

# THE EFFECTS OF STRESS ON MAGNETIC PROPERTIES AND THE USE OF MAGNETIC MEASUREMENTS FOR EVALUATION OF MATERIALS

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## ABSTRACT

*A new magnetic imaging system has been developed for non-destructive evaluation of structural and mechanical conditions of magnetic materials. The system produces a multi-parameter contour plot of the spatial variations of a variety of magnetic properties such as coercivity, remanence, permeability and Barkhausen effect (BE) signal. These can then be used for the detection of material conditions such as residual stress or the presence of cracks, since the magnetic and mechanical properties of materials are closely related via the magnetoelastic coupling. An integrated sensor probe capable of measuring both magnetic hysteresis and BE signals was developed using magnetoresistive devices. For comparison hysteresis loops and BE signals were measured in materials subjected to various tensile and compressive stresses within the elastic limit. A magnetic model has also been developed which provides a self-consistent description of the effects of stress on hysteresis loop and Barkhausen effect (BE) signals. BE signal was calculated based on the hysteretic-stochastic process model of domain wall dynamics, which has been extended to include the magnetomechanical effect.*

## INTRODUCTION

This paper describes some of the recent advances in understanding and application of magnetic methods for evaluation of materials. Properties such as coercivity, permeability and remanence, that all can be obtained from hysteresis, and Barkhausen effect measurements on materials, have the capacity for revealing structural changes in the materials. Changes in magnetic properties can result from such factors as change in microstructure, heat treatment change in applied stress, residual stress, dislocation density, fatigue damage, creep damage temper embrittlement. As a consequence of this they can be used for nondestructive evaluation. Several different magnetic measurements can be used simultaneously.

As a result of these advances new instrumentation has been developed to exploit this sensitivity of the hysteresis and Barkhausen effect to structure of the

material. The new portable equipment has been developed to enable practical implementation of these methods. The first of these was the Magnescope system which is a portable equipment for measuring hysteresis loops of materials. The second is the Magneprobe which measures Barkhausen emissions from the surface of materials. The third and most advanced equipment is the Magnescan which incorporates the measurement methods of both earlier pieces of equipment and extends them to allow imaging of the surfaces of materials. In this way regions of inhomogeneity are easily detected and from the quantitative results of both the hysteresis and Barkhausen effect measurements the levels of residual and applied stress can be determined. The Magnescan extracts several independent magnetic measurement parameters from each magnetization cycle at a particular location on the surface of the material. Surface images of the various magnetic measurement parameters can then be shown giving a rich variety of information about the material and how its various properties change from location to location.

The successful use of these techniques rests heavily on the theoretical models developed to describe both hysteresis and Barkhausen effect. Interpretation of results obtained with the instrumentation depends on the recent development of reliable model theories. In order to understand and interpret the observed changes we begin by describing the underlying phenomenological model theory. To be useful in this situation the theory must be applicable to the appropriate length scale at which the magnetic NDE measurements are made. The theoretical model that has been developed describes the effects of material structure and stress on magnetic hysteresis. In this case the description applies to multidomain magnetic specimens.

## **HYSTERESIS AND BARKHAUSEN EFFECT MEASUREMENTS**

It has been established that magnetic hysteresis loop is sensitive to structural conditions (e.g. defect density, texture) and stress state of materials. Several hysteresis loop properties such as coercivity, remanence, initial permeability, maximum differential permeability and hysteresis loss, can be obtained from a single measurement. Barkhausen effect signals arise from discontinuous changes in magnetization. These signals are also sensitive to microstructure and stress level of materials so that measurement of Barkhausen effect can also be used for evaluation of materials [1]. The information obtained from the Barkhausen results is complementary to that obtained from the hysteresis measurements. In particular these signals that are detected come only from a surface layer whose thickness is determined by the frequency of the emissions. The peak Barkhausen occurs at the coercive field and the amplitude is proportional to the irreversible component of the maximum differential permeability.

Fig. 1 shows the Barkhausen effect signal obtained as the magnetization is varied along the lower branch of the hysteresis loop. The signal is superimposed on the hysteresis loop. The maximum Barkhausen activity occurs normally at the coercive field. The coercivity and remanence of the simulated hysteresis loops exhibited a stress dependence consistent with that of the experimental data as shown in Fig. 2. As shown in the figure the experiment and modeled theory agree well with each other.

These magnetic properties were found to change systematically with the dynamic microstructural changes induced by the fatigue cycling. Variation of coercivity and remanence with expended fatigue cycling is shown in Fig. 3. After an initial period of settling down both become stable throughout most of the lifetime but critical changes begin to happen at 80 to 90% expended lifetime. Also shown is the variation in nominal elastic modulus (applied stress divided by original cross sectional area), which correlates well with the remanence.

Variation of magnetic remanence with nominal elastic modulus (stress divided by original cross sectional area) throughout the fatigue lifetime is shown in Fig. 4. Hysteresis loops at various stress levels for a 410 stainless steel having positive rate of change of magnetostriction with magnetization are shown in Fig. 5. The compressive stress reduces the permeability and remanence while increasing coercivity. The effects of tensile stress (which are not shown here) are the opposite.

Barkhausen measurements on cold-rolled steel sheet were carried out. Fig. 6 shows the variation of Barkhausen effect as a function of angle in cold rolled steel showing anisotropy in properties. The rolling direction is at 30 degrees to the reference direction. Fig. 7 shows the variation of Barkhausen effect as a function of direction, a) along the rolling direction, b) at 45 degrees to the rolling direction, c) at 90 degrees to the rolling direction. Fig. 8 shows the Barkhausen effect signals at case depths of 0.5 mm and 1.0 mm. The amplitude of the signal decreases with case depth as shown in Fig. 8.

## THEORY AND MODELING OF HYSTERESIS

### Hysteresis modeling

In order to provide a reliable interpretation of the results of the magnetic inspections a theoretical model of the magnetization process has been developed. This model includes descriptions of both hysteresis and Barkhausen effect.

This hysteresis model developed is based on the principle that domain wall motion, and domain rotation take place as a result of both reversible and irreversible processes. The changes in magnetization  $M$  can be separated into both irreversible and reversible components, and equations have been developed to describe both of these components.

$$\frac{dM_{irr}}{dH} = \frac{1}{k\delta - \alpha(M_{an} - M_{irr})} (M_{an} - M_{irr}) \quad (1)$$

Where the model parameter  $k$  contains information about the microstructure of the material, such as pinning site density, defect density or dislocation density. The reversible change in magnetization is given by

$$\frac{dM_{rev}}{dH} = c \left( \frac{dM_{an}}{dH} - \frac{dM_{irr}}{dH} \right) \quad (2)$$

Where the model parameter  $c$  carries information about the reversible processes such as reversible domain wall motion and reversible rotation.

The total change in magnetization  $M$  under an applied field  $H$  is given by the standard model equation obtained by summing the reversible and irreversible terms

$$\frac{dM}{dH} = (1-c) \frac{(M_{an} - M)}{\delta k - \alpha(M_{an} - M)} + \frac{dM_{an}}{dH} \quad (3)$$

where  $M_{an}$  is the anhysteretic magnetization, which for a completely isotropic material is given by

$$M_{an} = M_s \left( \coth \left( \frac{H + \alpha M}{a} \right) - \left( \frac{a}{H + \alpha M} \right) \right) \quad (4)$$

Solution of this equation gives the standard sigmoid shaped hysteresis loops. This theoretical model has been extended to include the effects of stress, anisotropy, frequency, and orthogonal bias field [2,3].

### Incorporation of stress through the effective field

Applied stress can be treated in most respects like an effective magnetic field which changes the anisotropy of the material [6].

$$H_\sigma = \frac{3\sigma}{2\mu_0} \left( \frac{\delta\lambda}{\delta M} \right)_T \quad (5)$$

The total field is then the sum of magnetic field  $H$ , exchange field  $\alpha M$  and "stress-equivalent field"  $H_\sigma$ ,

$$H_e = H + H_\sigma + \alpha M \quad (6)$$

The magnetization is then a function of this total field. For a completely isotropic material the anhysteretic magnetization has a particularly simple form,

$$M_{an(H,\sigma)} = M_s \left[ \coth \left( \frac{H + H_\sigma + \alpha M}{a} \right) - \frac{a}{H + H_\sigma + \alpha M} \right] \quad (7)$$

### Uniaxial stress at different directions to magnetic field

When a uniaxial stress is applied to a magnetic material this induces magnetoelastic anisotropy. The theory was extended to cover the case of a uniaxial stress at an arbitrary direction to the applied magnetic field. Applied stress causes a change in energy of magnetic moments that is directionally dependent

$$E_\sigma = \frac{3}{2} \sigma \lambda (\cos^2 \theta - v \sin^2 \theta) \quad (8)$$

This leads to a directionally dependent effective field,

$$H_\sigma(\theta) = \frac{3\sigma}{2\mu_0} (\cos^2 \theta - v \sin^2 \theta) \left( \frac{\partial \lambda}{\partial M} \right)_T \quad (9)$$

where  $\sigma$  is the stress,  $\theta$  is the angle between the stress axis and the direction of the magnetic field, and  $\nu$  is Poisson's ratio. A similar approach can be applied to cases of anisotropy and texture originating from other causes.

## THEORY AND MODELING OF BARKHAUSEN EFFECT

### Barkhausen modeling

A theoretical model description of BE signal has been developed based on the hysteretic-stochastic process model of domain wall dynamics. The model has been extended to include the magnetomechanical effect, allowing the effects of applied stresses on BE signals to be simulated. Theories of domain wall dynamics begin from the equation of Kittel, Shockley and Williams [4] which relates the domain wall velocity to the difference in field between the applied field and the internal field.

$$v \propto H_a - (H_{dem} + H_p) \quad (10)$$

From this it follows that the rate of change of flux is given by

$$\frac{d\phi}{dt} = \frac{1}{\sigma G} (H_a - H_{dem} - H_p) \quad (11)$$

Using the stochastic process model of Bertotti et al. [5] the second derivative of the flux is given by

$\tau = \sigma G \chi_{irr}$ , and this can be converted to a second time derivative of the intensity of magnetization  $I$

$$\frac{d\dot{\phi}}{dt} + \frac{\dot{\phi} - SI}{\tau} = \frac{1}{\sigma G} \frac{dH_p}{dt} \quad (12)$$

$$\frac{d\dot{I}_{irr}}{dt} = \frac{\chi_{irr}}{\tau} \left( \frac{dH_a}{dt} - \frac{dH_p}{dt} \right) - \frac{\dot{I}_{irr}}{\tau} \quad (13)$$

The pinning field  $H_p$  is described by

$$\frac{dH_p}{dI_{irr}} + \frac{S(H_p - \langle H_p \rangle)}{\xi} = \frac{dW}{dI_{irr}} \quad (14)$$

Where  $W$  is a white noise function given by,

$$\langle dW \rangle = 0, \langle [dW]^2 \rangle = 2ASdI_{irr} \quad (15)$$

Barkhausen jumps correspond to irreversible changes in magnetization. We therefore rewrite the model in terms of  $SI_{irr}$  rather than  $\phi$ . In the case of hysteretic processes such as occur in the magnetization of ferromagnets,  $\lambda_{irr}$  is calculated from the hysteresis model.

## Incorporation of stress into the Barkhausen model

The irreversible susceptibility  $\lambda_{irr}$  can be computed using the hysteresis model [6] via the equation

$$\chi'_{irr} = \frac{(M_a - M_{irr})}{(k_{eff}\delta/\mu_0) - \left[ a_{eff} + (3\sigma/2\mu_0) \left( \partial^2 \lambda / \partial M^2 \right) \right] (M_a - M_{irr})} \quad (16)$$

where  $\alpha_{eff}$  and  $k_{eff}$  are the effective pinning coefficient and the effective mean field parameter [7]. In this approach the effects of the applied stress on BE signal can be modeled via the parameters  $k_{eff}$  and  $\alpha_{eff}$  which are dependent on stress. Fig. 9 shows the variation of Barkhausen effect with stress and the prediction of the stress dependence according to the model theory.

## IMAGING USING MULTIPARAMETER MAGNETIC MEASUREMENTS

Since hysteresis gives several independent pieces of information about the materials properties, (coercivity, remanence, initial permeability, maximum differential permeability and hysteresis loss), and Barkhausen provides additional information (pulse amplitudes, frequencies, which can be either represented as a distribution or averaged) these can all be used to produce different magnetic images of the surface of the material that are useful for nondestructive evaluation.

Magnetic hysteresis and Barkhausen scans were obtained from plain carbon steel plates with artificially made surface or subsurface defects. During the experiments the sensor probe was scanned over the top surface of the samples in steps of 1.25 mm. The probe remained stationary when measuring hysteresis loops and BE signals. Magnetizing field was applied along the direction normal to the notches. The sample was demagnetized at each scanning step prior to conducting hysteresis loop measurements. All the surface notches are visible as stripes in the images of the measured magnetic hysteresis properties and BE signals.

Examples of some of these images are shown in Figs. 10-12. Fig. 10 shows the variation of measured coercivity across a plate with several artificially machined defects which can be seen from the coercivity variations as vertical stripes where there is anomalously high coercivity. The high coercivity results from the enhanced pinning of domains at the defect sites. It is evident that surface notches of small width can be readily detected using the magnetic scanning system. The contrast (colour depth) was in general found to be greater for deeper notches. Most of the notches and semi-circular grooves on the bottom side can be detected in the scanned hysteresis loop property images. Similarly in Fig. 11 the remanence also shows regions of anomalous remanence, which reflects the high levels of magnetic induction due to flux leakage in the vicinity of the defects. Fig. 12 shows the variation of the Barkhausen effect around two of these line defects. In this case the pinning at the defects results in less domain wall motion and hence lower Barkhausen emissions such as has been observed previously in other situations as a result of increased dislocation density resulting from plastic deformation.

## CONCLUSIONS

An integrated magnetic hysteresis and Barkhausen effect model has been developed which includes stress dependence of pinning site strengths for nondestructive evaluation of materials. This has been used to describe the effects of applied stress on hysteresis in magnetization and Barkhausen effect signals. Barkhausen signals were simulated using a hysteretic-stochastic model which has been extended to include the magnetomechanical effect. Interpretation of results for several different magnetic measurements depends heavily on the development of reliable model theories. A magnetic imaging system was developed for evaluating mechanical and structural conditions of materials by imaging the magnetic properties. Results of experimental studies on a variety of magnetic samples showed that the system can be used to detect surface or sub-surface notches, thickness variations and stress profiles in magnetic materials.

## ACKNOWLEDGMENTS

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## REFERENCES

1. D. C. Jiles, "Dynamic of domain magnetization and the Barkhausen effect", Czechoslovak Journal of Physics, 50 (2000) 893.
2. D. C. Jiles, "Theory of magnetomechanical effect", J. Phys. D: Applied Physics, 28 (1995), 1537.
3. M. J. Sablik and R. A. Langman, "Approach to the anhysteretic surface", J. Appl. Phys. 79(1996)6134.
4. H. J. Williams, W. Shockley, and C. Kittel, Phys. Rev. 80 (1950) 1090.
5. G. B. Alessandro, C. Beatrice, G. Bertotti, and A. Montorsi, "Domain-wall dynamics and Barkhausen effect in metallic ferromagnetic materials," J. Appl. Phys. 68 (1990) 2901.
6. M. J. Sablik and D. C. Jiles, "Coupled magnetoelastic theory of magnetic and magnetostrictive hysteresis", IEEE Trans. Mag., 29 (1993) 2113.
7. C. C. H. Lo, S. J. Lee, L. Li, L. C. Kerdus, and D. C. Siles, "Modeling Stress Effects on Magnetic Hysteresis and Barkhausen Emission Using a Hysteretic-Stochastic Model", IEEE Trans. Magn., 38 (2002) 2418.

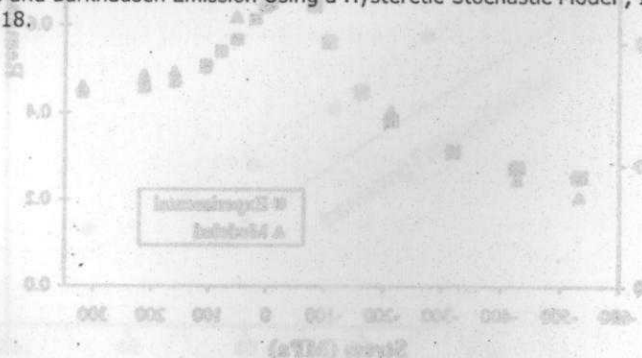


Fig. 5: The variation of coercivity and remanence with applied stress showing how these magnetic measurements can be used to assess stress. Also displayed is the prediction of the model theory.

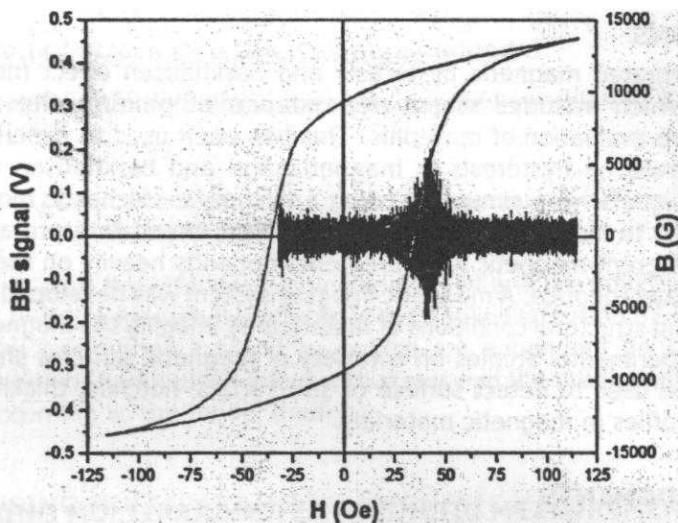


Fig. 1 : The Barkhausen effect signal obtained as the magnetization is varied along the lower branch of the hysteresis loop is shown here superimposed on the hysteresis loop. The maximum Barkhausen activity occurs normally at the coercive field.

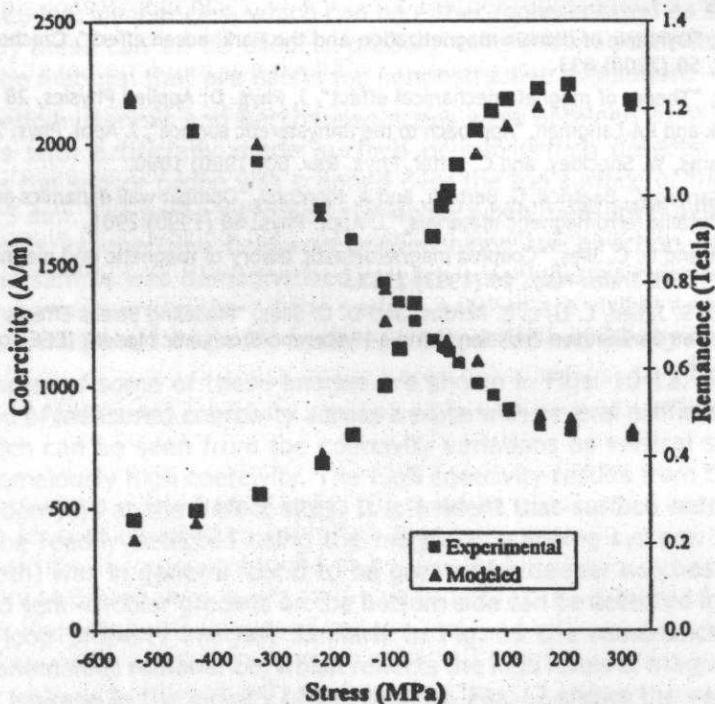


Fig. 2 : The variation of coercivity and remanence with applied stress showing how these magnetic measurements can be used to assess stress. Also displayed is the prediction of the model theory.

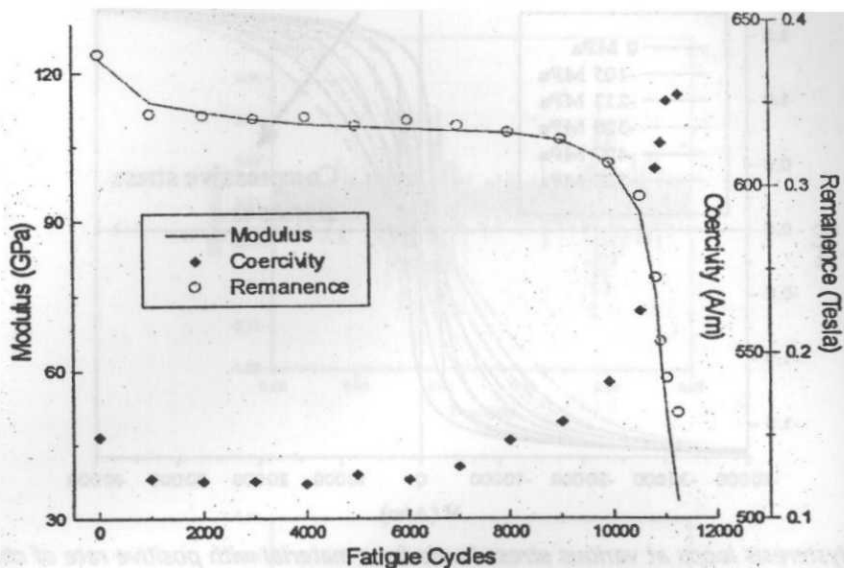


Fig. 3 : Variation of coercivity and remanence with expended fatigue lifetime. After an initial period of settling down both become stable throughout most of the lifetime but critical changes begin to happen at 80 to 90% expended lifetime. Also shown is the variation in nominal elastic modulus (applied stress divided by original cross sectional area), which correlates well with the remanence.

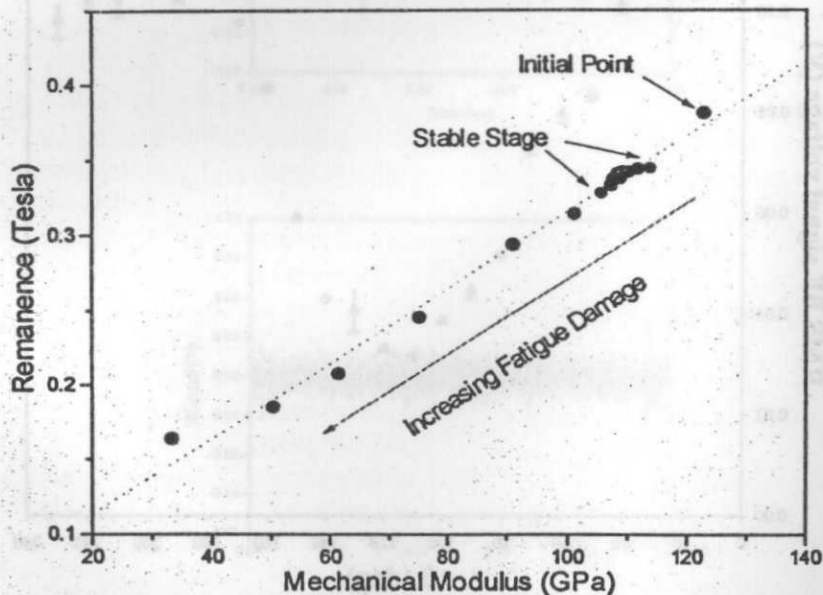


Fig. 4 : Variation of magnetic remanence with effective modulus (stress divided by original cross sectional area) throughout the fatigue lifetime.

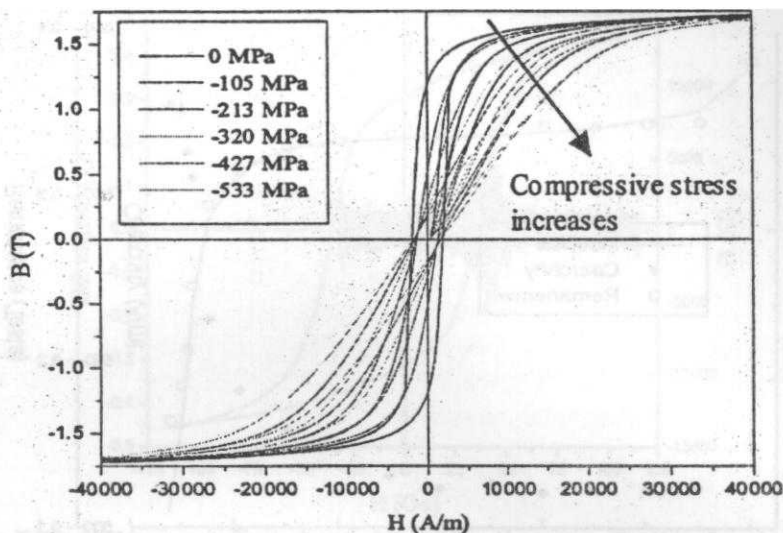


Fig. 5 : Hysteresis loops at various stress levels for a material with positive rate of change of magnetostriction with magnetization. The compressive stress reduces the permeability and remanence while increasing coercivity. The effects of tensile stress (not shown) are the opposite..

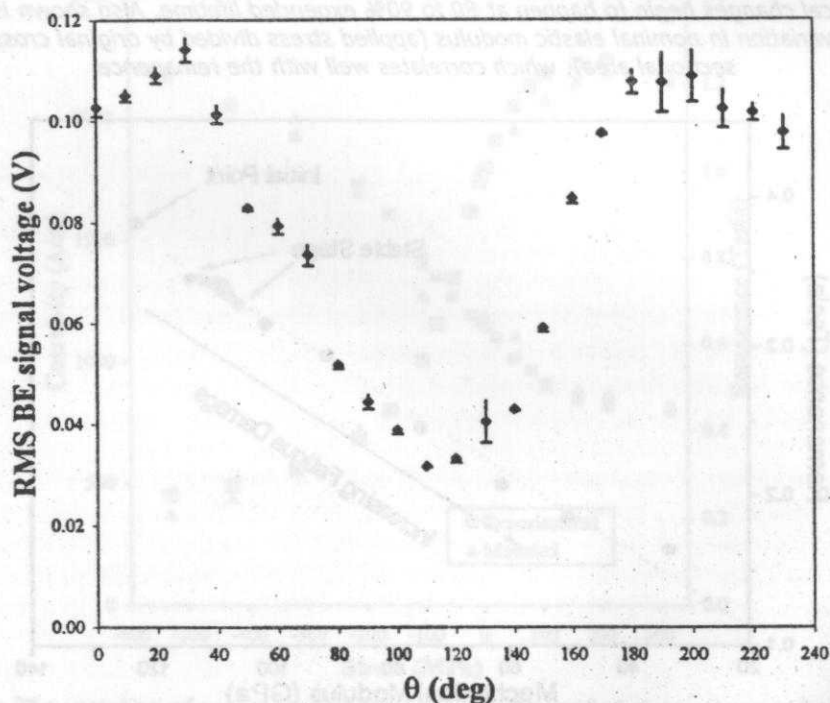


Fig. 6 : Variation of Barhausen effect as a function of angle in cold rolled steel showing anisotropy in properties. The rolling direction is at 30 degrees to the reference direction.

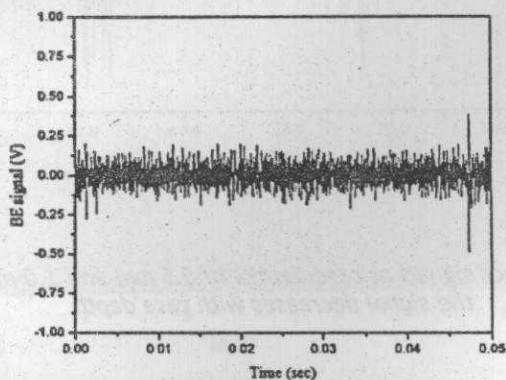
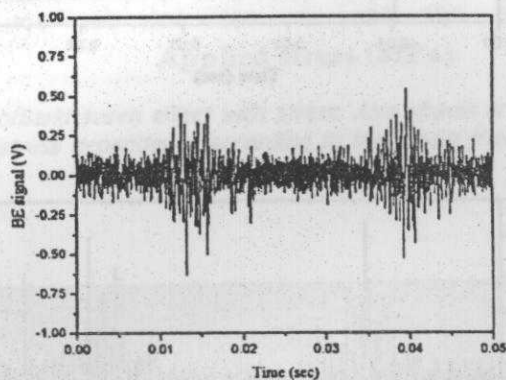
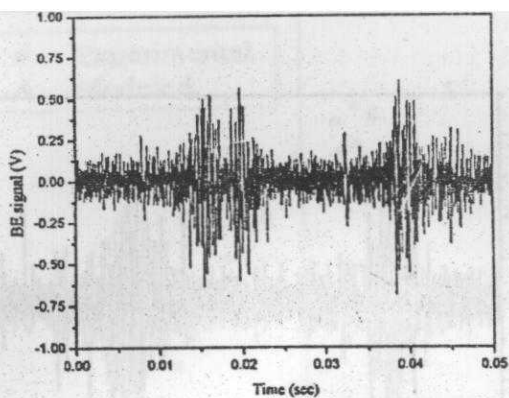


Fig. 7 : Variation of Barkhausen effect as a function of direction, a) along the rolling direction, b) at 45 degrees to the rolling direction, c) at 90 degrees to the rolling direction.

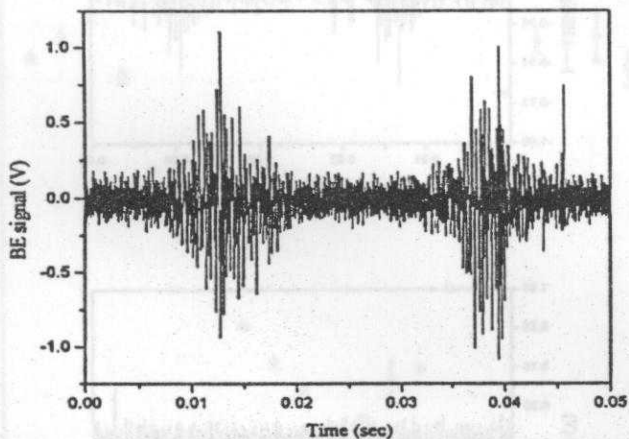
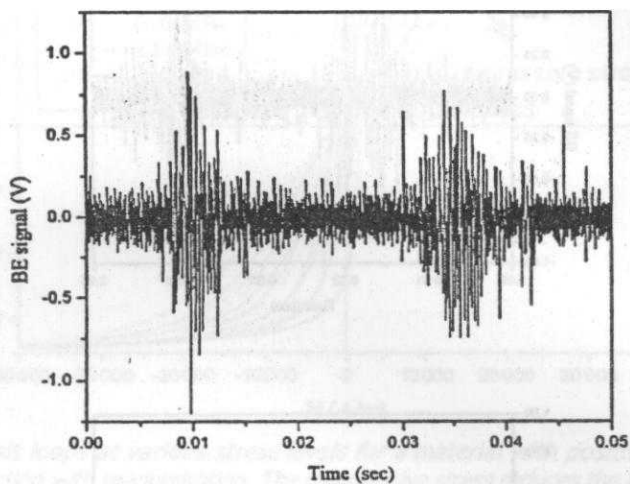


*Fig. 8 : Barkhausen effect signals at case depths of 0.5 mm and 1.0 mm. The amplitude of the signal decreases with case depth.*

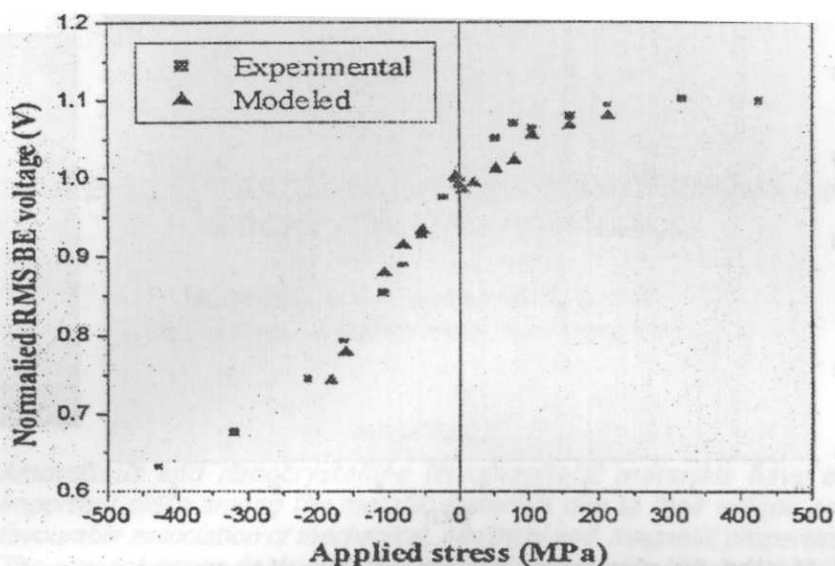


Fig. 9 : Variation of Barkhausen effect with stress. Also shown is the prediction of the stress dependence according to the model theory.

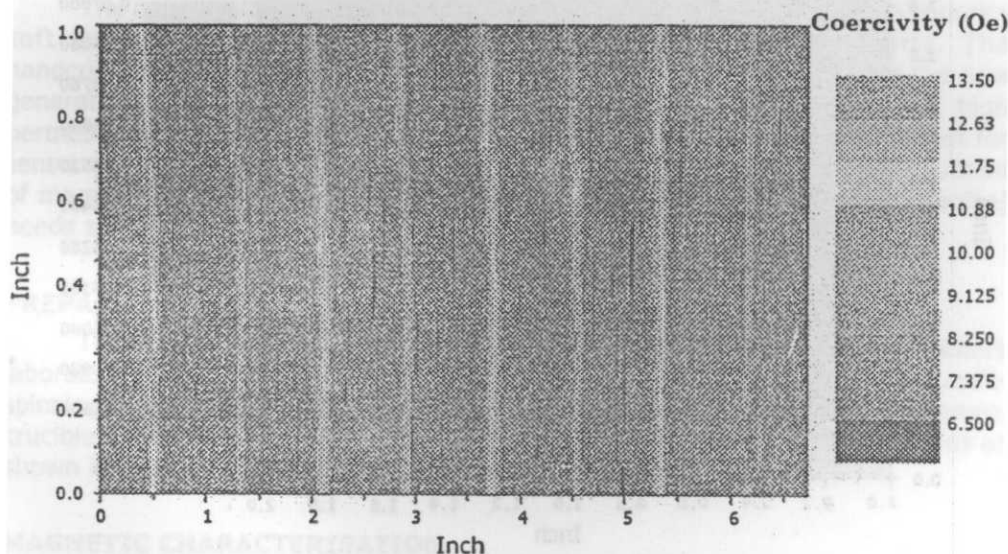


Fig. 10 : Variation of coercivity with position obtained by scanning a magnetic sensor across the surface of a material with artificial defects. The locations of the defects can be seen from the locations of the vertical lines.

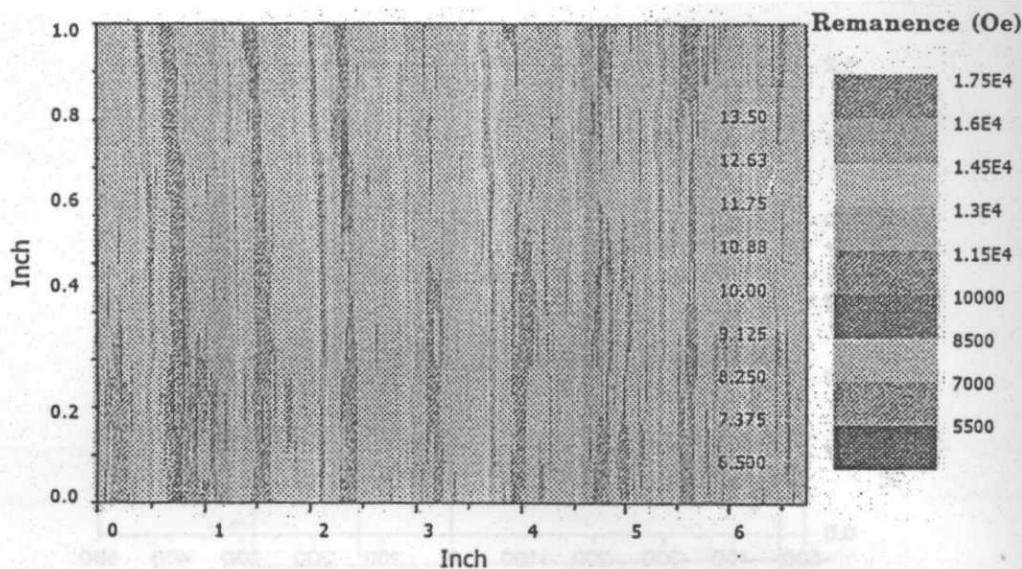


Fig. 11 : Variation of remanence with position obtained by scanning a magnetic sensor across the surface of a material with artificial defects. The locations of the defects can be seen from the locations of the vertical lines.

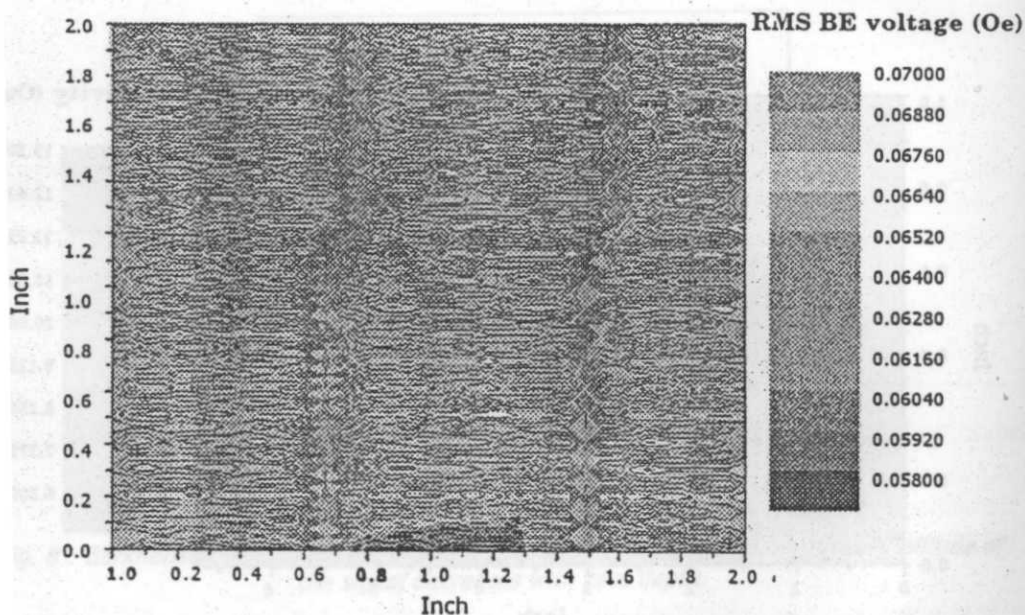


Fig. 12 : Variation of root mean square Barkhausen with position obtained by scanning a magnetic sensor across the surface of a material with two artificial defects. The locations of the defects can be seen from the locations of the vertical lines.