AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **73**, 5620 (1993); doi: 10.1063/1.353616
View online: http://dx.doi.org/10.1063/1.353616
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/73/10?ver=pdfcov
Published by the AIP Publishing

Measurements of magnetic circuit characteristics for comprehension of intrinsic magnetic properties of materials from surface inspection

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A transfer function is presented for calculating magnetic field and flux density inside a test material as a result of surface measurement. By considering flux leakage, we introduce a parameter η, called the leakage coefficient, which can be experimentally determined. It is introduced into the equations to make the transfer function more practical. The distribution of field inside a test material is then discussed in accordance with a surface magnetic charge model.

I. INTRODUCTION

Magnetic hysteresis measurements using the Magnescope, as a surface inspection technique,[1] have proved to be a powerful and convenient method for rapid, noninvasive measurement of magnetic parameters. This instrument has been widely used in the area of magnetic nondestructive evaluation recently for detecting fatigue damage,[2] creep damage,[3] and stress.[4] A transfer function which can interpret inherent magnetic properties of a test material from a surface measurement is still needed. This paper indicates how to derive this transfer function within a first approximation and then shows how to improve it by taking flux leakage into account.

II. FIRST APPROXIMATION THEORY AND LEAKAGE COEFFICIENT

The purpose of deriving the transfer function of an inspection head is to express the magnetic flux density B_s and magnetic field H_s inside a test sample, in terms of two measurable quantities which are the flux density inside the inspection head B_h and the magnetic field on the surface of sample H_{surface}. Due to the discontinuity of the magnetic circuit at the interface and the nonuniform distribution of magnetic field inside the test material, this is a quite complicated problem. Even when finite element methods are used, it is difficult to get a rigorous numerical solution. However, within the first approximation, which assumes that B and H fields inside samples are uniform and parallel to the sample surface, this problem can be solved. The measured magnetic quantities, H_{surface} and B_h are related to H_s and B_s by the following equations:

$$H_s = H_{\text{surface}}, \tag{1}$$

$$B_s = B_h \times \frac{A_h}{A_s}, \tag{2}$$

where A_h, A_s are the cross-sectional area of inspection head and sample, respectively. The first equation comes from the assumption of uniformity of H field inside the test sample and the continuity of the tangential component of H field. The second equation comes from the continuity of flux. However, some flux leakage always occurs in magnetic circuits involving surface inspections. Therefore, both Eqs. (1) and (2) need to be corrected for this leakage.

Due to the leakage field between legs of inspection head, the magnetic field detected on the surface of a sample will always be a little larger than that inside the sample. By using a Hall plate of high spatial resolution and mounting it in such a way that close contact with sample surface is assured, and with wide separation of the legs of the inspection head (Fig. 1), the H field measured by the Magnescope can be thought of as H_{surface}. Nevertheless Eq. (2) needs modification. The actual flux inside the test material is only a portion of the flux inside the inspection head. A parameter called the leakage coefficient, η, is defined to characterize the efficiency of inspection head as the ratio of total flux inside the sample to total flux inside the inspection head. Therefore the transfer function becomes:

$$H_s = H_{\text{surface}}, \tag{3}$$

$$B_s = \eta \times B_h \times \frac{A_h}{A_s}. \tag{4}$$

III. TEST RESULTS

By contacting an inspection head on the surface of test material, a magnetic circuit is formed. The testing configuration is shown in Fig. 1. In order to check the flux inside the magnetic circuit, two additional flux coils of 25 turns were wound one on the test sample and another on the leg of the inspection head. The Magnescope was used to record hysteresis loops of B-H. By multiplying flux density B by the cross sectional ones A. Flux versus field curves were calculated for locations 1, 2, 3 on the magnetic circuit,

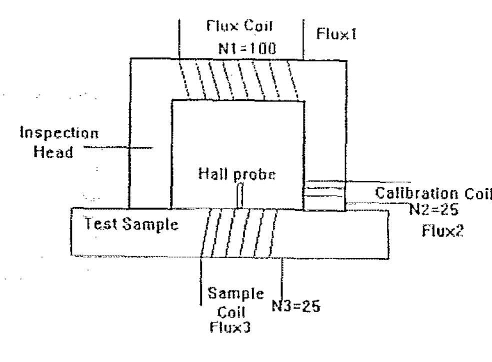

FIG. 1. Configuration of magnetic surface inspection.

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TABLE I. Testing samples.

Sample	Material (steel)	Cross section (cm^2)	Description
a	Armco	0.403	$2.54\times0.635\times0.635$ (cm^3)
c	Armco	0.202	$2.54\times0.635\times0.318$ (cm^3)
d	Armco	0.101	$2.54\times0.635\times0.159$ (cm^3)
1	Armco	2.42	$3.15\times2.64\times0.93$ (cm^3)
2	Armco	2.42	Irregular shape
3	Armco	3.76	Irregular shape
4	Armco	8.84	$7.3\times3.4\times2.6$ (cm^3)
W1	Medium carbon	5.00	Long steel bar
W2	Medium carbon	4.55	Long steel bar
W3[a]	Medium carbon	4.99	Long steel bar

[a]W1, W2, W3 have different composition.

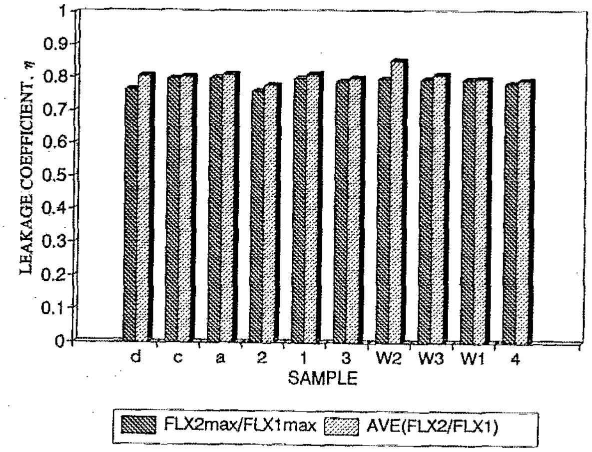

FIG. 3. Leakage coefficient for different samples. Flx2max/Flx1max is the ratio of maximum value of Flx2 to maximum value of Flx1 on flux-H loop. Ave(Flx2/Flx1) is the average value of the ratio of Flx2 to Flx1 on the flux-H loop.

which were identified as Flx1-H, Flx2-H, and Flx3-H, respectively. Flux continuity was checked in different test samples listed in Table I. The relation between these curves was quite similar. A typical example of data, taken on sample 2, is shown in Fig. 2.

It was found that the flux inside the inspection head in location 1 was larger than that in locations 2 and 3, but the latter two were almost identical. Therefore, it is quite clear that flux leakage occurred inside the inspection head and that flux leakage at the discontinuity between inspection head and the sample can be neglected.

The leakage coefficient η was calculated according to the definition of Flx3/Flx1, which is the same as Flx2/Flx1. Values of η measured on different samples are shown in Fig. 3. It can be seen that the values of η are almost constant at about 80% regardless of the differences in geometry and material composition of the test samples. This indicates that the amount of flux leakage is determined mainly by the inspection head itself. Thus η can be a parameter characterizing the efficiency of an inspection head.

While it is not always possible to wind a flux coil on a test sample in a practical situation, it is not difficult to wind a calibration coil in location 2 to find the leakage coefficient of an inspection head before using the transfer function. Figure 4 shows hysteresis loops from sample 3. Both direct measurement and inspection head measurement match each other excellently when the correct leakage coefficient is used.

IV. LIMITS OF FIRST APPROXIMATION

First approximation assumes magnetic flux passes through the cross section of the inspection head uniformly. According to the surface magnetic charge model,[5] both B and H are distributed inside test material nonuniformly and this distribution is a function of $1/(y^2+a^2)^{3/2}$, where a is half of the distance between the poles of the inspection head and y is the distance from the surface of the test sample.

According to this model, the penetration depth of the field, at which the magnetic field decays to $1/e$ of surface value, is about $0.97a$. Therefore, it can be seen that the first approximation, which gives B_s-H_s curves, works only when the thickness of the test sample is less than half the distance between the inspection head. When the dimension of the test material is larger, an effective cross-sectional area should be estimated in order to use the above transfer function. This can be achieved using the surface charge model.

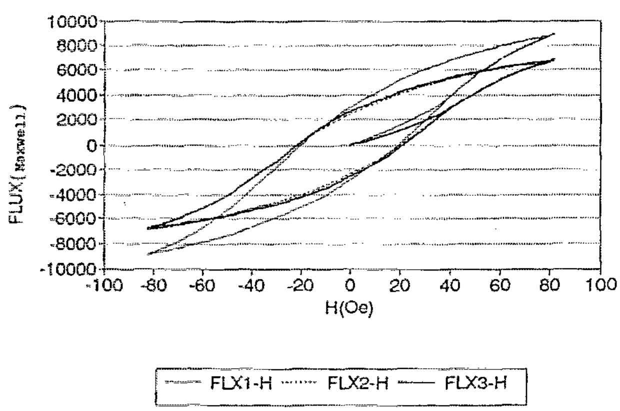

FIG. 2. Flux-$H_{surface}$ loop in locations 1, 2, 3 of the magnetic circuit.

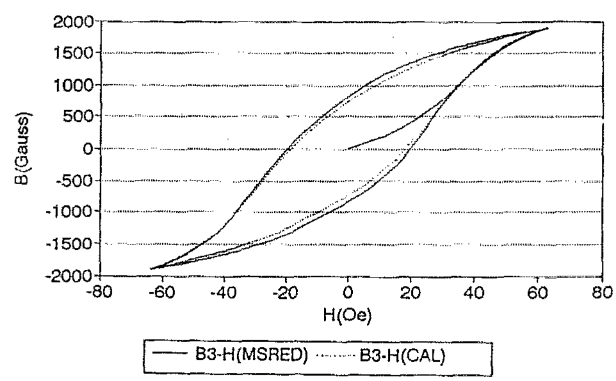

FIG. 4. Comparison of measured hysteresis curve and the one from first approximation.

V. CONCLUSIONS

The present study of the transfer function of an inspection head has shown that although there is an inherent flux leakage inside an inspection head, this can be corrected, since the amount of flux leakage is mainly determined by the configuration of the inspection head and can be characterized by a parameter called the leakage coefficient. According to this idea, each inspection should be tested first to find the leakage coefficient before taking magnetic measurements. Although this first approximation works well when the thickness of the test sample is no larger than the penetration depth of the field, it is generally quite safe to say that, by taking leakage coefficient into account, the flux inside a sample can be measured to a high degree of accuracy by this method.

ACKNOWLEDGMENT

This work was supported by the U.S. Nuclear Regulatory Commission through the Center for NDE at Iowa State University, under Grant No. NRC-04-91-098.

[1] D. C. Jiles, S. Hariharan, and M. K. Devine, IEEE Trans. Magn. **MAG-26**, 2577 (1990).
[2] M. K. Devine, S. Hariharan, L. J. H. Brasche, and D. C. Jiles, Rev. Prog. Quantitative NDE **10**, 2021 (1991).
[3] D. C. Jiles, Contract report prepared for Ontario Hydro, Research Division, November 1991.
[4] M. K. Devine, D. C. Jiles, and S. Hariharan, J. Magn. Magn. Mater. **104**, 377 (1992).
[5] Z. J. Chen, M. R. Govindaraju, and D. C. Jiles (these proceedings).