Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

The Effects of Hot Bending on the Low Cycle Fatigue Behaviors of 347 SS in PWR Primary Environment

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1. Introduction

The pressurizer surge lines in pressurized water reactors (PWRs) are typically made of stainless steels. They go through degradation by thermo-mechanical fatigue caused by operational transients and stratification. Thus, fatigue damage could be significant for some locations, especially the welds and bends where stress concentration is typically high. As a possible solution, a large radius hot-bending method has been suggested to eliminate some weld joints and all tight bends. However, for the hot-bending process which involves a high temperature thermal cycle, there is a concern about changes in mechanical properties including low cycle fatigue behaviors. In APR1400, Type 347 SS have been used as surge line pipes. Therefore, to verify the applicability of hot-bending on 347 SS surge line pipes, an environmental fatigue test program was initiated. In this paper, the preliminary results of the on-going test program are introduced. Also, the low cycle fatigue behaviors of 347 SS are compared with those of other grade of stainless steels.

2. Experimental

2.1 Test material

Test material used in this study was 347 stainless steel (SS). Specimens were obtained from the hot-bent pipe which was subjected to the high frequency induction heating. The bending radius is three times as large as diameter. Also, the bending angle is 90˚. As shown in Fig. 1, specimens from four different locations of hot bent pipe such as intrados, middle, extrados of bent pipe, heat-affected zone, and straight region, were tested. The chemical compositions and tensile properties of the test material are listed in Table I and Table II.

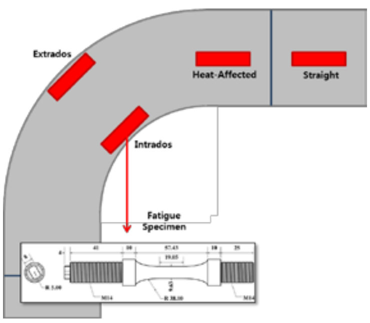

Fig. 1. Location of fatigue specimen taken from hot-bent 347 SS pipe

Table I: Chemical composition of 347 SS

C	Si	Mn	P	S	Fe
0.03	0.45	1.59	0.014	0.005	69.34
Ni	Nb	Cr			
10.7	0.17	17.7			

Table II: Tensile properties of 347 SS

ASME Spec.	Heat treatment	YS (MPa)	UTS (MPa)	Elong. (%)
SA 312 (Pipe)	1050 °C and quenching → Stabilzed at 899 °C for 2 h	250	580	68.5

2.2 Test system and conditions

The LCF tests were performed under fully reversed triangle waveform with strain rates of 0.04 - 0.4 %/s. The test environment were RT air, 330 °C air and simulated 330 °C PWR water which contained chemicals (1200 ppm of boric acid and 2.2 ppm of lithium hydroxide) and dissolved hydrogen (DH). Details of loading and environmental conditions are described in Table III. Smooth cylindrical specimens with a gauge length of 19.05 mm and a diameter of 9.63 mm were used for the fatigue tests. Details about the test facility have been described elsewhere [2]. The LCF life, N_{25}, is defined as the number of cycles for the tensile stress to drop 25 % from the peak value.

Table III: Test environments

Environment		Air, simulated PWR
Waveform		Fully reversed triangular (R = -1)
Control		Strain control
Strain rate		0.04 - 0.4 %/s
Strain amplitude		0.22 % - 0.83 %
Water chemistry	DO	< 5 ppb
	DH	~ 25 cc/kg
	Conductivity	~ 20~25 μS/cm (1200 ppm H_3BO_3 + 2.2 ppm LiOH)
	pH	6~7

3. Results and Discussion

3.1 LCF life

The LCF lives of 347 SS obtained from LCF tests in air and PWR water are shown in Figs. 2 and 3. For comparison, the estimated fatigue lives per NUREG 6909 rev. 1 are also showed in the figures. LCF lives in 330 ºC PWR water are shorter than those in RT air condition as expected. Also, based on some undergoing fractography and cross section analysis, it is estimated that hydrogen induced cracking (HIC) is the main environmentally assisted cracking (EAC) mechanism [4]. In air condition, fatigue life data are distributed around the value from NUREG 6909 rev. 1. Fig. 3 shows that while many fatigue life data are in good agreement with NUREG 6909 rev. 1, fatigue life data showed relatively large scatter for specimens in C direction of extrados. Currently, the reasons for the scatter are being investigated. However, limited data indicates that detrimental effects of hot bending may not be obvious. Additional tests are on-going to clarify the effect of hot-bending on LCF life in PWR water.

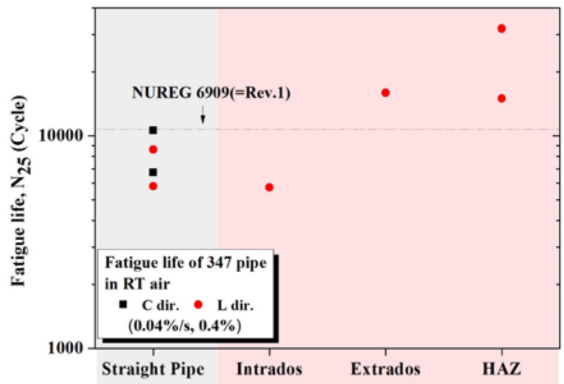

Fig. 2. Fatigue lives at several locations of hot bent 347 SS pipes in air

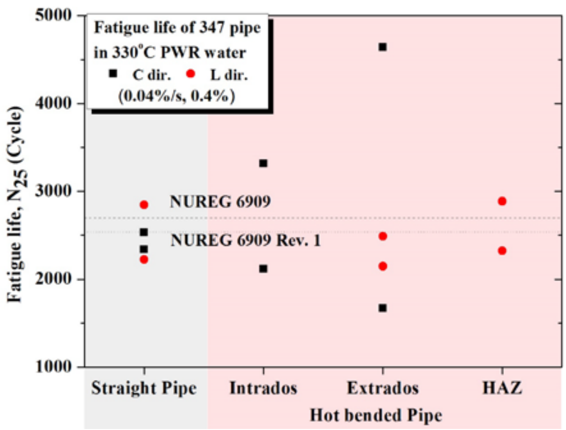

Fig. 3. Fatigue lives at several locations of hot bent 347 SS pipes in 330ºC PWR water

3.2 Cyclic stress response

The cyclic stress responses of 347 SS in RT air, 330 ºC air, 330 ºC PWR water are represented in Fig. 4. In RT air, cyclic stress response is characterized by strong secondary hardening after the stages of initial hardening, saturation, and slight softening due to stress concentration on the carbon-nitride particles at grain boundaries (GB) [3]. But in 330 ºC air and PWR water, the cyclic responses show no secondary hardening and peak tensile stresses decrease gradually. And the extent of hardening in PWR water is lower than that of 330 ºC air. Compared with other materials such as alloy 690, the extent of hardening in PWR water is higher than that of 310 ºC air [5]. In a type 316LN SS case, the cyclic stress responses of 347 SS exhibit more distinct behavior than that of 316LN [6].

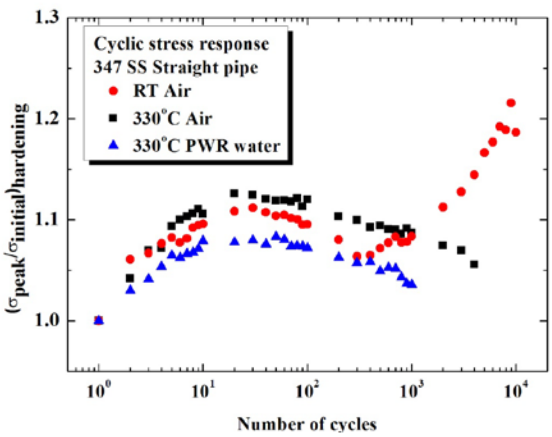

Fig. 4. Cyclic stress responses of 347 SS in RT air, 330 ºC air and 330ºC PWR water

4. Conclusions

The effects of hot bending on the low cycle fatigue behavior of 347 SS were quantitatively evaluated. The fatigue life was compared with the estimated values per NUREG 6909 rev. 1. There are no distinct differences between NUREG 6909 and LCF tests. According to fractography and cross section analysis in progress, basically, the reduction of LCF life of 347 SS in PWR water was caused by operation of HIC mechanism. The cyclic stress responses shows that there is no secondary hardening in 330 ºC air and PWR water. Currently, more LCF tests are underway. Also, the microstructure and fractography analyses are in progress to understand the EAC mechanisms and the effects of hot-bend on LCF behaviors of 347 SS.

ACKNOWLEDGMENTS

This study was supported by the Nuclear Research & Development Program. Financial support for one of the authors was provided as the BK-Plus Program of the MSIP of the Rep. of Korea.

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