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## **Optimising Stainless Steel Piping Fabrication Practice**

### **INTRODUCTION**

Stainless steels are selected for service in Oil and Gas systems because of their high level of corrosion resistance in typical producing environments. The stainless steels considered in this report are the 300-series austenitic stainless steels and the duplex stainless steels. Unfortunately these materials are not totally resistant to corrosion in other environmental conditions. In particular they are sensitive to pitting corrosion and crevice corrosion in aerated water environments with chloride ions present at certain temperature conditions.

Stainless steel piping systems are typically hydro-tested with water of varying quality from potable water through to seawater with or without various chemicals present. Depending upon the duration of exposure any of these environments may result in pitting attack. The resistance to pitting is strongly affected by the stability of the passive film on the stainless steel and this is deleteriously affected in various ways by welding.

The method for preventing pitting attack of stainless steels during hydro-testing and prior to service is by two approaches. Firstly the fabricator has to make every effort to optimise the quality of the weld and minimise the reduction of passive film quality. Secondly the commissioning procedures have to be optimised to minimise the corrosivity of the environment for the hydro-test period. The purpose of this report is to give guidance on optimum practice at every step in order to give the very best confidence in the quality of fabrications.

# CORROSION OF STAINLESS STEELS IN WATER

## *The Corrosion Mechanism*

Stainless steels owe their corrosion resistant properties to the presence of a passive film which is a mixture of iron and chromium oxide. If this passive film is broken at any point then that location will tend to corrode, becoming the anode in the corrosion circuit. The surrounding, unattacked, passive film acts as a large cathode area. This ratio of small anode to a large cathode is able to drive a very high corrosion rate at the anode resulting in surprisingly fast penetration of the steel at the pitted areas. Pitting rates of 1-2mm/week have been experienced in practice in a variety of situations. Once pitting has initiated it is difficult to stop whilst the aerated corrosive environment is present and therefore the key aim is to prevent the initiation of pitting i.e. to prevent initial local breakdown of the passive film.

The corrosion process which takes place is a very characteristic one where the surface passive film is locally broken down and then the underlying steel corrodes very rapidly forming a characteristic “bottle-shaped” pit below the surface. The process of dissolving the iron is the anodic reaction as shown below:



As the iron corrodes the positively charged iron ions attract negatively charged chloride ions from the external environment into the pit. The environment within the pit therefore is quite different and much more concentrated than external environment. In addition to this process the iron cations are hydrolysed and the associated water molecules release hydrogen ions,  $\text{H}^{+}$ , into this pit environment. This build up of concentration of hydrogen ions  $\text{H}^{+}$ , in the environment causes the pH within the pit to reduce. pH values as low as 1 or 0 have been measured within the pit. By these different processes the pit environment gradually becomes a highly concentrated solution of hydrochloric acid. The stainless steel corrodes very rapidly in this strongly reducing and concentrated acid solution. Because this local environment in the pit is not an oxidising solution the pit cannot re-passivate because it cannot form any surface oxides to stop the ongoing corrosion reaction.

Thus, the pit environment which develops is quite different in composition to the bulk environment outside the pit. The solution outside may be quite a normally innocuous aerated water with a moderate chloride ion concentration which is not particularly aggressive to the normal passive film. However, where that passive film has been weakened in any way, and a stable pit formed, the pit becomes a small volume of concentrated acid, preventing it from re-passivating. The outer environment is an aerated one, which supports a cathodic reaction over the passive surface of the steel, and the pit is an acidic de-aerated environment which causes the stainless steel to dissolve.

The rate of attack inside the pit is governed by the cathodic reaction outside the pit. The cathodic reaction in aerated water is the reduction of oxygen.



This means that the corrosion rate (iron dissolving) is directly controlled by the supply of oxygen. In an aerated water there is a good oxygen supply so the cathodic reaction is very efficient and drives the anodic reaction very fast at any initiated pits.

The best way to control this kind of reaction is to prevent the initiation of the pit in the first place. This means taking steps to optimise the passive film quality. This requires attention to detail at all stages of handling, fabrication, installation and the commissioning of stainless steel equipment.

Obviously control of the water quality also can influence the risk of pit initiation and the rate of pitting. Water which has an oxygen scavenger chemical added to remove oxygen will not support this cathodic reaction. Correspondingly, there will be no anodic reaction because the rate of supply and consumption of electrons has to be equal.

The optimum approach is to take steps at every stage of dealing with stainless steels to optimise their corrosion resistance and expose them only to carefully controlled water environments.

### ***Influence of Welding on the Corrosion Resistance of Stainless Steels***

When stainless steel piping is manufactured it is subjected to a final high temperature heat treatment (typically at 1050 °C) followed by water quenching. This leaves the material in the solution annealed condition which is the optimum for corrosion resistance. This heat treatment gives a poor quality high temperature oxide film on the surface which is quite thick and porous. During manufacturing this oxide film is normally removed by pickling and passivating the surface in oxidising acids. The oxide film which is formed at low temperature, either in the passivating solution or just by exposure to air, is thin and dense, giving good protection to the stainless steel.

The as-delivered piping is therefore in an optimum condition, with a solution heat treated microstructure and a well passivated surface oxide finish.

When welding is carried out, the metal close to the weld is reheated to high temperatures, from the melting point at the fusion line to lower temperatures through the heat affected zone. An unprotected heat affected zone which is exposed to air during welding will therefore show a high level of oxidation and this oxide is again a high temperature oxide. Characteristically it would be black in colour and in the worst condition may be visibly thick and porous. This oxide is far more easily broken down than the original passivated surface and

there is a zone of metal under this oxide which is lower in chromium content relative to the bulk metal.

It for this reason that the heat affected zone has to be protected from re-oxidising at high temperature during the welding process. This is done by shielding around the weld using an inert gas to keep air away, thus preventing oxidation whilst the weld metal and HAZ is hot. Once the weld is cooler the heat affected zone will re-oxidise slightly at lower temperatures but this oxide film is a more protective film than the high temperature oxide film. The oxide formed at the HAZ at lower temperatures is so thin that it forms interference colours, giving a characteristic blue colour.

### ***Influence of Surface Contamination on the Corrosion Resistance of Stainless Steels***

The other key problem that can cause breakdown of a properly passivated film is the presence of contaminants on the surface. The most common one found in fabrication shops is iron contamination. Contact of the stainless steel surface with tools, brushes, grinding wheels etc. which have previously been used on carbon steel equipment causes contamination of the stainless steel surface with iron. This may not initially be visible to the naked eye, but when stainless steel items with iron on the surface are left in a humid environment, they will show rust streaks on the surface where this iron contamination has corroded. The rust streaks and the original iron contamination are all areas where corrosion will start if the material is exposed to certain aerated water environments.

The dissolving iron ions become hydrolysed and the associated water molecules lose hydrogen ions,  $H^+$ , reducing the pH locally. They also attract chloride ions within the bulk solution so that a local higher concentration of chloride ions can build up. This development of a local environment, high in chloride ions and low in pH will tend to cause the passive film to break down. These changes are also associated with a rise in the potential (voltage) of the steel and at some potential the passive film will break down, exposing the underlying steel and initiating a pit.

These effects are always worst in conditions where the water is stagnant rather than flowing. The longer the condition remains stagnant, the greater the likelihood of developing this aggressive environment and resulting in passive film breakdown. Thus, short exposure periods (i.e. shorter commissioning periods) are safer than longer periods.

### ***Influence of Geometry of Crevices on the Corrosion Resistance of Stainless Steels***

When stainless steels are exposed to aerated water and there are crevices present there is a risk of initiating a further corrosion problem called crevice

corrosion. Typical crevices exist at flange connections, but also at some weld joints if poorly designed.

The environment within the crevices is stagnant and all the oxygen it has to begin with quickly reacts with the surface of the steel, leaving the environment deaerated within the crevice. This is essentially the same situation as a stable pit, and breakdown of the passive film within the crevice is even more easily initiated than the start of pitting attack.

Once the passive film is broken somewhere within the crevice, that location will continue to corrode. This generates iron ions at a rate driven by the rate of supply of oxygen molecules to the passive surface outside the crevice (the cathode in the corrosion circuit). The mechanistic steps are the same as in a pit, with the gradual development of a low pH environment with higher chloride ion concentration. Crevice corrosion rates, like pitting rates can be as high as 1-2 mm/week once established. This can rapidly damage flange faces or result in corrosion of weld regions.

### ***Influence of Chemical Composition on the Corrosion Resistance of Stainless Steels***

The resistance of stainless steels to pitting and crevice corrosion in aerated waters is strongly related to the chemical composition. Steels with higher levels of chromium, molybdenum and nitrogen are more resistant.

The resistance to pitting can be directly related to the composition using the Pitting Resistance Equivalent Number which is calculated as follows,

$$\text{PRE} = \%Cr + 3.3 \times \%Mo + 16 \times \%N$$

Generally speaking, stainless steels have to have a PRE value above 40 to be resistant to pitting corrosion in ambient temperature seawater.

It is important to ensure that the grades of stainless steels which are used in piping systems are not mixed up. A section of piping with lower resistance to pitting attack, as a consequence of its lower PRE value, may be more likely to initiate pitting when connected to higher alloyed stainless steel.

Weld metal has to have a pitting resistance equivalent to or better than that of the parent metal. This means that even in the root region, with some dilution of the filler metal composition by the parent metal, the pitting resistance will still be acceptable.

## **ASPECTS REQUIRING CONTROL TO PREVENT CORROSION OF STAINLESS STEELS**

The following table summarises good practice and explains the risks involved if these procedures are not followed.

Many of these procedures may already be established practice but some might be more rigorously controlled, or improvements made in current and future fabrication activities to prevent any failures in the period prior to handover for operation of any facility manufactured.

Control Point	Good Practice	Potential Problems and Comments
1. Materials traceability	<p>All incoming stainless steel materials should be checked against the certificate supplied and every piece should be identified with a code which relates it to the certificate and grade of the material.</p> <p>The coding selected should be one which is well recognised within the company and by the welders and should readily distinguish different grades of stainless steels. It is particularly important to identify L grade steels from others to avoid possible confusion.</p> <p>Optimum marking methods are low stress die stamping on the bevel ends for thicker pipe. Thinner pipe, where there is insufficient room on the pipe bevel, may be marked on the external surface.</p> <p>Markers used should be free of chloride ions. White markers which leave a heavy deposit should not be used.</p> <p>All markings should be on the external surface no markings should be on the internal surface under any circumstances.</p>	<p>The stainless steels are not distinguishable by visual inspection and it is easy to substitute the wrong piece of stainless steel, particularly where small piping components such as elbows and tees are welded into piping systems.</p> <p>The resistance of different grades of steel to pitting and crevice corrosion resistance depends strongly upon their composition. Systems with mixed grades of stainless steel are particularly a risk for initiating attack on the less resistant material.</p> <p>Markings on the surface made with the wrong kind of pen can act as pitting initiation points. Pits have initiated at marked numbers where the ink used contains chloride ions, or forms a thick deposit of the surface.</p> <p>Markings made on the external surface are safer than on the inside as these can be easily seen and rubbed away prior to painting of the external surface. Marks on the inside are easily ignored and invisible once welded into piping spools.</p>
2. Storage and Handling	<p>Stainless steels should be stored separately from carbon steel components.</p> <p>Stainless steels should be kept in a clean, dry condition, particularly internally. Ends of pipes should be capped off or covered to prevent dirt or rubbish being put in.</p>	<p>This avoids the risk of mix up with the risk of welding a carbon steel component into the stainless steel piping spool.</p> <p>Dirt or rubbish left in pipes may go unnoticed and can then act as sites for initiating crevice corrosion during hydrotest/commissioning.</p>

Control Point	Good Practice	Potential Problems and Comments
	<p>If stainless steel pipe or components are wet internally they should be racked to allow all the water to drain out, dried and then capped or covered.</p> <p>If external surfaces are exposed to wet or dirty conditions they should be washed down, dried and examined for any corrosion damage prior to use.</p> <p>Stainless steel pipes should not be handled, cut or ground with tools which are also used for carbon steel.</p>	<p>Water left to dry can leave a dry crust of solid deposits, sometimes rich in chloride ions on the surface which can initiate pitting when re-wetted during hydrotest/commissioning.</p> <p>External surfaces which are wet, especially where pipe is stacked or piled together, may initiate crevice corrosion – particularly in coastal/marine environments. Any areas of dull or corroded appearance should be carefully examined prior to use.</p> <p>This is to avoid contamination of the surface with iron which may then initiate pitting. A particular risk comes from grinding dust from carbon steel components.</p>
3. Weld Preparation Designs	<p>A defect-free root run is more critical in corrosion resistant alloys than in carbon steels.</p> <p>When there is access to both sides of the weld then the surface that will be exposed to the corrosive environment should be re-prepared for a capping pass that can be finished to an appropriate profile, free from irregularities and devoid of oxides and slag.</p> <p>Where the root is not accessible care should be taken to optimise weld design and fit-up to minimise root defects such as unmelted edges. Particular care is needed to avoid lack of root fusion, so the weld preparation should ensure adequate access to</p>	<p>Stainless steels have failed in systems carrying water containing chloride ions and oxygen because of crevice corrosion at welds, whilst the bulk of the steel has performed satisfactorily.</p> <p>When the weld is only accessible from one side then there will be no opportunity to correct any deficiencies in the root run, which makes the most demands on welding technique and metallurgy. The presence of physical or compositional defects may severely affect the service life of the fabrication. Root defects, e.g. lack of fusion, can be particularly dangerous if they form a crevice.</p> <p>The design of the weld preparation has a role in</p>

Control Point	Good Practice	Potential Problems and Comments
	<p>the root region.</p> <p>There should be no simple square butt joints, partial penetration joints or fillet joints used in stainless steel systems as these will leave a crevice accessible on the inside surface.</p>	<p>determining the amount of dilution, though other factors such as economics and process requirements may take precedence.</p>
4. Choice of Filler Materials	<p>Filler metal should always be used and autogenous welding is not acceptable.</p> <p>The filler metal should be the recommended one for the grade of stainless steel.</p> <p>The chemical composition of the weld root is inevitably affected by dilution from the base material and this portion of the weld is in contact with the potentially corrosive medium. There is no problem when a matching composition filler metal is used but modified composition or dissimilar filler metals require more care.</p>	<p>Autogenous welds show regions of lower corrosion resistance within the dendritic structure of the weld.</p> <p>It is a fundamental requirement that the weld metal should be at least as resistant to corrosion in service as the base material. If it is more resistant, then the possibility of intense localised attack in some environments, as the anode in galvanic corrosion, is removed.</p> <p>For example, it is necessary to maintain an elevated nickel content in duplex stainless steel weld metal to obtain a ferrite-austenite balance within specification limits and therefore dilution should be kept to no more than 30%.</p>
5. Heat Input Levels	<p>The heat input has to be balanced to ensure it is high enough to give good weld pool fluidity and achieve good fusion with the base metal, but kept as low as practical to minimise metallurgical changes in the heat affected zone.</p> <p>Repair welding should be limited to single repairs</p>	<p>Thermal cycles within the heat affected zone may induce precipitation or phase changes that are deleterious to both mechanical and corrosion properties. Therefore, although economics demands that weld metal is deposited at as high rate as possible, heat input must be controlled to ensure that both weld metal and base metal have the required</p>

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	<p>for most stainless steels.</p> <p>Special stainless steels such as duplex stainless steels have particular heat input limitations:</p> <table border="1" data-bbox="568 451 1301 627"> <thead> <tr> <th></th> <th>Heat Input kJ/mm</th> <th>Max Interpass Temp. °C</th> </tr> </thead> <tbody> <tr> <td>Duplex</td> <td>up to 2.5</td> <td>250</td> </tr> <tr> <td>Super duplex</td> <td>up to 1.5</td> <td>150</td> </tr> </tbody> </table> <p>The arc energy of the second pass in duplex stainless steels should be about 80% of the root pass while the arc energy of subsequent passes may be higher, up to 130% of the root pass.</p>		Heat Input kJ/mm	Max Interpass Temp. °C	Duplex	up to 2.5	250	Super duplex	up to 1.5	150	<p>properties.</p> <p>Even stabilised stainless steels and L-grade materials may precipitate chromium carbides in the heat affected zone causing sensitisation and loss of corrosion resistance if exposed to repeated cycles of high heat input. Heat input per pass should therefore not be excessive and repair welding operations should be limited with no re-repairing.</p>
	Heat Input kJ/mm	Max Interpass Temp. °C									
Duplex	up to 2.5	250									
Super duplex	up to 1.5	150									
6. Gas Purging	<p>An environment low in oxygen must be formed before welding commences and maintained by a continuous flow of inert gas during insertion of the root run and subsequently until at least 5mm of weld metal (usually 1 or 2 runs after the root run) have been deposited.</p> <p>Inert gases, typically argon (lowest cost) or argon-helium mixtures, are normally used for purging. The oxygen content is measured and welding is not commenced until it is below a level, e.g. 500 ppm, specified according to the degree of oxidation that can be accepted in the completed joint.</p>	<p>There are many examples of systems where corrosion failures have initiated on the heat-affected zone of stainless steel systems where a heavier oxide film is present. The importance of backing gas shield cannot be overestimated.</p> <p>It is not always recognised that internal oxidation can occur when welds are made on the outside of a pipe or vessel, for example fillet welds for attachment of supports. This can only be avoided by a rigorous purging procedure similar to that used for pipe joints. This is not a trivial matter as it may require careful</p>									

Control Point	Good Practice	Potential Problems and Comments
	Piping requires internal purging to the same standards if welds are made externally, e.g. for piping supports.	design planning of closure welds in piping runs to allow adequate access to set up internal dams etc.
7. Treatments after Welding	<p>Purging with an inert backing gas is the main defence against failures due to heat tint in stainless steels, while removal of slag and mechanical cleaning is a general requirement for all accessible welds.</p> <p>Where welds are accessible excessive heat tint can be removed by pickling and passivating the surface using standard products. Surfaces should be fully rinsed with clean water to ensure removal of any residual acids on the surface.</p>	<p>It is normally impracticable to remove any heat tint that is formed within pipe spools but welds within vessels may be accessible. In particular piping systems it may be possible to circulate a pickling solution through the piping. Whilst expensive, it could be cheaper than breaking into spools.</p> <p>In tests on super duplex stainless steel samples, pickling in a nitric/hydrofluoric acid mixture produced a substantial increase in critical pitting temperature.</p>
8. Quality Control Checks	Where there is access to the weld root, quality can be checked by visual inspection (to check the acceptance with respect to heat tint discolouration) and non-destructive testing (to ensure full root fusion).	<p>In terms of corrosion resistance evaluation of welds, the only QC check which is practically suitable is visual examination of the weld quality and extent of heat tint around the weld.</p> <p>Acceptance standards should have been established during welding procedure development and qualification.</p> <p>NDT to check for any lack of penetration or lack of root fusion are part of normal inspection requirements, but particularly critical for stainless steels where crevice corrosion may initiate at root defects.</p>

Control Point	Good Practice	Potential Problems and Comments
9. Construction Practice	<p>Installation of completed piping spools should maintain all previous quality requirements:</p> <ul style="list-style-type: none"> <li>• Stainless steel should be kept clean and dry</li> <li>• Materials should not be mixed up or incorrectly substituted because of pressure of time etc.</li> </ul> <p>Closure welds which cannot be internally purged should be avoided and replaced with flanged connections where possible.</p> <p>Welding of external pipe supports etc to the outside of piping spools should be avoided.</p> <p>If strictly required, with no design alternative option available, the internal surface of the pipe must be inert gas purged.</p>	<p>Every effort has to be made to prevent poor practice occurring during installation when pressures can be very high. It only takes one poor weld or crevice to cause a leak but the consequences of the single failure may result in major re-investigations of all other welds etc.</p>
10. Commissioning	<p>Hydrotesting of stainless steel piping systems should be carried out with potable water with a chloride content less than 200 ppm.</p> <p>If the water temperature is expected to exceed 30 °C because of solar warming etc. the water should be treated with an oxygen scavenger, such as sodium bisulphite, to remove any oxygen present.</p> <p>Where the potable water will remain in the pipe for more than 3 weeks, or will be recycled and re-used, it should be treated with a biocide such as glutaraldehyde at <math>\geq 250</math>ppm concentration to provide sterile conditions.</p>	<p>Potable water is not normally corrosive to stainless steels in flowing conditions. With a low chloride content there is little risk of pit initiation at low ambient temperature conditions.</p> <p>At higher temperatures there is more of a risk of pitting initiating, particularly if piping runs are partially filled with water and left stagnant for long periods. The drying out zone, or puddles in the system, may become more concentrated in chloride content than the original water source.</p> <p>Potable water is very low in bacteria and also in nutrients</p>

Control Point	Good Practice	Potential Problems and Comments
	<p>Any chemical dosing of water with oxygen scavenger and/or biocide should be rigorously checked to ensure that concentrations are correctly achieved.</p>	<p>for the bacteria. However, within the piping spools there may be nutrient sources, such as dissolved dams used for back-purging. These are sufficient to allow bacteria to multiply from low levels to significant levels. Bacteria form biofilms on the surface of the stainless steels and this affects the potential of the steel, raising it into a range at which pitting can initiate.</p> <p>Inadequately chemically dosed water is unable to prevent corrosion.</p>
<p>11. Performance Service</p>	<p>in Where the stainless steel has been correctly selected for service it should be totally inert to corrosion in service environment and therefore it is important that the stainless steels should be brought into service as soon as possible. Any delays only increase the risk of exposure of the stainless steel to conditions in which it is not fully corrosion resistant.</p> <p>Environmental conditions should be monitored to ensure that they are maintained within the original design tolerance range. Shifts outside of the original design conditions require checking to ensure that the material is still resistant.</p>	<p>Changes in the service conditions which may initiate corrosion in stainless steel piping may include the following:</p> <ol style="list-style-type: none"> <li>1. Increase in the temperature to a range which stainless steel is no longer corrosion resistant.</li> <li>2. Changes in the environment composition resulting in an increase in the level of hydrogen sulphide into a range that the selected stainless steel is no longer resistant to corrosion.</li> <li>3. Increases in the concentration of chloride ions in the environment to a range at which the stainless steel is no longer corrosion resistant.</li> <li>4. Deposition of solids particularly where these are rich in chloride ions, can result in local conditions which the stainless steel is not able to remain corrosion resistant.</li> </ol>
<p>12. Protection during plant shutdown</p>	<p>Piping runs which are known to be free of liquid and gases should be filled with nitrogen after depressurising to prevent ingress.</p>	<p>If the piping is opened to air and it contains any water with chlorides in it then there is a major risk of initiating pitting at any point on the piping and particularly at any welds.</p>

Control Point	Good Practice	Potential Problems and Comments
	<p>Piping runs which may contain solids or residual liquids should be flushed out with fresh water and then nitrogen blanketed.</p> <p>If it is possible to be confident that a particular piping run has been cleaned and is totally dry, because it has been drained out, that section could be left open to air without nitrogen blanketing.</p>	<p>Producing systems tend to have chlorides present and these may become locally more concentrated if opened to air so that the liquid phase evaporates. Hence, it is necessary to first wash out any liquids and deposits. If totally dry conditions can then be guaranteed, the piping could be left open to air, but if there is any doubt, then the system should remain sealed and filled with nitrogen to keep the partial pressure of oxygen low or zero.</p>
13. External Protection	<p>Stainless steel piping should not be exposed without protection to marine atmospheres and salt water spray (typical of offshore installations). The most critical installations are those which require thermal insulation as the material used may soak up water. Other critical design points can be piping supports or any straps around the pipes which may act as crevices, trapping water close to the pipe surface.</p> <p>Optimum long term external protection is thermally sprayed aluminium (TSA) coating which is suitable for externally protecting stainless steel both in the insulated and non-insulated condition. TSA is an essential coating for any stainless steel which will be insulated.</p> <p>For non-insulated piping a very high specification paint coating (selected to meet the operating temperature requirement) may be adequate, but maintenance should be of the highest standard to ensure full protection.</p>	<p>The 300 series austenitic stainless steels may suffer from external pitting corrosion or stress corrosion cracking if they are operating at elevated temperatures in a marine environment.</p> <p>Alternatively, cracking resistant materials such as duplex stainless steel may be selected but at higher capital cost.</p>