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Background noise limit of Alloy 690TT steam generator tube measured using rotating eddy current probe for detecting OD axial cracks

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1. Introduction

Nickel-based alloys are widely used as consisting materials of a pressurized water reactor (PWR) such as steam generator (SG) tubes, pressurizer instrument nozzles, SG drain nozzles, hot-leg instrument nozzles, control-rod drive mechanism nozzles and piping safe ends due to their superior corrosion resistance. Particularly, Alloy 690TT has been regarded as a promising SG tubing material to replace Alloy 600, which have been suffered by various corrosion damages such as stress corrosion cracking, intergranular attack and pitting. The corrosion damages of Alloy 690TT SG tubing material have not yet reported in current operating conditions of PWRs except for mechanical damages such as wear, since it was firstly used in 1989 as a SG tubing material. However, many researchers have been studying for corrosion characteristics of Alloy 690TT material such as crack initiation/propagation or general corrosion behaviors in various PWR environmental conditions in viewpoint of ensuring the integrity of SGs and the safety of nuclear power plant.

To assess the integrity of SGs, the eddy current test (ECT) method is widely used to detect new defects occurring in SG tubes and to monitor the growth of the pre-existing flaws during an in-service inspection (ISI). The detection probability and sizing accuracy of a flaw depends on the quality of the eddy current (EC) signals. The EC signals generated from the SG tubes often contain an undesirable signal, i.e., noise. Common noise sources are tube support structures, corrosion product deposits, changes in tube dimensions and geometry, and probe wobble and lift-off [1-3]. In addition, the probe response associated with the material property variations, non-uniform surface conditions, and electronic noise from the test equipment can also be caused as a noise source [3,4]. These noise signals make it difficult to detect and interpret flaw signals because these distort the phase angle and the amplitude of the defect signals. Thereby, several efforts have been implemented to reduce the noise through improving the signal quality and enhancing tube quality [5-8], and the EC noise limit has been recommended from the manufacturing step to improve the inspectability of the defect during the ISI.

In this work, we investigate the influence of the noise amplitude of Alloy 690TT SG tube on the detecting and sizing of axial outer diameter (OD) cracks. The axial OD cracks were produced on three tubes with different +point coil noise using ultrafast laser technique. The detection limit of the defects is discussed from the phase angle and amplitude of the crack signals.

2. Experimental

Three Alloy 690TT SG tubes with an outer diameter of 19.05 mm and a wall thickness of 1.1 mm were used to make artificial OD axial cracks. The tubes were manufactured by a pilgering process and had a different +point coil noise as summarized in Table 1. The axially-oriented cracks were made with 3 mm length using ultrafast laser scanner. The laser source is a commercial carbide laser system (Light Conversion Co.) providing linearly polarized laser pulses with a duration of 190 fs at a central wavelength of λ = 1030 nm and an repetition rate of 30 kHz. The focal length of scan lens was a 167 mm and scan speed was a 15 mm/s. The sixteen cracks were made on each tube at 10 mm intervals with increasing 10 scans. Then, the vapor generated by laser ablation was immediately removed by suction with argon blowing to prevent it fill up a crack.

The ECT signals were acquired using the Zetec MIZ-70 digital data acquisition system with a conventional 3-coil motorized rotating probe, which consists of two pancake coils and a plus point coil. The probe was inserted into the inside of the tube and is moved along the length of the tube at a pulling speed of 5.08 mm/s while being rotated at a constant rotating rate of 600 rpm. The signal from the axial throughwall electron discharge machining (EDM) notch of a 9.525 mm length was calibrated to be an amplitude of 20 V and a phase angle of 30 degrees at 300 kHz. The noise signals were measured at the region between an interest crack and next crack to reflect the local surface state of each tube. In addition, the +point coil signals were only compared to exclude the effect by thickness difference as a type of volumetric defect.

Finally, the cracks were destructively examined to measure their actual length and depth using optical microscope (OM).

Table 1. +Point coil noise of Alloy 690TT SG tubes.

Tube ID	+Point coil noise (Volt)	
	V_{vmax}	V_{pp}
Tube A	0.05	0.06
Tube B	0.11	0.38
Tube C	0.17	0.60

3. Results and discussion

Three tubes were selected with different tube noise levels measured using the +point coil probe for fabricating the axial OD crack. The average noise level was measured as a V_{vmax} and a V_{pp}. Herein V_{vmax} and V_{pp}

indicate a vertical maximum amplitude and a peak-to-peak amplitude of a tube noise signal, respectively. The relationship between V_{vmax} and V_{pp} can be explained by the following equation;

$$V_{pp} = \sqrt{V_{vmax}^2 + V_{hmax}^2} \quad (1)$$

where, V_{hmax} is a horizontal maximum amplitude of the +point coil noise. In other words, V_{pp} is an amplitude between two points that are farthest apart vectorially in the Lissajous of +point coil noise signal, i.e., a vector sum of the vertical component and the horizontal component. The average V_{vmax} noise of each tube was 0.05 V(tube A), 0.11 V(tube B), and 0.17 V(tube C) as summarized in Table 1. In addition, V_{pp} value of each tube was 0.06 V(tube A), 0.38 V(tube B), and 0.60 V(tube C), respectively.

Fig. 1 shows the C-scan of the horizontal component of +point coil noise measured at the frequency of 300 kHz. Tube A shows a smooth surface state. However, tube B and C has several ridges and valleys along the tube length. These axial irregularities seem to be produced during the inadequate cold pilgering process. From the equation (1), the horizontal component amplitude of the noise can be evaluated by 0.03 V(tube A), 0.36 V (tube B), and 0.58 V(tube C). This indicates that the horizontal noise level of tube B and C is 12~19 times comparing to that of tube A. Therefore, it is expected that the crack signals of tube B and C is difficult to be detected due to their high background noise.

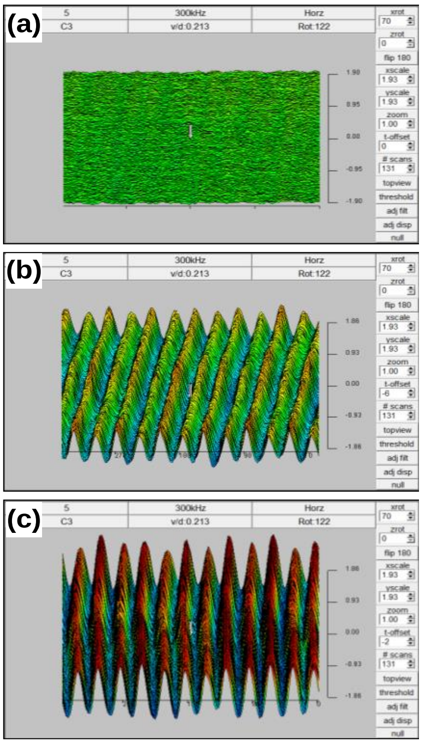

Fig. 1 C-scan of the horizontal component of noise signal obtained using +point coil probe: (a) tube A, (b) tube B, and (c) tube C.

Fig. 2 shows the optical microscope (OM) image of longitudinal fracture surface for a 40% OD crack made using the ultrafast laser and the variation of crack depth as a function of laser scanning number. The color of fracture surface was distinguished by 3 zones such as blackish, brownish, and silvery regions as shown in Fig. 2(a). The circumferential cross-section of the crack displayed V-shape and the width of crack mouth was similar with about 100 μm for all laser-processed cracks. The width of the crack became gradually narrower to the inner diameter (ID) surface and was narrowed to about 5 μm at the crack tip as shown in the inset of Fig. 2(a). The crack depth was evaluated by about 40% of the wall thickness of tube but it seemed to be slightly different along the longitudinal direction of the crack. In addition, the crack depth measured in the cross-sectional image seems to be agreed with the blue line including blackish and brownish regions. The crack depth increased gradually with increasing the number of laser scans and was similar value for the same treatment in all three tubes as shown in Fig. 2(b). The processability of the crack through laser scanning declined gradually as the crack depth became thicker.

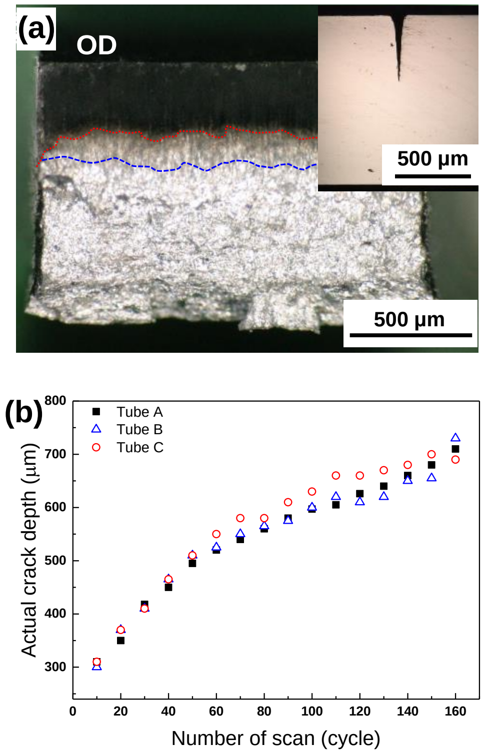

Fig. 2 (a) The destructive OM image of a 40% depth crack and (b) the relationship between the number of laser scan and the crack depth.

Fig. 3 shows the relationship between crack depth and phase angle of +point coil signal measured at 300 kHz frequency. The solid line indicates the phase angle of ID and OD EDM notches with different depth. Then, the phase angle was 0 ~ 30 degrees for ID defect and 30 ~ 105 degrees for OD defect, when the signal of throughwall EDM notch (100% depth) is calibrated to be a phase angle of 30 degrees. It is obvious that all cracks produced on tube A, which has the lowest +point coil noise, is the OD defect because their phase angles are located in the range of 80 ~ 105 degrees. However, the phase angles of tube B and C, which showed higher +point coil noise, were investigated in the range of 4~85%. Herein, the cracks having the phase angle lower than 30 degrees can be discriminated as the ID crack because it is in the range of the phase angle of ID crack. This result might be because the phase angle of crack decreased due to interference of the signal with the horizontal noise.

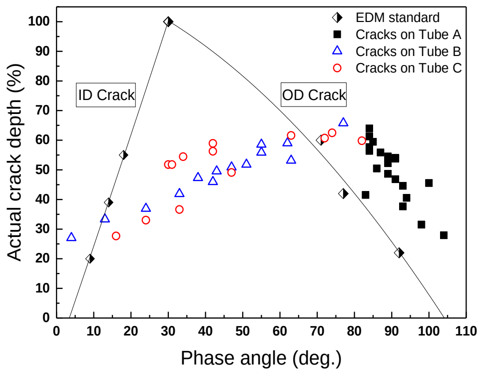

Fig. 3 The relationship between crack depth and phase angle; the solid line indicates the crack depth and phase angle of ID and OD EDM notches.

Fig. 4 shows the relationship between +point signal amplitude and the depth of cracks, which was discriminated to be a defect in their phase angle. The crack of 30% depth was discriminated as an OD crack in tube A, while the cracks having the depth over 40% were detected in tube B and C. Here, the amplitude of crack signal was denoted to $V_{Signal\text{-}vmax}$ and $V_{Signal\text{-}pp}$ to distinguish with the noise signal. The $V_{Signal\text{-}vmax}$ value of crack presented a proportional relationship with an actual crack depth in all three tubes as shown in Fig. 4(a). The $V_{Signal\text{-}pp}$ value of crack also showed similar property with the $V_{Signal\text{-}vmax}$ in tube A, which had very low background noise. However, the $V_{Signal\text{-}pp}$ value of the crack was deviated from the proportional relationship with the actual crack depth. In other words, the $V_{Signal\text{-}pp}$ amplitude is distributed in wide range for the crack with the same depth in tube B and C. This means that the resolution of detection for the crack with the same depth is degraded in the tube having high tube noise.

Fig. 5 shows the relationship between the signal-to-noise (S/N) ratio and the crack depth. All cracks fabricated on three tubes presented the value larger than 2 for the S/N ratio in a vertical component as shown in Fig. 5(a). However, the slope of the relationship between the $V_{Siganl\text{-}vmax}/V_{Noise\text{-}vmax}$ ratio and the crack depth became lower with increase of the +point coil noise. This indicates that the detection resolution of the crack in the vertical component decreases as the tube noise increases because the crack signal is interfered with the noise signal. The influence of the tube noise on the crack signal sizing was seen well in Fig. 5(b). The relationship of the $V_{Siganl\text{-}pp}$ with the $V_{Noise\text{-}pp}$, which is used to evaluate the size of crack, shows clear difference between tube A and other tubes.

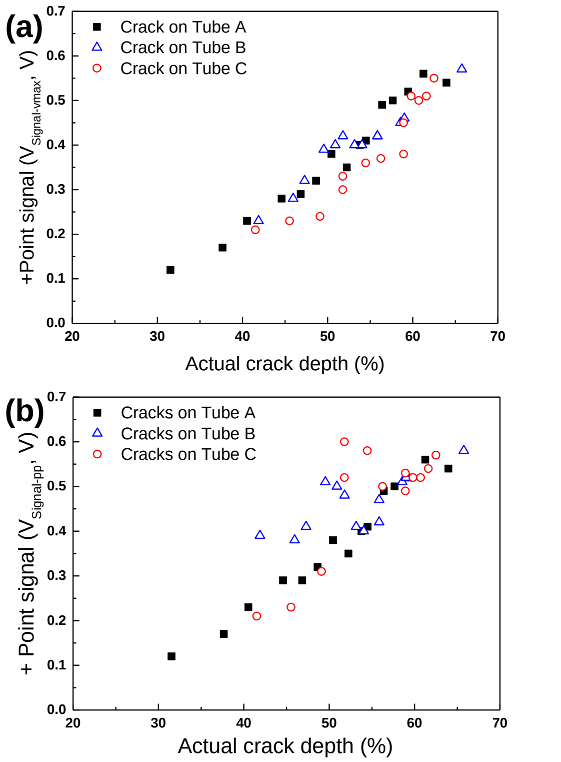

Fig. 4. The relationship between the +point signal amplitude and the depth of OD axial crack with length of 3 mm; (a) $V_{Signal\text{-}vmax}$ and (b) $V_{Signal\text{-}pp}$.

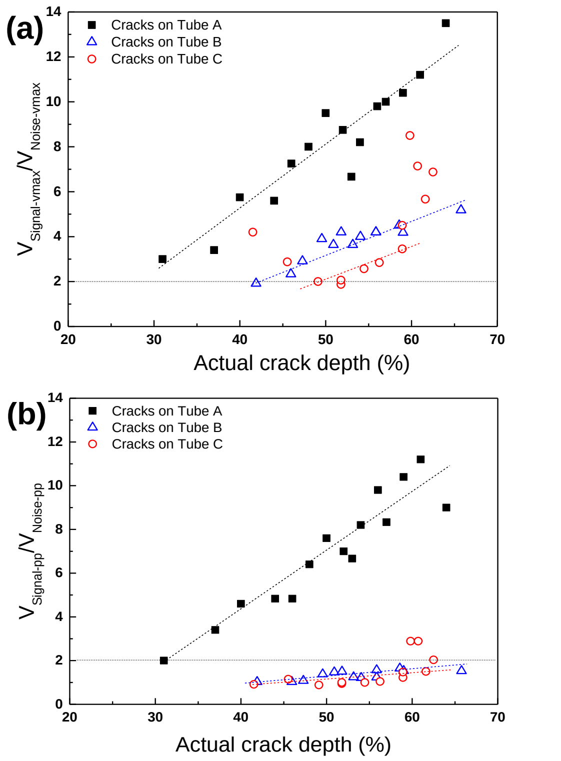

Fig. 5. The relationship between the signal-to-noise ratio and the depth of the crack with length of 3 mm; (a) $V_{Signal\text{-}vmax}/V_{Noise\text{-}vmax}$ and (b) $V_{Signal\text{-}pp}/V_{Noise\text{-}pp}$.

The $V_{Siganl\text{-}pp}/V_{Noise\text{-}pp}$ ratio also presented the value larger than 2 in tube A like as $V_{Siganl-vmax}/V_{Noise-vmax}$. However, the $V_{Siganl-pp}/V_{Noise-pp}$ ratio was about 1 for the cracks in tube B and C. In other words, this means that the sizing of the crack with 40~60% depth is difficult to be detected because the signal amplitude of the crack is equivalent to the noise amplitude.

Considering the results in Figs. 4 and 5, both of $V_{Signal-vmax}$ and $V_{Signal-pp}$ of tube A were larger than 2 times comparing to the noise amplitude for all cracks, while tube B and C presented very low $V_{Signal-pp}/V_{Noise-pp}$ ratio of about 1, although its $V_{Siganl-vmax}/V_{Noise-vmax}$ was about 2. The size of cracks in tube B and C is difficult to be evaluated because the crack size is evaluated using the $V_{Signal-pp}$ value in industry and the S/N ratio become at least larger than 2 in a viewpoint of probability of detection (POD) of the examiner or in automatic evaluation program [2,9]. Therefore, the +point noise level would be limited as low as possible to improve the detectability of the crack during ISI.

4. Conclusions

In this work, we fabricated the artificial cracks on Alloy 690TT SG tube using ultrafast laser scanning method to evaluate the influence of +point coil noise on the detectability of the axial OD crack. Tube A with low +point noise is easy to detect and to evaluate the size of the crack. However, tube B and C with high noise, which is equivalent to the amplitude of flaw signal, is difficult to evaluate the size of the cracks of 40~60% depth. Therefore, the +point coil noise would be limited from the manufacturing step to improve the detectability of the flaws during ISI as low as possible.

Acknowledgments

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REFERENCES

[1] J. García-Martín, J. Gómez-Gil, E. Vázquez-Sánchez, Non-destructive techniques based on eddy current testing, Sensors Vol. 11, p.2525, 2011.
[2] H. Cothron, Measuring and Monitoring Noise in Steam Generator Tubing Eddy-Current Data for Tube Integrity Applications, TR-1016554, EPRI, Palo Alto, 2008.
[3] S. Bakhtiari, D. S. Kupperman, W. J. Shack, Assessment of Noise level for Eddy Current Inspection of Steam Generator Tubes, NUREG/CR-6982, USNRC, Argonne, 2009.
[4] D. Hur, M. Choi, H. Shim, D. Lee, O. Yoo, Influence of Signal-to-Noise Ratio on Eddy Current Signals of Cracks in Steam Generator Tubes, Nucl. Eng. Technol. Vol. 46, p.883, 2014.
[5] R. Grimberg, Electromagnetic nondestructive evaluation: present and future, J. Mechanical Eng. Vol. 57, pp.204, 2011.
[6] H. Huang, N. Sakurai, R. Takagi, T. Uchimoto, Design of an eddy-current array probe for crack sizing in steam generator tubes, NDT&E International, Vol 36, pp. 515, 2003.
[7] O. Miyahra, K. Hirai, S. Nishiyama, S/N improvement and proposal of S/N calculation method for PWR SG tubing, Proc. Of the 31st EPRI Steam Generator NDE Workshop, New Hampshire, 2012.
[8] H. Cothron, Beaver Valley-1 Noise Pilot Project Results, Experience, and Recommendations, TR-1012985, EPRI, Palo Alto, 2006.
[9] R. Wolfe, Advanced Nuclear Technology: Alloy 690 Steam Generator Tubing Specification Sourcebook, TR-3002003124, EPRI, Palo Alto, 2014.