5-15-1993

Magnescope: Applications in nondestructive evaluation

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Abstract
This paper describes recent results obtained with the Magnescope, which has been used on location in industrial environments and has successfully detected impending fatigue failure, creep damage, applied stress, and microstructural differences. It is concluded that the device provides a useful nondestructive method for evaluating the mechanical properties of materials through the measurement of their structure sensitive magnetic properties.

Keywords
Center for Advanced Technology Development, Materials properties, Mechanical properties, Creep, Magnetic materials, Nondestructive testing

Disciplines
Electromagnetics and Photonics | Engineering Physics

Comments
The following article appeared in *Journal of Applied Physics* 73 (1993): 5617 and may be found at http://dx.doi.org/10.1063/1.353615.

AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **73**, 5617 (1993); doi: 10.1063/1.353615
View online: http://dx.doi.org/10.1063/1.353615
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/73/10?ver=pdfcov
Published by the AIP Publishing

Magnescope: Applications in nondestructive evaluation

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This paper describes recent results obtained with the Magnescope, which has been used on location in industrial environments and has successfully detected impending fatigue failure, creep damage, applied stress, and microstructural differences. It is concluded that the device provides a useful nondestructive method for evaluating the mechanical properties of materials through the measurement of their structure sensitive magnetic properties.

I. INTRODUCTION

The Magnescope[1] has found wide applications in nondestructive evaluation of the mechanical condition of ferromagnetic steels. Many investigations in the past have shown that the magnetic properties of steels are highly dependent on their mechanical and thermal treatment,[2–8] but without suitable instrumentation, it has proved difficult to make use of these findings in practical situations. With this instrument, we have been able to evaluate the condition of steels based on their magnetic properties. The instrument has proved useful in the detection of impending fatigue failure, creep damage, the quantitative evaluation of applied stress, detection of different metallurgies, and in sorting and quality control applications.

Unlike standard hysteresisgraphs which require a coil to be wrapped on the specimens, the Magnescope uses a sensor placed on the surface of the material to measure the magnetic properties. This allows inspections to be made on components *in situ* without extensive preparation of the material. The magnetic measurements obtained in this way reflect the magnetic properties of the sensor as well as the test material, but for comparative purposes this is not usually a problem. The instrument was also designed to be portable, allowing it to be used on location in industrial environments, as well as for laboratory measurements.

II. MAGNESCOPE

This instrument uses a small portable Dataworld computer which controls the entire instrument using a Keithley—Metrabyte data acquisition system. A Kepco BOP 20-10M bipolar power supply is connected to the sensor and this is used to generate a magnetic field in the sample. A Walker gaussmeter, Model MG-3D, is used for measuring magnetic field H, and a Walker fluxmeter, Model MF-3D, is used for measuring magnetic flux ϕ. A block diagram of the electronics and schematics of the sensor have been shown previously.[9,10]

An integrated program performs all magnetic field control, data acquisition, and data analysis. Algorithms have been developed to perform various inspections. Currently, the program can acquire the hysteresis curve, the initial magnetization curve, and the anhysteretic magnetization curve. This article will focus only on changes in the hysteresis properties. Several software routines are able to process the acquired data (such as smoothing data, or finding and eliminating offsets) along with analysis routines which calculate various parameters from the data. Some of these calculated parameters include coercivity, remanence, hysteresis loss, and maximum differential permeability. A comprehensive macro capability is also included to totally automate the task of processing and analyzing the data.

III. RESULTS

Results from an investigation into the magnetic detection of creep damage are shown in Figs. 1 and 2. The objective was to identify changes in magnetic properties resulting from the effects of creep damage. Measurements were taken around the diameter of various Cr-Mo hot reheat pipes in a hydroelectric power plant. The pipes were not in service at the time of the inspection because of routine maintenance. Measurements were taken on the pipes

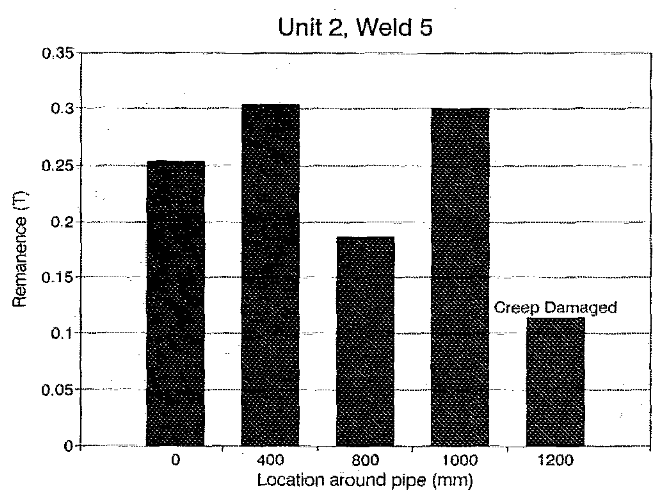

FIG. 1. Remanence measurements around the diameter of creep damaged pipeline of diameter 1600 mm. Creep damage was identified at a location corresponding to 1200 mm around the diameter. This can be seen to correspond to a low remanence.

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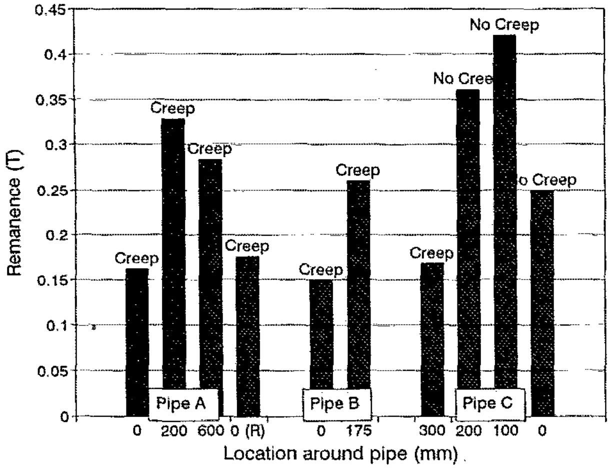

FIG. 2. Remanence measurements on welds of three creep damaged pipelines. The remanence at creep damaged locations was generally smaller than the remanence at most of the undamaged locations.

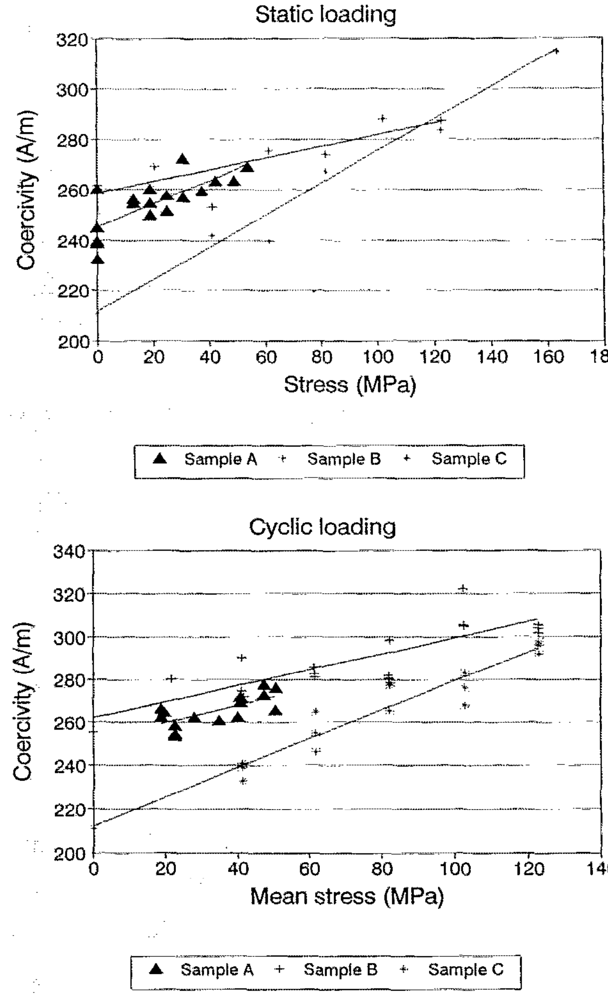

FIG. 3. Coercivity measurements on samples of steel bridge material subjected to (a) static loading and (b) cyclic loading.

after minimal surface preparation. Some of the locations had creep damage, as verified by replication work performed by the operator of the power plant. As can be seen in both figures, the remanence was substantially smaller at the locations where creep damage existed. In Fig. 2, almost every location where creep damage existed had a remanence below 0.35 T. The locations 100 and 200 mm around the diameter from the reference zero point on Pipe C had remanences above 0.35 T, substantially larger than the remanence at any creep damaged location. One could envision a threshold value of 0.35 T for identifying creep damaged locations. One problem was the measurement at the reference zero point on Pipe C, with a remanence of 0.25 T. It is possible that there was creep damage at this location and the replication work missed it. Similar behavior was found in the coercivity measurements in which low coercivities corresponded to creep damage. This work confirmed observations from previous laboratory work[11] on specimens of Cr-Mo steel.

The reason for the decrease in remanence due to creep is not entirely understood, although the initiation and growth of cavities will lead to localized demagnetizing fields and spike domains which should reduce remanence.

Some results from an investigation into the effects of cyclic stress on the magnetic properties of steels are shown in Figs. 3 and 4. In this investigation, samples of service aged low carbon steel were stressed in either cyclic or static mode. Static stress varied from 0 to +160 MPa, cyclic mean stress varied from +20 to +120 MPa. The frequency and stress ratio of the cyclic stressing was kept constant. None of the samples were subjected to compressive stress. The objective of this treatment was to produce fatigue damage in the material which simulated fatigue damage encountered through in-service conditions. Magnetic measurements were taken while the samples were loaded either statically or cyclically.

The static loading results are presented in Fig. 3(a) and the cyclic loading results are shown in Fig. 3(b). The coercivity was seen to increase with stress under both types of loading conditions. In addition, for a given specimen, the coercivity was similar for a given static or cyclic load. The coercivity change from zero stress appeared to be independent of the type of applied stress, whether static or cyclic. The scatter band was larger under cyclic loading conditions, but this was probably due to dynamic stresses acting on the samples. Similar results were seen in the remanence measurements [Figs. 4(a) and 4(b)]. The maximum differential permeability did not vary much under cyclic conditions.

Stress changes the magnetocrystalline anisotropy energy of the material through an additional contribution to the magnetic field, as described by Sablik *et al.*:[12]

$$H_\sigma = \frac{3}{2} \frac{\sigma}{\mu_0} \left(\frac{d\lambda}{dM} \right) T.$$

We consider this contribution also occurs during cyclic stress conditions, with σ being the mean stress.

In an investigation performed on specimens under uniaxial stress, a relationship has been determined between some of the magnetic parameters and the angle of the measurement with respect to the sample. Figure 5 shows the

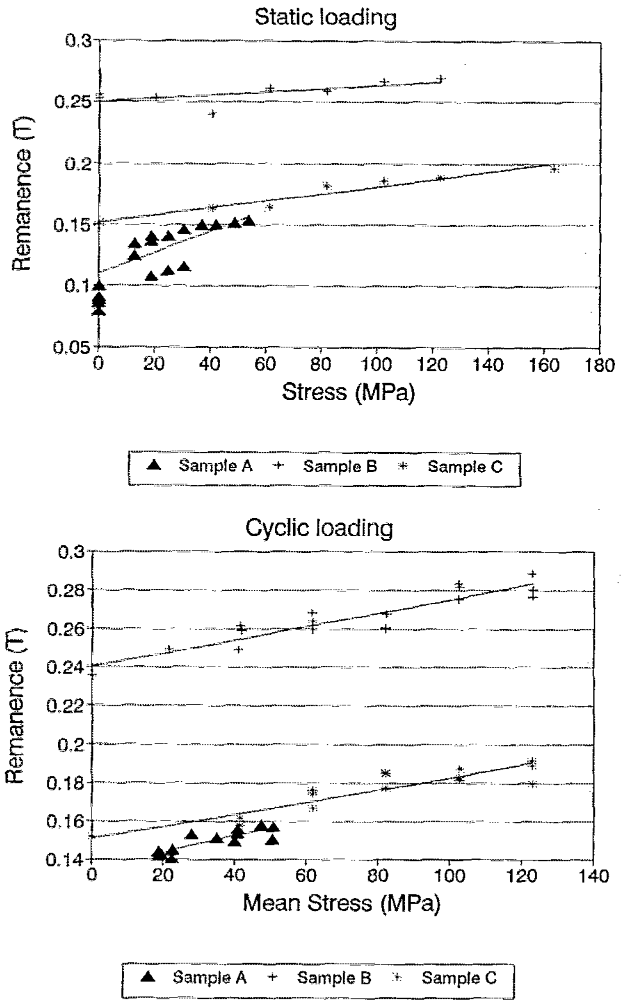

FIG. 4. Remanences measurements on samples of steel bridge material subjected to (a) static loading and (b) cyclic loading.

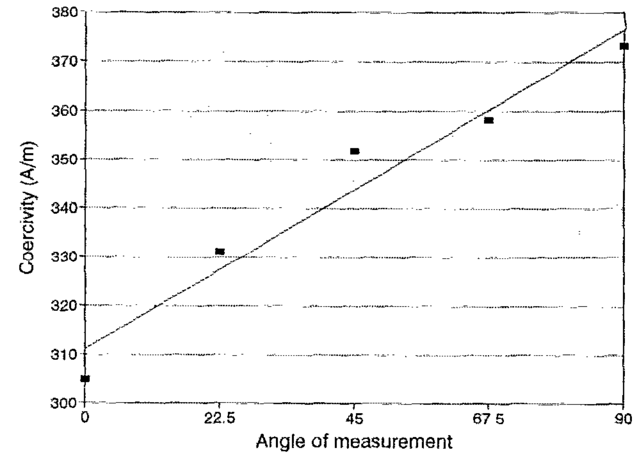

FIG. 5. Coercivity measured with respect to angle for service aged Cr-Mo steel.

results of a linear regression analysis that indicates a relationship between coercivity and the angle of the measurement. Here, five measurements were made on a sample of service aged Cr-Mo steel pipe with the sensor oriented at different angles. A 0° measurement corresponds to the long axis of the pipe. As shown in the figure, the coercivity shows an upward trend as the angle of measurement is increased. The resulting correlation coefficient for the linear regression was 0.954 and the results from a t-test indicated that the correlation coefficient is between 99.5% and 99.95% significant. These numbers show that there is a high probability of a relationship between coercivity and the angle of measurement relative to the stress axis in this material.

IV. CONCLUSIONS

The Magnescope represents a significant advance over previous technology because it allows *in situ* magnetic property measurements to be performed in the industrial workplace. To date, the main applications have been found in the evaluation of the properties of steels and in nondestructive evaluation, particularly in plant life extension. It can be seen from the results presented here that a close relationship between magnetic and mechanical properties exist which can be exploited for the purposes of *in situ* materials evaluation.

ACKNOWLEDGMENT

This work was supported by the U. S. Department of Commerce through the Center for Advanced Technology Development at Iowa State University under Grant Number ITA-87-02.

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