Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Diagnosis of PWSCC-induced Burst and Leak Processes in U-bend Regions of Steam Generator Tubes Using Acoustic Emission Method

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1. Introduction

In the pressurized water reactor, steam generator (SG) tubes play the important role in transferring the heat from the primary reactor coolant to make steam in the secondary-side to drive turbine generators. Existence of defects like the primary water stress corrosion cracks (PWSCC) can lead to the tube burst and leak failure events [1]. As the pressure of primary reactor coolant is higher than that of secondary coolant, any leakage in the SG tubes can result in release of radioactivity to the environment outside. Therefore, in-service monitoring and evaluation of the tube failure process is very necessary in preventing the catastrophic accidents.

Acoustic emission (AE) is an in-situ nondestructive evaluation method that senses the transient elastic waves from a rapid release of energy during a material damage process. This feature allows AE to provide a dynamic perspective on the tube failure evolution. Accordingly, this work was aimed to evaluate the detailed stages of crack burst and leak processes in SG tubes using AE method.

2. Experimental method

The previous experiences in operating power plants have shown that the U-bend regions of tubes with lower row number are more susceptible to PWSCC [1-2]. So the U-bend tube with row-1 was chosen as the research sample for this work. The straight Alloy 690 SG tubes with OD 19.05 mm and WT 1.07 mm were bent to 180 degrees by a non-friction type rotating die to produce the samples. Natural SCC cracks were manufactured on the ID surface of U-bend region by exposing to a solution of sodium tetrathionate [3]. After this process, the tube samples were inspected using eddy current testing (ECT) with a commercial motorized rotating coil probe.

An internal pressurization test was employed to cause the pre-cracked tubes to rupture using a hydraulic pump. During this process, a piezoelectric AE sensor with a resonant frequency of 150 kHz was attached on the tube surfaces via a wave guide to collect the AE signals, which were filtered by a band pass between 100 and 300 kHz. After the occurrence of tube failure, the AE test was stopped. The threshold level was determined as 32dB and preamplifier was set at 40dB.

3. Results and discussion

3.1 ECT signals

Fig. 1 shows the ECT signals in C-scan graphs from different tube samples. Here, samples #a, #c and #d are U-bend tubes which were previously exposed to sodium tetrathionate and sample #b is a straight tube with EDM notched crack. It is clearly observed that the great ridges along the axial direction are distinguished from the

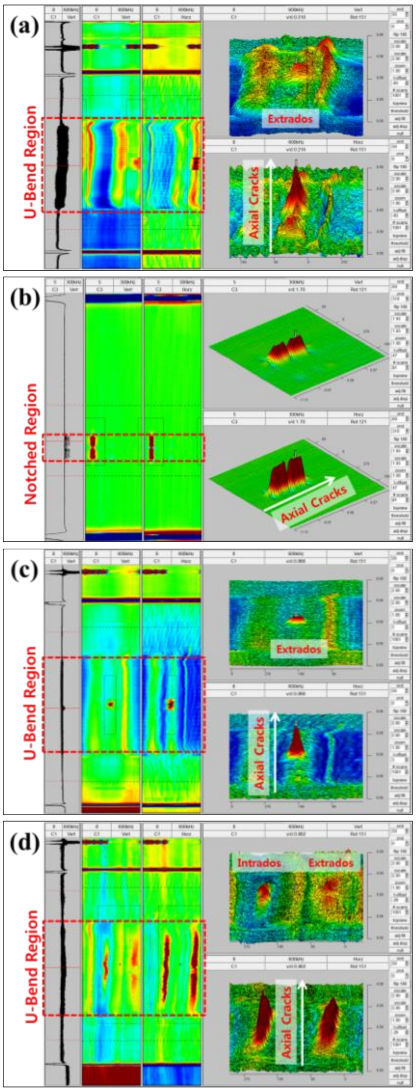

Fig. 1. C-scan graphs of plus point coil signals from the tube samples #a, #b, #c, and #d.

background noise signals. These results confirm the existence of pre-made axial cracks inside the tube samples.

3.2 Internal pressurization test and tube failures

Fig. 2 shows the tube failures in different samples and post-observations of the failure sites. It clearly shows that rupture bursts occurred in samples #a and #b with resultant "fish-mouth" openings [1], while leak failures occurred in samples #c and #d with through-wall cracks. The details of the tube failures are given in Table I.

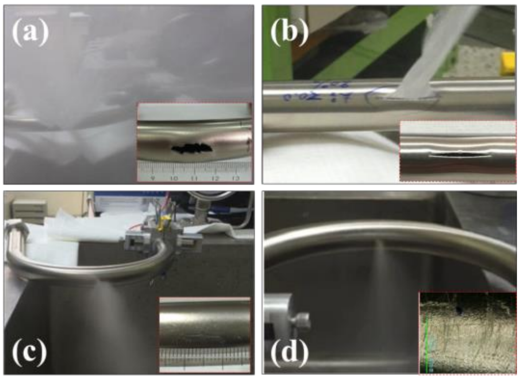

Fig. 2. Photographic showing of the tube failures during the pressurization tests in different tube samples: #a, #b, #c and #d.

Table I: Summary of the internal pressurization test for generation of tube failures.

Sample	Failure type	Failure site	Failure pressure
#a	Crack burst	Apex Extrados	361 bar
#b	Crack burst	Notched site	278 bar
#c	Crack leak	Apex Extrados	332 bar
#d	Crack leak	Apex Intrados	87 bar

3.3 AE results of the tube burst process

Fig. 3a and 3b show the AE results during tube burst process in samples #a and #b. Based on AE hits evolutions in Fig. 3a-1 and 3b-1, it clearly shows two stages. In stage I, AE activity was very active and hits number almost increased to a maximum by the end of Stage I. Once Stage II initiated, AE activity decreased but was still detectable. Finally, AE was activated again upon the burst rupture. From the AE energy evolutions in Fig. 3a-2 and 3b-2, AE signals in both stages I, mainly lower than 10^3 aJ, may be produced by plastic deformation around the crack tip. While the distinct features between samples #a and #b in AE stage II may be attributed to the different manufacture history. In stage II of sample #a, which had experienced work hardening during U-bent process, the energy loop with a

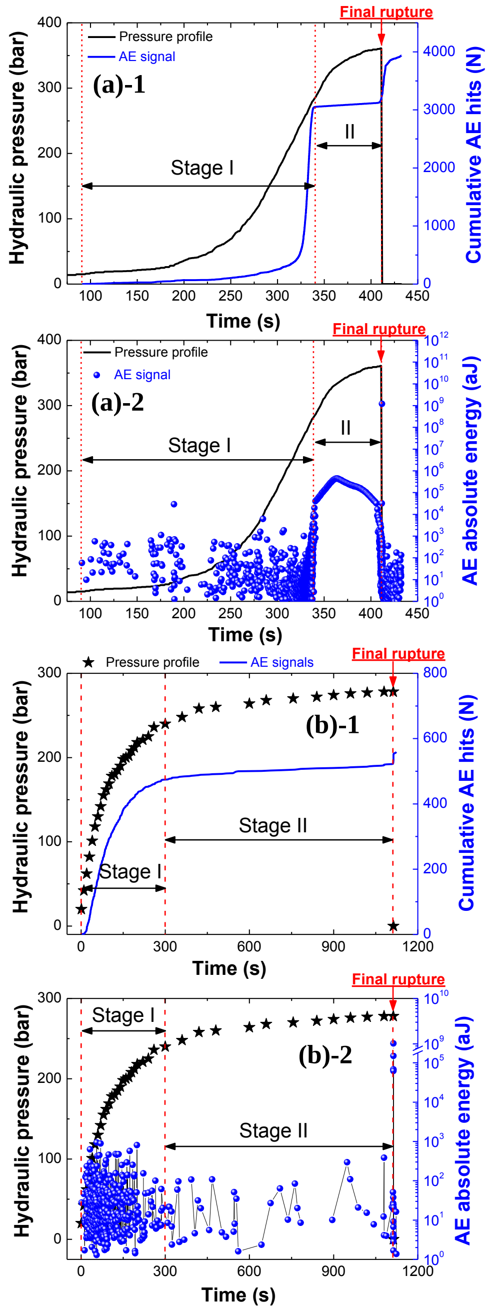

Fig. 3. AE results of hits and energy detected during the pressurization test for tube burst process: (a) 1-2: sample #a; (b) 1-2: sample #b.

peak around 10^6 aJ might be associated with the formation and coalescence of micro-voids. Upon the final rupture, ductile tearing of the ligaments between cracks may be responsible for the AE with high energy up to 10^9 aJ.

As for the case of notched straight tube sample #b, AE during the failure process may be interpreted by comparison with a tensile deformation of a pre-notched 304 stainless steel specimen [4]. Around the yielding, massive mobile dislocation during plastic deformation produced intense AE in stage I. But as strain increased, increasing of dislocation density can restrict the moving dislocation and thus glide distance for moving dislocations decreases, which may interpret the rare AE in stage II. Approaching the final rupture, micro-void formation with the immediate coalescence may account for the high-energy AE signals (10^5-10^9 aJ).

3.4 AE results of the tube leak process

Fig. 4c and 4d shows the AE results during tube leak failure in samples #c and #d. Apparently, AE signals were detected before leak initiation. In the case of sample #c, AE evolution could be divided into two stages based on the energy feature. Considering the possible damage processes, stage 1 of relatively low energy below 10^3 aJ may be corresponding to the plastic deformation around the crack tips. As internal pressure increased, AE stage II with higher energy may be in association with the micro-void formation. Upon the leak initiation, linking between the micro-voids and tearing penetrated the tube wall, which could be responsible for the highest-energy signal at the leak point up to 10^6 aJ.

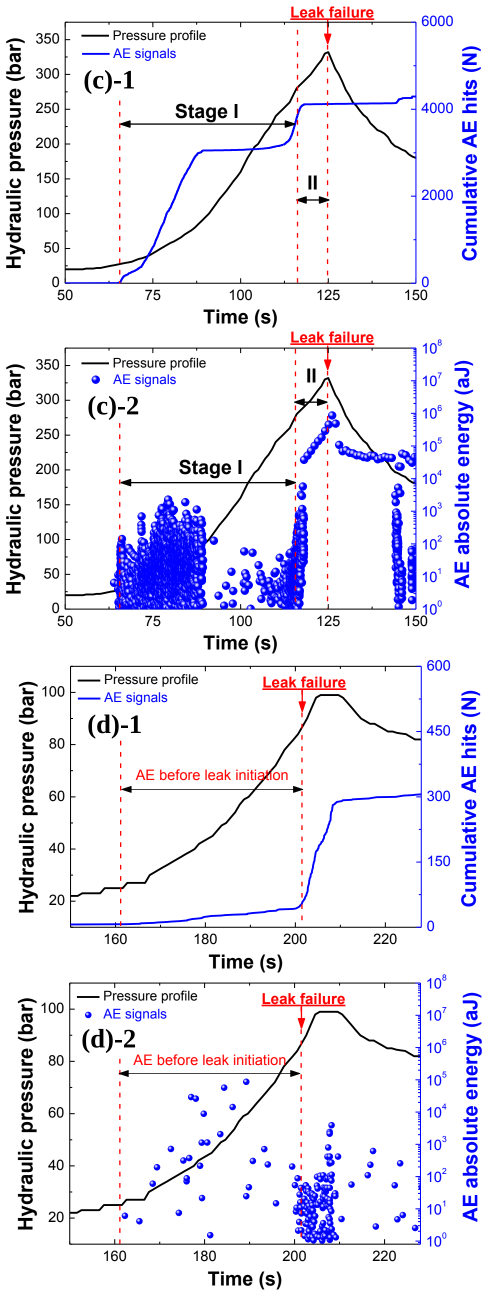

Fig. 4. AE results of hits and energy detected during the pressurization test for tube leak process: (c) 1-2: sample #c; (d) 1-2: sample #d.

In the leak failure of sample #d, AE energy feature before leak failure was dispersive and high up to 10^5 aJ (Fig. 4d-2), suggesting that the formation and coalescence of void may occur simultaneously. Since the natural crack was deep enough and the wall to penetrate was thin (Fig. 1d), the linking between micro- and macro-voids is supposed to interpret the final leak failure. Here, it is worth noting that, AE signals after the leak failure, i.e., leak-AEs, are three orders of magnitude lower than the case of sample #c (Fig. 4c-2). This may be interpreted as follows: since failure pressure was very low (87bar, Table I), leak rate was accordingly lower, which is contributed to the relatively low-energy leak-AEs.

4. Conclusions

In this work, AE characteristics during the processes of PWSCC-induced burst and leak in the U-bend regions of SG tubes were studied. AE activity presented different features before and after the tube failures. Also, AE differences between burst and leak processes were confirmed. Based on the AE analysis, the possible processes before tube failure, such as plastic deformation, formation and coalescence of micro-voids, and ductile tearing, could be qualitatively identified by stages. These findings reveal the potential of using AE signals to study the processes of crack rupture and leak.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP).

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