DEVELOPMENT OF NON DESTRUCTIVE TECHNIQUES FOR CHARACTERIZATION OF CREVICE CORROSION IN TUBE-TO-TUBESHEET JOINT

N. Jothilakshmia, P.P.Nanekara, Arbind kumara, V.Kainb and B.K.Shahc

a Quality Assurance Division, Bhabha Atomic Research Centre, Mumbai, India
b Material Science Division, Bhabha Atomic Research Centre, Mumbai, India

ABSTRACT

Austenitic Stainless Steel (AISI 304 NAG) is widely used as a material of construction for tubes in thermal siphon evaporators. Though highly resistant to uniform corrosion this material is prone to localized corrosion. The tube-to-tubesheet joint in the evaporator has shown frequent failures due to crevice corrosion degradation. There is a need to develop non-destructive techniques to detect and characterize crevice during In-Service Inspection (ISI), so as to avoid the catastrophic failure of component and unplanned shut-down of plant. To simulate crevice corrosion in tube-to-tubesheet joint, the austenitic stainless steel tube samples were exposed to FeCl₃ solution as per ASTM G48 test procedure. Two NDE methods, viz., eddy current test and ultrasonic imaging were developed for detection and characterization of crevice corrosion in evaporator tubes. This paper describes the procedure for generation of samples containing varying degree of crevice and the studies carried out for optimization of test parameters for ultrasonic and eddy current examination for detection and characterization of crevice. The paper also discusses in details the results of ultrasonic and eddy current examinations and how these results compare with the true depth of crevice found out by metallography.

INTRODUCTION

The thermo-siphon evaporator tubes in waste management plants have shown frequent failures, one of the reasons for this could be the crevice corrosion at tube to tubesheet weld joint [1]. This type of attack occurs due to chloride induced acidic environment produced in the interstitial region or impurity concentration and deposits at the tube to tube sheet joint [2-5]. The corrosion rate depends on the geometry of crevice, severity of the operating conditions (chemical composition, pH, Temperature, Hydrolysis reaction) and metallurgical condition of the material [6]. For safe and reliable plant operation and to avoid catastrophic failure, it is desirable to develop suitable non destructive technique for carrying out in-service inspection so that the crevice attack can be detected at an early stage. The sizing accuracy and the probability of detection are dependent on the location and orientation of the crevice, and the artifacts such as corrosion deposits and tube support structures [7, 8]. In this study, the SS 304L NAG tubes with varying degree of crevice corrosion were generated as per ASTM G 48. The crevice attacks were monitored using multi frequency eddy current technique and ultrasonic imaging. The results were verified with the actual depth, which was found by metallography.

EXPERIMENTAL PROCEDURE

Sample generation

The SS304L NAG tube of outer diameter 25mm with 4mm thickness was taken for this study. The chemical composition of the tube material is shown in table 1. The crevice corrosion is generated in the test sample in FeCl₃ solution as per ASTM G 48 [9]. Test solution is prepared by dissolving 100 g of reagent grade ferric chloride, FeCl₃·6H₂O, in 900 ml of Type IV reagent water (about 6 % FeCl₃ by mass). Crevice former is used to provide preferential site for crevice generation. Samples with varying depth of crevice were prepared by varying the time of exposure to the test solution.

Table 1 : Chemical composition of SS 304L NAG Tube

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;0.025</td>
<td>0.88</td>
<td>1.17</td>
<td>0.014</td>
<td>0.013</td>
<td>18.56</td>
<td>11.04</td>
<td>0.063</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Eddy current testing

Eddy current testing (ECT) is based on measuring changes in probe impedance as the probe passes over the defects. The defect depth is estimated by comparing the ECT signal with the signals obtained from machined calibration defects. For eddy current examination of tubes, a bobbin coil was designed. 25 KHz frequency was selected to achieve the acceptable sensitivity and depth of penetration. In order to simulate the tube sheet region, a plate (100 mm X 100 mm X 25 mm), made of austenitic stainless steel 304L with a central hole (dia. 26 mm) was fabricated. The circumferential grooves of width 1 mm and different depths (0.2, 0.4 mm & 0.8 mm) were made in the tubes to simulate the crevice corrosion of varying depths. To simulate the through wall defect, a hole of 1.6 mm was made on the tube. The phase of the signal from the through wall hole (calibration) was set to 40 degrees as per ASME code section V, article 8. Signals that show phase below 40 degrees represent ID defects while signals that show phase greater than 40 degrees represent OD defects. Multi frequency ECT was used to cancel out the support plate signal. Initially, the coil was placed in the tube and balanced on the defect free material. ECT was standardized and parameters were optimized to detect these grooves on the tube OD at tube to tube-sheet location. The probe was drawn through the tube and the corresponding variations in coil impedance were recorded. The impedance changes are related to the type and size of a defect. The impedance screen displays the change of the coil impedance in terms of amplitude and change. The phase angles of the standard artificial flaws were measured and calibration curve was drawn. After this, the eddy current data was collected on samples having real crevice corrosion. The phase angle was measured for all the crevices and the depth of attack was found from the calibration curve.

Ultrasonic imaging

Crevices of various depths were also characterized using ultrasonic imaging. Ultrasonic simulation studies were carried out using CIVA 9.2 to select the most suitable test parameters for detection and characterization of crevice. The SS tube of 25 mm diameter with 4 mm thickness was considered for this study. The flat bottom holes of size 0.2mm, 0.4mm, 0.8mm and 1mm were introduced on the OD surface of the tube. The simulation was conducted for different probe frequencies viz. 2 MHz, 5 MHz, 10 MHz and 20 MHz. A and B Scan results were obtained for the above mentioned probe frequencies, whose results were compared in terms of sensitivity and resolution. For detection and characterization of real crevice, 20 MHz side looking immersion transducer was used. B-scan images were collected during scanning. The depths of crevices were measured at time-of-flight.

Metallography

After NDE characterization, the samples were cut and prepared for metallographic examination to measure the true depth of crevice. Metallography was carried out at 50X.

RESULTS AND DISCUSSION

Corrosion Rate Measurement

The tube samples were exposed to FeCl₃ for different duration to obtain varying depth of crevice attack. The corrosion rate was found by the following formula:

\[
\text{Corrosion Rate (mm/month)} = \frac{7290 \times W}{A \times d \times t}
\]

Where, 
- \( t \) = time of exposure, h,
- \( A \) = area, cm²,
- \( W \) = weight loss, g,
- \( d \) = density, g/cm³.

Figure 1 shows the variation of corrosion rate with the time of exposure. The corrosion products produced increase the severity of the media and lead to increase in corrosion rate.

Fig 1 : Variation of corrosion rate with time

Fig 2 : Microstructure of crevice attacked samples exposed to test solution for (a) 96 hrs (b) 192 hrs (c) 240 hrs and (d) 288 hrs
Fig. 3: ECT response obtained from reference sample in which artificial defect machined at 5%, 10% and 20% depth of wall thickness and through hole of dia. 1.6mm (b) Calibration Curve of ECT testing.

Fig. 4: ECT response obtained from sample s exposed to test solution for (a) 92 hours, (b) 144 hours, (c) 240 hours, and (d) 288 hours.
with time. The metallographic results of the samples, which are exposed to test solution for different time periods are shown in Figure 2. Metallography indicates that the extent of corrosion attack increases with increase in exposure period, which is in line with the experimentally measured corrosion rate.

**Eddy Current Test**

Two test variables, namely frequency and phase, are available while conducting the eddy current test. For the present study, the phase of the signal is optimized so as to set the signal from 100% through hole to 40p, as per ASME code. The ECT response (Lissajous plot) obtained from artificial grooves is shown in Figure 3(a). The phase angle obtained from artificial grooves and hole was measured and calibration curve was generated, which is shown in figure 3(b).

Figure 4 shows the Lissajous plots obtained while carrying out eddy current test on samples with varying degree of crevice attack. The phase angle of crevice attacked samples were measured which are given in Table 2. From the measured phased angle, the depth of crevice attack was found using calibration curve.

The ECT response provides the information on the amplitude and the phase of Lissajous signal. The phase angle of the signal decreases and amplitude increases with increase in depth of OD attack. The increase in amplitude is due to increase in volume of the defect.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Exposure Time to test solution (Hrs)</th>
<th>Phase Angle (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>192</td>
<td>132</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>116</td>
</tr>
<tr>
<td>4</td>
<td>288</td>
<td>105</td>
</tr>
</tbody>
</table>

**Ultrasonic imaging**

Ultrasonic simulation was performed to select the suitable probe for monitoring of crevice corrosion. Figure 5(a)-(d) shows the A and B scan results obtained for test frequencies at 2, 5, 10 and 20 MHz, which reveals the presence of four flat bottom holes of 1 mm dia. (0.2 mm, 0.4 mm, 0.8 mm and 1 mm deep), which were introduced at different locations. The B-Scan and A-Scan result for 2 MHz probe indicates that the tube ID signal is not resolved from the OD signal and the defects are not clearly seen. Hence it can be concluded that 2 MHz probe is not suitable for this geometry. At 5 MHz and 10 MHz, although the tube ID and OD signals are resolved, the resolution is poor for detection of shallower defects viz. 0.2 mm and 0.4 mm deep. The 20 MHz immersion probe shows optimum resolution and sensitivity for the detection of shallower defects and thus it is chosen for present study.

![Fig. 5: Ultrasonic Simulation results obtained from ultrasonic probe of (a) 2 MHz, (b) 5 MHz, (c) 10 MHz and (d) 20 MHz frequency](image)
The crevice attacked samples were characterized by ultrasonic imaging. The water path was optimized to focus the sound beam at the tube OD. The B-Scan images obtained from four samples with varying degree of crevice are shown in Figure 5.

The depth of the crevices were estimated from B-scan images using time-of-flight.

Table 4: Depth of crevice attack measured by different techniques

<table>
<thead>
<tr>
<th>Sample</th>
<th>Actual depth (mm)</th>
<th>Depth by measured by UT (mm)</th>
<th>Depth measured by ECT (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.29</td>
<td>0.28</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.73</td>
<td>0.71</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>1.37</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 4 summarizes the results of crevice depth measurements obtained through metallographic examination, ultrasonic and eddy current testing. The accuracy of depth assessment from phase angle during eddy current testing is based on the method used for phase angle determination viz. peak to peak method and tangent method [5]. During the present study peak to peak method was used for phase angle determination and the error of 1 to 2 degrees could occur in the measurement. This could lead to the uncertainty in the eddy current based depth estimation of the order of 20-50 micron. The depth measurement using ultrasonic testing is based on time of flight. The ultrasonic analog signal is sampled at 200MHz sampling rate, which could lead to an in-accuracy in time-of-flight measurement of 5 µsecond. In terms of depth, it corresponds to an in-accuracy of ±30 micron. The results of the investigation indicates that the depth sizing accuracy for crevice attack using ultrasonic is better than eddy current testing.

CONCLUSION

Ultrasonic and eddy current techniques were developed for detection and characterization of crevice corrosion that occurs in tube-to-tubesheet weld joint of thermal siphon evaporators. The probe parameters for ultrasonic examination were optimized by simulation studies. Crevice attacks of various depths were generated on the SS 304L NAG tubes as per
ASTM G 48, to simulate the crevice corrosion attack that occurs at the tube-to-tube sheet weld joint. These samples were examined by eddy current testing using bobbin coil and ultrasonic imaging using side looking immersion transducer. The depth of crevices estimated by both the NDE techniques are close to the actual depth found through metallography. The observations indicate that ultrasonic imaging shows better depth sizing accuracy for crevice corrosion as compared to eddy current testing.

REFERENCES


