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The European Stainless Steel Development Association

Performance of Stainless Steels in Waste Water Installations

Materials and Applications Series, Volume 13

Euro Inox

Euro Inox is the European market development association for stainless steel.

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- European stainless steel producers
- national stainless steel development associations
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A prime objective of Euro Inox is to create awareness of the unique properties of stainless steels and to promote their use in existing applications and new markets. To this end, Euro Inox organises conferences and seminars and issues guidance in printed form and electronic format, to enable architects, designers, specifiers, fabricators and end users to become more familiar with the material. Euro Inox also supports technical and market research.

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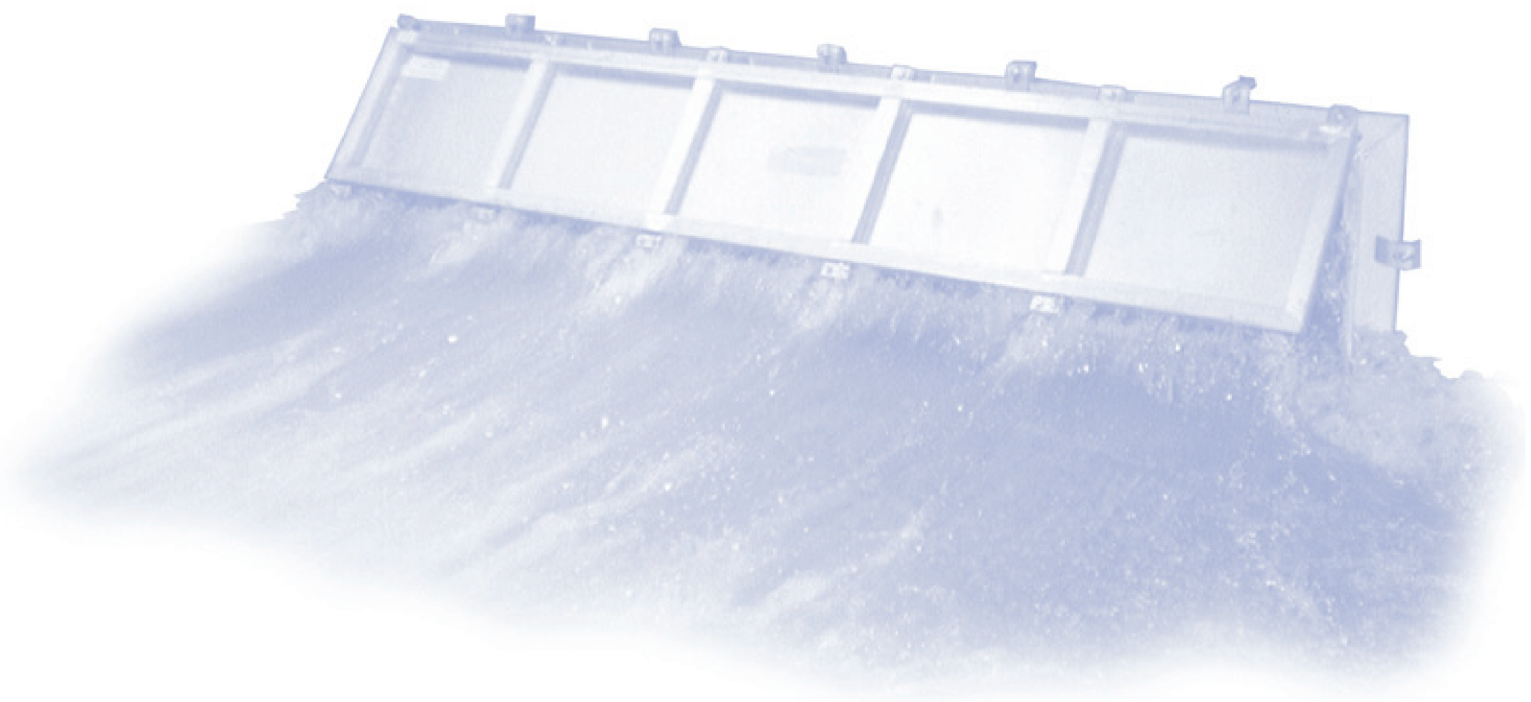
Contents

Introduction

When correctly selected and fabricated, stainless steels can provide low maintenance and long-life construction solutions for waste water installations. Stainless steels are also fully recyclable. Whereas the excellent corrosion resistance of these materials has been known for many years, it is only more recently that their mechanical properties have received particular attention. A design adapted to stainless steel allows a thinner wall thickness to be used which results in weight and cost savings. A further increase in strength may be achieved by cold deformation of austenitic stainless steels allowing additional savings. Austenitic stainless steels are easy to fabricate on site in the field since their high ductility allows them to be readily formed. If, in addition, life cycle costs are taken into account, the use of stainless steel becomes even more attractive.

Normally the use of 1.4404 (316L) stainless steel is recommended for water pipes and underwater construction, whereas 1.4307 (304L) stainless steel is the material of choice for many applications above the water line. This is based on both corrosion resistance and cost considerations. Grade 1.4462 duplex (ferritic-austenitic) stainless steel, in its solution-annealed condition, offers a combination of both higher corrosion resistance and strength. Consequently, its use can be considered for both submerged applications and those above water, where large components have to be moved and therefore lightweight construction is advantageous, e.g. large clarifier arms.



1 Definition of stainless steels, general survey and standards

View across the aerated basins of a waste water treatment plant
Photo: CDA La Rochelle (F)

From the great number of available stainless steels, Table 1 shows a selection of those materials which are normally considered for application in waste water systems. Groups 1 and 2 comprise of the austenitic Type 304 and 316 alloys which on average contain about 18 % chromium (Cr) and 10 % nickel (Ni) and, in the case of Type 316, from 2.0 to 2.5 % molybdenum (Mo). The corrosion resistance of these stainless steels is due to the main alloying constituents. The steels also contain minor amounts of carbon. If not bound to stabilising elements, e.g. titanium, the carbon may result in intergranular corrosion after welding heavier sections. Therefore, the traditional 1.4541 and 1.4571 grades are alloyed with titanium and denoted as “stabilised”. However, modern steel making practice allows the carbon content to be kept very low and so avoid the need for stabilisation. Such low carbon materials are available as the grades 1.4306, 1.4307 and 1.4404. Nevertheless, the more traditional grades 1.4301 and 1.4571 are still popular.

Although the current European standardisation [1] mentions many more grades, the need to reduce inventories and ongoing globalisation is expected to result in the preferential or exclusive use of grades 1.4307 and 1.4404 in future. This is largely because they correspond to the internationally preferred Type 304L and 316L alloys and are widely available and straight forward to weld.

In addition to the grades mentioned in Table 1, there is a multitude of higher alloyed stainless steels (see Table 2) which can be considered for use in waste water systems where aggressive conditions prevail; and these are also mentioned in [1]. Particular attention should be given to grade 1.4462. This two-phase 22 % Cr ferritic-austenitic, or duplex, stainless steel is of special interest both for its increased corrosion resistance and for its high proof stress.

Table 1: Stainless steels for waste water installations

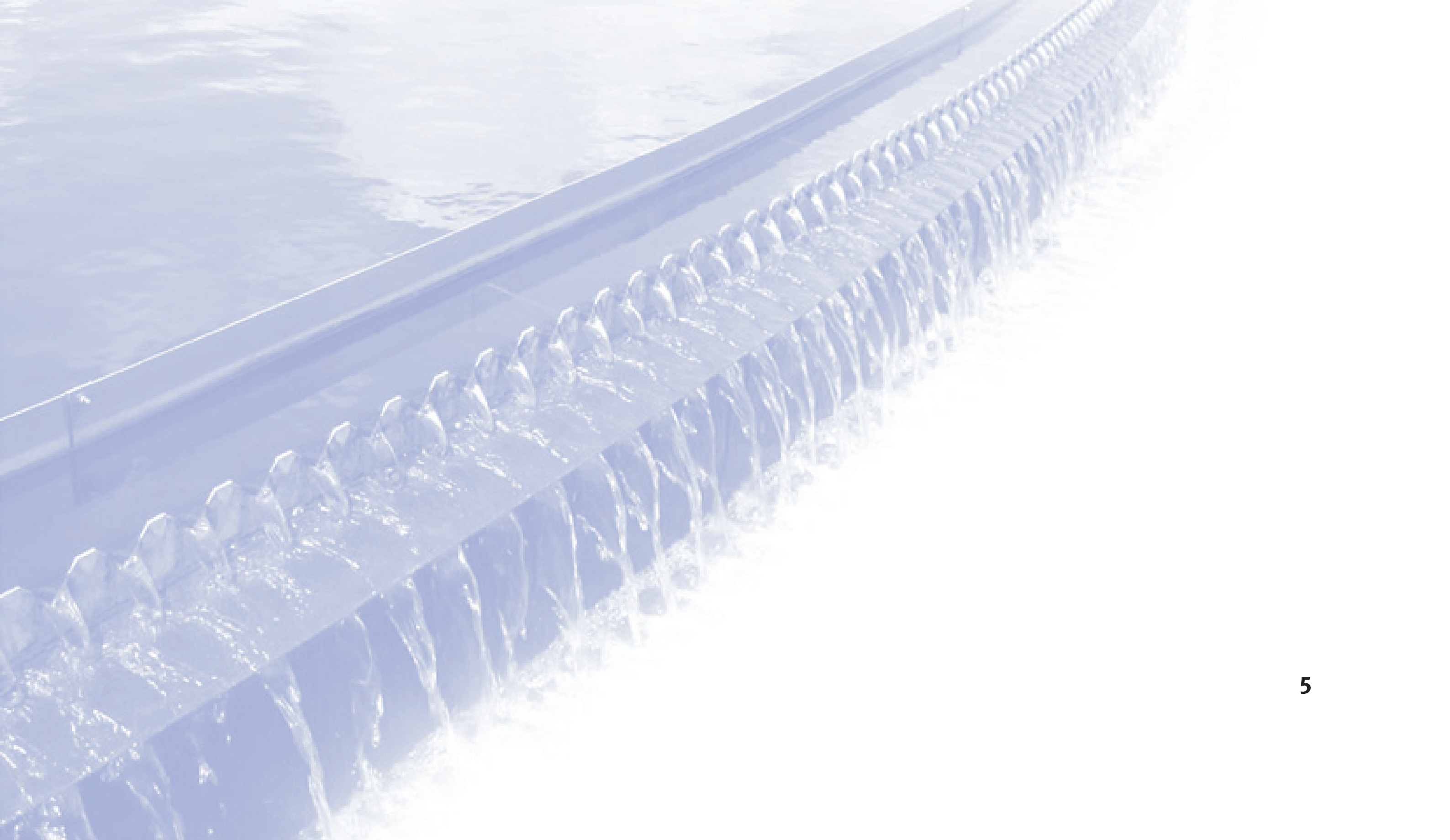
Group (Type)	Designation according to EN 10088		Composition, % by mass				
	Name	Nr.	Cr	Ni	Mo	Cmax.	other
1 (304)	X5CrNi18-10	1.4301	17.5–19.5	8.0–10.5		0.07	max. 0.11 N
	X2CrNi18-9	1.4307	17.5–19.5	8.0–10.5		0.03	
	X2CrNi19-11	1.4306	18.0–20.0	10.0–12.0		0.03	
	X6CrNiTi18-10	1.4541	17.0–19.0	9.0–12.0		0.08	Ti: 5xC–0.70
2 (316)	X5CrNiMo17-12-2	1.4401	16.5–18.5	10.0–13.0	2.0–2.5	0.07	max. 0.11 N
	X2CrNiMo17-12-2	1.4404		10.0–13.0		0.03	
	X6CrNiMoTi17-12-2	1.4571		10.5–13.5		0.08	Ti: 5xC–0.70

Table 2: Stainless steels for waste water installations with special requirements

Group	Designation according to EN 10088		Composition, % by mass				
	Name	Nr.	Cr	Ni	Mo	Cmax.	other
3	X2CrNiMo18-14-3	1.4435	17.0–19.0	12.5–15.0	2.5–3.0	0.03	max. 0.11 N
4	X2CrNiMoN22-5-3	1.4462	21.0–23.0	4.5–6.5	2.5–3.5	0.03	0.10–0.22 N
	X2CrNiMo17-13-5	1.4439	16.5–18.5	12.5–14.5	4.0–5.0	0.03	0.12–0.22 N
5	X1CrNiMoCuN20-18-7	1.4547	19.5–20.5	17.5–18.5	6.0–7.0	0.02	0.18–0.25 N 0.5–1.0 Cu
	X1NiCrMoCuN25-20-7	1.4529	19.0–21.0	24.0–26.0	6.0–7.0	0.02	0.15–0.25 N 0.5–1.5 Cu

Sectional view of the waste water treatment plant with stainless steel pipes and railings
Photo: Cedinox, Madrid (E)

Whereas Tables 1 and 2 show the chemical compositions according to Part 1 of the European standard EN 10088 [2], Part 2 of this standard defines the technical delivery conditions for sheet / plate and strip for general purposes, and Part 3 for semi-finished products, bars, rods and sections. These standards also describe the various delivery conditions and surface finishes of the products. Additionally, there is a European standard EN 10312 for welded stainless steel tubes for the conveyance of aqueous liquids [1] and a European standard EN 10217–7 for welded tubes for pressure purposes [3]. A multitude of national standards also apply.



2 Requirements for stainless steels in waste water systems

Corrosion resistance to waste water and the products being used for the treatment of the water is the primary requirement which has to be met by stainless steels in waste water handling. The substances dissolved in the incoming waste water, primarily chlorides, should be considered first, followed by the additions made during waste water treatment which are intended for oxidation and flocculation. Chlorine which may be added as a disinfectant is also a strong oxidising agent. Corrosion resistance to the surrounding atmosphere should also be considered – including to the gaseous products which may develop during waste water treatment.

Compatibility with other materials of construction may require attention, as well as corrosion resistance to the surrounding soil for buried installations. The mechanical stress may be not only static but also dynamic, e.g. with aeration piping. Finally, resistance to erosion may be a requirement due to the solid substances being carried by the water.

Stainless steel containers and piping in a waste water treatment plant
Photo: Hans Huber, Berching (D)

3 Corrosion resistance to waters

3.1 General

Corrosion resistance – the most important criterion for stainless steels – is not a materials property but results from the interaction between the material and the surrounding medium at the material's surface. Therefore, in addition to a careful consideration of the corrosive nature of the water and the appropriate selection of the material, the whole manufacturing, fabrication and joining processes have to be considered as they influence the surface quality. Even so, the general corrosion behaviour of stainless steels [4] in waste water can be summarised as:

- The stainless steels mentioned in Table 1 are resistant to uniform corrosion in potable water and waters of similar chemical composition, surface waters including seawater and, therefore, normally in waste water too. Apart from possible deposition of dirt, the metallic bright surface of the stainless steels will be maintained during service. Resistance to uniform corrosion is not impaired by additions of acids down to a pH of about 4 and therefore not an issue when using stainless steels in contact with most waters [5].

Front view of two counterflow coarse screens made from stainless steel
Photo: Werkstoff + Funktion Grimmel Wassertechnik, Ober–Mörlen (D)

- Intergranular corrosion can be avoided if, when welding heavier sections of more than 6 mm thickness or 20 mm diameter [6], stainless steel grades are used with carbon contents of max. 0.03 %, e.g. 1.4307 or 1.4404 or those with titanium stabilisation, e.g. 1.4541 or 1.4571.

- Stress corrosion cracking of austenitic stainless steels in chloride containing waters is generally observed only above temperatures of about 50–60 °C [7]. Duplex grades as e.g. 1.4462 are even less sensitive. Provided fabrication is properly [8] carried out, i.e. avoiding sensitisation and extreme degrees of cold forming [7], stress corrosion cracking of stainless steels in waste water installations is normally not a matter for concern.

Bare and painted stainless steel surface is used in Lavis (I)
Photo: Centro Inox, Milan (I)

- In contrast to the aforementioned types of corrosion, there are two forms of attack which require special attention with stainless steels in waters: pitting corrosion and crevice corrosion. For both types of corrosion the chloride content of the water is one crucial factor. This has to be countered by an appropriate selection of the stainless steel grade and other measures. For a better understanding, pitting corrosion and crevice corrosion are examined in more detail below.

- Microbiologically influenced corrosion (MIC), which occurs mainly in or near welded areas, has a low incidence in waste water installations [9]. The most important factor in avoiding MIC is careful removal of any heat tint scale after welding [9]. This is most effectively carried out by immersion pickling, although other means are available [10].

3.2 Effect of Alloy Composition

The resistance of stainless steels to pitting and crevice corrosion in chloride containing waters is a function of their chemical composition and increases with the so-called pitting resistance equivalent number: PREN = % Cr + 3.3 × % Mo + X × % N. This relationship is valid for homogenous materials in the as-delivered condition. Obviously the molybdenum content is of great influence since it has a factor of 3.3. Nitrogen is important too; a factor of 16 is usually assumed for the duplex grades such as 1.4462 and a factor of 30 for the very high alloyed stainless steel grades [7]. Nitrogen has little effect on the steels of groups 1 and 2 (see Table 1). Based on this, the following general guidelines for optimum selection of stainless steels in chloride containing waters apply [5].

- Stainless steels from group 1 (see Table 1) are suitable for use with potable and industrial waters with moderate chloride content. Stainless steels from group 2 are the right choice for potable and industrial waters with increased chloride content whereas the steels in group 3 are suitable for industrial and cooling waters with relatively high chloride content. For use in brackish water and seawater, steels from groups 4 and 5 have to be selected. Additional explanations are given in section 3.3.1 below.

- The titanium stabilised grades 1.4541 and 1.4571 are sometimes said [11] to possess a somewhat lower resistance to pitting corrosion compared with the other grades within the same groups. This is supported by technical literature [12, 13] which indicates that the presence of titanium in stainless steels may increase the likelihood of pitting corrosion.

- The so called free-machining grades, have high sulphur content, e.g. grade 1.4305, and are not suitable for continuous handling of water because sulphide inclusions in their structure lead to reduced resistance to pitting corrosion.

Piping system below the sandfilter basins in sewage treatment plant in Stockholm (S)
Photo: Outokumpu, Avesta (S)

3.3 Effect of Water Chemistry

3.3.1 Chloride ions

It is clear from the statements in section 3.2 for the selection of stainless steels in waters, including waste water; the chloride (Cl^-) content of the water is the most influential factor. Due to the multitude of other factors which influence selection, no precise definitions have been given in [5] to describe what is meant by the terms “moderate”, “increased” and “relatively high” chloride contents in terms of concentration levels. The allowable upper concentration limits depend on the pH, temperature, extent to which other oxidising agents are present as well as other substances dissolved in the water such as nitrates, sulphates, etc. The latter may act as inhibitors and the beneficial effect of these anions is greatest for OH^- and decreases in the order NO_3^-, CH_3COO^-, SO_4^-, ClO_4^- [14].

The chloride concentration limits found in literature, e.g. [15], must not be used too literally. The concentration limits given for pure water may not apply to the more practical waters which are considered here. Generally, due to the presence of other anions, the allowable chloride concentration limits in potable and fresh waters will be significantly higher than in pure water. The temperature limits in most waters will normally be lower at higher chloride concentrations and, in the case of crevice corrosion, crevice geometry is also important. Tight crevices are critical and may exist between metals and plastics, below sediments brought in by the water from outside or under deposits of corrosion products.

The selection of material for pipes helps to reduce costs in the construction Photo: H. Butting, Knesebeck (D)

Several decades of practical experience [14] with Type 304 stainless steels (group 1 in Table 1) indicate that they are satisfactory for handling waters with chloride contents less than about 200 mg/l. Type 304 stainless steels are marginally satisfactory at levels of chloride between 200 and 1000 mg/l and their successful use would depend on other factors such as high content of other anions (see above), the nature of crevices present etc., and the possibility of toleration of some degree of crevice corrosion in the application [16]. However, stainless steel from group 2 in Table 1 (Type 316) is preferred for critical applications where the chloride content exceeds 200 mg/l, and other adverse factors such as low sulphate contents and tight crevices are involved [14] with an upper guideline limit of about 1000 mg/l chlorides [16]. Statements made in 1990 [17] and later [18] say that stainless steel of group 1 (Type 304) is resistant to crevice corrosion below a chloride level of about 200 mg/l, and that crevice corrosion of Type 304 / 304L is rarely reported in fresh waters – which are generally in the range of 20–100 mg/l chlorides – whereas stainless steel of Type 316 is resistant below a chloride level of about 1000 mg/l. Recent waste water related literature [9], endorses that Type 1.4404 (316L) is preferred to type 1.4307 (304L) where chlorides exceed 200 mg/l. Practical experience with potable waters [19] shows that stainless steels of Type 304 can handle potable water with chloride levels up to about 200 mg/l. According to the European standard EN 12502-4 [20], molybdenum-free ferritic and austenitic stainless steels show a high likelihood of pitting corrosion in cold water with chloride contents above about 6 mmol/l (about 200 mg/l), whereas in hot water this limit is reduced to about 1.5 mmol/l (about 50 mg/l).

However with molybdenum-free stainless steels, crevice corrosion may occur in cold water at chloride contents distinctly lower than about 200 mg/l [20]. Crevices have to be tight – as a result of design, or under sediments – for crevice corrosion to occur. As a rule, crevice gaps of more than 0.5 mm are uncritical [20] but the depth of the crevice is important as well. The method of joining is a decisive factor in determining the risk of crevice corrosion. When press fittings are used, the stainless steels from group 1 in Table 1 (Type 304) are not completely resistant to crevice corrosion in the range of chloride contents allowed in potable water by the drinking water directive 98/83/EC, i.e. up to 250 mg/l [5]. In this case, it is necessary to use steels from group 2 in Table 1 (Type 316) for which an upper limit of 500 mg/l chlorides is indicated for conditions such as in a drinking water installation [5].

3.3.2 Other substances dissolved in or added to the water

In addition to chlorides, there are other substances which may affect the corrosive behaviour of the water. Special attention has to be paid if halides other than chlorides are present, such as bromides or iodides. Another important factor is the content of oxidising agents since the risk of pitting corrosion increases with increasing oxidising power of the water. Chlorine is a strong oxidising agent. Stainless steels are generally resistant to chlorine at the concentrations normally encountered in waste water treatment plants [9]. Chlorine contents of 2 mg/l in chlorinated fresh water did not result in corrosion of stainless steels of the Types 304 and 316. Continuous exposure to 3–5 mg/l residual chlorine in chlorinated fresh waters resulted in crevice corrosion of Type 304/304L stainless steel and much less on Type 316L [21]. Therefore, Type 316L would be a more con-

Multi-rake bar screens
Photo: Hans Huber, Berching (D)

servative choice in such applications [9]. Ozone is an increasingly common alternative oxidising agent which can be used separately or in conjunction with chlorine. Type 316 stainless steel is a preferred construction material for ozone generators [9].

Ferric chloride is sometimes used for flocculation in waste water treatment plants. Types 304 and 316 stainless steels can suffer from both pitting and crevice corrosion when concentrations are too high for the alloys; [9] refers to the presence of 250–300 mg/l ferric chloride in activated sludge causing corrosion. Additions need to be well mixed and diluted with the waste waters upstream of the stainless steel, to avoid exposure to harmful concentrations. Ferrous sulphate is another chemical that is frequently added in waste water treatment plants but experience gained so far indicates that the corrosion rate for stainless steel in acid-free ferrous sulphate environments will be negligible [9].

3.4 System Construction

3.4.1 Design

To obtain a high resistance to corrosion of stainless steels in waters, the design must provide the maximum practical flow but with a minimum flow of about 1 m/s in order to reduce the likelihood of pitting and to minimise the deposition of sediments. In addition, it is important to avoid crevices wherever possible. If crevices cannot be avoided they should be made as wide as possible. Metal/metal crevices are generally less critical than metal/plastic crevices. An increased risk of corrosion due to crevices may be compensated by selection of a more corrosion resistant material e.g. a stainless steel from group 2 in Table 1 instead of group 1. Horizontal pipes should be sloped sufficiently to allow ease of draining. When sludges are to be handled, it is important to avoid any dead legs and pockets where sludge could adhere and lead to deposit build up.

Completely roofed purification plant in Vallarsa (I)
Photo: Centro Inox, Milan (I)

Stainless steels are frequently combined with other materials in waste water installations and hence the question of compatibility arises [22]. When two different metallic materials are in electrical contact while immersed in an electrically conducting liquid, electrochemical reactions occur which may cause corrosion of the less noble material. This is called galvanic corrosion or bimetallic corrosion. In most cases, stainless steel is the nobler partner and will not suffer corrosion. The less noble partner may be, for example, the zinc coating on galvanised steel. The ratio of the exposed areas of the two metals in such a couple is very important in determining the extent of galvanic corrosion. To avoid bimetallic corrosion, the two metals have to be electrically insulated from each other or other active or passive measures taken [15].

Micro-strainers for the removal of finely suspended solids from the secondary clarifier's effluent
Photo: Hans Huber, Berching (D)

When pipes have to be connected by flanges or fittings, it is important to select gasket and sealing materials which will not release any chlorides [4]. As a rule, components made from stainless steel must not come into contact with leachable chloride-containing materials of construction. Attack by chlorine or chloride containing atmospheres or vapours also has to be avoided [4]. Insulating substances are not allowed to have chloride contents of more than 0.05 %. In mineral wool, the content of water soluble chlorides shall not exceed 6 mg/kg [4]. Acoustic damping components of fixing elements for piping systems have to be free of water soluble chlorides [4].

More detailed information is to be found in [15] and [22]. Design should also take into account the fabrication guidelines discussed below.

3.4.2 Fabrication

The corrosion resistance of stainless steels is to a large extent determined by their surface quality [5]. The best corrosion resistance is achieved with stainless steel which has a clean and bright metallic surface, free from imperfections where crevice corrosion may initiate such as slag residues, solidification cracks and porosity caused by welding.

Thus, the modification of welding procedures to suit the requirements of stainless steel deserves special attention [23]. Experience has shown that mechanised welding processes with sufficient inert gas purge and without misaligned edges result in better corrosion resistance than manual welding processes. Attention has to be paid to producing full penetration welds which are free of cracks, overlaps and cold laps. Any heat tint, other types of oxidation, splashes and slag residues have to be avoided or removed by grinding or pickling as necessary. Only heat tint of a light straw colour may be tolerable [20] depending on the severity of the corrosive environment. Under critical conditions, straw-coloured heat tints may still increase the likelihood of pitting corrosion [20]. As reported in [10], test specimens with a clean surface produced by pickling were markedly more resistant against pitting corrosion than specimens with a straw-yellow temper colour, whereas the difference in corrosion resistance between straw-yellow and violet/blue temper colours was distinctly smaller. Figure 1 illustrates this with an example: the pitting potential of grade 1.4571 as a measure of its resistance to pitting in water containing 0.01 m NaCl at 30 °C is greatest for the pickled state and falls steeply to the surface condition with straw-yellow temper colour, and then continues to fall somewhat less steeply to the red/violet and violet/blue temper colours [24]. The same applies to the pitting potential of grade EN 1.4301. However, it shows a significantly smaller decrease, with the result that the pitting potentials of both materials ultimately coincide.

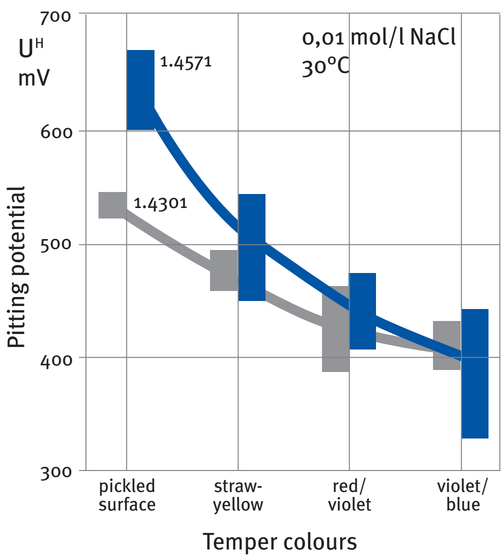


Fig. 1: Pitting resistance of two austenitic stainless steels as a function of surface condition [10], after Diab and Schwenk [24]

Fine bar screen for water pollution control in case of emergency discharges and its installation in a sewer overflow
Photos: Steinhardt Wassertechnik, Taunusstein (D)

If heat tint is not prevented from forming, it should be removed by pickling [25] or initially treated mechanically by careful soft grinding with a rotating fibre brush or by glass bead blasting followed by pickling. However, carbon steel brushes can lead to iron pick up on the stainless steel surface and must not be used. It has to be kept in mind that beneath the heat tint scale there is often a very thin metallic surface layer which is depleted in chromium and, therefore, has also to be removed by pickling in order to achieve the stainless steel's optimum corrosion resistance. Removal of heat tint and the absence of crevices have been found to significantly enhance the resistance to microbiologically influenced corrosion and other forms of localised corrosion [9, 26]. All other kinds of dirt or foreign substances adhering to the surface, such as embedded iron or rust, have to be eliminated too. The type and extent of cleaning operations which may be necessary depend on the surface damage that is present, and how it was created [27].

It is clear that stainless steel will exhibit its excellent corrosion resistance to waters only if care is taken during fabrication. A high standard of work in the fabrication shop and during erection and on-site welding is essential for satisfactory service. Only companies experienced in manufacturing of stainless steel components and systems can offer the high standard and quality of fabrication which are required to minimise corrosion problems during service. Prefabrication in the shop offers the optimum working conditions with cleaning operations available which often include full immersion pickling of the components. This leaves a minimum number of welds to be made on-site where lack of accessibility makes them difficult to complete to a high quality level [28].

Detail from waste water treatment plant
Photo: Regeneracija, Lesce (SI)

3.5 Service conditions

Many of the considerations related to service conditions have already been mentioned in connection with water chemistry in section 3.3.

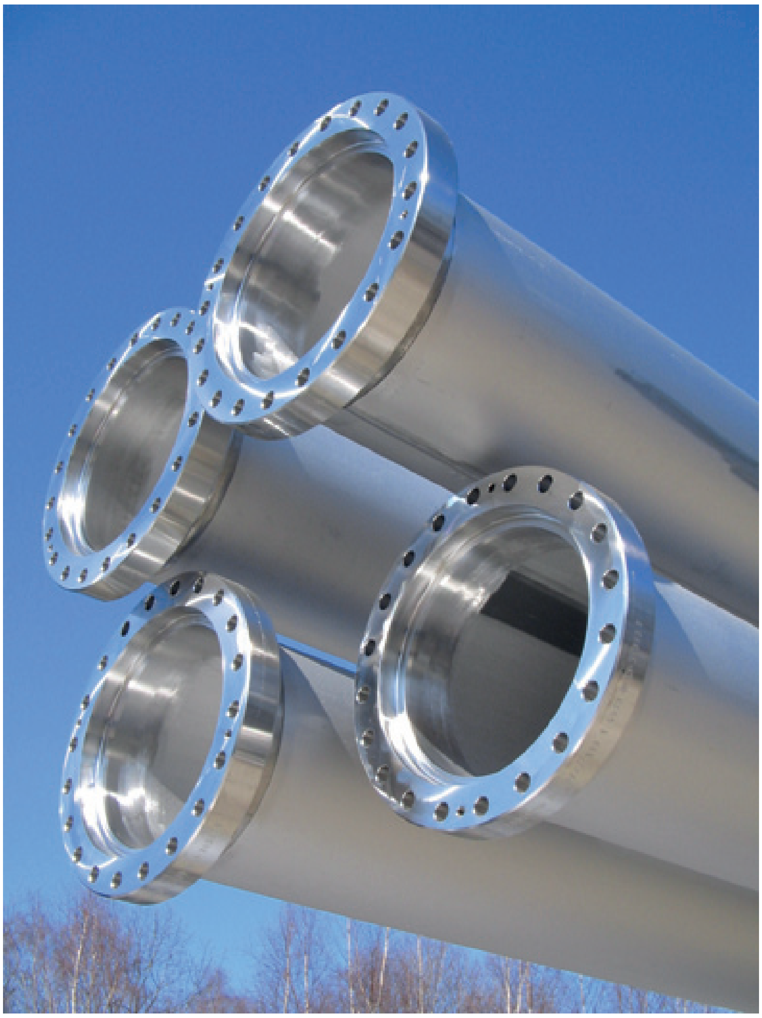
Hydrostatic testing of pipelines and vessels represents a common approach in checking the integrity of systems after construction. However, it is crucial to drain and dry stainless steel systems after testing if the equipment is not going directly into service. This is particularly important if raw waters are used for testing where bacteria and water stream sediments can settle out when left stagnant and initiate under-deposit corrosion attack in the area of welds. Potable water or filtered waters are therefore preferred for testing. Where draining is not possible, regular flushing of the system on a daily basis should limit potential problems [29] until it goes into service.

The influence of temperature is also important. In general, the pitting and crevice corrosion resistance decreases with increasing temperature. However, if the concentration of oxidising agents decreases with increasing temperature, as in installations not under pressure, the influence of temperature on pitting corrosion will only be small [5].

The flow speed of the water is another important parameter. As a rule, in water flowing with sufficient velocity (e.g. more than about 0.5 m/s to 1 m/s), corrosion resistance is always relatively high whereas pitting may be initiated in stagnant waters. Slow flowing water may allow deposition of sediments under which crevice corrosion may occur. Water which is carrying sludges should have a flow speed of at least 0.6 m/s to avoid sediment deposition [9]. Effective counter measures involve cleaning and flushing of the installation at regular intervals.

Mud dehydration entry to storage silo
Photo: Cedinox, Madrid (E)

In addition, moist hydrogen sulphide and chlorine-containing vapours may occur in waste water installations. Though a negligible corrosion rate is reported for Type 304 and Type 316 stainless steels in moist hydrogen sulphide [9], it is also reported that both Type 304 and 316 stainless steels may suffer corrosive attack when large amounts of moist hydrogen sulphide are arising in waste water installations [30]. This corrosive attack might be due to the strong depolarizing action of hydrogen sulphide which is promoting pitting corrosion [31]. A suitable remedial action is appropriate ventilation [30]. The stainless steels also exhibit surface attack and pitting in atmospheres where wet chlorine vapours can accumulate and eventually condense. Appropriate ventilation and / or water washing and cleaning at regular intervals are essential under such service conditions [30].



Clean metallic surfaces ensure long-term performance
Photo: Butting, Knesebeck (D)

4 Atmospheric corrosion resistance

Outdoor atmospheres can vary greatly. Carbon containing particles and sulphur dioxide constitute the aggressive substances in town and industrial atmospheres far from the sea. Chloride aerosols are the most important aggressive substances near coastlines and also at relatively large distances from the sea under unfavourable wind conditions. In comparison, rural atmospheres far from the sea are not aggressive. From experience gained to date [32], the stainless steels of group 1 in Table 1 (Type 304) are the best choice in rural atmospheres far from the sea, both with respect to corrosion resistance and cost. The same is also true for locations near the sea and in town atmospheres if the corrosivity is low to moderate. However, in both locations, the corrosive attack can also be high enough to require the application of the higher alloyed stainless steels of group 2 (Type 316). In industrial atmospheres, the use of group 2 stainless steels has always to be considered. In both industrial atmospheres and close to the sea, even the application of stainless steels of group 4 in Table 2 may become necessary if unfavourable conditions (high relative humidity and temperature, aggressive pollutants in the atmosphere) prevail. More details are to be found in [32].

5 Corrosion resistance in soils

Soils differ in their corrosive nature depending on factors like chloride content, pH and resistivity. Stainless steels have performed well in a variety of soils. Selection criteria given in [33] recommends the group 1 stainless steels in Table 1 for use in soils where the chloride content is less than 500 ppm and the resistivity above 1000 Ω·cm. It also suggests group 2 for chloride contents of less than 1500 ppm and a resistivity above 1000 Ω·cm, and group 5 in Table 2 for chloride contents of less than 6000 ppm and a resistivity above 500 Ω·cm. These recommendations relate to a pH of more than 4.5, the absence of stray currents and use without any coating and / or cathodic protection.

Round tank flushing system – wave flush for circular and small rectangular tanks Photo: Steinhardt Wassertechnik, Taunusstein (D)

6 Mechanical properties

Some important mechanical properties for the stainless steels under consideration in groups 1—4 (see Tables 1 and 2) are given in Table 3. Cold rolled strip up to a thickness of 8 mm in the solution annealed condition has been selected as an example. It is this product form from which sheets are cut for manufacturing tanks and containers, and in making the longitudinally welded tubes used in waste water installations. As Table 3 shows, the 0.2 % proof stress of the preferred stainless steels in groups 1 and 2 is ≥220 N/mm², and for group 2 ≥240 N/mm². These austenitic stainless steels are comparable in strength to the lower range of the general structural steels [34].

Table 3: Mechanical properties of stainless steels for waste water installations. The data refer to the solution annealed condition of cold rolled strip up to a thickness of 8 mm, according to EN 10088-2:2005

Group	EN Number	0.2 % Proof Stress $R_{p\,0.2}$ N/mm² min.	Tensile Strength R_m N/mm² min.	Elongation A % min.
1	1.4301 1.4306 1.4307 1.4541	230 220 220 220	540 520 520 520	45 45 45 40
2	1.4401 1.4404 1.4571	240 240 240	530 530 540	40 40 40
3	1.4435	240	550	40
4	1.4462 1.4439	500 290	700 580	20 35

Prefabricated pipe work components for a sewage plant in the Netherlands
Photo: H. Butting, Knesebeck (D)

The high ductility of the austenitic stainless steels deserves special mention as it is far above that of general structural steels with elongations to fracture of at least 40 % for the stainless steels of groups 1 and 2 in Table 3. The high ductility means that austenitic stainless steels are easy to fabricate on site and easy to adapt even to the irregularities of concrete structures. In this respect, austenitic stainless steel is easier to handle in construction and repair than aluminium or galvanised steel.

The considerable strain-hardening potential which is associated with high ductility is another special feature of the austenitic stainless steels. This characteristic allows the 0.2 % proof stress to be increased through a cold forming operation adapted to the type of product, e.g. by drawing or cold rolling. This is demonstrated in Figure 2 for the austenitic stainless steel grade X5CrNi18-10 (1.4301) in comparison with the ferritic stainless grade X6Cr17 (1.4016) and another austenitic stainless grade X10CrNi18-8 (1.4310) which was developed with the aim of an extra-high strain-hardening potential for the manufacturing of springs and knives. The graph [35] indicates that the 0.2 % proof stress of the austenitic stainless steel grade 1.4301 can be increased easily by cold forming up to 460 N/mm² with a considerable ductility still remaining. In waste water technology, this strength increase can be effectively used [36]. Thin sheets, e.g. of austenitic stainless grades 1.4301 or 1.4571, which have been strain-hardened by cold rolling to a high proof stress can be used for large tanks and containers. This allows lower weight and corresponding decreased cost but unchanged structural stability, e.g. for use as waste water treatment tanks for various kinds in breweries. The extra strength which results from cold forming operations can be used [37] to reduce wall thickness. However, to make use of this benefit, joining techniques other than welding have to be applied as welding would cause a localised softening of the material [6].

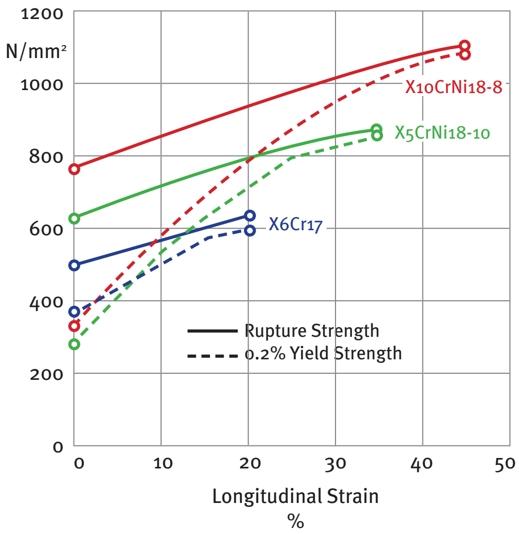


Fig. 2: Strain hardening behaviour of various stainless steels: austenitic standard grade 1.4301 (X5CrNi18-10) in comparison to the strongly strain-hardened austenitic grade 1.4310 (X10CrNi18-8) and to the ferritic grade 1.4016 (X6Cr17), from [35]

Mention must also be made of the high 0.2 % proof stress of the duplex stainless steel grade 1.4462 which, according to Table 3, is as high as ≥500 N/mm² in the solution annealed condition. This is well above the yield stress of the general structural steels. In Table 2, this stainless steel is part of group 4 which comprises the materials with increased corrosion resistance in the media considered here. Therefore application of this high strength grade can be considered where a lightweight design may be advantageous, e.g. in case of large clarifier arms. However, if welding is not necessary, the use of the strain hardened austenitic grades with proof stress levels up to 460 N/mm² or even 690 N/mm² [37] may be considered there too.

Inside the container with membrane housing stainless steel boxes Photo: Centro Inox, Milan (I)

Some piping systems, such as aeration piping, are subject to vibration during service. In this case, the allowed design stress is derived from the fatigue endurance limit which is below the 0.2 % proof stress. Although the Type 304 and 316 stainless steels exhibit excellent fatigue strength, it is important in design to blend smoothly areas such as transition joints and where members of an assembly intersect since these areas represent the weakest point of the structure where vibrational stresses tend to concentrate [9].

7 Applications of stainless steels in waste water installations

The applications of stainless steels in waste water installations are so numerous that only some important ones are mentioned here. In waste water installations, stainless steels are used primarily as tubing and pipes e.g. for aerators. Tanks made from work hardened stainless steel sheet have already been mentioned. In addition, the settlement equipment for both circular and rectangular tanks, such as underwater equipment and weirs of clarifiers, can be made advantageously from stainless steel. Also the machinery for waste water treatment is largely made from stainless steel; for screening, washing, compacting, dewatering of screenings, grease and oil separation, thickening and de-watering of the various types of sludge, sieve filtration etc. Stainless steel is also a preferred material of construction for auxiliary equipment, e.g. climbing systems, stairs [38], ladders, railings [38], hand rails, manhole covers, general architectural equipment and roofing [39].

Large, longitudinally welded stainless steel pipes for a sewage plant in Greece
Photo: H. Butting, Knesebeck (D)

If there are no special considerations for water quality or atmosphere, the use of the grade 1.4404 (316L) stainless steel may serve as a reasonable general standard recommendation for waste water piping and underwater construction. Even if the selection of this grade is not required by today's waste water composition, it allows for a possible future worsening of the waste water quality, which can never be ignored. In contrast, for many above water applications, grade 1.4307 (304L) stainless steel can be the optimum material based on both corrosion resistance as well as cost considerations. The potential of the high-strength duplex grade 1.4462 and the strain-hardened austenitic grades for lightweight constructions, which may also include considerable cost savings because less material is needed, has already been mentioned.

Pipe systems after assembly in a sewage plant
Photo: CDA La Rochelle (F)

8 Economic benefits

8.1 Life cycle cost analysis

Stainless steel is a valuable material. Components made from galvanised steel are often less expensive when the purchase price alone is considered. However, if cost of maintenance and repair are also taken into account over the system lifetime, stainless steel may become the more cost-effective choice [40]. The most important factor is the corrosion resistance of stainless steel which results in long service. This factor also contributes to lower cleaning and maintenance costs. At the end of their service life, stainless steel components are fully recyclable.

Pipe systems before assembly in a sewage plant
Photo: Cedinox, Madrid (E)

It has been reported [41] that a manhole cover made from galvanised steel had been available at a price 20 % lower than the same cover made from grade 1.4301 (304) stainless steel. However, due to much higher maintenance costs for the galvanised steel, the manhole cover made from stainless steel results in a 24 % lower cost when a life cycle cost analysis is made over a lifetime of 25 years. The break even cost occurred at 13 years.

When expected lifetimes are different, the total cost has to be calculated as total cost / year in order to make a comparison. This has been reported in 1998 for a waste water fine screen [41]. If this fine screen was manufactured from galvanised steel, the investment cost would be about 15 % lower than when manufactured from stainless steel, but the lifetime estimate was limited to 12 years. In contrast, the same fine screen manufactured from the stainless steel grade 1.4301 (304) would have a much longer lifetime of 18 years. Consequently the fine screen made from stainless steel would be about 19 % per year cheaper than if made from galvanised steel. A very similar cost relation has also been established for a sludge thickening press [41]. If the different lifetimes of 20 years for a design with stainless steel and of only 10 years for a design with galvanised steel are taken into account, the cost per year is about 20 % less for the design in stainless steel.

Another example is the selection of a grade 1.4401 (316) stainless steel (group 2 in Table 1) ducting to vent hydrogen sulphide from a treatment plant in the North West of England. Thin sections and lack of coatings meant that the initial cost difference between stainless and coated steel was not as great as first expected. Overall costs were similar after about 5 years when the first main maintenance schedule was planned. This was because coating in situ was not needed and there was a sizeable cost advantage after 15 years when replacement of the coated steel would be planned [29]. Similarly, stainless steel was chosen in the replacement and redesign of distributors for a biological treatment process in a plant owned by Yorkshire Water, UK. The pyramid design, used grade 1.4301 (304) stainless steel (group 1 in Table 1) for the main frame and grade 1.4401 (316) for the chassis. It was predicted to have a process availability of 97 % and a cost saving of 50 % over a 20 year life compared to the coated steel units the pyramids replaced. After 2 years service, the stainless steel exceeded expectations as the maintenance had already been cut by over 90 % [29].

Two stainless steel containers with oxygenising tanks
Photo: Centro Inox, Milan (I)

8.2 Additional aspects of cost savings

In the piping sector, the wall thickness of tubes made from stainless steel may be selected more appropriately for the design pressure whereas galvanised tubes usually have to be purchased with a significantly greater standardised wall thickness. At DN 200 for example, the wall thickness of galvanised tubes is at least 4.5 mm, but in most cases only 6.3 mm is available from stock. Alternatively tubes made from stainless steel may be used with dimensions of 204 mm × 2 mm or 219 mm × 2.5 mm. The weight difference results in a lower cost for the stainless steel tubes [42].

An additional cost saving may be obtained in making use of the full potential stainless steel has to offer with respect to flow speed. The high permissible value of 30 m/s reported in [43] can allow smaller pipe diameters leading to lower weight and cost compared to other materials.

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