MEASUREMENT OF THICKNESS OF MAGNETITE LAYERS THROUGH ALLOY 600

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INTRODUCTION

It is well known that magnetite builds on the outside of boiler and steam generator tubes. Low-frequency (10 kiloHertz) eddy-current testing (ECT) has been used in attempts to quantify magnetite deposits on alloy 600 steam generator tubes. At this frequency, ECT has some sensitivity to the presence of magnetite on the outside of the tube with measurements made inside the tube. However, it has been historically impossible to resolve differences in deposit thickness, a quantity of some interest to power plant operators. ECT can be further inhibited by layers of copper which may be deposited on the outer surface of Inconel tubing. AC magnetics (ACM) may be conveniently operated at a few hundred Hertz where the small thicknesses of Inconel and the copper deposits are essentially transparent to the electromagnetic fields. The problem then becomes detection of magnetite at large lift off. Here again, ACM is a good technique to use. Preparatory to the design of an ACM probe to fit within steam generator tubing, a feasibility study was conducted which is described here. Flat copper-cladded Inconel plates were used to simulate the tubing, and magnetite of various thicknesses were placed on the side opposite a magnetic-circuit gap. The results indicate that the depth of magnetite through Inconel and copper can be quantified through the use of ACM to about 10 mm.

Electromagnetic flux is injected in samples through ACM, and the real and the imaginary components [1] of the complex reluctance to this flux are measured. The imaginary reluctance is a function of the conductance of the sample. The real reluctance is the sum of the real reluctance of the lift-off area between the sample and the circuit gap and the real reluctance of the sample.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

SIGNIFICANCE OF REAL AND IMAGINARY COMPONENTS OF RELUCTANCE

The configuration of the gap used in ACM is responsible for its ability to detect separately real and imaginary reluctance. A gap in an arm of a magnetic-bridge circuit consists of two poles. These poles are seen in the "footprint" which faces the sample and which is shown in Fig. 1. A cross section of the pole structure is shown in Fig. 2. The poles are separated by an inserted piece of copper which insulates the alternating magnetic

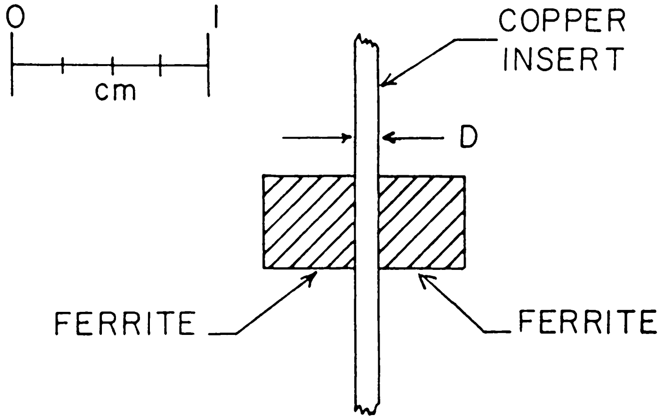

Fig. 1. Typical gap-face presented to the sample.

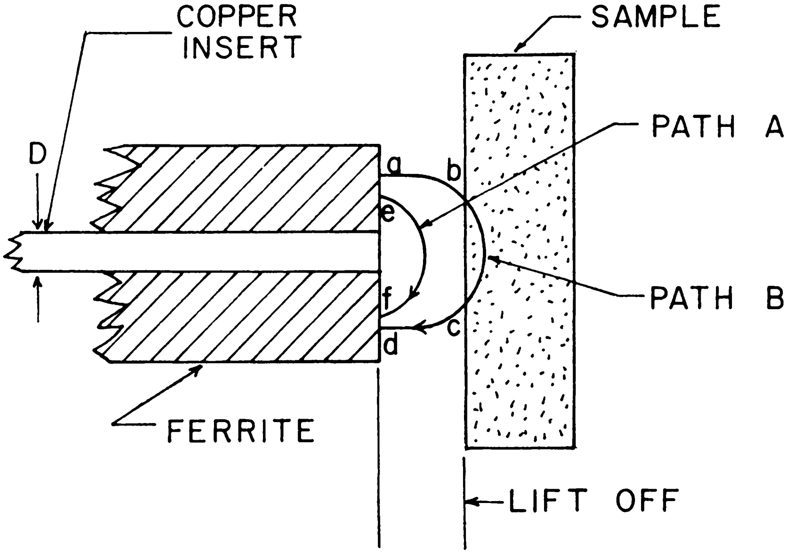

Fig. 2. Cross section of gap and sample showing various flux paths.

flux from bypassing the poles, electromagnetically shields the input side of the bridge from the output side, and shapes the magnetic field in the vicinity of the sample. The action of the insert has been described elsewhere [2,3,4, and 5].

The bridge gap is balanced for measurement [6]. The bridge requires both real and imaginary reluctances to be adjusted for balance. These quantities are calculated with respect to some reference, a requirement for all electrical, magnetic, or electromagnetic bridges. Resistances and capacitances attached to the arms of the ac magnetic bridge allow calculation of the complex reluctance. Typically the bridge is constructed so that two of the gaps which balance each other are geometrically identical. The gap which balances the measuring gap may or may not have a reluctance equal to that of the measuring gap. In most cases, the balancing gap has similar geometry and is left empty. Measurements are usually made in the manner of most nondestructive- evaluation measurements, i.e. by placing a standard sample, a reference, in the measuring gap, recording the electrical parameters balancing the bridge, and then placing the sample of interest in the measuring gap and recording the new electrical parameters.

The operation of the gap shown in Fig. 1 can best be understood by examining the reluctance paths of Fig. 2. The magnetic flux path e-f is entirely in the lift-off space and therefore entirely in air (or in plastic spacers usually used to establish lift off). With the dimensions shown in Fig. 1, with the knowledge that a conductive samples causes the maximum flux to emerge from the center of the gap [7], and with a lift off of 0.25 mm, the real reluctance of this path calculates to about 3800 megaAmps/Weber (mA/W). The real reluctance of the combined paths a-b and c-d calculate to about 19 mA/W. Absolute measurements, i.e. measurements made where the matching bridge arm has no gap [8] indicate that the magnitude of the complex reluctance for frequencies between 200 and 5000 Hertz for a 3.9-mm thick sample of 6061 aluminum is about 10 mA/W. Of course, the real and imaginary reluctances change over this frequency interval. The flux paths A and B are parallel. However, it is clear that the reluctance of Path A is much, much greater than that of Path B, the path through the sample. Therefore the flux through Path A can be ignored. The consequence is that the measured reluctance is essentially the complex reluctance through the sample. The imaginary part (varying from 4.14 to 10.14 mA/W in the above absolute measurement)is measured separately of any real reluctance. The real part consists of the real reluctance of the lift-off gap (a-b and c-d) and the real part of the reluctance of the sample. The real reluctance of the sample can be negative where Lenz's Law produces opposing flux. Depending on the reference, i.e. what the sample in the measuring gap is being compared to, the actual measured reluctances may be positive or negative.

INSTRUMENTATION

The electronics to drive an ac bridge consists of an audio oscillator, an impedance-matching device in the range of conventional audio speakers capable of delivering a few tenths of an Ampere, and a tuned amplifier capable of amplifying microvolts. The bridge input typically ranges from 20 to 40 Amp-turns. An amplifier is necessary at the output to process the microvolt voltages seen at null. The amplifier must be tuned to remove harmonics generated in the ferrite of the ACM circuits and in ferritic samples. For the most sensitive measurements, the tuned amplifier should be off by 40 db or greater at the first harmonic for aluminum and 60 db or greater for steels.

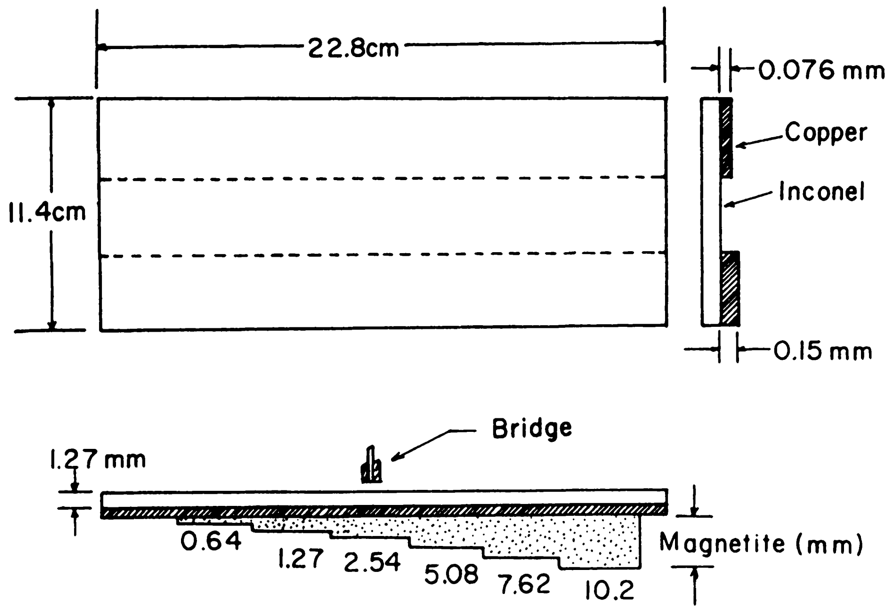

Fig. 3. Schematic of experiment to detect various depths of magnetite.

MEASUREMENTS

The system which was being measured is sketched in Fig. 3. It consists of a plastic container (not shown) with steps milled into its base. There were seven such steps, and each step was 3.26 cm wide and 11.4-cm long. Where the first step was at 0, the second was 0.64 mm followed successively by steps at 1.27, 2.54, 5.08, 7.62, and 10.2 mm. Just beyond the 10.2-mm step there was a small step at the 0 level. Magnetite was packed into the container so that the depth of the step represented the thickness of the magnetite as measured from the first step. The magnetite was covered by a 1.27-mm thick Inconel sheet with 2 copper foils bonded to one side in strips 3.8-cm wide and 22.8-cm long as shown in the upper drawing of Fig. 3. The Inconel sheet was placed across the 0 levels. One copper foil was 0.076-mm thick and the other was 0.15-mm thick. The Inconel sheet was placed with the foils down on the magnetite as shown in the lower part of Fig. 3. The configuration of Fig. 3 was adopted as a reasonable approximation to measurement of gradual magnetite buildup.

The bridge was placed above the Inconel with a 0.25-mm lift off. Three scans were made with the bridge. These scans were made in the 22.8-cm direction over the center of each copper foil and over the center of the section of Inconel to which no foil was bonded. The bridge was stopped above the center of each of the 7 steps and the real and imaginary reluctances required for bridge null recorded. This operation was carried out at three frequencies, 500, 1000, and 2000 Hertz.

RESULTS

The complex-reluctance plane which resulted from these measurements for the scan over the Inconel alone is shown in Fig. 4 while that for Inconel and the thickest piece

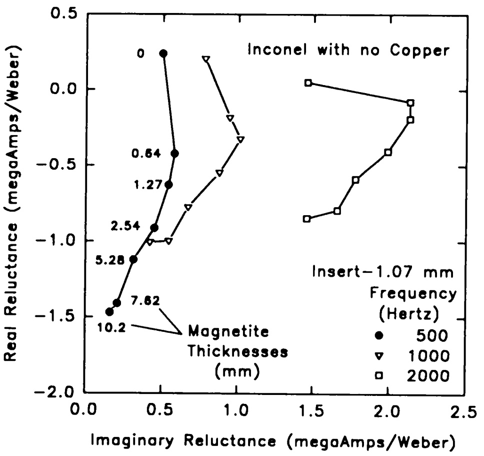

Fig. 4. Complex-reluctance plane representation of depth of magnetite through Inconel with no copper bonded to it.

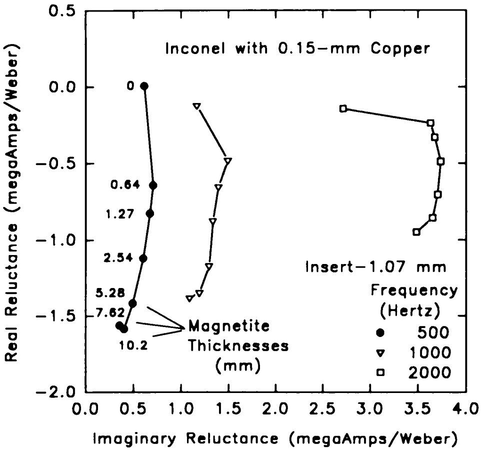

Fig. 5. Complex-reluctance plane representation of depth of magnitite through Inconel with copper bonded to it.

of copper is shown in Fig. 5. It is clear from comparison of these two figures that the copper makes little difference except at the largest values of magnetite depth where the 500-Hertz data shows a slightly greater ability to distinguish depth. The skin depth of copper at 500 Hertz is about 2.5 mm, at 2000 Hertz about 0.5 mm. Therefore, the depth of penetration of the electromagnetic fields at both frequencies is greater than the maximum width of the copper foils used here, which is 0.15 mm. Note that there is little shift in the average imaginary reluctance of the 500-Hertz curves with the inclusion of the 0.15-mm copper foil, but there is a greater shift at 2000 Hz as expected, about 1 megaAmp/Weber).

Assuming that the skin depth of Inconel is probably about that of titanium or stainless steel, which would be between 7 and 8 mm at 500 Hertz, the Inconel would have

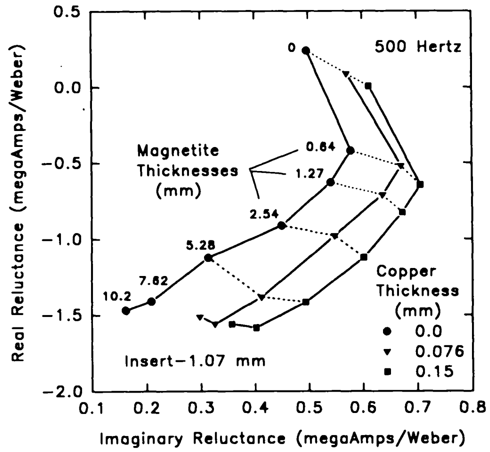

Fig. 6. Complex-reluctance plane representation of depth of magnetite through Inconel with bonded copper at 500 Hertz.

no effect on the measurement. Therefore, the Inconel essentially increases the lift-off value of the experiment.

The greatest sensitivity to differences in magnetite thicknesses near the 10-mm depth of magnetite is shown in the 500-Hertz data. Therefore, these data are plotted in Fig. 6, where data from both thicknesses of copper-cladding are included. Reproducibility in the imaginary reluctance was about 3 parts in 1000. Therefore, it was far smaller than the size of the symbols used to indicate the data. Between the 7.62 and 10.2 depths, the accuracy of measurement calculates to about 0.4 mm. Between 0.64 and 1.27 mm, this accuracy calculates to about 0.1 mm.

CONCLUSION

AC magnetics seems capable of measuring the depth of magnetite to about 10 mm through Inconel of thicknesses of about 1.27 mm and Inconel of this thickness bonded to copper to thicknesses of copper of 0.15 mm when the samples are flat sheets. There is no *a priori* reason why these results will not be approximately the same when the Inconel sample is tubular.

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