Magnetic Barkhausen Noise: Aspects of Generation and Modeling

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Abstract - **The Magnetic Barkhausen noise (MBN) technique measures discrete changes in magnetization, known as "Barkhausen jumps", which can be seen as steps in the hysteresis curve. When a ferro-magnetic material is subjected to an external varying magnetic field, the magnetization of the material will change in a non-linear way. These changes in magnetization are described by the hysteresis curve and are the result of modifications of domain structure of the material. Changes in magnetization are caused by domain wall creation, domain wall annihilation, domain wall motion and rotation. In order to improve the interpretation of Barkhausen noise, models are needed which describe the dependence of magnetization on material properties.**

Index Terms—**Hysteresis, Barkhausen noise, susceptibility, permeability.**

I. INTRODUCTION

A. Barkhausen Noise and Magnetic Hysteresis

There is a close connection between the rectified Barkhausen noise output and BH loops. In effect, BH loops are obtained experimentally using a similar experimental setup as the former. It is worth recalling how BH curves for ferromagnetic materials are obtained with the traditional method using elementary equipment. Absolute BH data are difficult to obtain using anything other than specimens machined in a toroidal form (e.g. Fig. 1).

The magnetic field H is easily determined from the primary current with a closed magnetic circuit, as in Fig. 1. The field for the toroid is directly proportional to the current I in the primary coil by the following expression:

$$H = N_p I/L \quad (1)$$

where N_p is the number of turns in the primary coil and L is the length of the coil. The field is more difficult to measure or calculate with other specimen forms because of magnetic leakage or demagnetizing effects. The secondary windings (Fig.1) are connected to a flux meter or a ballistic galvanometer. The primary circuit also includes a current reversing switch that is used in the following procedure.

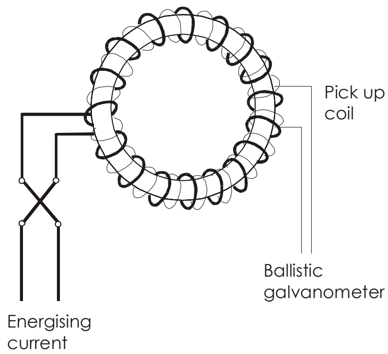

Figure 1. Schematic Illustration of Traditional Apparatus for BH Loop Determination

The specimen is first demagnetized, and then the applied field is raised in predetermined steps to obtain data for the magnetization curve (OAB in Fig. 2). Let us assume that we are at the stage where the field corresponds to point A in Fig. 2. With the flux meter or ballistic galvanometer short-circuited or isolated, the current is then reversed several times. This has the effect of taking the specimen around the hysteresis loop (Fig. 2) a few times to reach an equilibrium state. Finally, the fluxmeter is connected to the circuit, the current is reversed one more time and the flux meter is recorded.

The flux density B can be calculated using the fluxmeter reading. However, to understand the basics of the measurement, it is worth considering how flux is measured with a ballistic galvanometer. This instrument has very low damping. If the current I passes for a time t that is so short that the coil has no time to move appreciably, the impulse (product of force and time) given to the coil is proportional to the product *It*. But *It* is the total charge Q that passed through the galvanometer. It can be shown that the maximum swing of the instrument is proportional to the impulse and thus proportional to Q. The relation between the flux change and the total charge flowing in the secondary circuit is:

$$\Delta\Phi = \frac{QR}{N_s} \quad (2)$$

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where R and N_s are the resistance and number of turns in the secondary windings, respectively.

Finally, we note that $\Delta\Phi = \Phi - (-\Phi) = 2\Phi$ in the above experiment and that flux density $B = \Phi/A$, where A is the area of cross section of the specimen. Thus, a pair values (H, B) can be determined from these measurements.

The procedure is repeated for increasing values of the field to obtain points along the curve OAB. The complete hysteresis curve can be obtained using a procedure similar to the above, with a simple modification of the apparatus in Fig.1.

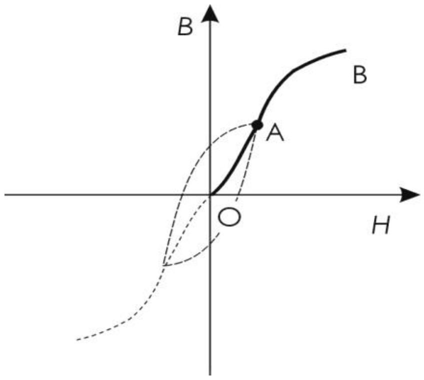

Figure 2. Magnetisation Curve for a Ferromagnetic Material

Now imagine calculating the magnetising curve using a current sweep generator and an oscilloscope or equivalent fast data logging equipment, which is more like the procedure used in MBN measurements. Imagine starting at point O with a demagnetised specimen and increase the current (and field) at a constant rate. If we consider applying one quarter of a complete cycle of a triangular current waveform of frequency f, the rate of primary current increase is $4f\,I_m$ where I_m is the maximum primary current. The differential permeability is

$$\frac{\mathrm{d}B}{\mathrm{d}H} = \frac{1}{A}\frac{\mathrm{d}\Phi}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}I_p}\frac{\mathrm{d}I_p}{\mathrm{d}H} \tag{3}$$

Where A is the area of cross section of the specimen and I_p is the instantaneous primary current. We have the following relations:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{V_s}{N_s} \tag{4}$$

Where V_s is the electromotive force (emf) induced in the secondary coil and N_s is the number of turns; and

$$\frac{\mathrm{d}I_p}{\mathrm{d}H} = \frac{L}{N_p} \tag{5}$$

It follows that the differential permeability can be obtained by measuring the *emf* using the following relation

$$\frac{\mathrm{d}B}{\mathrm{d}H} = \left[\frac{1}{4f\,I_\mathrm{m}}\frac{L}{A}\frac{1}{N_p N_s}\right]V_s \tag{6}$$

Alternatively, one can take the differential permeability as given and predict the emf V_s in the secondary coil. In this case

$$V_s = \left[4f\,I_\mathrm{m}\,N_p N_s A/L\right]\mathrm{d}B/\mathrm{d}H \tag{7}$$

It can be seen from (3) that V_s increases linearly with the rate of excitation (f), all other factors being equal.

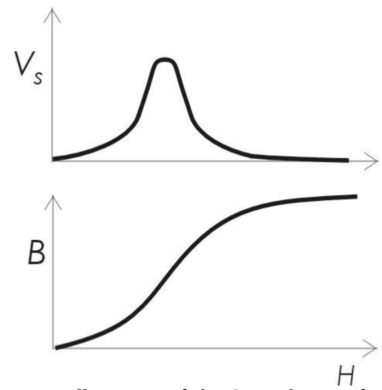

Figure 3. Schematic Illustration of the Secondary emf and BH Curves

Finally, the magnetisation BH curve is constructed by integration, as illustrated in Fig. 3. Estimates based on (7) show that the emf in the secondary coil is relatively large. For instance, if we take N_s=10^3, N_p=10^2,f=0.1 Hz, A/L=2.25×10^{-3} m, I_m=2 A, and dB/dH=10^{-3} NA^{-1}, the value of V_s is predicted to be of the order of 200 mV.

Clearly, this output is very much larger than any emission from Barkhausen noise, which is in the order of microvolts. The Barkhausen emission appears as a "noisy" signal (Fig. 4), which can be displayed in more detail by filtering and amplification.

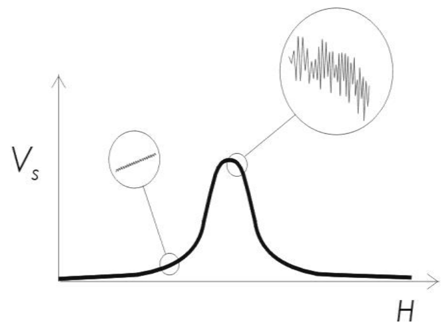

Figure 4. Schematic Illustration of Barkhausen Noise in a V_s- H Curve

There is a significant difference between the signal and the noise illustrated in Fig. 4. Because of the high frequency of the noise and the skin effect, the noise is representative of events in the surface layers of the specimen. In contrast, the main signal is of the same frequency as the energising current and so is representative of events in the bulk of the specimen.

A number of theories [2, 3] give the result that, to a good approximation, the magnitude of MBN is proportional to the differential permeability dB/dH, i.e. the noise in the signal is proportional to the magnitude of the signal (Fig. 4).

II. BARKHAUSEN NOISE MODELLING

Since models of MBN are often expressed in relation to the magnetisation M versus field H curve, rather than to the more familiar BH curve, the relation between these quantities is reviewed. The relation between flux density B and H is:

$$B = \mu_0 \mu_r H \tag{8}$$

where μ_0 is the permeability of free space (= $4\pi \times 10^{-7}$ TmA^{-1}) and the dimensionless parameter μ_r is the relative permeability of the material of the core of the solenoid. The relation between magnetisation and H is [1]:

$$M = \mu_r H - H = \chi H \tag{9}$$

where the quantity $\chi = \mu_r - 1$ is the magnetic susceptibility of the material. The various forms of magnetism (dia-, para- or ferro-) are defined in terms of the characteristics of χ for the material. It follows that $B \approx \mu_0 M$ for materials with high relative permeability.

A simple phenomenological model of the emission of Barkhausen noise was presented by Jiles *et al* [4] and Jiles and Suominen [5]. The model focuses on the connection between MBN and the magnetic hysteresis loop, but also brings in the stochastic aspects of the phenomenon. A basic assumption is that the rate of Barkhausen emission is proportional to the differential irreversible susceptibility i.e.

$$\frac{\mathrm{d}M_{JS}}{\mathrm{d}t} = \gamma \frac{\mathrm{d}M_{irr}}{\mathrm{d}H} \frac{\mathrm{d}H}{\mathrm{d}t} \tag{10}$$

Here, M_{JS} is termed the "jump sum" and the suffix "*irr*" refers to irreversible magnetisation. It should be noted that M_{JS} is very small compared with M_{irr} so that the constant γ has the role of connecting microscopic events with macroscopic behaviour. The proportionality constant γ can be further subdivided into the number N of Barkhausen events, which varies in a random manner, and the mean size of an event $\langle M_{disc} \rangle$, resulting in

$$\frac{\mathrm{d}M_{JS}}{\mathrm{d}t} = \langle M_{disc} \rangle \frac{\mathrm{d}N}{\mathrm{d}M_{irr}} \chi'_{irr} \frac{\mathrm{d}H}{\mathrm{d}t} \tag{11}$$

The stochastic nature of Barkhausen emission enters the equation through N and the following iterative scheme for calculating N in the time interval t from its value in the preceding time interval has been proposed

$$N_t = N_{t-1} + \delta_{rand} \sqrt{N_{t-1}} \tag{12}$$

where δ_{rand} is a random number in the range ±1.47.

It is anticipated that the microstructure of the material will affect MBN in two ways. First, the terms with a stochastic aspect $\langle M_{disc} \rangle$ and N in (11) will be influenced by microstructure. The greater the number of impediments to domain wall motion, the greater the number of individual Barkhausen events, but the smaller the amplitude of the event. Second, microstructure will also influence MBN through its effect on the differential susceptibility of the material in (11).

It is anticipated that stress or strain will affect MBN only by affecting the differential susceptibility in (11). To understand the role of stress in MBN, the theory of the hysteresis loop has to be considered.

B. *Magnetoelastic Models of Hysteresis*

A model of the hysteresis loop, incorporating the influence of stress was developed by Sablik and Jiles [6]. A starting point is the definition of the relation between the anhysteretic magnetisation M_a and the applied field. M_a is the ideal magnetisation that would occur if domain wall movement were reversible i.e. if domain walls moved smoothly with no pinning and no sudden changes. The relation is given by:

$$M_a = M_s \mathrm{L}(H / a) \tag{13}$$

where L is the Langevin function $L(x) = \coth x - 1/x$, M_s is the magnetisation at saturation and a is a scaling constant for the material. The form of the relation is shown in Fig. 5.

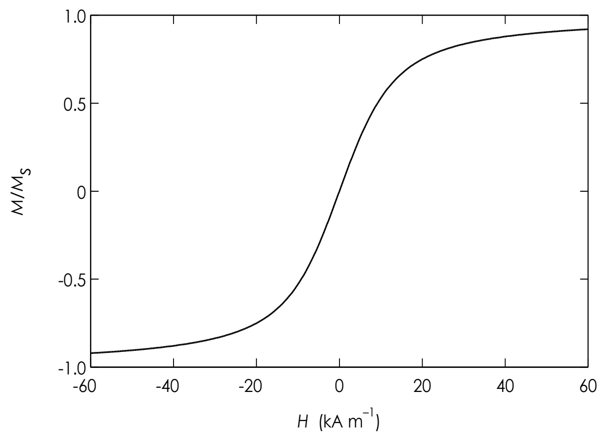

Figure 5. Anhysteretic Magnetisation as a Function of H

There is no hysteresis because there is no jerky movement of the domain walls. However, the field experienced by domain walls is not the same as the external applied field H. Internally, the field is modified by the demagnetising effect of other domains and by the effect of magnetostriction. Thus, an effective field (H_{eff}) must be used to calculate the effect on magnetisation.

This requires a correction to be made to the applied field, as shown in the following expression.

$$H_{eff} = H + \alpha M + \tfrac{3}{2}\frac{\sigma}{\mu_0}\frac{\partial \lambda}{\partial M} \quad (14)$$

Here, α is the domain interaction constant, λ is the magnetostriction and σ is the applied stress. Various expressions for the magnetostriction have been used. One form gives:

$$\frac{\partial \lambda}{\partial M} = \tfrac{7}{2}\frac{\lambda_s M}{M_s\sqrt{M^2 + {}^{21}/_4\left(M_s^2 - M^2\right)}} \quad (15)$$

where λ_s is a dimensionless constant containing the elastic constants for the material. It should be noted that the computation of the M_a versus H relation has to be made using numerical iteration because M ($\equiv M_a$) appears on both sides of equation (13) when H_{eff} is substituted for H. It follows from (13) and (14) that stress influences the anhysteretic magnetisation curve through the magnetostriction. Although this curve is not the one required for prediction of MBN and indication of how it is affected by stress is given below.

Equation (11) shows that stress affects MBN through the χ'_{irr} = dM_{irr} / dH term. If we assume that dM_a/ dH shows a parallel dependence on stress, a simple calculation can be made after noting that the maximum value of dM_a/ dH occurs when M_a= H = 0. Differentiation of (6) and using (14) and (15), gives the following relation

$$\left(\frac{\mathrm{d}M_a}{\mathrm{d}H}\right)_{\max} = \left[\frac{3a}{M_s} - \alpha - \tfrac{21}{2}\frac{\sigma}{\mu_0}\frac{\lambda_s}{M_s^2}\right]^{-1} \quad (16)$$

Taking typical values for steel, $M_s = 1.6\times10^6$ A m^{-1}, a= 4500 A m^{-1}, $\alpha = 6.9\times10^{-5}$ and $\lambda_s = 6.2\times10^{-6}$, the relationship in (16) is plotted in Fig. 6. It can be seen that the curve in Fig. 6 gives a qualitatively similar relation to that observed for MBN intensity versus stress in hard materials [6].

C. Irreversible Magnetisation

As indicated above, the magnetoelastic aspect of MBN emission must be computed using the irreversible magnetisation. This is a relatively difficult computation because of hysteresis, the uncertainty of the values of the large number of parameters involved, and potential instabilities in the solutions, as discussed below.

Sablik and Jiles [7] derived the following differential equation for M_{irr}:

$$\frac{\mathrm{d}M_{irr}}{\mathrm{d}H} = \frac{M_a - M_{irr}}{k\delta/\mu_0 - \left[\alpha + \left(3\sigma/2\mu_0\right)\partial^2\lambda/\partial M^2\right]\left(M_a - M_{irr}\right)} \quad (17)$$

The equation has to be integrated numerically to obtain the relation between M_{irr} and H. Only then can the critical quantity dM_{irr} / dH be evaluated. In (17), k is the pinning constant that indicates the strength of interaction between defects and domain walls and δ takes the value ±1 depending on whether H is increasing or decreasing. Numerical integration is carried out in three stages. First, the initial condition M_{irr} = H = 0 is assumed and the equation is integrated between H = 0 and the maximum value $H_{\max}$. This gives the initial condition for the second stage of integrating between $H_{\max}$ and $-H_{\max}$. Using the final values obtained in the second stage, the third stage is to integrate between $-H_{\max}$ and $H_{\max}$. In the original formulation [7], k was taken to be constant for a given material, but in a recent extension of the model [8], the pinning constant was deduced to be linearly dependent on stress.

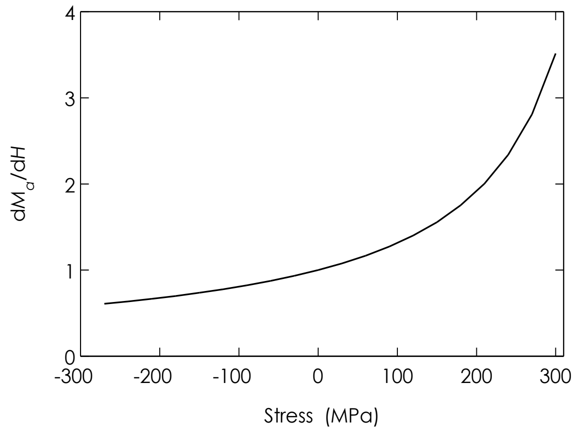

Figure 6. Effect of Stress on the Maximum Anhysteretic Slope. Note That the Graph is Scaled so the Slope with Zero Stress is Unity.

It should be remarked that the calculations are not simple to implement. Because of instability in the solution, the range of stress that can be handled is relatively small and depends on the other parameters. In addition, for general use, the values of the many parameters that enter into (17) are not known with precision for a range of microstructures. However, for the purpose of demonstration, an example is given below. An M_{irr} vs. H loop was constructed by integrating (17) in three stages, as described. The effect of stress on the hysteresis loop is shown in Fig. 7.

As anticipated, an applied tensile stress has the effect of making the hysteresis loop narrower and increasing the maximum slope. Having obtained the M_{irr} vs. H curve, the differential susceptibility was calculated directly from (17). The result is shown in Fig. 8. As might be deduced by inspection of Fig. 8, χ'_{irr} as a function of H shows a single peak at a position H> 0 (increasing field). This is qualitatively similar to the MBN profile in many cases.

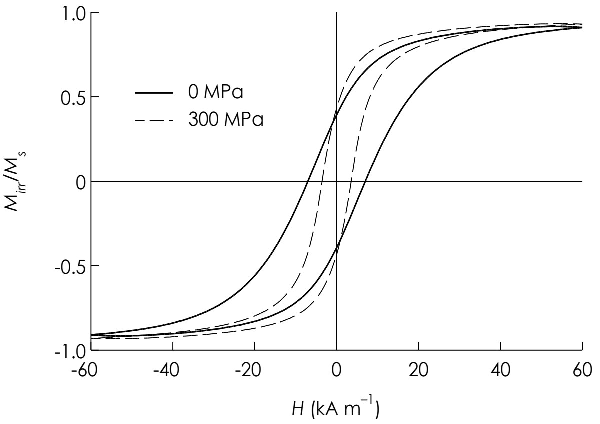

Figure 7. Effect of Applied Stress on M_{irr} vs. H curve, Constructed by Integrating eqn. (17) using: $a = 4500$ A/m; $\alpha = 6.9 \times 10^{-5}$; $k/\mu_0 = 8\times10^3$

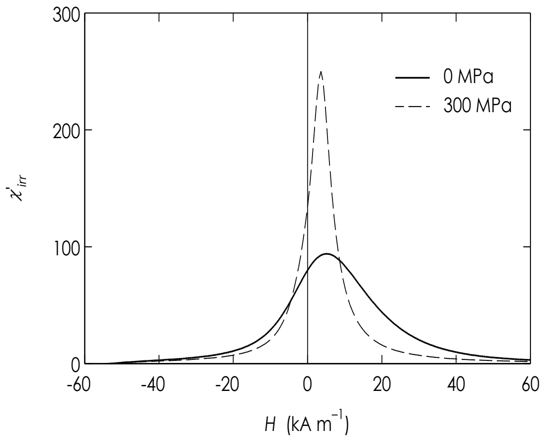

Figure 8. Differential Susceptibility χ'_{irr} Calculated from Equation (17) using the M_{irr}vs. H Data in Fig. 7 (increasing Field Only)

Lo *et al.* [8] used (17) to compute the effect of stress on the hysteresis loop for ferritic stainless steel and hence to compute the relation between stress and root mean square MBN. The variation of the experimental hysteresis loop parameters and stress was used to obtain values for k as a function of stress. Good agreement between the model and experimental MBN results was obtained.

III. CONCLUSION

1- There is a close connection between magnetic Barkhausen noise and the magnetic hysteresis of ferromagnetic materials.
2- The effect of stress on magnetic hysteresis can be evaluated using the irreversible magnetisation model.
3- It is proposed to combine the hysteresis and the BN techniques in practice, in order to obtain more detailed magnetic information about the investigated materials.
4- It should be stated that the model is not easily adapted to general use because of the considerations given above. For this reason, we attempt to draw only qualitative conclusions from it.

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BIOGRAPHIES

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