# Applications for Stainless Steel in the Water Industry
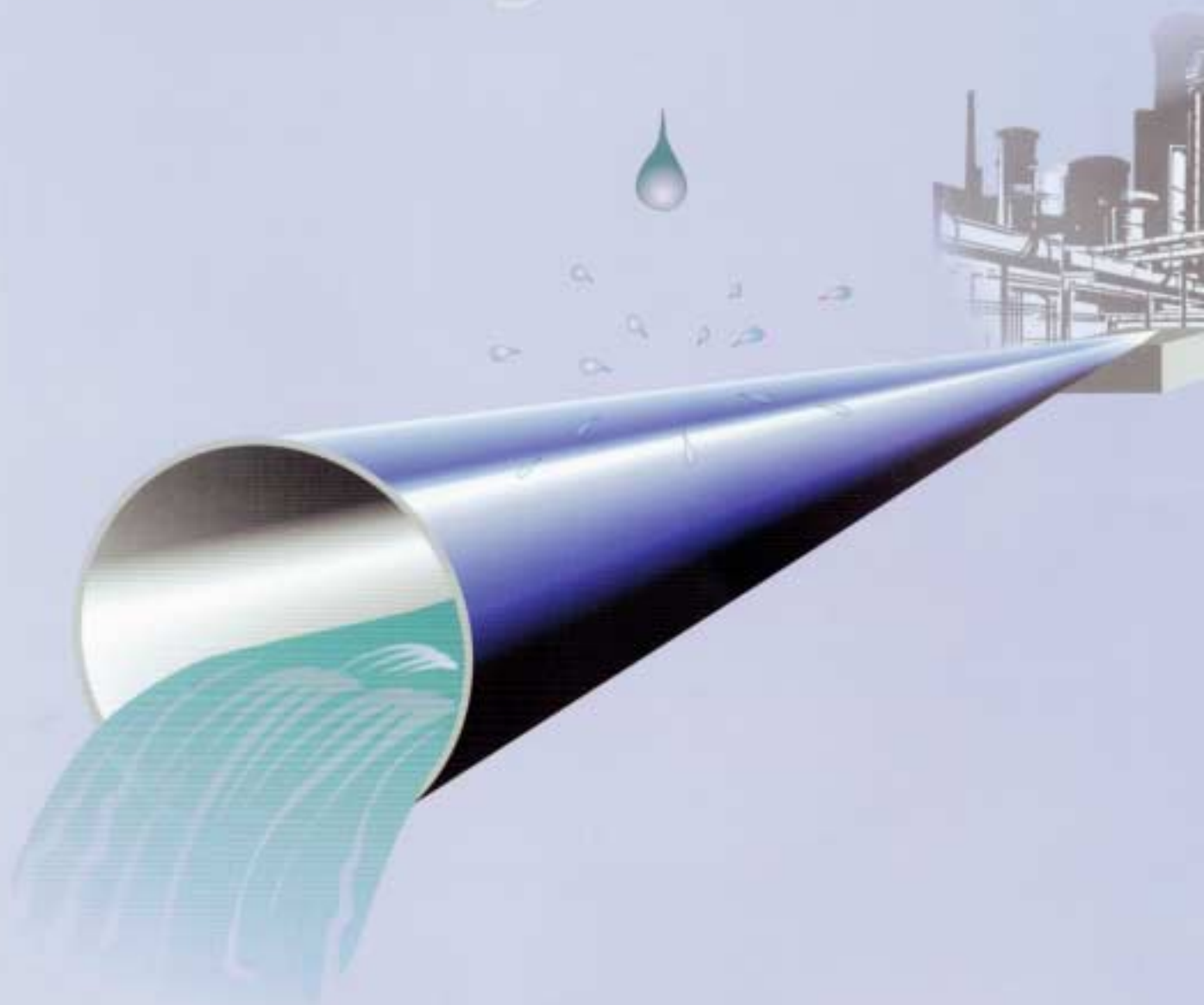
# Applications for Stainless Steel in the Water Industry

This guide has been prepared 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. Their assistance is gratefully acknowledged.

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UK Water Industry

# APPLICATIONS FOR STAINLESS STEEL IN THE WATER INDUSTRY

## 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 also given on material selection for corrosion resistance, design of structural members, tanks and pipework systems, fabrication and installation.

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, there is a perception that they are 'expensive' materials, confined to specialist plant items. However, the intrinsic advantages of stainless steels allow them to be used to economic advantage in a wide range of potable and waste water treatment and storage plant, as has been demonstrated successfully elsewhere, for example in Germany, the USA and the Nordic countries. Table 1 lists some proven applications of standard grades of stainless steel in water collection, storage, treatment and distribution.

| Mechanical Systems | Biological and Oxidation Systems |
|---|---|
| • Screening systems, sieves | • Sedimentation tanks |
| • Grit chambers | • Inlet and outlet construction |
| • Aeration trenches and tanks | • Aeration installations |
| • Inlet and outlet constructions for sedimentation tanks | • Ozone treatment |
| • Scraper installations | • Sludge separator installations |
| • Screening drums | • Anaerobic waste water treatment |
| • Sludge/scrapers | • Disinfection - UV systems |
| • Pre-treatment tanks | • Tank covers |
| • Syphons and lifting devices | |
| • Weirs and overflows | **Pipe Systems** |
| • Slide gates | • Sewage water transportation |
| • Valves and pumps | • Potable water mains and distribution systems |
| • Bolting | • Sludge transportation |
| | • Gas transportation |
| **Sludge Treatment** | |
| • Tanks, containers for mixing, thickening, dewatering sludge and digesters for processing sludge | **Hardware & Miscellaneous** |
| | • Linings for concrete tanks |
| | • Manholes and covers |
| • Sludge circulation installations | • Shaft covers |
| • Filter-presses | • Climbing rungs |
| • Stop logs, valves, stop gates | • Ladders |
| | • Railing and platforms |
| **Subsoil Water Technology** | • Firedoors, safety doors, pressure doors |
| • Groundwater separation casings and membranes | • Wellheads |
| • Pumps | • Ventilation stacks |
| • Agitators | |
| • Supports for pipe-systems | |
| • Clayware pipe separators | |

**Table 1**    *Proven applications of stainless steels in the water industry*

Table 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.

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 or whole life 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.

2

| Characteristics | Advantages conferred |
|---|---|
| High corrosion resistance | No re-investment, consistent operation |
| No corrosion or leachant 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 |
| Recyclable | Cost benefits and low environmental impact |
| Good ductility and weldability | Compatible with system construction |
| Low weight (for tubular components) | Simple construction and erection |
| Good mechanical properties | High material utilization factor |
| 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 |

**Table 2**   *Relevant attributes of stainless steels for the water industry*

# 3 AN 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 which, if damaged by abrasion, 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 materials, 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. The EN grade designations given in the table are explained in more detail in Section 4.1. The popular name originates from the (now partly superseded) British Standards and AISI system.

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 conventional painted or galvanised carbon steels. The ***FERRITIC*** grades shown in Table 3 are generally restricted to use in sections below about 3 mm in 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.

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 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, 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 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.

| Family | BS EN 10088 designation | Popular 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 | - | - | - | - | |
| | 1.4016 | 430 | 0.08 | 16.0-18.0 | - | - | - | - | - | |
| Austenitic | 1.4307 | 304L | 0.03 | 17.5-19.5 | 8.0-10.0 | - | - | - | - | This family of stainless steels meet most of the requirements in the water industries. Good combination of corrosion resistance, forming and fabrication properties; 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 | - | - | - | - | |
| | 1.4404 | 316L | 0.03 | 16.5-18.5 | 10.0-13.0 | 2.0-2.5 | - | - | - | |
| | 1.4401 | 316 | 0.07 | 16.5-18.5 | 10.0-13.0 | 2.0-2.5 | - | - | - | |
| | 1.4432 | 316L | 0.03 | 16.5-18.5 | 10.5-13.0 | 2.5-3.0 | - | - | - | |
| | 1.4436 | 316 | 0.05 | 16.5-18.5 | 10.5-13.0 | 2.5-3.0 | - | - | - | |
| | 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 | - | - | Better corrosion resistance than simpler austenitic grades. Pitting and crevice corrosion resistance improves with increasing molybdenum and nitrogen content. 1.4547 was specifically developed for use in saline conditions. |
| | 1.4547 | 6% Mo grades | 0.02 | 19.5-20.5 | 17.5-18.5 | 6.0-7.0 | 0.5-1.0 | 0.18-0.25 | - | |
| Duplex | 1.4362 | 2304 | 0.03 | 22.0-24.0 | 3.5-5.5 | 0.1-0.6 | - | 0.05-0.20 | - | High strength and wear resistance with very good resistance to stress corrosion cracking. 1.4462 (2205) has better corrosion resistance than 1.4362 (2304). |
| | 1.4462 | 2205 | 0.03 | 21.0-23.0 | 4.5-6.5 | 2.5-3.5 | - | 0.1-0.22 | - | |
| High strength martensitic & precipitation hardening (PH) | 1.4418 | 248SV | 0.06 | 15.0-17.0 | 4.0-6.0 | 0.8-1.5 | - | | - | 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 | 17-4PH | 0.07 | 15.0-17.0 | 3.0-5.0 | - | 3.0-5.0 | | Nb | |

Notes [1] The popular name originates from the (now partly superseded) British Standards and AISI system.

[2] Titanium is added to stabilise carbon and improve corrosion performance in the heat affected zones of welds. However, except for very heavy section construction, 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.

**Table 3** *Contents of main alloying elements in selected grades of stainless steels covered by BS EN 10088-1*
*(The austenitic and duplex grades are those most likely to be encountered in the water industry)*

However, in current production, the standard austenitic grades now often have carbon contents of 0.05% or below, closer to those of the 'L' grades, and the grade distinction is less important. 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. Stabilised steels are normally only likely to be considered for relatively heavy section welded fabrications involving multiple, high heat input passes. Where necessary, guidance on the need for a stabilised or 'L' grade steel for a particular fabrication should be sought from the steel supplier or fabricator.

For simplicity, reference is made later in this IGN to the '304' or '316' types of stainless steels, without quoting directly an EN designation. This means that the results quoted were obtained on steel grades containing about 18% chromium, 9% nickel, or 17% chromium, 11% 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 illustrates the drawback of using this short notation.

Generally, corrosion resistance increases with the chromium, molybdenum, nitrogen and nickel contents of the steel. 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 (Nitrogen)' or 'PRE(N)', which sums the effects of the alloying elements present. The higher this number the better the corrosion resistance, in principle. The 'PRE(N)', 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 'superaustenitic' grades, are available, *e.g.* grade 1.4547 in Table 3. 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 stress corrosion cracking (SCC), compared with the standard austenitic grades.

The high strength *MARTENSITIC AND PRECIPITATION HARDENING* steels shown in Table 3 illustrate 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.

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 Section 10, Bibliography.

Stainless steels are available in the following forms:

- Plate, sheet, strip ('flat products'),

- Pipe and tube (welded and seamless),

- Bar, rod, wire and special wire sections ('long products'),

- Cold formed structural sections (*e.g.* channels, angles),

- 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 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

The material standard for stainless steels is BS EN 10088: 1995, *Stainless Steels*. It comprises three 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.

- 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.

Stainless steel producers and suppliers throughout Europe are now following this standard. Further explanation of the contents of BS EN 10088 is available[2].

The designation systems adopted in the European standard are 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 x % 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 partly 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.

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. BS EN 10088 quotes 0.2% proof strengths of around 220 N/mm$^2$ for the standard grades of austenitic stainless steel. This strength relates to material in the annealed condition. In practice, these values will be exceeded if the material is cold worked. There is provision within BS 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.

The martensitic and precipitation hardening grades shown in Table 3 can be heat treated to a range of 0.2% proof strength levels between 650 and 1150 N/mm$^2$. Guidance should be sought from the steel supplier when using these higher strength materials.

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 aerobic pipework and stainless steels are markedly superior to plastics in this respect. The principal differences in behaviour between structural carbon steels and the austenitic stainless steels are due to the effects of work-hardening in the latter. Work hardening may occur in the early stages of fatigue loading and can be important in low cycle fatigue. Also, in high cycle fatigue, the austenitic stainless steels, in common with other non-ferrous metals and alloys of similar crystal structure, do not show so pronounced a 'knee' defining the 'fatigue limit' in the Stress-Number of cycles (S-N) plot.

In terms of conventional high cycle S-N data, results are available which allow comparison between the stainless and carbon steels. The *endurance ratio* (*i.e.* the ratio of the fatigue strength at a given endurance to tensile strength) for the austenitic stainless steels has been found to lie in the range of 0.3 - 0.5 for fully reversed loading. (This holds for tests in air at endurances greater than 10$^6$ cycles.) This may be compared with the range of about 0.35 - 0.60 for steels with a ferrite-pearlite structure (as found in structural carbon steels) and 0.45 - 0.65 for the duplex stainless steels. This higher ratio, combined with their higher strength, gives the duplex steels an advantage in fatigue.

Tests in distilled water indicate an endurance ratio (at 10$^7$ cycles) of between 0.30 and 0.55 for a range of austenitic steels, with values of 0.30-0.50 in synthetic seawater. However, fatigue endurance ratios are lowered in the presence of chlorides as the pH falls below 4[3].

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.)

| Steel number (popular name) | Product form [1] | Maximum thickness (mm) | Minimum 0.2% proof stress [2] (N/mm²) | Minimum 1.0% proof stress [2] (N/mm²) | Tensile strength (N/mm²) | Minimum elongation after fracture % t < 3 mm | t ≥ 3 mm |
|---|---|---|---|---|---|---|---|
| **Ferritic** | | | | | | | |
| 1.4512 (409) | C | 6 | 220 | | 380 - 560 | 25 | |
| | H | 12 | | | | | |
| 1.4003 | C | 6 | 320 | | 450 - 650 | 20 | |
| | H | 12 | | | | | |
| | P | 25 [3] | 280 | | | 18 | |
| 1.4016 (430) | C | 6 | 280 | | 450 - 600 | 20 | |
| | H | 12 | 260 | | | 18 | |
| | P | 25 [3] | | | 430 - 630 | 20 | |
| **Austenitic** | | | | | | | |
| 1.4307 (304L) | C | 6 | 220 | 250 | 520-670 | 45 | |
| | H | 12 | 200 | 240 | | | |
| | P | 75 | | | 500-650 | | |
| 1.4301 (304) | C | 6 | 230 | 260 | 540-750 | 45 [4] | |
| | H | 12 | 210 | 250 | 520-720 | | |
| | P | 75 | | | | 45 | |
| 1.4404 (316L) | C | 6 | 240 | 270 | 530-680 | 40 | |
| | H | 12 | 220 | 260 | | | |
| | P | 75 | | | 520-670 | 45 | |
| 1.4401 (316) | C | 6 | 240 | 270 | 530-680 | 40 | |
| | H | 12 | 220 | 260 | | | |
| | P | 75 | | | 520-670 | 45 | |
| 1.4436 (316) | C | 6 | 240 | 270 | 550-700 | 40 | |
| | H | 12 | 220 | 260 | | | |
| | P | 75 | | | 530-730 | | |
| **Duplex** | | | | | | | |
| 1.4362 (2304) | C | 6 | 420 | | 600-850 | 20 | |
| | H | 12 | 400 | | | | |
| | P | 75 | | | 630-800 | 25 | |
| 1.4462 (2205) | C | 6 | 480 | | 660-950 | 20 | |
| | H | 12 | 460 | | | | |
| | P | 75 | | | 640-840 | 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

**Table 4**   *Minimum specified mechanical properties to BS EN 10088-2*

## 4.3   Physical properties

Table 5 gives some physical properties at room temperature, as quoted in BS 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 7.1.5) 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.

| Steel designation | Density (kg/m$^3$) | Modulus of elasticity (kN/mm$^2$) | 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) | | | 10.5 | | 460 |
| 1.4003 | 7700 | 220 | 10.4 | 25 | 430 |
| 1.4016 (430) | | | 10 | | 460 |
| Austenitic | | | | | |
| 1.4307 (304L) 1.4301 (304) | 7900 | | | | |
| 1.4404 (316L) 1.4401 (316) 1.4436 (316) | 8000 | 200 | 16 | 15 | 500 |
| Duplex | | | | | |
| 1.4362 (2304) 1.4462 (2205) | 7800 | 200 | 13 | 15 | 500 |

**Table 5**   *Room temperature physical properties to BS EN 10088-1 (annealed condition)*

## 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 (descaling) operation prior to despatch.  The pickling removes all surface oxide formed during high temperature processes, together with any surface layer depleted in chromium as a result of oxidation.  Pickling or mechanical removal of both high temperature oxide and chromium-depleted layers is necessary to obtain optimum corrosion performance from stainless steels.

The standard finishes within BS EN 10088 and their designations are given in Table 6.  Generally, cold rolled products have better surface finishes and closer tolerances than hot rolled products of equivalent thickness.

The finishes designated as 1D or 2D (hot rolled or cold rolled, softened and descaled) and 2B (cold rolled, softened, 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.  They normally do not need further 'passivation' treatments. 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 or modifications, are made good following a suitable procedure.  Guidance on surface rectification measures is given in Section 7.1.6.

| 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 |

**Table 6**    *Selected standard surface finishes from BS EN 10088-2*


## *SUMMARY OF SECTION 4*

*Stainless steel flat and long products for general purposes are covered by the material standard, BS EN 10088: Parts 1,2 and 3.*

*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 N/mm² and 460 N/mm² 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 full economic benefit, 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, 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 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

Provided they are fabricated and finished to suitable standards, the standard austenitic grades such as 1.4301 (304) and 1.4401 (316) can retain their bright appearance on atmospheric exposure for many years[5], particularly when any surface deposits which build up are removed by periodic cleaning[6]. The ferritic grades may develop continuous adherent surface rust staining without general loss of section, which makes them unsuitable for atmospheric exposure applications where appearance is important.

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 or chloride-bearing atmospheres, 316 types are recommended.

## 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 a 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 and addresses 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 30 m/s.

Experience has shown that optimum performance of stainless steel is achieved when a minimum velocity of 0.5 m/s in clear 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 The significance of 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 ppm and 316 types for chloride levels up to about 1000 ppm[7][8]. 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 available[4][9].

It is important to note that pitting and crevice corrosion can occasionally occur at lower water chloride levels[10]. This may be in local environments where the protective surface film is weakened, as described later. It 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 ppm and 316 types for chloride levels up to 250 ppm: for example, the use of 2-3% molybdenum grades in preference to the 304 types has also been advocated for waste water treatment plant, where chloride levels run typically at 70 ppm[11].

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, clean, 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, non-porous 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 ppm chloride and where heat tint oxide scale from welding has not been removed[12]. To minimise the risk of this, heat tint scale should be prevented or removed (Section 7.1.6). 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.

Experience in the USA 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 was left stagnant in pipework 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.

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 a larger surface area, more corrosion of the less noble metal must be expected.
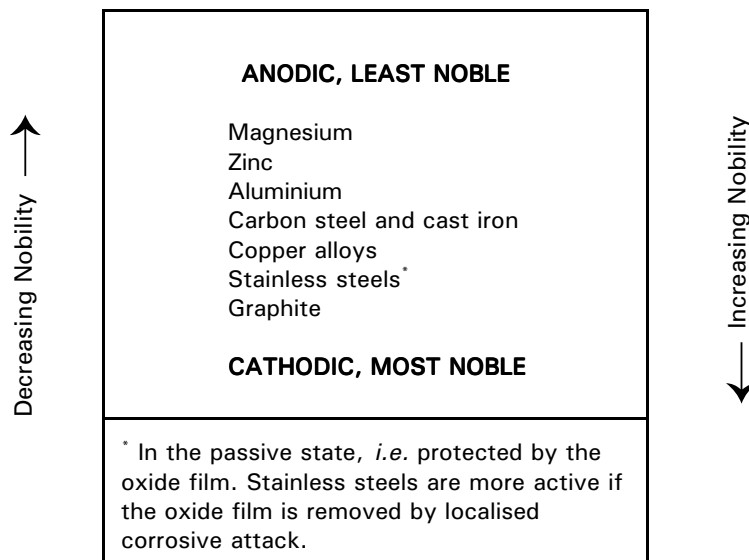


**ANODIC, LEAST NOBLE**

Magnesium
Zinc
Aluminium
Carbon steel and cast iron
Copper alloys
Stainless steels[*]
Graphite

**CATHODIC, MOST NOBLE**

Decreasing Nobility →

Increasing Nobility →

[*] In the passive state, *i.e.* protected by the oxide film. Stainless steels are more active if the oxide film is removed by localised corrosive attack.

**Table 7**    *Galvanic series for fresh water*

Table 7 shows the relative behaviour of different materials immersed in fresh water.  (Slight differences in ranking may be found in other media.)  The vertical separation indicates the electrical driving force for reaction.  Thus, there is a large driving force for dissolving magnesium or zinc when coupled to stainless steel.  This ranking holds under normal conditions but, as noted in the table, the position of stainless steels is changed if there should be localised corrosion creating an 'active' metal surface.

An example of galvanic corrosion risk is the use of carbon 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.  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,

* providing cathodic protection,

* use of isolation spools.

A 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. 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. 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).

Galvanic attack of stainless steels has been experienced in chemical plant, under crevice corrosion conditions created by the use of graphitised 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[13].

Codes of practice and other literature are available giving further guidance on avoiding galvanic corrosion[14][15].

### 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 stainless steel where chloride levels are less than 250 ppm[16]. Where SCC does occur in hot water pipework, it is often on the outside of pipework exposed to salt water spray or leakage of chloride-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[17] and BS 5422[18] 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, higher nickel austenitic or duplex stainless steels are available. Specialist advice should be sought.

### 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 in systems operated for the first time [16][19][20]. 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 25 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 (Reference 16).

Stainless steels are accepted under DWI regulations 25(1)C on the basis of historical use. They are also approved in the US under the ANSI/NSF61 regulations[21].

## 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 conditions. 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 and 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 tubercules, the microbes, which can be either aerobic or anaerobic, may form reducing acids that can attack 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 been treated with 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[22]. 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 also favour pitting attack by concentration of any chlorides present in the stagnant water. Good practice dictates that good quality waters should be used for 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[23].)

Although waste water treatment plants handle sludges and use bacteria for their decomposition, there has been a very low incidence of MIC[24]. (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.

### 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.  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[25] due to hydrogen sulphide gas.

## 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' chorine 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.  There are fewer data available for lower chloride waters[26].

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 above can be avoided either by providing adequate ventilation or, if necessary, by using a more corrosion resistant 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.

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 stainless steels and a range of other building materials[27].  Not only has this led to staining and surface micropitting, but cases of SCC of cold worked standard 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 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.

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. 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 4, 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 ppm. 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 flocculent.

### 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 are available for contact with more concentrated solutions.

### Granular activated carbon (GAC)

The galvanic series in Section 5.3.4 shows that 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. Theoretically, 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 Section 5.3.3.

### Phosphoric acid

Although the standard grades of austenitic stainless steel are resistant to pure phosphoric acid over a wide range of concentrations, attack is dependent in a complex way on the level of impurities, principally chlorides, fluorides and sulphuric acid. Information is available to aid grade selection for specific types of acid (Reference 4).

### Polyelectrolytes

Both anionic and cationic polyelectrolytes are used as flocculents 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 flocculent manufacturers.

### Sodium hydroxide (caustic soda)

The standard grades of austenitic stainless steel are suitable for handling sodium hydroxide at ambient and near ambient temperatures.

### Sulphuric acid

Guidelines for grade selection are given in Reference 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 and higher alloy austenitic stainless steels are available with enhanced performance, for example grade 1.4539 (904L) was specifically developed for sulphuric acid processes.

## 5.6    Resistance to abrasion and erosion

All austenitic stainless steels are ductile at temperatures well below ambient 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, presence of chemical contamination, microbiological activity and surface 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 soils[28].  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.  Stainless steel pipes can also be cathodically protected.

## 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)[29].  The general principles of protection of stainless steels have been reviewed by Bardal[30] and by Linder[31].  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 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 BS 6105).

* For more severe cases, use a proprietary high work-hardening rate stainless steel alloy for one component (Reference 25).

* Adjust joint fit and surface tolerances.

* In severe cases, use hard surface coating technologies, *e.g.* nitriding or 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.

## 5.10 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.

### 5.10.1 Choice of steel grade

- The molybdenum-containing 316 types have a 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.

- 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 ppm. Oxidising treatment additions will reduce this limit. 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 ppm under the same conditions.

- The presence of oxidising agents such as chlorine increase the possibility of crevice corrosion for a given level of chloride in waters. Trials in US plants with flowing raw waters with less than 23 ppm chloride indicate that the 304 types can be used for chlorine levels up to the highest level investigated, 2 ppm (Reference 26). The 316 types offer a greater margin of corrosion performance.

- In areas of plant where moist chlorine vapours may collect and concentrate, good ventilation 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 0.05% carbon, should be specified. In special cases, usually involving heavy section fabrications with multiple, high heat input passes, guidance on the possible use of a stabilised stainless steel grade should be sought from a welding engineer or steel supplier.

- 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 are available for unusual environments and applications requiring high strength, see Table 3. Guidance can be obtained from stainless steel manufacturers.

### 5.10.2 General design principles

- Design the plant to have free liquid flow, avoiding regions of stagnation, 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 and tank bottoms to allow complete draining (Figure 1).

- 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 5.10.4).

- For light gauge stainless steel pipework, ensure that the mounting methods take account of any acoustic damping required as a result of pressure pulsing.

## 5.10.3  Design for fabrication

- Eliminate deposit traps and crevices as far as possible (*e.g.* if plates are lapped, all lapping edges are sealed, Figure 1).

- Select weld procedures appropriate to the grade of steel being used.

- Ensure that the fabrication route allows easy access for welding, to achieve the optimum geometry of weld and ease of final finishing or the avoidance of heat tint formation.

- Aim for conditions allowing full-penetration welded joints with smooth contours and weld bead profiles.  (A detail in Figure 1 shows how a return on a plate bottom gives a smooth corner and allows easy access for execution and cleaning of a butt weld.)

## 5.10.4  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, raw water lines, where manganese and iron-bearing deposits may form ahead of sand filters: provision for periodic flushing and hydroblast cleaning should be made.

- 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.


### 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 UK ambient temperatures are:*
- *the chloride level,*
- *the presence of oxidising agents*
- *flow rate.*

*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.*

*Grades of stainless steel with enhanced corrosion resistance are available for use in more severe conditions, such as in air spaces containing moist chlorine gas.*

*The possibility of corrosion can be reduced significantly by good design of plant, for example by allowing free draining, preventing deposit build-up and minimising crevices.*

*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.*
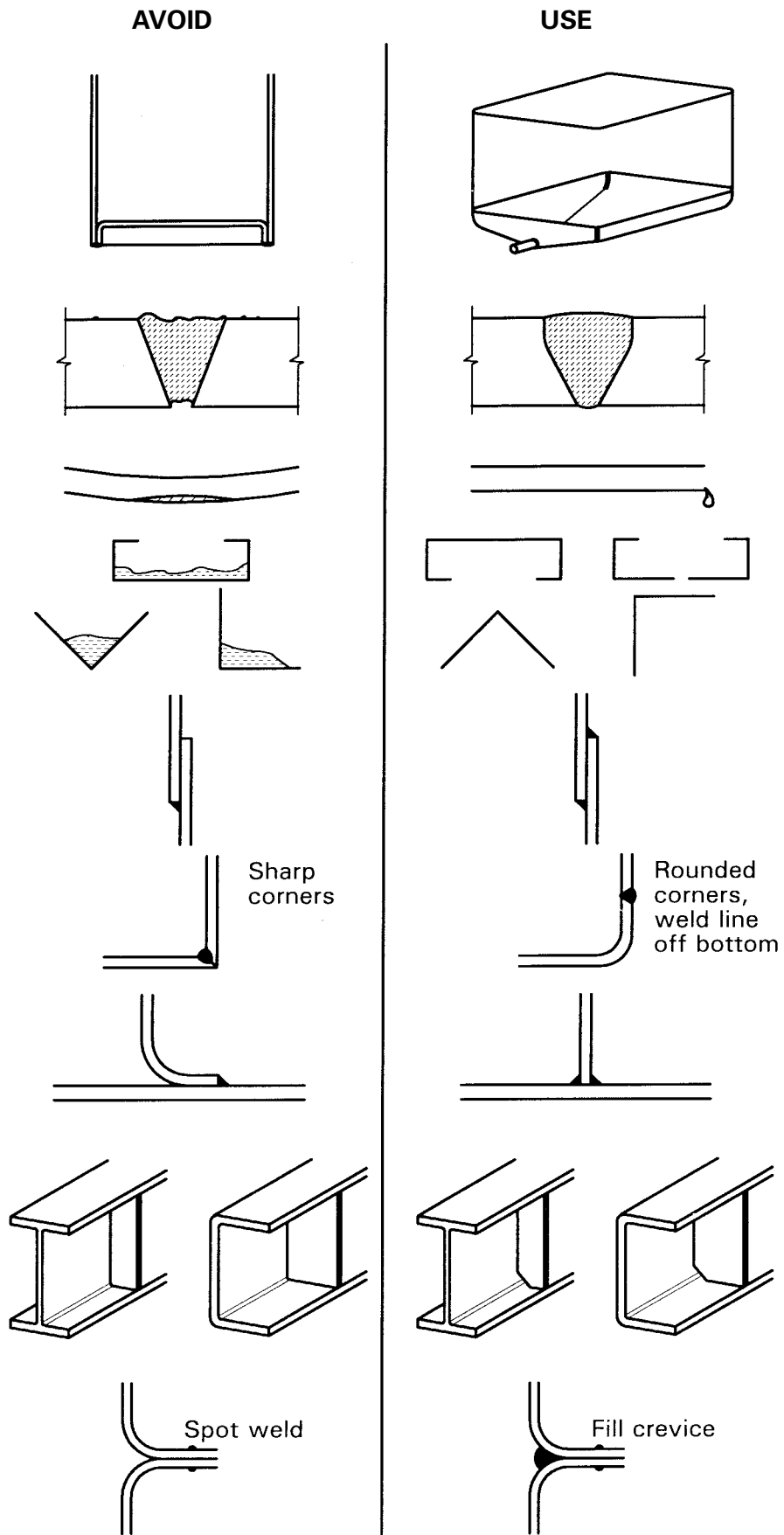
AVOID                                           USE

Sharp
corners

Rounded
corners,
weld line
off bottom

Spot weld                                       Fill crevice

**Figure 1**  *Poor and good design features for durability*

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# 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 2). 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 2, which shows typical experimental stress-strain curves. The curves shown are representative of the range of material likely to be supplied and should not be used for design. For grade 1.4307 (304L) and 1.4404 (316L) steels, the two curves shown indicate the extreme values from a series of tests and thus they represent a scatter band.
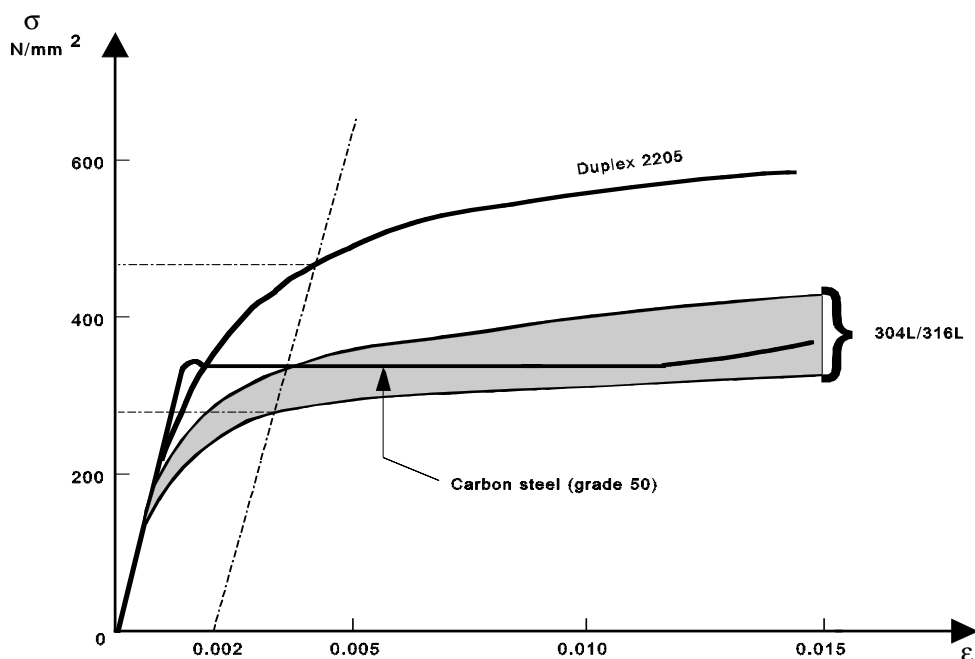


**Figure 2** *Stress-strain curves for stainless steel and carbon steel (longitudinal tension)*

This difference in stress-strain behaviour has implications on the buckling resistance (both local, flexural and lateral torsional) and deflection of stainless steel members. Buckling curves which are appropriate to the grade of stainless steel must therefore be used. Suitable methods must also be used for deflection calculations. These issues are covered in a design guidance document[32].

## 6.2    Structural members

Recommendations on the design of stainless steel structural members are given in the *Concise guide to the structural design of stainless steel*[32]. These are based on limit-state principles and are closely aligned to those in the British Standard for structural carbon steel, BS 5950: Part 1[33]. The recommendations apply to standard austenitic grades, such as 1.4307 (304L) and duplex grade 1.4462 (2205). Design tables have been published[34] giving section properties and member capacities for cold-formed structural forms, including rectangular and square hollow sections, channels, double channels back-to-back, equal angles and double equal angles back-to-back.

A European PreStandard, Eurocode 3: Part 1.4, has recently been issued covering the structural design of stainless steel members[35]. An American Standard is also in existence[36].

Design guidance on stainless steel fixings and ancillary components is also available[37].

## 6.3    Tanks and vessels

### 6.3.1    Tanks in general

Stainless steel tanks can be assembled using bolted connections with mastic joints, but welded assemblies offer longer design lives and bolted tanks are not recommended because the crevices around the bolts are susceptible to corrosion. The guidance given below, therefore, relates specifically to welded tanks.

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. Welded tanks are demountable and can be re-erected in a different location.

### 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 two design standards most widely used for designing welded cylindrical tanks are the American Petroleum Institute standard API 650[38] and the British Standard BS 2564[39]. These two standards have much in common although there are some differences. BS 2654 is both a design standard and a construction specification. The design recommendations are based on allowable-stress principles. As mentioned previously, the design guidance for structural stainless steel is based on limit-state principles. Interaction between the two types of 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 steel tanks. The standard for cylindrical tanks, BS 2654, may be used as a basis for design, especially for some of the details, but Reference 32 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 Reference 32 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 will be constructed to the requirements of the appropriate design codes, *e.g.* BS 5500[40] and ASME VIII[41]. These call up the appropriate materials properties for the stainless steels to 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 or 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.

## 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. Three 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.

*Metric* - This system is characterised by having a uniform bore diameter through tube and fittings for any one specified pipe size from 4.0 - 1200 mm internal diameter, with wall thicknesses of 1, 2 or 3 mm. It offers a lightweight design solution where free flow of liquids and semi-solids is required at up to 16 bar pressure. Having its origins in the pulp and paper industry, this pipework system is manufactured to Swedish materials, design, dimensions and testing standards. However, as shown in Table 9, the principal steel grades used are equivalent to the 1.4301 (304) and 1.4436 (316 high molybdenum) austenitic steels.

Table 8 summarises the main characteristics of these process piping systems and Table 9 gives typical national/international standards for design, dimensions and testing (Appendix B gives the titles of these standards). All three piping systems are readily available in 304 and 316 types of stainless steel with inside diameters from 6 mm to 1200 mm.

| Piping system | Operating conditions | | Benefits |
|---|---|---|---|
| | Typical pressures | Typical temperatures | |
| ANSI | Up to 100 bar | Up to 150°C | Used very widely in many industries |
| ISO | Up to 40 bar | Up to 150°C | Thinner walls than ANSI are more appropriate to stainless steel and lead to cost savings |
| Metric | Up to 16 bar | Up to 150°C | Lightweight, smooth bore, easily demountable |

**Table 8**  *Characteristics of stainless steel process piping systems*

As will be seen in Section 8.1, the material and fabrication costs for stainless steel pipework systems can be considerably lower than those of equivalent carbon steel and ductile iron pipework systems.

Inspection levels for components and welded joints, together with the weld acceptance criteria, are given in the relevant design standard (Table 9).

Water industry standards adopt the same principles as national or international standards but are generally less onerous because the service conditions are less severe than those anticipated by national or international standards. For example, the use of the actual material strength (at temperature) rather than the minimum specified values may be adopted. Such differences may well have limited significance at low pressures as the pipe wall thickness is generally determined by fabrication and installation rather than service and pressure requirements.

| System | Grade | Design standard | Dimension | Testing |
|---|---|---|---|---|
| ANSI | TP304L  TP316L | ASME B31.3 | ASME B36.10 | ASTM A312 |
| ISO | 1.4301 (304)  1.4436 (316) | DIN 2413 | ISO 5252 (pipe)  ISO 5251 (fittings) | DIN 17457  DIN 17455 |
| Metric [1] | SS 2333 (1.4301 / 304)  SS 2343 (1.4436 / 316) | RN1978 | SSG 1361 | SS 219711  SS 219716 |
| Note 1):  This pipe class refers to Swedish standards. | | | | |

**Table 9**  *Examples of combinations of standards for stainless steel process piping systems*

Similarly, industry standards may also have less prescriptive non-destructive examination (NDE) requirements than national standards. This is discussed in greater detail in Section 7.1.7. It is important that the designer utilises safety factors appropriate to the service conditions and the required levels of inspection and quality, in order to produce a safe design that satisfies both the owner and the insurance authorities or certifying bodies. The designer may need to consult the welding engineer to achieve this.

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 so 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 1. Also, the high ductility and work-hardening characteristics of the austenitic 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, plane 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. Quality engineering must also be involved at appropriate stages.

### 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 and section property/member capacity tables are available for stainless steel structural members. These can be applied to the design of welded stainless steel tanks, along with general principles in existing design standards for carbon steel tanks. Bolted tanks are not recommended.*

*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 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

Fabricating stainless steels presents no real problems and uses largely standard equipment and techniques.  Where methods differ from those commonly used to fabricate carbon steels and other materials or where particular conditions are required, appropriate advice is included in this Section.

The recommendations in this Section are appropriate for material up to about 6 mm thick.  This covers the majority of the stainless steel components encountered in the water industries. The thickness of most stainless steel structural components and pipework systems used will be governed by fabrication and installation considerations.  Because of the absence of corrosion allowances, minimum thicknesses are often determined by the need to resist distortion and impact damage, rather than service or pressure loadings.  Appropriate quality assurance and control routines should be used throughout.

The requirements for duplex and more highly alloyed austenitic stainless steels are very similar to those of the standard austenitic steels, but require slightly more attention to detail.  Specialist advice, however, should be taken in order to optimise fabrication and production routines to achieve the full corrosion and strength characteristics of these steels.

### 7.1.1     Materials handling and storage

Cleanliness is the most important aspect of operations with stainless steel.  Care should be taken to keep the steel clean and free from contamination during storage, handling and fabrication.  Cleanliness is essential to ensure trouble-free operation.

In order to avoid potential corrosion damage or unsightly surface marking, measures must be taken to prevent contamination by iron, aluminium, copper, chlorides or sulphides from lifting equipment, marker pens, dust from adjacent fabrication areas and tooling.

Iron particles embedded in stainless steel surfaces during fabrication are a frequent cause of 'surface rusting' on commissioning.  Stainless steel slippers or wooden packers, for example, should be used on fork-lift trucks to prevent contamination.  Plate and pipe lifting methods which avoid damage or contamination of the steel should be followed.

Segregation of stainless steels from carbon steels and non-ferrous materials is critical.  Material is best stored under cover, both for security reasons and to prevent accumulation of dust and deposits, particularly in industrial or marine locations.

Steel racking for stainless steel requires protection, usually by wooden slats and runners.  These should be inspected regularly to prevent scratching of stock by exposed fastenings.

### 7.1.2     Cutting

Normal thermal and cold cutting techniques can be used on austenitic stainless steels.  The steel can be guillotined, sheared and sawn on normal machine tools.  When shearing and guillotining, the capacity of the equipment should be downrated by 50-60% relative to carbon steels, because of the work hardening characteristics of the austenitic grades.  Close attention must be given to the clearance between the blades: it should be maintained at 3-5% of the plate thickness using true, sharp blades.

The cut edges should be examined for contamination and, particularly if there will be subsequent cold work, should be dressed smooth.

When sawing stainless steel, sharp high speed steel blades should be used with cutting fluids. For thicknesses of 3-6 mm, blades with approximately 10 tpi (or more) are appropriate. The 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.

Thermal cutting can be successfully completed with plasma and laser cutting. The cutting kerfs and heat affected zone should be removed before further processing is undertaken.

Cutting and sawing can produce and redistribute residual stresses within a component; this can result 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 that needs to be taken into account during fabrication. Although it is relatively easy to accommodate this ovality during prefabrication of spool pieces, it is helpful to use mill ends as far as possible for site and tie-in welds.

### 7.1.3 Forming

Cold forming with standard equipment is generally appropriate for thicknesses up to about 8 mm. As in storage and handling, contamination from iron particles by pressure contact with rollers or tooling must be avoided. Local application of adhesive plastic films or tape can be used to prevent direct contact. 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% compared with structural carbon steels. Allowance must also be made in bending and rolling for the greater springback characteristics of stainless steels. Although the austenitic stainless steels retain their ductility after forming to a greater extent than carbon steels, it must be remembered that the duplex steels have higher yield strengths and are less suited to extensive cold working.

Dished heads can be pressed and spun on standard equipment. Multiple sheets are often simultaneously pressed, 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 each other, usually by means of plastic interleaving.

Tees can be pulled in thin walled pipe using appropriate equipment. This eliminates the cost of fittings and significantly reduces the welding associated with tee pieces.

Pipe bending and other fabrication activities on site should be avoided as far as possible. Straight pipe runs may be connected with elbows and bends in the normal manner. Spooling is preferred.

### 7.1.4 Machining

Sharp, high speed steel or cemented carbide tip tooling is used for machining austenitic stainless steels. Cutting fluids should be used in order to extend tool life and increase cutting efficiency. Information on cutting speeds and feeds is available from both steel and tool manufacturers.

Resulphurised, 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 causes a significant reduction in corrosion resistance, particularly where the cut edge is exposed. For applications such as strainers and

tube-plates involving extensive drilling, proprietary grades with lower sulphur content and improved machinability are available. These offer a better compromise between machinability and corrosion resistance.

## 7.1.5 Welding

A specification for the fusion welding of austenitic stainless steels is given in BS 7475[42]. Austenitic stainless steels are readily weldable by manual or automated techniques. All the normal arc welding processes can be used.

All welding requires the adoption of safe working practices. Specialist advice should be sought as necessary. In addition to hazards associated with electrical and technical aspects of welding, in the UK there are limits in respect of welding fume which are prescribed by COSHH regulations. These limits are given in the Health and Safety Executive (HSE) list of Occupational Exposure Limits (OELs) Guidance Note EH40. General guidance on weld fumes and their control is also available[43]. The current OEL limit (8 hour TWA value) of $5mg/m^3$ particulate fume generally ensures that no individual constituent of the fume from wires for welding stainless steels will exceed its own recommended limit. However, there are consumables incorporating fluxes which give fumes containing elements such as chromium, nickel, manganese and copper in sufficient quantity that, even at $5mg/m^3$ total, their own limits would be exceeded. For these consumables, manufacturers issue guidance data giving total particulate levels to be observed, to ensure that individual element limits are not exceeded.

Table 10 lists some of the factors which must be taken into account when welding stainless steels. Many of them are common to welding other steels; specific comments on certain aspects are given below. Whilst the same principles apply when welding duplex or more highly alloyed austenitic stainless steels, the attention to detail may be different and specialist advice should be taken, especially regarding design for ease of fabrication.

| Weld procedure | Heat input |
|---|---|
| Process | Root pass |
| Consumable | Fill and cap passes |
| Bevels | Stop/starts |
| Fit-up | Weld volume |
| Backing | Deposition rate |
| Welding technique (balanced passes) | Welding position |
| **Temperature** | **Cleanliness** |
| Preheat | Joint preparation (degreasing and |
| Interpass | mechanical cleaning) |
| Post weld heat treatment | Consumable |
| | Shielding gas |
| | Backing gas |

**Table 10**   *Welding stainless steel - summary of issues requiring consideration*

### *Procedure design and the welding process*

Welding should be undertaken in accordance with a written welding procedure, with both welder and procedure qualified to the welding standard being followed. Although the manual skills are similar to those required for welding carbon steels, the welder needs to adhere to the welding procedure for stainless steels and be familiar with their thermal characteristics and the nature of flow in the stainless steel weld pool. The welding process will be selected to balance factors such as the grade of material and corrosion performance, thickness, skill requirements and joint completion rates. The principal welding methods are TIG (GTA), MIG (GMA) and their variants, plasma, and MMA (SMA). Light gauge materials, including pipework, are often welded using TIG. Although autogenous (welding without additional filler metal) TIG welding is possible for thin materials, most often a suitable consumable is used and this is essential for welding duplex stainless steels.

At the design for fabrication phase, the joint type and welding process will be selected. These in turn will determine the root gap, root face and bevel angles. Bevelled (prepared) ends may not be essential for welding thin material but are preferred practice. It is essential to prepare the pipe ends when welding thicker material. The bevel angle is chosen to ensure good access for the welder, with 30° being a normal value. Joint fit-up and root configuration depend initially on the structural requirements of the joint and then on the practical weld and metallurgical requirements.

Line-up clamps, either internal or external, are extremely helpful when welding, particularly for thin-walled pipe. There must be no risk of contamination of the weld region from any copper strips which may be incorporated into clamps to aid heat flow away from the weld and help offset the effects of the low thermal conductivity of austenitic stainless steels.

Use of a balanced welding technique is a major factor in countering the risks of distortion from the combined effects of the low thermal conductivity and high thermal expansion coefficient of the austenitic steels.

### Temperatures

Unlike some carbon and alloy steels, austenitic stainless steels can be welded from room temperature and do not normally require preheating before starting to weld.

Interpass temperature is the maximum temperature of the weld zone allowed immediately prior to starting any subsequent weld pass. Interpass temperature should be measured with a contact pyrometer. While the whole weld zone should be checked, the underlying weld bead is generally the hottest area. Temperature indicating crayons should only be used with great caution as they can leave a contaminating deposit in the weld zone. A maximum interpass temperature of 150°C is appropriate for 304 and 316 types.

Post-weld heat treatment is not normally necessary for any of the austenitic stainless steels.

### Heat input

The significance of heat input during welding on the development of the correct microstructure must be recognised. In practical terms, for 304 and 316 types the heat input is probably limited more by practical welding considerations (*e.g.* control of the weld pool while completing a root pass) than by metallurgical factors. It is advisable to reduce the heat input slightly for the second pass of a single-sided weld.

At weld stop/starts it is important to ensure geometrical integrity of the pick-up whilst avoiding over-heating at this location. Cleaning and feathering the crater will ensure its freedom from crater cracks and aid pick up. Good crater filling techniques should be used.

Continuous addition of filler will maximise the joint completion rate and help to control the welding heat input.

### Cleanliness

The importance of cleanliness has been discussed in the context of materials handling; it is even more important during welding.

The weld zone should be degreased and mechanically cleaned to bright metal prior to starting welding. Contamination of the weld zone with iron, copper, zinc, lead *etc.* must be avoided. Tooling must be

chosen and used accordingly. For example, iron-free slitting wheels and grinding discs must be used. Normal welding wire and flux storage and handling requirements must be followed to ensure cleanliness and dryness of the materials.

Argon is normally used as a shielding gas to form the arc plasma and protect the weld pool from oxidation and air entrapment.

An inert backing gas must be used to protect the penetration bead of single-sided, full-penetration welds and should be used where possible to protect root runs from oxidation, including tack welds. It is essential for optimum corrosion performance where there will be no access for subsequent cleaning of the weld surface, as in single-sided full-penetration butt welds for tube joins. Argon or a 90% nitrogen - 10% hydrogen gas mixture may be used. The combination of gas purity and purging system employed should ensure oxygen and water contents below 25 ppm at the weld location (including tack welds). Shielding should be maintained until the metal temperature has fallen below 250°C.

### 7.1.6    Post-weld cleaning

The optimum corrosion performance of stainless steel welded joints is achieved by removing crevice features and all weld heat tints, by mechanical dressing or cleaning as necessary and then acid pickling and passivating the joint. For optimum corrosion performance both oxide films and any chromium-depleted layers beneath them must be removed.

The extent to which heat tinting must be removed before the item is put into service is dictated by the type of component and its environment. As a general rule, anything other than a pale yellow coloured oxide film should be removed. (Oxide film colours vary from pale yellow to brown to blue to black as their thickness increases.)

For mechanical cleaning, all abrasive media must be iron-free and wire brushes must be made of a suitable grade of stainless steel wire to avoid contamination. Generally, mechanically cleaned surfaces should be taken to at least a 180 grit finish. (For certain, principally hygienic, requirements, a finer mechanical polish followed by electro-polishing is appropriate.)

### 7.1.7    Weld inspection and acceptance

Examination procedures and guidance on weld acceptance criteria are laid down in standards such as BS EN 25817[44]. The following should be covered in the purchase specification requirements:

* The type of test/examination method to be used and the relevant standards,

* The weld acceptance criteria to be applied,

* The proportion of the welding that must be inspected.

Visual inspection of all welds is a minimum requirement in all cases. Guidance on the visual examination of welded joints is given in BS 5289[45]. 100% of the weld cap should be examined and as much of the root side as is accessible. The fabricator/contractor must be satisfied that the welder is competent to complete this first stage inspection.

Weld quality must comply with the requirements of the standard quoted in the specification. A simple visual examination of the cap is a very useful indicator, but by no means a definitive or rigorous inspection. If the cap (in the as-deposited condition) is smooth, even, regular, not excessively high or wide and free from undercut, it strongly suggests that good welding technique has been used and the quality is probably reasonable. If the cap is erratic, or if it has been mechanically dressed (even though the specification does not call for dressing), a much closer inspection is warranted.

Subject to requirements in the specification, this can be supplemented by liquid-penetrant, ultrasonic-testing and radiographic examination. Ultrasonic testing of thin-walled components (less than approximately 6 mm) is extremely difficult.

## 7.2    Installation

### 7.2.1    Site fabrication and installation

Site fabrication should be avoided as far as possible. Components should be prefabricated for mechanical fastening, taking advantage of the range of conversion couplings available, or for tie-in welding. Pipework systems should be spooled.

Spool pieces and pressure vessels joined with stainless steel connections should be bolted using compatible stainless steel bolts.

Tie-in welding may be necessary at some locations. The green end of the pipe should be cold cut to length and then prepared. The use of slitting wheels should be avoided as they can easily introduce a heat-affected zone into the pipe end before starting to weld. The pipe end should be prepared for welding with the same care and attention as for a shop fabrication joint. Pipe end preparing machines are preferred in order to produce a reliable joint bevel and joint fit up.

The gas backing requirements discussed in Section 7.1.5 are relevant. Bladders or dissolvable gas dams can be used to reduce the purged volume.

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. As in the initial storage and fabrication stages, precautions must be taken to avoid contamination with iron particles, either as dust or spatter from cutting or sawing operations, or embedded by contact, for example as a result of scaffold poles being dragged over the metal. Iron contamination can be removed by applying a nitric acid based cleaning (or pickling) and passivating agent. Proprietary formulations are available.

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. In any case, plant should be washed down with potable grade water at the end of installation operations. 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 (Reference 19). Packaged units involving stainless steel pipework systems will probably have been subject to cleaning, possibly sterilisation, passivation and rinsing/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, see for example BS 8010: Part 2.8[46] and CP 2010: Part 2[47]. In assessing corrosion risks, 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.

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.

### 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 C5I[48] (*Industrial areas with high humidity and aggressive atmospheres*) 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.

The use of zinc-containing paints on stainless steels should be avoided.

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 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 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 steel 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 particles, which can lead to 'surface rusting' or staining. Only iron-free abrasives should be used on stainless steel.*

*Stainless steel work-hardens more than carbon steels; thus cutting, forming etc. require increased machine tool power and re-working is more difficult. Stainless steels show more springback than other metals, making overbending necessary.*

*The higher thermal expansion coefficients and lower thermal conductivity of austenitic stainless steels increase the likelihood of distortion; a balanced welding technique can minimise this effect.*

*Optimum corrosion performance after welding is obtained by removing any crevice features and weld heat tint mechanically using non-contaminating media and wire brushes, followed by pickling.*

*During installation, stainless steel should be protected from iron contamination, dust, mortar/concrete splashes, mechanical damage etc. and once installation operations are complete, washed down with clean water.*

*Stainless steel can be thoroughly washed down with clean water as often as necessary for cleaning without the risk of rusting.*

# 8    ECONOMIC BENEFITS OF USING STAINLESS STEEL

The use of stainless steel can provide economic benefits to the water industry both through lower initial plant costs and lower plant operating costs.

## 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.

*   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.

A comparison has been made between the initial costs of a 6 m run of stainless steel, carbon steel and ductile iron pipework (Figure 3). Table 11 shows the potential cost and weight savings that arise from using stainless steel. These savings result from the elimination of corrosion allowance and coatings and the simplification of jointing and assembly made possible by using stainless steel. Additional advantages (not taken into account in this cost comparison) are that spooled pipework assemblies in stainless steel allow compact layouts and the reduced requirement for lifting gear helps achieve a small 'site footprint' on installation.
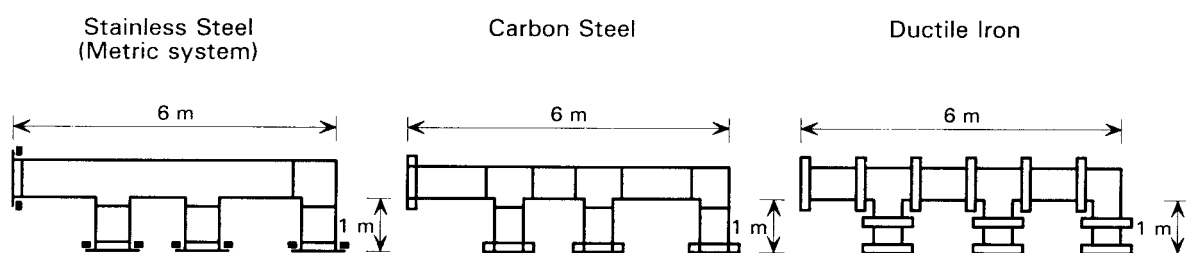


**Figure 3**    *Comparable 6 m runs of stainless steel, carbon steel and ductile iron pipework*

| | DN150 6" NB | | DN200 8"NB | | DN250 10" NB | | DN300 12" NB | |
|---|---|---|---|---|---|---|---|---|
| | Cost* | Weight | Cost* | Weight | Cost* | Weight | Cost* | Weight |
| Stainless steel | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Carbon steel | 208 | 346 | 244 | 408 | 244 | 466 | 234 | 395 |
| Ductile iron | 144 | 428 | 155 | 450 | 170 | 465 | 157 | 384 |
| Saving over carbon steel | 52% | 71% | 59% | 75% | 59% | 79% | 57% | 75% |
| Saving over ductile iron | 31% | 77% | 35% | 78% | 41% | 78% | 36% | 74% |
| * Cost based on an index of 100 for stainless steel systems. | | | | | | | | |

**Table 11** *A comparison of relative cost and weight for an equivalent run of pipework for 16 bar service in stainless steel, carbon steel and ductile iron* (Based on market rates prevalent in 1998)

## 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.

• long service life.

## 8.3    Life cycle costs

There is increasing awareness that life cycle (or whole life) costs, not just initial costs, should be considered when making decisions relating to new or replacement plant.  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, calculation of the life cycle cost is straightforward and a simple computer program is available[49]. Euro Inox have 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[50]. Significant cost savings arose from specifying stainless steel.

Figures 4, 5, 6 and 7 show the results of life cycle cost studies on different materials for four pieces of water industry plant. The following comments relate to these figures.

### *Manhole equipment*[51] (Figure 4)

Stainless steel (304 type) was compared with galvanised carbon steel for construction of an 800 mm diameter manhole with ventilation chimneys, sump cover and a ladder. It was assumed that the galvanised steel required regalvanising at regular intervals and, eventually, replacement after 25 years. The stainless steel equipment was designed for a 50 year service life, with no maintenance costs in addition to regular inspections. Stainless steel showed a life cycle cost advantage after just over 4 years, simply by avoiding the costs of regular maintenance. An 8% interest rate and a 3% inflation rate were assumed, giving a discount rate of 4.85%.

### *Elevated tank equipment*[51] (Figure 5)

The equipment under consideration comprised a pressure door, entrance door, platform, window, guardrail, railing and louvres. Stainless steel (304 type) was compared with galvanised steel (for the interior) and aluminium (for the doors and windows). It was assumed that the galvanised steel and aluminium required maintenance (in addition to inspection) at regular intervals and replacement after 25 years. The stainless steel equipment was designed for a 50 year service life, with no maintenance costs in addition to regular inspections. Stainless steel showed a life cycle cost advantage following replacement of the galvanised steel/aluminium plant after 25 years. An 8% interest rate and a 3% inflation rate were assumed, giving a discount rate of 4.85%.

### *Pipeline equipment for a valve and water chamber*[51] (Figure 6)

Stainless steel (304 type) was compared with ductile iron for the inlet and outlet pipes for a water chamber as well as for the pipe equipment in the valve chamber. It was assumed that the ductile iron equipment required maintenance (in addition to inspection) at regular intervals and replacement after 25 years. The stainless steel equipment was designed for a 50 year service life, with no maintenance costs in addition to regular inspections. Stainless steel showed a life cycle cost advantage following replacement of the cast iron structure after 25 years. An 8% interest rate and a 3% inflation rate were assumed, giving a discount rate of 4.85%.

### *Ductwork to remove odorous fumes in a sewage inlet works*[52] (Figure 7)

Galvanised carbon steel and stainless steel (316 type) were both candidate materials for ductwork to remove odorous fumes in a sewage inlet works. The galvanised steel required a multi-stage site-applied painted coating whereas stainless steel permitted installation in a single operation. It was assumed that the galvanised steel required maintenance (in addition to inspection) at 5 yearly intervals and replacement after 15 years. The stainless steel equipment was designed for a 30 year service life, with maintenance (in addition to regular inspections) every 10 years. Stainless steel showed a life cycle cost advantage following replacement of the galvanised steel plant after 15 years. A 10% interest rate and a 5% inflation rate were assumed, giving a discount rate of 4.76%.

### SUMMARY OF SECTION 8

*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.*

*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 savings in operating costs far outweigh any higher initial capital costs.*
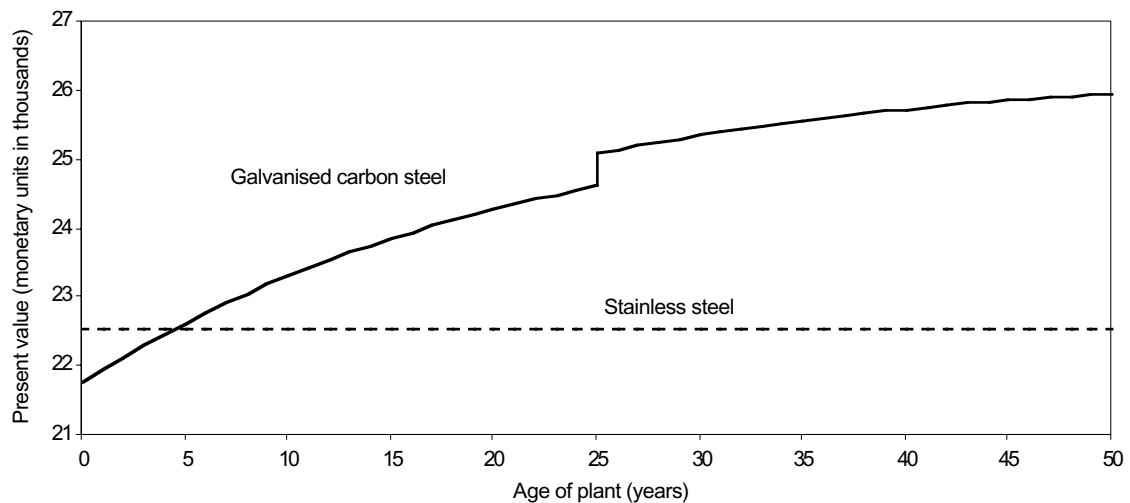


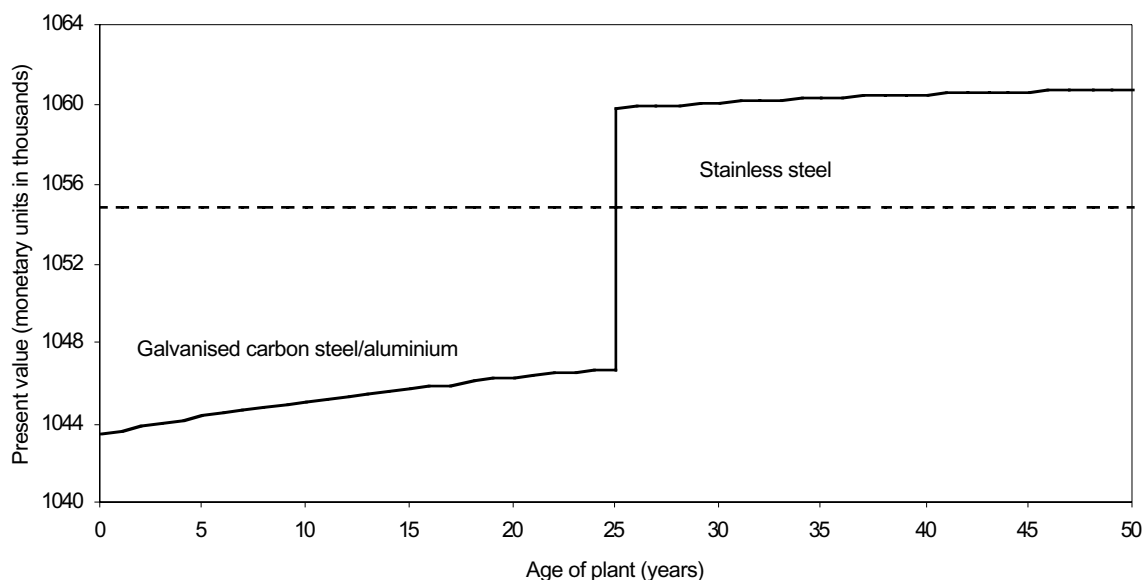**Figure 4**   *Life cycle cost comparison for manhole equipment*



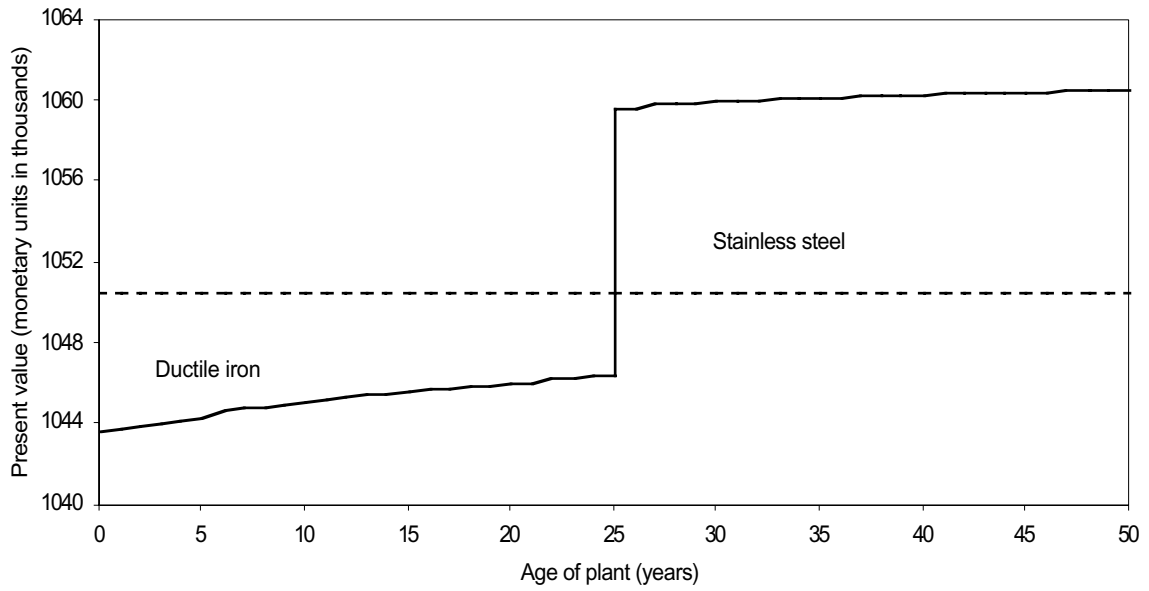**Figure 5**   *Life cycle cost comparison for elevated tank equipment*

**Figure 6** *Life cycle cost comparison for pipeline equipment for a valve and water chamber*
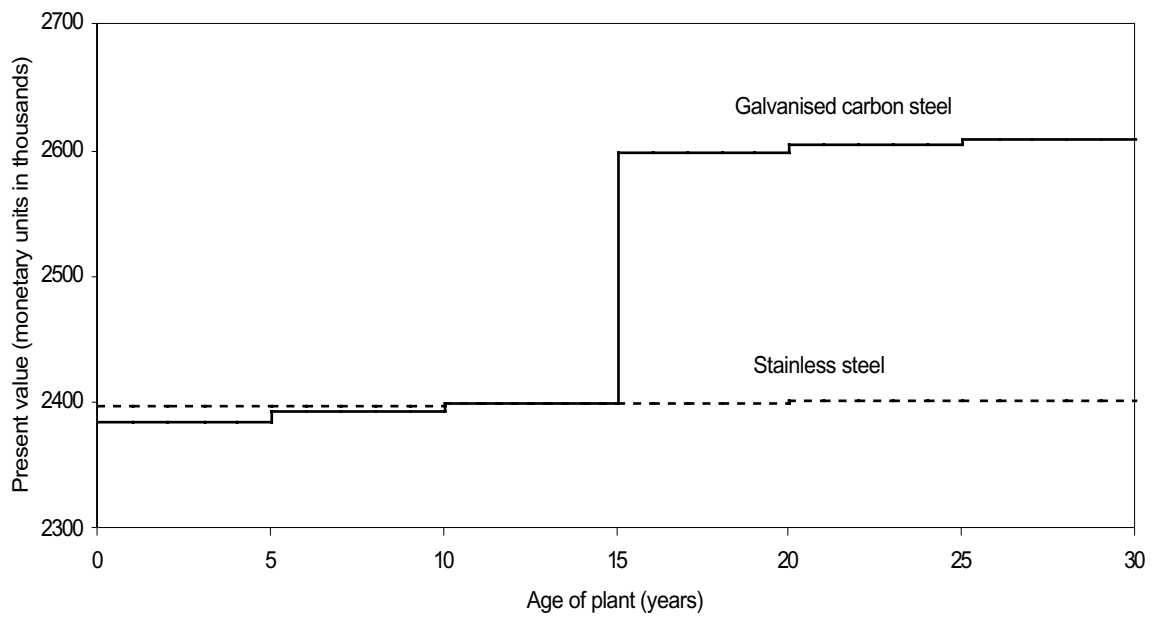


**Figure 7** *Life cycle cost comparison for ductwork to remove odorous fumes in a sewage inlet works*

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# 11    SOURCES OF FURTHER INFORMATION

Stainless Steel Advisory Service
The Steel Construction Institute
Silwood Park
Ascot, Berks SL5 7QN
Tel:      01344 623345               Fax:     01344 622944

*For queries concerning the application of stainless steel in construction.*

Avesta Sheffield Technical Advisory Centre (ASTAC)
Avesta Sheffield Ltd
PO Box 161
Shepcote Lane
Sheffield S9 1TR
Tel:      0114 244 0060               Fax:     0114 242 0162

*For queries concerning grade selection, corrosion, product forms and availability.*

Nickel Development Institute (NiDI)
European Technical Information Centre
The Holloway, Alvechurch
Birmingham, B48 7QB
Tel:      01527 584777               Fax:     01527 585562

*For queries concerning grade selection, corrosion and end-uses in all industries.*

National Corrosion Service
National Physical Laboratory
Queens Road
Teddington
Middlesex TW11 0LW
Tel:      0181 943 6179               Fax:     0181 943 6177

*For queries concerning corrosion.*

# 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 into the crevice creates acidic conditions, leading to migration of chloride ions, further aiding corrosion. The risks of initiating corrosion are reduced the wider the crack 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 (Nitrogen), or PRE(N), is calculated from the composition of the steel and provides a simple means of ranking different steels for their resistance to attack.

$$PRE(N) = wt\%Cr + 3.3wt\%Mo + 30wt\%N$$

This equation is based on the work of G Herbsleb, (Werkstoffe und Korrosion, **33** (1982) pp 334-40). Alternative terms, principally for nitrogen, have been proposed, although the overall ranking on composition remains similar.

However, materials selection decisions cannot be based on PRE(N) 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. Table A.1 gives the approximate PRE(N) ranges for selected steels, based on the composition ranges permitted in BS EN 10088: Part 2.

For further information, see *The crevice corrosion engineering guide* from the Nickel Development Institute.

| Steel grade | Type | Approximate PRE(N) range |
|---|---|---|
| 1.4003 | 11-12% Cr ferritic | 11 - 14.5 |
| 1.4016 | 17% Cr ferritic | 16.5 - 20 |
| 1.4301 | Standard austenitic | 17.5 - 23 |
| 1.4401 | Austenitic 2% Mo | 23.5 - 29 |
| 1.4436 | Austenitic 2.5% Mo | 25.5 - 30 |
| 1.4362 | Lean duplex | 24 - 32 |
| 1.4462 | Standard duplex | 32 - 41 |
| 1.4410 | Super duplex | 40 - 50 |
| 1.4547 | 6% Mo Super austenitic | 44.5 - 51 |

**Table A.1** *Approximate PRE(N) range for selected stainless steels*

# APPENDIX B. NATIONAL, EUROPEAN AND INTERNATIONAL STANDARDS RELATING TO STAINLESS STEEL

| | | |
|---|---|---|
| Designation | BS EN 10027:1992 | Designation systems for steel<br>Part 1: Steel names, principal symbols<br>Part 2: Steel numbers |
| Flat and long products - material | BS EN 10088:1995 | Stainless steels<br>Part 1: List of stainless steels<br>Part 2: Technical delivery conditions for sheet/plate and strip for general purposes<br>Part 3: Technical delivery conditions for semi-finished products, bars, rods and sections for general purposes |
| | BS 970: Part 1: 1996 | Specification for wrought steels for mechanical and allied engineering purposes<br>Part 1: General inspection and testing procedures and specific requirements for carbon, carbon-manganese, alloy and stainless steels |
| Flat and long products - tolerances on dimension and shape | BS EN 10029:1991 | Tolerances on dimensions, shape and mass for hot rolled steel plates 3 mm thick or above |
| | BS EN 10048:1997 | Tolerances on dimensions and shape for hot rolled narrow steel strip |
| | BS EN 10051:1992 | Continuously hot-rolled uncoated plate, sheet and strip of non-alloy and alloy steels - tolerances on dimensions and plate |
| | BS EN 10259:1997 | Tolerances on dimensions and shape for cold rolled stainless steel wide strip and sheet/plate |
| | BS EN 10258:1997 | Tolerances on dimensions and shape for cold rolled stainless steel narrow strip and cut lengths |
| Pipework systems - ANSI | ASME B 31.3:1996 | Process piping |
| | ASME B 36.10M:1996 | Welded and seamless wrought steel pipe |
| | ASTM A 312:1995A E1 | Specification for seamless and welded austenitic stainless steel pipe (0.25"-30") |
| | ASTM A 403:1996 | Standard specification for wrought austenitic stainless steel piping fittings |
| | ASTM A 774:1994 | Specification for as-welded wrought austenitic stainless steel fittings for general corrosive service at low and moderate temperatures |
| Pipework systems - ISO | DIN 2413-1:1993<br>DIN 2413-2:1993 | Steel pipes; calculation of wall thickness of steel tubes subjected to internal pressure<br>Steel pipes; calculation of wall thickness of bends subjected to internal pressure |
| | ISO 5251:1981 | Stainless steel butt welding fittings |
| | ISO 5252:1991 | Steel tubes; tolerance systems |
| | DIN 17455:1985 | General purpose welded circular stainless steel tubes; technical delivery conditions |
| | DIN 17457:1985 | Welded circular austenitic stainless steel tubes subject to special requirements; technical delivery conditions |
| | DIN 2463-1:1981 | Welded austenitic stainless steel pipes and tubes, dimensions, conventional masses per unit length |
| | ISO 1127:1992 | Stainless steel tubes; dimensions, tolerances and conventional masses per unit length |

| Pipework systems - Metric | RN 1978:37 | Swedish Piping System Code |
|---|---|---|
| | SSG 1361 | Longitudinally welded tube/pipe (Dimensions) |
| | SS 219711:1984 | Stainless steels - Tubes for pressure purposes.  Test category 1.  Technical delivery requirements |
| | SS 219716:1984 | Stainless steel tubes - Welded tubes for pressure purposes.  Technical delivery requirements |
| Castings | BS 3100:1991 | Steel castings for general engineering purposes |
| Fasteners | BS 6105 (equivalent to ISO 3506) | Specification for corrosion-resistant stainless steel fasteners |
| Wire | BS 3111:Part 2:1979 | Steel for cold-forged fasteners and similar components Part 2: Stainless steels |
| Design of structural members | ENV 1993-1-4:1996 | Design of steel structures Part 1.4: General rules; Supplementary rules for stainless steels |
| Welding | BS EN 287-1:1992 | Approval testing of welders - Fusion welding Part 1: Steels |
| | BS EN 288:1992 | Specification and approval of welding procedures for metallic materials |
| Quality Assurance | BS EN ISO 9001:1994 | Quality systems.  Model for quality assurance in design, development, production, installation and servicing |
| | BS EN ISO 9002:1994 | Quality systems.  Model for quality assurance in production, installation and servicing |
| Note: European standards for stainless steel tube, forgings, castings, welding consumables and fittings are in preparation. | | |