Fabricating

Stainless Steels for the Water Industry

Guidelines for Achieving Top Performance

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Fabricating Stainless Steels for the Water Industry

Guidelines for Achieving Top Performance

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Scope

This document provides information for fabricators, designers, specifiers and end users about stainless steel fabrication practices and their implications on corrosion behaviour when exposed to waters and waste waters. Originally written to assist engineers involved in the UK water industry, its content is also relevant internationally. Additional information, frequently requested, about grade selection guidelines, alloy properties, design and health and safety aspects is included.

In the UK, approval of stainless steel products by the Drinking Water Inspectorate invokes the "Operational Guidelines and Code of Practice for Stainless Steel Products in Drinking Water Supply" (OGCP) which is available from www.bssa.org.uk. This Nickel Institute brochure provides information to support the OGCP **but does not replace it**.

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Introduction

Stainless steels are selected for their corrosion resistance and durability when used in water and wastewater service. They are strong yet ductile, require no corrosion allowance or coatings, can withstand very high flow rates and are lightweight making them easy to transport and install. Metal leaching into water is minimal from stainless steels.

There are stainless steel grades with different strengths and levels of corrosion resistance suitable for the range of conditions encountered in water and wastewater treatment and distribution. The name "stainless" should not imply however that each steel grade is corrosion resistant in every situation experienced. To obtain the high performance expected and achievable, attention is needed not only to ensure correct grade selection for the particular environment but also to using good fabrication practices. Unnecessary problems in service can readily be avoided if basic fundamentals about the behaviour of stainless steels are understood, introduced into design requirements, and observed during manufacture and assembly. The main aim of this booklet is to describe important issues relating to fabrication, which can influence performance of stainless steels in waters. To do this requires that fabricators and water engineers alike understand why fabrication methods can influence corrosion performance and how to avoid the pitfalls. Additional information, frequently requested by engineers in assessing wider stainless steel fabrication issues for water industry use, is provided in the Appendices; namely alloy selection, chemical analyses, properties, surface finishes, related design issues, fasteners, and health and safety.

Stainless Steels Used in Water and Waste Waters

UNS S30403 (steel number 1.4307, Type 304L) and S31603 (steel number 1.4404, Type 316L) are the two grades of stainless steel most frequently used in the water industry. (See Appendix A for explanation of alloy designations given here). The UNS S31603 (steel number 1.4404, Type 316L) grade contains molybdenum, which provides a higher corrosion resistance and is therefore used for more exacting conditions. Both have an austenitic structure which in practical terms means they are ductile and strong and do not embrittle in freezing temperatures. A range of more highly alloyed superaustenitic alloys is available for critical applications. Their composition provides stronger alloys with very high corrosion resistance.

The third most common grade used in the water industry is the duplex alloy UNS S32205 (steel number 1.4662, alloy 2205). This has a higher corrosion resistance to waters than UNS S31603 (steel number 1.4404, Type 316L). The name duplex indicates that the alloy structure contains both austenite and ferrite in roughly similar amounts. This appreciably increases the alloy strength whilst retaining a reasonable ductility. It will embrittle at very low temperatures, but as this occurs below -45°C there is no practical significance. A range of superduplex grades is available which are like the superaustenitic alloys in that they have high corrosion resistance and are used for exceptionally severe conditions.

Chemical compositions of these commonly used stainless steels are given in Table A1 of Appendix A; more comprehensive lists are available.[1,2] Mechanical properties are shown in Table A2 of Appendix A.

Figure 1. These sluice gates were fabricated of stainless steel and control the flow of waste water between storage basins.

Importance of the Protective Surface Oxide Film For Corrosion Resistance

The corrosion resistance of stainless steel is achieved by the formation of a protective oxide film on the metal surface. This oxide film is not thermally induced and forms naturally and immediately when exposed to air. It is only atoms thick, invisible to the naked eye and is predominantly chromium oxide. There is enough oxygen in most waters to maintain the film and it will repair itself if damaged. Good fabrication is based on maintaining the protective film in a robust condition so that the alloy chosen can fulfill its potential. This involves avoiding conditions that can be harmful to the film, particularly artificial crevices or contamination. Alternatively, certain alloying additions, such as molybdenum or nitrogen, can help stabilise the oxide film and improve corrosion resistance.

For a given grade of material, the smoother and cleaner the surface finish, the higher the corrosion resistance. However, surfaces contaminated by pickup or damaged by crevices from such processes as rough grinding or weld spatter have lower corrosion resistance.

Passivation is the term given to the formation of the protective oxide film on stainless steel. Stainless steels will naturally passivate to a high degree on exposure to air such that air exposure is normally all that is required to achieve acceptable corrosion resistance. The passive layer can be improved further by an additional chemical treatment, typically using nitric acid. Passivation will be discussed in more detail later in Pickling and Passivation.

Careful Handling and Preparation

Fabrication practices should aim to maintain the surface integrity of the stainless steel being processed, avoiding any contamination, and removing any effects of welding that would interfere with the corrosion resistance of the stainless steel in service. Therefore, processing activities should be separated from those for carbon steels right from the point where stock material arrives. Storage is required in such a way as to prevent scratching and scoring of the surface and to avoid contact with iron or carbon steel. Timber spacers or even old carpet or cardboard should be interposed between stainless steel material and the bearers of support racks. Where sheets or plates are stored vertically, they should not contact one another and should be handled carefully to avoid abrasion. Ideally, all material should be stored under cover to keep it clean, although being outdoors will not normally harm it. Ideally, a separate workshop should be provided for fabricating stainless steel, so that other materials are not handled with the same equipment. In some cases, it may be necessary to use large items of plant, such as press brakes or bending rolls, for a range of materials. Care must then be taken to avoid contamination by iron, for example by covering the stainless steel sheet with plastic film or simply by pressing or bending a scrap piece of sheet first. Stainless steel should be protected from abrasion by equipment used for handling, such as the forks of lift trucks, and slings made or covered in polymer should be substituted for the wire rope type.

A particular aim of these measures is to prevent iron contamination of the stainless steel surface. Apart from handling, this usually originates from hand tools being used for different materials. It is essential that grinding discs, flapper wheels and other abrasive materials have not previously been used on carbon steel and that rotary brushes and hand brushes, if used for cleaning welds, are made from stainless steel wire, otherwise fragments of carbon steel become embedded in the surface of the stainless steel.

On exposure to a humid atmosphere or when wetted, an iron-contaminated surface is soon revealed by rust staining. In general, this is unsightly but not necessarily harmful, although the crevice formed between the embedded carbon steel fragment and the surface of the stainless steel could be a seat for corrosion in some more aggressive environments. While there are no standards for the acceptability of iron contamination, it is suggested that it should always be removed if it will be exposed to process fluids and, if external, when the fabrication will be sited in coastal or polluted regions. Iron contamination can be removed by one of the pickling methods described later but these should not be seen as an alternative to correct handling in the workshop.

Contamination can also originate from paints, marking crayons and temperature-indicating markers, cutting fluids, oils and greases. All such contamination must be avoided as much as possible but, if it is present, must be removed before welding commences. Owing to the potential for concentration in crevices and the subsequent risk of corrosion, non-chlorinated solvents such as acetone should be used rather than chlorinated solvents.

Good Handling Practices

- Segregate from carbon steel fabrication.
- Clean environment.
- When outdoors, store materials under cover if possible and in such a way that mud does not splash and pools of water do not form on the surface.
- Avoid walking on material particularly in footwear that can damage the surface of thin-wall piping, plate or sheet.
- Protect from carbon steel contamination as well as dirt, brick-washing acid, weld spatter and grinding sparks.
- Use polymer or polymer covered ropes and straps rather than steel.
- Avoid surface damage.
- Use non-chlorinated solvents and marking inks with low chloride content.

Cutting and Forming

Thinner plate or sheet can be cut to size by guillotining and pipe can be sawn. An abrasive disc can be used if other facilities are not available. Plasma cutting is used for thicker materials whereas laser, which cuts very accurately, is particularly useful for producing profiles. Oxy-fuel cutting is not practicable since the necessary exothermic reaction between iron and oxygen is inhibited by the presence of chromium; only rough severing cuts are possible.

The steel can be guillotined, sheared and sawn on standard machine tools. Cold forming with standard equipment is generally appropriate for thicknesses up to about 8 mm. When shearing and guillotining UNS S30403 (steel number 1.4307, Type 304L) or S31603 (steel number 1.4404, Type 316L), the capacity of the equipment should be down-rated by 50-60% relative to carbon steels because of the work hardening characteristics of the austenitic grades. The maximum thickness capacity of a particular shear for duplex and superduplex stainless steels is respectively 50% and 40% of that for carbon steels.

1. Clearance between the shear blades 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.
2. When sawing stainless steel, sharp, high-speed steel (or carbide/PCD-tipped, or other appropriate) blades should be used, with cutting fluids. For thickness 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 should lift clear of the cutting face to minimise work hardening effects.
3. The cutting kerfs and heat-affected zone should be removed after plasma cutting before further processing is undertaken.
4. Contamination from iron particles by pressure contact with rollers or tooling should, if at all possible, be avoided. Adhesive plastic films or tape can be used to prevent direct contact. They should be removed after fabrication is completed.
5. Cold forming equipment for stainless steels should be of adequate rigidity and power to cope with the higher work hardening rates. 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.
6. Allowance must be made in bending and rolling for the greater spring-back characteristics of stainless steels compared with carbon steels, which can be quite severe in the duplex grade.

Preparation for Welding

A square edge preparation is adequate for butt-welding material up to about 3 mm thick but a bevel is required for thicker material. Bevels are wider for stainless steels than for carbon steels, root faces are smaller and root gaps are wider, to compensate for the poorer penetration characteristics of stainless steel welding consumables and the reduced fluidity of the weld pool. Any visible oxide scale must be removed before welding, normally by grinding.

A machined preparation is preferred, particularly for automatic welding, while a ground preparation is acceptable for manual welding, when the welder has to correct for small variations in fit-up. It is essential that any contaminants, such as oil, grease and crayon markings, should be removed from the weld area, since they can contain elements e.g. sulphur or lead, that cause weld cracking and other defects, This can be ensured by cleaning the weld preparation and an area of the steel surface at least 50 mm wide adjacent to it with a non-chlorinated solvent such as alcohol or acetone before welding commences. Clean solvents and cloths should be used. Likewise zinc, which can be picked up by contact with galvanised steel or from zinc-rich paints, is particularly damaging and needs to be avoided, since it can initiate cracking in the weld area by liquid metal embrittlement.

Spatter from the welding operation is difficult to remove and can be prevented from adhering in the first place with a proprietary anti-spatter compound which is cleaned off on completion.

Iron particles should not be embedded into the surface during cleaning. Wire brushes should be stainless steel and grinding wheels should be clean and not previously used for grinding carbon steel.

Welding

In many respects, stainless steels are easier to weld than low-alloy steels; preheat is normally unnecessary. Clean working conditions promote consistent quality. When welding procedures are developed for stainless steels, it is important to recognise that stainless steels have higher coefficients of thermal expansion than carbon steels (except for the duplex steels) and lower coefficients of thermal conductivity. The consequence is that they have a greater tendency to distortion, which can be offset by close tack welds (about half the spacing than that used for carbon steel), low heat input and balanced welds. Interpass temperature should be low, at least below 150°C. The finalised procedure, describing the welding process conditions and variables, should be recorded as a qualified Weld Procedure Specification (WPS), normally in accordance with an appropriate code or standard; see section on Welding Specifications. Similarly, welders should be approved as qualified to follow the procedure, Welder Performance Qualification (WPQ). Arrangements for inspection of fabrications also require specification.

Stainless steels can be welded by all of the conventional arc processes and specific details about welding techniques are well documented[3,6,7,8] including Nickel Institute Reference Book Series 11007 "Guidelines for the Welded Fabrication of Nickel Containing Stainless Steels for Corrosion Resisting Services" and 16000 "Practical Guidelines for the Fabrication of Duplex Stainless Steels". Health and Safety are discussed in Appendix E.

Autogenous welding is possible in appropriate circumstances but optimum corrosion resistance is obtained by the addition of filler metal. While the manual metal arc process is still widely used, the gas shielded processes TIG (GTAW) and MIG (GMAW), have particular advantages for welding light gauge stainless steels and complex shapes. Welding consumables (Table 1) generally deposit weld metals similar in chemical composition to the base metals but with sufficient alloying elements to compensate for segregation so as to ensure that the weld is more noble than the base metal (see Galvanic Issues in Appendix D) if galvanic corrosion is likely. The element balance of the austenitic stainless steel consumables considered here (Type 308L, 316L, and 318), particularly of chromium and nickel, is slightly varied from that of the base metal to ensure that welds contain a small proportion of ferrite to enhance weld metal crack resistance. Carbon contents of austenitic stainless steel weld metals are low, typically 0.02%, but are suitable for both the standard and the 'L' grade steels, which were introduced to avoid the possibility of intergranular corrosion in weld joints, now rarely encountered with modern stainless steels. The nickel content of duplex stainless steel consumables is higher than that of the steel to avoid a fully ferritic weld microstructure. For the 6% molybdenum superaustenitic steels, it is necessary to use nickel-base alloy consumables, since ‘matching’ weld metals have reduced corrosion resistance, due to segregation.

Table 1
Welding Consumables for Stainless Steels

	Covered Electrodes		
Steel Grade	**AWS A5.4/A5.11**	**EN 1600**	**EN ISO 14172**
304L	E 308L	E 19 9 L	
316L	E 316L	E 19 12 3	
316Ti	E 318	E 19 12 3 Nb	
22%Cr duplex	E 2209	E 22 9 3 N L	
25%Cr superduplex	proprietary	E 25 9 4 N L	
6% Mo superaustenitic	E NiCrMo-3 E NiCrMo-10		E Ni 6625 E Ni 6022
	Bare Wires		
Steel Grade	**AWS A5.9/A5.14**	**EN 12072**	**EN ISO 18274**
304L	ER 308L	W 19 9 L	
316L	ER 316L	W 19 12 3	
316Ti	ER 318	W 19 12 3 Nb	
22%Cr duplex	ER 2209	W 22 9 3 N L	
25%Cr superduplex	proprietary	G 25 9 4 N L	
6% Mo superaustenitic	ER NiCrMo-3 ER NiCrMo-10		S Ni 6625 S Ni 6022

When pipe is welded, attention must be focused on the condition of the weld root, since it will be exposed to the process fluid flowing through the system when in service. The root pass is normally made by the TIG (GTAW) process. While the argon shielding gas protects the surface of the weld pool, metal penetrating into the bore of the pipe is subject to heavy oxidation and appears blackened and uneven giving the appearance of burnt sugar, hence the term sugaring. Welds that display the sugaring condition may have gross weld defects such as lack of fusion and porosity, as well as poor corrosion resistance of the underlying weld metal.

The interior of the pipe is therefore purged with an inert gas (usually argon) before welding, following a repeated flushing procedure to reduce the oxygen content to a level below 100 ppm, preferably down to 50 ppm. Solid or inflatable dams are employed to confine the purged volume to a practicable level; where access is difficult or impossible after completion of the weld, it is often convenient to use soluble material dams, which dissolve during testing or operation of the system. The successful use of gas purging equipment for site fabrication can have a major impact on limiting stainless steel weld discolouration and improvement of the final weld quality. Since it is less easy to adopt this procedure in the field, as much fabrication as possible should be done in the workshop.

General Principles for Welding

- Avoid contamination and remove crayon and paint markings.
- Thorough degreasing is required before welding.
- Compared with carbon steels, wider bevels, smaller root faces and wider root gaps are required.
- Welds should be full penetration, free of cracks overlaps and cold laps.
- Correct selection of consumables for welding.
- Inert gas back purging is necessary during welding to avoid sugaring and minimise heat tint.

Post-Fabrication Cleaning

Surface damage, defects, dust and dirt, loose iron particles, embedded iron, heat tint and other oxidation, rust spots, grinding burrs, oil and grease, residual adhesives, and paint, chalk and crayon marks may arise from fabrication of equipment. Often they are unintentional but nonetheless can have significant implications for the performance of the fabricated stainless steel in water industry service.

The service performance of welded joints depends to a large degree on the finishing operations carried out after welding. There may be surface damage, either accidental or due to careless treatment, such as deep grinding marks, welding spatter and arc strikes. Areas of weld spatter form crevices with the underlying material and are vulnerable to corrosive attack in service.

Figure 2 illustrates many of these. However, it is the effect of heat on the weld metal and surrounding zone that creates the greatest threat to good performance. On full penetration welds and attachments, heat tint is often unavoidable on the side the weld process is being conducted even with inert gas shielding but can be controlled by inert gas purging on the underside. As shown below, heat tint can also occur on the underside of plate or other product forms where an attachment is made to one side and the surface underneath gets sufficiently hot locally to form visible oxides.

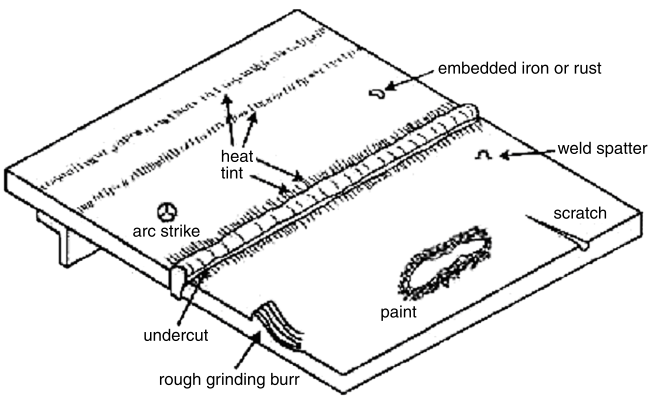


Figure 2. Potential surface defects in stainless steel fabrications.

Heat Tint Removal

Interference colours ranging typically from dark blue to straw yellow on and adjacent to the weld indicate the presence of a thickened layer of a modified oxide formed at high temperatures. Figure 3 shows typical colours of a grossly heat tinted weld root on UNS S31603 (steel number 1.4404, Type 316L) stainless steel pipe.

This heat tint should not be confused with the ultra-thin, naturally occurring, transparent, passive oxide film present on all stainless steel surfaces which is largely responsible for the alloy's excellent corrosion resistance. The composition of the heat tint layer varies but is essentially a mixture of chromium and iron oxides. The heavier the oxide layer, the darker it appears. Underneath, the base metal is left depleted in chromium by oxide formation and therefore its resistance to corrosion is diminished.

Unless the uniform, invisible passive oxide layer characteristic of unaffected metal is restored, weld joints are prone to corrosion even though the base metal is resistant. This includes pitting, crevice corrosion and microbiologically influenced corrosion. In potable water, it is recommended that all traces of heat tint darker than straw yellow should be removed. Removal of heat tints by post-weld acid pickling or electrochemical cleaning (electropolishing) can restore the weld corrosion resistance to that of the parent metal. However, mechanical grinding and bead blasting of heat tints will remove the coloured oxides present but may distort or contaminate the base metal surface and they are not as effective as acid pickling or electropolishing as described later.

Figure 3. Heat tints (weld discolouration) on the root of a stainless steel butt weld (TIG/GTAW with argon gas purging) of 3 mm thick UNS S31603 (steel number 1.4404, Type 316L) pipe (300 mm ID).

Although heat tints are normally removed by post-weld cleaning of shop fabrications, in some applications of stainless steels where construction is carried out on-site the difficulty of ensuring very pure inert gas purging of inaccessible weld roots has resulted in the question of acceptability of residual heat tint levels.

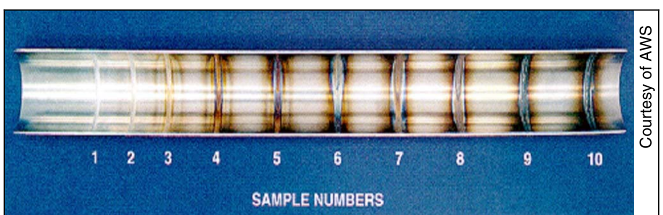
Experience in the water industries has shown that a light straw-coloured (yellow) heat tint on austenitic and duplex stainless steel welds could be accepted for most service, as long as certain conditions are fulfilled. One condition is that the stainless steel used should have an inherent corrosion resistance which exceeds that needed to accommodate the most aggressive environment expected in service. A second condition is that any heat tints on stainless steel welds should be inspected and the observed heat tints compared with a colour reference chart for heat tinted stainless steel welds. Although not intended specifically for the water industry an appropriate chart could be that shown in Figure 4. A straw-coloured or yellow heat tint, up to and including AWS D18.2 Number 3 on the colour reference chart, would be considered acceptable in most situations.

Heat tints formed on stainless steel welds consist of surface metal oxide films that exhibit different colours depending upon the alloy type, oxide thickness, surface finish, composition and purity of the purging gas, gas flow rate, weld geometry and the heat input during welding. Although the degree of heat tint developed in Figure 4 changes by level of oxygen in the purging gas, it is more practical to refer to colour number rather than oxygen level of the purge gas for the maximum allowable heat tint acceptance criterion.

Currently, there are no similar reference colour charts available for duplex and superaustenitic stainless steels. However, it is known that the corrosion resistance of higher alloyed stainless steels is usually less affected by weld heat tinting, although cleaning is still beneficial.

Table 2
Heat Tint Removal Methods

Method	Comments	Effectiveness
Stainless Steel Wire Brushes	Often used for cleaning welds. If used for heat tint removal can deform surface and may lead to surface staining unless used in conjunction with a more effective treatment.	Least ↑
Grinding (Al oxide discs or flapper wheels)	Do not smear or overheat surface by worn abrasives or excessive pressure.	
Blasting (glass bead, garnet, walnut shells)	Avoid carbon steel shot or blast media contaminated with iron.	
Acid Pickling	Immersion, circulation, spray or paste methods are available.	
Electrocleaning/ Polishing	Site or shop treatment.	↓ Best



Sample Numbers refer to amount of oxygen in purging gas:
No. 1- 10 ppm No. 2 - 25 ppm No. 3 - 50 ppm
No. 4 - 100 ppm No. 5 - 200 ppm No. 6 - 500 ppm
No. 7 - 1000 ppm No. 8 - 5000 ppm No. 9 -12500 ppm
No. 10 - 25000 ppm

Note: Welds on UNS S30403 (steel number 1.4307, Type 304L) stainless steel showed no significant difference in heat tint colour from UNS S31603 (steel number 1.4404, Type 316L).

Figure 4. AWS D18.2 (1999)[4]: Heat tint (weld discolouration) levels on the inside of mechanically polished UNS S31603 (steel number 1.4404, Type 316L) austenitic stainless steel tube.

Removal of Embedded Iron

When new stainless steel equipment develops rust spots, it is nearly always the results of embedded free iron. The iron particles corrode in moist air or when wetted leaving rusty areas. In addition to being unsightly, they may initiate corrosion in the underlying steel when conditions are severe.

The simplest test for detecting embedded iron is to spray the surface with clean water, periodically allowing for dry periods of at least eight-hours during the test cycle. Inspection for rust streaks can be carried out after 24 hours.

A more sensitive and quicker indication is obtained by use of the ferroxyl test for free iron. A solution containing nitric acid and potassium ferro-cyanide is sprayed onto the surface and iron contamination is indicated by the appearance of a blue colour after a few minutes. The depth of colour is a rough indication of the degree of contamination. The solution should be removed after a few minutes with a damp cloth or water spray.

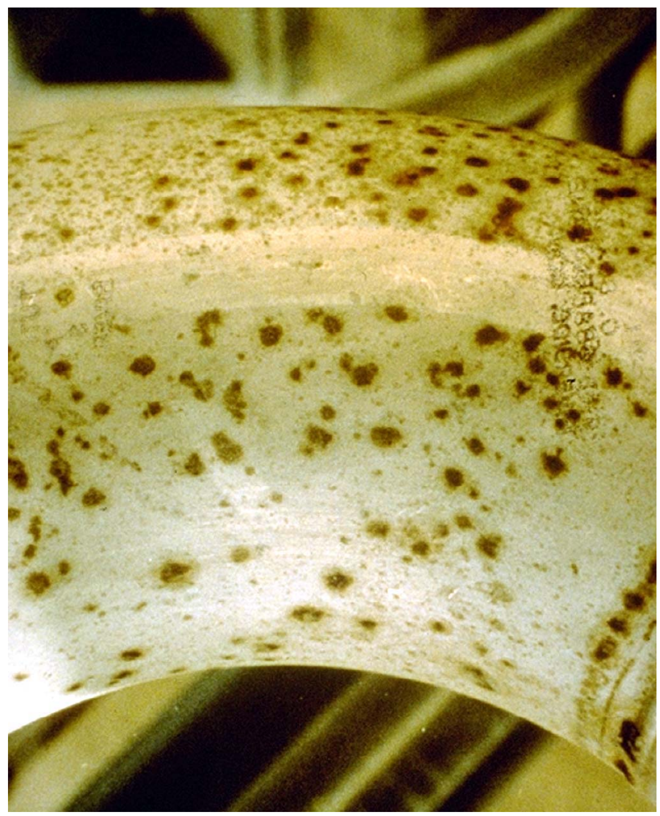


Figure 5. Iron pick up caused by an operator grinding steel close by.

The tests are detailed in ASTM A380 Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems (and also described in Nickel Institute Reference Book Series 11007 "Guidelines for the Welded Fabrication of Nickel Containing Stainless Steels for Corrosion Resisting Services") which additionally notes that it is not recommended for process surfaces of equipment which will be used for products for human consumption unless all traces of the ferroxyl test solution can be completely removed.

Pickling, after an initial degreasing, is the most effective method for removing embedded iron and this is described later; nitric acid alone will remove superficial iron contamination but few if any of the larger embedded particles.

Mechanical Removal

Mechanical damage can be rectified by grinding, providing the amount of metal removed does not reduce the thickness of the steel below the minimum specified in the design and that the restored surface must be smooth and unblemished. Heat tint, spatter and any islands of slag can also be removed by this method. Glass bead, garnet or walnut shell blasting is effective in producing a uniform surface finish locally or over large areas. While wire brushing can produce a superficially bright and clean result, distortion of the metal surface particularly by power brushing can lower corrosion resistance. Also, heavy surface oxides that are encountered in repair welding are not effectively removed by wire brushing. However, grinding with aluminium oxide discs or flapper wheels or non-woven abrasive finishing products is a convenient manual operation that should be carried out progressively to a fine finish (at least 180 grit or finer). In general, these mechanical cleaning methods are adequate but not completely satisfactory: they can leave a deformed layer on the steel surface, often with residues of grit or glass beads embedded in it. A better outcome is achieved when they are supplemented by pickling.

Pickling and Passivation

Figure 6. A stainless steel tank before pickling.

Figure 7. The same stainless steel tank after pickling. Acid pickling effectively removes heat tint and other surface contamination which results from fabrication, such as embedded iron and rust.

Degreasing is an essential pre-requisite for chemical treatments to allow effective surface wetting as well as for removing areas of organic contamination. It is essential that non-chlorinated solvents are used with stainless steels as residual chlorides can remain in crevices and give rise to corrosion.

Chemical treatments are sub-divided into pickling processes and passivation processes, frequently referred to as a combination, i.e. 'pickling and passivation'. As such, their purpose is often misunderstood. Pickling processes are aggressive and are intended to remove a surface layer of the steel (less than 0.025 mm), including all foreign matter, together with the oxides formed during welding and the layer of metal depleted by oxidation. This leaves an atomically clean surface that immediately starts to react with the atmosphere, or even the oxygen in rinsing water, to reform the uniform chromium oxide layer that characterises stainless steels and gives them their distinctive corrosion resistance. This natural process is called passivation. For many purposes, such as the applications in the water industry, this is quite adequate and no further treatment is necessary.[11] Nevertheless, separate chemical processes are available, the purpose of which is to accelerate and possibly improve the formation of the protective oxide. These treatments are also called passivation and are found to be beneficial in some circumstances. Examples are for plant to be used in the pharmaceutical or semiconductor industry, each of which imposes stringent requirements on surface finish, sometimes coupled with the need for resistance to very corrosive environments. Another example is for added protection when final welding and pickling are carried out on site and the fabrication is exposed immediately to severe service environments which can contaminate the surface (e.g. railings at an aggressive coastal site). Typically, treatments are based on a 20-25% nitric acid solution, which removes all traces of free iron on the surface. A 4-10% citric acid solution is also specified for the same purpose, often in proprietary products containing additives such as chelants, and there are other commercial passivating agents that are claimed to be disposable after use without the neutralising treatment required for acids. Chemical passivation can also be used on its own (and not simply as an addition to pickling) to remove surface contamination. Selection of the appropriate passivating agent depends on the degree of contamination but none is capable of removing deeply embedded iron, for which pickling is necessary.

Chemical pickling treatments are usually based on a mixture of acids, typically 10-20% nitric acid and 0.5-3.5% hydrofluoric acid. If a fabrication is of a suitable size and a facility is accessible, it is ideally treated by immersion. Pipework can be treated by circulation of the acid mixture. Alternatively, the fabrication can be sprayed with a viscous solution or a gel, usually by a contractor having the facilities for protection of personnel and the surroundings. A simpler method for local treatment of weld areas is to apply a paste containing the acid mixture in a binding agent, by brush or roller. This process has the advantage of requiring a minimum of equipment and skill but carries the need to follow the procedure correctly to avoid over-pickling and damage to the underlying material. In all cases, appropriate safety procedures should be followed and thorough rinsing with clean water is essential, with appropriate disposal of the effluent according to the relevant regulations.

ASTM A380 Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems provides detailed compositions of pickling and passivating solutions.

Electropolishing and Electrochemical Cleaning

Electropolishing produces a finish superior to all other methods of surface treatment. It is carried out by a process in which the whole fabrication is immersed in baths similar to those used for electroplating. The outcome is a product that is highly polished in appearance, with excellent corrosion resistance. Electrochemical cleaning is a process used for local treatment of welds to remove heat tint and rust spots with the aid of a hand tool connected to a portable DC power source. The tool comprises a cathode and a sponge soaked in an electrolyte; the circuit is completed by a connection to the fabrication, which acts as the anode. The tool is passed slowly over the weld and is claimed to leave a clean surface that is smoother than that obtained by chemical methods, which tend to have an etching effect. Solutions used for electrochemical cleaning are usually based on phosphoric acid and only small volumes of water are required for removal of residual solution. The power source and the need for tools with special heads to accommodate different weld configurations represent a capital cost that must be justifiable.

Further details are in ASTM B912-02 Standard Specification for Passivation of Stainless Steels Using Electropolishing.

Table 3

Surface Defects and Suggestion for Their Removal

Defect	Removal
dust and dirt	Wash with water and/or detergent. If difficult to remove, use high pressure water or steam.
loose iron particles	Immerse in 20% nitric acid solution. Rinse with clean water. Confirm removal with ferroxyl test.
embedded iron	Immerse in 10% nitric-2% hydrofluoric acid solution. Rinse with clean water. Confirm removal with ferroxyl test. Remove all traces of ferroxyl test with clean water or dilute nitric or acetic acid.
scratches	Smooth surface by fine grit grinding.
heat tint and other oxidation	Degrease with non-chlorinated solvent followed by one of three procedures: a. Pickle surface with 10% nitric-2% hydrofluoric acid solution until all traces are gone. Rinse with clean water. b. Use proprietary pickle paste and wash with clean water. c. Electropolish and rinse with clean water.
rust areas	Immerse in 10% nitric-2%HF solution. Rinse with clean water. Confirm removal with ferroxyl test. Remove all traces of ferroxyl test with clean water or dilute nitric or acetic acid.
rough grinding and rough machining	Remove by fine grit grinding.
welding arc strike marks	Remove by fine grit grinding and repair and re-finish if necessary.
weld spatter (possible from incorrect welding parameters with GMAW and FCAW)	Prevent from adhering with anti-spatter compound or remove by fine grit grinding.
welding slag	Remove by chipping and fine grit grinding.
weld defects	If unacceptable remove by grinding and re-weld, and then refinish.
oil and grease	(Can be detected by the water break test as in ASTM A380) Remove with non-chlorinated solvent or alkaline cleaners.
residual adhesives	Remove with non-chlorinated solvent if soft or fine grit grinding if hardened.
paint, chalk, crayon	Scrub with clean water and/or alkaline cleaner. If tenacious, use high-pressure water or steam.

General Principles

- Brushing with carbon steel brushes and use of iron-contaminated tools should be avoided.
- As a general rule for heat tint, anything other than a pale yellow coloured oxide film should be removed.
- Heat tint and contamination can be removed by mechanical and/or chemical means.
- For mechanical cleaning methods, blasting methods and fine grinding are preferred for subsequent corrosion resistance. Stainless steel wire brushing is the least effective.
- Generally, mechanically cleaned surfaces should be taken to at least a 180-grit finish or finer.
- Pickling is normally applied as an alternative to mechanical procedures but will also improve the corrosion resistance if used after mechanical cleaning.
- Only non-chlorinated solvents should be used for degreasing.

Welding Specifications

Traceable records of the qualified weld procedure specification, post-weld cleaning procedure, purging gas, and the allowable maximum heat tint on welds, should accompany the contract documentation when stainless steel welds are made in the workshop or the field, to ensure that high quality welding is carried out. Current applicable weld standards are given below together with a suggested specification to assess and define allowable heat tint.

BS EN 287-1:2004 Qualification test of welders. Fusion welding. Part 1: Steels

BS EN ISO 15607:2003 Specification and qualification of welding procedures for metallic materials. General rules.

BS EN ISO 15614-1:2004 Specification and qualification of welding procedures for metallic materials. Welding procedure test. Arc and gas welding of steels and arc welding of nickel and nickel alloys.

BS EN 970:1997 Non-destructive examination of fusion welds. Visual examination.

BS EN 1011-3:2000 Welding. Recommendations for welding of metallic materials. Arc welding of stainless steels.

BS EN 25817 Arc welded joints in steel. Guidance on quality levels for imperfections.

BS ENV 1993-1-4 Eurocode 3: Design of steel structures. Part 1.4: 1996 General rules–Supplementary rules for stainless steels.

EN 1600 Welding consumables. Covered electrodes for manual metal arc welding of stainless and heat resisting steels. Classification.

EN 12072 Welding consumables. Wire electrodes, wires and rods for arc welding of stainless and heat-resisting steels. Classification.

ENV 1090-6 Execution of steel structures. Supplementary rules for stainless steel.

EN ISO 14172 Welding consumables. Covered electrodes for manual metal arc welding of nickel and nickel alloys. Classification.

EN ISO 18274 Welding consumables. Wire and strip electrodes, wires and rods for the arc welding of nickel and nickel alloys. Classification.

AS/NZS 1554.6 Structural steel welding–Part 6: Welding stainless steels for structural purposes.

ASME Boiler and Pressure Vessel Code, Section VIII Pressure vessels. ASME, 2004.

ASTM A380-99e1 Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems

ASTM A967-01e1 Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts

ASTM B912-02 Standard Specification for Passivation of Stainless Steels Using Electropolishing

AWS A5.4 Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding

AWS A5.9 Specification for Bare Stainless Steel Welding Electrodes and Rods

AWS A5.11 Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding

AWS A5.14 Specification for Nickel and Nickel Alloy Bare Welding Electrodes and Rods

AWS D1.6 1999 Structural Welding Code–Stainless Steel

AWS D18.1 1999 Specification for Welding of Austenitic Stainless Steel Tube and Pipe Systems in Sanitary (Hygienic) Applications

Suggested Specification for Assessment of Inaccessible Weld Roots

The most commonly used stainless steels for structural applications involving site welding are the 300 Series austenitic alloys–UNS S30403 (steel number 1.4307, Type

304L) and S31603 (steel number 1.4404, Type 316L)–although the duplex alloys are also increasingly employed. There has been debate regarding the need to remove all weld heat tints and there is general agreement that all coloured tints need not be removed when the stainless steel offers a good margin of corrosion resistance over that required for the particular environment. This is significant for the field fabrication of stainless steel pipework where access to pickle/passivate internal welds is not possible. In the past, the issue has been overcome by employing mechanical joints, limiting the assembly lengths to accommodate internal weld cleaning, and producing completely heat tint-free welds. However, situations can arise in the field where these options are not always achievable, and a decision has to be made as to the acceptability or otherwise of heat tinted welds.

Based upon the criterion that stainless steel welds displaying a straw colour (i.e. shades of yellow) heat tint are acceptable–AWS D18.2 Reference Colour Chart, Level Number 3 or less–heat tints on weld roots are permitted in the Water Industries as long as the alloy welded has excellent corrosion resistance in the service environment.

A possible procedure[5] for assessment of inaccessible weld roots that owners, fabricators and contractors may adopt is as follows:

1. Determine whether a post-weld cleaning procedure is to be carried out. If so, draw up a specification for the cleaning treatment and the cleaning procedure.
2. Contractor to develop for approval the welding and inspection procedures to be employed including the purging gas type and purity, in order to ensure that heat tinting produced on welds will comply with the maximum allowable heat tint level.
3. Owner to specify the maximum allowable heat tint level according to the Reference Colour Chart, where AWS D18.2 (1999) is the recommended Standard. Alternatively, specify the maximum allowable heat tint level to be judged against a weld reference sample of the material being welded to the same welding procedure specification (WPS).
4. Contractor to maintain a high level of documentation for the welding procedure, gas purging, all inspections and testing carried out to check or confirm the results.

The documented specification required and the post-weld testing carried out on heat tinted welds should be incorporated into the project contract document between owner and contractor. The required level of documentation for a project would consist of the Welding Procedure Specification, with supplementary weld purging gas purity specifications, and weld inspection instructions. If there still remains doubt about an acceptable level of weld heat tinting on the stainless steel, either as-welded or after post-weld cleaning, weld samples should be subjected to appropriate corrosion testing with the methodology chosen by agreement between the owner and the contractor.

Transportation and Installation

Fabrications have to be transported to sites, often where substantial civil engineering works are in progress. They need to be protected from damage by suitable packing and to be carefully stored until installed, following the precepts indicated above. Ingress of dirt into pipework should be prevented by end caps. Temporary covers should be provided and any dust washed off the stainless steel before welding. Although conditions are often unhelpful, welds made in the field require the same degree of care as those made in the workshop. Nevertheless, requirements such as internal purging present considerable difficulties and when internal purging is difficult to set up and tape is also impractical or cannot be removed, it may be necessary to substitute bolted flange connections for welded joints. It is important that site welders are trained and approved for stainless steel welding and that appropriate arrangements are made for inspection of installed fabrications.

Components prefabricated for mechanical fastening can take advantage of the range of conversion couplings available, or for tie-in welding. Pipe spool sections can be fabricated in the workshop and supplied to site where they can be assembled using mechanical joints. Spool pieces and pressure vessels joined with stainless steel connections require compatible stainless steel bolts and gaskets.

Commissioning

For stainless steels, flow rates in raw waters should preferably be more than 1 m/s and more than 0.6 m/s in cleaner, treated waters. In bacterially active waters e.g. well waters, surface waters and raw waters, bacteria can colonise in stagnant conditions and certain types may initiate microbiologically influenced corrosion (MIC) in the lower-alloyed grades of stainless steel [e.g. UNS S30403 (steel number 1.4307, Type 304L); S31603 (steel number 1.4404, Type 316L); and S32205 (steel number 1.4462, Type 2205)]. MIC has not been encountered on superaustenitic or superduplex stainless steel grades. Although MIC occasionally occurs in the base metal, the normal locations are on irregular surfaces or in the area of welds from which heat tint has not been removed and so it is essential to clean welds. If equipment is not going into service within 5 days, the system should be drained and dried thoroughly after hydrotesting, otherwise bacterial colonisation is possible. An alternative is to flush the system every 2 days. MIC is far less likely to occur in treated or potable waters and so potable waters, steam condensates or filtered waters should be used for testing rather than raw waters. Care needs to be taken during hydrotesting at the commissioning stages of plant equipment including pipelines and tanks when raw waters are used. This is when there is the greatest risk of this type of corrosion.

Good Practices

- Protect prefabricated assemblies from dust, mechanical damage and the ingress of contamination by the use of covers and end caps prior to final assembly.
- Any accidental iron contamination is readily removed by applying a nitric acid based cleaning (or pickling) and passivating agent.
- Wash down stainless steel components with potable grade water at the end of installation operations, to remove dust and other contamination, and dry.
- Flush pipework systems through to remove any debris and, if left to stand empty prior to commissioning, wash with clean water and dry.
- After hydrostatic pressure testing or other procedures which allow water to stagnate, and regardless of water quality, drain water immediately or circulate daily.
- After draining completely, ensure the pipework is dry.

Reference List and Bibliography

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2. Steel Construction Institute. *Operational Guidelines and Code of Practice for Stainless Steel products in Drinking Water Supply*. British Stainless Steel Association. 2002
3. R. E. Avery and A.H. Tuthill. "11007 – Guidelines for the Welded Fabrication of Nickel Containing Stainless Steels for Corrosion Resisting Services." *Nickel Institute Reference Book Series.* 1992
4. American Welding Society. *AWS D18.2 Guide to Weld Discoloration Levels on Inside of Austenitic Stainless Steel Tube*. 1999
5. L.H. Boulton and R.E Avery. "Heat Tinted Stainless Steel Welds–Guidelines for Acceptance." *Stainless Steel World.* 2004, April, pp42-49
6. Euro Inox. "Welding of Stainless Steels." *Materials and Applications Series*. Volume 3. 2001
7. Euro Inox. "Working with Stainless Steels. A Manual for Craftsmen and Technicians." *Materials and Applications Series*. Volume 2. 2001
8. International Molybdenum Association. "Practical Guidelines for the fabrication of Duplex Stainless Steels." *Nickel Institute Reference Book Series No. 16000.* 2002
9. R. Francis. *Galvanic Corrosion: A Practical Guide for Engineers*. Houston: NACE International, 2001
10. New Zealand Stainless Steel Development Association. *The Code of Practice for Fabrication of Stainless Steel Plant and Equipment*. 2001
11. L. Wegrelius and B. Sjoden. *Passivation Treatment of Stainless Steel*. Outokumpu Stainless. ACOM. 4-2004

Other Useful References in the Nickel Institute Reference Book Series:

9001 Cleaning and Descaling of Stainless Steel

9003 Stainless Steel Fasteners

10 004 Fabrication and Post Fabrication Clean Up of Stainless Steels

10 068 Specifying Stainless Steel Surface Treatments

10 080 Cleaning Stainless Steel Surfaces Prior to Sanitary Service

10 085 MIC of Stainless Steels by Water Used for Cooling and Hydrostatic Testing

10 087 Stainless Steel for Potable Water Treatment Plants

11 021 High Performance Stainless Steels

12008 Piping Manual for Stainless Steel Pipes for Buildings

14018 Guidelines for Welding Dissimilar Metals

14050 Heat Tint On Stainless Can Cause Corrosion Problems

14056 Stainless Steels; An Introduction to Their Metallurgy and Corrosion Resistance

Figure 8. Stainless steel pipework in a water treatment plant. Attention has been given to both good welding and post-fabrication cleaning practices.

APPENDIX A

Chemical Compositions and Mechanical Properties

Table A1
Chemical Compositions of Commonly Used Stainless Steels

Common Name	EN 10088-2	% Carbon (max.)	% Chromium	% Nickel	% Molybdenum	Other Elements	UNS Equivalent
304L	1.4307	0.03	17.50–19.50	8.00–10.00	---	---	S30403
316L	1.4404	0.03	16.5–18.5	10.0–13.0	2.0–2.5	---	S31603
316Ti	1.4571	0.08	16.5–18.5	10.5–13.5	2.0–2.5	Ti	S31635
22% Cr duplex (alloy 2205)	1.4462	0.03	21.0–23.0	4.5–6.5	2.5–3.5	N	S31803[a]
	1.4462	0.03	22.0–23.0	4.5–6.5	3.0–3.5	N	S32205[a]
25% Cr superduplex	1.4507	0.03	24.0–26.0	5.5–7.5	2.7–4.0	Cu, N	S32550
	1.4410	0.03	24.0–26.0	6.0–8.0	3.0–4.5	N	S32750
	1.4501	0.03	24.0–26.0	6.0–8.0	3.0–4.0	Cu, N, W	S32760
alloy 904L	1.4539	0.02	19.0–21.0	24.0–26.0	4.0–5.0	Cu	N08904
6% Mo superaustenitic	1.4529	0.02	19.0–21.0	24.0–26.0	6.0–7.0	Cu, N	N08926
	1.4547	0.02	19.5–20.5	17.5–18.5	6.0–7.0	Cu, N	S31254
	---	0.03	20.0–22.0	23.5–25.5	6.0–7.0	N	N08367

[a] UNS S32205 has a composition range restricted to the higher end of the UNS S31803 range which has the better corrosion resistance and structural stability. It has become the more widely used 22% Cr duplex in recent years.

Table A2
Mechanical Properties from EN 10088-2 (Cold Rolled, Solution Annealed Strip)

Common Name	0.2%Proof Stress,[a] MPa	Tensile Strength, MPa	Elongation,[a] %
304L	220	520-670	45
316L	240	530-680	40
22% Cr duplex	480	660-950	20
25% Cr superduplex (steel number 1.4507)	570	690-940	17
alloy 904L	240	530-730	35
6% Mo superaustenitic (steel number 1.4547)	320	650-850	35

[a] Single values are minimum values.

APPENDIX B

Physical Properties and Surface Finishes

The physical properties of ordinary carbon steels and austenitic stainless steels are quite different and these call for some revision of welding procedures. Physical properties, Table B1, include such items as melting point, thermal expansion, thermal conductivity and others that are not significantly changed by thermal or mechanical processing. As illustrated in Table B2, the melting point of the austenitic grades is lower, so less heat is required to produce fusion. Their electrical resistance is higher than that of mild steel so less electrical current (lower heat settings) is required for welding. These stainless steels have a lower coefficient of thermal conductivity, which causes heat to concentrate in a small zone adjacent to the weld. The austenitic stainless steels also have coefficients of thermal expansion greater than mild steel, which calls for more attention to the control of warpage and distortion.

Table B1
Typical Physical Properties According to EN 10088-1[a] and ASM Metals Handbook[b]

Physical Property	Austenitic Grades[a]	Duplex Grades[a]	Carbon Steel[b]
Density, g/cm^3	7.9	7.8	7.85
Melting Point, °C	1400-1450	1425-1510	1490-1525
Magnetic Response	Non magnetic*	Magnetic	Magnetic
Modulus of Elasticity at 20°C, GPa	200	200	210
Coefficient of Thermal Expansion between 20 and 100°C, 10^{-6}/°C	16	13	12
Thermal Conductivity at 20°C, W/m°C	15	15	50
Electrical Resistivity at 20°C (Annealed), $\mu\Omega\cdot cm$	73	80	16
Specific Heat Capacity at 20°C, J/kg°C	500	500	485

* UNS S30403 (steel number 1.4307, Type 304L) and S31603 (steel number 1.4404, Type 316L) can show weak magnetic response after cold work or in the weld metal.

Table B2
As Supplied Surface Finishes from EN 10088-2 Typically Used in Water Industry

Form	Finish	Process	Applications
Hot Rolled	1D	heat treated, pickled	tanks, gates and penstocks
	1M	roll patterned	floor plates
Cold Rolled	2D	heat treated, pickled	general purposes
	2B	heat treated, pickled, light cold rolled	

APPENDIX C

Guidelines for Alloy Selection for Waters and Waste Water Service

Waters

Stainless steels do not suffer uniform corrosion when exposed to water environments. On the other hand, they can be susceptible to localised corrosion under certain circumstances which designers and end users need to recognise and avoid. Such attack, if it occurs in water environments, is usually localised as pits or in creviced areas. Design and good fabrication can minimise such corrosion sites but this needs to be combined with correct alloy selection to avoid the problem.

Pitting and crevice corrosion requires the presence of chlorides and, for a given chloride level, the more highly alloyed stainless steels are more resistant. In general, the higher the chromium, molybdenum and nitrogen contents of the steel, the better the corrosion resistance. While there are other factors that have an effect on corrosion rate in waters, chloride content is a major factor for selection of an appropriate grade and is easily measurable. As crevice corrosion tends to occur at lower chloride levels and temperatures than pitting, it is normally the parameter used to guide selection. The guidelines in Table C1 are based on laboratory tests and service experience over many years.

For the chloride levels given in the table, crevice corrosion is rare at pH levels above 6 and ambient temperatures, typical of most water industry environments. However, where conditions are severe, e.g. very tight crevices, lower pH, higher temperatures, low flow rates and other situations where there is a risk of local concentration of higher chloride levels–or just on grounds of conservatism–UNS S30403 (steel number 1.4307, Type 304L) can be selected for chloride levels in the region of 50 ppm and UNS S31603 (steel number 1.4404, Type 316L) for chloride levels up to 250 ppm. Alternatively if the stainless steel is cathodically protected, the waters are de-aerated, or there is only transient exposure to these chloride levels then the requirements in Table C1 can be relaxed.

Table C1
Suitability of Stainless Steels in Waters

Chloride Level	Stainless Steel Grade
< 200 ppm	304L, 316L,
200–1000 ppm	316L, duplex alloy 2205
1000–3,600 ppm	duplex alloy 2205 6%Mo superaustenitic, superduplex
> 3,600 ppm	6%Mo superaustenitic, superduplex
15,000–26,000 ppm (seawater)	6%Mo superaustenitic, superduplex

Some free-machining grades of stainless steel contain high levels of non-metallic stringers which significantly lower their resistance to pitting in waters. Therefore, free-cutting high sulphur or selenium bearing grades such as UNS S30300 (Type 303) and S30323 (Type 303Se) should not be used.

Bacterial control and management is often achieved by chlorine dosing. UNS S31603 (steel number 1.4404, Type 316L) stainless steel performs well and the molybdenum additions in this alloy provide greater pitting and crevice corrosion resistance than its UNS S30403 (steel number 1.4307, Type 304L) counterpart. Data to evaluate acceptable free chlorine levels are limited but those available for raw waters suggest up to 2 ppm for UNS S30403 (steel number 1.4307, Type 304L) and 5 ppm for UNS S31603 (steel number 1.4404, Type 316L). However, stainless steel can tolerate considerably higher levels of chlorine for short periods of time, as would be the case during disinfection treatments e.g. 25 ppm chlorine for 24 hours. It is important however that such levels are well flushed through the system immediately after treatment.

Plant Atmospheres

When fabricated and finished to suitable standards, the UNS S30403 (steel number 1.4307, Type 304L) and S31603 (steel number 1.4404, Type 316L) can retain their bright appearance in atmospheric exposure for many years particularly when any surface deposits which build up are removed by a periodic wash down. In marine (within 5–15 miles of the coast depending on wind and temperature) and chloride bearing or industrial polluted atmospheres, the UNS S31603 (steel number 1.4404, Type 316L) is preferred where maximum life and good appearance are required.

In enclosed plant atmospheres, where wet chlorine vapours collect and concentrate, acid condensates can begin to stain and pit stainless steel. Good venting or regular washing down is recommended in pipe galleries and other areas where chlorine gases can collect. However, where this is not possible, a higher grade of stainless such as UNS S32205 (steel number 1.4462, alloy 2205) or super stainless alloys may be required.

Waste Water Processing

Hydrogen sulphide gas can contribute to the general corrosion that occurs on copper alloys, aluminium alloys, hot-dipped galvanized steel, and painted/unpainted steel in wastewater treatment plants. In contrast, general corrosion rates of UNS S30403 (steel number 1.4307, Type 304L) and S31603 (steel number 1.4404, Type 316L) stainless steels in the atmosphere and in closed systems (e.g. pipework), where moist hydrogen sulphide is present are negligible at near ambient temperatures. However in closed systems there may be a propensity for localised corrosion attack (pitting and crevice corrosion) to occur in UNS S30403 (steel number 1.4307, Type 304L) and S31603 (steel number 1.4404, Type 316L) stainless steels if moist hydrogen sulphide and chlorides are present together at elevated temperatures. The acidity of wastewaters may also be raised so that they become more corrosive if condensates containing dissolved sulphur dioxide are generated, forming sulphurous acid. These more corrosive environments may require higher molybdenum austenitic stainless steels [e.g. UNS N08904 (alloy 904L, steel number 1.4539)] or duplex stainless steels [e.g. UNS 32205 (steel number 1.4462, alloy 2205)] to be considered as materials of construction.

APPENDIX D

Design for Corrosion Resistance

General

Careful plant design provides a key means of securing the advantages that stainless steels offer for the treatment and distribution of water. While the principles are the same as those followed for carbon steels, they have to take into account the smooth stress-strain curve of stainless steels, without a well-defined yield point. Without the need for a corrosion allowance or protective coatings, components such as pipework are thin-walled and lightweight. High ductility and work hardening facilitate manipulation of pipes reducing the number of welds required. Detailed design focuses on the avoidance of crevices and locations where stagnant water can accumulate. For example, complete drainage from tanks and pipework is essential as sediments may initiate crevice corrosion and microbiologically influenced corrosion can develop. Consideration should be given to such details as rounded corners, the avoidance of corner welds, smooth contours and sloping tank bases with drainage outlets. Intermittent fillet welds should not be specified for attachment of items such as reinforcing pads, even though adequate on strength grounds, since the gaps between the welds are crevices which are potentially susceptible to corrosion. If they are unavoidable and the environment is potentially corrosive, as in high chloride waters, the gaps should be permanently sealed. Butt welds must be designed for full penetration, particularly in pipe joints, since the weld root is crucially exposed to the water passing though the pipe and must be continuous and uniform.

Where possible, the plant should be designed to:

1. Have free liquid flow, avoiding regions of stagnation and dead legs, low flow and deposit build up.
2. Have, where flow is intermittent, any horizontal pipe runs and tank bottoms sloped to allow complete draining.
3. Where light gauge stainless steel pipework is used, have the mounting methods take account of any acoustic damping required as a result of pressure pulsing. Acoustic damping may benefit from the use of double swept tees to avoid sharp internal edges in the pipework and subsequent eddy formation.

4. Ensure deposit traps and crevices are eliminated as far as possible (e.g. if plates are lapped, all lapping edges are to be sealed).
5. Provide weld procedures appropriate to the design and grade of steel being used and employ experienced and qualified welders.
6. 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.
7. Give conditions allowing full-penetration welded joints with smooth contours and weld bead profiles.

8. Incorporate some flange connections to allow ease of disassembly and to perform internal cleaning and inspection without cutting piping. Similarly, where harmful deposits are unavoidable, such as where manganese and iron-bearing deposits may form ahead of sand filters, ports should be provided to allow access for periodic flushing or hydro-blast cleaning.
9. Repairs and modifications should be designed, specified and executed to the same standards as for the original equipment.

Useful design reference:

1. N. Baddoo and B. Burgan. *Structural Design of Stainless Steel.* The Steel Construction Institute, SCI-P-291. Available from the Nickel Institute or the Steel Construction Institute, UK

Fasteners

Stainless steel fasteners are generally produced to ISO 3506 "Corrosion-resistant stainless steel fasteners". Bolt and nut materials are classified A for austenitic, F for ferritic and C for martensitic. Austenitic alloys are the most commonly used and the A is followed by the numbers 1, 2 or 4 which reflect the corrosion resistance. A4 has the highest corrosion resistance with a UNS S31600 (Type 316) composition and A2 has a UNS S30400 (Type 304) composition. A1 is UNS 30300 (Type 303) composition having high levels of manganese sulphide inclusions to facilitate free machining; however, this results in inadequate resistance in waters and is not recommended for most water industry applications.

The austenitic fasteners can be obtained in three minimum strengths; known as classes 50, 70 and 80. These refer to UTS levels for bolts and proof load stress for nuts of 500, 700 and 800MPa respectively. It is normally recommended that the bolting material should be in the cold worked condition (Class 70 minimum) as there is a greater likelihood for galling in the softened condition.

Equivalent ASTM fastener specifications for general service are F593 (bolts) and F594 (nuts). These specifications also define the classes of fastener, as annealed and strain hardened or cold worked, along with their minimum mechanical property characteristics.

Galling occurs when the stainless steel oxide film breaks down as a result of direct metal contact leading to surface damage and seizing up. This can occur when stainless steel nuts and bolts are used together where the contact points are subjected to high tightening torques. Fasteners made to international standards should ensure uniformity of threaded products. Care is still required when handling to avoid any thread damage and to keep the threads clean and free from dirt, coarse grime or sand.

The risk of galling can be reduced by using rolled as opposed to machined threads as already mentioned and avoiding fitting thread forms. Rolled threads have a smoother surface and grain lines follow the threads rather than cut a cross it which is the case with machined threads.

Bolts should be tightened to the correct torque using a torque or wrench. Application of appropriate lubrication or anti-seize compounds prior to assembly can also be helpful. Proprietary grease type lubricants containing tenacious metals, oils etc are available. Some commonly used lubricants contain molybdenum disulphide or nickel powder although approvals for use with drinking water for individual proprietary products should be checked for the country of use. Graphite should preferably be avoided being galvanically very noble.

Galling can also be reduced by using two stainless steels of significantly different hardnesses on the mating surfaces. A Brinell hardness difference of 50HB may overcome galling. Another solution in the USA has been the use of nuts made from UNS S21800 (high manganese austenitic stainless steel with high galling resistance) with UNS S30400 (Grade 304) or S31600 (Grade 316) bolts. Alternatively, PTFE coated fasteners have been another solution.

A common misconception is that the use of UNS S31600 (Grade 316) bolts with UNS S30400 (Grade 304) nuts will avoid galling. This is incorrect; there is no notable difference between them.

Galvanic Issues

It is often necessary to use a number of different alloys to construct a treatment plant or processing system and the galvanic compatibility of these materials must be considered. Galvanic corrosion can occur when two different alloys are in contact in a common electrolyte (e.g. rain, condensation, fresh and treated waters and waste water) forming a galvanic corrosion cell. If current flows between the two, the less noble alloy (the anode) corrodes at a faster rate than it otherwise would if the alloys were not in contact.

Prediction of corrosion rates can be complicated by area ratios of the metals, temperature, surface films and the electrical conductivity of the electrolyte and are not always easy to accurately assess. Galvanic series are available to indicate which alloy is the least noble in a metal couple but these are usually based on seawater as the electrolyte. Less information is available about other waters but *Galvanic Corrosion–A Practical Guide for Engineers* by Roger Francis published by NACE Press goes some way to assembling existing information. Table D1 indicates typical rankings for fresh water.

The greater the potential difference or, put more simply the vertical separation, between two metals in the series, the greater the driving force for corrosion. Stainless steels are noble alloys in this ranking and they are the protected component of the combination.

Table D1
Typical Ranking for Fresh Water

Anodic (Least Noble)
magnesium
zinc
aluminium
carbon steel and cast iron
copper alloys
stainless steels
graphite
Cathodic (Most Noble)

Should the stainless steel become active by the passive film becoming damaged or removed by localised corrosion attack, its position in the series can change to between copper alloys and carbon steel and thus become less noble.

In practice galvanic corrosion is particularly relevant when considering joining stainless steel and carbon or low alloy steels. The risk of deep attack is greater if the stainless steel area is large compared with the steel; for example, galvanised or steel fasteners in a stainless steel flange.

Methods of avoiding galvanic corrosion are:

1. Design to ensure the more noble area is small in comparison with the less noble area.
2. Insulate the joint. e.g. insulating gaskets, sleeves and washers, paint and tapes.
3. Use of isolation spools.
4. Cathodic protection.
5. Coating the joint region to ensure adequate coverage on either side. If this is difficult, coat only the more noble metal. If only the less noble metal is protected, then attack at any coating defects will be severe.

Galvanic corrosion is also a reason why it is important to select a weld consumable that is at least as noble as the parent metal.

In fresh waters as opposed to seawater, copper-base alloys are compatible with stainless steel unless extreme stainless steel to copper area ratios exist; for example, copper alloy valves can be used in stainless steel piping. However, steel, zinc and aluminium are significantly less noble than stainless steel and generally should be insulated from stainless steel.

APPENDIX E

Health and Safety

Handling of stainless steels poses no special problems, as their widespread use in commercial and domestic applications demonstrates. Also, because of the requirement to avoid contamination, the working conditions in workshops set up for processing these steels tend to be better than the environment in general fabrication workshops.

When any material is welded, fume may be produced. Fume comprises particulates and gases, the composition of which may vary, not only with the type of filler metal but also with the welding process. The rate of generation of fume differs between processes and varies with operating parameters for individual processes. Since inhalation of fume can induce temporary or chronic disease, exposure of welders and ancillary personnel must be controlled. Regulatory authorities, for example OSHA in the USA and the HSE in the UK, prescribe concentration limits for individual elements and, in most cases, for the total fume. For stainless steels, the key elements of concern are chromium, nickel, and manganese.

The measures required to comply with regulations depend on particular exposure limits, which differ between countries. However, there are two principal methods of control: selection of welding process and ventilation. For example, among the arc processes the least amount of fume is generated by the TIG (GTAW) process, whereas the flux-shielded processes generate the most fume, in this case containing chromium in the hexavalent form, for which limits are stringent.

General ventilation is unlikely to be sufficient to reduce fume concentration below the required limits. Efficient local exhaust ventilation is necessary and arrangements must be made to ensure that the exhaust hood remains close to the arc throughout the welding operation when a mobile hood is needed. A suitable device such as a tell-tale should be provided to show that the extraction system is working and the fume should be captured or exhausted outside the building.

Welding in confined spaces (these include open tanks) requires special care, since they present hazards by allowing the accumulation of fume constituents and shielding gases and the reduction of oxygen concentration. Safe working procedures are defined by regulations and codes of practice of the health and safety organisations in each country.

Further information can be obtained from:

UK:
1) Health and Safety Executive
http://www.hse.gov.uk

Germany:
1) Bundesanstalt für Arbeitsschutz und Arbeitsmedizin
http://www.baua.de
2) Hauptverband der gewerblichen Berufsgenossenschaften (HVBG)
http://www.hvbg.de

USA:
1) Occupational Safety & Health Administration
www.osha.gov

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