ELECTROMAGNETIC ACOUSTIC TRANSDUCERS FOR TESTING POWER STATION BOILER TUBES

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INTRODUCTION

Certain types of oxide scales on steel are known to enhance the efficiency of Electromagnetic Acoustic Transducer (EMAT) operation [1,3]. This paper presents results from the oxides which form on the boiler pipes in fossil fuel fired power stations. Two principal oxides form, firstly a thin layer of black magnetite which is covered by a thicker outer layer of reddish hematite.

In practice, the real oxides are never either pure magnetite of hematite, they can be a solid solutions with the analogous chromium oxides, for example, or oxides of other alloying elements present in the steel. In addition, magnetite can form a solid solution with hematite and there is another form of hematite (maghemite) which has the magnetite structure.

Measurements of EMAT efficiency as a function of applied magnetic field on the oxides show a peak in efficiency at relatively low fields easily achievable with small permanent magnet EMATs. In conventional ultrasonic inspection of boiler tubes, the surface oxides have to be laboriously removed to permit good ultrasonic coupling. Examples of EMAT operation on a range of boiler tubes without any preparation from National Power's plant are presented. We have developed an adapter which enables EMATs to be used with conventional ultrasonic flaw detectors, EMAT inspection of boiler tubes are now replacing piezoelectric wall thickness measurements on National Power's plant.

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MECHANISMS FOR EMAT TRANSDUCTION

On non-magnetic conductors a simple Lorentz force mechanism operates (linear with B or $\mu_0 H$). On metals, which are also magnetic, combinations of Lorentz force and Magnetoelastic coupling mechanisms are possible [4]. Magnetoelastic mechanisms are non-linear as a function of B. Some magnetic materials are good insulators, for example the iron oxides magnetite and hematite. This rules out the Lorentz force mechanism leaving the magnetoelastic mechanisms as the only explanation for EMAT operation. In the case of a send-receive EMAT, the amplitude of the ultrasonic echoes would be expected to vary linearly as a function of B^2 if the Lorentz mechanism is predominant. Any deviations from a straight line would indicate magnetoelastic mechanisms are important.

Magnetoelastic mechanisms are related to magnetostriction but the EMAT transduction efficiency (coupling of the electromagnetic energy into an elastic wave) also depends upon the magneto-crystalline anisotropy energy, the elastic constants and spin wave spectrum. Hematite in particular exhibits giant magnetoelastic coupling which has been attributed to a magnetoelastic contribution leading to a "frozen" energy gap occurring in the low frequency branch of the spin waves [5,7.]

STRUCTURE AND MAGNETIC PROPERTIES OF IRON OXIDES

Magnetite (Fe_3O_4) is a cubic ferrimagnet with an inverse spinel structure. In an antiferromagnet the magnetic moments are aligned parallel and antiparallel, the magnetic moments are equal and opposite giving no net moment. In a ferrimagnet, the moments are not equal resulting in a net moment. In magnetite, the iron atoms can occupy two distinct sites having octahedral or tetrahedral co-ordination by oxygen atoms. The two sites have different moments and hence magnetite has a net magnetic moment.

Hematite (α-Fe_2O_3) is a weak ferromagnet with a cubic structure. The primitive cell is a rhombohedral sub-lattice of the larger cubic unit cell. At room temperature, the basic structure is antiferromagnetic with the magnetic moments lying along the [111] directions. Slight canting of the spins away from the [111] directions is responsible for weak ferromagnetism in the {111} planes.

Maghemite (γ-Fe_2O_3), this is a form of hematite which has the magnetite structure but with some of the iron sites unoccupied. A complete range of intermediate compositions is possible between Fe_2O_3 and Fe_3O_4

Figure 1 shows the simplest form of these magnetic structures, where the moments rotate through 180 degrees in a single layer. More complex spiral structures are also possible.

EXPERIMENTAL SET-UP FOR EMAT EFFICIENCY

A pulsed electromagnet constructed from a laminated E-shaped silicon iron transformer core was used to provide a variable magnetic field, a small r.f EMAT pancake coil was wound onto the central pole piece. The basic geometry of the magnetic bias field and the EMAT coil is the same as shown in figure 2 for a permanent magnet EMAT. If the Lorentz force mechanism were considered, this type of EMAT would generate a radial shear stress. The pancake coil was surrounded by a single turn monitoring coil, which was used to

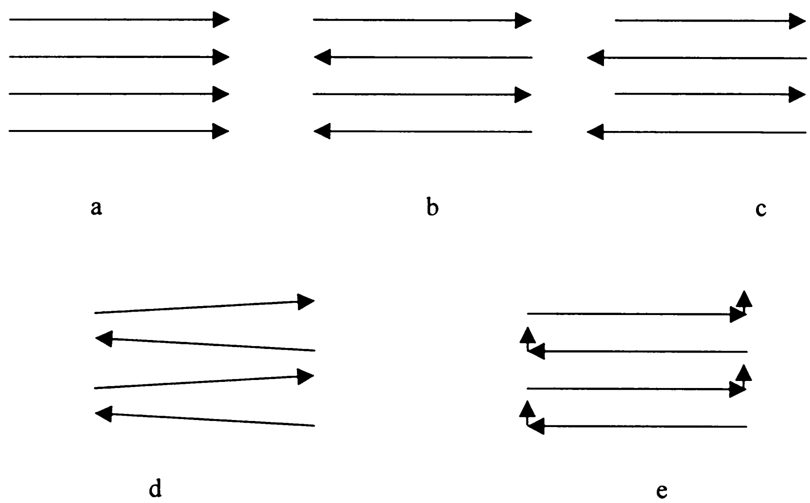

Figure 1. Magnetic Structures of a, ferromagnet, b, antiferromagnet, c, ferrimagnet, d, "canted" antiferomagnet and e, "d" resolved into ferromagnetic and antiferromagnetic components

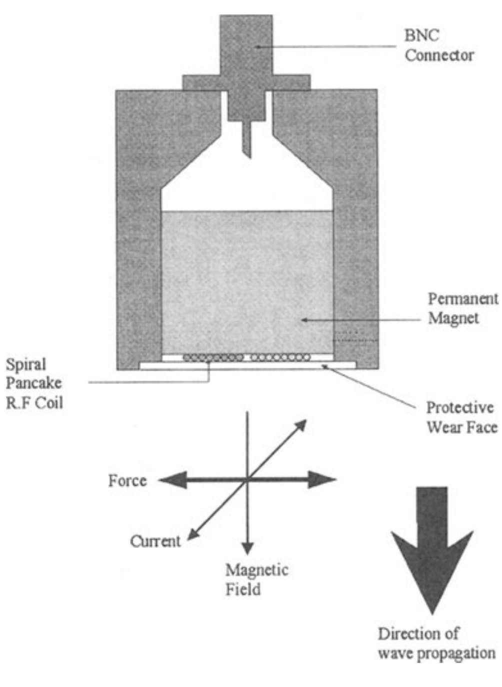

Figure 2. Schematic of EMAT showing field vectors

measure the magnetic field. The electromagnet was pulsed for 4ms, the EMAT was driven at the peak field, the decay time of the field was large compared to the ultrasonic timescales. In addition to being able to control the bias magnetic field, the pulsed current through the EMAT coil could also be varied to enable measurements to taken on materials with a wide range of transduction efficiency. On very efficient materials, such as Hematite, the drive current was reduced to a very low level (~1 A) to prevent amplifier saturation, whilst maintaining the same stand-off as on low efficiency materials such as bare steel tubes, where a pulsed current of approximately 30 A was used.

RESULTS

Figure 3 shows typical results obtained on a boiler tube with and without oxide, the tube with oxide has a send-receive EMAT efficiency around 4 orders of magnitude larger than the bare metal tube. The curve for the bare metal tube shows an almost linear dependence on B^2 , whereas the tube with oxide shows a maximum at low fields corresponding to a flux density of ~0.35 T. The boiler tubes are normally made of creep resistant Chrome-Molybdenum steel and the oxides tend to have a higher chromium content than the parent metal.

Power Station Site Trials

Power station boilers are large structures containing many miles of boiler tubes, they operate at temperatures of up to 600 °C and the tubes are subject to metal loss due partly to oxide formation. Regular ultrasonic thickness surveys are carried out in, particularly to monitor the thickness of boiler tubes in locations that are susceptible to accelerated wall loss. Battery powered equipment is preferred due to access difficulties, typical conditions for EMAT testing are shown in figure 4.

In order to use EMATs in this environment, an adapter, which enables EMATs to function with conventional Ultrasonic Flaw detectors, is needed. The Flaw detector is operated in dual mode, a send-receive EMAT is driven from the Flaw Detector drive pulse via the adapter EMAT. Received signals from the single EMAT are boosted in the adapter

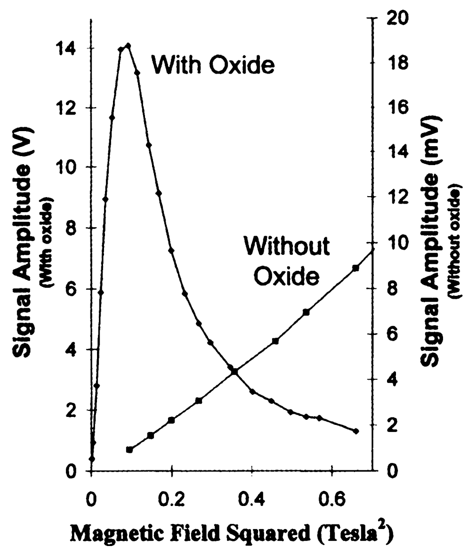

Figure 3. EMAT transduction efficiency as a function of magnetic bias field

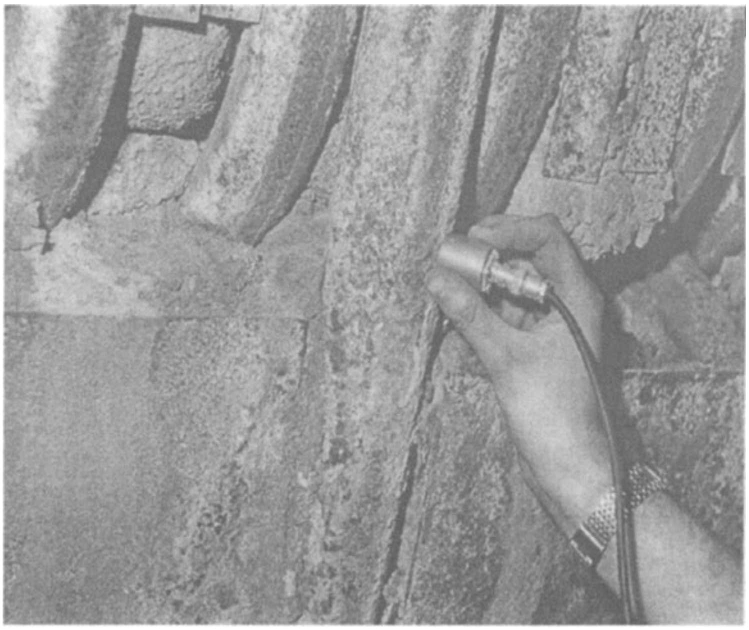

Figure 4. Typical conditions for EMAT tests on boiler tubes

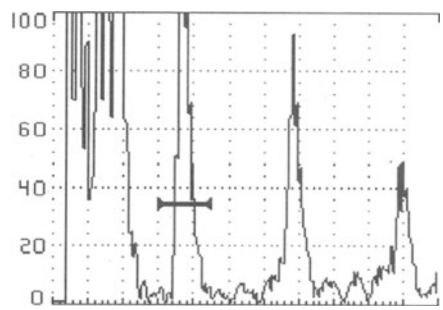

Figure 5. Typical EMAT waveform, the gate on the Ultrasonic Flaw Detector is set on the first backwall echo

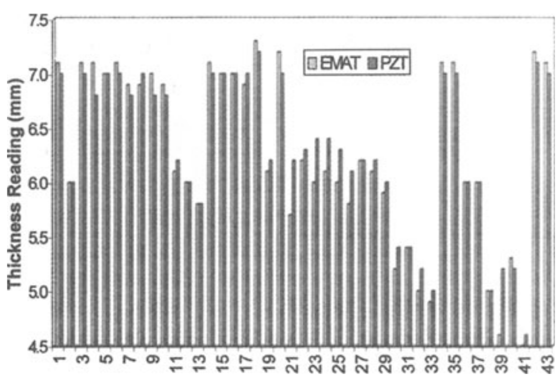

Figure 6. Comparison of EMAT and Piezoelectric Thickness Measurements

before being fed into the second channel of the Flaw Detector. Wall thickness measure measurements were carried out on boiler tubes with no surface preparation, the oxide scales were subsequently removed by aquablasting and the thickness measurements were repeated with conventional piezoelectric transducers. Figure 5 shows a typical EMAT waveform from a boiler tube, good correlation was obtained between the send-receive EMAT and piezoelectric results as shown in figure 6. The EMAT has a ceramic wear face to protect the coil from the rough surface of the tubes, some tubes have very high EMAT efficiencies and testing is possible with stand-offs of up to 10mm.

CONCLUSIONS

EMATs function very efficiently on certain types of magnetic oxides, which form on steel components. The transduction mechanism is well understood in the pure iron oxides and is due to a large magnetoelastic spin-wave energy gap. This effect is particularly large in hematite. The real oxides, which form on boiler tubes, vary in composition, thickness and have non-magnetic inclusions such as silicate ash from the fossil fuels.

Further work is needed to study the effect of alloying elements in the parent steel on the composition of the oxides and EMAT efficiency. An investigation of the Fe_3O_4-Cr_3O_4 solid solution series could give an insight into the chromium rich oxides, which form on boiler tubes.

On a more practical basis, battery powered EMAT equipment suitable for field operation has been developed and is now being employed for boiler tube surveys in power stations during outages.

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