

CORROSION DAMAGE ANALYSIS OF DRINKING WATER PIPING

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Abstract

The article describes the corrosion attack and premature damage in stainless steel drinking water piping installed in a hospital. After only two years of service, intensive pitting and crevice corrosion was observed near welded joints, resulting in wall perforation. The analyses made on damaged tubes revealed that corrosion attack started in the root parts of weldments due to welding defects, mainly incomplete root penetration, lack of fusion, and inadequate weld root shielding. Such defects formed narrow crevices in which a restricted exchange of ions and electric charge with the environment caused fast and extensive corrosion damage. The presence of chlorine dioxide, used for water disinfection, also played a significant role in the initiation of corrosion, as chlorine or chloride ions disrupt the protective oxidic film on the metal surface and facilitate the penetration of oxygen.

Keywords: Water piping, welding defects, pitting and crevice corrosion, austenitic stainless steel, water disinfection, chlorine dioxide

1. INTRODUCTION

Due to the excellent mechanical, corrosion and hygienic properties, most pipelines and technological elements in water treatment plants and reservoirs are made of corrosion-resistant steels. Experience has shown that a significant portion of the corrosion problems that occur in water treatment plants are not caused by the choice of material but by its improper processing, in many cases welding. While the base material usually commonly demonstrates excellent corrosion resistance, different situation can be often observed in weld joints. Welding defects, namely defects in the root of the weld, like incomplete root penetration, shrinkage grooves, misalignments and lack of fusion, as well as insufficient weld root protection by inert gas, negatively affect their service life and reliability. In the case of welding pipes and other parts which cannot be properly cleaned, demineralised and passivated from the inside. High quality of welds is necessary especially when welding pipes and other parts that cannot be properly cleaned and passivated on the inner side. The selective corrosion attack of these weakened weld root areas by pitting and/or crevice corrosion then crucially affects the reliability of the whole structure.

Pitting corrosion starts by pit initiation on the surface of the metal by the electrochemical action of aggressive ions such as chlorides, sulphates, thiosulfates, etc., see **Figure 1**. Although pit formation is a random process, it starts at specific regions, sites or flaws in the protective oxide layer. Once a pit nucleates, its propagation then proceeds autocatalytically. Chlorides are most commonly responsible for pit formation on stainless steels as they locally disrupt the passive oxide film. Inside the pit, the metal dissolves allowing chloride ions to migrate to the positive charge in the pit. The resultant metal chloride hydrolyses, forming an insoluble hydroxide (Fe(OH)₂) and hydrochloric acid. Outside the pit, oxygen reacts to hydroxide. While pitting corrosion initiates randomly on small defects of the passivated surface, the formation of crevice corrosion is geometrically conditioned by the existence of a narrow crevice, which limit ionic interaction with the electrolyte outside the crevice. Thus, the oxygen inside the crevice will be consumed due to the absence of flow. The dissolution

process of metal, however, continues inside the crevice. This results in a positively charged solution through which chloride ions migrate into the crevice to form iron chloride [1-3].

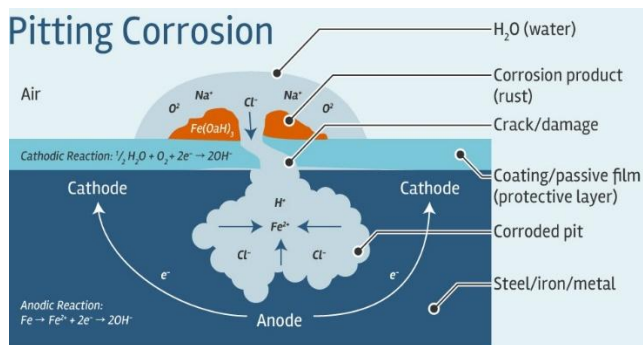


Figure 1 Scheme of pitting corrosion attack [1]

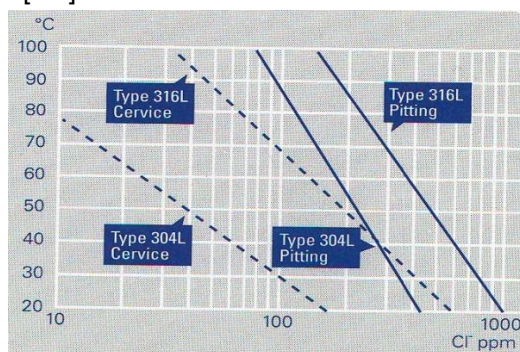


Figure 2 Areas of pitting and crevice corrosion in AISI 304L and AISI 316L steels [4]

Even steels that are otherwise stated as corrosion-resistant can suffer to crevice and/or pitting corrosion, especially in environments where chlorine or chlorides are present. It is reported that in crevices, chlorides, together with the reduced pH, initiate corrosion mostly by locally accelerating the electrochemical reaction. In water with pH 6.5-8.0, crevice corrosion is rare in AISI 304/304L steel when the water contains up to 200 mg/l chloride or when the free chlorine concentration is less than 2 mg/l. AISI 316/316L stainless steel can then be exposed to chlorides up to 600 mg/l or if the free chlorine concentration is less than 4 mg/l, see **Figure 2** [4]. It is also clear from this figure that the resistance of these steels to both types of localised corrosion attack decreases strongly with increasing temperature, but still AISI 316L steel can tolerate at least twice as high chlorine or chloride concentration as AISI 304L steel.

In the present paper the attention will be paid to the corrosion damage of water piping made of austenitic stainless steel and installed in a hospital. The water was extra disinfected by adding of chlorine dioxide (ClO₂) in order to minimize the risk of namely Legionella and methicillin-resistant Staphylococcus aureus (MRSA) infection.

2. EXPERIMENTAL MATERIAL

Intensive pitting and crevice corrosion was revealed in a hospital water pipeline made of pipes ø 114.3 mm x 2 mm (branch A) and ø 88.9 mm x 2 mm (branch B) made of steel AISI 316L (1.4404) after only two years of service. Several wall perforations were detected near weld joints, resulting in water leakage. The pipes were made as longitudinally welded by laser welding and on-field transverse welds were made by GTAW welding technique without preheating and post weld heat treatment with matching wire of AISI 316LSi type. Welds were then mechanically cleaned on the outer side of piping.

3. RESULTS OF MATERIAL ANALYSES

Samples delivered for analysis were cut around the damaged welds in both branches of the piping. At first glance, the appearance and surface finish of pipes from branch A differ from those in branch B. Samples forming branch A had a matte finish on both surfaces and were probably originally supplied in a pickled or sandblasted state, while pipes in branch B were shiny and polished. Besides the corroded ring around cross welds inside and outside there was also heavy attack of welds around nozzles and even numerous small corrosion spots were found around the whole inner pipe circumference in branch A, see **Figure 3**. The extent of corrosion of pipes in branch B was much less than in branch A, corrosion products were only found locally around the cross welds on the inner surface of the pipe, see **Figure 4**. Absolutely no corrosion attack was

detected around the longitudinal laser in-shop welds, **Figure 5**, on the other hand, relatively large internal defects (corrosion pits) were found even under the apparently flawless weld surface, see **Figure 6**.



Figure 3 Corrosion attack of cross welds, fillet weld of nozzles and inner surface of a pipe in branch A

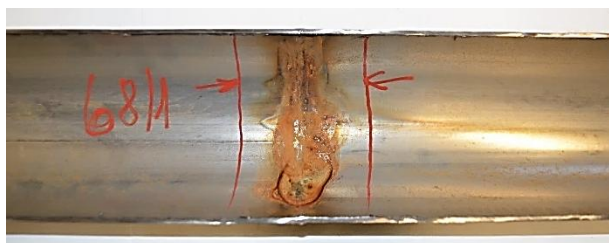


Figure 4 Corrosion of cross welds in a pipe in branch B

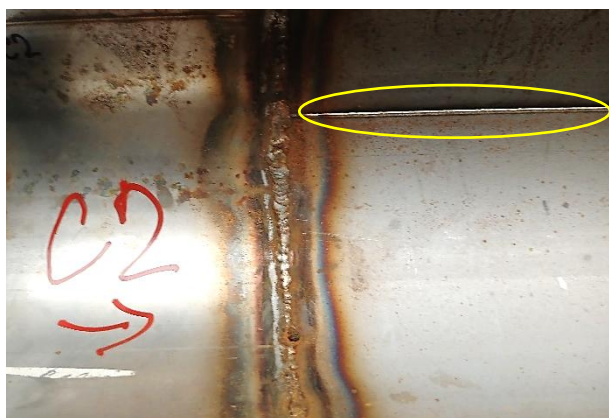


Figure 5 Clean surface around longitudinal in-shop laser weld, pipe in branch A

Figure 6 Corrosion pits inside the weld metal, pipe in branch B

The analysis of chemical composition of pipes from both branches revealed missing alloying by molybdenum, lower content of nickel and unexpectedly high concentration of vanadium in pipe from branch A compared to the nominal composition of steel AISI 316L [5] as well as to the pipe from branch B. The material of pipe A thus does not match the steel grade AISI 316L, but it is the steel grade AISI 304.

Table 1 Chemical composition of pipes from branch A and B (wt%)

| Branch | C | Mn | Si | P | S | Cr | Ni | Mo | Cu | V | Ti | Nb | W | Co |
|-----------|---------------|-------|-------|---------------|---------------|-----------|-----------|---------|------|------|-------|--------|-------|------|
| A | 0.038 | 1.73 | 0.33 | 0.032 | 0.001 | 18.08 | 8.01 | 0.25 | 0.34 | 0.08 | <0005 | <0.003 | 0.019 | 0.20 |
| B | 0.027 | 1.48 | 0.36 | 0.023 | 0.002 | 17.92 | 12.01 | 2.14 | 0.35 | 0.04 | <0005 | <0.003 | 0.026 | 0.15 |
| AISI 316L | max. 0.030 | ≤2.00 | ≤1.00 | max. 0.040 | max. 0.015 | 16.5-18.5 | 10.0-13.0 | 2.0-2.5 | - | - | - | - | - | - |

The detailed visual analysis performed on optical-digital microscope Keyence VHX 5000 revealed the details of damage concentrated mainly in the root of the welds. Besides lack of fusion in the root there were detected other welding defects like linear misalignment, shrinkage grooves, spatter on the inner surface and temper colour (oxide bands around welds indicating insufficient weld root protection by inert gas), see **Figures 7, 8**.



Figure 7 Lack of fusion in the weld root and corrosion spot indicating attack of weld metal, pipe in branch B



Figure 8 Linear misalignment forming a crevice and spatter on inner surface of pipe in branch A

Samples for the analysis of microstructure were prepared using a standard grinding, polishing and final etching in V2A etchant for stainless steels. The first sample was prepared from the heavily corroded area close to the nozzle in the branch A, **Figure 9** and **10**, and shows in detail the difference between extensive attack of the pipe (including weld metal) and very limited corrosion damage of the nozzle that was made of AISI 316L. Regardless of whether it is base material or weld metal, corrosion pits penetrated through the entire thickness of the pipe wall in branch A. While in branch A practically all the pipe circumference was corroded, the completely different was the situation in branch B, where corrosion was restricted just around the weld joints, pitting started either just in the fusion line or at the end of heat affected zone (HAZ), see **Figures 11** and **12**.

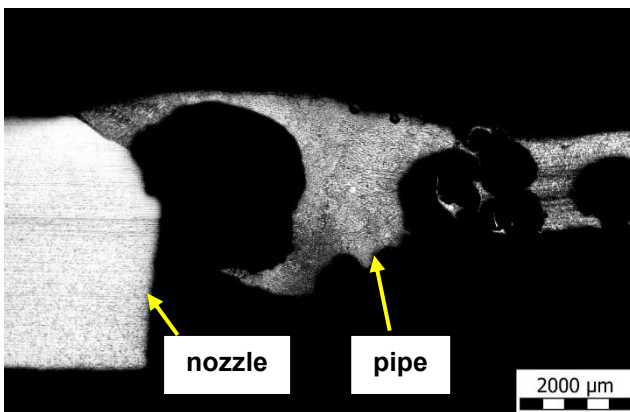


Figure 9 Different intensity of corrosion attack on the pipe and the nozzle, pipe in branch A

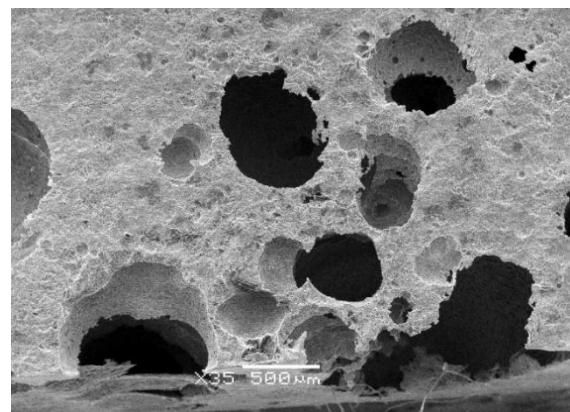


Figure 10 Corrosion pits penetrating through the whole pipe wall in branch A (SE, SEM)

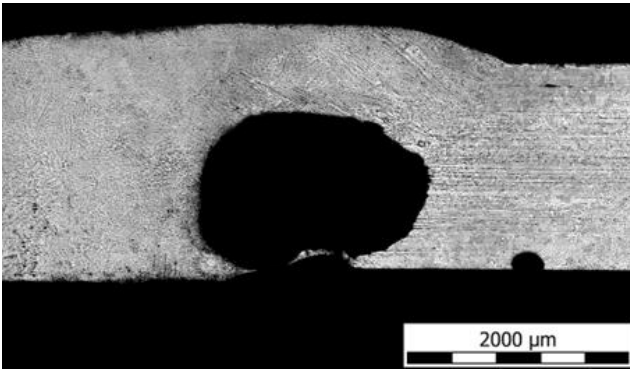


Figure 11 Pitting corrosion starting in the fusion line and small pit at the end of HAZ, pipe in branch B

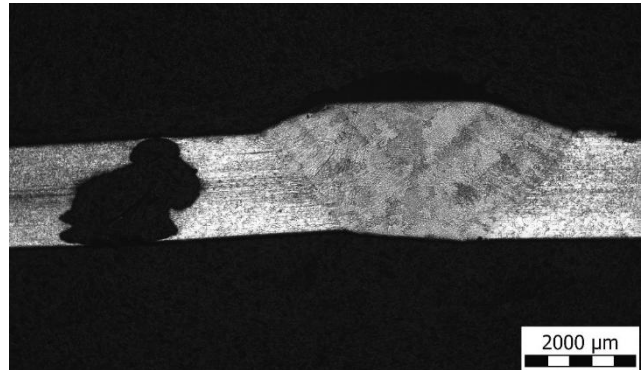
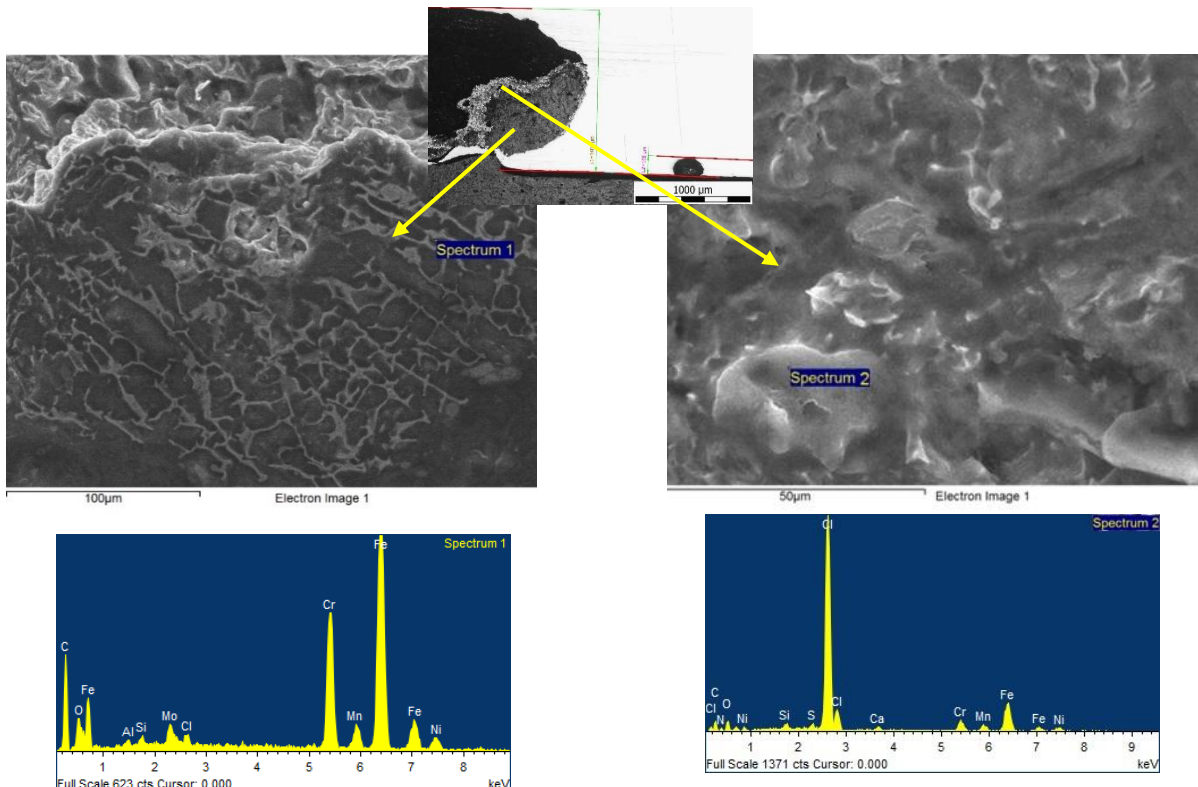


Figure 12 Pitting corrosion attack starting at the end of HAZ, pipe in branch B

On the edge and inside the large corrosion pit shown in **Figure 10** there was an area with corrosion products that were analyzed by EDX microanalysis. The results of this analysis are shown in **Figure 13**. Apart from the absolute dominance of the carbon content, the analysis on the left side of the figure is one that was apparently carried out on the residues of the corroded matrix from which the corrosion products were washed away (high concentrations of Fe, Cr, presence of both Ni and Mo), the results on the right side of the figure represent most probably corrosion products with high concentrations of chlorine, oxygen, but also nitrogen and a complex of other elements including sulfur and calcium.



| Spectrum | C | Fe | Cr | O | Mo | Ni | Mn | Cl | Al | Si | N | S | Ca |
|----------|------|------|------|------|-----|-----|-----|------|-----|-----|------|-----|-----|
| 1 (wt%) | 41.1 | 32.7 | 12.7 | 6.8 | 2.3 | 2.3 | 0.8 | 0.6 | 0.4 | 0.3 | - | - | |
| 2 (wt%) | 30.4 | 9.2 | 2.4 | 12.4 | - | 1.4 | 1.3 | 25.4 | - | 0.5 | 16.1 | 0.4 | 0.5 |

Figure 13 Analyzed areas and results of EDX microanalysis inside the corrosion pit, pipe in branch B

4. DISCUSSION

It is well-known that the decisive role in pitting corrosion resistance has molybdenum content: by stabilizing the passive film, formation of molybdate ion (MoO_4^{2-}), which effectively blocks the adsorption of chloride ion, or raising the pitting potential of materials [6,7]. Many years of experience have proven the suitability of using AISI 316L steel for drinking water pipelines, even under conditions where additional disinfection with chlorine-based substances is carried out as in this case. The hygiene limit of chlorine dioxide concentration in drinking and hot water is 0.8 mg/l, which is guaranteed in the presented case by adding around 2 mg/l of ClO_2 at the base of the water pipeline. In cold slightly chlorinated (<1mg/l) water with a pH of 6.5-8.0, general corrosion attack is rare in steel AISI 316(L) up to 600 mg/l of chlorides or if the free chlorine concentration is less than 4 mg/l [4]. Although the resistance of this steel decreases strongly with increasing temperature, the limit is still much higher than the amount of ClO_2 used. But in welding defects (like in the weld root) the concentration of chlorine/chlorides can locally increase and overcome the potential limit for pitting/crevice corrosion. The steel AISI 316L itself has adequate corrosion resistance, which has been proven by the fact that damaged area in pipes was limited to the weldments and the nearest surroundings limited both to HAZ and oxide bands resulting from insufficient weld root shielding, The absence of molybdenum in branch A was then destructive and the corrosion products adhering to the pipe wall made it easier to attack it even far outside the weld area.

5. CONCLUSION

The analyses of the damaged welds on the cold drinking water pipes confirmed that the perforation of the pipe wall was due to crevice and pitting corrosion initiated on the inner surface of the pipes at and in the close vicinity of the weld joints. The fact that chlorine dioxide is added to the water was not in itself decisive for the damage, the main cause was the many weld defects (lack of fusion, linear misalignment, insufficient weld root shielding). On the basis of the findings, it was recommended to replace all parts of the pipeline made of AISI 304 steel and those made of AISI 316L where corrosion has spread outside the weld area. In the other welds with only local corrosion attack around welds, cut off approximately 10 cm of pipe from each side of the weld and then join the pipes by mechanical couplings, not by welding.

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