by location - such as coastal or rural - and exposures to winter de-icing salt. Resistivity provides a guideline to a soil's water retention (clay, sand, loam) with the higher the resistivity, the better the drainage. Based on tests in Japan and the US, stainless steels have performed well in a variety of soils and especially soils with a high resistivity. Some pitting has occurred in low resistivity, moist soil (36). Stainless pipelines benefit from pipeline bedding and backfill materials such as clean low chloride sand, loams and fine stone which can help with drainage from the pipe. For wet and contaminated soils, a higher alloy stainless steel should be considered for the relevant section of pipe run, with the selection based on an investigation of soil chemistry.

Table 5-4 provides typical guidelines for stainless steel in soils based on chloride level and resistivity, assuming good fabrication practices and soils with pH> 4.5, and no stray currents or harmful bacterial activity. Super-austenitic alloys could be used as an alternative to superduplex.

Table 5-4 Typical stainless steel grade recommendations for soil (37)

Resistivity Ω.cm	**Chloride ion concentration (mg/L)***			
	200	1000	2000	15,000
>5000	304			
2000-5000	316		2205	Superduplex
1000-2000	2205		Superduplex	
<1000	Superduplex			

*Chlorides can be both present naturally in the soils and also from external sources such as the result of de-icing roads in winter.

Alternative approaches under aggressive conditions or to avoid stray currents are to wrap the stainless pipe in a protective material such as a petrolatum tape prior to burial (with no less than 55% overlap of the wrap width), encasement and/or or cathodic protection (37).

5.8 Cathodic protection

Operating experience of cathodic protection (see Section 5.3.4) for stainless steels is derived mainly from offshore exposure conditions and the protection of individual plant items. These include seawater turbine components (sacrificial anode method) and pulp and paper machinery exposed to oxidising, chloride-containing bleach liquors (impressed potential method) (38). The general principles of protection of stainless steels have been reviewed by Bardal (39) and by Linder (40). Various protection potentials to maintain passivity and current densities are quoted in the literature and guidance from specialists in protection methods should be sought.

5.9 Galling and seizure

Galling is a form of surface damage that results from local adhesion and rupture of contact surfaces in relative motion under load. The load must be sufficient to disrupt the protective oxide layers covering surface asperities and permit metal to metal contact. In severe cases, where large areas of weld bonding have occurred, seizure results. The susceptibility to galling or seizure depends upon the contact pressure, the nature of the materials, surface roughness and the presence of any lubricant.

Situations in water industry applications where galling of stainless steels may need to be considered include fasteners and intermittently moving loaded parts such as yokes, bushes, valve spindles and balls. Equipment manufacturers have considerable experience in the design and materials selection methods to avoid galling problems and may adopt one or more of the following methods:

- Use clean-cut, deburred threads
- Use appropriate torque and / or a suitable anti-seize compound. Use dissimilar, standard grades of stainless steels, varying in composition, work hardening rate and hardness (*e.g.* grade A2-C4 or A4-C4 bolt-nut combinations from EN ISO 3506 (41).

- For more severe cases, use a proprietary high work hardening rate stainless steel alloy for one component
- Adjust joint fit and surface tolerances
- In severe cases, use hard surface coating technologies, *e.g.* nitriding, hard chromium plating.

Whichever method is used, it is essential to ensure that the required corrosion performance is maintained. For example, nitriding treatment of the steel surface considerably reduces the corrosion resistance of austenitic stainless steel. However, surface technologies are available (42) which have minimal impact on corrosion resistance and, when necessary, advice should be sought.

5.10 Desalination

5.10.1 Reverse osmosis and membrane desalination

The reverse osmosis (RO) desalination process is being used globally as a method of producing drinking water primarily from seawater, but also from brackish water. The process occurs at ambient temperatures, which in some parts of the world can be up to 40 °C, and at high sea water pressures up to 90 bar. The low pressure (max 10 bar) feed water must be pre-treated through a coagulation and filtration process which provides clean, disinfected feed water at the correct pH for the RO process. Chlorine has to be removed before passing through the membrane separators, often by chemicals such as sodium bisulphite. Once separated, the permeate and brine streams are formed; these usually undergo a second pass treatment. In essence, two litres of seawater must be processed to form one litre of drinking water. Where chlorination is used to prevent fouling in the low pressure section, it should be at a level just enough to control fouling, as any excess must be removed with chemicals prior to the high pressure pumps to prevent damage to the membranes.

Seawater and brackish water RO-conversion to fresh waters involves an extensive use of stainless steel pipelines and ancillary equipment, depending upon the concentration of chlorides that are being handled. In the low pressure section fibre reinforced plastic and rubber lined carbon steel are used, with superduplex or 6% Mo austenitic for critical components, such as seawater pumps. In the high pressure side all the wetted metallic components (pipes, pumps, valves etc) are typically superduplex, because of its lower cost. Grades such as 1.4404 (316L), 1.4462 (2205) and 1.4539 (904L) and even occasionally superduplex stainless steels have all experienced localised corrosion attack (4) (43), particularly crevice corrosion, when used at pressurised sea water pipe flanges. Flange design and gasket materials are exceptionally important in avoiding this type of corrosion (13) (44). Reference (45) describes how to avoid crevice corrosion of superduplex stainless steel pipes under the tight crevices in the high pressure couplings.

Typically, 316 type stainless steel pipe systems are used for the processed-side fresh waters, while the higher corrosion resistant materials, such as the superduplex and super-austenitic materials, handle the higher chloride-containing and brine water streams. Some of these corrosion resistant materials also have to be used for handling the cleaning and backwash waters of the membranes. These streams are mildly acidic in nature, consisting of buffered organic acids and small quantities of hydrochloric acid.

Although lower grades of alloys can be successfully applied in less severe areas of the plant such as membrane racks and peripheral equipment, it is important that they are not exposed to the more severe conditions that exceed their corrosion resistance.

Although RO remains the primary method of seawater desalination, other membrane technologies are being developed. A leading contender is Electrodialysis (ED) which promises to be a viable contender to RO, particularly with brackish water rather than actual seawater.

Whilst the principle of using membranes to separate salts from fresh water remains the same, ED is a relatively low pressure application avoiding the 70 bar pressures required for RO. A developing technology, ED materials are similar to RO although brackish water below 4,000 mg/L chloride can use duplex 2205 for the raw water feed rather than more expensive superduplex and 6%Mo super-austenitics.

5.10.2 Thermal Desalination

The older desalination processes are thermal, and are still used in many countries. These are multi-stage flash (MSF), and multiple effect distillation (MED).

The multi-stage flash distillation process is basically similar to distillation by boiling. Water can be made to boil just as effectively by reducing the pressure as by raising the temperature. In a closed vessel, the temperature and pressure are roughly proportional so that a decrease in pressure can cause instantaneous boiling of some of the water, with the characteristic “flashing” off of some of the water vapour.

A multi-stage flash distillation plant consists of a series of chambers (often 20 or more), each operating at a pressure lower than the preceding one. As heated brine (~110°C at the inlet) flows from one chamber to the next, some of it flashes off into vapour at progressively lower temperatures. The vapour passes through de-misters to remove any entrained brine droplets and then condenses on cooler condenser tubes. The distillate then drops into collection trays and passes from stage to stage in a distillate channel, prior to distribution as drinking water. This usually involves the injection of CO_2 (sometimes in the form of non-condensable gases extracted from the distiller) to lower the pH. This distillate is then passed through limestone beds to increase hardness and finally has a small quantity of chlorinated seawater added to provide some minerals and also to disinfect the final product.

Stainless steels are rarely used for the heat exchangers, but they have been used in the flash chambers (evaporators). The shells were originally in carbon steel, but as corrosion problems developed, the critical areas were clad with 316L stainless steel. In some plants the flash chambers are solid 316L because this avoids the need to paint the outside. More recently it has been shown that flash chambers in lean duplex 2304 or duplex 2205 stainless steel are lower cost on a life cycle cost basis. A few MSF plants have utilized this concept.

Stainless steel is also used in the steam ejector vent system for the flash chambers, often 316L, and the temperatures are very high (>100°C), so SCC may be a problem. If the vent conditions are very aggressive, duplex 2205, superduplex or 6% Mo austenitic may be used.

MED plants require a source of heat, which is usually steam and so are often run in conjunction with a power station. In most MED plants, a thermo-compressor or a mechanical vapour compressor is added to improve efficiency. These are known as thermo-compression distillation (TCD) and mechanical vapour compression (MVC) plants, respectively. The higher efficiency of TCD plants means that they are the most common variant.

A typical MED plant may contain from 2 to 14 stages, or effects. Vapour at about 75°C is introduced into the first stage evaporator tubes, where it is condensed by externally sprayed raw water. In cooling the evaporator tubes, the raw water in stage 1 is heated and part of it vaporizes. The vapour enters the tubes of the second stage, where it is condensed by raw water, as in stage 1, forming more condensate. This process repeats itself in the subsequent stages. Part of the vapour produced in an intermediate stage is drawn up by the thermo-compressor, which increases its pressure and mixes it with high pressure steam to feed the first stage. The remainder of the vapour passes to the following stages and then to a final heat exchanger, where it condenses on the outside of tubes cooled internally by raw water. Part of this raw water becomes the feed to the evaporator stages and the rest goes to waste. The product water is collected and piped away, while the brine goes to blow down.

Because of the lower temperatures in an MED plant and the efficiency of modern anti-scaling compounds, MED plants are more efficient and lower cost than MSF plants.

The evaporators have traditionally used copper alloy tubes with a 316L shell, tube sheets and support plates. Although the 316L is exposed to seawater, the dissolved oxygen is low because it comes out of solution with the water vapour. Hence, crevice corrosion is not a problem. More recently the tubes have been titanium and the tube sheets and support plates have been 2304 lean duplex stainless steel to reduce costs. The shell may be 2304 or a mixture of 2304 and 2205 duplex stainless steel depending on the design.

In a modern MED plant the final heat exchanger uses titanium tubes with stainless steel water boxes and tube sheets. These were originally 316L with cathodic protection by carbon steel anodes to prevent crevice corrosion. In modern plants duplex 2205 is now used, also with carbon steel anodes, because it can have reduced thickness due to its higher strength.

As for MSF plants, MED plants vent the incondensable gases from the evaporators with a steam ejector. The vents are often in 316L stainless steel, but 2205, superduplex or 6% Mo austenitic may be used under more aggressive conditions.

5.11 Design for durability

Stainless steels can give excellent service in water industry applications. To achieve the optimum performance, particularly in chemical treatment stages, the process specification and plant component design must be examined to assess potential corrosion hazards, including possible effects of excursions from normal operating conditions. The majority of corrosion problems can be anticipated and are avoidable. Good design, appropriate steel grade selection, good specification and control over fabrication methods, correct commissioning and operating practices all combine to give long plant life.

The following sections give recommendations for good practice to ensure durability.

5.11.1 Choice of steel grade

- The molybdenum-containing 316 types have higher corrosion resistance than the 304 types and can be used under higher levels of chloride and chlorine. In Europe the 316 types are the more frequently used for water and waste water treatment plants. For building water systems, with numerous fittings and periods of stagnation, German experience favours the use of 316 types. Press type fittings with a non-metallic sealing ring applied on the outside of the pipe have been successfully used in drinking waters in spite of the crevice formed. 316 types have proven to be resistant even in hot water systems (4).

Table 5-5 Suitability of stainless steels in water: general guideline to avoid localised corrosion

Chloride Level, mg/L	Stainless Steel Grades
<200	304, 316 and lean duplex 2101, 2102 and 2202*
200-1000	316, duplex 2304* and 2205
1000-3600	2205
>3600	6% Mo super-austenitic and superduplex
15,000-26,000(seawater)	6% Mo super-austenitic and superduplex

*Note that lean duplex alloys are generally only available as plate and sheet and 316L or 2205 must be used for flanges, piping etc. This is a common practice.

- Subject to the requirements for good design and standards of workmanship, 304 types are suitable for use in most flowing water systems at ambient temperature, where chloride levels are less than 200 mg/L. They are well suited to applications where abrasion and erosion resistance are required, as in screens and grids.

- The molybdenum-containing 316 types, with their higher resistance to pitting and crevice corrosion, may be used for waters with chloride levels of up to around 1000 mg/L under the same conditions.
- The presence of oxidising agents such as chlorine increases the possibility of crevice corrosion for a given level of chloride in waters. The trials in US plants and Sheffield University, UK indicate that the 304 types can be used for chlorine levels up to 2 mg/L (31) (32). The 316 types offer a greater margin of corrosion performance than 304 at up to 5 mg/L for long term service.
- In areas of plant where moist chlorine vapours may collect and concentrate, good ventilation and regular washdowns are required, or, if not possible, a more corrosion resistant grade of stainless steel may be required.
- For optimum corrosion performance in the as-welded condition, the low carbon 'L' grades, or grades with a maximum of 0.03% carbon, should be specified. Today, commonly available 304 and 316 types are commercialized as "dual certified" 304/304L - 316/316L grades, except when a high carbon content is specifically sought after.
- Good system design and maintenance of good fabrication practices are essential to obtain the optimum performance from stainless steels, whatever the grade selected.
- Special grades – such as the ones in Table 5-5 - are available for unusual environments and applications requiring high strength. Guidance can be obtained from stainless steel manufacturers.

5.11.2 General design principles

- Design the plant to have free liquid flow, avoiding regions of stagnation (including ponding of any tank roof structure), low flow and deposit build-up.
- Where processes permit, ensure good agitation to minimise sludge build-up, particularly in waste water treatment plant.
- Design to achieve velocities over 1 m/s for raw water and over 0.5 m/s for finished water, where sediment is less likely.
- Avoid 'deadlegs' where stagnant air-water interfaces are formed and deposits may be trapped. Where flow is intermittent, slope any horizontal pipe runs, tank bottoms and tank roofs to allow complete draining, as shown in Figure 5-5.
- Where possible, design to allow regular wetting of pipework and vessels which cannot be fully drained down and otherwise may stand for long periods after intermittent use (this will minimise salt and deposit formation on drying out, see 5.11.4).
- For light gauge stainless steel pipework, ensure that the mounting methods take account of any acoustic damping required as a result of pressure pulsing.

5.11.3 Design for fabrication

- Good design must be backed up by good fabrication practices for stainless steel plant and equipment.
- Eliminate deposit traps and crevices as far as possible (*e.g.* if plates are lapped, all lapping edges are sealed, see Figure 5-5).
- Ensure that the fabrication route allows easy access for welding, to achieve the optimum geometry of weld and ease of final finishing of the avoidance of heat tint formation.
- Select weld procedures appropriate to the grade of steel being used. Removal of heat tint darker than a light straw colour is important for stainless steels. Where heat tint is present, pickling procedures are necessary for optimum corrosion resistance, see Section 7.

- Passivation usually occurs naturally on the surfaces of stainless steels, but it may sometimes be necessary to assist the process with oxidising acid treatments (46). Unlike pickling, no metal is removed from the surface during acid assisted passivation. The quality and thickness of the passive layer are however quickly developed during acid passivation treatments. There may be circumstances when the pickling and passivation processes occur sequentially (not simultaneously), during acid treatments involving nitric acid. Nitric acid alone will only passivate stainless steel surfaces. It is not an effective acid for pickling stainless steels, unless activators, such as hydrofluoric acid, are also present.
- Aim for conditions allowing full-penetration welded joints with smooth contours and weld bead profiles. (A detail in Figure 5-5 shows how a return on a plate bottom gives a smooth corner and allows easy access for execution and cleaning of a butt weld.)

5.11.4 Design for cleaning

- After hydrostatic pressure testing, drain completely.
- Where deposits are unavoidable, provide ports to allow access for cleaning and specify schedules for flushing out. For example, provision for periodic flushing and hydroblast cleaning should be made for raw water lines, where manganese and iron-bearing deposits may form ahead of sand filters.
- Specify schedules for prolonged plant shutdowns. For example, to prevent corrosive deposit formation drying out, specify either that pipework is kept wet by circulating water for a minimum of one hour every two days, or that pipework be flushed with clean water, drained completely and blown down to dry out.
- Where detritus or similar is likely to accumulate, the externals of the structure or fittings should periodically be washed down.

SUMMARY OF SECTION 5

Standard austenitic stainless steels perform well in most of the conditions encountered in water treatment and handling equipment.

The 316 types offer significant corrosion performance advantages over 304 types.

Key parameters determining the performance of stainless steels and the selection of an appropriate grade for waters at ambient temperatures are:

- *chloride level*
- *presence of oxidising agents*
- *flow rate*
- *temperature.*

For most potable and fresh waters, variations in bulk pH do not have a significant effect on the behaviour of stainless steels, but localised conditions, for example in crevices, can be important.

Maintaining water flow is beneficial as it can reduce the likelihood of:

- *a concentration of chlorides and other dissolved salts forming by the evaporation of trapped liquid*
- *crevices forming under sedimentary deposits*
- *MIC occurring under biofilms.*

Good plant design, for example by allowing free draining, preventing deposit build-up and minimising crevices, will minimise the possibility of corrosion.

Good design must be backed by good fabrication standards.

Stainless steel has excellent erosion-corrosion characteristics.

There is negligible transfer of metals from the surface of stainless steel into potable and non-aggressive waters.

Higher grades of stainless steels are available to provide corrosion resistance for more aggressive conditions such as high chloride waters, areas close to oxidant dosage points and RO desalination.

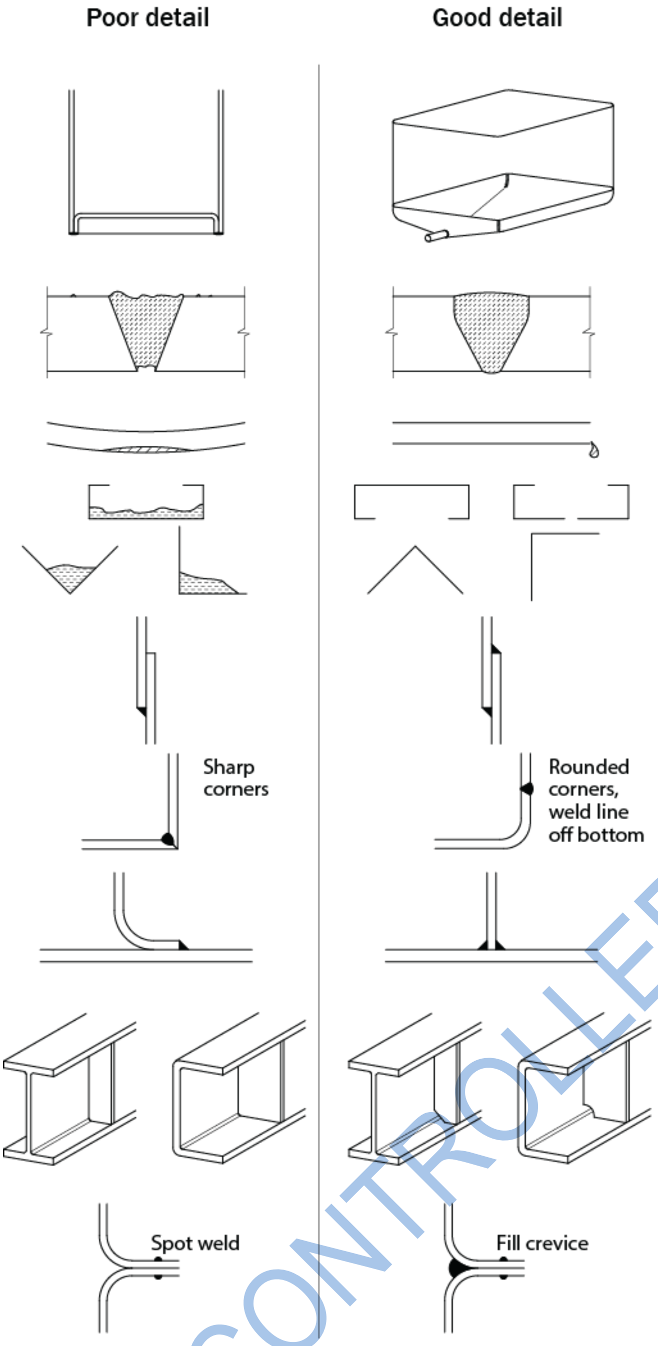


Figure 5-5 Poor and good design features for durability

6 STRUCTURAL DESIGN

The design of any items of process plant, irrespective of the type of material, involves two distinct and equally important phases:

- Structural design to withstand the service conditions (i.e. to ensure adequate strength, stability, stiffness, durability etc.)
- Design for fabrication - relating contract specification, structural design and fabrication with commissioning and handover.

6.1 Structural behaviour

In most respects, structural design in stainless steel is similar to design in carbon steel and requires comparable design checks and considerations. The only significant difference stems from the different shape of the stress-strain curve for stainless steels.

Whereas carbon steel typically exhibits linear elastic behaviour up to the yield stress and a plateau before strain hardening, stainless steel has a more rounded response with no well-defined yield stress (see Figure 6-1). This results in a difference in structural behaviour between carbon steel and stainless steel. Stainless steel ‘yield’ strengths are generally quoted in terms of a proof strength defined for a particular offset permanent strain (conventionally the 0.2% strain) as indicated in Figure 6-1, which shows typical experimental stress-strain curves. The curves are representative of the range of material likely to be supplied and should not be used for design.

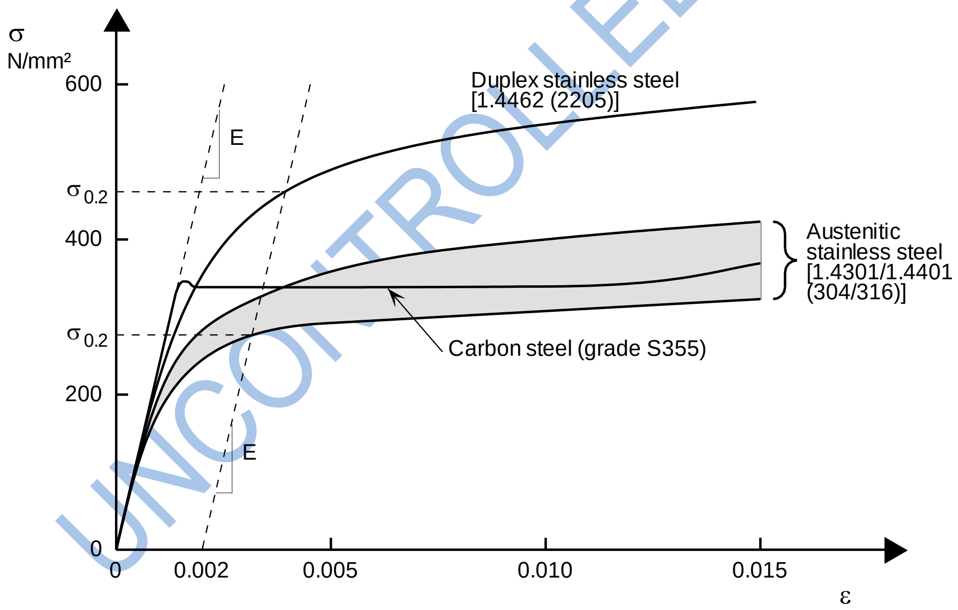


Figure 6-1 Stress-strain curves for stainless steel and carbon steel

This difference in stress-strain behaviour has implications on the buckling resistance of members (local, flexural and lateral torsional buckling); buckling curves derived for stainless steel should be used in design. Additionally, the deflection of a heavily loaded stainless steel beam will be greater than the deflection of an equivalent carbon steel beam due to the non-linear stress-strain curve and an appropriate method should be used for estimating the deflection. Methods of connection also require particular guidance.

6.2 Structural members

The design of structural stainless steel is covered by the European Standard EN 1993-1-4 *Eurocode 3: Design of steel structures, Supplementary rules for stainless steels* (47). EN 1993-1-4 extends the application of EN 1993-1-1 (covering general rules for the structural design of building-type structures made from hot rolled and welded carbon steel sections (48)) and EN 1993-1-3 (covering design of cold-formed light gauge carbon steel sections (49)) to hot rolled, welded and cold-formed stainless steels.

EN 1993-1-4 gives rules for the design of austenitic, duplex and ferritic stainless steels. It includes the design of members, bolted connections and welded connections.

As EN 1993-1-4 has supplementary status, it only supplements, modifies or supersedes the equivalent provisions for carbon steel, and as such it cannot be used in isolation but must be used alongside EN 1993-1-1, EN 1993-1-3, etc. To provide designers with one guidance document containing nearly everything needed for designing structural stainless steel, the 4th Edition of the Design Manual for Structural Stainless Steel was published in 2017 (50). Additional supporting design tools are listed in Table 6-1.

Table 6-1 Supporting design tools to EN 1993-1-4

Design Manual for Structural Stainless Steel Design guidelines with worked examples, a background commentary, webinar and design software available in 10 languages	www.steel-stainless.org/designmanual
Online Information Centre for Stainless Steel in Construction Resources for the design, specification, fabrication and installation of stainless steel in construction.	https://www.teamstainless.org/resources/information-center-for-stainless-steel-in-construction

EN 1993-1-9 (3) gives guidance on estimating the fatigue strength of carbon steel structures and is also applicable to austenitic and duplex stainless steels.

6.3 Tanks and vessels

6.3.1 Tanks in general

Although stainless steel can be welded on site, it is generally recommended that tanks are fabricated under shop conditions wherever transportation of the finished product is practicable. Manufacture of the tank off-site while site preparation works are being undertaken maximises the speed and efficiency of the construction process.

All stainless steel potable water tankage should be finished smooth internally to minimise the potential for bacterial growth and consequent water quality incidents; there should be minimal ledges and protruding bolt threads into the tank should be avoided.

All tank pipework should be designed to accommodate any shear forces exerted by changes in tank dimensions due to temperature fluctuations. Design should take account of the differential thermal expansion and contraction of materials, and between austenitic and duplex stainless steels, for example at the roof/wallhead joint.

6.3.2 Welded cylindrical tanks

Welded cylindrical tanks are perhaps more commonly used to store oil and oil products; the petroleum industry has therefore been responsible for the development of many of the design procedures and standards relating to tank design. Clearly, these are generally applicable whether a tank holds oil or water.

The design standards most widely used for designing welded cylindrical tanks are briefly described below:

API 650 (51)

This US standard covers the design of cylindrical welded tanks supported on the ground, with an open or closed roof. This standard is used to design oil, gas, chemical, water, and biofuel storage tanks. The standard has three Appendices which deal specifically with stainless steel:

- Appendix S *Austenitic Stainless Steel Storage Tanks*
- Appendix SC *Stainless and Carbon Steel Mixed Materials Storage Tanks* (provides requirements for mixed stainless/carbon steel in the same tank for shell rings, bottom plates, roof structure, and other parts of a tank requiring high corrosion resistance)
- Appendix X *Duplex Stainless Steel Storage Tanks*

EN 14015 (52)

This European Standard specifies the requirements for the materials, design, fabrication, erection, testing and inspection of site built, vertical, cylindrical, flat bottomed, above ground, welded steel tanks for the storage of liquids at ambient temperatures and above. It applies to closed-top tanks, with and without internal floating covers and open-top tanks, with and without floating roofs. Austenitic, duplex and ferritic stainless steels are within the scope of this standard.

EN 1993-4-2 (53)

This is part of EN 1993, Eurocode 3, dealing specifically with the design of steel tanks. Austenitic and duplex stainless steel tanks are covered.

There are significant differences between the three standards. The design recommendations in the first two standards are based on allowable stress principles whereas the design guidance for structural stainless steel given in all parts of Eurocode 3 is based on limit state principles. Interaction between allowable stress and limit state codes is not straightforward because the limit state code requires partial factors on loading and strength which are not normally defined explicitly in an allowable stress code.

6.3.3 Welded rectangular tanks

Although rectangular tanks are not as structurally efficient for containing liquids as cylindrical tanks, there may be many situations where a rectangular form is more suitable, either for service reasons in dealing with the water or for siting reasons.

There are no specific standards applicable to rectangular stainless steel tanks. The standards for cylindrical tanks may be used as a basis for design, especially for some of the details, but EN 1993-1-4 should be used for the actual structural design of the tank.

Rectangular tanks can be formed from profiled panels or stiffened plate.

For stiffened plate construction, the plate forming the shell acts like a wide beam between support lines which are either stiffeners or the other walls of the tank. The plate can then be designed according to the recommendations in EN 1993-1-4 for members in bending. Vertical stiffeners should be supported by ring frames or ties at the top and bottom of the tank and welded to the shell plate. They may be designed as simply supported beams.

6.3.4 Pressure vessels

Pressure vessels in stainless steels should be constructed to the requirements of the appropriate design code: in the EU the Pressure Equipment Directive 2014/68/EU (PED) sets out the standards for the design and fabrication of pressure equipment. EN 13445 (54) provides rules for the design, fabrication, and inspection of austenitic, duplex and ferritic pressure vessels and replaces BS 5500. However, BS 5500 is retained as PD 5500 (55) for the design and construction of export equipment. EN 10028-7 is the material specification for stainless steels for pressure vessel applications (56).

Additionally, Part VIII of the ASME Boiler and Pressure Vessel Code (BPVC) (57) is widely used to design stainless steel pressure vessels.

6.3.5 Bolted tanks

Large cylindrical stainless steel bolted tanks may be used for a variety of applications in the water industry. They are usually constructed on site by bolting together individual stainless steel sheets up to 2 m wide. The sheets are not curved prior to erection. The segment construction allows the parts to be easily transported and avoids scaffolding. Assembly is from top to bottom with ring stiffeners giving the tank stability during installation. The procedure begins with the top ring of the tank. Once the top ring is complete, it is lifted and the next ring constructed beneath it. The tank wall is secured with an anchoring system onto the base and permanently sealed. At the end of the service life, the tank can be dismantled, cleaned and re-assembled in another location. By comparison, large welded tanks can present practical challenges i.e. transport, on-site welding, quality control, lifting etc.

Stainless steel bolts must be used to connect the stainless steel sheets, and they must have at least as good corrosion resistance as the sheets being connected. For example, if the tank is made from 316 type sheet, then the bolts should be grade A4 in accordance with EN ISO 3506. Where the stainless steel sheet material is operating close to its chloride limit (200 mg/L for 304L and 1,000 mg/L for 316L) then crevice corrosion of the bolts is a risk. One solution is to use a higher alloy grade for the bolting (including nuts and washers), so that A4 would be used with 304L and duplex 2205 with 316L.

Another solution is to seal each bolted connection to prevent crevice corrosion and leakage. It is essential that the sealant 'wets' the surface because crevices can be formed if it dries and shrinks. Care is needed in choosing the right sealant to ensure satisfactory long-term performance under the operating conditions in contact with the contents of the tank. Sealants may take the form of semi-rigid gaskets or adhesives. A semi-rigid gasket can be made of neoprene, nitrile, silicone, or other similar material and has firm outer edges around a pliable inner surface. PTFE should not be used as it creates a tighter, more aggressive crevice than a metal-to-metal seal. Modern sealants are anaerobic adhesives that cure under the air-free conditions in the crevice. It is important to select an adhesive that is resistant to water and is industry-acceptable if it is in contact with drinking water. It is also important to select an adhesive that has an appropriate release torque so that a bolt can be undone if required. It is suggested that a dialogue with adhesive manufacturers be established to select the most suitable grade. It is important that all mating surfaces are, clean, dry and grease-free before applying adhesive.

Sealant should be applied around the underside of the bolt head, and beneath the washer on the outside of the tank. Adequate ‘squeeze out’ of the sealant should be ensured when the bolts are tightened to the correct torque. The sealant around the bolt head and sheet joints/edges should be regularly inspected for hardening, cracking, lack of adhesion or chemical degradation.

Depending on the contents of the tank, an internal synthetic butyl or EPDM rubber membrane liner may also be used.

6.4 Linings and membranes

To counter specific corrosion conditions, stainless steel sheeting can be used to line either existing or new concrete vessels, or for groundwater separation membranes.

Both circular and rectangular vessels can be lined (‘wall-papered’) using methods generally accepted within the pulp and paper industry. The lining forms a clean and hygienic surface. Typical thicknesses vary from 2 – 3 mm. There are established techniques for the application of linings, based on welding sheets onto pre-fixed stainless steel backing strips (58).

6.5 Pipework systems

Pipework systems, as with pressure vessels, are designed to contract requirements in accordance with industry, national and international design standards. Selection of piping systems is dictated by operating conditions and cost considerations. The following systems of stainless steel process piping are commonly used, each having its own attributes and benefits:

ANSI – Traditionally used worldwide as the standard for process piping systems. It was developed from American carbon steel specifications for high pressure and temperature requirements.

ISO – The international standard for process piping utilising ANSI outside diameter sizes but with more appropriate wall thicknesses reflecting the strength and corrosion resistance of stainless steel. The lighter sections can offer cost savings.

Metric – This system is characterised by having a uniform bore diameter through tube and fittings for any one specified pipe size from 15 - 1600 mm internal diameter, with wall thicknesses between 1-8 mm. The lower wall thicknesses can confer significant cost savings. It offers a lightweight design solution where free flow of liquids and semi-solids is required at low to medium pressure.

EN 10312 (59) is generally for use with capillary press and compression systems.

Table 6-2 gives typical national/international standards for design, dimensions and testing (Appendix B gives the titles of these standards).

Table 6-2 Examples of combinations of standards for stainless steel process piping systems

System	Grade	Design standard	Dimension	Testing
ANSI	TP304L TP316L	ASME B31.3	ASME B36.10	ASTM A312
ISO	1.4307 (304L) 1.4404 (316L) 1.4432 (316L HiMo)	EN 13480-3	EN ISO 1127	EN 10217-7 EN 10296-2
Metric	1.4307 (304L) 1.4404 (316L) 1.4432 (316L HiMo)	EN 13480-3	EN ISO 1127	EN 10217-7 EN 10296-2

Duplex and higher alloy austenitic stainless steels may be appropriate for pipework in areas where enhanced corrosion resistance is required or where it is appropriate to utilise the higher strength of these alloys.

6.6 Design for fabrication

The principle of *design for fabrication* is that the contract specification is converted into a design which can be built efficiently. This affects all aspects of fabrication, including documentation, and involves ensuring that the work in progress is maintained at an efficient and steady level.

It is essential that production routines, welding and fabrication, NDE requirements and quality should be considered in the design phase. The interrelationship of these factors has a direct influence on cost as well as the ease of construction, commissioning and handover to the owner.

Every opportunity should be taken to locate welds in such positions that the welder has good access to produce smooth, sound welds. For example, use a rolled edge to eliminate a corner or lap joint, as shown in Figure 5-5. Also, the high ductility and work hardening characteristics of the austenitic stainless steels allow tees in pipework to be made by means of a simple circumferential weld onto material 'pulled' from the tube wall. This avoids the joint preparation and welding associated with a conventional tee joint, where the side-piece penetrates into the tube.

Thin-skinned structures, especially flat plate for tankage or architectural applications, can experience unacceptable fabrication-induced buckling distortion unless there is close liaison between design and fabrication engineers. Structural design must take into account fabrication stresses as well as plate thickness and material physical properties if flat surfaces are to be produced. Heat line straightening techniques that may be appropriate for carbon steels should not be used to correct distortion in stainless steel. Correct fabrication first time is crucial.

It is essential that the designer, materials/welding engineer and fabricator work together closely in converting the contract specification to an engineering specification and drawings for construction and installation.

EN 1090-2, the European specification for fabrication and erection of structural carbon and stainless steel, gives requirements for storage and handling, forming, cutting, joining methods, tolerances, and inspection and testing (60). EN 1090-2 covers cold formed and hot finished austenitic, duplex and ferritic stainless steel products. Specific guidance just for stainless steels, based on this standard, is also available (61).

SUMMARY OF SECTION 6

The structural design principles for stainless steels differ from those for carbon steel, mainly with respect to buckling behaviour and deflection under load.

Design guidance is available for stainless steel structural members and tanks.

Stainless steel sheeting can be used to line existing or new concrete vessels.

The three stainless steel process piping systems in common usage are the ANSI, ISO and Metric systems.

Ease of fabrication must be considered throughout the design phase; the contract specification must be capable of being converted into a design which can be built efficiently and effectively.

7 FABRICATION, INSTALLATION, MAINTENANCE AND INSPECTION

To ensure that the full benefit is obtained from using stainless steel, best practice should be adopted at all stages of plant construction, commissioning and operation. Having been careful to select the optimum grade of stainless steel and to design the plant to use it to best effect, care is also needed in fabrication, installation, maintenance and inspection. This section describes good practice at those stages.

7.1 Fabrication

While fabrication of stainless steels presents few problems and uses methods broadly similar to those for carbon steels, it is important to be aware of the differences and to follow the specific advice given in this Section to obtain optimum performance. The dominant factor at all stages is maintaining the self-healing property of the surface oxide film, which is responsible for the excellent corrosion resistance of stainless steels. A secondary factor is their relatively high work hardening rate, requiring more powerful and rigid forming equipment than that for lower-alloyed materials.

Due to the simple structure of the austenitic stainless steels, there are no complex metallurgical considerations to be taken into account in welding them. Duplex stainless steels, on the other hand, have a mixed structure of austenite and ferrite in approximately equal proportions; this structure is affected by welding, and procedures have to be adapted to compensate for this. Similarly, welding procedures for the super-austenitic stainless steels are more complex than those for the simpler austenitic steels.

The recommendations in this Section are appropriate for material up to about 6 mm thick, covering the majority of the stainless steel components encountered in the water industry. The general principles apply to thicker materials but there may be specific factors and effects that are not dealt with here. Advice is readily available from manufacturers of the steels and from producers of welding consumables.

7.1.1 Materials handling and storage

Apart from preventing superficial damage from abrasion or apparently harmless actions such as walking over the surface of sheet or plate, it is of the utmost importance to avoid contamination of the steel surface, that is, the deposit of foreign materials such as metal particles, grit etc. which can be embedded into the surface. These surface inclusions can physically affect corrosion resistance by forming a crevice; in the case of carbon or low-alloy steel contamination, which is manifested by rusting within a short period of exposure, they can react with chlorides from dust in the atmosphere to accelerate the corrosion rate. The presence of iron on the stainless steel surface can be verified visually as a rust stain by spraying the surface with water and leaving it overnight. The faster ferroxyl test (62) will give certainty that there is no residual iron on the surface, but surface staining is normally an adequate guide.

It is therefore essential that work areas for processing stainless steels are segregated from those for carbon and low-alloy steels to prevent contamination. Apart from direct contact, there are numerous sources of contamination by such steels, such as grinding operations that project abraded material over significant distances, or working with hand tools previously used with lower-alloyed steels, that can cause particles to deposit and adhere to stainless steel surfaces. Operations such as cutting and forming of carbon steels can leave traces on tooling that can be transferred to stainless steels processed on the same equipment. Ideally, separate equipment should be provided in the stainless steel work area. If this is not possible, steps should be taken to clean the equipment directly, or indirectly, for example, by initially processing scrap stainless steel to remove adherent carbon steel deposits before the main operation; an alternative is to protect the material by local application of adhesive plastic films or tape.

Material should preferably be stored under cover; if kept in the open air, it should be protected to avoid the accumulation of dust and deposits, particularly in industrial or marine locations. When it is stored on racks, contact with the steel structure should be prevented by inserting timber, cardboard etc. between the stainless steel and the support, to prevent contamination and surface abrasion that can transfer steel to the material surface. While carbon or low-alloy steel embedded in the surface of the stainless steel will quickly rust and be unsightly, in initiating localised corrosion of the stainless steel, it may ultimately cause penetration through the material thickness. Paint marking is inadvisable and it must be possible to remove temporary markings (to be made with low-chloride marking inks) completely, especially in areas adjacent to welds. Stainless steel slippers or wooden packers, for example, should be used on fork-lift trucks to prevent contamination, and similar precautions should be taken with lifting equipment.

To avoid potential MIC it is good practice to temporarily store stainless steel components on wood to keep the material off the ground.

7.1.2 Cutting

Stainless steels can be guillotined, sheared and sawn using standard machine tools. When shearing or guillotining, the capacity of the equipment should be downrated by 50–60% relative to carbon steels, to accommodate the relatively rapid work hardening rate of austenitic and duplex stainless steels. Blades should be true and sharp and the clearance between them should be maintained at 3–5% of the plate thickness. The cut edges should be examined for contamination and, particularly if there will be subsequent cold work, should be dressed smooth. Abrasive cutting can be used, preferably wet to avoid overheating of the material.

When sawing stainless steel, sharp high speed steel or carbide-tipped blades should be used with cutting fluids, sawing at slow to moderate speeds. For thicknesses of 3 to 6 mm, blades with approximately 10 tpi (or more) are appropriate. Sawing efficiency will be considerably improved by ensuring that, on the return stroke, the blade does not drag in the groove; it must lift clear of the cutting face to minimise work hardening effects.

Oxy-fuel cutting is not feasible - chromium interferes with the exothermic reaction between iron and oxygen - but plasma cutting, preferably on a water table, is appropriate; laser cutting is also possible and advantageous for forming profiles. Nitrogen can be used as the assist gas to produce oxide free edges. The kerf and heat affected area should be removed before further processing is undertaken. Waterjet cutting produces excellent quality cuts and can be readily automated. Its flexibility enables small series cutting operations.

Cutting and sawing can generate and redistribute residual stresses within a component, resulting in distortion, which can be particularly significant in thin walled pipework. Pipe ends are gauged to size and roundness, but this gauging does not extend beyond the mill length ends. A cut end may show ovality, which is relatively easy to accommodate during prefabrication by using a clamp to round up the cut end. On site, it is helpful to use mill ends for tie-in and similar welds.

7.1.3 Forming

Cold forming with standard equipment is generally appropriate for thicknesses up to about 8 mm. As with cutting and shearing, cold forming equipment for stainless steels needs to be of adequate rigidity and power to cope with the higher work hardening rates. Generally, the maximum thickness handled in standard equipment must be downrated by about 50% for austenitic stainless steels, and more for duplex steels (63), compared with structural carbon steels. Allowance must be made in bending and rolling for the greater springback characteristics of stainless steels.

Dished heads can be pressed and spun on standard equipment. Multiple sheets are often pressed simultaneously, subject to machine capacity. It is important not only to avoid contamination of the stainless steel by the press head but also to prevent the sheets from damaging one other, usually by means of plastic interleaving.

Branches can be formed in thin-walled pipe, using appropriate equipment for what is often termed ‘pulling tees’. The advantages are that butt welds are eliminated at the branch location and that the smooth transition improves flow and prevents the entrapment of entrained material that might otherwise occur at the branch weld.

Pipe spooling in the workshop should always be preferred to bending and other fabrication activities on site, which potentially lead to poor results, due in part to the difficulty in providing the clean conditions and the control of welding conditions required for high quality welds.

7.1.4 Machining

The main factor governing the machinability of stainless steels is their work-hardening rate. Practical measures therefore emphasise the sharpness of tools and relatively high feed rates. Tools should be made of high speed steel or have cemented carbide tips, which may be disposable inserts. Machines should be rigid and tools should be well supported to avoid vibration which could lead to chipping of the tools. Tools are designed to maintain the sharp edge and to avoid rubbing the workpiece (thereby causing work hardening and making further progress difficult); they should be designed to prevent contact of the tool flanks with the workpiece while offering adequate support to the cutting edge. When cutting, feed rates should be relatively high, to reduce work hardening. These aspects are particularly relevant to the duplex stainless steels, which require higher cutting forces than the austenitic stainless steels. The flow of cutting fluid should be generous, to cool the tool and minimise thermal stresses. Further information is available on machining characteristics from producers of the steels and from tool manufacturers.

Re-sulphurised, free machining versions of the standard grades of austenitic stainless steels are available *e.g.* 1.4305 (303). However, the high sulphur contents of these steels cause a significant reduction in corrosion resistance, particularly where the cut edge is exposed. This disadvantage is avoided to some extent by proprietary grades based on 304, 316 and duplex 2205 stainless steel, which possess sulphur on the high side of the respective composition, but are treated to control composition, size, shape and distribution of the non-metallic inclusions (sulphides and oxides) to give improved machinability. These offer a better compromise between machinability and corrosion resistance.

7.1.5 Welding

Recommendations for the arc welding of stainless steels are given in EN 1011-3 (64). Austenitic and duplex stainless steels can be readily welded by all conventional processes, whether manual or automatic.

All welding requires the adoption of safe working practices. In addition to the hazards associated with electrical aspects of welding, arc welding generates fume, which represents a respiratory hazard. The quantity and chemical composition of the fume depend on the filler metal selected and the welding process, The level of protection required for the welder and others in the workplace is defined in the UK by statutory exposure limits (WELs) for individual components of the fume. Guidance on the measures necessary to comply with these limits is given in a series of leaflets published by the UK Health and Safety Executive (HSE) (65).

For welds to be of consistently high quality, it is essential that a welding procedure specification (WPS) is drawn up for each type of weld, containing sufficient details to enable any competent person to apply the information and produce a weld of acceptable quality. The content of such a specification is defined by an international standard EN ISO 15609-1 (66). EN 15614-1 (67) provides for welding procedure tests while EN ISO 9606-1 (68) covers qualification tests for welders themselves. Table 7-1 lists some of the factors which should be defined when welding stainless steels.

Table 7-1 Factors to be defined when welding stainless steels

Prior to welding Selection of welding process and consumable Weld and joint types Joint design Weld preparation Pre-cleaning	**Welding** Preheating Welding parameters Sequence of passes Interpass temperature Shielding and backing gases
Post-weld treatment Cleaning and finishing operations Removal of heat tint	**Inspection** Visual Non-destructive testing

Preparation for welding

Selection of the welding process is based on the thickness of the material, the position in which it is to be welded, the location where welding is carried on, and the length of the weld. For thinner materials, the gas-shielded tungsten arc (TIG/GTAW) process is appropriate and produces high-quality welds, although it is not always suitable for site welds, where shielding gas coverage can be imperfect unless special measures are taken. The manual metal arc process (MMA/SMAW) is versatile and can be used on site and in all positions, while the gas-shielded metal arc process (MIG/GMAW) is economical for long welds. In general, it is preferable to produce sub-assemblies in the workshop and to limit the amount of site welding to a reasonable minimum. Conditions in the workshop are conducive to good and consistent quality and automatic welding can be applied, for which the gas-shielded processes are suitable and economical.

Filler metals

It is possible to make welds in material less than about 3 mm in thickness without using a filler metal but this is not advisable, since optimum corrosion resistance is only obtained by the use of a filler metal; this is particularly the case with the duplex stainless steels. Welding consumables are designed to deposit weld metals with a metallurgical structure similar to that of the material being welded while being adjusted in composition to compensate for any inadequacy of corrosion resistance due to their essentially cast structure. International standards cover stainless steels (69) (70) and nickel alloys (71) (72). Table 7-2 shows standard specifications for covered electrodes and bare filler wires for welding grades of austenitic and duplex stainless steel.

Table 7-2 Standard specifications for covered electrodes and bare filler wires

Steel Grade			
	Covered Electrodes		
	AWS A5.4/5.4M:2012 **AWS A5.11/5.11M:2010**	**EN ISO 3581:2016**	**EN ISO 14172:2015**
304L	E 308L	E 19 9 L	
316L	E 316L	E 19 12 3	
316Ti	E 318	E 19 12 3 Nb	
22%Cr Duplex	E 2209	E 22 9 3 N L	
25%Cr Superduplex	E 2594	E 25 9 4 N L	
6% Mo Super-austenitic	E NiCrMo-3 E NiCrMo-10		E Ni 6625 E Ni 6022
	Bare wires		
	AWS A5.9/A5.9MM2010	**EN ISO 14343:2017**	**EN ISO 18274:2010**
304L	ER 308L	W 19 9 L	
316L	ER 316L	W 19 12 3	
316Ti	ER 318	W 19 12 3 Nb	
22%Cr Duplex	ER 2209	W 22 9 3 N L	
25%Cr Superduplex	ER 2594	G 25 9 4 N L	
6% Mo Super-austenitic	ER NiCrMo-3 ERNiCrMo-10		S Ni 6625 S Ni 6022

<u>Austenitic stainless steels</u>

Filler metals for austenitic stainless steels are designed to deposit weld metals slightly over-alloyed when compared to the steel, to compensate for segregation in the weld structure, and also to ensure the presence of a small proportion of ferrite to counteract the susceptibility of austenitic weld structures to micro-cracking in restrained or thick joints.

Duplex stainless steels

It is essential that the weld has the austenite + ferrite structure that characterises the duplex stainless steels. In the wrought steel, this is obtained by a heat treatment process, which is not normally feasible for welded joints, though the weld metal would solidify with a completely ferritic structure if it had the same composition as the steel. However, by increasing the nickel content of the filler metal, typically by 2-4%, it is possible to obtain the required structure. While the proportion of ferrite cannot be controlled closely, it is normally within a range of 30-60%.

Apart from this adjustment, filler metals for all grades of duplex steel deposit weld metals of similar composition to the related steels. While filler metals have been designed specifically for some of the lean duplex stainless steels, it can be convenient to use 2209, the matching filler metal for 2205.

Super-austenitic stainless steels

Weld metals of similar composition to the super-austenitic steels have inferior corrosion resistance, due to segregation of alloying elements in the weld structure. Therefore nickel-base alloy filler metals are preferred, particularly the nickel-chromium-molybdenum alloys (71) (72).

Weld preparations

For the range of thicknesses under consideration here, a single-V preparation is normally used, with an included angle of 60-70°, when welding is from one side only. In general, bevels are wider, root faces are smaller, and root gaps are wider than for lower-alloy steels, to compensate for the poorer penetration characteristics of stainless steel filler metals. The preparation should be machined, to avoid the inevitable variability of manually ground preparations. It is essential that dirt, oil and grease are removed from the surface of the material up to 50 mm either side of the weld preparation, along with contaminants such as paint and crayon markings; these may contain sulphur or lead, which can cause welds to crack. A non-chlorinated solvent should be used, such as acetone; a subsequent check by wiping with a clean cloth can give an assurance of cleanliness.

Welding

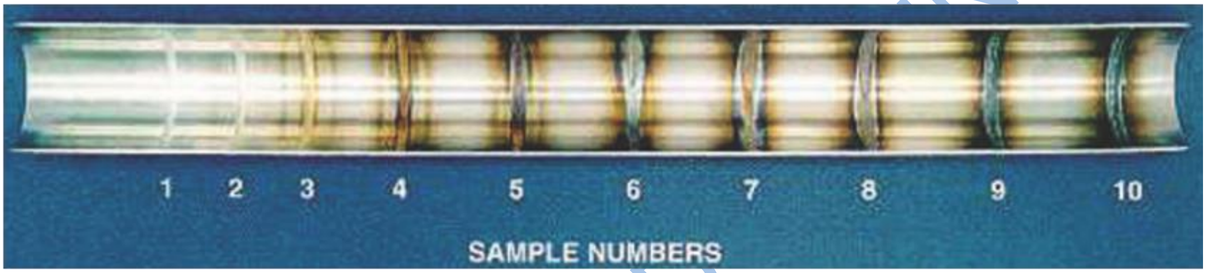
No preheat is required when welding austenitic and duplex stainless steels, but in some circumstances, it may be necessary to apply heat to remove surface moisture, limiting the temperature of the material to no more than about 100 °C.

Initially, tack welds 10-15 mm long should be inserted in a staggered sequence to maintain the components to be welded in position and to avoid distortion, since the austenitic stainless steels have a relatively high coefficient of expansion; tacks should be ground before the weld is made.

The welding procedure for austenitic stainless steels should avoid heat build-up, by the use of moderate heat inputs and maintenance of an interpass temperature no higher than 150 °C. For duplex stainless steels, heat input should be controlled to ensure that the weld and HAZ have the required structure. Thus very rapid cooling, that might occur with a small root run or an arc strike may result in fusion zones and a HAZ which are excessively ferritic with a corresponding loss of toughness and corrosion resistance. Slow cooling through the red-heat temperature range may lead to the formation of unwanted intermetallic phases, with similar loss of toughness and corrosion resistance. Duplex 2205 can nevertheless be welded at relatively high heat inputs, while maintaining a maximum interpass temperature of 150 °C , while slightly lower heat input is required for the lean and superduplex grades, for which the interpass temperature should be less than 100 °C (to avoid the risk of detrimental precipitation in the HAZ). The measurement should be made with a contact pyrometer rather than temperature indicating crayons, which would leave contaminating residues on the material surface.

Where thin flat sheet is welded from one side, a ceramic backing bar can be used to control penetration, but it is preferable to use a grooved copper bar with provision for supplying inert gas, to prevent oxidation. For pipe welding, it is particularly important that oxidation in the bore is minimised and weld penetration is uniform, since this region is exposed to the flowing medium. This is achieved by initially flushing the interior of the pipe with a dry inert backing gas to expel air, at least from the vicinity of the joint, and thereby to reduce the oxygen content, which is monitored with a meter. Welding can commence when a specific oxygen level has been reached and gas flow is maintained at least until several layers have been deposited over the root run.

The effect of residual oxygen is shown in Figure 7-1 (73), in which the oxide thickness has been varied by control of oxygen concentration in the bore of a tube into which autogenous weld beads have penetrated, analogous to a pipe joint with an imperfect purge. Heat tint is the visible evidence of oxidation at high temperature, as interference colours ranging from blue-black, where the oxide is thickest, to straw colour, where it is thinnest. The chart is intended to form the basis of a specification defining a backing gas oxygen limit (74) (75). For the water industry, a light straw colour has been found to be acceptable, representing an oxygen level in the backing gas of about 50 ppm (example 3 in Figure 7-1).



Concentration of oxygen in ppm added to the pure argon backing gas of each sample:

No.1: 10 ppm
No.2: 25 ppm
No.3: 50 ppm
No.4: 100 ppm
No.5: 200 ppm
No.6: 500 ppm
No.7: 1000 ppm
No.8: 5000 ppm
No.9: 12,500 ppm
No.10: 25,000 ppm

Figure 7-1 Heat tint produced in bore of 316L stainless steel tube at different oxygen levels
(Heat tint increases from left to right.)

A number of dam systems are available to confine the volume of gas required to a region adjacent to the weld, such as inflatable bladders and water-soluble paper dams. The latter are useful when there is no access after welding, for example to closing welds. External ingress of air through the root gap of the weld preparation can be prevented by use of adhesive tape which is removed as the weld progresses. Without such protection, the root bead is unlikely to penetrate fully and may be heavily oxidised; the aim is to obtain a smooth, slightly convex bead that forms a gentle transition with the pipe internal surface, to prevent interruption of flow and the accumulation of solids in service. Normally, argon is used as the backing gas but nitrogen may replace argon or be added to it for duplex stainless steel welds, to compensate for the loss of nitrogen from the weld deposit. It is also possible to add about 2-3% of nitrogen to the shielding gas for a root run made by the TIG/GTAW process (more would damage the tungsten electrode).

Deposits must be carefully cleaned between passes to remove slag residues and excessive oxidation. Since it is exposed to the ambient conditions in service, the capping pass is particularly important, and should not be excessively convex and should be free from undercut and gaps, slag residues etc.

7.1.6 Post-weld treatment

Post-weld heat treatment is not required for austenitic or duplex stainless steels. There is a range of surface defects that may have been caused during handling, preparation and welding (Figure 7-2), including areas of slag, formed particularly by the fluxed welding processes, and weld spatter, which represent crevices that may promote corrosion in subsequent service. These must be eliminated by careful grinding to a fine finish. It is essential to remove the heat tint that inevitably occurs on and adjacent to the weld (and on areas more remote that have been at a high temperature, for example the back of a plate having a fillet-welded attachment on the other side). On the external surface of a weld, the heat tint ranges from blue-black colouration on and immediately adjacent to the weld to straw colour where it is thinnest, in areas more remote from the weld. Oxidation removes chromium from the underlying steel and thereby reduces its resistance to corrosion.

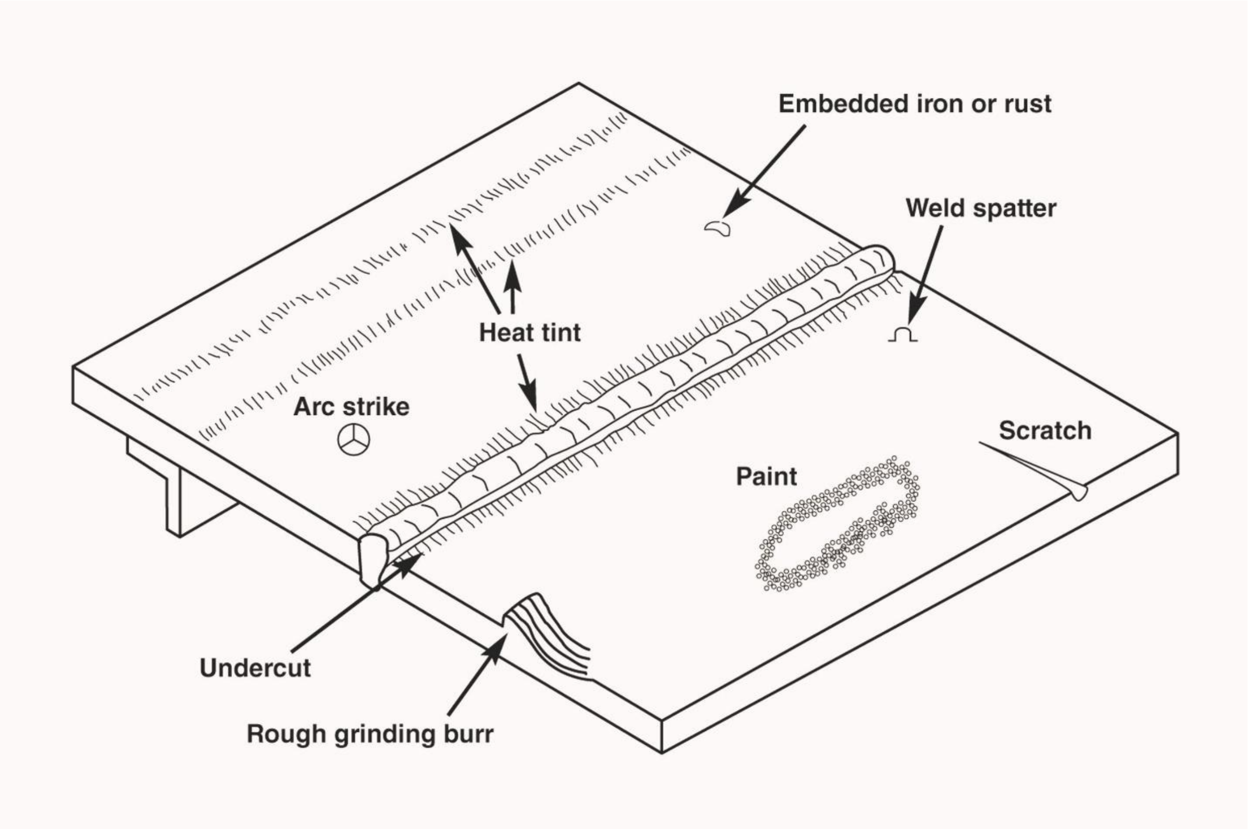


Figure 7-2 **Potential surface defects on stainless steel fabrications**

Figure 7-3 shows corrosion of weld spatter on a 304L pipe in a rural atmosphere.

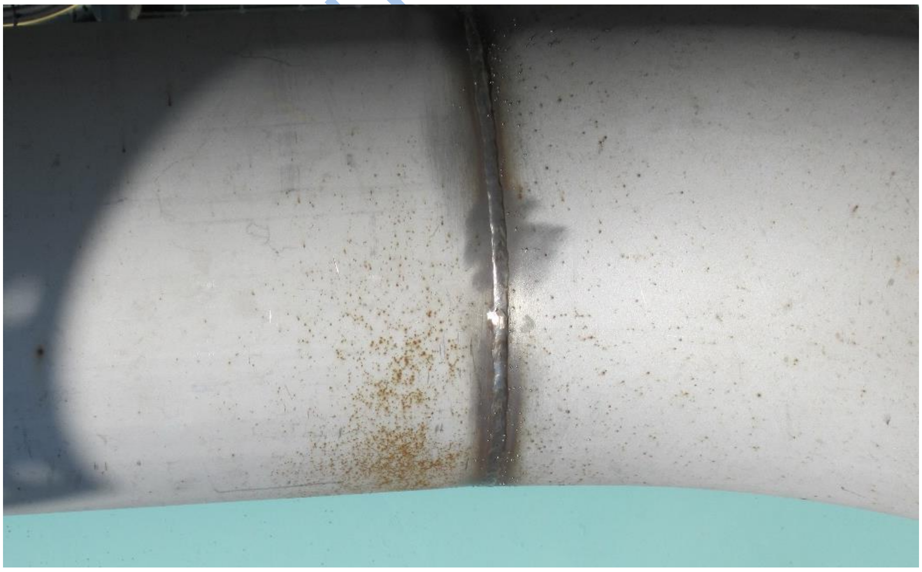


Figure 7-3 **Corrosion of weld spatter**
(© Roger Francis)

When removing heat tint, hand brushing (for which it is essential to use stainless steel brushes, to prevent contamination) may appear to remove damaged material but is unlikely to be completely effective; flapper wheels, which have multiple sheets of abrasive, are more suitable. Light grinding to a fine finish (220 grit or better), or possibly glass bead blasting, can restore a large measure of corrosion resistance. However, chemical treatment is necessary to achieve the full potential of the original material.

Fabrications of a suitable size can be pickled in a bath of a nitric/hydrofluoric acid, typically 10-25% nitric acid with 0.5-3.5% hydrofluoric acid, to remove a surface layer of the steel (less than 0.025 mm), to dissolve the chromium-depleted layers and remove contaminants. Larger assemblies can be sprayed with an acid mixture in thixotropic form; this is usually carried out by a specialist contractor, who is able to remove the used chemicals and water safely. More conveniently, there are proprietary pickling pastes and gels, which can be applied by brush for the prescribed treatment period. Duplex and super-austenitic stainless steels are more difficult to pickle than the basic austenitic steels and require longer treatment times for removal of oxides.

Once the steel has been treated and the residues of the pickling substance have been completely removed by rinsing, the steel undergoes passivation, that is, the reforming of the uniform layer of chromium oxide (actually a complex chromium-iron oxide layer) on the surface. In a normal atmosphere, this process commences immediately and the layer is mature after a day or two. In this condition, it is quite suitable for applications in the water industry. It is also possible to carry out passivation chemically (76) in a nitric acid bath. Proprietary passivation agents can also be sprayed onto the fabrication surface to accelerate the reformation process. Such treatments are used, for example, for parts that have been contaminated during machining and for applications exposed to solutions likely to cause localised corrosion.

For especially demanding applications, components can be passivated by electropolishing (77) in a process that reduces the relative roughness of a surface, producing a highly reflective finish which provides enhanced corrosion resistance. Although it is normally applied after pickling, the process is capable of removing free iron and heat tint on the stainless steel surface. This technique is applied where hygiene or chemical contamination is of critical importance. There is also a technique known as electrochemical cleaning, in which a hand tool comprises an electrode with a sponge head to which an electrolyte is fed; the fabrication forms the other electrode, and both are connected to a portable AC or DC source. The process is claimed to produce a clean and passivated surface. A range of equipment is available commercially.

7.1.7 Weld inspection and acceptance

There is a range of standards relating to the qualification of welders and inspection of welds to ensure that they are of the quality required in the application. For example, EN ISO 5817 (78) sets out quality levels that can be applied to a wide range of welded fabrications.

The essence of the standards is that welders must be familiar with the specific requirements for the stainless steels to be welded and competent to produce welds that are free from the surface imperfections, such as undercut, that can increase the susceptibility of fabrication to localised corrosion. Visual examination is therefore the basis of inspection and can be supplemented by liquid penetrant testing and radiographic examination where necessary. In the case of duplex stainless steels, assurance of the ferrite level, expressed as the ferrite number, FN, can be obtained using a meter, such as the ‘Feritscope’®.   .

[Note; Feritscope is a registered trademark of Fischer Instruments, Germany.]

7.2 Installation

7.2.1 Site fabrication and installation

Site fabrication should be minimised by prefabrication and pipe spooling in the workshop. Prefabricated assemblies should be protected from dust, mechanical damage and the ingress of contamination by the use of covers and end caps prior to final assembly. Temporary coverings should be used to protect assemblies from grinding, concrete and masonry dust. Under no circumstances should mortar cleaners based on hydrochloric acid be used on stainless steels. If surface dust contamination is heavy, stainless steel components should be thoroughly washed down during construction.

While mechanical connections can be provided, it is usually necessary to make some welds on site, necessitating similar procedures to those recommended above. Material and prefabrications should be protected in storage and contact with structural members should be avoided to prevent iron contamination. If embedded iron or iron staining is encountered, then it should be removed by local treatment with a pickling agent or a passivation product can also be used. Prior to making pipe welds, the oxygen level in at least the region of the joint must be reduced by purging with an inert gas, using the methods described earlier and to the same standard.

At the end of installation, plant should be washed down with potable water. Pipework systems should be flushed through to remove any debris and if left to stand empty prior to commissioning, washed with potable water and dried (23). Packaged units including stainless steel pipework systems will probably have been subject to cleaning, possible sterilisation, passivation and rinsing or drying treatments prior to delivery. Manufacturers will advise if such units require further treatment after installation.

7.2.2 Pipe burial

The same general principles for the handling and burial of carbon steel pipe apply to stainless steels (79). In assessing corrosion risks (80), the preliminary site survey must take account of soil chemistry as well as the possible presence of stray electrical fields. The risks of post-installation contamination, for example by de-icing salts for pipes laid under roads, should be assessed. Normal precautions must be taken against damage on lifting and laying. The prevention of dirt, contamination and small animals entering partly completed lines, and inadequate drainage are also necessary.

It should be remembered that stainless steel pipes, although very ductile, are likely to be of thinner wall section than ductile iron or some carbon steel equivalents, and they may not be protected by a wrap. Accordingly, it is essential to select an inert, smooth, fine bedding and back-fill material to avoid the risk of rocks or irregular stones denting the pipe wall on laying and covering. Suitable load-bearing performance for the restored surface must be established. See also Section 5.7.

7.2.3 Specialised protection, painting, minor fitments and insulation

Normally, stainless steel equipment is only painted externally for protection against a local chloride or aggressive solution (and where the risk of contact does not justify a material upgrade), or for identification/aesthetic reasons. Paint manufacturers will advise on the combination of surface treatment, primer and finishing coat combinations suited to a given environment. Initial surface preparation must observe the requirement to avoid contamination by iron. Thin gauge stainless steel surfaces may be distorted or damaged by conventional abrasive blasting operations that are normally used to provide a keying surface.

Coating systems used must take account of the water contact requirements of DWI where appropriate. A typical external coating specification for the environmental category C5 (81) (*Temperate and subtropical areas with very high pollution and/or significant chloride effects*) would be:

- Two pack epoxy or polyurethane primer suitable for stainless steel at 30–50 μm dry
- High build MIO (Micaceous iron oxide) at 100 μm dry
- Recoatable polyurethane finish at 60 μm dry.

Paints that contain metallic zinc should not be used on stainless steel as embrittlement of the stainless steel substrate can occur in the event of severe fire damage.

Painting any stainless steel structure internally or externally has an associated long term risk of crevice corrosion forming under the paint, even if a high quality paint system is used. If it is necessary to paint a stainless steel structure, then selecting higher grades of stainless steel will help to minimise the initiation of crevice corrosion underneath the paint coating.

If the reflectivity of a stainless steel component is unacceptable, then the surface can be shot peened using stainless steel balls, glass beads or ceramic balls to achieve a low reflectance surface.

The attachment of features such as identity tags or earth continuity leads to stainless steel components must be regulated, especially if made post-installation. The components in direct contact with the stainless steel should be made of a grade of stainless steel matching the corrosion performance of the parent material and fitted in such a way as to avoid crevices. If stud or tack welding is used, a clean finish is essential and the heat input should be adjusted to avoid heat tinting the inaccessible inner side of the component.

The risk of chloride-induced stress corrosion cracking (SCC) has been mentioned in Section 5.3.5, which outlines the selection of insulation and protection of pipework and tank systems that may operate at temperatures of above about 50 °C.

7.3 Maintenance

Although stainless steels are ‘maintenance free’, it is important to reiterate the points made in Section 5 about avoiding build-up of dirt deposits and crevice conditions on both the inside and outside of components. At non-coastal sites, free exposure to rainwater is often enough to keep most stainless steel components clean, with periodic washing down of shadowed or dribble regions as necessary. In marine, salt-spray environments, and in enclosed chambers where there is chlorine present in the atmosphere, regular wash-down procedures should be followed.

Repairs and modifications must be designed, specified and executed to the same standards as for the original equipment.

7.4 Site inspection

It is very unlikely that a problem of general corrosion (extensive and nearly uniform loss of section) will be encountered with stainless steels in water industry plant. Accordingly, conventional wall thickness checks using appropriate ultrasonic equipment will normally only be needed in regions which are subject to abrasive wear.

The main objective of inspection will be to check for any localised corrosion at critical locations. These may include, on external structures:

- Where there are dirt and deposit traps sheltered from rainwater washing, and regions exposed to evaporating liquids from leaks and dribbles.
- Any sites of brown staining. On newly commissioned plant this is often a result of undetected iron contamination that only becomes apparent early in the life of the plant. Once the iron contamination is detected and removed, this staining does not recur. Recurrent brown staining is an indication of the presence of a corrosive agent, such as a combination of chlorine gas and moisture.

Once the staining has been removed, a check should be made for the presence of localised pitting. This can be done with a ×10 or ×20 hand lens. A portable microscope with a suitable focussing mechanism capable of displacements in steps of the order of 0.002 mm can be used if it is necessary to measure micropit depths.

The same general principles apply to internal surfaces. The following should be checked:

- Areas under deposits in ‘dead’ areas and any ‘waterline’ markings in vapour spaces should be inspected after the removal of the deposits.
- Flange-gasket surfaces in systems carrying corrosive media should be checked periodically for crevice corrosion. Similarly, rubbing surfaces such as valve spindles and balls, or pump components, should be checked at a frequency advised by the manufacturer.

SUMMARY OF SECTION 7

Stainless steels can be cut, formed, machined and welded by standard methods practised throughout the steel fabrication industry.

It is important to maintain a high level of cleanliness at each stage of the fabrication and installation process to prevent surface contamination by iron and non-metallic particles, which can lead to surface rusting and staining and potentially to initiation of localised corrosion. Tooling and hand tools for forming and finishing stainless steels should be segregated from those for lower-alloyed materials.

Stainless steels work-harden more rapidly than carbon and low-alloy steels; therefore more highly-powered and rigid machine tools are required for forming operations, particularly on the duplex stainless steels. Allowance must be made for the relatively high springback of stainless steels.

Stainless steels can be welded by the common flux-shielded and gas-shielded processes. Welding procedures should be documented and welders should be qualified in welding these steels. Workshop fabrication is preferred where possible to reduce the necessity for site welding.

Surface defects and weld heat tint must be removed by mechanical and chemical post-weld treatment. Optimum corrosion resistance is obtained by pickling to remove heat tint.

During installation, stainless steels should be protected from contamination, dust, mortar/concrete splashes, mechanical damage etc. Once installation is complete, fabrications should be washed down with clean water. The interior of vessels and piping should be drained and dried before commissioning.

8 ECONOMIC BENEFITS OF USING STAINLESS STEEL

8.1 Savings in initial installed costs

Whilst the raw material cost of stainless steel is higher, weight for weight, than some alternative materials, the overall installed cost of plant which utilises stainless steel may be less. Savings can be achieved in many ways, including:

- Corrosion-resistant coatings are unnecessary, so there are no costs associated with applying them or maintaining their integrity during fabrication.
- Lack of corrosion results in reduced maintenance, so there is a reduced need for capital expenditure on stand-by plant.
- No corrosion allowance is needed (compared with cast iron or steel); lighter components can be used, which need less structural support and are easier and cheaper to transport, handle and install.
- Far easier to flush or clean pipework after installation
- Taking advantage of the high strength can allow thinner, lighter components to be used. With thin wall tubing, it may be possible to form tee joints by trepanning a hole and then pulling a lip on it.
- The resistance to erosion means that smaller bore, thinner wall pipes can be used.
- The use of standard grades and sizes can allow economy of scale during purchase.

8.2 Savings in operating costs

The prime reason for using stainless steel is that it will not degrade in service, thanks to its excellent corrosion resistance. This produces many operating benefits:

- Smooth surfaces lead to lower friction and less energy needed for pumping etc.
- Reduced inspection frequency and costs.
- Reduced maintenance costs; surfaces can be easily cleaned and kept hygienic due to a lack of corrosion. There is no risk of subsequent rusting after hosing down with water or steam cleaning.
- Repair or replacement of surface coatings is not necessary.
- Greater resistance to damage (accidental or caused by vandalism) leading to lower repair costs.
- Reduced downtime and cost of access for inspection, maintenance and repair.

8.3 Life cycle costs

There is increasing awareness that the life cycle (or whole life) costs, not just initial costs, should be considered when making decisions relating to new or replacement plant (82). This approach evaluates the cost of plant over its whole life in terms of:

- Initial or capital costs (materials, fabrication, installation).
- Operating costs (day-to-day running, inspection, maintenance, downtime, replacement etc.).
- Residual value (at the end of the plant's life).

For ease of comparison, it is usual to adjust all the future costs to present day values using a discount rate which encompasses inflation, bank interest rates, taxes and possibly a risk factor (in the event that the plant will be obsolete before the end of its design life).

Viewed in this way, stainless steel can often be an economical choice because the savings in operating costs far outweigh any higher material costs. Stainless steel components can be recycled at the end of their useful life but, despite their high residual scrap value, this is rarely a deciding factor for plant with a long projected life (for instance over 50 years) as the discounted value is then very small.

The two main difficulties with carrying out a life cycle cost study are determining the future operating costs and selecting the discount rate. When all the data are available, the calculation of the life cycle cost is straightforward. Euro Inox has published the results of studies comparing the life cycle costs of different materials for mechanical screens, travelling bridges and hand railing in an Italian waste water treatment plant (83). Significant cost savings arose from specifying stainless steel.

SUMMARY OF SECTION 8

Savings in initial installed costs: specifying stainless steel can lead to cost savings because neither protective coatings nor a corrosion allowance are required and the resulting thinner, lighter components are easier to transport and install.

Savings in operating costs: specifying stainless steel can lead to cost savings because of reduced inspection, maintenance and repair costs.

Life cycle cost studies evaluate the cost of plant over its whole life; stainless steel can often be an economical choice of material since the savings in operating costs can far outweigh higher initial capital costs.

9 SUSTAINABILITY AND STAINLESS STEEL

9.1 Sustainable development

"Development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" – that is the familiar definition of sustainable development (84). In our world today, sustainable development is a major issue. It comprises the three overlapping pillars, namely

a) economic growth
b) environmental protection
c) social equality

The use of stainless steels can enhance sustainable development in the water industry, and more broadly in society particularly in other usage sectors including construction, food & drinks preparation, healthcare, transport & mobility and process industries. Choosing stainless steels as a primary material reduces operational costs, reduces the overall use of resources, reduces the environmental impact of appliances and installations and safeguards human health.

As discussed in previous chapters, the major benefits of using stainless steel in the water and many other industries stem directly from its corrosion resistance. Products and components produced from stainless steels can be used without any additional corrosion protection, such as coatings. This choice generally saves cost and avoids environmental damage. The inherent corrosion resistance also means that the components will suffer minimum degradation in service and so have long, low maintenance, operational lives. These factors generally mean that using stainless steels gives lower overall life cycle costs, in comparison with alternative materials, when all the initial, operating, maintenance and end-of-life costs are considered. There are already established methodologies for undertaking life cycle cost analyses (82).

Stainless steels have very low leaching levels into water which have a minimal impact on water purity. Similarly, stainless steel equipment will not cause contamination of discharge water or the waste products from the water treatment process.

The properties and attributes of stainless steel can be exploited in the design of lightweight process plant which uses much less material. Furthermore, stainless steel process plant needs lighter supporting structures resulting in lower transport and erection costs.

All these impressive benefits reduce environmental impacts in additional to delivering economic benefits.

9.2 Evaluation of sustainability

The sustainability benefits which come from using a particular material must always be evaluated alongside the environmental impact of the production of the material itself.

Stainless steels are produced from a mixture of recycled and virgin raw materials. The major alloying elements namely Chromium (Cr), Nickel (Ni) and Molybdenum (Mo) are all valuable elements in their own right.

Consequently, stainless steels have a high residual value at the end of their long service lives. This ensures that wherever possible, items will be refurbished and reused, for example, tanks, pipes and pumps. Where equipment has to be scrapped, it can be returned to the melting furnaces by the mature and well-established scrap recovery route which has existed for many years.

Stainless steels are 100% recyclable, with no loss in quality. In 2019, the global average was that 70% of stainless steels available for recycling at the end of life were recycled as new stainless steels. Of the remaining 30%, around 26% was recovered through the carbon and low alloy steel recycling route (85).

“Recycled content” is often used as a sustainability measure but it is a misleading measure for stainless steels and many other metals and alloys which also have long service lives. For stainless steel, the average service life has been calculated to currently be around 20 years. Furthermore, there has been steady growth in use of stainless steel, in that world stainless steel melting in 2019 was 52.2 million tonnes and yet just 20 years beforehand it was around half that value. The growth in production and consumption of stainless steels has consistently been in excess of 5% year-on-year since 1980 (85) (86).

In summary there are insufficient ‘end-of-life’ stainless steel scrap products available for melting to meet today’s demand for new stainless steels. Process and manufacturing scrap are also recycled as they arise. In combination, the two stainless steel scrap categories show that the average global end-of-life recycled content is at around 37%. Some carbon steel scrap is also used in the production of new stainless steels which then raises the total average recycled content to around 48% (85).

Energy usage is an important sustainability parameter. Energy is a major cost for both raw material and stainless steel production so there are already strong economic pressures for production to be energy-efficient. This is another reason why new stainless steel production already uses all the available stainless steel scrap. With current production practice, 33% less energy is needed overall than if 100% virgin raw materials were to be used (87).

Production CO_2 emissions for stainless steels have a profile that is very different to that for carbon and low alloy steels. At a global average level the Scope 3 emissions from upstream raw materials production account for around 66% of the cradle-to-grave production emissions for stainless steels. However, there are two rather different stainless steel production systems in play today. The scrap-based system which is aligned to Europe, the Americas, Asia (other that China, Indonesia and India) is capable of delivering production emissions between 1.90 and 3.30 tonnes of CO_2 per tonne of stainless steel produced. The higher the recycled content the lower the emissions level. The Nickel Pig Iron (NPI) based system which is essential for stainless steel production today is reliant on the smelting of NPI which is currently highly fossil fuels intensive. This production system currently delivers emissions averaging around 7.3 tonnes of CO_2 per tonne of stainless steel produced. This average value is expected to fall in the coming years as renewable energy systems provide the needed electricity supply to the NPI smelting process (88).

Minimising environmental and human health impacts throughout the supply chain is receiving increasing attention, both to minimise costs and to achieve society’s expectations. Stainless steel industry associations and individual companies now produce assessments of environmental impact which can be used to make comparisons with other materials. A cradle-to-grave approach should always be used to make the most meaningful comparisons. Life Cycle Assessment (LCA) is a systematic approach to determining the environmental impacts of a product throughout its life cycle, including production, use and disposal phases. To enable LCA to be done on a sound basis, worldstainless (formerly ISSF) has published a Life Cycle Inventory (LCI) using the recognised ISO methodology for some standard stainless steel semi-finished products (89). The LCI includes inputs of water, energy, and raw materials, and releases to air, land, and water, and takes full account of the credits from recycling. Manufacturers are also now publishing Environmental Product Declarations (EPDs) for their products. All these data can be used in other assessments and rating methods, *e.g.* BREEAM, the UK Building Research Establishment Environmental Assessment Method for buildings and large scale developments.

Stainless steel is a well-established, well-understood, well-documented, widely available, commodity product. Whilst it is always necessary to evaluate each individual project, the characteristics and performance of stainless steel, make it a credible, sustainable candidate for use throughout water treatment, distribution and use installations.

SUMMARY OF SECTION 9

The inherent corrosion resistance of stainless steel enables it to contribute to sustainability in the water industry through its influence on water purity, reduced environmental impact, 100% recyclability and lower costs. This is reflected in cradle-to-grave Life Cycle Assessments and Life Cycle Costs for stainless steel products.

10 FURTHER READING

10.1 Corrosion and corrosion prevention

AVERY, R.E LAMB S, POWELL.C.A ,TUTHILL, A.H.
Stainless Steel for Potable Water Treatment Plant Nickel Institute Technical Series 10087. 1999. Available from www.nickelinstitute.org

BSSA
British Stainless Steel Association Technical Library: www.bssa.org.uk

DAVIES, M & SCOTT, PJB,
Guide to the Use of Materials in Waters, 2003, NACE International,

EURO INOX
Stainless Steel in Contact with Other Metallic Materials. Materials and Application Series Volume 10, 2009. Available from www.worldstainless.org

FRANCIS, R.
Galvanic Corrosion: A Practical Guide for Engineers. 2nd Edition. 2017. NACE International.

FRANCIS, R.
The Corrosion of Duplex Stainless Steels: A Practical Guide for Engineers, NACE International, 2018.

HEUBNER, U.
Performance of Stainless Steels in Waste Water Installations. Materials and Application Series Volume 13, 2010, Euro Inox. Available from www.edelstahl-rostfrei.de

WORLDSTAINLESS (formerly ISSF)
Stainless steel in Sewage Treatment Plants 2012 Available from www.worldstainless.org

KOBRIN, G & STOECKER, J.
A practical manual on Microbiologically Influenced Corrosion, , G. Kobrin, Ed., Vol 1, 1993, & J. Stoecker, Ed., Vol 2, 2001. NACE International, Houston, USA

OUTOKUMPU
Corrosion Handbook for Stainless Steels. Eleventh Edition 2015. Available via www.outokumpu.com/choose-stainless/stainless-basics/handbooks

POLLOCK, W. and STEELEY, C N .
Corrosion under wet thermal insulation. 1990 NACE International .

POWELL, C.
Stainless Steels – A Review of Important Considerations for Effective Applications in Waters, Australasian Corrosion and Prevention Conference, Adelaide, Australia, November 2002

SEDRIKS A.J
Corrosion of stainless steels, 2nd edition 1996, Wiley-Interscience ISBN 0-471-00792-7

TUTHILL, A.H
Guidelines for the selection of nickel stainless steels for marine environments, natural waters and brines. Nickel Development Institute, NiDI Technical Series 11003, 1987 Available from www.nickelinstitute.org

10.2 Welding and Fabrication

IMOA
Practical Guidelines for the Fabrication of Duplex Stainless Steel. 3rd edition.2014 International Molybdenum Association (available from www.imoa.info) (also Nickel Institute publication 16000 available from www.nickelinstitute.org

Practical Guidelines for the Fabrication of High Performance Austenitic Stainless Steels 2010 (available from www.imoa.info) (also Nickel Institute publication 16001 available from www.nickelinstitute.org

LIPPOLD J. C. and. KOTECKI D. J.
Welding Metallurgy and Weldability of Stainless Steels. Wiley-Blackwell 2005

OUTOKUMPU
Outokumpu Welding Handbook. 1st edition 2010 Available from www.outokumpu.com/choose-stainless/stainless-basics/handbooks
Outokumpu Sheet Metal Forming Handbook, 2017 Available from www.outokumpu.com

Welding metallurgy of Stainless Steel, Springer-Verlag Wien New York, first edition 1988 ISBN-13: 978-3-7091-8967-2

POWELL,C and JORDAN, D.
Fabricating Stainless Steels for the Water Industry. Nickel Institute Reference Book Series No. 11026. 2005 .Available from www.nickelinstitute.org

SCI
Design Manual for Structural Stainless Steel, 4th Edition, Steel Construction Institute 2017
Available from www.steel-stainless.org/designmanual

TUTHILL, A.H.
Fabrication and Post Fabrication Cleanup of Stainless Steels. Chemical Engineering 93(18)9
Also available from Nickel Institute. Publication 10004. 1986 www.nickelinstitute.org

10.3 Stainless steels in desalination plant

WORLDSTAINLESS (formerly ISSF)
Desalination in Stainless Steel 2012. Available from www.worldstainless.org

FRANCIS,R.
Avoiding Corrosion in Desalination Plants 2019. NACE International

FRANCIS, R
Materials Selection for Desalination Plants, Nickel Institute Technical Report 11029, 2022

Pipework and tubing systems within buildings

BSSA
The Suitability and Use of Stainless Steel for Plumbing Applications. BSSA Special Report 2003
Available from www.bssa.org.uk

CAMPBELL, I
Domestic hot and cold water systems for Scottish Health Care Premises
Scottish Health Technical note, Edinburgh, HMSOI, 1994

WORLDSTAINLESS (formerly ISSF)
A Workable Lasting Solution for Water Losses through Leaking Water Pipes. 2018 Available from www.worldstainless.org

Stainless steel in drinking water supply 2014. Available from www.worldstainless.org

IMOA and NI
Stainless Steel Service Pipes: A proven solution to water loss and water quality everywhere 2018. International Molybdenum Association. Available from www.imoa.info/molybdenum-media-centre/downloads and also from Nickel Institute: www.nickelinstitute.org

10.4 Sustainability

https://www.worldstainless.org/sustainability/

11 REFERENCES

1. *ASM Speciality Handbook on Stainless Steels.* 1994.
2. BCSA. *Steel Construction UKCA Marking, Version 4.* s.l. : Available from www.steelconstruction.info, 2021.
3. *EN 1993-1-9:2005 Eurocode 3: Design of steel structures. Part 1-9: Fatigue. CEN.*
4. *Outokumpu Corrosion Handbook for Stainless Steels. 11th Edition 2015.*
5. *Stainless steels in Architecture, Building and Construction. Nickel Institute Publication11024. 2014.*
6. *Care and Maintenance of Stainless steel; British Stainless Steel Association, Sheffield. SSAS Information Sheet No.7.20 .* 2001.
7. *SUSSEX G and GOUCH A. Don't let salt assault your stainless surface 18th International Corrosion Congress 2011 Australia Paper 488.*
8. *The corrosion performance of metals for the marine environment: a basic guide. Edited Powell C and Francis R. European Federation of Corrosion No 63 Maney Publishing 2012.*
9. *EN 12502-4: 2004 Protection of metallic materials against corrosion. Guidance on the assessment of corrosion likelihood in water distribution and storage systems. Influencing factors for stainless steels.*
10. *HERBSLEB, G. Der Stahlbau, Issue 9, pp 269 278, 1978.*
11. *SCHWENK, W Werkstoff und Korrosion 35, pp 581 82, 1984.*
12. *BINDSCHEDLER, D GWA, 73 Jahrgang, pp 808 815, October 1993.*
13. *AVERY, R E et al. Materials Performance 35, 9, pp 56 62, 1996.*
14. *BOULTON L H, Service Experience with Stainless steels in corrosive waters Corrosion and Protection 2011, ICC Paper 115, Australia.*
15. FRANCIS, R.,. *Galvanic Corrosion: A practical Guide for Engineers, Second Edition, AMPP, 2017.*
16. *ARLT N, BURKERT A and ISECKE B, Stainless steel in contact with other metallic materials, Materials and applications Series Number 10, EURO INOX, 2009, http://www.worldstainless.org/Files/issf/non-image-files/PDF/Euro_Inox/Contact_with_Other_EN.pdf. .*
17. *Nickel containing materials for water control applications. Nickel Institute, Technical Guide 11010, 1993.*
18. *BAUER A. Stainless Steel in Waters: Galvanic Corrosion and its Prevention https://www.nickelinstitute.org/media/1806/stainlesssteelinwatersgalvaniccorrosionandit-preventionaebauer.pdf.*
19. *PD 6484 Commentary on corrosion at bimetallic contacts and its alleviation. BSI 1979.*
20. *POWELL C.A and STRASSBURG F.W., Stainless steel in Potable water service Stainless steel 96 Neuss/Dusseldorf June 1996.*
21. *BS 5970 Thermal insulation of pipework, ductwork, associated equipment and other industrial installations in the temperature range of -100 degreesC to +870 degreesC. Code of practice. BSI, 2012.*
22. *BS 5422 Method for specifying thermal insulating materials on pipes, ductwork and equipment in the temperature range −40°C to + 700°C BSI, 2009.*
23. *SCHWENK, W. British Corrosion Journal, Vol 26, No 4, pages 245 249, 1991.*
24. *LEWUS, M O et al. Proceedings Stainless Steels 96, pages 236 243, VDEh, Düsseldorf, 1996.*
25. *Operational Guidelines and Code of Practice for Stainless Steel products in Drinking Water Supply. 2002. www.bssa.org.uk.*
26. *ANSI/NSF61 Sections 1 to 9, Drinking water system components – health effects. NSF International.*
27. *KOBRIN, G et al. Microbiologically influenced corrosion of stainless steels by water used for cooling and hydrostatic testing. Nickel Institute, Technical Guide 10085, 1997.*
28. *Guidance notes on the safe use of stainless steels in chemical process plant. Institute of Chemical Engineers, Rugby, 1975.*

29. ***TUTHILL, A and LAMB, S. Stainless steel in municipal waste water treatment plants, Nickel Institute Technical Guide 10076, 1995.***
30. ***TUTHILL, A and AVERY, R. Survey of stainless steel performance in low chloride waters. Public Works Magazine, USA, November 1994.***
31. ***TUTHILL, A, AVERY, R, LAMB, S and KOBRIN, G. Effect of chlorine on common materials in fresh water. NACE, paper 708, Corrosion 1998.***
32. ***POWELL, C. , EDYVEAN, R VALPULANT,K.LAMB.S. Evaluation of chlorination levels on the localised corrosion resistance of 304 and 316L stainless steels in waters of 200-2000ppm chlorides. Paper 1098. Eurocorr 2012 Istanbul.***
33. ***Stainless steel in swimming pool buildings. Nickel Institute Technical Series 12010, 1995.***
34. FRANCIS, R. ***Corrosion of Duplex Stainless Steels: A Practical Guide for Engineers.*** **s.l. : AMPP, 2018.**
35. FRANCIS, R., The Performance of Stainless Steels in Concentrated Sulphuric Acid, Stainless Steel World, Vol 22, page 53, January 2010.
36. ***A report on the performance of stainless steel pipe for water supply in underground soil environments. Volumes 1 and 2, Nickel Development Institute, Nickel Institute Technical Series 12005, 1988.***
37. ***Guidelines for Use of Stainless steel in Soil. Australian stainless No 51 Autumn 2012. ASSDA.***
38. ***GARNER, A. Materials Performance, Volume 21, Number 5, page 43, 1982.***
39. ***BARDAL, E et al. Polarisation properties of stainless steel under different conditions in seawater and some practical consequences. Proceedings of 10th Scandinavian Corrosion Congress, NKM 10. Swedish Corrosion Institute, June 1986.***
40. ***LINDER, B. Corros. Australas, Volume 20, Issue 1, pages 6 10, Feb 1995.***
41. ***EN ISO 3506-1:2020 Fasteners — Mechanical properties of corrosion-resistant stainless steel fasteners — Part 1: Bolts, screws and studs with specified grades and property classes.***
42. ***BSSA Technical Notes on Surface hardening.***
43. ***BYRNE G. et al The Family of Duplex Stainless Steels in the Desalination Industry. Duplex Stainless Steel 2010, October 2010, Beaune, France.***
44. ***FRANCIS, R, and BYRNE, G, Gasket selection for stainless steels in seawater' Materials performance, October, 2007.***
45. FRANCIS, R. Materials Selection for Desalination Plants, Nickel Institute Technical Brochure 11029, 2022.
46. ***CROOKES, R, Pickling and Passivating Stainless Steel, Materials and applications Series Number 4, EURO INOX, 2005.***
47. ***EN 1993-1-4: 2006 +A2:2020 Eurocode 3: Design of steel structures. General rules. Supplementary rules for stainless steels. CEN.***
48. ***EN 1993-1-1: 2005+A1:2014 Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings. CEN.***
49. ***EN 1993-1-3: 2006 Eurocode 3: Design of steel structures. Part 1-3: General rules. Supplementary rules for cold-formed members and sheeting. CEN.***
50. ***Design Manual for Structural Stainless Steel, 4th edition, 2017, Steel Construction Institute, downloadable from www.steel-stainless.org/designmanual.***
51. ***API Standard 650 Welded tanks for oil storage, API, Thirteenth Edition 2020.***
52. ***EN 14015:2004 Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above.***
53. ***EN 1993-4-2: 2007+A1:2017 Eurocode 3. Design of steel structures. Tanks. CEN.***
54. ***EN 13445: 2009 Unfired pressure vessels.***
55. ***PD 5500:2012+A1:2012 Specification for unfired fusion welded pressure vessels.***
56. ***EN 10028-7:2007 Flat products made of steels for pressure purposes. Stainless steels.***
57. ***ASME Boiler and Pressure Vessel Code, Section VIII Rules for Construction of Pressure Vessels, ASME, 2010.***

58. *Stainless Steel Sheet Lining of Steel Tanks and Pressure Vessels, Nickel Institute, Technical Series, 10039, 1989. https://www.nickelinstitute.org/media/1816/stainlesssteelsheetliningofsteeltanksandpressurevesselsl_10039_.pdf.*
59. *EN 10312:2002 Welded stainless steel tubes for the conveyance of aqueous liquids inclu ding water for human consumption. Technical delivery conditions.*
60. *EN 1090-2 Execution of steel structures and aluminium structures, Part 2: Technical requirements for steel structures, CEN, 2018.*
61. Baddoo, N R. *Execution of stainless steel structures, ED018.* Ascot : The Steel Construction Institute, 2014.
62. *ASTM A380 Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment and Systems.*
63. *International Molybdenum Association. Shop Sheet 102 Bending, cold forming, and springback of duplex stainless steels. 2009.*
64. *EN 1011-3:2000. Welding. Recommendations for Welding of Metallic Materials. Arc Welding of Stainless Steels.*
65. *WL - COSHH Essentials for welding, hot work and allied processes. Health and Safety Executive.*
66. *ISO 15609-1:2019 TC. Specification and qualification of welding procedures for metallic materials. Welding procedure specification. Part 1: Arc welding.*
67. *ISO 15614-1:2017. Specification and qualification of welding procedures for metallic materials - welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys.*
68. *ISO 9606-1: 2017 - Qualification testing of welders - Fusion welding - Part 1: Steels.*
69. *ISO 3581:2016. Welding consumables. Covered electrodes for manual metal arc welding of stainless and heat-resisting steels - Classification.*
70. *ISO 14343:2017. Welding consumables. Wire electrodes, strip electrodes, wires and rods for arc welding of stainless and heat resisting steels - Classification.*
71. *ISO 14172:2015. Welding consumables. Covered electrodes for manual metal arc welding of nickel and nickel alloys.*
72. *ISO 18274:2010. Welding consumables. Solid wire electrodes, solid strip electrodes, solid wires and solid rods for fusion welding of nickel and nickel alloys - Classification.*
73. *AWS D18.2:2020. Guide to weld discoloration levels on inside of austenitic stainless steel tube.*
74. *AWS D18.1/D18.1M:2009. Specification for welding of austenitic stainless steel tube and pipe systems in sanitary (hygienic) applications.*
75. *BOULTON L.H. and AVERY R.E. Heat tinted Stainless Steel Welds - Guidelines for Acceptance. Stainless Steel World, April 2004.*
76. *ASTM A967 - Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts.*
77. *ASTM B912 - Standard Specification for Passivation of Stainless Steels Using Electropolishing.*
78. *ISO 5817:2014. Welding. Fusion-welded joints in steel, nickel, titanium and their their alloys (beam welding excluded). Quality levels for imperfections.*
79. *EN 14161:2011+A1:2015. Petroleum and natural gas industries. Pipeline transportation systems.*
80. *CUNAT P-J Corrosion Resistance of Stainless Steels in Soils and Concrete. Plenary Days of the Committee on the Study of Pipe Corrossion, CéoCorr Conference, Biarritz, 2001.*
81. *ISO 9223:2012. Corrosion of metals and alloys. Corrosivity of atmospheres - Classification, determination and estimation.*
82. *http://www.worldstainless.org/Files/issf/non-image-files/PDF/Life_Cycle_Costing_Report_from_Sorbonne_University.pdf.* Paris : Published jointly by Université Paris 1 and ISSF, 2011.
83. FASSINA L, and POWELL C. SECTION 5: THE LIFE CYCLE COST ANALYSIS AT THE PLANNING STAGE. [book auth.] Centro Inox and Cermet. *STAINLESS STEEL FOR THE MUNICIPAL COMPANIES.* Bologna :

https://www.nickelinstitute.org/media/1846/wastewaterstainless-steelequipmentpowellfassina.pdf, 2001.
84. *Our common future, the Brundtland report, UN. 1987.*
85. GLOSER-CHARHOUD, S, Development of a Dynamic Global Stainless SteelFlow Model, Karlsruhe Institute of Technology (KIT), December 2022.
86. www.worldstainless.org/files/issf/non-image-files/PDF/Stainless_Steel_in_Figures_2022_public_English.pdf.
87. Johnson, J., B.K. Reck, T. Wang, and T.E. Graedel. 2008. The energy benefit of stainless steel recycling. Energy Policy 36(1): 181-192.
88. COLLINS T & MOCHIZUKI K, Stainless Steels and CO2; Industry Emissions and Related Data; ISSF Report,January 2022, /www.worldstainless.org/files/issf/non-image-files/PDF/ISSF_Stainless_Steel_and_CO2.pdf.
89. http://www.worldstainless.org/health_and_environment/life_cycle_inventory_and_analysis.

APPENDIX A. CREVICE AND PITTING CORROSION

Crevice and pitting corrosion are both localised forms of attack which can lead to penetration of a metal section without significant weight loss from the component.

A crevice is caused by any feature, such as a washer, crack, surface lap, weld sputter, interrupted weld bead or solid deposit, forming a blind crack into which liquid can penetrate. Attack of the oxide film on the surface of the metal at the crevice site can be driven by the difference in oxygen level, or concentration gradient, between the liquid outside and inside the crevice. Once attack is initiated by penetration of the oxide film, the dissolution of metal in the crevice creates acidic conditions, leading to migration of chloride ions, further aiding corrosion. The risks of initiating corrosion are reduced the wider the crevice and the greater the opportunity for liquid flow to prevent formation of concentration gradients.

Pitting attack is driven by similar mechanisms and can be initiated at discontinuities in the metal surface, for example at inclusions. Propagation of the pits depends upon the environment: the creation of a local acidic environment within the pit attracts chloride ions and sustains attack after initiation. High flow rates are beneficial in preventing these concentration differentials building up, but the conditions within active, established pits can deviate markedly from those of the bulk medium. Resistance to both pitting and crevice attack is improved as the alloy content of the steel is raised. The Pitting Resistance Equivalent Number, or PREN, is calculated from the composition of the steel and provides a simple means of ranking different steels for their resistance to attack, in accordance with ISO 15156-3:

$$\text{PREN} = \%\text{Cr} + 3.3\text{x}(\%\text{Mo}+0.5\text{x}\%\text{W}) + 16\text{x}\%\text{N}$$

Alternative terms, principally for nitrogen, have been proposed, although the overall ranking on composition remains similar.

However, material selection decisions cannot be based on PREN rankings alone. These rankings relate to the relative performance of the different compositions tested under optimum conditions of heat treatment and surface finish. Other factors, such as processing and fabrication methods, surface finish and operating conditions, must be taken into account when assessing actual performance. TableA-1 gives the approximate PREN ranges for stainless steels listed in Table 3-1, based on the composition ranges permitted by EN 10088: Part 2.

Table A-1 Approximate PREN range for stainless steels and their compositions in Table 3-1

Steel grade	Type	Approximate PREN range
1.4512	11-12%Cr ferritic	10.5-12.5
1.4003		10.5-12.5
1.4016	17% Cr ferritic	16 – 18
1.4307	Standard Austenitic	17.5-19.5
1.4301		17.5 – 19.5
1.4404	2% Mo Austenitic	23.5 – 28.5
1.4401		23.5 – 28.5
1.4432	2.5% Mo Austenitic	25-28
1.4436		25-28
1.4541	Ti stabilised standard austenitic	17-19
1.4571	Ti stabilised 2%Mo Austenitic	23.5-28.5
1.4539	4.5%Mo Austenitic	32-37
1.4547	6% Mo Super-austenitic	42-47.5
1.4482	Lean duplex	19
1.4062		26
1.4162		24.5-28.5
1.4362		27-29
1.4462	Standard duplex	31-39
1.4410	Superduplex*	38*-46
1.4501		38*-45.5
1.4507		37*-44
1.4418	High strength martensitic and precipitation hardening	17.5-22
1.4542		15-17

* In practice, superduplex normally has a PREN > 40 as this is the generally accepted requirement for good sea water resistance at ambient temperature (4).

APPENDIX B. STANDARDS FOR STAINLESS STEELS AND PRODUCT FORMS

Table B-1   Standards for stainless steels and product forms

Designation	EN 10027	Designation systems for steels Part 1: Steel names Part 2: Steel numbers
Flat and long products - material	EN 10088	Stainless steels Part 1: List of stainless steels Part 2: Technical delivery conditions for sheet/plate and strip for corrosion resisting steels for general purposes Part 3: Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products for corrosion resisting steels for general purposes
Flat and long products – tolerances on dimensions and shape	ISO 9444	Continuously hot-rolled stainless steel -- Tolerances on dimensions and form Part 1: Narrow strip and cut lengths Part 2: Wide strip and sheet/plate
	ISO 9445	Continuously cold-rolled stainless steel -- Tolerances on dimensions and form Part 1: Narrow strip and cut lengths Part 2: Wide strip and sheet/plate
	ISO18286	Hot-rolled stainless steel plates -- Tolerances on dimensions and shape
Pipework systems – ANSI	ASME/ANSI B 31.3	Process piping
	ASME/ANSI B 36.10	Welded and Seamless Wrought Steel Pipe
	ASTM A312	Specification for Seamless, Welded, and Heavily Cold Worked Austenitic Stainless Steel Pipes
	ASTM A403	Specification for Wrought Austenitic Stainless Steel Piping Fittings
	ASTM A774	Specification for As-Welded Wrought Austenitic Stainless Steel Fittings for General Corrosive Service at Low and Moderate Temperatures
Pipework systems – ISO and metric	EN 13480-3	Metallic industrial piping - Part 3: Design and calculation
	ISO 1127	Stainless steel tubes -- Dimensions, tolerances and conventional masses per unit length
	EN 10296-2	Welded circular steel tubes for mechanical and general engineering purposes - Technical delivery conditions - Part 2: Stainless steel
	EN 10217-7	Welded steel tubes for pressure purposes - Technical delivery conditions - Part 7: Stainless steel tubes
	ISO 5251	Stainless steel butt-welding fittings
	ISO 5252	Steel tubes - Tolerance systems
Castings	EN 10283	Corrosion resistant steel castings
Fasteners	ISO 3506	Mechanical properties of corrosion-resistant stainless steel fasteners Part 1: Bolts, screws and studs

		Part 2: Nuts Part 3: Set screws and similar fasteners not under tensile stress Part 4: Tapping screws
Wire	EN 10263-5	Steel rod, bars and wire for cold heading and cold extrusion - Part 5: Technical delivery conditions for stainless steels
Design of structural members	EN 1993-1-4	Eurocode 3 - Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels
Welding	ISO 9606-1	Qualification testing of welders - Fusion welding - Part 1: Steels
	ISO 15609	(formerly EN 288 Part 2) Specification and Qualification of Welding Procedures for Metallic Materials
Quality Assurance	ISO 9001	Quality management systems -- Requirements
	OHSAS 18001	Occupational health and safety management systems
	ISO 50001	Energy management systems -- Requirements with guidance for use
	ISO 14001	Environmental management systems -- Requirements with guidance for use