Thermal Cycling of Bimetallic Weld Joints between SA 516 Grade 65 Carbon Steel and SS 304 L for Steam Generator Application

ABSTRACT

The used of welded construction for nuclear plants at elevated temperatures, where time dependent deformation can occur under possibly novel service condition. Better understanding of the behavior of welds may contribute to confidence in the conservative nature of design practice or tightening of safety factors.

The scope of this paper is to study of mechanical behavior in bimetallic welds undergoing thermal cycling. The effect of temperature range, cycle time and number of cycles would be the varying parameters. We intended to summarize the understanding of weld behavior that may be applicable in the design of welded components for nuclear power plant systems.

Keywords: Bimetallic joints; SA 516 gr. 65 carbon steel; SS 304 L; SS 309 L weld metal; Thermal cycling.

I. INTRODUCTION

Dissimilar metal joints between austenitic stainless steels and carbon steels containing low amounts of carbon are being extensively utilized in many high-temperature applications in energy conversion systems. In steam generating power stations, the parts of boilers that are subjected to lower temperatures as in the primary boiler tubes and heat exchangers are made of ferritic steel for economic reasons. Other parts, such as the final stages of the super heaters and reheaters operating at higher temperatures where increased creep strength and resistance to oxidation are required, are constructed with austenitic stainless steels. Therefore, transition welds are needed between the two classes of materials [1].

There have been several studies on the welding of carbon steels and stainless steels because the failure in bimetallic joints can occur before the components reach their design life [2]. These investigations have shown that large thermal stresses arise in these joints during temperature fluctuations owing to the difference in thermal expansion coefficients [1-5]. The highest risk zone in the joints is the interfacial region between the weld metal and carbon steel and all of the austenitic-ferritic dissimilar alloy weld failures that have occurred in service [6-9] or in laboratory test programs [10-11] have been in the ferritic alloy close to the weld. Thermal cycling in power plant operation during the numerous start-ups and shut-downs thus plays a major role in premature service failure of these joints [12-13]. These cyclic stresses superimposed on the residual welding stresses, external loads and internal steam pressures cause the ultimate service failure of the dissimilar joint [14]. The service life of the joint can be improved by reducing the magnitude of cyclic thermal stresses through a gradual change in thermal expansion coefficients of the joint components. One approach in this direction is to use a filler material having a Coefficient of Thermal Expansion (CTE) intermediate between those of the carbon steel and the stainless steels [12-13]. One such material is Alloy 800 and King, et al. [15] who suggested it have shown that a considerable reduction of cyclic thermal stress could result from its use.

This paper discusses the results of thermal cycling tests conducted using this procedure on the joints between Grade 91 steel and Alloy 800.

II. EXPERIMENTAL DETAILS

A single V-groove butt joint was made between 20 mm thick plates of SA 516 grade 65 carbons steel and SS 304 L steel using gas-tungsten arc welding and SS308 L filler material was used to fill the groove. The chemical compositions of the base metals and the filler materials are given in Table 1. The joints were then subjected to a post-weld tempering treatment at 725 for three
hours [16]. The weld pads were then milled to a thickness of 4 mm, and transverse weld sheet specimens (132 × 20 × 4 mm) were cut from the joint, with the weld at the centre of the specimen. The samples were then loaded in a three-point bending fixture with set-screws, as shown in Fig. Three starting stress levels were employed, viz. 0, 200 and 400 MPa. The displacement, y, to be applied at the center of specimen by the set-screw corresponding to the bending stresses.

The bending stress at the mid span on the outer fibers is given by [2]:

$$\sigma = \frac{6Ey}{L^2}$$

where; $\sigma$ is the maximum stresses in MPa, $y$ is the displacement in mm of the outer fiber normal to the surface at the center of the specimen, $E$ the modulus of elasticity in MPa, $t$ the specimen thickness in mm, and $L$ the distance between the outer supports in mm.

Table 1: Chemical compositions of base and filler materials used, mass contents in %

<table>
<thead>
<tr>
<th>Type of steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
<td>0.03</td>
<td>2.0</td>
<td>1.0</td>
<td>18.0-20.0</td>
<td>8.0-12.0</td>
<td>0.045</td>
<td>0.03</td>
</tr>
<tr>
<td>SA 516 Grade 65</td>
<td>0.24</td>
<td>0.85-1.20</td>
<td>0.15-0.40</td>
<td> </td>
<td> </td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>308L (filler material)</td>
<td>0.03</td>
<td>2.0</td>
<td>1.0</td>
<td>19.0-21.0</td>
<td>10.0-12.0</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>309 L (buttering material)</td>
<td>0.03</td>
<td>2.0</td>
<td>1.0</td>
<td>22.0-24.0</td>
<td>12.0-15.0</td>
<td> </td>
<td> </td>
</tr>
</tbody>
</table>

Fig.1. Schematic of three-point-loaded, bent-beam test apparatus

After loading, the specimens were thermally cycled between room temperature and 625 °C. The test fixtures with the samples were first held at 625 °C for 22 hour in a muffle furnace, then removed and cooled to room temperature for about 2 hours in still air, and subsequently reintroduced into the furnace to repeat the cycle. The high starting stresses and the high hold temperature were used for the purpose of acceleration as in the case of stress-rupture tests.

The details of the test conditions used are listed in Table 2.

Table 2: Details of thermal cycling test on bimetallic weld specimens

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>$y$ (mm)</th>
<th>$\sigma$ (MPa)</th>
<th>Initial temp. $\theta$ $\degree$C</th>
<th>Final temp. $\theta$ $\degree$C</th>
<th>Heating time (hr)</th>
<th>Cooling time (hr)</th>
<th>No. of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>200</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>400</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>100</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>400</td>
<td>28</td>
<td>625</td>
<td>21</td>
<td>3</td>
<td>20</td>
</tr>
</tbody>
</table>

After completing twenty thermal cycling of specimens, these are taken out from the furnace then these samples are taken out from the test apparatus. The specimens are prepared for EPMA test, tensile test, microstructure test and hardness test to find out the effect of thermal cycling on mechanical behavior of bimetallic weld samples. For tensile test the flat tensile specimen are made as per ASTM E-8 and for microstructure, EPMA and hardness samples are cut from the center contained weld at centre.

III. RESULTS AND DISCUSSION

(a) Tensile Test Survey

The tensile test conducted as per ASTM E-8 std. on bimetallic weld samples. The mechanical properties of samples are given in Table 3.

Table 3. Mechanical properties of bimetallic weld samples

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Y.S. (MPa)</th>
<th>U.T.S. (MPa)</th>
<th>VHN (weld metal)</th>
<th>% EL</th>
<th>% RA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>217.6</td>
<td>388.86</td>
<td>252</td>
<td>21.6</td>
<td>65.0</td>
</tr>
<tr>
<td>2</td>
<td>222.5</td>
<td>403.50</td>
<td>252</td>
<td>21.2</td>
<td>58.33</td>
</tr>
<tr>
<td>3</td>
<td>246.7</td>
<td>423.30</td>
<td>286</td>
<td>20.4</td>
<td>57.75</td>
</tr>
<tr>
<td>4</td>
<td>288.3</td>
<td>505.95</td>
<td>286</td>
<td>29.0</td>
<td>68.07</td>
</tr>
</tbody>
</table>

where;

Y.S. = Yield strength in MPA
U.T.S. = Ultimate tensile strength in MPA
VHN = Vickers hardness number
% RA = Percentage reduction in cross-section area in mm
% EL = Percentage change in length
The tensile strength of bimetallic weld samples decreases after the thermal cycling. Also the tensile strength of the samples depends on the pre-stress as the pre-stress level the tensile strength is also increases.

(b) Hardness Survey

Standards

Vickers test methods are defined in the following standards:

- ASTM E384 – micro force ranges – 10 g to 1 kg
- ASTM E92 – macro force ranges – 1 kg to 100 kg
- ISO 6507-1,2,3 – micro and macro ranges

We used ASTM E92 – macro Vickers hardness test at a load of 5 kg. The hardness of bimetallic weld samples decreases after thermal cycling and also the hardness depend on the pre-stress as the pre-stress level increases the value of hardness is also increases. The migration of carbon takes place from SA 516 gr. 65 to weld metal when the samples are explored to high temperature. Because of the carbon migration the concentration of carbon at Sa 516 gr. 65 and weld metal decreases and form a soft zone and also the concentration of carbon increase near the weld metal and SS 304 L interface and form a hard zone. Now these soft zones are responsible for hardness drop near SA 516 gr. 65 and weld metal interface also these hard zone are for high hardness.

IV. CONCLUSIONS

After conducting the thermal cycling experiments on bimetallic weld samples the following conclusions are made:

- The carbon migration takes place from SA 516 gr. 65 to weld metal when the bimetallic weld samples subjected to thermal loading at temperature 6250 °C.
- Due to carbon migration the soft zone forms near the interface of SA 516 gr. 65 and welds.
- Metal also the hard zone forms near the interface of weld metal and SS 304 L. This soft zone is responsible for hardness drop near interface of SA 516 gr. 65 and hard zone for hardness rise near the interface of weld metal and SS 304 L.
- The hardness of bimetallic weld samples increase as the value of pre-stress increase.
- To prevent carbon migration the temperature should not be high and also can be prevent by the increasing the thickness of buttering layer on carbon steel.

REFERENCES


