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Development of magnetic flux leakage technique for examination of steam generator tubes of prototype fast breeder reactor

W. Sharatchandra Singh, B. Purnachandra Rao *, S. Thirunavukkarasu, S. Mahadevan, C.K. Mukhopadhyay, T. Jayakumar

Non-Destructive Evaluation Division, Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, Tamil Nadu, India

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ABSTRACT

For non-destructive examination of small diameter (outer diameter, OD 17.2 mm) and thick walled (wall thickness, 2.3 mm) ferromagnetic Modified 9Cr–1Mo steel steam generator (SG) tubes of Prototype Fast Breeder Reactor (PFBR), this paper proposes magnetic flux leakage (MFL) technique. Three dimensional finite element (3D-FE) modeling has been performed to optimize the magnetizing unit and inter-coil spacing of bobbin coils used for axial magnetization of the tube. The performance of the technique has been evaluated experimentally by measuring the axial (B_a) component of the leakage fields from localized machined defects in SG tubes. The MFL technique has shown capability to detect and image tube outside defects with a signal-to-noise ratio (SNR) better than 6 dB. Study reveals that Inconel support plates surrounding the SG tubes do not influence the MFL signals. As the MFL technique can detect localized defects in the presence of support plates as well as sodium and the remote field eddy current technique is sensitive to distributed wall thinning, their combined use will ensure comprehensive inspection of the SG tubes.

1. Introduction

The Prototype Fast Breeder Reactor (PFBR) being commissioned in Kalpakkam, India uses Modified 9Cr–1Mo ferromagnetic steel (Grade 91) as the material for fabrication of steam generators (SG). This material has been chosen in view of its favorable high temperature creep and fatigue resistance properties (Jayakumar et al., 2013; Chetal et al., 2006). The SG tubes has an outer diameter (OD) of 17.2 mm and wall thickness (WT) 2.3 mm. Periodic in-service inspection (ISI) of these tubes is essential as any damage in the tube can lead to sodium–water reaction, resulting in, catastrophic failure of the tube. Among various non-destructive evaluation (NDE) techniques, remote field eddy current (RFEC) technique is preferable for ISI of SG tubes due to its easy use and its ability to detect both inner diameter (ID) and OD defects in the tubes with equal sensitivity (ASME Section V, Article 26, SE 2096; Krzywosz and Dau, 1990; Thirunavukkarasu et al., 2008). This technique is capable of detecting wall thinning and large volumetric defects. However, it has been shown that the RFEC technique has limited sensitivity for detection of localized flaws such as pits and small volumetric defects which may form during service due to corrosion. Moreover, the RFEC signals are influenced by the resence of support structures (Inconel-718) and sodium deposits (non-magnetic and highly conducting) on the outer surface of the tube as well as in the defective regions of the tube (Thirunavukkarasu et al., 2008). In this context, magnetic flux leakage (MFL) technique is being explored as it can detect both shallow surface and deep sub-surface defects in ferromagnetic materials (Dobmann, 1985).

Magnetic flux leakage technique involves uniform magnetization of the ferromagnetic pipe wall close to saturation and measurement of leakage magnetic flux from defects, using magnetic field sensors (Udpa and Moore, 2004; Rao, 2012). The sensors can measure axial, radial or circumferential (tangential) field components of the leakage magnetic fields, although in practice only one component is usually measured (Jiles, 1990). The magnetization can be continuous (Singh et al., 2009), pulsed (Sophian et al., 2006; Wilson and Tian, 2007) or residual (Babbar and Clapham, 2003). MFL technique is used for nondestructive evaluation of metal loss due to corrosion in underground oil and gas pipelines (Udpa and Moore, 2004; Nestleroth and Battelle, 1999). MFL technique is also found to be useful in testing ferromagnetic heat exchanger tubes in petrochemical plants (Krzywosz and Dau, 1990; Gotoh and Takahashi, 2007; Gotoh et al., 2011). Krzywosz and Dau (1990) used permanent magnets for axial

* Corresponding author.
E-mail address: bpcrao@igcar.gov.in (B.P. Rao).

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magnetization of carbon steel tubes (OD 25.4 mm and WT 2.77 mm) and induction coils to measure the leakage fields from defects on the outer surface and reported detection of 40% WT (1.1 mm) deep ASME-type flat bottom hole of diameter 2.77 mm. Gotoh et al. (2011) proposed alternating MFL technique for inspection of OD defects in thin SUS 430 steel tube (OD 25 mm and WT 1.5 mm). They used an inner coil with 60 Hz excitation and a search coil receiver and showed detection of 0.5 mm (33% WT) deep circumferential defects (Gotoh and Takahashi, 2007). Gotoh et al. (2011) also used a differential search coil for detection of OD defects on ferritic steel tube (SUS 430) with ferritic steel support plate (SS 400).

In all the above studies, the diameter of the ferromagnetic tubes is sufficiently large (OD > 25 mm and OD/WT ratio is $\geqslant$10). However, MFL inspection of small diameter (OD < 20 mm) and thick walled (OD/WT ratio <10) ferromagnetic tubes such as Modified 9Cr–1Mo tubes of steam generators of PFBR is challenging due to weak leakage magnetic fields from small localized defects and physical constraints for placing the magnetizing coils and sensing units. Possible ways to overcome this situation is optimal design of the magnetizing unit and use of highly sensitive magnetic field sensors such as giant magneto-resistive (GMR) sensors. Table 1 gives a list of commonly used sensors in MFL testing and their comparative sensitivity and performance (Han et al., 2005). GMR sensors are compact, energy efficient, and have high sensitivity for magnetic fields in the range of 10^{-12}–10^{-2} Tesla. They are finding widespread use in eddy current testing of aging aerospace components (Nair et al., 2006; Sasi et al., 2007). GMR sensors may saturate for larger leakage fields while they are ideally suited for detection of feeble magnetic fields from shallow surface defects and buried or deep sub-surface defects. Recently, Reimund et al. (2014) investigated the applicability of GMR sensors for detection of surface breaking micro-cracks via observation of stray fields, after detailed finite element analysis and experimental studies on roller bearings.

This paper presents design and development of tandem GMR array sensors based MFL technique and its model based optimization towards detection of small localized defects in small diameter and thick walled ferromagnetic steel steam generator tubes of PFBR. Experimental results of detection of localized defects such as notches and holes in the SG tubes are discussed. Further, the influence of Inconel-718 support plate on MFL signals is analyzed in this paper.

2. Magnetic flux leakage technique

The schematic of the proposed MFL technique for testing the SG tubes is shown in Fig. 1. It consists of two bobbin coils for magnetization, a variable DC power supply, tandem GMR array sensors, differential amplifiers and a personal computer. The bobbin coils are wound on a ferrite core which concentrates the magnetic field lines along the central axis of the tube and hence, reduces the compression of leakage fields due to direct magnetizing fields. In addition, ferrite rings that guide the magnetic field lines into the tube are also studied. The separation between the two bobbin coils

Table 1
Commonly used sensors in MFL testing.

Sensor	Detectable field range (T)	Sensitivity (V/T)	Response time (MHz)	Sensor head size	Power consumption (mW)
Induction coil	10^{-4}–10^{4}	0.25	0.1	1–100 mm	10
Hall	10^{-6}–10^{2}	0.65	1	10–100 μm	10
SQUID	10^{-14}–10^{-6}	10^{-14}T/$\sqrt{}$Hz	1	10–100 μm	10
AMR	10^{-10}–10^{-3}	80	1	10–100 μm	10
GMR	10^{-12}–10^{-2}	120	1	10–100 μm	10

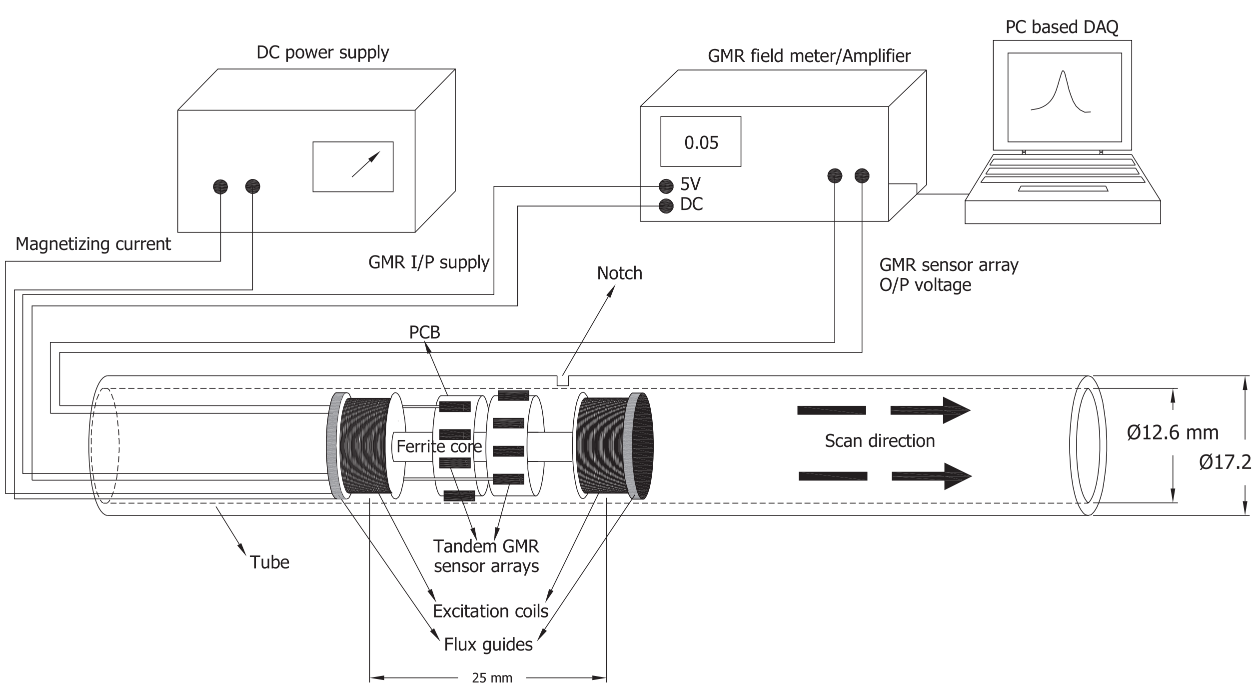

Fig. 1. MFL technique proposed for inspection of SG tubes.