Relation between PWSCC and residual stress on Alloy 600 Nozzle of a PWR

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1. Introduction

Primary water stress corrosion (PWSCC) of alloy 600 in a PWR has been reported in the control rod drive mechanism (CRDM)[1], steam generator nozzles[2], pressurizer heater[3]etc. Since the first report of a PWSCC in a steam generator (SG) drain nozzle at the Shearon Harris plant in 1988, other plants have experienced cracking at the dissimilar weld regions around the world. Recently, two cases of a boric acid precipitation were reported on the bottom head surface in two units of a SG in Korea. Because hot leg side drain nozzles were replaced with corrosion resistant alloy 690, no cracks were observed at the hot led side nozzles. The cracks, however, were found in the cold leg drain nozzles made of alloy 600.

The objective of the present work is to evaluate the crack morphology of the degraded nozzle, and to seek the causes of the cracking.

2. Experimental Procedures

The drain nozzle, which was contaminated with radioactive materials was transferred to a hot laboratory at the Korea Atomic Energy Research Institute (KAERI). The location of the cracked area was marked on the nozzle before the destructive examination.

The specimens for the microstructural analysis were prepared by the general metallography procedures such as cutting, mounting, grinding and polishing. To observe the carbide distribution, the specimens were etched in a bromine solution and a two-step etching solution [orthophosphoric acid, and then nital].

The bromine solution enables the carbide morphology to be clearly observed by scanning electron microscopy (SEM), the orthophosphoric acid reveals the grain boundaries carbide, and the nital etchant clearly reveals the grain boundaries of the alloy 600 specimens. All the samples were examined by SEM or optical microscopy. A transmission electron microscope (TEM-JEOL 2000FX-II) equipped with an Oxford Link EDX (Model ISIS-5947) was utilized for analysis of the carbide structure and the chemical composition.

3. Results and discussion

3.1 Carbide morphology

Grain boundary carbides were relatively well developed in the material as shown in Fig. 3. A Cr-depletion was not observed near the grain boundaries as shown in Fig. 1.

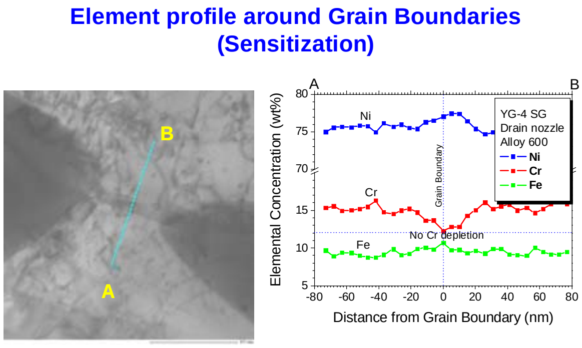


Fig.1 Element profile around the grain boundary

From the observed SCC resistant microstructure [4,5], it was considered that the material itself was not the cause of the cracking. Rather, the weld residual stress could be the main cause of the PWSCC of the alloy 600 nozzle.

Based on literature [6], PWSC susceptible grain size is about 8-16 um. The grain size of the analyzed specimen was 17.45 um, which is just out bound of the susceptible region as seen in Fig. 2. Small grain sized materials have high tensile strength, The yield strength of eh nozzle was not so high level of 413~451 MPa .

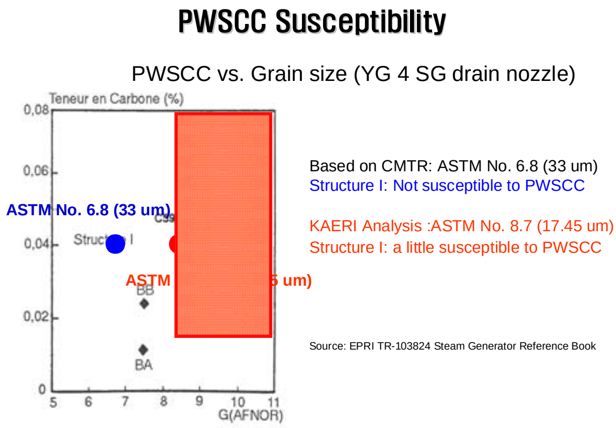


Fig. 2 Relation between grain size and PWSCC susceptibility

3.2 Fracture surface analysis

A typical morphology of the cracks is shown in Fig. 3. The cracks were developed from the inside of the pipe wall and propagated outward. Intergranular nature of the cracks suggests that the nozzle was attacked by a PWSCC.

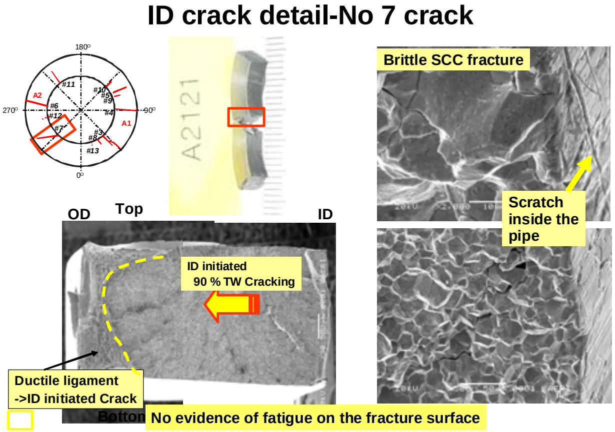


Fig. 3 Feature of cracks developed on the nozzle

It was found that two cracks out of twelve had fully penetrated the pipe wall, and the maximum length was 7.2 mm.

3.3 Residual stress analysis

The residual stress in the region was analyzed using the ABAQUS and Elastic Plastic Fracture Mechanics (EPFM). The maximum residual stress region at the nozzle weld generally coincided with the cracked location. In this study, PWSCC initiation threshold value of Alloy 600 is assumed to range on 210~240MPa at 325°C based on the previous study result [7].

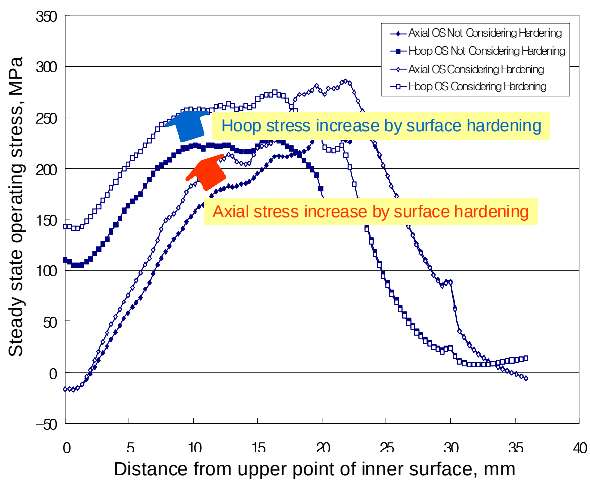


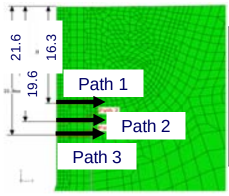
Fig. 4 Increase of residual stress after surface hardening

An effect of work hardening on inner surface was illustrated in Fig. 4. Hoop stress and axial stress were increased by a surface hardening. The PWSCC initiation might be accelerated by work hardening on the inner surface.

Fig. 5 represents crack depth ratio corresponding to the PWSCC growth threshold SIF (9MPa m^0.5.) From this table, we can expect that axial PWSCC along path 1 penetrates the wall while circumferential PWSCC along path 2 and 3 stops at the crack depth ratio around 0.83.

Calculation of Stress Intensity Factor

- Comparison with PWSCC threshold SIF(9MPa $m^{0.5}$)
- Axial crack: Wall penetration
- Circumferential crack: Stops at depth ratio of 0.83-0.84



Path	Crack Direction	Initial Crack Depth Ratio	Final Crack Depth Ratio
1	Axial	0.0372	**1.0 (Penetration)**
2	Circumferential	0.0347	**0.8307**
3	Circumferential	0.0364	**0.8459**

Fig. 5 Stress intensity factor and crack propagation

4. Conclusions

(1) Grain boundary carbides were well developed in the material, therefore, the material itself was not considered to be the cause of the cracking.
(2) Residual stress due to the welding process could be the main cause of the PWSCC of the alloy 600 nozzle.
(3) Two cracks out of twelve had penetrated 100 % of the wall thickness, and the maximum length was 7.2 mm.
(4) PWSCC initiation potential will increase if there is work hardening on the inner surface.
(5) Axial PWSCC may penetrate the wall thickness.

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