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Theory and Practice – Making use of the Barkhausen Effect

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Workshop on Large Fluctuations and Collective Phenomena in Disordered Materials
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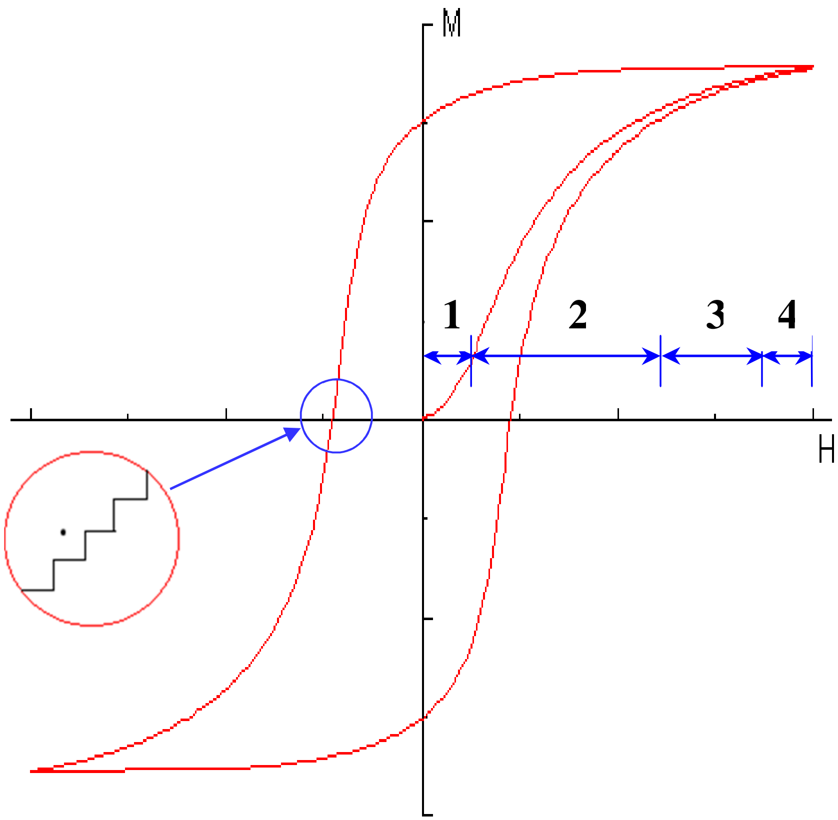
Summary

- **Stochastic/deterministic Barkhausen model**
  - Equations describing the phenomenon
  - Comparison of theory and experiment
- **Variation of emissions with other factors such as stress**
  - Variation of Barkhausen signal amplitude
  - Theoretical predictions – inverse law
- **Variation of signal with frequency and distance**
  - Possibilities for depth profiling of properties
  - Challenges

The variation of magnetization with magnetic field looks deceptively simple



- Yet behind it lies a large number of very complicated interrelated mechanisms which are hard to model
- A further problem is that magnetic behavior is inhomogeneous and does not "scale" easily as dimensions change
- The result has been a number of different models which do not fit together very well

Langevin-Weiss Model

- An array of magnetic moments at temperature T and in a magnetic field H will distribute themselves among the available energy states according to the probability distribution P

$$P = P_0 \exp\left(-\mu_0 m H / k_B T\right)$$

- Integrating over all possible angles and normalizing gives

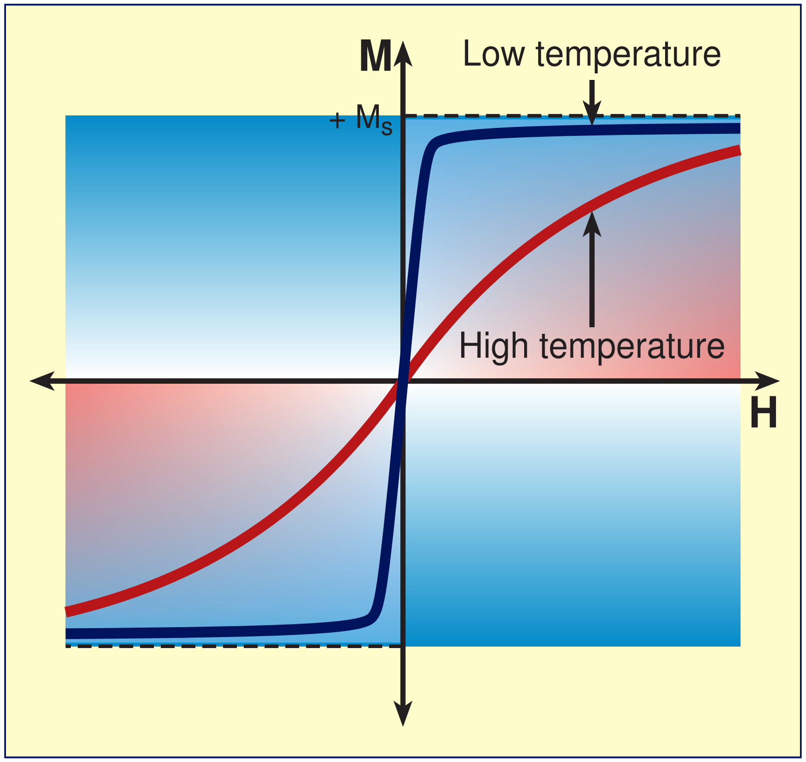
$$M = Nm\left[\coth\left(\mu_0 m H / k_B T\right) - \left(k_B T / \mu_0 m H\right)\right]$$

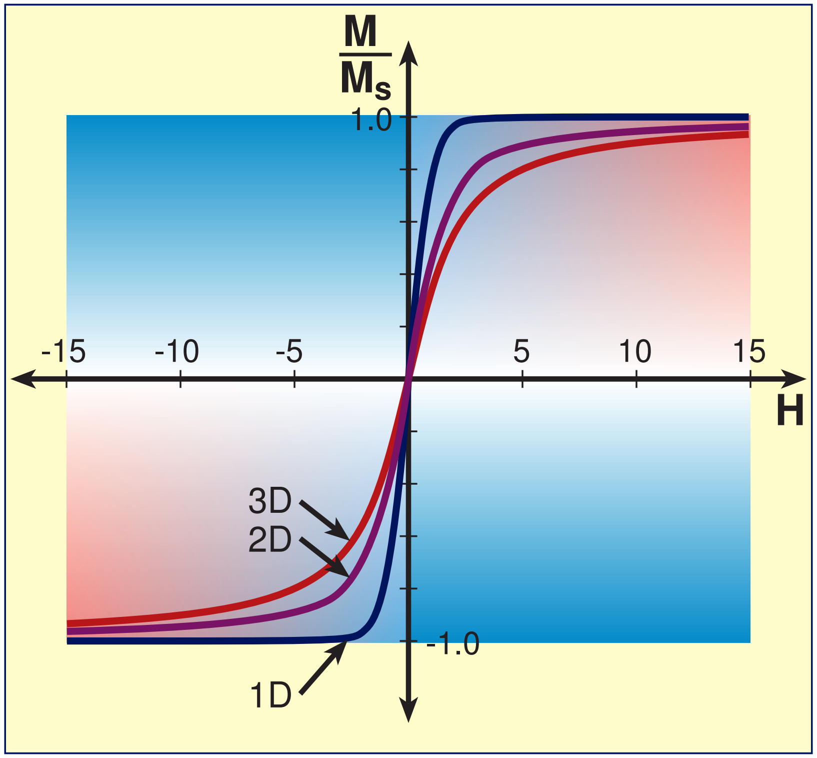
- Weiss extended this to include internal coupling proportional to the magnetization He = aM with the result

$$M = Nm\left[\coth\left(\mu_0 m\left(H + \alpha M\right) / k_B T\right) - \left(k_B T / \mu_0 m\left(H + \alpha M\right)\right)\right]$$

which decribes the **anhysteretic** magnetization curve for ferromagnets

Anhysteretic magnetization curves with different temperatures and different anisotropies





"Superparamagnetic magnetization equation in two dimensions," D.C. Jiles, S.J. Lee, J. Kenkel and K. Metlov. *Applied Physics Letters*, 77, 1029, 2000.

Energy Dissipation and Hysteresis

- **Energy is only dissipated by irreversible magnetization processes**

- **A model with dissipation proportional to change in M gives good results**

$$E_{pin}(M) = \frac{n\langle \varepsilon_\pi \rangle}{2m} \int_0^M dM_{irr} = \mu_o k \int_0^M dM_{irr}$$

- **Energy output (change in magnetostatic energy) must equal energy input minus energy dissipated due to any losses such as hysteresis**

$$\mu_0 \int M_{irr} dH_e = \mu_0 \int M_{an} dH_e - \mu_0 k \int dM_{irr}$$

Irreversible Changes in Magnetization

- **Differentiating the energy equation lead to a differential for the rate of change of magnetization**

$$\frac{dM_{irr}}{dH_e} = \frac{1}{k}\left(M_{an} - M_{irr}\right)$$

- **This can be written in the form of a differential with respect to the applied field H**

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

Isotropic Model of Hysteresis

- The irreversible component of magnetization varies according to the differential equation

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

- The reversible component of magnetization varies as

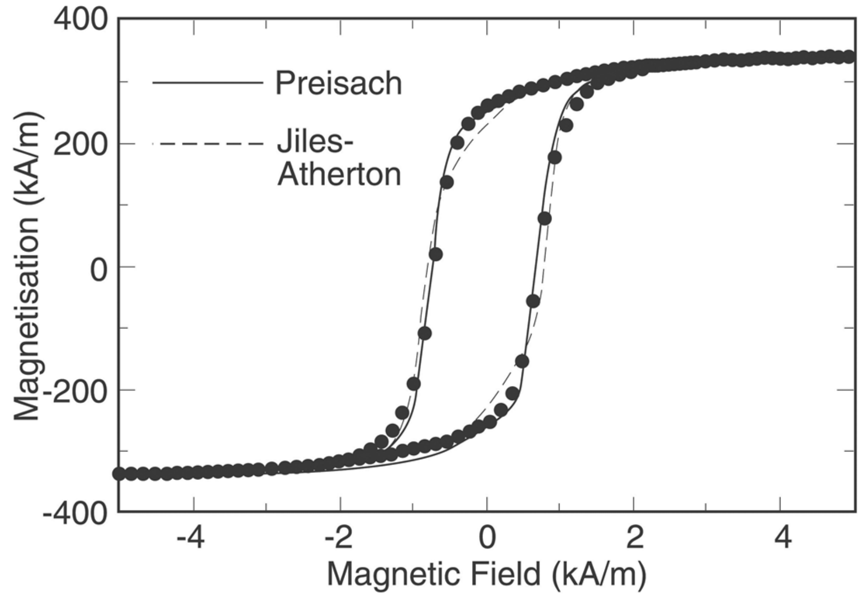
$$\frac{dM_{rev}}{dH} = c\left(\frac{dM_{an}}{dH} - \frac{dM_{irr}}{dH}\right)$$

- Therefore hysteresis can be represented in terms of Ms, a, α, k, and c using the equation

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

"Determination of theoretical parameters for modelling bulk magnetic hysteresis properties using the theory of ferromagnetic hysteresis," D.C. Jiles, J.B. Thoelke and M.K. Devine. *IEEE Trans. Mag.*

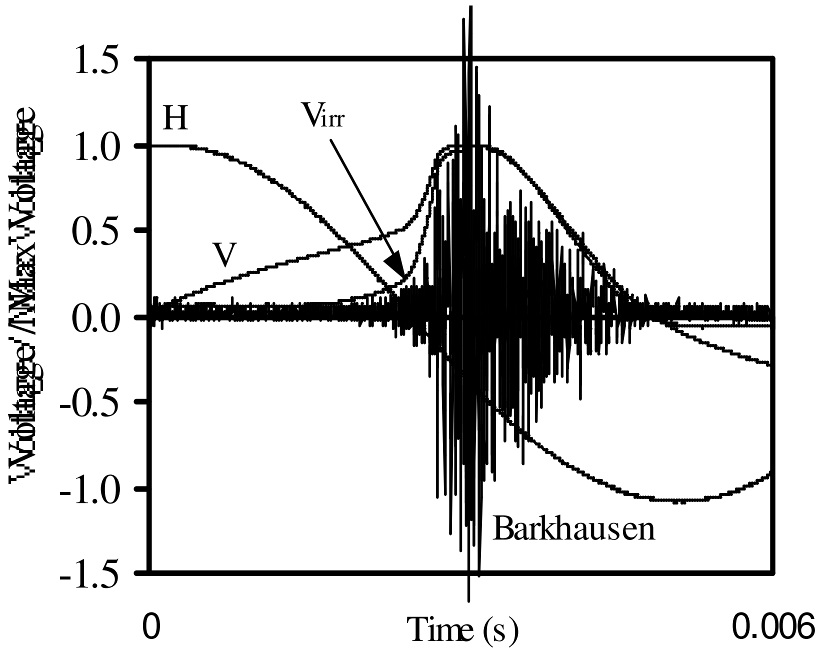
Comparison of Model and Experimental Measurement



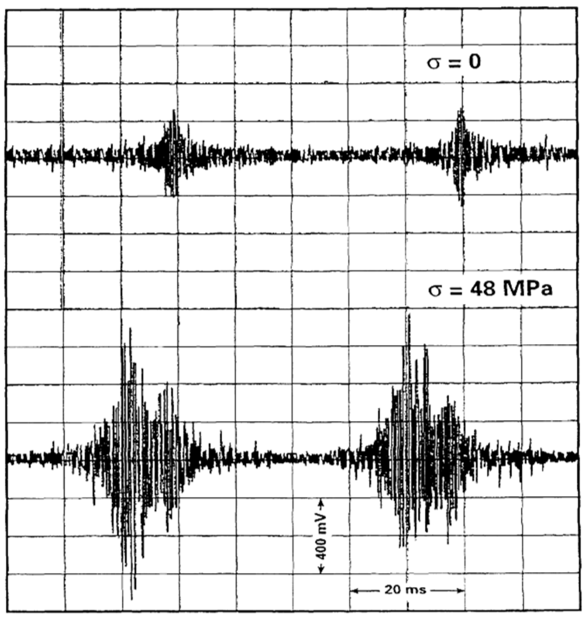
- **Comparison of measured and modelled hysteresis curves of cobalt modified gamma iron oxide material**

After P. Andrei and A. Stancu, "Hysteresis in particulate recording media. Experiment and simulation with Preisach and Jiles-Atherton models," *Journal of Magnetism and Magnetic Materials*, **206**, 160-164, 1999.

Other magnetic properties - Barkhausen effect



Barkhausen signal shown as voltage against time. The time dependence of magnetic field H, voltage in flux coil V, and envelope of irreversible component of voltage in flux coil V_{irr} are also shown on the same time scale.



Changes in Barkhausen emissions in carbon steel as a result of applied tensile stress.

Stochastic Process Barkhausen model

Model assumes Barkhausen activity is proportional to the rate of irreversible change in magnetization

$$\frac{dM_{BE}}{dt} \propto \dot{M}_{irr} = \chi'_{irr}\dot{H} \qquad M_{BE} = N < M_{disc} >$$

$<M_{disc}>$: Average discontinuous change in magnetization due to Barkhausen jump

Avalanches: Number of Barkhausen events $N(t_n)$ in a given time interval is correlated with number of events in the previous time interval t_{n-1}

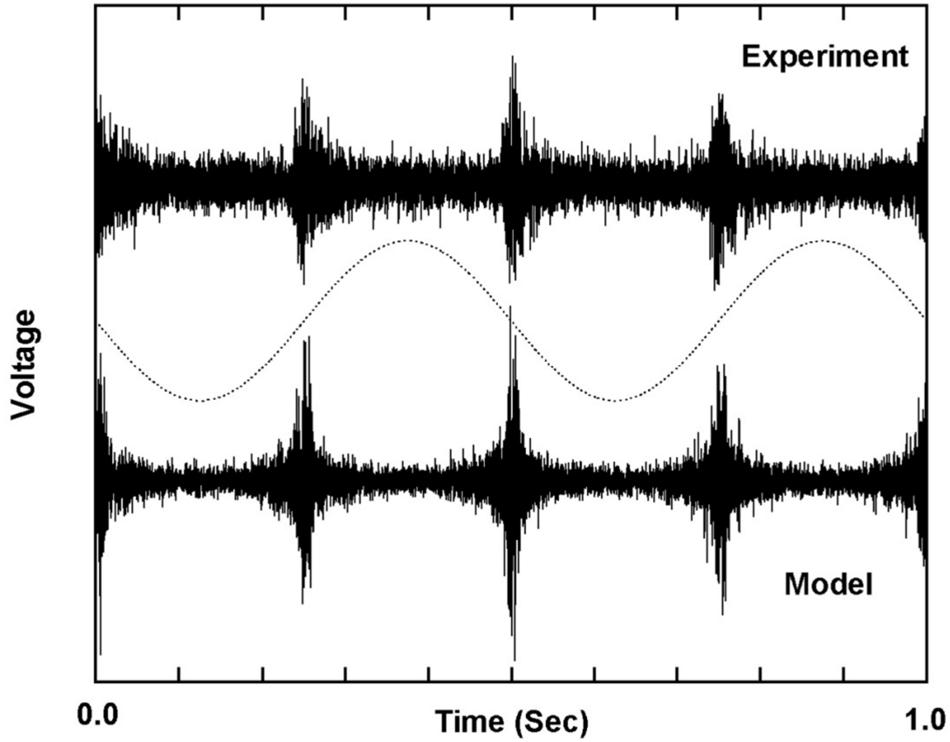
$$N(t_n) = N(t_{n-1}) + \Delta N(t_{n-1})$$

$$\Delta N(t_{n-1}) = \delta_{rand}\sqrt{N(t_{n-1})}$$

$$\dot{M}_{BE}(t_n) = < M_{disc} > \chi'_{rr}\dot{H}\left[N'(t_{n-1}) + \delta_{rand}\sqrt{N'(t_{n-1})}\right]$$

δ_{rand} : Random number ($-1.47 < \delta_{rand} < 1.47$)

Comparison of model with experiment



Other Factors – Effects of Stress

- **Applied stress can be treated in most respects like an effective magnetic field which changes the anisotropy of the material**

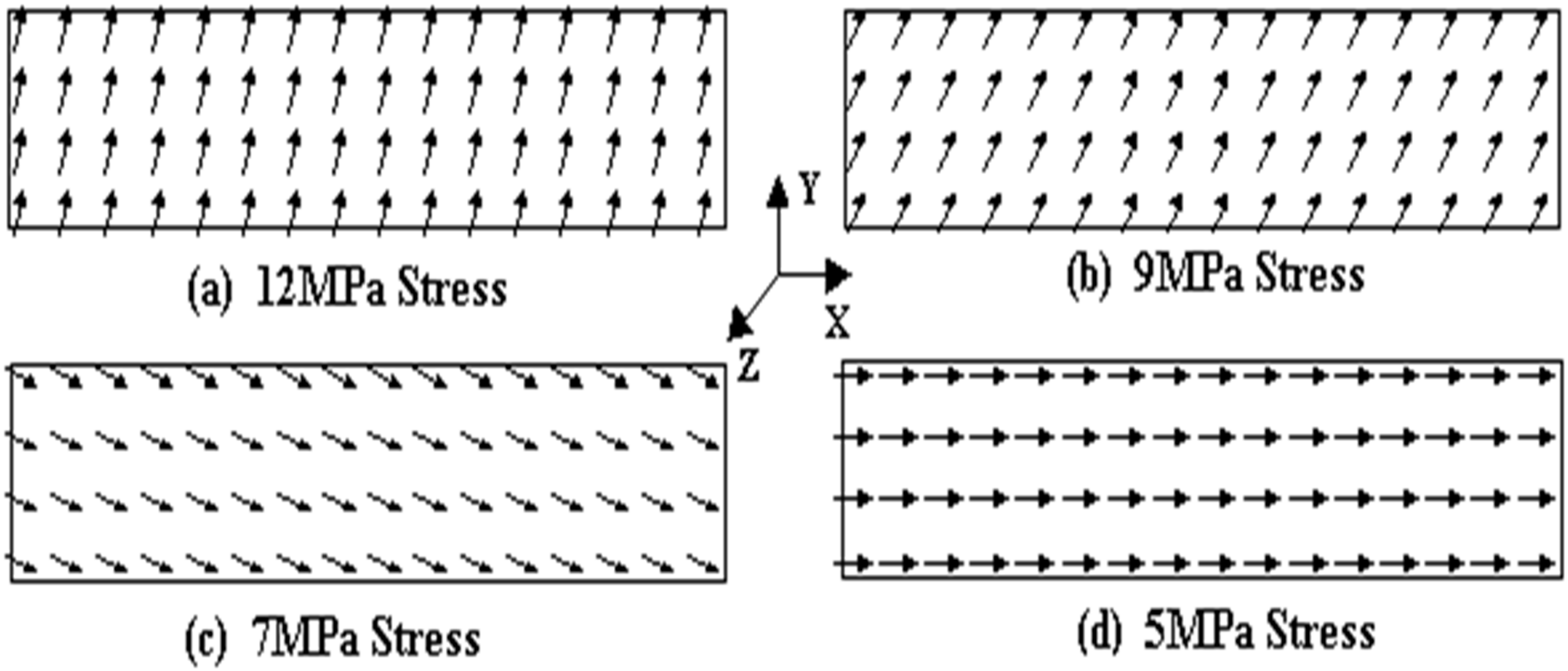
$$H_\sigma = \frac{3}{2}\frac{\sigma}{\mu_o}\left(\frac{\partial \lambda}{\partial M}\right)_T$$

- **Later this was extended to cover the case of a uniaxial stress at an arbitrary direction to the applied magnetic field**

$$H_\sigma(\theta) = \frac{3}{2}\frac{\sigma}{\mu_o}\left(\cos^2\theta - \nu \sin^2\theta\right)\left(\frac{\partial \lambda}{\partial M}\right)_T$$

- **σ is the stress, θ is the angle between the stress axis and the direction of H_σ, and ν is Poisson's ratio.**

Modelled Effects of Stress on Magnetic Moment Orientation

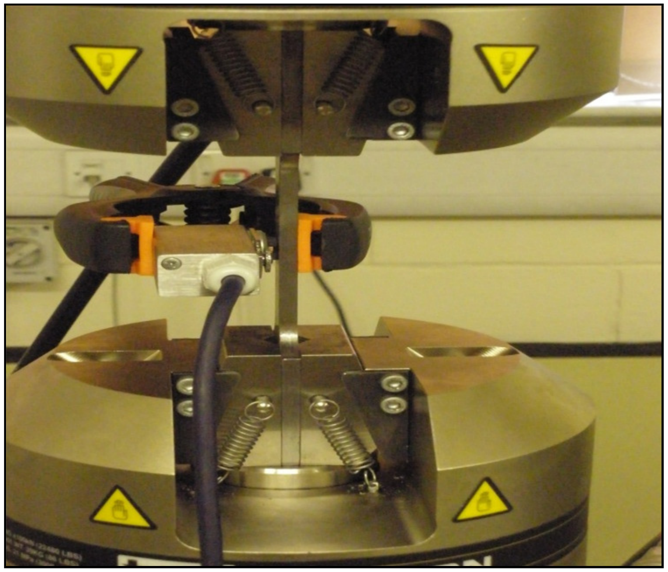


Positive magnetostriction stress applied along the y axis

Detection of Stress

Specimens calibration tested under load in Instron Tensile Test machine

BN sensor in the middle of gauge length of sample

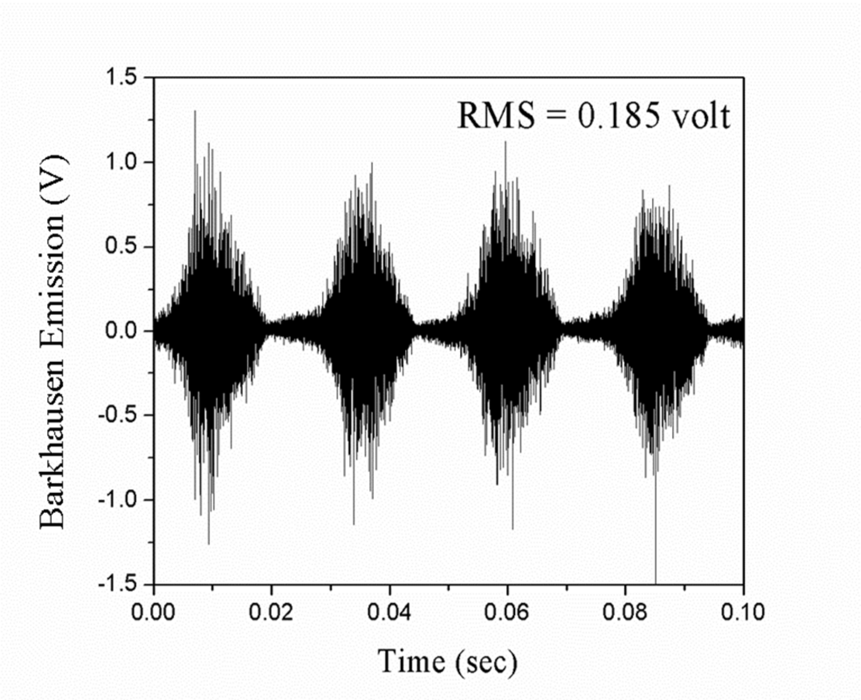


Typical Magnetising and Analysis Conditions :

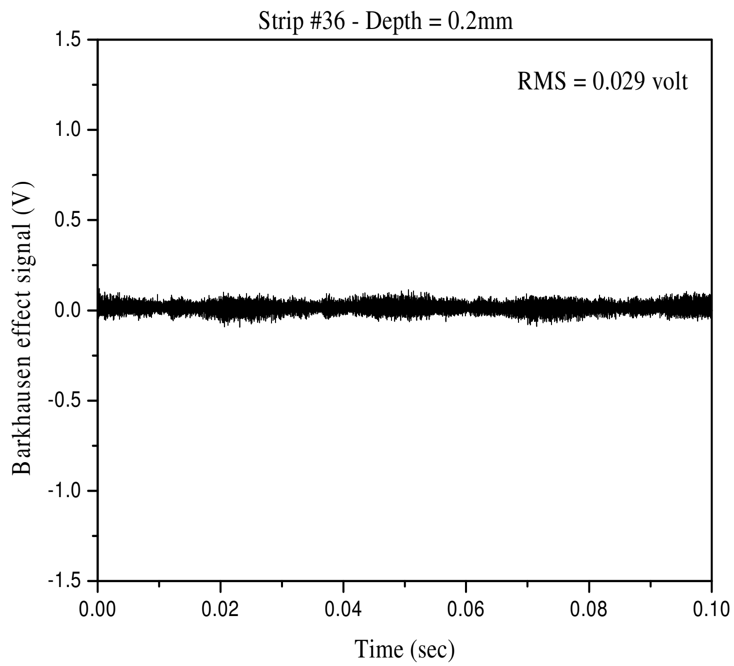
Magnetising frequency : f = 300 Hz
Magnetising voltage : V = 12 volt
No of bursts : 20
Analysing bandwidth frequency : fa = 20-1250 KHz (about nearest 100 µm)
Smoothing parameter: sp = 100
Sampling frequency: fs =2.5 MHz

Measured Barkhausen Results

Core



Surface



Effects of Stress on Barkhausen Emissions

Applied stress causes a change in anisotropy energy of magnetic moments

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

This can be expressed as an equivalent field

$$H_\sigma = -\frac{1}{\mu_0}\frac{\partial E_\sigma}{\partial M} = \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{\partial\lambda}{\partial M}\right)_\sigma$$

The total field is then the sum of magnetic field, exchange field and "stress-equivalent field" H_σ

$$H_e = H + H_\sigma + \alpha M = H + \left(\frac{3\lambda_s\sigma}{\mu_o M_s^{\ 2}}\right)M + \alpha M$$

The magnetization is then an anisotropic function of this total field

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

Effects of Stress on Barkhausen Emissions

$$\chi'(\sigma) = \frac{dM_{an}}{dH}(H,\sigma) \cong M_s\left[\frac{1}{3a - (\alpha_\sigma + \alpha)M_s}\right] = M_s\left[\frac{1}{3a - \left(\frac{3\lambda_s\sigma}{\mu_o M_s^2} + \alpha\right)M_s}\right]$$

This predicts how the rate of change of magnetization with field depends on stress and so can be used to calculate stress. However there is a much easier way...

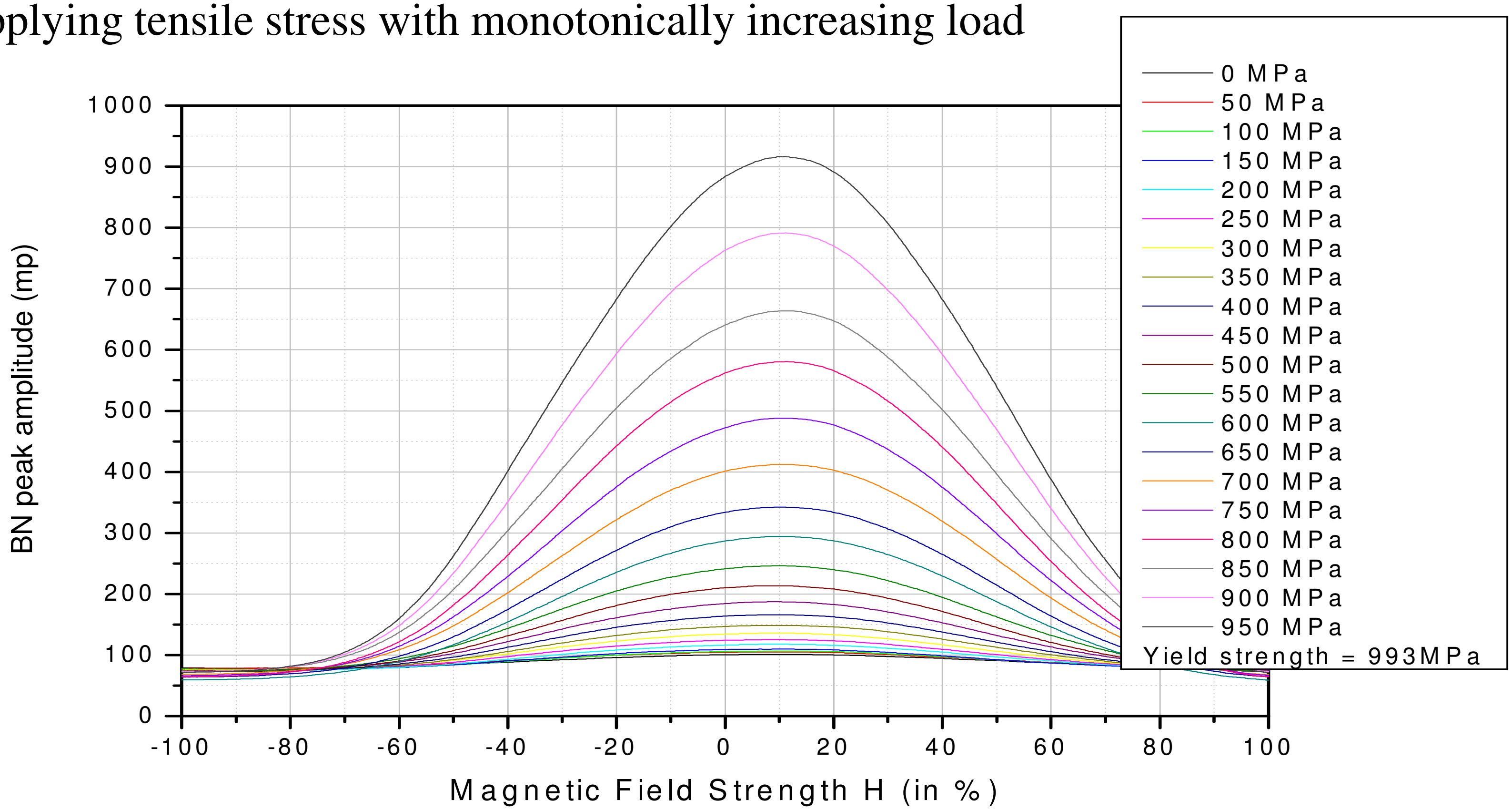
$$\frac{1}{\chi'(\sigma)} = \frac{3a - (\alpha + \alpha_\sigma)M_s}{M_s} = \frac{3a - \left(\alpha + \frac{3\lambda_s\sigma}{\mu_o M_s^2}\right)M_s}{M_s}$$

$$\frac{1}{\chi'(\sigma)} = \frac{1}{\chi'(0)} - \frac{3\lambda_s\sigma}{\mu_o M_s^2}$$

which predicts a straight line graph of $1/\chi'$ against σ

Detection of Tensile Stress - test results

Applying tensile stress with monotonically increasing load



Dependence of Barkhausen emissions on stress

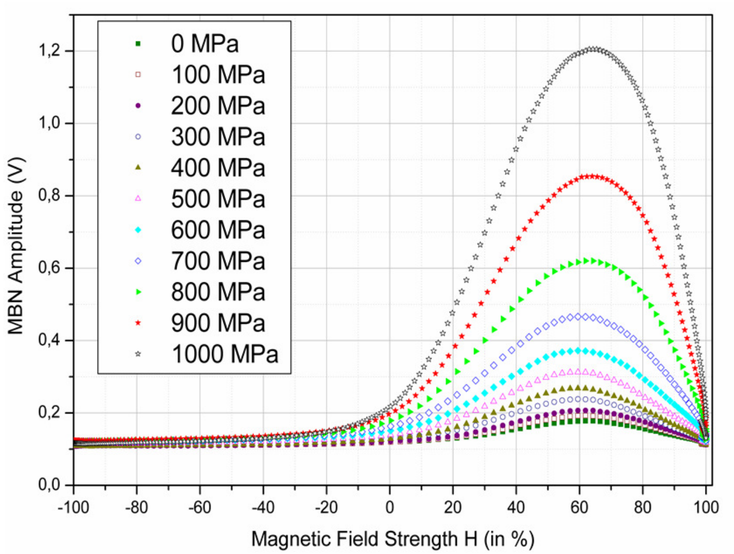


Fig. 1. Envelope curves of the rectified MBN bursts for carburized SAE 9310 specimen for different amplitudes of applied stress using a tensile test machine (residual stress value from XRD measured before stress application was -805MPa).

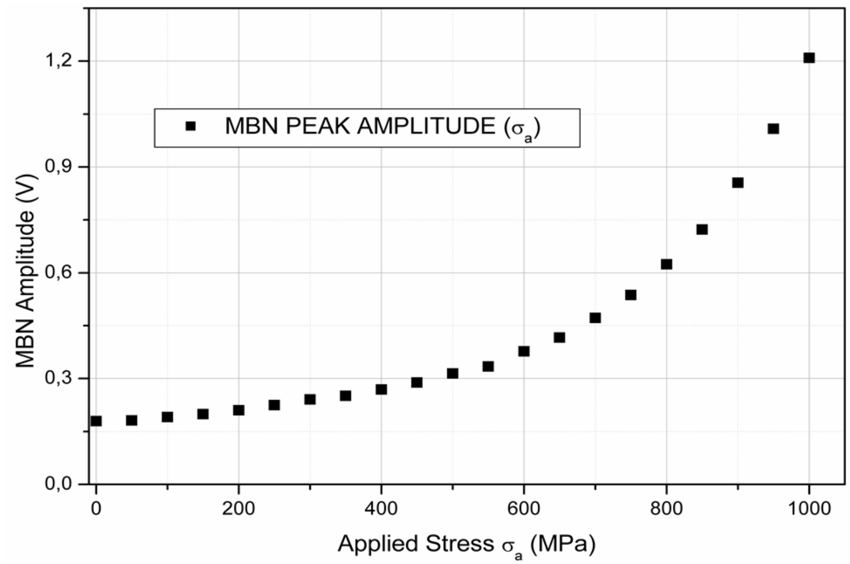


Fig. 2. MBN Peak Amplitude for carburized SAE 9310 specimen as a function of applied stress.

Effects of Stress on Differential Susceptibility and Barkhausen Emissions

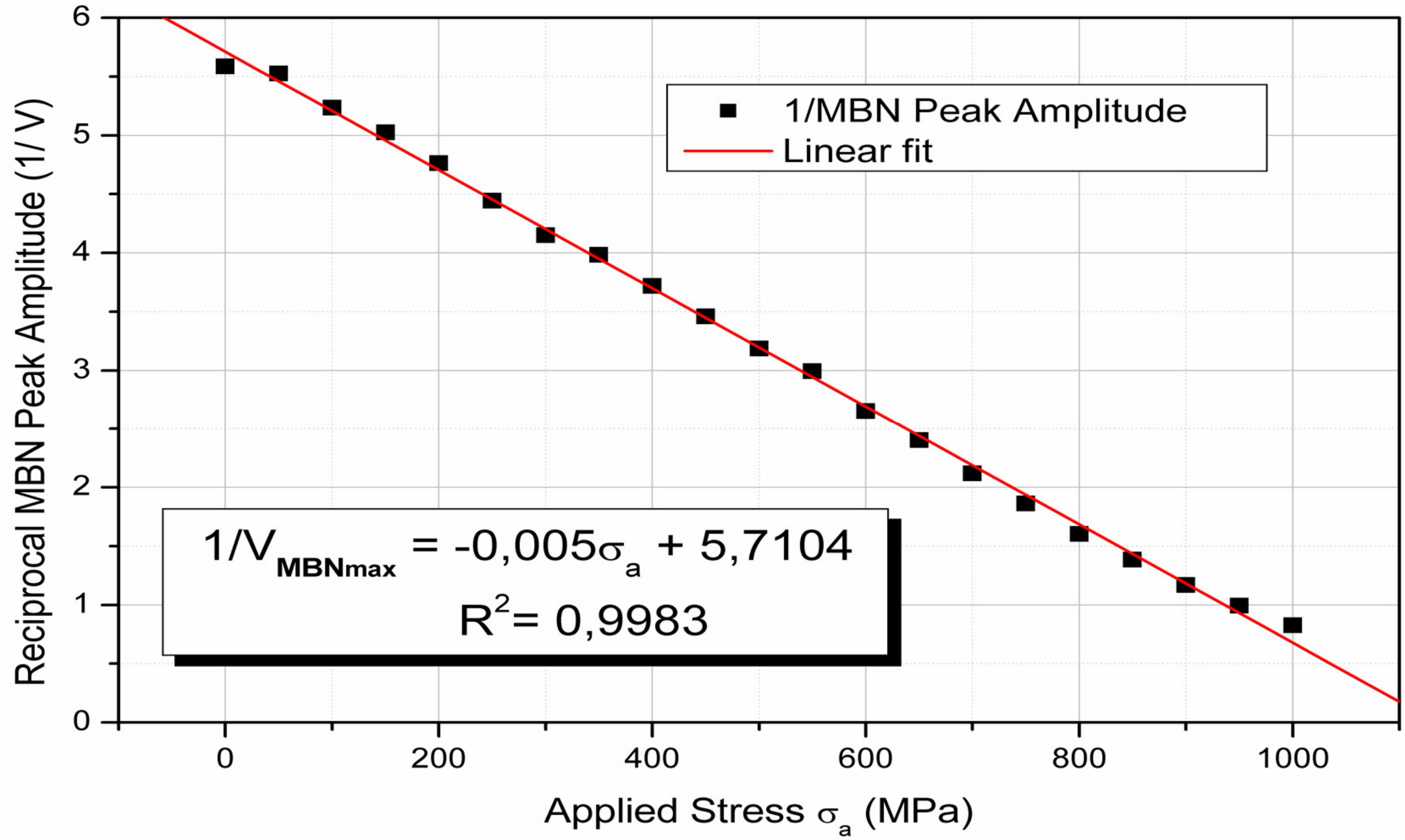
- Barkhausen voltage V_{MBE} is known from previous work* to be proportional to the differential susceptibility

- Therefore, a similar linear expression should hold for reciprocal Barkhausen voltage as a function of stress as for the reciprocal differential susceptibility

$$\frac{1}{V_{MBE}(\sigma)} = \frac{1}{V_{MBE}(0)} - \frac{3b'\sigma}{\mu_o}$$

- This suggests that the most useful calibration curve for Barkhausen effect as a function of stress is the reciprocal plot

Comparison of Model equation with Measurements



Conclusions

- **Magnetic properties, including permeability and Barkhausen effect depend on other external factors such as stress.**
- **A phenomenological/stochastic model has been developed to describe Barkhausen and these effects**
- **Development of models is essential for understanding and interpretation of measurement results and for predicting changes, such as with stress.**
- **Measurements of these properties can be used for determination of stress and even its variation with depth.**

Depth Profiling using Barkhausen Effect

There are three key equations

- The change in flux density that propagates to the surface is

$$B_{meas}(0, x_{\max}, \omega_1, \omega_2) = \int_{\omega 1}^{\omega 2} \int_0^{x\max} B_{origin}(x, \omega) \exp\left(-\frac{x}{\delta}\right) dx d\omega$$

- The voltage measured in an induction coil on the surface is

$$V_{meas}(0, x_{\max}, \omega_1, \omega_2) = NA \int_{\omega_1}^{\omega_2} \int_0^{x_{\max}} \frac{dB_{origin}(x, \omega, \sigma)}{dH} \frac{dH(x)}{dt} \exp\left(-\frac{x}{\delta}\right) dx\, d\omega$$

- The component of the measured signal coming from a particular depth is

$$V'(x, \omega_1, \omega_2) = \left(\frac{-4}{x^3 \mu_o \mu_r \sigma} \frac{d}{d\omega} V_{meas}(0, x_{\max}, \omega_1, \omega_2) \right)$$

Comparison with X-ray results

	Ground side surface	Unground initial surface	TOP	BOTTOM
BN PEAK VALUE	939,9	106,0	1416,6	1035,4
BN PEAK POSITION	59,15	48,6	45,4	46,2