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Development of Magnetic Phase Detection Sensor for the Steam Generator Tube in Nuclear Power Plants

Derac Son[1]*, Won Ik Joung[1], Duck-Gun Park[2], and Kwon Sang Ryu[3]

[1]*Physics, Hannam University 133, Daedeuk-gu Daejeon 306-791, Korea*
[2]*Nuclear Materials Development, KAERI, P. O. Box 105, Daejeon 305-353, Korea*
[3]*Safe Metrology, KRISS, Daedeuk-gu Deajeon 305-340, Korea*

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A new eddy current testing probe was developed to separate the eddy current signal distortion caused by permeability variation clusters and ordinary defects created in steam generator tubes. Signal processing circuits were inserted into the probe to increase the signal-to-noise ratio and allow digital signal transmission. The new probe could measure and separate the magnetic phases created in the steam generator tubes in the operating environment of a nuclear power plant. Furthermore, the new eddy current testing probe can measure the defects in steam generator tubes as rapidly as a bobbin probe with enhanced testing speed and reliability of defect detection.

Keywords : non-destructive testing, eddy current testing, steam generator tube, magnetic phase detection

1. Introduction

The steam generator tube (SGT) in a nuclear power plant is a boundary between the primary and secondary sides, whose integrity is one of the most critical factors for nuclear safety. The SGT is exposed continuously to harsh environmental conditions, including high temperatures, pressures, fluid flow rates and material interactions, resulting in a variety of degradation mechanisms, such as mechanical wear between the tube and tube support plates, outer diameter stress corrosion cracking (ODSCC), pitting, volumetric changes, primary water stress corrosion cracking (PWSCC), and inter granular attack (IGA) [1]. Multi-frequency eddy current inspection techniques are currently among the most widely used techniques for the rapid inspection of SG tubing in the nuclear power industry [2]. Although use of the eddy current technique (ECT) is widespread in the nuclear industry, it has a limitation in determining the size of flaws accurately because the eddy current measures the impedance from the change in conductivity associated with the volumetric change in the flaws, where the permeability of a flaw is considered to be unity. The EC test is currently applied to nonferrous materials with a relative permeability of 1, such as Inconel alloy, because the magnetic permeability of magnetic materials severely limits the penetration depth of the induced eddy currents. Furthermore, a small magnetic phase with permeability variations inherent in SGT can cause spurious ECT results [3]. Some parts of the SGT that change as a magnetic phase under high pressure and temperature conditions, which is the operating environments of a nuclear power plant, are known as permeability variation clusters (PVC).

The relative permeability of the magnetic phase is > 1 and the number of ferromagnetic phases can reach several thousand. Internal stresses caused by drawing, straightening and similar working of the material can cause severe fluctuations in permeability. These fluctuations interfere with the test signals. In order to eliminate this interference effect during testing, the ferromagnetic test piece can be magnetized by a suitable device, such as a magnetized ECT probe. The relative permeability will approach unity using a suitable device. The magnetic properties of the ferromagnetic test piece become similar to those of a non ferromagnetic material. Hence, the interference from permeability fluctuation can be eliminated [4]. Recently, a magnetized probe with a built-in permanent magnet was used in SGT inspections to eliminate ECT signal fluctuations because the strong magnetic field

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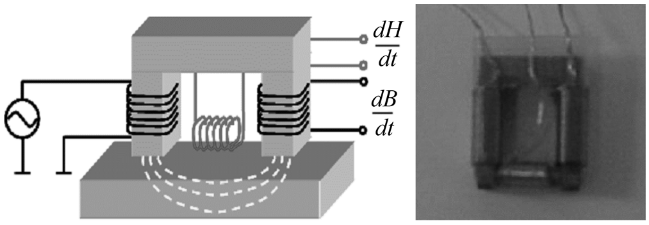
*Corresponding author: Tel: +82-42-629-7512
Fax: +82-42-629-8313, e-mail: deracson@hannam.ac.kr

of this probe can reduce the variations in magnetic permeability, which improves the S/N ratio. If the magnetic phase can be separated selectively from the flaws using a magnetic sensor, the reliability of ECT in a SGT inspection will be enhanced considerably. This paper reports the possibility that the permeability sensor can be applied to detect the magnetic phase in steam generator tubes and measure them quantitatively.

2. The Principle of Magnetic Phase Detection Sensor

The measuring principal of the magnetic phase in Inconel alloy is based on measuring the magnetic flux density of a sample. It is composed of a U-shape yoke wound magnetizing coil, a *B*-sensing coil and an *H*-sensing coil as shown in Fig. 1-(a). The appearance of the magnetic phase in the Inconel alloy results in a change in the magnetic flux density of the B-searching coil. The change in flux density due to the magnetic phase can be obtained by measuring the applied field and induced flux using the H-sensing coil and B-sensing coil, respectively. In this testing, the magnetizing coil is generally close to the test sample in order to minimize the lift-off. The magnetic flux line that it creates affects the sample, as shown in Fig. 1-(a). The constructed probe shown in Fig. 1-(b) consists of an exciting coil, a magnetic field sensor and a Si-Fe yoke with two solenoids: the driving coil and pick-up coil. This probe detects the change in voltage and phase shift induced by the magnetic field caused by the presence of the magnetic phase in the structure under test.



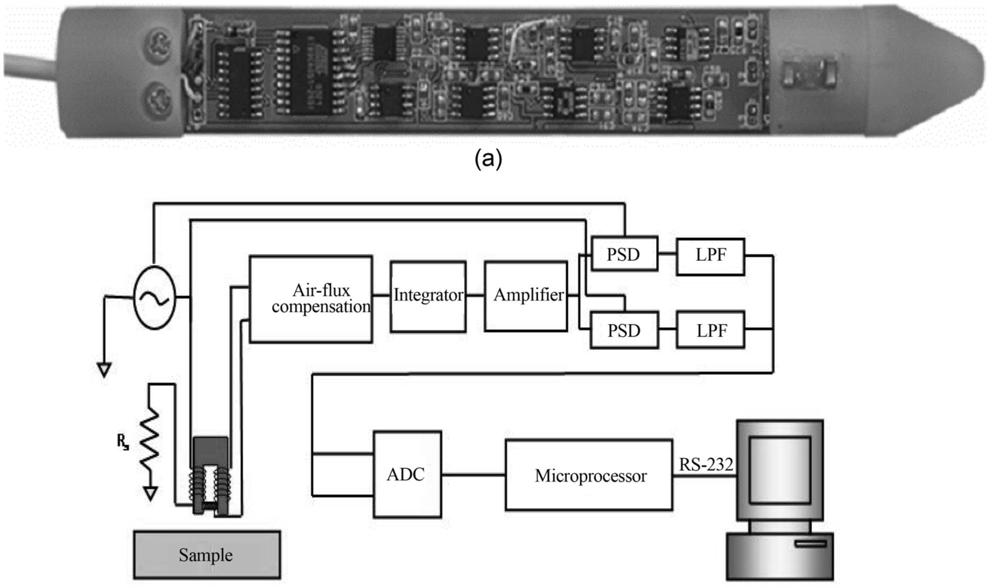
(a) (b)

Fig. 1. (a) Structure of the sensor for magnetic phase detection, and (b) Photograph of the sensor.

The measurement system was constructed using a waveform generator to excite the coil with a sinusoidal current and a lock-in amplifier to detect the vector component of magnetic flux. The x- and y-components represent the phase and out of phase signals, respectively. Fig. 2 shows a photograph of the test probe and block diagram of the measuring system. The probe for measuring the flaws and magnetic phase in the SGT was constructed to the size of the eddy current test. Therefore, the new probe passed through the 7/8" SGT tube with an ID of 19.69 mm. The electronic circuits for magnetizing the yoke, which measure the voltage induced by the magnetic phase, were inserted in the probe. The induced voltage was converted to a digital signal using 4-channel 16 bit analog digital converter (ADC) circuits, and an 8bit embedded micro-controller 89C4501 in the probe. The digital signals were transmitted to a personal computer through a RS232C interface.

3. Results and Discussion

An Inconel 600 plate specimen containing various



(a)

(b)

Fig. 2. (a) New eddy current test probe and (b) Block diagram of the measuring system.

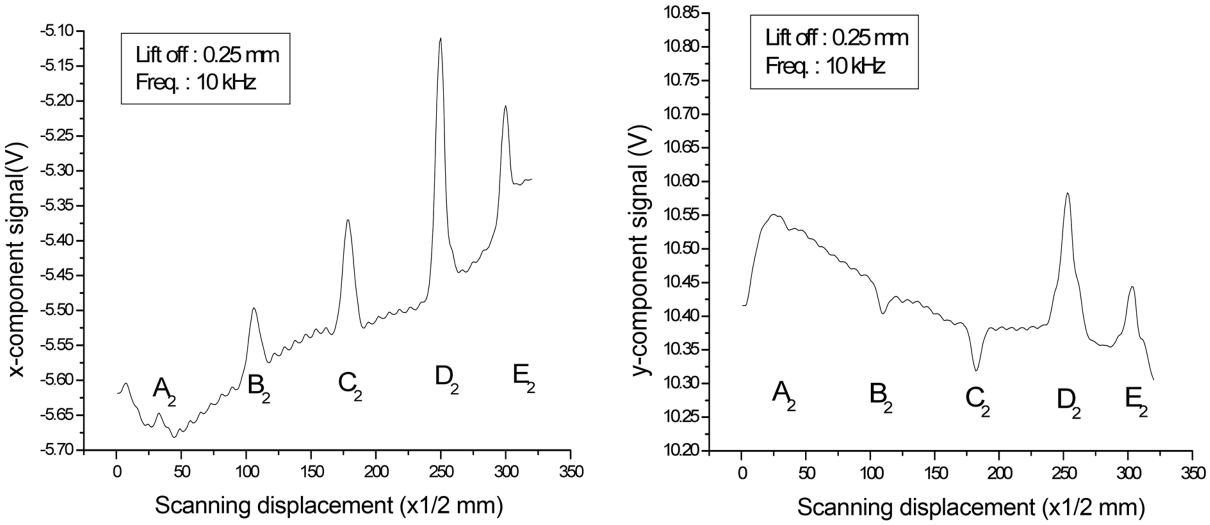


Fig. 3. Experimental results on the Inconel 600 plate with the artificial flaws (A2, B2, C2) and a ferromagnetic phase (D2, E2).

artificial slots and magnetic phases was used in this experiment to assess the performance of the magnetic phase detection sensor. The detecting capability of the magnetic phase was examined using the developed sensor and plate type specimen. The results were applied to the manufacture of a bobbin type probe to detect the SGT. Fig. 3 shows the experimental results obtained by analyzing the Inconel plate containing artificial flaws and magnetic phase with the permeability detection probe. In this figure, A2 is the EDM slot, which is 0.127 mm in width, 4.013 mm in length and 0.229 mm in depth. Flaws B2 and C2 have the same area but the depths were 0.457 mm and 0.686 mm, respectively. In the D2 and E2 positions, a slice of the ferromagnetic materials, 0.15 mm × 1.6 mm × 0.2 mm in size with a permeability of 510 and 780, respectively, were inserted in the Inconel plate. The measurements were carried out at a frequency of 10 kHz. The lift-off was varied from 0.25 mm to 0.75 mm. In this experiment, the different sizes of the crack and magnetic phase could be detected using the permeability measurement based system. The induced voltages are proportional to the sizes of the artificial cracks, and the y-component signal is reversed in the ferromagnetic fragments.

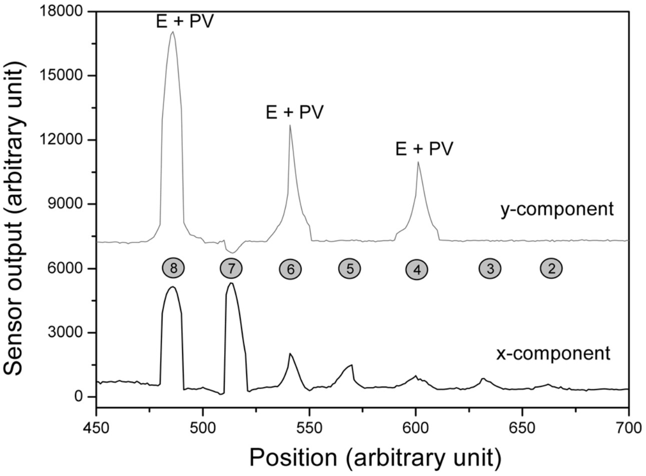


Fig. 4. Change in magnetic flux density in the artificial flaws and magnetic phase.

Fig. 4 shows the experimental results obtained by analyzing the Inconel tube containing the artificial flaws and magnetic phase using the permeability detection probe. The sample had an EDM slot, 0.5 mm in width, 10 mm in length and 0.254 mm in depth, through the hole, as shown in Table 1. The ferromagnetic phases were inserted in the sample positions 4, 6, and 8 to simulate the PVC effects. In this experiment, the different sizes of the cracks and magnetic phases can be detected using the permeability measurement based system. The induced voltages are proportional to the sizes of the artificial cracks, and signs of the x- and y-component signals are the same in the

Table 1. Dimensions of the artificial flaws and ferromagnetic phases according to the sample position in the Inconel 600 tube

Sample position	Width (mm)	Length (mm)	Depth (mm)
1	0.5	10	0.254
2	0.5	10	0.508
3	0.5	10	0.762
4	0.5	10	0.762
5	0.5	10	1.016
6	0.5	10	1.016
7	0.5	10	Hole
8	0.5	10	Insert

case of ferromagnetic fragments and opposite in the case of artificial cracks. The minimum detectable size was 0.127 mm in width, 4.013 mm in length and 0.229 mm in depth. Conventional ECT cannot distinguish between cracks and magnetic phases. On the other hand, the magnetic phase generated in Inconel600 SGT could be measured, and the magnetic phase and cracks could be distinguished using the developed sensor

4. Conclusion

A probe with a magnetic field biased by a permanent magnet has been used in a SGT inspection to eliminate the ECT signal distortion caused by permeability variation clusters (PVC) in the SGT. However, the ferromagnetic phases of PVCs are not saturated by the built-in permanent magnetic of probe, resulting in a decrease in the S/N ratio. In this work, a new technology based on magnetic permeability measurements was introduced. Cracks and magnetic phases created in the SGT could be distinguished selectively using the developed sensor.

Acknowledgements

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