CEOCOR 7th International Congress of Corrosion Protection
May 30 - June 2, 2006. Mondorf-les Baines, Luxembourg

Corrosion resistance of stainless steel pipes in soil – Three years testing in Swedish marine clay

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ABSTRACT

Four stainless steel grades were exposed in soil during three years for testing of their corrosion resistance and suitability as pipe material from the corrosion point of view. The exposure site was one of the Swedish Corrosion and Metals Research Institutes test sites in soil, near the sea shore at the Swedish West Coast (Gothenburg). The soil type is marine clay with extremely high chloride content and high content of organic matters. Earlier long-term testing of carbon steel, galvanized steel and non-ferrous metals has shown this site to be very corrosive.

The tested steel grades are ASTM 316/EN 1.4436 (17Cr/11Ni/2,7Mo), ASTM S31254/1.4547 (20Cr/18Ni/6,1Mo), ASTM S32304/EN 1.4362 (23Cr/4,3Ni/0,3Mo) and ASTM S31803/EN 1.4462 (22Cr/5,5Ni/3Mo). The test specimens consist of two meter long pipes and plates. Before burial a rubber sleeve was put at both ends on some of the pipes as a crevice former. The specimens were placed in different positions in the test pit: some directly in the original clay soil of the site and some embedded in sand. Between 20 and 24 specimens from each steel grade were buried. In total 91 specimens were included in the exposure programme.

After the three-year exposure period corrosion attacks, both pitting corrosion and crevice corrosion, were found on 3 of totally 24 exposed specimens of steel grade ASTM S32304/EN 1.4362. No corrosion attacks were found on specimens of the three steel grades ASTM 316/EN 1.4436, ASTM S31254/1.4547 and ASTM S31803/EN 1.4462.

In the paper the suitability of using the different tested steel grades as pipe material in soil is discussed. The importance of comparatively high molybdenum content for the corrosion resistance of stainless steels in soil, which was observed in this investigation, is in accordance with results in other field investigations in Sweden.

INTRODUCTION AND BACKGROUND

In Sweden stainless steel pipes are used since long for underground applications at a certain extent. They are used as pipelines for i.e. municipal water distribution, air fuel at airports, liquid propane gas and fire extinguish water at industrial sites and for motor gas at petrol stations. As pipe material various stainless steel grades have been used during the years. During recent years, however, a number of pipe leaks caused by corrosion and penetration through the pipe wall has been reported. It is believed that the corrosion damage in most cases is a result of improper choice of steel grade for the pipe material in the actual soil environment. In some cases, however, the corrosion damage was caused by electrical influence due to the presence of stray currents in the ground.

In order to find out which stainless steel grades that are suitable, from the corrosion point of view, for buried stainless steel pipes a field exposure programme was started in 1999 by the Swedish Water Works Association, Avesta Sheffield Stainless Steel (now Outokumpu Stainless Sweden), Avesta Sandvik Tube and the Swedish Corrosion Institute (now the Swedish Corrosion and Metals Research Institute). In the programme four stainless steel grades were buried at two locations in Sweden, one with a highly corrosive soil and the other with low-corrosivity soil.

Later this Swedish programme was incorporated in an expanded international research program concerning the corrosion resistance of stainless steel pipes in soil, which was started in 2002 and which is partially financed by the European Coal and Steel Community (ref.1).

In 2002, three years after the burial, a first set of specimens from the earlier Swedish field exposure programme were taken up from the ground at the highly corrosive test site (site Gothenburg) and evaluated with respect to corrosion attacks. The result of this part of the field investigation is reported in this paper.

WHAT IS STAINLESS STEEL ?

Stainless steel could be looked upon as ordinary carbon steel, to which has been added one or more alloying metals in certain proportions. These alloying elements “produces” a very dense and thin (only some nano-meters thick) oxide layer on the steel surface when the steel later comes in contact with humid air, after the production in the steel works. This oxide layer protects the steel effectively against corrosion, and it is immediately self-healing in humid environments if it has been damaged mechanically. It consists mainly of chromium-oxide, and that is why chromium (Cr) is the main alloying element in stainless steels. The chromium content of the steel must be at least 11-12 mass- % for the oxide layer to receive the intended properties. If the chromium content is lower than 11 mass- %, it is no longer a stainless steel.

Further alloying elements, which often are added to stainless steels, are nickel (Ni) and molybdenum (Mo). Nickel is improving both the corrosion resistance and the weldability of the steel. Molybdenum has already at low concentrations a very large improving effect on the passivating and protecting effect of the oxide layer, and thereby it contributes in a large extent to the steels’ resistance against pitting corrosion and crevice corrosion. In some types of stainless steel, also titanium (Ti), copper (Cu) and nitrogen (N) are added as alloying elements e.g. to improve the corrosion resistance. The carbon (C) content is always low in stainless steels, today usually 0,05 % or lower, with the exception of martensitic stainless steels, in which the carbon content is higher. Phosphorus (P) and sulphur (S) are contaminating elements, whose content always is being kept low.

The alloying elements and their internal proportions determine a number of properties of the steel, and thereby also its applicability in various types of constructions and environments. This concerns above all the mechanical strength, ductility, weldability, high temperature resistance and certainly its corrosion resistance.

Thus, there is not only one single stainless steel, but instead a large number of these steels, all having different material properties including different degree of corrosion resistance. Almost all stainless steels are standardised, both on national and international level.

CORROSION TYPES AND CORROSION APPEARANCES ON STAINLESS STEEL PIPES IN SOIL

The types of corrosion, which may appear on stainless steels in soil, are:

- ***Pitting corrosion:*** Clearly defined pits, either separated far from each other or gathered in a group close to each other.
- ***Crevice corrosion:*** Clearly defined attacked area. Usually larger area corroded compared to the area corroded in pitting corrosion. .
- ***Corrosion at welds:*** Localised corrosion attacks, usually as pitting corrosion, in or very close to welds.
- ***Stress corrosion cracking:*** Cracks in the steel. Two types are distinguished: a) Inter-crystalline cracking and b)Trans-crystalline cracking

Characteristic for the corrosion of stainless steel in soil is that it appears as local and concentrated attacks. On stainless steels with low or no nickel and molybdenum content, the attack may, however, be more widespread over larger areas. Uniform (general) corrosion does not appear on stainless steels in soil. Further, when an attack well has started it grows deeper at a higher speed compared to what it does on "ordinary" steel in soil.

Pitting corrosion takes place spontaneously wherever on the steel surface. It is above all caused by the presence of chloride ions in the corrosion media. The higher the chloride content, the higher is the risk for pitting corrosion. Characteristic is that pitting corrosion caused by high chloride content starts quite soon after the burial of the pipe in soil. Recently, pitting corrosion caused by a complicated oxidation/reduction cell in the presence of sulphides in sea bottom sediments has been discussed.

Crevice corrosion is a type of oxygen concentration cell and it appears in narrow, water filled crevices, such as in socket pipe joints with rubber tightening rings, in screw threads, underneath tapes on stainless steel surfaces et cetera. The environment inside the crevice is poor in oxygen and the steel surface there becomes anodic and corrodes. The supporting cathodic process is taking place outside the crevice mouth. Such crevices may also occur on a pipe surface in fine-grained and "sticky" soils, e.g. wet clay soil, where the soil easily is irregularly packed towards the steel surface. Crevice corrosion is, as pitting corrosion, strongly stimulated by the presence of chloride ions.

Corrosion at installation welds. This type of corrosion occurs as a result of improper welding procedure and/or improper removal of the oxides, which occur during the welding. These oxides have a disadvantageous effect on the corrosion resistance of the welded surface region. This type of corrosion appears mostly at installation welds produced in the field e.g. to join pipe sections at site, mainly because it is difficult to perform a proper weld outdoors. It occurs very seldom on factory welds, which are produced under strictly controlled conditions.

Stress corrosion cracking only appears at considerable increased temperature, 50-60 ^{0}C. In soil, which normally has a low temperature, stress corrosion cracking may occur on a stainless steel pipeline, which is transporting a liquid with high temperature, e.g. process water, and where the pipe is exposed to mechanical stresses above a certain limit.

Countermeasures against corrosion in soil: All these types of corrosion can be avoided by choosing a proper (medium or highly alloyed) stainless steel grade for the pipe manufacturing, which is suitable in the actual soil environment. Corrosion in installation welds is avoided by proper welding procedure according to the recommendations from the steel producer.

EXPERIMENTAL

The exposure programme

The exposure programme consists of two parallel test series; i.e. there are two identical groups of test specimens which were buried in two separate test pits at the Gothenburg test site. This made it possible to withdraw specimens at two separate occasions. Here the results of the first withdrawal are reported.

Tested stainless steels

As already mentioned, four stainless steel grades were tested. They are: ASTM 316/EN 1.4436 (17Cr/11Ni/2,7Mo), ASTM S31254/1.4547 (20Cr/18Ni/6,1Mo), ASTM S32304/EN 1.4362 (23Cr/4,3Ni/0,3Mo) and ASTM S31803/EN 1.4462 (22Cr/5,5Ni/3Mo). The nominal/standard recommended composition is given within brackets. The actual heat analyses for the exposed steels are given in **table 1**.

Test site and soil analysis

The test site, which is being used for this investigation, is one of the Swedish Corrosion Institutes test sites that are used for long-term exposures of ferrous, non-ferrous and polymer materials in soil. It is known from more than 20 years of testing of these materials that the "nominal" soil corrosivity is very high, mainly because of the very high chloride content in the marine clay.

The test site is situated near the seashore at the Swedish West Coast just outside Gothenburg. The soil type is marine clay with extremely high chloride content. There are no electrical installations (neither d.c. nor a.c.) in the neighbourhood that could cause stray current corrosion.

The soil character at the site can be summarized as follows:
– Poor soil aeration – reducing environment (ground constituted sea bottom previously)
– High ground water level (approx. 1 m below ground surface)
– Low pH near ground surface - neutral pH deeper down
– Very high chloride content
– High content of organic matter
– Low sulphide content near ground surface – high sulphide content deeper down
– Low calcium carbonate content
– Presence of aggressive soil bacteria (sulphate reducing bacteria, SRB)
– Very low soil resistivity

The analysed chemical composition of the soil and some measured physical soil properties are shown in **table 2**. The corrosion properties of the soil at this site have been discussed in earlier publications (ref. 2 - 8).

Test specimens and positioning of specimens in the ground

The test specimens consist of 2 m long pipes and plates. The pipe diameter varies between approx. 60 and 75 mm, depending on the steel grade tested. The width of the plates is 100 mm and the thickness is 1,5 mm. See **figure 1** and **2**. The hot rolled steel sheets, intended for the test material, were finalized in the steel works by pickling and cold rolling. The pipes were produced with a longitudinal weld.

Table 1. Stainless steel grades and their composition, which were tested in soil by the Swedish Corrosion Institute. (ASTM = American Society for Testing and Materials, EN = European Standard, SS = Swedish Standard).

Materials				Chemical composition (heat analysis), mass %										
Standards			Type (micro structure)											
EN	ASTM	SS		C	Si	Mn	Fe	P	S	Cr	Ni	Mo	Cu	N
1.4436	316	2343	Austenitic	0,035	0,43	1,40	Bal	0,029	0,007	16,75	10,61	2,58	- -	- -
1.4547	S 31254	2378	Austenitic	0,011	0,34	0,73	Bal	0,020	0,001	20,09	17,89	6,08	0,66	0,201
1.4362	S 32304	2327	Duplex	0,017	0,47	1,53	Bal	0,026	0,001	22,78	4,87	0,30	0,34	0,088
1.4462	S 31803	2377	Duplex	0,015	0,34	1,52	Bal	0,020	0,001	21,85	5,80	3,00	- -	0,185

Table 2. Type of soil and chemical composition of the soil at the test site Gothenburg.

Depth of soil analysis m	Type of soil	Resistivity ohm·cm	Water content wt-% of wet soil	Organic content wt-% of dry soil	pH value	Carbonate $CaCO_3$ wt-% of dry soil	Chloride mg Cl^-/kg dry soil	Sulphur compounds mg S/kg dry soil		
								Sulphide S^{2-}- S	Sulphate SO_4^{2-}- S	Total sulphur
0.5-1,0	Marine clay	1 710	41	3,7	4,4	0,16	170	8	412	1 480
1.0-1.7	Marine clay	345	54	4,6	7,4	0,16	2 200	82	322	14 600

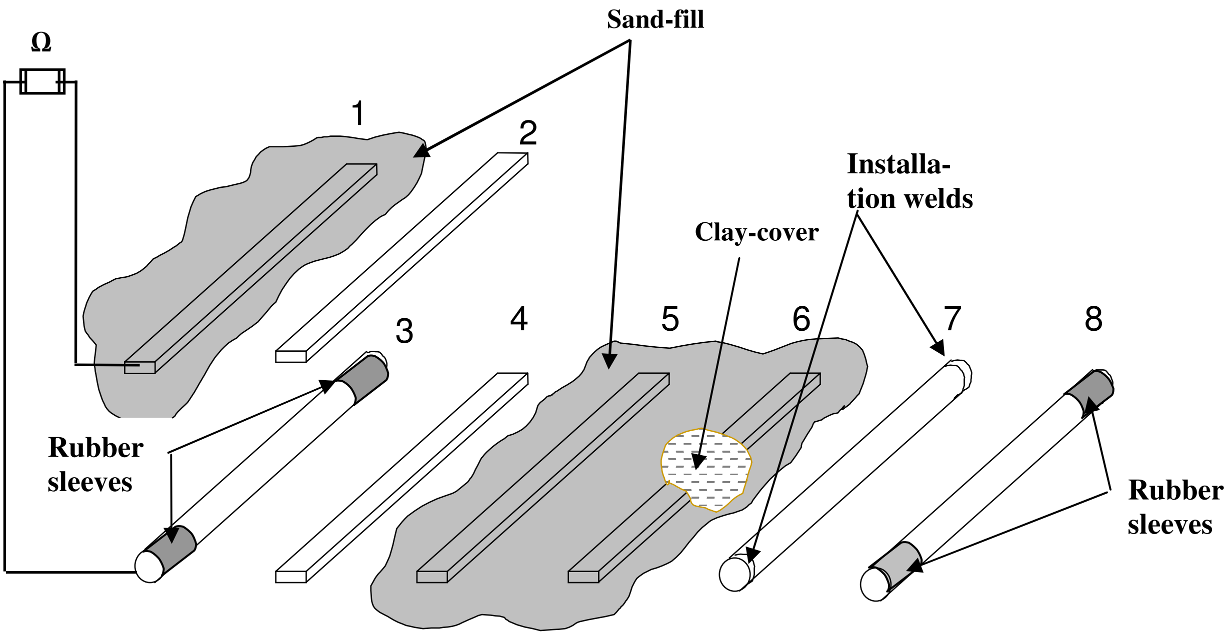

Figure 1. Positions of the test specimens in the soil at the test site Gothenburg (based on a figure from Usinor Industeel).

The specimens were placed in eight different positions in a test pit in the ground according to a special scheme, see **figure 1**. The scheme includes two test levels; one upper level at approx. 1 m below ground surface and a lower level at approx. 2 m below ground surface. Because of seasonal variations, the groundwater table fluctuates between the two test levels. In each position triplicate specimens were used. In all, 91 specimens were buried in one test pit. A complete matrix would have required a total of 96 specimens in each pit, but it was not possible to use triplicate specimens in all positions.

The specimens in position 1 and 3 were connected to each other by a test cable, which was led via a measurement cabinet placed above ground. The cable connection included a permanent low-ohmic resistance to be used for the shunt- measuring of cell corrosion currents. The purpose of this specimen arrangement was to allow recording of a corrosion current which possibly could flow in the corrosion cell, having a well aerated steel surface (upper specimen) and a non-aerated surface placed in an environment with high sulphide content (lower specimen). The specimens in position 1 were placed comparatively near the ground surface and embedded in sand fill in order to create, as far as possible, a good aeration of the steel surface. The specimens in position 3 were placed in the original clay soil of the test site. A rubber sleeve was put at both ends of the pipe in position 3 in order to produce a deliberate crevice on the steel surface. The point of this was to test the steels resistance against crevice corrosion.

The specimens in position 2 and 4 were placed in the original clay soil of the site but at different test levels. Specimens in position 5 and 6 were embedded in homogenous sand-fill at the lower test level and, further, the specimens in position 6 were partially covered by clay soil. By this arrangement the specimens in these two positions could be compared with each other with respect to corrosion. The aim was to test the effect of a homogeneous environment on the corrosion.

Specimens in position 7 and 8 were placed at the lower test level directly in the original clay soil of the site. On specimens in position 7, an installation weld was provided at both pipe ends, in order to simulate welds carried out in the field. Finally, a rubber sleeve was put at both ends of the pipe in position 8 in order to create a crevice on the steel surface. Further, a test cable was connected to some pipes for corrosion potential measurements.

RESULTS AND DISCUSSION

After the three years-exposure in the soil, the specimens were dug up and transported to the Swedish Corrosion Institute for cleaning the steel surfaces and evaluation of any corrosion attacks.

Lost test specimens

Two plate specimens were lost during the withdrawal of the specimens, and could not be evaluated with respect to corrosion attacks.

Corrosion potentials and cell corrosion currents

The results from the measurements of corrosion potentials and cell corrosion currents have not yet been fully interpreted, and can not be presented here.

Corrosion rates and the appearance of the corrosion

The corrosion was evaluated by visual inspection and by measurement of the maximal depth of each observed corrosion attack. The depth was measured using a needle-micrometer instrument with an accuracy of +/- 0,05 mm (+/-50 µm).

Corrosion attacks were found only on specimens of steel grade ASTM S32304/EN 1.4362 and only on three of the totally 23 exposed specimens. No corrosion was found on specimens of the other three steel grades: ASTM 316/EN 1.4436, ASTM S31254/1.4547 and ASTM S31803/EN 1.4462. The result of the evaluation is summarised in **table 3**.

Table 3. Results from the evaluation of the three years exposure of stainless steel specimens in soil at test site Gothenburg (marine clay soil). The depth is given as deepest measured single attack and the corrosion rate as calculated highest mean rate during the exposure period

Steel grade			Number of specimens with corrosion attack	Type of corrosion	Max corrosion depth	Max. penetration rate	Number of specimens without corrosion attack
EN	ASTM	SS					
1.4436	**316**	**2343**	**0**	**-**	**-**	**-**	**24**
1.4547	**S 31254**	**2378**	**0**	**-**	**-**	**-**	**23**
1.4362	**S 32304**	**2327**	**3**	**a) Crevice corrosion under rubber sleeve on two pipe specimens** **b) Pitting corrosion on open surface on one plate specimen**	**a) Crevice corrosion: 1 mm and 1,3 mm respectively** **b) Pitting corrosion: 0,1 mm**	**a) Crevice corrosion: 333 µm/year and 433 µm/year respectively** **b) Pitting corrosion: 33 µm/year**	**20**
1.4462	**S 31803**	**2376**	**0**	**-**	**-**	**-**	**22**

Deep crevice corrosion attacks were found under the rubber sleeves on two of the triplicate pipe specimens. The pipes had been exposed in position 3, i.e. buried directly in clay soil at the lower test level, and each being connected to a plate at the upper test level. The maximal depth of the crevice attack was 1,3 mm. See **figure 3.** It is possible that the anodic process within the crevice was enhanced during the exposure by a cathodic process outside the crevice, taking place not only on the specimen with the sleeve but also on the connected specimen in position 1, which was placed in the comparatively well aerated sand- fill.

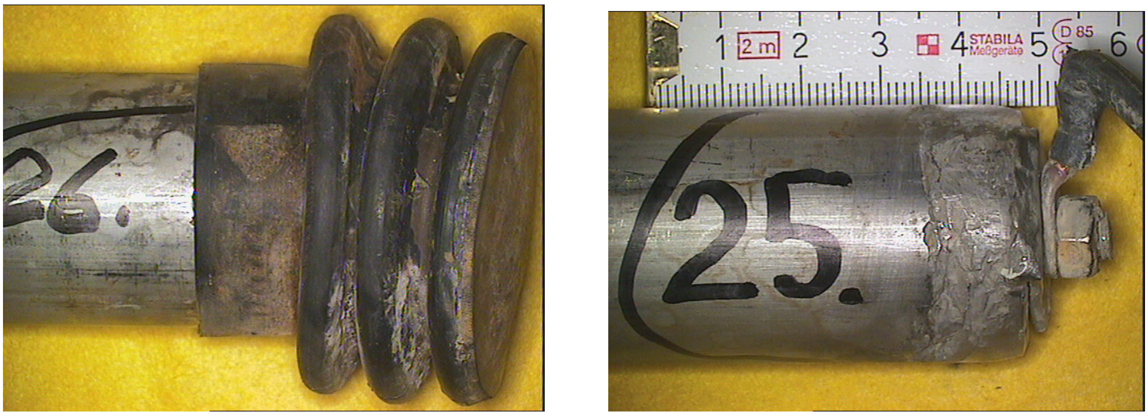

Figure 2. Test pipe of steel grade ASTM S32304/EN 1.4362 with intentional crevice under rubber sleeve. Left photo: before removal of the sleeve. Right photo: after removal – deep crevice corrosion attack (max. 1,3 mm) under sleeve.

Pitting corrosion was observed on one of the triplicate plate specimens. The plate had been exposed in position 2, i.e. buried directly in clay soil at the upper test level. The pits were concentrated in two groups in the middle of the plate and on the plate side which had faced downwards during the exposure period. The maximal depth of the pitting attack was 0,1 mm. See **figure 4**. It is striking that no corrosion attacks were found on specimens placed in position 4 (lower test level), which differs from position 2 (upper test level) only with respect to their depth below ground surface and their relation to the ground water table, that lays betweens these two positions.

The fact that the groundwater table constitutes an obstacle for the diffusion of oxygen downwards in the soil means that the rate of oxygen diffusion to the cathodic areas on the upper specimens has been higher, thus enhancing the cathodic reaction, compared to the situation on the specimens placed at the lower test level. This effect of the groundwater table on the corrosion has been observed on other metals (ref. 4-8).

Figure 3. Test plate of steel grade ASTM S32304/EN 1.4362 with pitting corrosion attack (max. depth 0,1 mm). Pits concentrated close to each other in two groups.

Effect of the molybdenum content of the steels

It is interesting to note that corrosion occurred only on the steel grade, which has very low molybdenum content and that no corrosion attacks occurred on the three steels with considerably higher molybdenum content. This observation strengthens the findings in earlier Swedish field investigations on stainless steels in soil, that molybdenum is of vital importance for the corrosion resistance of stainless steel in highly corrosive soil (ref. 9).

Thus, it is believed that the main cause of the corrosion attacks is the high chloride content of the soil and that the molybdenum content of the steel was too low to protect against corrosion.

Corrosion resistance of the steel grades in soil

It seems that stainless steels with a considerable content of chromium and a comparatively high content of molybdenum, like ASTM 316/EN 1.4436, ASTM S31254/1.4547 and ASTM S31803/EN 1.4462, are suitable for use as material for pipes to be placed in soil. In strongly corrosive soils, as soils with high chloride content, the steel grades ASTM S31254/1.4547 and ASTM S31803/EN 1.4462 are expected to withstand corrosion totally. Steels with lower molybdenum content, like ASTM S32304/EN 1.4362, should not be used for pipes in soils with high chloride content.

CONCLUSIONS

The main conclusions from the investigation are:

- High chloride content in the soil can cause severe pitting and crevice corrosion attacks on low-alloyed stainless steels.

- In this investigation the steel grade ASTM S32304/EN 1.4362 (23Cr/4,3Ni/0,3Mo) suffered severe pitting and crevice corrosion after only three years exposure in a soil with high chloride content. On the other hand no corrosion attacks were found on test specimens made of the steel grades ASTM 316/EN 1.4436 (17Cr/11Ni/2,7Mo), ASTM S31254/1.4547 (20Cr/18Ni/6,1Mo) and ASTM S31803/EN 1.4462 (22Cr/5,5Ni/3Mo), which all have relatively high molybdenum content.

- Corrosion can be avoided on non-protected stainless steels in corrosive soil by choosing the proper stainless steel grade for the intended pipeline. In corrosive soils, above all soils with high chloride content, steel grades with high chromium and comparatively high molybdenum content should be chosen as pipe material. The results in this investigation can be used as a guide for the choice of the proper steel grade.

- The importance of high chromium and molybdenum content for the corrosion resistance of stainless steels in soil environments, which was observed in this investigation, is in accordance with results in earlier Swedish field investigations.

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