PREVENTION OF SCC OCCURRING IN A EXPANSION TRANSITION REGION OF STEAM GENERATOR TUBING BY Ni-PLATING IN PWRS

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Abstract

Applicability of a nickel-plating technique was investigated for a possible proactive method to prevent stress corrosion cracking in the expansion transition region of pressurized water reactor steam generator tubing around the top of the tubesheet. The surface of steam generator tubes is plated with nickel in the region from the bottom ends of the U-tubes up to above the location where the tube is to be expanded, before the expansion process. The nickel-plated regions of the tubes are then inserted into the holes of the tube sheet and expanded to build up a steam generator. In order to verify the applicability and the effectiveness of the technique, mockup tests were performed for nickel-plated Alloy 600 HTMA tubes with hydraulic expansions. Integrity of the expanded nickel plating layers was examined and susceptibility to SCC was evaluated by using the C-ring and the slow strain rate tests in simulated pressurized water reactor environments.

1. Introduction

It is well known that nickel-base Cr-Fe alloys, especially, Inconel 600 (or Alloy 600), used as steam generator (SG) tubes, is susceptible to stress corrosion cracking (SCC) in the primary and the secondary side water environments of the pressurized water reactor (PWR) nuclear power plants (NPPs). However, since the pure nickel (Ni) was found to be immune to SCC in the NPP environments.[1], Ni-plating techniques have been utilized to repair the cracked SG tubes in operating NPPs [2,3]. An excellent in-service performance of the technique was indeed demonstrated from examination of the some SG tubes that were plated with ductile Ni-plating over pre-existing cracks and pulled out from the operating plants after two or three year operation. Due to the relatively weak mechanical strength of the ductile Ni plating on the damaged tubes, the structural integrity of the tubes could not be ensured by the ductile Ni-plating alone. But less ductile Ni-platings cracked when they were applied over long cracks ( > 10 mm) in the SG tubes [2]. In the middle of 1990s, a new plating technology was developed by the name of Electrosleevin which is to plate a nano grain size Ni-P alloy on the inside diameter (ID) surface of cracked SG tubes [4,5]. The electrodeposition of nano grain size Ni-P alloy provides mechanical properties strong enough for the SCC-damaged tubes to be reused without a great concern about their structural integrity and also resistance to primary and secondary side SCC in the SG tubing in operating NPPs. These existing techniques have primarily been utilized for repairing damaged SG tubes.

In this study, a Ni-plating technique was investigated for a possible proactive method to prevent SG tubes from corrosion damages during operation. Most corrosion damages, such as, pitting, SCC, wastage, etc., were experienced to occur on the expansion transition region which is located around the top of the tube sheet (TTS), where high residual stress is induced by tube expansion processes and also sluge is piled in the secondary side. In order to prevent corrosion damages occurring around the expansion transition region, the SG tubes could be
plated with pure Ni or Ni-alloys in the region from the bottom ends of the U-tubes up to above the location where the tube expansion is to be applied, before the expansion process. The tubes are then inserted into the holes in the TS and subsequently expanded by using a hydraulic or other expansion method in accordance with the nominal SG manufacturing procedures.

2. Experimental procedures

2.1 Ni-plating

Commercial Alloy 600 HTMA (high temperature mill annealed) SG tubes (19.05-mm outer diameter (OD) and 1.07-mm wall thickness) were used for this study. The chemical composition is shown in Table 1. Before Ni electroplating, the tube specimens were cleaned with acetone and then immersed in 5 vol.% H$_2$SO$_4$ to activate the specimen surfaces for deposition of a Ni strike layer. The strike layer was deposited on the ID and the OD surfaces of the tube specimens in an aqueous solution of 1.6 mol/l NiCl$_2$ + 0.6 mol/l H$_3$BO$_3$ at 40°C for about 2.5 min., then Ni-electroplating was performed in an aqueous solution of 1.39 mol/l Ni(SO$_3$NH$_2$)$_2$ + 0.65 mol/l H$_3$BO$_3$ at 60°C for 40 min. During the strike layer deposition and Ni electroplating, a direct current was applied between the tube specimens and a Ni anode at a current density of 100 mA/cm$^2$. The thicknesses of the strike layer and Ni-plated layer were about 5 $\mu$m and 50–80 $\mu$m, respectively. After Ni electroplating, the adhesion strength between the plated Ni layer and the original surface of the tube was measured to be about 330 Mpa by tensile tests. This value is about the half of the tensile strength (about 660 Mpa) of Alloy 600 HTMA.

Table 1. Chemical composition of Alloy 600 HTMA used for this study

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Fe</th>
<th>Co</th>
<th>Ti</th>
<th>Cu</th>
<th>Al</th>
<th>B</th>
<th>S</th>
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<td>Wt%</td>
<td>0.025</td>
<td>0.05</td>
<td>0.22</td>
<td>0.07</td>
<td>15.67</td>
<td>75.21</td>
<td>8.24</td>
<td>0.005</td>
<td>0.39</td>
<td>0.011</td>
<td>0.15</td>
<td>0.0014</td>
<td>0.0013</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Expansion procedures

The Ni-plated tube specimens were expanded hydraulically in SA 508 carbon steel tube sheet (TS). The expansion was carried out at the pressure of 32,000 psi by a SG manufacturing company using the typical expansion procedures and parameters used for actual NPP SGs. Additional specimens were also fabricated by expansion at 35000 psi, higher than the typical pressure, to evaluate any degradation of performance at a higher non-typical expansion pressure.
2.3 Stress corrosion tests

After the hydraulic expansion, the TS was removed and the expanded Ni-plated tubes were cut into C-ring and SSRT (slow strain rate test) SCC test specimens. Ring specimens for the microstructural examinations were also fabricated to evaluate soundness of the interface between the plated Ni-layer and the tube surface, and the Ni-layer itself. The shapes and dimensions for the SCC test specimens are shown in Fig. 1.

![FIG. 1. Schematics and dimensions of SCC tests. (a) C-ring and (b) SSRT specimens](image)

Stress corrosion cracking tests were performed in an aqueous solution of 40% NaOH at 315°C and 200 mV above the corrosion potential for simulating the secondary side condition, and in pure water containing 1200 ppm B, 2.2 ppm Li, 5 ppb O₂ and 30 cc/kg H₂, at 330°C for simulating the primary side condition, respectively. A static nickel autoclave was used for the secondary SCC tests, while a 316 stainless steel autoclave with a solution-circulating loop system was used for the primary SCC tests. The SSRT tests were performed at a strain rate of 1.2x10⁻⁷/sec.

2.4 Microscopic Examinations

The interface between the plated Ni-layer and tube surface, the microstructures of plated Ni before and after expansion, and SCC morphologies were examined using an optical microscope (OM) and a scanning electron microscope (SEM).

3. Results and discussion

3.1 Examinations of expanded tubes

Figure 2 shows the Ni-plated tubes before and after hydraulic expansion in the SA 508 TS. In Fig. 2(a), two TSs and two Ni-plated Alloy 600 HTMA tubes before the expansion are seen, while Fig. 2(b) shows the Ni-plated tubes hydraulically expanded in the TSs. The bare tube shown in Fig. 2(c) is the one expanded at a pressure of 35,000 psi, while the tube in tube sheet in Fig. 2(c) is the one expanded at 32,000 psi pressure. No physically noticeable difference was observable between these two tubes. The color tone of the expanded region of the Ni-plated surface (lower part of the tube) is slightly brighter than that of the unexpanded surface (upper part of the tube) (Fig. 2(c)). This is probably due to the plastic deformation of the plated Ni layer in contact with the TS under high pressure during the expansion. There was no observable anomaly such as surface crack on the Ni-plated surface expanded and squeezed by the high hydraulic pressure by OM, compared with the surface of the Ni-layer of the unexpanded tube. This observation may be interpreted that the plated Ni layer on the tube is remained undamaged and sound even under the hydraulic expansion pressure as high as 35,000 psi.
The average expansion ratio of the two tubes was calculated from the equation (1):

\[ R(\%) = \{1 - \frac{(H_{ID} - I_{ID})}{(D_{OD} - D_{ID})}\} \times 100 \quad (1) \]

where
- \( H_{ID} \) Inner diameter of tubesheet hole
- \( I_{ID} \) Inner diameter of tube after expansion
- \( D_{OD} \) Outer diameter of tube before expansion
- \( D_{ID} \) Inner diameter of tube before expansion

The calculated average expansion ratio was 1.23 % for the expansion pressure of 32,000 psi and 1.67 % for the 35,000 psi, respectively. The tube expanded at high pressure (35,000 psi) showed a higher value compared with that expanded at low pressure (32,000 psi), as expected. However, these amounts of expansion are not big enough to give a noticeable plastic deformation to the Ni layer plated on the tubes and a mechanically harmful damage to the interface between the plated Ni layer and the original tube surface, as seen in Fig. 3.

The integrity of the plated Ni layer was examined by OM and SEM of the interface between the plated Ni layer and the original tube surface. Figure 3 shows cross-sectional SEM micrographs of the interface after the hydraulic expansion. The cross-sectional micrographs were obtained after etching in a 80 vol. % \( \text{H}_3\text{PO}_4 \) solution for about 30 min. at room temperature. As shown in these figures, no discernible faults were observed along the interface and the plated Ni layer itself after the hydraulic expansion under the pressure of 32,000 or 35,000 psi. This observation is interpreted that SGs could be manufactured with Ni-plated and expanded tubing around the TS regions.
FIG. 3. SEM micrographs showing the plated Ni layer and the interface between the plated Ni layer and the Alloy 600 specimen surface after expansion by hydraulic pressures at (a) 32,000 psi and (b) 35,000 psi. [Etched in a 80 vol. % H₃PO₄ solution for 30 min. at room temperature.]

3.2 Stress corrosion cracking tests
3.3
The susceptibility to secondary side outer diameter stress corrosion cracking (ODSCC) was evaluated for the Alloy 600 HTMA tubing that was plated with Ni on the ID and the OD surfaces and subsequently expanded by the hydraulic expansion. The C-ring and the SSRT were carried out. The C-ring tests were performed in an aqueous solution of 40% NaOH at 315°C and 200 mV above the corrosion potential using static nickel autoclaves. The applied stress at the apex of the C-ring specimens was controlled to be 150% of the yield strength of Alloy 600 HTMA according to ASTM G38 [6]. After the tests, the cross-section, fracture surface and specimen surfaces were examined by OM and SEM. Figure 4 shows the C-ring test results obtained from the specimens Ni-plated only on the ID that were tested for 7 days. As shown in the figure, SCCs were initiated from the OD surface, propagated toward the ID but arrested at the interface of the Ni-layer. This means that the Ni layer plated on the Alloy 600 tube surface can prevent the propagation of secondary side ODSCC for Alloy 600 SG tube even in a strong caustic solution.

The resistance of the Ni-plated on the surface of Alloy 600 HTMA to the secondary side SCC was further evaluated for a severe loading condition such as SSRT. The SSRT specimens were prepared from Alloy 600 HTMA tubes with and without Ni-plated. The SSRT was performed in a 40% NaOH solution at 315°C at a strain rate of 1.2x10⁻⁷/sec. until the test specimen failed by rupture. The fractured surfaces were examined using SEM. Figure 5 shows SEM of the
FIG. 4. Optical micrographs showing cracks formed in the C-ring specimens tested in a 40% NaOH solution at 315°C and 200 mV above the corrosion potential for 7 days and arrested at the interface of the Ni layer and the tube surface.

Fracture surfaces for the two different specimens tested in the same conditions. As seen from the figures, the Alloy 600 HTMA specimen without the Ni plating is very susceptible to intergranular SCC. Cracks initiated and propagated along grain boundaries. On the other hand, no cracking was observable for the Ni-plated Alloy 600 HTMA tube specimen. Some rough traces of teared-like grooves were observed on the plated specimen surface. This type of traces is usually observed on the surface of severely deformed ductile metals.

Fig. 5 SEM micrographs showing the surface morphologies of (a) the bare Alloy 600 HTAM and (b) the Ni-plated Alloy 600 HTMA specimens tested in a 40% NaOH solution at 315°C under a strain rate of 1.2x10^{-7}/sec..

It was reported that the ductile Ni layer plated on the ID surface of SG tubes is immune to primary water stress corrosion cracking (PWSCC) under the conditions of operating PWR nuclear power plants.[2] In this study, susceptibility to PWSCC is evaluated for the Alloy 600 HTMA tubing that was plated with Ni on the ID and the OD surfaces and then subsequently expanded by the hydraulic expansion. The SSRT and C-ring tests are being performed in pure water containing 1200 ppm B, 2.2 ppm Li, 5 ppb O₂ and 30 cc/kg H₂, at
330°C for simulating the primary side environment. Type 316 stainless steel autoclaves are used with solution-circulating systems. The test results should be available in a short time.

4. **Summary**

In this study, applicability of a nickel-plating technique was investigated for a possible proactive method to prevent SCC in the expansion transition region of PWR SG tubing around the TTS. The surface of SG tubes is plated with Ni in the region from the bottom ends of the U-tubes up to above the location where tube expansion is to be performed, before the tube expansion process. The Ni-plated regions of the tubes are then inserted into the holes of the TS and expanded to build up a SG at a manufacturing site. In order to verify the applicability and the effectiveness of the technique, mockup tests were performed for Ni-plated Alloy 600 HTMA tubes with hydraulic expansions. The integrity of the plated and then hydraulically expanded Alloy 600 HTMA tubes was examined for microstructural and SCC points of view.

The structural soundness of the interface between the plated Ni layer and the original tube surface after the hydraulic expansion was confirmed. A strong resistance against SCC was also verified for the Ni-plated and expanded tubes in simulated environments of the operating nuclear power plants. From the results of this study, it may be concluded that the Ni-plating can prevent SCC around the expansion transition region including the expanded tube ID in operating SGs. The technique could become a viable proactive method adaptable as a part of SG manufacturing processes for a countermeasure against SCC and other corrosion damages in the expansion transition regions of SG tubes in operating nuclear power plants.

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**REFERENCES**