A Study on the Corrosion Characteristics of Welded Stainless Steels Used in the Fabrication of Brine Circulating Pumps

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Abstract— Two types of stainless steel are suggested to substitute Ni resist iron in manufacturing brine recirculation pump casings used in desalination plants. These are austenitic stainless steel UNS S31600 and super duplex stainless steel UNS S32750. In addition to cast stainless steels, original pump manufacturers use welded construction of wrought stainless steels to build other related components such as column pipes, elbow discharge piece and others. The study of stress corrosion cracking (SCC) of wrought stainless steels is significant since the long-term performance of these materials is still to be seen. In earlier works, characterization and SCC of these two types of stainless steels had been reported. This work aims at studying the mechanical, metallurgical, electrochemical and SCC properties of welded joints made from the above mentioned two types of wrought stainless steels. Welded samples prepared as per ASME section IX-Welding, were corrosion tested under comparable service conditions found in the desalination plant where failure of brine circulating pumps has been reported. Results have shown that welding has no negative effect on the resistance to SCC of UNS 32750 stainless steel samples. On the other hand, a deteriorating effect of welding on the resistance to SCC of UNS 31600 samples has been observed. No pitting has been observed for the welded UNS 32750 samples, whereas, pitting has been observed and different pitting potentials have been measured for the welded UNS 31600 samples.

Keywords—Stress corrosion cracking, Brine circulating pumps, Welded stainless steels, Desalination plants, Pitting.

I. INTRODUCTION

In desalination plants, the service life of pumps is one of the important factors affecting the selection of a pump for service. The material of the pump casing and its resistance to the corrosive process environment such as brine water solution are crucial in consideration of the pump suitability for a brine circulation process. Currently different grades of ductile iron are used in manufacturing casings for the recirculation pumps. When these pumps are put in service, casing failures have been reported at different intervals. SCC found to be the cause of these failures [1]. Stainless steel castings have been used to manufacture pump casings to replace ductile iron in order to avoid SCC and hence increase the service life of pumps [2]. Fabricated wrought stainless steels are another option to be used in manufacturing of casing, column, and other parts of the pump. The performance of welded stainless steels, and its resistance to SCC are of a prime concern.

In this investigation, the corrosion characteristics and SCC of welded joints made from two types of stainless steels namely UNS 31600 and UNS 32750 have been studied under similar environmental conditions to that found in desalination plants.

II. EXPERIMENTAL WORK

A. Welded Samples Preparation

Test samples were prepared from two strips provided from the two types of the wrought stainless steels. Each strip has a thickness of 12.7 mm and has been cut to two parts subsequently bevelled and prepared for double bevel butt-welding. A qualified welding procedure as per ASME Section IX has been utilised to perform a GTAW welding process by a qualified welder in compliance with the same code[3]. GTAW welding parameters such as current, voltage, gas flow, welding speed and heat input have been closely monitored to comply with welding procedure specifications and to eliminate any possible cause of failure due to defective weld [4]. Filler metals have been selected in a compliance with the requirements of ASME Section II Part C [5].

B. Radiographic Testing

The quality of the welded specimens has been examined by gamma ray radiography. ASME Section V has been followed to perform the radiography tests on the welded specimens [6]. ASME Section VIII has been followed to evaluate the quality of welded joints [7].
C. Chemical Compositions

The chemical composition of the two as received stainless steel materials have been provided by the steel manufacturer as given in table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical Composition of the as Received Austenitic Stainless Steel UNS 31600 and Super Duplex Stainless Steel UNS 32750 [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>UNS 31600</td>
<td>0.025</td>
</tr>
<tr>
<td>UNS 32750</td>
<td>0.017</td>
</tr>
</tbody>
</table>

The chemical composition of the two types of filler metals used in GTAW welding process have been provided by the filler metal manufacturer as given in table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Chemical Compositions of Filler Metal ER 316 for Austenitic Stainless Steel, and ER 2594 for Super Duplex Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler metal for Welded Austenitic SS UNS S31600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>AWS ER316</td>
<td>0.010</td>
</tr>
<tr>
<td>Filler metal for Welded Super Duplex SS UNS S32750</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>AWS ER2594</td>
<td>0.012</td>
</tr>
</tbody>
</table>

D. Tensile Testing

Tensile test samples [figure 1] have been prepared from the welded strips prepared in section 2.1 from both types of stainless steel. These samples have been prepared and tested in compliance with the requirements of ASTM A370-07 [10].

E. Metallographic Testing

Test samples from the welded both types of stainless steel have been cut into thin transverse sections, as shown in figure 1-c, using thin sectioning machine. Coolant liquid was used during the cutting process in order to avoid overheating of these sections. Each section represents the three zones of welding namely, welded zone, heat affected zone and parent metal. Each section was then mounted in a moulded phenolic powder using a mounting device. Surface of each sample was ground using 240, 400, 600, 1000, and 2400 grid emery paper. The surface was then polished using 6µm, and 1µm diamond past respectively to be ready for etching.

Welded austenitic stainless steel samples have been electrolytically etched using a 10% oxalic acid at 3 volts, whereas, welded super duplex stainless steel samples have been etched using an electrolyte of 20% NaOH and 100 mL of distilled water at 3 volts for 20 second [11, 12]. Following etching, welded stainless steel samples have been examined using an optical microscope. A digital image capturing device was mounted on the microscope to examine the microstructure of both types of welded stainless steel[11,12].

F. Hardness Testing

The objective of hardness testing is to have a hardness survey across different zones of welding as shown in figure 2 to guaranty the elimination of possible embrittlement due to welding procedure as per ISO 15156-2009. To have a hardness survey a cross the welded transverse section, Vickers hardness testing device has been used to apply a load of 200 gm on different locations across the transverse section of the welded samples[13].
Figure 2: Hardness test locations for welded stainless steel samples [ISO 15156:2009][13]. A: weld heat affected zone, B: Lines of hardness survey, C: hardness impressions.

G. Electrochemical Testing

1) Sample Preparation and Testing Set-Up: Samples for electrochemical tests have been prepared from the welded austenitic and super duplex stainless steels as shown in figure 3. Samples have been round machined and cut to small thin sections using a thin sectioning devise. Each round section represents one of the three welded zones. Two austenitic stainless steel strips acting as reference electrode and auxiliary electrode have been connected to insulated copper terminals. Similarly the thin round section representing different welding zones have been connected to the insulated copper terminals to represent the various working electrodes. The assembly for each sample was then moulded in epoxy resin to fix the stainless steel samples in the mould and to ensure the isolation of the stainless steel strips and samples representing different welding zones. This setup avoids short-circuiting during testing. Extra care has been given during the moulding process to avoid air gaps between stainless steel samples and epoxy resin to avoid crevice corrosion. The surface of the moulded stainless steel samples have been manually ground with 100, 200, 400, 600, and 1000 emery papers. The samples were degreased using 5% caustic soda solution and rinsed in fresh water to remove any oil or debris residuals from samples.

Figure 3: Different sections of welded sample moulded in epoxy for electrochemical testing.

An ACM potentiostat Gill 6 connected to a computer was used to perform the electrochemical tests. The machine was equipped with a sequencer software to control and record test results. Electrochemical test samples have been immersed in Pyrex container filled with brine solution at controlled temperature as shown in figure 4. The brine has an average of 34,000 ppm of chloride concentration and pH of 8.1. The test solution was collected from a desalination plant where brine circulation pumps are used.

Figure 4: Electrochemical test set up [8].

2) Potential Measurement and Cyclic Sweep Testing: An ACM potentiostat has been used to measure the open circuit potentials of different welded zones of both types of stainless steels. Long term potential measurement has been used to measure the potential of samples in brine at 60 °C for one hour. Potentials were measured against the austenitic stainless steel UNS 31600 as reference electrode. A Potentiostat has been set to have normal averaging option which gives 20 numbers of averages [14,15].

Cyclic sweep testing has been performed for each welding zone under the above-mentioned conditions on both types of stainless steel welded samples. For austenitic stainless steel, the start potential for different welding zones has been set to -250 mV and the reverse potential to +750 mV with reference to its open circuit potential. The later potential is expected to exceed the pitting potential of austenitic stainless steel (maximum of 400 mV reported under similar conditions) [8]. For super duplex stainless steel, the start potential for the different welded zones has been set to -250 mV and the reverse potential to +1000 mV with reference to its open circuit potential with respect to austenitic stainless steel electrodes. The sweep rate has been set to 30 mV/min [16].

H. SCC Testing

1) Sample Preparation and Test Rig: SCC test samples have been prepared from samples of two welded joints prepared in section 2.1 for the two types of stainless steel.
The samples have been cut, machined and prepared in accordance to the requirements of ASTM A370-07 tensile test and NACE type A SCC test method [10,17]. The shoulder diameter of the test samples machined to be 10 mm. The gauge diameter and length are 6.24 mm and 40 mm respectively. All samples have been machined to be identical and have the same dimensions. Coolant has been used during the machining process to avoid overheating of these samples. Test samples have been manually ground using 100, 200, 400, 600, and 1000 emery papers then degreased using acetone solution, and rinsed in fresh water. An SCC test rig has been designed and constructed to simulate the reality of the service conditions of the pump casings under which it had failed during the service life in the desalination plant. The test chamber of the stress corrosion cracking testing has been made from a transparent polypropylene material to contain SCC samples subjected to the controlled tensile stress through a proof ring. These samples are subjected to the circulated hot brine water of controlled temperature passing through the testing chamber. Dial gauge has been attached to the proof ring to indicate any deflection during the SCC test. A web camera is fixed to record the changes in the proof ring deflection and failure times of SCC samples [8].

2) SCC Tests: An offset anodic potential of +400 mV with respect to the rest potential for each welded austenitic stainless steel and welded super duplex stainless steel was applied using the potentiostatic test facility of ACM sequencer software [15,17]. For the sake of comparison between SCC lives of welded and unwelded SCC samples the value of this used accelerating anodic potential has been determined from cyclic sweep tests previously reported and based on observed pitting potentials for unwelded austenitic stainless steel samples [8]. Welded austenitic and super duplex steel samples have been subjected to a constant load of 8403 N provided by the proof ring. This load represents 95% of the yield load of the as received austenitic stainless steel material and 43% of the yield load of the as received super duplex stainless steel. Each stress corrosion-cracking test has been stopped upon sample fracture or completion of 335 testing hours (14 days). The fracture of the test samples have been confirmed by the dial gauge upon indicating a zero deflection reading [8].

III. RESULTS AND DISCUSSION

A. Radiographic Testing

The review of the radiography test results of welded joints of both types of stainless steel has confirmed that welded joints are free of welding defects as shown in the radiographs of figure 5. These radiographs show no indication of different types of welding defects such as cracks, inclusions, or porosities. The acceptance criteria of weld quality as indicated by ASME section VIII has been used to evaluate these radiographs [7]. Thus the possibility of sample failure during SCC due to over stresses or welding defects is eliminated.

![Figure 5: Radiography of a. an austenitic stainless steel welded sample and b. a super duplex stainless steel welded sample showing no welding defects.](image)

B. Tensile and Hardness Testing

Table 3 shows the average results of tensile tests of as received and welded samples of both types of stainless steel. This table illustrates considerable differences in the yield and ultimate strengths of the as received and welded two types of stainless steel. For austenitic stainless steel, welding has caused an increase of yield strength on the expense of the ductility as measured by the elongation percent. For the super duplex stainless steel, welding has increased the yield strength with negligible change in ductility. The increase in Ni, Cr, and Mo, contents of filler metal, used in welding as compared to the as received materials is believed to be the reason for the increase in yield strengths of both types of welded stainless steel joints.

<table>
<thead>
<tr>
<th>Type</th>
<th>Condition</th>
<th>Strength</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>YS N/mm²</td>
<td>UTS N/mm²</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>Unwelded</td>
<td>284</td>
<td>597</td>
</tr>
<tr>
<td>steel UNS</td>
<td>Welded</td>
<td>395.5</td>
<td>598.5</td>
</tr>
<tr>
<td>Super duplex stainless</td>
<td>Unwelded</td>
<td>608</td>
<td>852</td>
</tr>
<tr>
<td>steel</td>
<td>Welded</td>
<td>690.5</td>
<td>876.5</td>
</tr>
</tbody>
</table>
Figure 6 shows Vickers hardness profile for austenitic stainless steel and super duplex stainless steel for the three weld zones. No significant change in hardness takes place at the weld or heat affected zones indicating good quality welding and mechanical properties similar to that of the parent metal.

C. Metallographic Testing

Figure 7 shows micrographs for the microstructure of as received and three welded zones of austenitic stainless steel samples. The micrographs show that some degree of sensitization has taken place and affected the microstructure of the parent metal. The degree of sensitization has increased in the HAZ and weld zone. This sensitization in three zones of weld has taken place for welded joints having a thickness of 12.4 mm.

Figure 8 shows micrographs for the microstructure of as received and three welded zones of super duplex stainless steel samples. The micrographs show a similar microstructure for the as received and the parent metals of the welded joints. Weld zone microstructure show dendritic growth of austenite phase in ferrite phase.

D. Electrochemical Testing

Figure 9 and figure 10 show the open circuit potentials against time for the welded austenitic and super duplex stainless steels respectively. All potentials have been measured against austenitic stainless steel reference electrode in brine at 60 °C.
Open circuit potentials for both metallurgies did not give much information as both of them were almost around similar potentials with weld sections being relatively cathodic to the rest of the rest of the weld.

Figure 11 shows the cyclic sweep test results of welded austenitic stainless steel for weld zone, HAZ, and parent metal. All potentials have been measured against austenitic stainless steel reference electrode in brine water at 60 °C. The plots show that the pitting potential of the weld zone is 327 mV. This is considerably less than the pitting potentials of both the heat affected zone and parent metal, approximately 560 mV and 578 mV respectively. This reduction in resistance to pitting of the weld zone is believed to be directly related to sensitization of austenitic stainless steel caused by welding as indicated in the micrographs of figure 7d. The big hysteresis loops for the three zones of welding indicate energy losses due to breakdown of passivity. This break down in passivity under accelerated anodic potential was also supported by visual observation of clear pitting on the surface of the electrochemical electrode.

When compared to the behaviour of the welded austenitic stainless steel, it is clear that under the influence of anodic polarisation, the super duplex showed relatively higher resistance to breakdown in passivity under test conditions. This corrosion resistance eventually was damaged under severe and aggressive anodic polarisation. This is showed by the size of hysteresis loops indicating a break down in passivity and inability to go back and repassivate easily to original state. The visual observation of clear pitting on the surface of the austenitic stainless steel supports the relatively lower corrosion resistance of the weld and the metallurgy under test conditions in comparison to enhanced performance of unwelded super duplex stainless steel.
E. Stress Corrosion Cracking

Table 4 shows times to failure of the as received and welded austenitic stainless steel due to SCC. The table shows that welding has caused a severe reduction in the stress corrosion cracking resistance of the austenitic stainless steel UNS 31600. Under the given SCC testing conditions the average time to failure of the non welded samples is 118 hours whereas the average time to failure for the welded samples is only 27 hours.

Visual observations of SCC test samples show sever, and deep pitting corrosion concentrated in the weld zone at the centre of the samples. This has caused a damage to the SCC resistance and failure of the tested samples as shown in Figure 13. It is believed that the abrupt reduction in time to failure in SCC of welded samples in comparison with time to failure of as received unwelded samples of the austenitic stainless steel is due to the breakdown of the passive layers and consequent accelerated corrosion occurred at welded zone, HAZ and parent metal. This accelerated corrosion has resulted from welding sensitization and changes in the microstructure of the austenitic stainless steel as shown in figure 7 and cyclic sweep plots of figure 11. These cyclic sweep plots show a reduction in pitting potential to 300 mV and increase in pitting current density to 3.1 mA/cm² of the welded zone in comparison to the pitting potential and current density of both the HAZ and parent metals which are 560 mV and 2.6 mA/cm² respectively. SCC tests of the welded samples of super duplex stainless steel show no failure after completion of test period of 335 hours (14 days).

IV. CONCLUSIONS

- Results obtained through metallurgical and electrochemical tests can explain the SCC behaviour of welded samples of both types of stainless steel under the reported test conditions.
- Electrochemical results highlighted better corrosion resistance of welded super duplex stainless steel over similar welds made from austenitic stainless steel under similar test conditions.
- The relative poor performance of austenitic steel welds was demonstrated by visual observation of clear pitting on the surface of electrochemically tested samples.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>TIMES TO SCC FAILURE OF THE AS RECEIVED VS WELDED AUSTENITIC AND SUPER DUPLEX STAINLESS STEELS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>Times to failure of 3 different samples (h)</td>
</tr>
<tr>
<td>As received non welded austenitic stainless steel samples [8]</td>
<td>Sample 1  160.3</td>
</tr>
<tr>
<td></td>
<td>Sample 2  76.4</td>
</tr>
<tr>
<td></td>
<td>Sample 3  117.6</td>
</tr>
<tr>
<td>Welded austenitic stainless steel samples</td>
<td>Sample 1  48.4</td>
</tr>
<tr>
<td></td>
<td>Sample 2  26.3</td>
</tr>
<tr>
<td></td>
<td>Sample 3  6.1</td>
</tr>
<tr>
<td>As received non welded super duplex stainless steel samples [8]</td>
<td>Samples 1, 2 and 3</td>
</tr>
<tr>
<td></td>
<td>No SCC failures after 14 days of testing</td>
</tr>
<tr>
<td>Welded super duplex stainless steel samples</td>
<td>Samples 1, 2 and 3</td>
</tr>
</tbody>
</table>

Visual observations of the SCC tested samples showed no pitting and cyclic sweep plots of figure 12 shows no pitting potentials have been observed. It is believed that despite the hysteresis of the cyclic sweep plots, the damage in the passive layer was not severe enough to initiate pitting and severely damage the SCC resistance of the super duplex stainless steel.
• Sensitisation of microstructure was observed on welded austenitic stainless steel. This could be the main reason leading to shorter failure time under SCC, relatively lower pitting potentials, and pits visually observed on the tested electrodes.
• Welded super duplex stainless steel offers a higher SCC resistance over austenitic stainless steel in brine environment.
• Post weld heat treatment should be considered for welded austenitic stainless steel strips, having a thickness of 12.8 mm, to possibly counterbalance the damaging effect of microstructure sensitisation.

REFERENCES