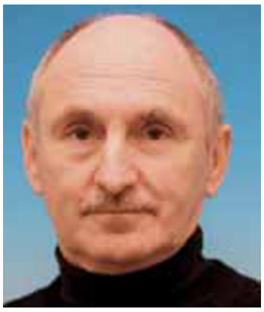
SUITABLE CORROSION TEST METHODS FOR STAINLESS STEEL WELDS



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ABSTRACT

When a fabricator wants to verify that a welding procedure is fit for purpose, it is usually advisable to perform a verification test as described in, for example, EN SO 15614-1. It is important to select the corrosion test method in such a way that test results reflect the performance in the actual application environment. In this paper, standardised test methods suitable for welded joints are discussed. It is also pointed out that many test methods used today should be revised to permit adequate testing, as they are not applicable to welded joints.

IIW-Thesaurus keywords: *Corrosion tests; Stainless steels; Steels; Welded joints.*

1 INTRODUCTION

To achieve optimum properties of a welded construction, it is important to choose suitable steel grades, suitable welding procedures and fillers, and in some cases also suitable post weld treatments. It is also important to know the purpose of subjecting a weld to corrosion testing. One objective can be to investigate if a weld will show the expected behaviour in a certain environment. This type of testing is often done during development of new products and when a material is considered for a new application. Such testing is often used as a procedure test before production is started and can be extensive. Another reason can be that a corrosion test is used to verify that a certain product meets a specified requirement. In this case, it is important to agree on a standardized method, which is not too time-consuming to perform and with clearly interpretable results. Corrosion tests can also be used to qualify workshop procedures (EN ISO 15614-1). Naturally well-defined and reasonable fast and simple tests have to be selected for this purpose.

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Verification testing of various welding procedures often includes some type of accelerated laboratory corrosion test. The aim of this document is to facilitate the choice of standardised corrosion test methods for stainless steel welds that can be used to confirm agreed corrosion properties. Test requirements have to be an agreement between involved parties. To facilitate corrosion testing and avoid unnecessary complications it is mostly advisable to test butt welds.

In combination with accelerated laboratory corrosion tests, field-tests or in-plant tests may be performed. Field-tests are very useful as these are performed under actual service conditions. However, field-tests are very time consuming as often exposure times from at least six months, up to more than a year, are needed.

The aim with this paper is to help a "specifier" or fabricator to choose a corrosion test method suitable for weldments and highlight the necessity to improve current international test standards.

2 SITUATIONS WHERE CORROSION TESTS OF WELDMENTS MAY BE CONSIDERED

As mentioned in the introduction there exist several objectives for performing corrosion tests of stainless steel welds. The situations considered in this paper are:

1. For material development purpose where basic knowledge of a parent material joined with different welding procedures are investigated. This work is primarily done at research laboratories.

2. In the material selection phase: testing of combinations of base material, fillers and welding procedure as one part in establishing the requirements which will form the specification to be handed over to a fabricator.

3. Pre-qualification of welding procedures at a fabricator, to ensure that the requirements of the specification can be met.

Naturally these situations have different demands on the type of corrosion test and on how the results shall be interpreted.

Figure 1 shows pitting corrosion on a coarse ground surface inside a fishing boat. If a suitable laboratory corrosion test method had been used on the pre-qualification stage, this kind of unexpected phenomenon could have been avoided.

Figure 1 – Image from the inside of a fishing boat showing coarse ground surface attacked by corrosion

3 CORROSION OF STAINLESS STEELS

Although named stainless, these steels can also suffer from several forms of corrosion attacks. Traditionally these are divided into the following groups.

As different types of corrosion occur in different environments it is very important to select test methods depending on the actual expected service conditions. For example, if pitting corrosion is the main concern, a pitting corrosion test should be used, and if uniform corrosion is the main risk, a uniform corrosion test should be used, etc.

When welded joints are exposed in different laboratory corrosion tests, they may give somewhat inferior test results compared to parent material in as-delivered condition. There are several possible contributing factors such as residual stresses and a different microstructure compared to the parent metal.

The International Institute of Welding (IIW) recently finished a project [1] with the purpose to list widely used laboratory test methods for corrosion testing of welded joints. Some of these methods (Table 1) are discussed below.

4 ACCELERATED LABORATORY CORROSION TEST METHODS

4.1 Uniform corrosion

This type of corrosion may occur in different types of acids or in hot alkaline solutions.

Strongly oxidising environments may cause transpassive corrosion, which is another form of uniform corrosion. Typical transpassive environments can be bleach plants in the pulp and paper industry where Cl_2, ClO_2 and NaClO are used as bleach media.

The resistance to uniform corrosion is normally evaluated by weight loss measurements by means of immersion test in a selected solution at a relevant temperature. A “rule of thumb” is that the steel grade is considered suitable, or the specimen passed the test, if the corrosion rate was below 0.1 mm/y.

If uniform corrosion is expected, the ASTM G157 standard may be used for testing. ASTM G157 describes

Corrosion type	Description
Uniform corrosion	Uniform corrosion may occur in acidic or strongly alkaline environments. Strongly oxidising environments may cause transpassive corrosion, which is another form of uniform corrosion.
Pitting corrosion	Pitting corrosion may occur in halide containing environments.
Crevice corrosion	Crevice corrosion may occur in halide containing environments in presences of crevices in the construction.
Stress corrosion cracking	Stress corrosion cracking (SCC) may occur in environments where the constructions are exposed to stress and halide or strong alkalic solutions. SCC may lead to catastrophic failures.
Intergranular corrosion	Intergranular corrosion may occur in higher carbon grades but is rarely a problem with modern low carbon containing stainless steels and weldments.
Galvanic corrosion	Galvanic corrosion may occur when different metals are joined together. Joining of different stainless steel grades, or use of over-alloyed fillers, do not normally cause galvanic corrosion.
Corrosion fatigue	Corrosion fatigue may occur when cyclic loads appear in the construction in combination with a corrosive environment.

Table 1 – Examples of corrosion test methods applicable for stainless steel welds

Steel type	Uniform corrosion	Pitting corrosion		Crevice corr.		SCC[d]	Intergranular corrosion		Galvanic corrosion	Corrosion fatigue
Standard	ASTM	ASTM	ISO	ASTM	MTI	ASTM	ASTM	ISO	ASTM	ISO
Low Alloy e.g. 1.4301 1.4401	G 157	G 150[a, c] G 48 E[c]	17864[a, c]		MTI-4	G 123 G 36	A262 E[b] A262 C[e]	3651-2[b] 3651-1[e]	-	11782-1 11782-2
High Alloy e.g. 1.4462 1.4539 1.4547	G 157	G 150 G 48 E	17864	G 48 F G 78	MTI-2	G 123 G 36 NACE TM 0177[f] NACE TM 0198	A262 E A262 C[e]	3651-2[g] 3651-1[e]	-	11782-1 11782-2
Dissimilar welding									G 71	

[a] ASTM G 150 and ISO 17864 are identical.
[b] ASTM A 262 Pr E and ISO 3651-2 Method A are very similar.
[c] Not suitable for 1.4301 (G 48 E and G150 can be used for higher alloyed grades).
[d] U-bend test specimen is a suitable geometry, ISO 7539 or ASTM G 58.
[e] A strongly oxidizing environment should in the first place be used on non-molybdenum alloyed stainless steels.
[f] Mostly used in oil and gas ind. where H_2S and high pressure could cause SCC.
[g] For higher alloyed welded joints, method B or C should be used.

the testing procedure and suggests testing in 14 different media, but the method can also be used for other media. The specimen of size 50 x 20 mm (welded specimen with the weld in the centre parallel to the longer side) is exposed for 96 h. Both base metal specimens and welded specimens are tested. The corrosion rates are then compared to see if welding has influenced the result. A specimen attacked by uniform corrosion is shown in Figure 2. Results from G157 testing of weldments are normally at the level of non-welded specimens. Uniform corrosion tests are commonly performed in the material selection phase.

4.2 Pitting corrosion

If the environment contains halides (most commonly chlorides) there is a risk of local corrosion attacks such as pitting. A pitting corrosion test method should then be used.

The most common method to rank the resistance to pitting corrosion of different stainless steel grades and their weldments has been the ASTM G 48 A method. The G 48 standard has however been revised during recent years and today there is a method to determine the critical pitting corrosion temperature (CPT) for stainless steels, designated as ASTM G48 method E. In method E the specimen of size 50 $\times$ 25 mm is exposed for 24 h in 6 % $FeCl_3$ + 1 % HCl at a fixed temperature. The test is repeated at different temperatures until the lowest temperature to cause pitting is determined, i.e. the CPT. The standard does not describe testing of welds but praxis is to expose welded specimen with the weld in the centre, parallel to the shorter side. After testing, the specimen is examined in binocular to determine if pitting attacks occurred or not. For qualification/acceptance purposes the test can be performed at a single specified temperature. When performing these tests, specimens free from weld oxides should be used. Both methods are very aggressive, therefore the most common standard grades (less alloyed than e.g. 1.4401) cannot be tested with these methods. An example of a tested specimen is shown in Figure 3.

Other useful standardised methods for determination of CPT are ASTM G150 and ISO 17864. These two methods are in fact basically identical electrochemical methods involving rather sophisticated test equipment. One

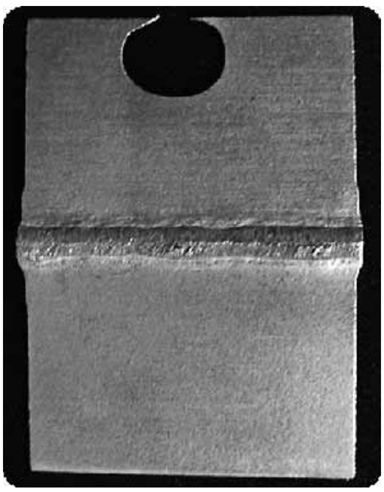

Figure 2 – Specimen with uniform corrosion attack

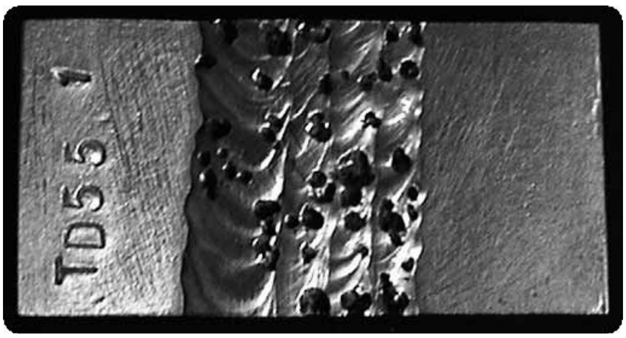

Figure 3 – Specimen with pitting corrosion in weld

advantage with these methods is that cut edges of specimens are not tested. Cut edges are more sensitive to pitting attacks and these attacks may influence the result of e.g. the G48 E test. Testing of weldments is not described in ASTM G150 and ISO 17864.

For weldments, the results from the G48 and G150 testing are normally lower than for non-welded samples. The reduction varies depending on many factors and ranges from a few degrees for lower alloyed grades to ten's of degrees for highly alloyed steels.

4.3 Crevice corrosion

This type of corrosion may occur in halide (most commonly chlorides) containing environments when the construction contains crevices. A typical situation is overlap-welded joints or where deposits may create a crevice on the metal surface. As crevice corrosion occurs under the same environmental conditions as pitting corrosion, steels with high pitting corrosion resistance also exhibit high crevice corrosion resistance.

There is today no standardised test method available for crevice corrosion testing of as-welded specimens. For good reproducibility, a well-defined crevice should be applied on the specimen. The weld bead therefore needs to be machined to produce a flat specimen. This means that the test is rather a metallurgical evaluation of the weld and not a practical test of the as-welded condition.

ASTM G48 F was developed for determining the critical crevice corrosion temperature (CCT) for stainless steels and is commonly used today. This method was developed because the older method, ASTM G 48 B, had too many technical drawbacks. The test conditions in G 48 F (6 % $FeCl_3$ + 1 % HCl, 24 h exposure) are very aggressive and the method is therefore not suitable for testing of standard stainless steel grades such as 1.4301 and 1.4401.

A variant of the ASTM G 48F method, named MTI-2 (6 % $FeCl_3$, 24 h exposure), is less aggressive as a lower torque is used for fastening the crevice formers. This means that this method may be used when the ASTM G48 F method is slightly too aggressive for a specific stainless steel.

For low-alloyed grades (1.4301 and lower alloyed) method MTI-4 is a better alternative than MTI-2 or ASTM G 48 F. In MTI-4 testing, the critical chloride concentration causing crevice corrosion is determined instead of critical temperature.

Due to the difficulty to perform relevant crevice corrosion test of welds, an alternative would be to perform a pitting corrosion test as described above. This will reasonably well indicate the performance of the weld under creviced condition.

4.4 Stress corrosion cracking (SCC)

This type of corrosion may occur when the welded joint is exposed to a combination of halides (mostly chlorides) and elevated temperatures, commonly above 60 °C but below the boiling point. A third factor, stress, is also needed. Residual stresses are always present in weldments, but can be reduced by post-weld heat treatment.

It is often very difficult, if not impossible, to verify that the welding has not impaired the SCC resistance of the construction. Most laboratory test solutions are either very aggressive or rather harmless. Furthermore, interpretation of the results is not entirely straightforward and the scatter in test results can be rather large. Thus, it may be appropriate to combine several environments and loads, and as far as possible, replicate the conditions to which the weldment will be exposed.

Under all circumstances it is a good idea to use a standardised test specimen format, as described in ISO 7539–3 and ASTM G 58 (U-bend). By using the restrained U-bend test sample, stresses in the weld area can be quantified to the yield stress level. The most relevant test method is ASTM G 123 (boiling 25 % NaCl, pH 1.5, 1 000 h). Another commonly used test is ASTM G 36 (boiling $MgCl_2 \cdot 6H_2O$). Testing in 40 % $CaCl_2$ + 1 % $Ca(CH_3COO)_2$, pH 6, 100 °C, 500 h is also sometimes used. ASTM G 123 is designed to provide better correlation with chemical process industry experience for stainless steels than the more severe ASTM G 36. Stress corrosion testing is normally performed in the material development and the material selection phase.

Figure 4 shows a cracked U-bend specimen in machined condition.

Another type of stress corrosion cracking is encountered in environments containing hydrogen sulphide named sulphide stress cracking (SSC). Equipment in oil and gas industry that comes in contact with this type of environment has to be rated for sour service according to e.g. NACE TM 0177 standard (5 % NaCl + 0.5 % CH_3COOH, H_2S saturated, RT, 720 h). Results from TM 0177 testing of weldments are in many cases at the level of the non-welded specimens. The NACE TM 0177 test is generally performed to qualify materials/welds for sour service environments. Approved materials are listed in NACE MR 0175 standard.

A more advanced test procedure for testing the stress corrosion cracking resistance of welds might be the slow

Figure 4 – Specimen with SCC in the weld metal

strain rate test (SSRT), as described in NACE TM 0198 standard. The SSRT is sometimes regarded as a too conservative procedure to evaluate the sour service performance of stainless steels, due to tearing to final rupture. But, it is providing some strong advantages:

1. The test duration is much shorter as compared to 720 h constant load tests. At a strain rate of 1×10^{-6} 1/s for the specimen type defined in the NACE standard TM 0177-96 method A, for instance, the test period can be reduced to less than one tenth, even for very ductile materials.

2. Straining of the material is performed in a very controlled way as compared to uncontrolled strains occurring during loading and due to creep in constant load tests.

3. The specimen is strained to rupture and thus effects of hydrogen degradation can be better identified by the reduction in strength and/or in ductility of the test material. Regarding welds, SSRT represents a good procedure to identify crack susceptible weld microstructures.

4.5 Intergranular corrosion (IGC)

Intergranular corrosion of stainless steels is caused by precipitation of chromium carbides that depletes the adjacent matrix of chromium making it sensitive to corrosion attack. This is seldom a problem with modern stainless steels, or weld metals, as they have sufficiently low carbon content to avoid this phenomenon. One of few reasons to make an IGC test of a weldment could therefore be if there is a risk that carbon, by improper handling, has been added to the weld area during welding.

There are very few practical environments where there is any reason to test the resistance of welds against this type of corrosion. For low carbon grades (< 0.03 %) it may be interesting in urea production plants or when hot concentrated nitric acid shall be handled. In such cases ISO 3651-1 and ASTM A262 Pr C (boiling 65 % HNO_3, 5×48 h) could be suitable test procedures.

Another commonly used procedure is ISO 3651-2 (boiling $H_2SO_4 + CuSO_4$, 20 h, or boiling $H_2SO_4 + Fe_2(SO_4)_3$, 20 h, bend test). The aim with this test is to verify that the base material has been properly produced. There is normally no reason to qualify welding procedures according to this method.

In some of the standard methods given above, a sensitising operation is prescribed prior to testing. This operation can be excluded for welded joints, as the welding procedure in itself will result in sensitisation of any susceptible regions.

Results for weldments subjected to ISO 3651-2 testing are at the level of non-welded but sensitised specimens. If ISO 3651-1 IGC testing is performed on welds containing some ferrite, the result will be lower than for non-welded specimens. However, fully austenitic weldments will only show a small reduction in corrosion resistance.

4.6 Galvanic corrosion

If the cathode (most noble) area is much larger than the anode (less noble) area, the corrosion rate of the anode increases. However, the risk for galvanic corrosion is minimal when joining different stainless steel grades, or when over-alloyed fillers are used for welding as long as they are all resistant to the environment in which they will be used. A typical situation where galvanic corrosion may occur is when mild steel is welded to a stainless steel and both materials are exposed to an electrolyte.

Testing the resistance to galvanic corrosion may be performed according to ASTM G 71 using a test electrolyte similar to the environment the construction will be exposed to, but is not applicable for testing welded joints. If welded joints shall be tested this could be performed as an immersion test where the thickness reduction could be an indication of galvanic effects.

4.7 Corrosion fatigue

The simultaneous action of fatigue and corrosion is called corrosion fatigue and normally results in shorter life than for fatigue only. Testing is time-consuming and is therefore only used in very special cases.

Two testing standards have been proposed, ISO 11782-1 and ISO 11782-2, which are quite different and very general [1]. ISO 11782-1 provides guidance and instruction on corrosion fatigue testing and is concerned with cycles to failure testing, while ISO 11782-2 considers crack propagation testing. Both standards can be used to test welds, and the selection has to be made according to the application. ISO 11782-1 appears to be the most appropriate to assess the effect of a weld on the corrosion fatigue resistance. However, the conditions for the test, e.g., specimen geometry, surface conditions, notch effect, loading and environment, have to be decided depending on the objective of the study.

Corrosion fatigue tests could be considered for the material development or the material selection phase.

5 CONCLUDING REMARKS

The main aim of this document is to facilitate the choice of standardised corrosion test methods for stainless steel welds that can be used for documentation of weld properties and to confirm agreed corrosion properties. Test requirements obviously have to be agreed between involved parties. However, there are two points, valid for all corrosion tests methods discussed, that should be kept in mind when testing welded joints:

– to facilitate corrosion testing and avoid unnecessary complications it is mostly advisable to test butt welds.

– test specimen should be free of weld oxides. A combination of mechanical and chemical methods should preferably be used to ensure sufficient post weld cleaning.

Furthermore, there is a need to revise existing standards to make them more applicable to welds.

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