MICROSTRUCTURE AND STRESS DEPENDENCE OF THE MAGNETIC PROPERTIES OF STEELS

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INTRODUCTION

This paper is concerned with recent investigations of the effects of both microstructure and stress on the magnetic properties of steels. In particular the paper focuses on how the changes in material condition due to differences in microstructure and stress lead to changes in magnetic NDE measurements using techniques such as Barkhausen effect sensors, magneto acoustic emission sensors, hysteresis and the magnetoelastic (magnetically induced velocity change) method.

Effects of Microstructure on Magnetic Properties

The microstructure of steels has a crucial effect on the magnetic properties at low field strengths. In particular it is known that microstructure strongly affects coercivity, initial permeability and hysteresis loss. The reason for this is twofold. Regions of inhomogeneous microstrain, such as those associated with dislocations, form energy barriers which prevent magnetic Bloch walls from moving freely within the material. These regions of inhomogeneous strain can also be caused by precipitation of second phase particles such as carbides in steels. These effects were first discussed by Becker [1] and more recently by Kronmuller [2]. Also regions with different magnetic properties from the matrix material, known as magnetic inclusions, have a similar effect on magnetic domain wall motion. This was first discussed by Kersten [3] and later by Leslie and Stevens [4] and English [5]. An increase in the number of these inhomogeneities, whether strains or second phase particles, leads to a decrease in permeability and an increase in coercivity.

Effects of Stress on Magnetic Properties

Of all the factors affecting the magnetic properties of materials, the effects of applied stress are the most misunderstood. From the viewpoint of NDE they are also the most important and therefore a clear understanding is essential. The subject has been discussed in detail in previous papers [6,7]. The effects depend crucially on the spatial extent of the stresses. Stresses of the first kind (Type I Stresses) have a range of typically 10^{-2} m down to 10^{-5} m. These long range stresses lead to changes in the anisotropy of the material through the magnetoelastic coupling. Stresses of the third kind (Type III Stresses) have a range of typically 10^{-7} to 10^{-8} m. These short range stresses include those associated with dislocations. They affect the pinning of Bloch walls and therefore lead to reduced permeability and increased

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coercivity. The effect of stresses of the second kind (Type II Stresses), which have a range of typically 10^{-5} to 10^{-7} m, is as yet poorly understood.

In dealing with applied stress we mean type I stresses, which are long range. However even here there are two distinct effects as noted by Bozorth and Williams [8]. These are distinguished by the order of application of the stress and magnetic field. In this paper we shall consider only cases where the stress has been applied before the magnetic field and is held constant (isostress case).

Barkhausen Effect

Among magnetic methods for non destructive evaluation of stress and microstructure [9], the most widely used technique is the Barkhausen effect. The discontinuous changes in magnetization M or flux density B, as the magnetic field is varied continuously can be analyzed in many ways. The most common is to measure the count rate of the pulses over a particular frequency band. In this case it has been shown by Bozorth [10] that in iron and steel the maximum Barkhausen count rate occurs at the coercive field, as indicated in Fig.1.

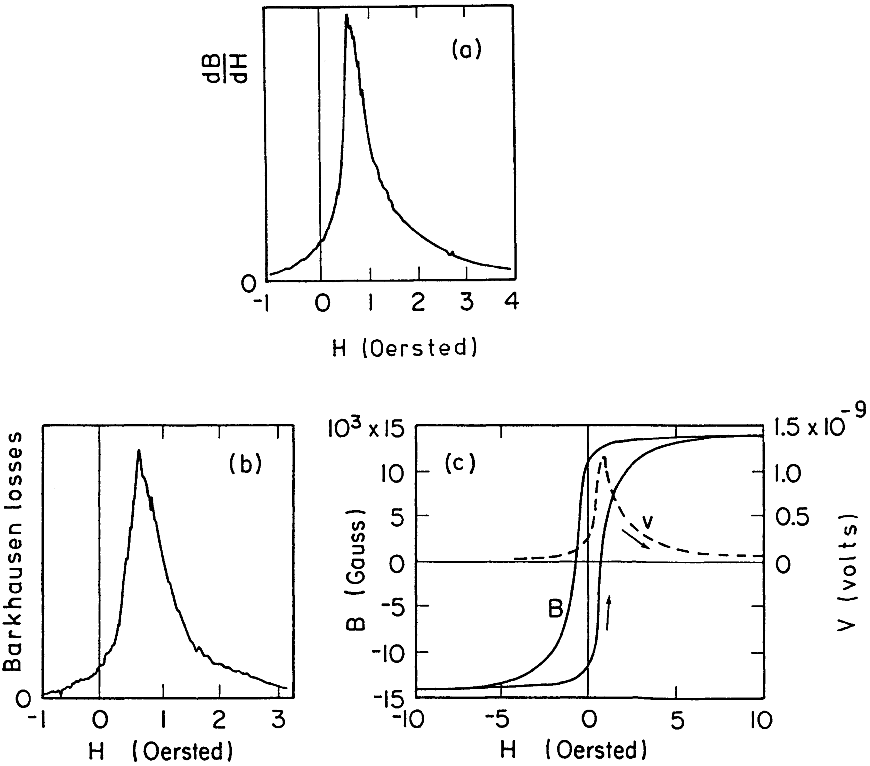

Fig. 1. (a) Rate of change of magnetic induction with field dB/dH in iron.
(b) Barkhausen energy losses in the same specimen of iron as a function of field.
(c) Volume of Barkhausen discontinuties in relation to the hysteresis loop.
Results reported by Bozorth [10]

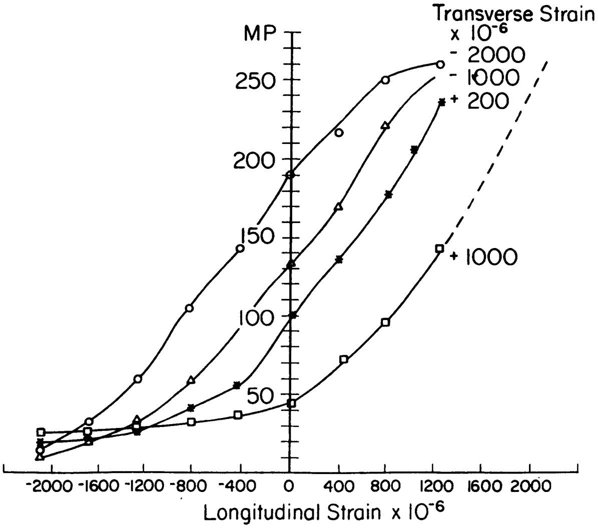

Fig. 2. Calibration curves for Barkhausen effect parameter MP as a function of longitudinal strain in the presence of different transverse strains.
Results reported by Tiitto [12].

The Barkhausen effect has been used as a technique for detecting stress in steels by a number of investigators. Tiitto [11] used the measurement of Barkhausen pulse amplitude distribution profiles as an NDE technique. From these profiles a mean value of amplitude was defined and this was found to vary in a systematic way with stress and grain size. Later work by Tiitto [12] used the peak level of Barkhausen activity, and it is this parameter which is now most widely used for stress detection. Recent work by Tiitto has been concerned with the problem of biaxial stress, and as shown in Fig. 2, the presence of a transverse stress changes the dependence of the Barkhausen activity on longitudinal stress. Tiitto [11] has also shown that information about the grain size can be deduced from the Barkhausen pulse height distribution spectrum.

Theiner and coworkers have made extensive investigations of the dependence of Barkhausen activity on stress. From the rectified Barkhausen noise signal measurements they have identified two parameters, M_{max}, the maximum of the Barkhausen noise amplitude and H_{cm} the field strength at which M_{max} occurs, which is very close to, if not identically equal to, the coercivity H_c in most steel samples.

It has been shown by Theiner and Altpeter [13] for example that M_{max} is sensitive to the applied stress, as indicated in Fig. 3. This parameter is particularly sensitive to tensile stresses, but apparently less so for compressive stresses. It was also found that H_{cm} was not very sensitive to applied stress. These results can be understood in terms of the effect of stress on anisotropy. This has been discussed by Garikepati et al [14] and Jiles [15].

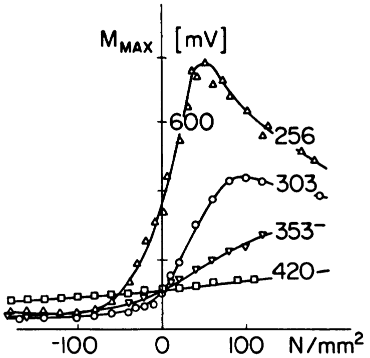

Fig. 3. Dependence of the parameter M_{max} on applied stress [13].

The evaluation of stress as a function of depth can also be determined from Barkhausen measurements by measuring the rectified Barkhausen signal amplitude over different frequency bands. As the frequency is increased the sampling depth decreases because of the skin effect. The skin depth δ is related to the conductivity σ and differential permeability μ' by the relation, $\delta = \sqrt{\frac{1}{\pi\sigma\mu'\nu}}$ where ν is the frequency. The results of Fig. 4, which are taken from the work of Bach, Goebbels and Theiner [16] show how the Barkhausen signal depends on frequency in induction hardened steel components.

Magnetoacoustic Emission

The discontinuous movement of non-180° Bloch walls leads to the emission of acoustic signals in magnetic materials with non zero magnetostriction. These magneto acoustic emissions have much in common with the Barkhausen effect, but nevertheless they convey different information about the material since 180° domain wall processes which contribute to the Barkhausen effect do not contribute to the magnetoacoustic signals.

Early work by Kusanagi et. al. [17] and by Ono and Shibata [18] has shown that the magnetoacoustic signal amplitude was dependent on stress and plastic deformation. The signal was detected as a single voltage amplitude as the magnetic field was cycled at 60 Hz. The signal was also found to be dependent on the carbon content of the steel.

The most extensive investigation of the use of magnetoacoustic emission for the evaluation of stress and microstructure to date has been that of Buttle, Briggs and co workers. [19,20,21]. Results of the effect of stress on the magnetoacoustic emission profiles of a specimen of BS 4360 mild steel which had been annealed at 650°C for 600 seconds prior to the measurement are shown in Fig. 5. This specimen, which had a ferrite/pearlite microstructure exhibited good sensitivity of the magnetoacoustic emission to stress. However it was found that specimens subjected to different heat treatment procedures, which contained martensite, revealed much less sensitivity to stress. [22]. The reason for this is thought to be that martensite does not accommodate 90° domain walls which are essential for generation of magnetoacoustic emission. However tempering of the marsensite leads to a progressive replacement of martensite by ferrite/cementite and this was found to cause an increase in magnetoacoustic emission signals with tempering.

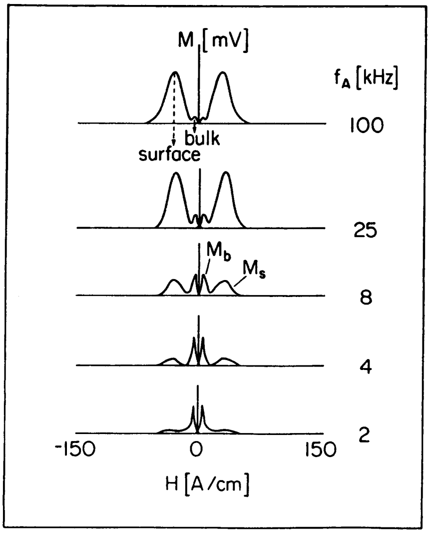

Fig. 4. Frequency dependence of the rectified Barkhausen activity in an induction hardened steel component [16].

Hysteresis Measurements

Hysteresis measurements allow several independent magnetic properties to be determined simultaneously. Furthermore there have been a number of investigations which have attempted to relate properties such as coercivity and initial suseptibility to the microstructure. This means that there is a better opportunity for making fundamental interpretations of magnetic measurements based on hysteresis than there is for other measurements such as Barkhausen effects and magnetoacoustic emission.

It has been shown that the hysteresis properties are affected by stress [23,24], plastic deformation [25,26] and microstructure [27]. In particular the application of stress changes the anisotropy which leads to an increase in maximum differential permeability μ'_{max} under tension, and a decrease under compression. This has now been given a quantitative interpretation in terms of the magnetostriction coefficient [24]. An alternative method of evaluating stress is to measure the third harmonic amplitude of the magnetisation under a sinusoidally varying field. This technique has been used by Burkhardt and Kwun [28].

In the case of steels the effect of microstructure on the magnetic properties is quite difficult to investigate because of problems in controlling the microstructure during heat treatment procedures. It is known that higher carbon content will, in the absence of other differences in microstruture, lead to higher coercivity and lower initial permeability. The work of English [5] has shown that carbides in the form of cementite and in the form of pearlite have very different effects on the motion of domain walls and therefore lead to differences in coercivity. More recent work [27] has confirmed these findings and shown that specimens with spheroidised cementite particles have lower coercivity than specimens with the same chemical composition and with pearlite grains.

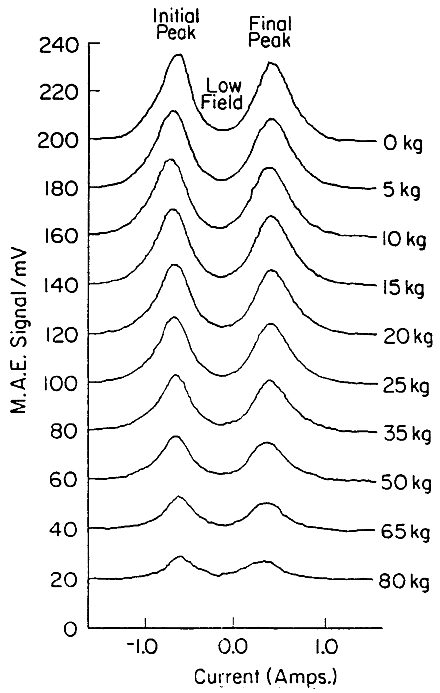

Fig. 5. Magneto acoustic emission signal amplitude as a function of magnetic field H for different applied stresses ranging from 0-192 MP_a (loads 0-80 kg). Each data set is displaced by 20 mv along the y-axis for clarity [22].

CONCLUSIONS

Magnetic non destructive evaluation techniques are sensitive to both the mechanical stress state and the microstructure of the material. Therefore in order to unambiguously determine stress from such measurements it is essential to be able to separate the effects of microstructure. The only exception to this occurs in cases where the microstructure is invariant (eg. measurements made on a single specimen or a limited set of specimens with identical microstructures).

In steels the principal microstructural features are the second phase carbide particles. In steels with low carbon contents the grain boundaries also become significant, but their effect is only of secondary importance above compositions of 0.2 wt % carbon.

In addressing the problem of separating the effects of microstructure and stress on the magnetic properties of steels, the most promising procedure is to measure a number of independent magnetic properties. Some of these, for example coercivity, are largely independent stress, while others, for example maximum differential permeability, are strongly affected by stress.

Among the techniques that are currently in use the hysteresis measurements give the most fundamental information about the material properties, but in some cases this can be difficult to measure. Barkhausen measurements although more empirical are often more easily adapted to fieldable measurement. This is also true for magnetoacoustic measurements, although in some cases extraneous acoustic noise has interfered with the measurement of magnetoacoustic emission signals.

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