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Designing a magnetoacoustic emission measurement configuration for measurement of creep damage in power plant boiler tubes

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We discuss design features that are needed for magnetoacoustic emission (MAE) measurement of creep damage in the outer walls of boiler tubes. MAE is used because it decreases monotonically with increasing creep damage. Features of magnet design for boiler tube inspection are presented. Relationship of total MAE to Barkhausen noise path integrals is discussed. Also, dependence of MAE on frequency and tube wall thickness is delineated. Finally, measurements are discussed which show how azimuthal asymmetry in creep damage is echoed in azimuthal asymmetry in MAE. All tests were performed on 2Cr–1Mo Polish steel tube specimens. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1450851]

I. INTRODUCTION

In a power plant boiler tube, creep damage occurs at first on the outside of the tube wall, where hot gases contact the steel tube. In the United States, the amount of creep damage is estimated by an ultrasonic measurement of the thickness of the oxide layer on the inside, not outside, of the tube wall. Such oxide layer thickness is not necessarily strongly correlated with the creep damage and can be an unreliable indicator of the creep damage, especially since the creep damage is on the outside of the tube wall.

Because creep damage results in changes of magnetic properties,[1] a magnetic approach using magnetoacoustic emission (MAE) is currently under investigation[2] as a new alternative nondestructive evaluation (NDE) approach to measuring the creep damage. The Barkhausen noise (HBN) effect cannot readily be used because it allows inspection of only a near surface layer, owing to eddy currents. MAE makes inspection possible much deeper into the material.

MAE is the acoustic analogue of HBN. The MAE pulses consist of acoustic wave pulses which are generated via magnetoelastic coupling during magnetic domain wall jumps and also during creation and annihilation of magnetic domains. The pulses are detected with a piezoelectric transducer attached to the specimen. Acoustic waves do not readily attenuate, and MAE pulses originating entirely within the depth of penetration of the primary magnetic field H are detected by the transducer. It was first suggested by magnetic modeling[3,4] that MAE could be used to probe the amount of creep damage in a specimen. The modeling suggested that MAE would decrease in amplitude monotonically as a function of the creep damage amount. This occurs because creep damage causes increase of precipitates and creation of microcavities near grain boundaries. Such defects create a demagnetization field, which reduces the rate at which magnetization changes with field H in the material.[1,4] Consequent reduction of magnetic domain wall activity leads to decrease of MAE intensity. Monotonic decrease of MAE intensity was detected along a seam weld in a power plant pipe section that was creep damaged on one end.[5] Decrease of MAE intensity (~50%) with increasing creep damage was also confirmed recently in 2Cr–1Mo Polish steel while mechanical parameters such as hardness, yield strength and tensile strength decreased at a considerably reduced percentage rate.[6] The mechanical measurements are destructive, so MAE, being nondestructive, is a more preferred way to measure creep damage.

This article reports on the design of such MAE instrumentation for boiler tube inspection and presents results of laboratory measurements used to test the basic performance of this instrumentation.

II. MEASURING SET

The MAE measurement had to be capable of detecting not only the creep damage in relatively small-diameter power plant boiler tubes, but also the asymmetry in the creep damage around the tube. The MAE set contains the magnetizing electromagnet, the MAE signal transducer and the MAE voltage analyzer. The magnetizing C-core magnet pole (cross section 20 mm×20 mm) is subdivided into steel slats with rectangular cross section, which slide easily along each other, thus greatly reducing the air gap spacing between pole piece and curved tube surface. In addition, the magnet arms swivel so that the pole piece approaches the pipe radially when the magnet is aligned in the azimuthal or axial direction. The electromagnet, consisting of magnet arms and cross-bar and magnetizing coils, was magnetized with a current of triangular-like time dependence, increasing linearly to a positive maximum, and then decreasing linearly back to the original negative minimum. The MAE voltage signal was detected with a piezo-ceramic transducer (frequency resonance of about 200 kHz). An HBN voltage signal was also detected with a pickup coil positioned in or near the magnetized region. The electronic pass band of the MAE detector circuit was from 30 up to 400 kHz, with the HBN from 1 to

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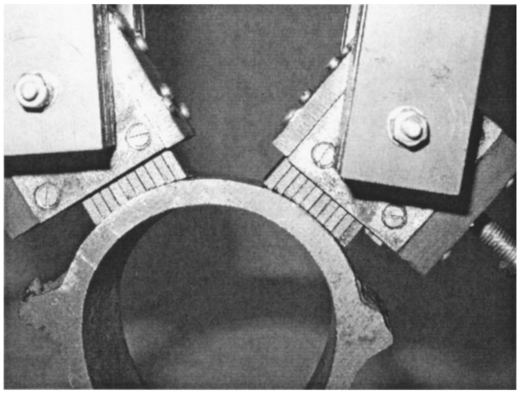

FIG. 1. Photograph of the way in which the electromagnet poles contact the tube when the field is aligned in the hoop direction.

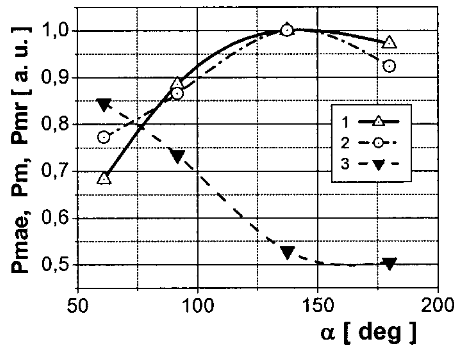

FIG. 2. Angular dependence of: 1-MAE intensity (*Pmae*, open triangles), 2-HBN path integral around the tube wall circumference (*Pm*, open circles), 3-HBN integral contribution from bottom part of tube (*Pmr*, solid triangles).

100 kHz. The ''local'' root mean square (rms) intensity was evaluated for both MAE and HBN voltage signals and recorded as a function of the voltage *Ug* of the current generator. Magnetic field strength H was assumed to be proportional to *Ug*. By local rms intensity is meant that the measuring set uses standard circuits that make a rms calculation ''on line'' during voltage signal analysis. Inside these circuits, the time-varying squared voltage signal is integrated over short time period τ, then divided by τ, and finally the square root is taken, giving thus a local rms value. Error bars on the MAE measurement are less than 5% and on the HBN measurement, less than 10%. Figure 1 is a photograph of how the magnet poles contact the steel tube.

III. EXPERIMENTAL RESULTS

Tested specimens were cut from 2Cr–1Mo Polish steel tubes taken from power plants. Steel chemical composition was [in wt%, mean values and standard deviation] as follows: $C-0.12\pm0.01$; $Si-0.24\pm0.02$; $Mn-0.45\pm0.03$; $Cr-2.11\pm0.01$; $Mo-1.03\pm0.02$. The specimens had the dimensions: outer diameter $D=50$ and 32 mm, wall thickness $h=5.4$ mm, and length $l=100$ cm.

The magnetic properties of the 2Cr–1Mo steel in the tube were measured as follows: Saturation flux density was ~1.2 T and coercivity was ~300 A/m. The hysteresis loops were of a classical shape, with a smooth change of $M(H)$ from the zone of domain wall movement to the zone of domain rotation along the magnetization curve. For our MAE measurements, the flux density swing in the specimen was $2B_{\max}\sim 1$T.

The goal of the first experiment was to find the optimal angular position of the pole pieces on the tube wall for magnetization oriented in the azimuthal (or hoop) direction. The pole pieces touching the tube made different angular displacements (angle α) relative to each other. For each angle α, the MAE was recorded, and the HBN intensity was measured at different points along the line between the poles for both sides of the tube, making a complete circuit. Figure 2 shows the angular dependence of three quantities: MAE intensity (*Pmae*—integral of local rms values of MAE voltage over time for one period of magnetization); HBN intensity (rms value of HBN over one period of magnetization) additionally path-integrated along the line between the poles in a complete circuit around the tube (parameter *Pm*), and contribution to this HBN path integral from the bottom of the tube (parameter *Pmr*). The levels of *Pmae* and *Pm* were normalized to their maximum values, respectively, and *Pmr* was normalized to the maximum value of *Pm*. Note that the rms value of HBN over one period of magnetization is defined as integrating the squared local rms value of the HBN voltage over period of magnetization T, dividing by T, and then taking the square root. Note that for the first experiment, frequency $f=1/T=1.7$ Hz. Using a Hall probe, an average applied field H level of about 12.5 kA/m was found in the specimen midway between the electromagnet poles, with the level depending of course on the applied current. We tried to get the field amplitude as high as possible, in order to bring about the greatest amplitude of MAE.

In Fig. 2, plot 1 reveals that the optimal angular separation for the MAE measurement occurred at 140°. This same angle is also the angular separation at which *Pm* (plot 2)is a maximum. Plot 3 shows that the HBN rms intensity path integral contribution from the lower path is larger than the HBN integral for the upper path. For $\alpha=180°$, the two parts of the *Pm* integral become equal (i.e., $Pmr=0.5$) because the magnetic flux is essentially equally divided between upper and lower path. The MAE voltage at a given time is the accumulation of emissions from different points which each are experiencing different magnetization time derivatives. The MAE intensity (time integrated over a period of magnetization) is proportional to the sum of the magnetizations experienced at each different point. The time derivative of magnetization at a given point is also roughly proportional to the HBN voltage. The HBN intensity (time integrated over a period of magnetization as defined above) is path-integrated azimuthally around the tube to get parameter *Pm*, which should thus be proportional to the sum of the magnetizations experienced at each different point on the path, and hence to the total MAE (*Pmae*). This is well confirmed by the evident close correlation between plot 1 and plot 2 in Fig. 2, where, again, *Pm* and *Pmae* are normalized to their maximum values, respectively.

A second experiment checked the dependence of MAE intensity on frequency and wall thickness of the tube. Frequency of magnetization was set between 0.5 and 50 Hz, and

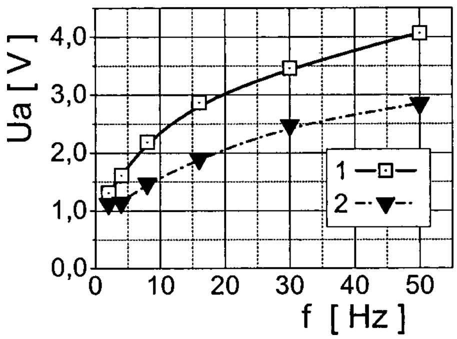

FIG. 3. Frequency dependence of rms value of U_a (MAE intensity) detected in tubes of different wall thickness (1–2.7 mm; 2–5.4 mm).

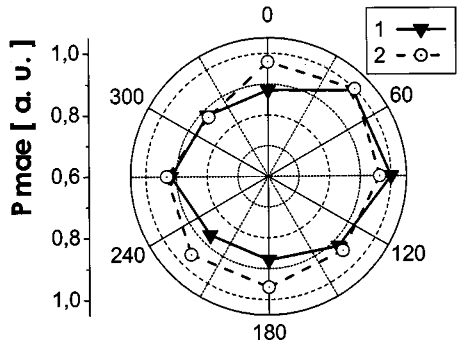

FIG. 4. Polar diagrams of normalized MAE parameter *Pmae* for two directions of magnetization: 1-hoop, 2-axial.

the tube wall thickness was lowered by machining with a lathe to $h=2.4$ mm. Figure 3 shows the frequency dependence of the rms value of the MAE (*Ua*) for two external tube wall thicknesses. This frequency dependence exhibits a behavior more like a dependence on the square root of frequency, as suggested by the MAE model[3,4] and as suggested by an earlier model of Ng *et al.*[7] It is due to eddy currents which screen the magnetic effect of the primary field to a certain skin depth, depending on frequency. Reduction of tube wall thickness leads to an increase of MAE intensity due to increase of the magnetic flux density rate inside the tube while the magnetic flux amplitude provided by the magnetizing magnet remains constant. At higher frequencies, the MAE eventually becomes independent of tube wall thickness since it is produced by changing magnetization confined to the skin depth of the field produced by the primary current of the magnet. We see this tendency toward a more constant value of *Ua* at the higher frequencies in Fig. 3.

The last experiment deals with detection of asymmetrical damage azimuthally around the boiler tube. Figure 4 shows a polar diagram displaying MAE intensities *(Pmae)*, measured with the magnet centered at different angular positions around the tube for field in the axial direction (plot 1) and in the hoop direction (plot 2). A similar pattern is observed in the two cases, with MAE minimum in the range 270–360° in both cases, so that one would conclude that creep damage is greatest in that angular range. Thus, it is possible for the magnet configuration designed for boiler tubes to produce asymmetry in MAE, echoing what is expected for creep-damaged boiler tube sections near the hot gas entry in the boiler.

Finally, it should be noted that moving down the steel tube does not change the results for the unexploited tube. For the exploited tube, there are small local changes in magnetic properties owing to local changes in the creep damage. This is particularly true for the third experiment in which azimuthal changes are studied.

IV. CONCLUSIONS

The designed MAE measuring system has been shown capable of detecting extent and asymmetry of creep damage in power plant boiler tubes.

ACKNOWLEDGMENT

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