

NON-DESTRUCTIVE TEST TECHNIQUES FOR BOILER SYSTEMS

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Introduction

A boiler is a system in which water is heated and converted into steam. The steam may be used for process applications or for generating power - whether it is motive power (such as in steam locomotive) or electric power. The main parts of a boiler for an electrical power plant are the following: (a) Furnace, (b) Waterwall tubes, (c) Superheater tubes, (d) Reheater tubes, (e) Economiser, (f) Steam pipes and (g) Headers. Terminologies such as steam generators are used in some cases, such as in nuclear power plants.

The main damages in a boiler system occur in boiler tubes, headers and steam pipes. The distinction among these components is essentially one of size and not of function. The failure mechanisms in boiler tubes are the following: stress rupture - water side corrosion - fire side corrosion - erosion - fatigue - creep - creep/fatigue. The failures in tubes are more common and they can be plugged and/or replaced without much difficulty; though these failures affect the availability factor. Failures in other components such as steam pipes, headers, etc.,

are less common, but these failures pose problems since their replacements are time consuming; such failures may also pose safety problems. The important types of failures in these components are cracks due to creep. Non-Destructive Testing (NDT) is very important for a high availability factor of boiler systems and their prolonged lives.

The life of a component consists of two parts, namely (a) materials degradations before the initiation of cracks, and (b) crack propagations leading to failure. Often, the component life in stage (a) predominates over the stage (b). Upto the present time, most of the developments in the NDT techniques have taken place for flaw (physical discontinuities) detections and their sizing. NDT techniques for materials degradations which pertain to the stage (a) of component life are comparatively new and much of the R & D are taking place in this area. In this paper, the NDT techniques would be discussed in general terms so that their scopes and applicabilities for specific boiler systems and for the assessment of the associated damage modes can be understood by the readers on the basis of the knowledge of the failure modes in various components.

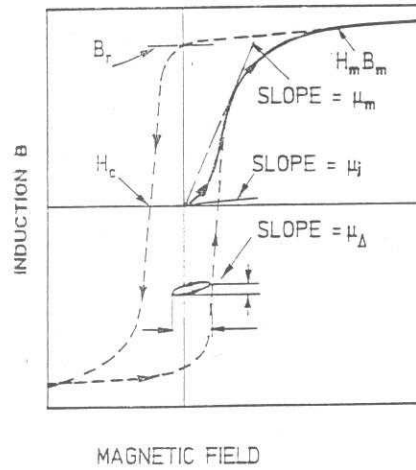


Fig. 1. Parameters derivable from a magnetic hysteresis loop.
 H_c = Coercivity; B_r = Retentivity; B/H = permeability;
 μ_i = initial permeability; μ = incremental permeability.

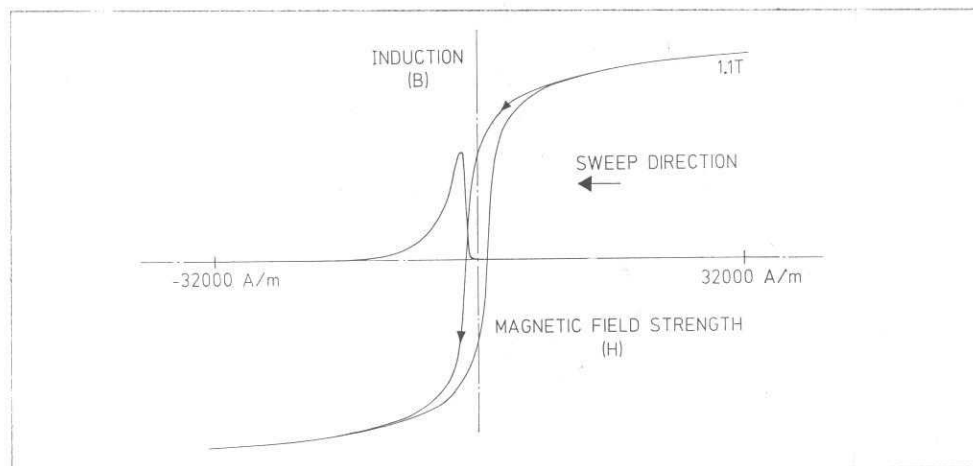


Fig. 2. A typical MBN rms voltage plot superimposed on a hysteresis loop. The maximum intensity of MBN is seen to occur at the coercivity point i.e. at the belly region of the loop. ABN occurs at the knee regions of a loop before magnetic saturation.

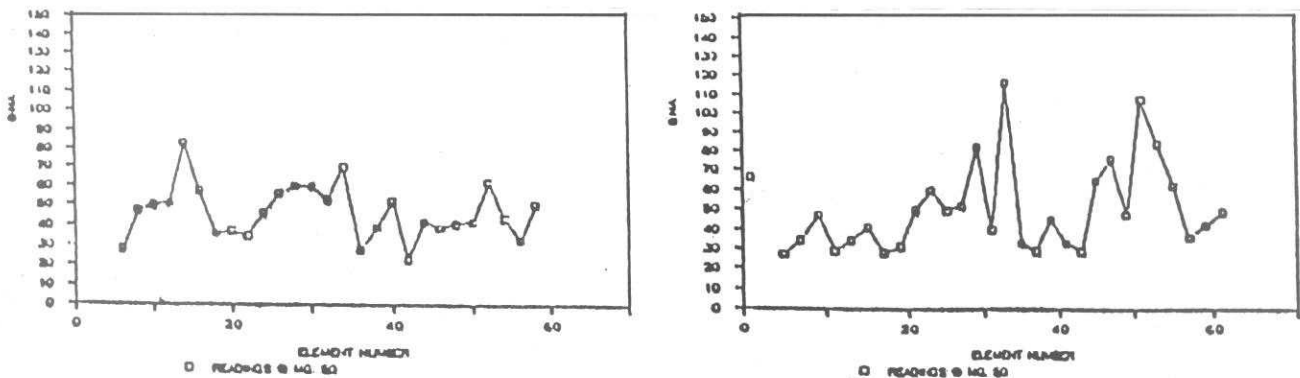


Fig. 3. MBN peak height (vertical axis) versus element number (points in a grid pattern - horizontal axis) for a primary superheater unit [Ref 8].

Types of NDT Techniques***NDT Techniques before Crack Initiation***

As already indicated, before the crack initiation, the NDT techniques should be able to assess the materials degradations. These techniques are often termed as NDT techniques for materials characterisation. Either the conventional techniques have been tailored to get information on the materials or new techniques have been introduced for the purpose. Several of the techniques have been developed to extents suitable for application in practice. Others are under development. The following list gives an idea of the techniques that are useful or has potential.

- (i) In-situ metallography and replica metallography.
- (ii) Magnetic techniques including the use of parameters related to the magnetic hysteresis loop (such as coercivity, retentivity, permeability etc.) and the use of Barkhausen noise parameters (magnetic & acoustic - known in abbreviated forms as MBN & ABN respectively, the later also being known as magnetomechanical acoustic emission or in an abbreviated form as MAE).
- (iii) Ultrasonic attenuation, ultrasonic signal analysis, pattern recognition of ultrasonic signal, ultrasonic velocity measurement etc.

- (iv) X-ray diffraction (XRD) analysis using either the shift of diffraction peak (to measure macro-residual stress), full width at half maximum (FWHM - to measure micro-stresses due to thermo-mechanical damages in service), & peak intensity analysis for texture analysis.
- (v) Eddy current testing (ECT) to measure permeability changes and conductivity changes which are the manifestations of material degradations.
- (vi) Exotic techniques such as positron annihilation, nuclear magnetic resonance analysis, microdensitometry, surface reflectance measurement etc.

NDT Techniques for Crack Detection and Monitoring of Crack Propagation

The techniques under this category are the following:

- (i) Liquid penetrant testing (LPT) or dye penetrant testing (DPT)
- (ii) Magnetic particle testing (MPT) or magnetic particle inspection (MPI)
- (iii) Radiography (RT)
- (iv) Ultrasonic Testing (UT)
- (v) Eddy current testing (ECT)
- (vi) Magnetic flux leakage (MFL) technique
- (vii) Potential drop technique or electric perturbation technique
- (viii) Magnetic Barkhausen Noise (MBN) analysis technique

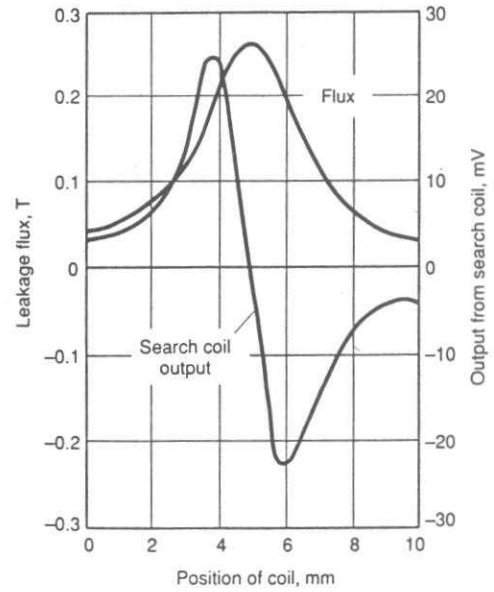
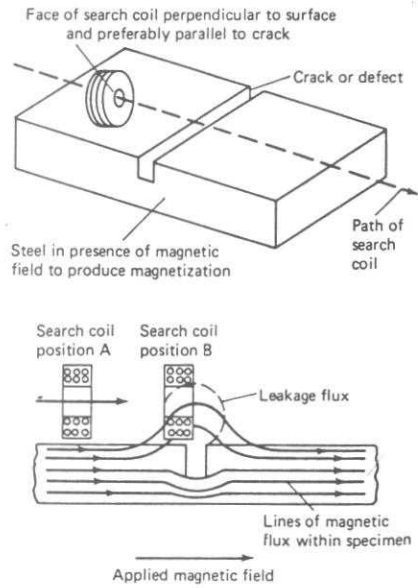


Fig. 4. Schematic configuration of flux leakage technique.

Fig. 5. Flux leakage output at a crack.

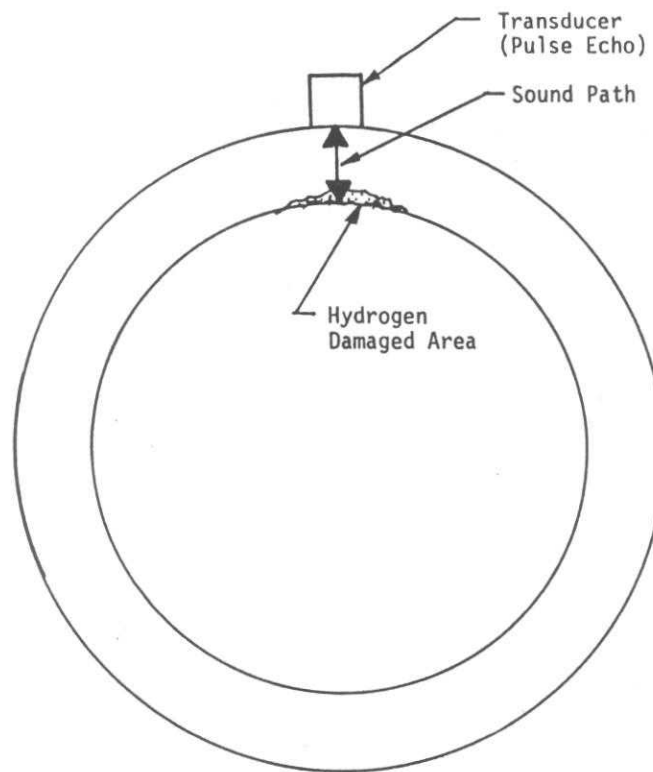


Fig. 6. Ultrasonic attenuation technique for the detection of hydrogen damage.

- (viii) Magnetic Barkhausen Noise (MBN) analysis technique
- (ix) Visual testing and equipment aided visual testing
- (x) In-situ metallography and replica metallography
- (xi) Thermography
- (xii) Acoustic emission testing (AET)
- (xiii) Vibration monitoring.

The main issues here are the detection and sizing of cracks so that a correct decision between replacement of a component or repair the cracked region can be taken.

Magnetic Techniques

Magnetic Hysteresis Loop

The parameters derived from a magnetic hysteresis loop are important for assessing material degradation before crack initiation. Magnetic hysteresis behaviour in a ferromagnetic (and ferrimagnetic) material is a well known phenomenon which has been extensively discussed in several treatises^(1,2). The occurrence of the magnetic hysteresis is a consequence of the existence of magnetic domains within a ferromagnetic material. A domain represents a localized region which is magnetically saturated. In a demagnetized state, magnetization in different domains are randomly oriented leading to a small net magnetic field strength. A domain wall is a boundary between two adjoining domains, within which the direction of magnetization gradually changes. The domain walls can be classified into 180° walls, in which

the spins rotate by 180° from one domain to the other, and 90° walls in which the spin rotates by 90° or so.

The domain related activities such as domain nucleations at microstructural features and domain wall motions, domain rotations etc., have been characterized by both theoretical analysis and experimental investigations. The importance of such analyses is related to the fact that the wall motions are affected by the microstructural features such as dislocations, secondary phase precipitates, inclusions, domain morphology etc. The nature of the domain wall motions specially the 180° walls controls the coercivity of a material, an important material property. The domain nucleation at various microstructural features determine retentivity. Other parameters of importance derivable from hysteresis loops are permeability (B/H), differential permeability (dB/dH), and incremental permeability $(B/H)_\Delta$. Figure 1 shows the parameters derivable from a magnetic hysteresis loop. Hysteresis loop parameters have been considered for assessment of materials degradation due to fatigue in pressure vessel steel [3] and creep in high temperature materials [4]. It is expected that they would be useful for assessing boiler system components as well.

Barkhausen Noise Analysis

During the hysteresis sweep in a ferromagnetic material, Barkhausen noise of the following two types are generated.

- (a) Magnetic Barkhausen Noise (MBN)

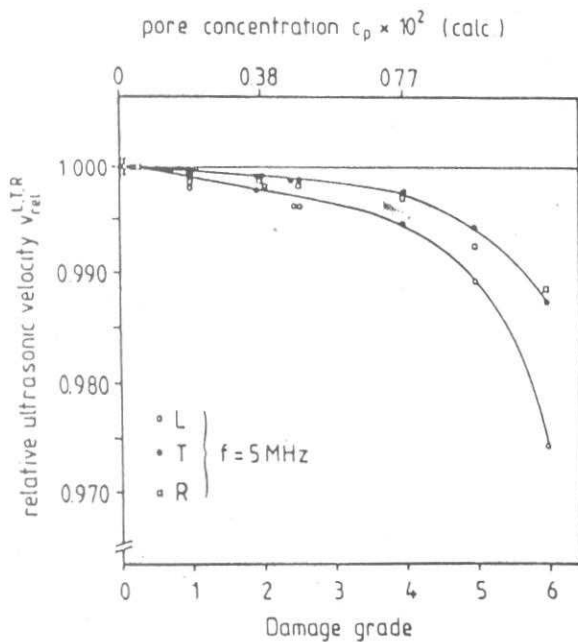


Fig. 7. Relative ultrasonic velocities versus "damage grade" in creep damaged 14MoV63 steel. 'L', 'T', & 'R' pertain to longitudinal, transverse, and Rayleigh waves.

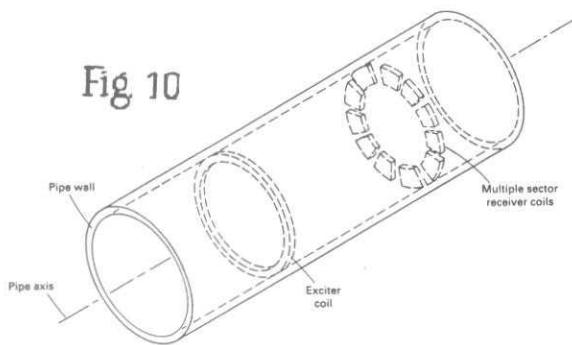


Fig 8

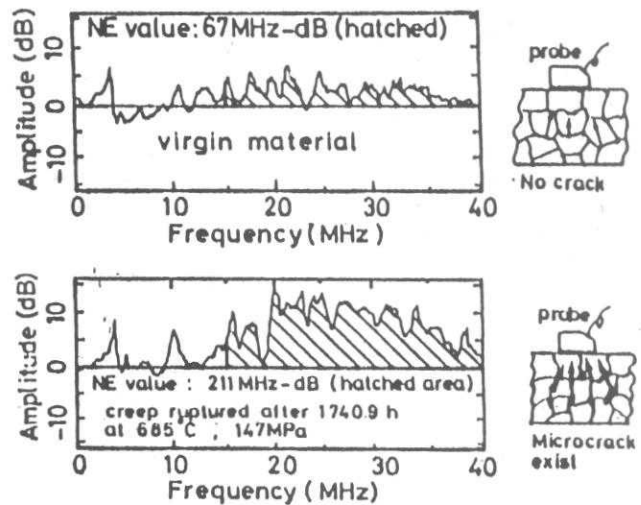
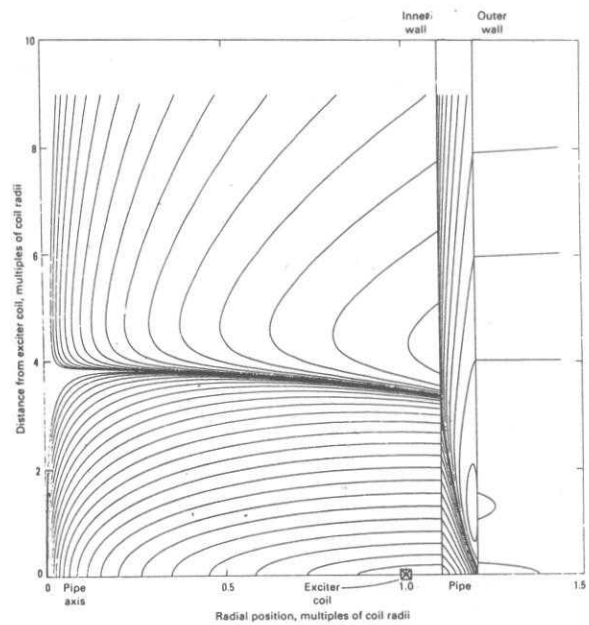


Fig. 9
↓



due to the movement of 180° domain walls from one pinning point to another [2,5]. The maximum intensity of the noise signal occurs at the coercivity point of hysteresis loop [Fig.2] i.e. the belly portion of the hysteresis loop.

(b) Acoustic Barkhausen Noise (ABN) occurring due to the motion of 90° domain walls and domain rotations. This is an elastic wave and occurs at the Knee region of a loop. ABN has found less application as compared to MBN.

The term "Noise" has come into use since MBN was discovered in the form of a crackling sound in a telephone speaker in 1919[6]. ABN was discovered much later in 1975[7].

The peak height of MBN has been an important parameter to assess fatigue and creep damages, and residual stresses [3-5]. This parameter has been used to help identification of sites for detailed examination by in-situ metallography and magnetic particle inspection [8]. In this work, higher MBN peak heights seemed to coincide with a higher propensity towards creep damage during early stages of creep. Figure 3 shows a typical MBN peak height plot taken from Ref.8 for a primary superheater header unit. The increased peak heights of MBN signifies stress relaxations due to creep.

Magnetic Flux Leakage Technique

Figure 4 explains the technique. The presence of a surface breaking

flaw such as a crack leads to a leaking magnetic flux i.e. flux lines coming out in the air. Otherwise, all the flux lines would be confined within the component. The leakage flux can be detected by a suitable sensor such as a Hall effect probe, or a sensor coil. If the output is obtained not as integrated flux (like the induction B in the hysteresis loop) but as flux lines the sensitivity of detection might increase [Fig.5].

Magnetic Particle Inspection

This is one of the most popular techniques for boiler systems for crack detections, either on the surface or in the sub-surface region. The principle of the technique is similar to magnetic flux leakage technique. In this case the sensor is in the form of finely divided magnetic particles of high permeability and low retentivity that accumulate at the regions of magnetic leakage flux lines.

Ultrasonic Techniques

Ultrasonic Attenuation

The general equation for ultrasonic attenuation can be written as follows:

$a = k_1 \cdot f^a \cdot D^b + k_2 \cdot f \dots$ [1], where a = attenuation coefficient, k_1 and k_2 are constants, f = ultrasonic test frequency, D = average grain diameter of the material through which the ultrasonic wave is passing, 'a' and 'b' are the power coefficients the values of which depend on the sizes of the grains in relation to the ultrasonic wave lengths. Term K_1

f^a, d^b denotes the attenuation due to scattering, and the term $K_2 \cdot f$ denotes the term due to absorption. Scattering takes place due to the presence of grain boundaries, crack surfaces, and other boundaries on either sides of which materials of different acoustic impedances are present. Absorption takes place in the form of conversion of the elastic energy to heat.

With the usual test frequencies upto 15MHz, the scattering term predominates over the absorption term. However, before the cracks initiate, it is normally the changes in the dislocation density and dislocation morphologies which are important in any damage mode. Therefore, ultrasonic attenuation is not a suitable technique for the assessment of the material degradations before the crack initiations stage unless the test frequency is increased to higher values (> 50 MHz). Empirical correlations have, however, been found between attenuation coefficient on one hand and grain size, fracture toughness, and yield strength of materials. Ultrasonic attenuation monitoring is now an established technique for the assessment of hydrogen damage in water wall tubes⁽⁹⁾. Figure 4 shows a common configuration in ultrasonic attenuation technique for the detection of hydrogen damage.

For crack detection, ultrasonic technique is perhaps the best known and most researched technique. Several variations of the technique are available such as (a) defect echo height method, (b) decibel drop method,

(c) edge echo method, (d) scattering method. New concepts and the use of signal analyses have made the crack sizing more accurate than before. The examples are: (a) ultrasonic phased array, (b) ALOK, (c) time of flight diffraction (TOFD), and (d) synthetic aperture focusing technique (SAFT). In ultrasonic phased array method, a number of sensor elements are excited with different time delays, and thus the ultrasonic beam can be steered and focused electronically. This helps in getting a better idea of the crack size and morphology. In ALOK method which originated in Germany, the echoes from a reflector (a crack surface for example) and the probe positions are considered simultaneously. The flaw reconstruction is made by geometric planar triangulation method. To reduce the amount of data to be handled, only the peak position from the raw rf signal is considered. SAFT has a principle similar to what has been developed in radar imaging. The basic idea of SAFT is to measure the complete sound field scattered by a crack on an orbit around the crack. During reconstruction, this sound field is calculated back into the region where the scattering occurred making use of well known wave propagation characteristics. The result is a three dimensional amplitude distribution of the sound field inside the scanned orbit. In TOFD developed mainly in the UK, it is possible to locate and size a crack. Here, the diffraction of ultrasonic wave is considered instead of reflection of the wave (10, 11).

Ultrasonic Velocity

Ultrasonic velocity is related to Young's modulus and density through the following equations:

$$v = (M/r)^{1/2} \quad [2]$$

$$r = \text{density}$$

where, v = ultrasonic velocity, M = is an appropriate combination of elastic moduli for the type of ultrasonic wave being considered. For longitudinal and shear wave, the following equations are valid:

$$M_L = E(1 - m) / [(1 + m)(1 - 2m)] \quad [3]$$

$$M_S = E/2(1 + m) = G \quad [4],$$

where

subscripts 'L' and 'S' are related to longitudinal and shear wave, E = Young's modulus, m = Poisson's ratio, and G = Shear modulus.

Ultrasonic velocity measurement is only successful if the microstructural changes or development of cracks within a material lead to a significant change in the modulus and/or density of a material. Normally this is not the case. However, in some specific cases, such as during the development of creep damage due to which cavities form in a material, modulus values change and in such cases the velocity measurement would be successful. Figure 5 shows the relative ultrasonic velocities in a creep damaged Cr - Mo - V steel with respect to a non creep damaged specimen. Subscripts L, T and R refers to Longitudinal, transverse and Rayleigh waves.

Ultrasonic velocity changes can

be used to measure the residual stresses in materials. To determine the velocity, a knowledge of the travel path is necessary. It is also necessary that the transit time of ultrasonic wave is measured with a high degree of precision and accuracy. Several techniques are available for measuring the transit time accurately such as pulse echo overlap technique ⁽¹³⁾ autocorrelation technique ⁽¹⁴⁾.

Eddy Current Testing (ECT)

In ECT, an alternating current (frequency range kHz-MHz) is made to flow in a coil (also called probe) which, in turn, produces an alternating magnetic field around it. The coil when brought close to the surface of an electrically conducting material under inspection, induces an eddy current flow in the material due to electromagnetic induction. These eddy currents are generally parallel to the direction of coil winding. The presence of any defect or discontinuity in the material disturbs the eddy current flow, which in turn generate an alternating magnetic field (in opposite direction) which may be detected either as a voltage across a second coil or by the perturbation of the impedance of the original coil [15]. A significant progresses have been made in the recent times to use signal analysis for ECT [10], finite element analysis [16].

A major deficiency of conventional ECT is its inability to test ferromagnetic materials due to the interference from the localised varia-

tions of magnetic permeability with the signal variations due to the presence of physical discontinuities and other microstructural features. To overcome this, instead of the near field eddy currents, the far field of the remote field eddy currents are utilised [17]. Figure 9 shows the magnetic fluxes in the near field region consisting of more closely spaced lines near the exciter coil in a pipe interior, and the remote field region in the less dense region further away from the exterior. Figure 10 shows the configuration of exciter coil and multiple receiver coil.

Potential Drop Technique

This technique is useful to detect the presence of a surface or subsurface crack and to measure the crack depth. Either DC or AC can be used. The former is useful for surface or subsurface cracks and the latter is useful for only surface breaking cracks. When the current sent into the component through two electrodes is perpendicular to the crack direction, there is a significant change in the current potentials due to the presence of the crack faces and thus there is a voltage drop which is a measure of the crack depth.

In-situ Metallography

This technique of obtaining a microstructure from an actual component by using portable metallographic grinder, mechanical polisher, electrochemical polisher, electrochemical etcher, microscopes with or without camera attachment has been developed to an impressive

level. Apart from using a microscope, it is possible to take replicas by softened (by alcohol or ethyl acetate) cellulose acetate films, which when pressed gently on a metallographically prepared surface takes the contour of the surface. The replicas can then be observed as such under an optical microscope or by a SEM after giving a coat of gold on the surface.

Liquid Penetrant Testing

Liquid penetrant testing (LPT) is widely used to detect the presence of and determine the length of a crack on the surface of a component. The technique uses a penetrant which is sucked inside the crack volume due to surface tensions and capillary actions. Later, the sucked in penetrant is taken out of the crack volume by using a developer. Either fluorescent or coloured (red) dyes are used in the penetrants so that the indications are perceived with a good contrast. There are three variations of the technique depending on the method of removal of the penetrant after it is applied on the surface - water washable, post emulsifiable, and solvent removable.

Acoustic Emission Testing

Acoustic emission testing is a passive nondestructive technique. In this, there is no medium that is used to interrogate a material and detect the response (such as is true for other nondestructive techniques which are active in nature). The acoustic waves in kilo Hertz range generated during (a). crack initiation and propagation,

(b). leaking of a pressurised fluid from inside a vessel are monitored by (generally) piezoelectric transducers positioned in carefully determined locations and in numbers so that the location of the source of acoustic emission can be known by using triangulation techniques. Sometimes, it is necessary to use signal analysis such as frequency spectrum analysis, pattern recognition techniques etc. to correlate the nature of the acoustic emission signals with the source of the signals. The acoustic emission technique can be used either at the time of hydrotests carried out during shut-down periods, or can be used on-line during the operation of a plant.

Concluding Remarks

A short overview has been given in this paper on the nondestructive test techniques that would be useful for the assessment of the health of boiler systems. The techniques can be useful either in the stage before the initiation of a crack and/or during the crack propagations.

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