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Characterization of magnetic materials by Barkhausen noise measurement

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Abstract : Ferromagnetic materials generate magnetic Barkhausen noise (MBN) mainly due to 180° domain wall motion. MBN measurement can be used for the characterization of magnetic materials. In the present work, the direction of magnetic easy axis of a polycrystalline steel material has been studied in presence of different stresses using MBN measurement The stress distributions around a circular shaped defect in a ferromagnetic material has also been investigated using the same measurement.

Keywords . Magnetic Barkhausen noise, applied stress, stress concentration.

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1. Introduction

Magnetization in ferromagnetic materials mainly takes place by reversible and irreversible domain wall displacement and rotation of local domain magnetization. Magnetic Barkhausen noise (MBN), discovered by Henrich Barkhausen in 1917 [1], is caused by jerky domain-wall motion in ferromagnetic materials and is an indirect proof of the existence of magnetic domains in these materials [2]. Presently, MBN measurement is used for the characterization of magnetic materials such as to study the microstructure and particle size [3], to estimate the residual and applied stress [4], to determine the magnetic easy axis in a ferromagnetic material [5].

The magnetization in a magnetic material changes with the direction in which it is measured and depends on the domain configuration and anisotropy energy of the materials which gives rise to the direction of magnetic easy axis. Usually an excess population of 180° domain walls exists along the direction of magnetic easy axis giving rise to maximum MBN along that direction. Therefore, by measuring MBN, the direction of magnetic easy axis can be determined [5].

The domain structure of a magnetic material can be changed by changing stress within a material. The stress alters the magnetic energy by changing the magnetoelastic anisotropy energy. As the MBN energy changes with domain structure, the applied stress and residual stress can be estimated from MBN. Recently, high-resolution MBN measurements have been used to determine stress distributions around defects in a magnetic material with different shapes and sizes [4].

In the present paper, MBN measurement has been used to determine the magnetic easy axis in ferromagnetic steel sample. It is observed that the direction of easy axis changes with the application of external stress. The stress distribution around circular shaped defects has also been studied by this technique.

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2. Theoretical background

Magnetic Barkhausen noise is expressed by different parameters such as 'RMS value of MBN', 'MBN energy', 'pulse height distribution' *etc*. In the present work, the parameter 'MBN energy' has been used for the analysis of experimental data. MBN energy can be calculated from MBN noise using the following model. Let us consider a simple closed domain structure shown in Figure 1 in a single grain. In presence of a magnetic field, magnetization increases along the direction of the field due to the increase in volume of those domains having magnetization directions close to the direction of magnetic field. The possible domain structure after the application of a magnetic field is also shown in Figure 1. This changed domain structure can be

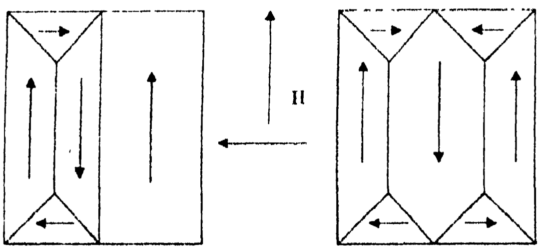

Figure 1. A simple closed domain structure in a grain of a ferromagnetic sample (a) in absence and (b) in presence of a magnetic field

considered as a magnetic dipole. The energy of a single dipole within a magnetic field is given by

$$E_p = -\mu H \cos(\theta - \varphi), \quad (1)$$

where μ is the magnetic moment and θ and φ are the directions of the magnetic field and the magnetic easy axis of the crystal respectively with respect to a particular direction. H is the resultant field, which is the sum of the applied magnetic field and the mean field in the vicinity of the interaction region. Due to the 180° domain wall motion, MBN is generated. The distance moved by a domain wall under the action of a magnetic field can be obtained by the minimization of the total energy and is given by the expression [2]

$$d = \frac{2}{\alpha} I_s H \cos(\theta - \varphi), \quad (2)$$

where α is a constant. The change in magnetic moment is proportional to the distance d that the 180° domain wall has moved, the length l of the crystal and its thickness T. Therefore the change in the moment is given by

$$\Delta\mu = \Delta p l = (T d I_s) l, \quad (3)$$

where Δp is the change in the pole strength. Combining eqs. (2) and (3), the change in moment during a Barkhausen event, associated with the motion of a 180° single domain wall may be written as

$$\Delta\mu = \frac{2Tl}{\alpha} I_s^2 H \cos(\theta - \varphi) = KH \cos(\theta - \varphi), \quad (4)$$

where $K = 2TlI_s/\alpha$ is a constant. Substituting eq. (4) in eq. (1), the change in energy due to a Barkhausen event can be described as

$$\Delta E = -KH^2 \cos^2(\theta - \varphi). \quad (5)$$

The change in MBN energy, E_{MBN} due to total n number of Barkhausen events can be written as

$$E_{MBN} = \sum_{i=1}^{n} \Delta E_i = \sum_{i=1}^{n} K_i H_i^2 \cos^2(\theta - \varphi_i), \quad (6)$$

where i represents the i-th event, K_i is the coefficient associated with that event, and φ_i, the angle of the i-th moment.

The total MBN energy can be divided into two parts, the contribution towards the net magnetic easy axis comes from those domains having magnetization direction close to the easy axis direction and the contribution to the isotropic background due to other domains. Eq. (6) can be written as

$$E_{MBN} = \sum_{e} K_e H^2 \cos^2(\theta - \varphi) + \sum_{j} K_j H^2 \cos^2(\theta - \varphi_j), \quad (7)$$

where the e and j-components are the contributions towards the easy axis direction and isotropic background respectively. Now representing

$$\alpha = \sum_{e} K_e H^2 \quad (8)$$

and

$$\beta = \sum_{j} K_j H^2 \cos^2(\theta - \varphi_j), \quad (9)$$

total MBN energy, E_{MBN} can be written as

$$E_{MBN} = \alpha \cos^2(\theta - \varphi) + \beta. \quad (10)$$

The eq. (10) can be used to determine the direction of magnetic easy axis of a magnetic material.

3. Experimental

The experimental setup developed for the surface MBN measurement is shown in Figure 2. A magnetic field, which

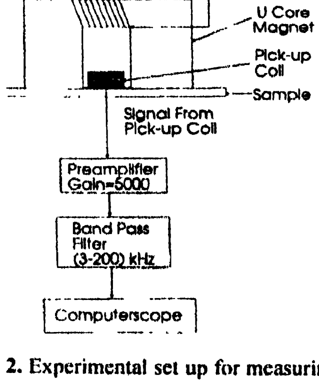

Figure 2. Experimental set up for measuring magnetic Barkhausen noise.

is sufficient for the technical saturation of the sample, is generated by passing a 12 Hz sinusoidal current through a *U*-shaped ferrite core. A small pick-up coil is placed between the two pole pieces of the *U*-core magnet to detect the MBN signals. The signal from the coil is passed through a 3–200 kHz band-pass filter after amplifying it by 1000 times and then interfaced with a personal computer having a resident digital oscilloscope board (Computerscope). The MBN signal is sampled at intervals of 1 μs for 16 ms with a buffer size of 8 K and eight traces are taken for each measurement. Only those voltage signals having amplitude higher than a selected threshold of ± 150 mV are considered for analysis. The MBN energy, E_{MBN} is calculated by integrating the square of these voltages with respect to time ($E_{MBN} = \int v^2 dt$). For high-resolution measurements, instead of a pick-up coil, a magnetic read-head is used.

A polycrystalline ferromagnetic steel section with a chemical composition (in % wt) C : 0.12, Mn : 1.46, P : 0.02, S : 0.003, Si : 0.22, V : 0.060, Ti : 0.020, Nb : 0.040 was chosen as the sample. An arrangement was made to give stress to the sample as shown in Figure 3. A circular shaped defect

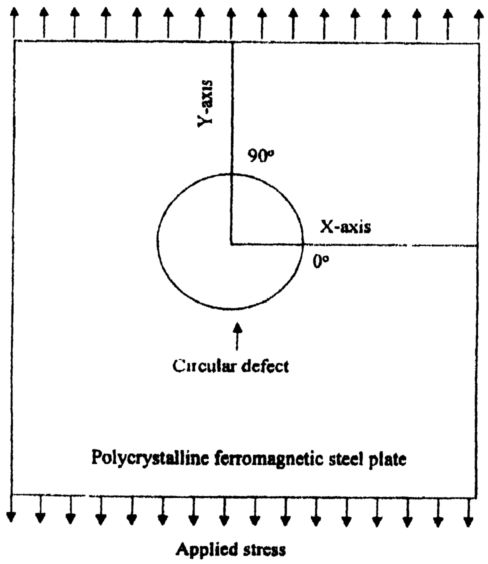

Figure 3. A schematic figure showing the stress applied to a steel sample and the position of a circular shaped defect.

with diameter 15 mm, and depth 4.5 mm (50% of the wall thickness) was made on the surface of the sample by electrochemical machining to study stress distribution around it by MBN.

4. Results and discussion

The angular dependence of MBN energy of the surface of the sample was studied under the influence of different stresses (up to 330 MPa). A reference direction was considered as 0° and the stress was applied along 90°–270° direction (Figure 3). MBN measurement was taken by rotating the ferrite magnet with 10° steps and the experimental results are shown in Figure 4. Eq. (10) was fitted to the experimental data to determine the magnetic

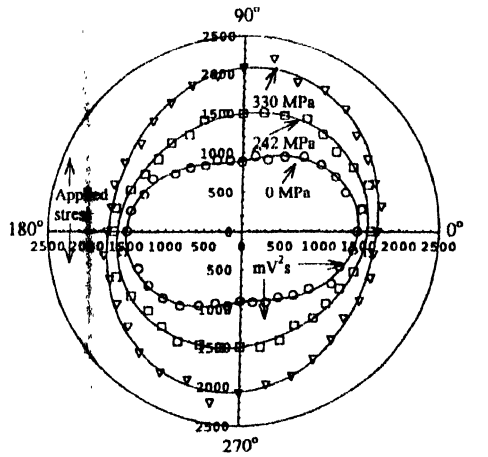

Figure 4. Anguar dependence of MBN energy for 0 MPa (o), 242 MPa (□) and 330 MPa (∇) applied stresses.

easy axis of the sample, φ. The variation of φ and angular averaged MBN_{Energy}, ($\alpha/2 + \beta$) with applied stress are shown in Figure 5. Under the influence of stress, φ changes from ~0° to ~90°, *i.e.*, from its initial magnetic easy axis direction to the direction of applied stress.

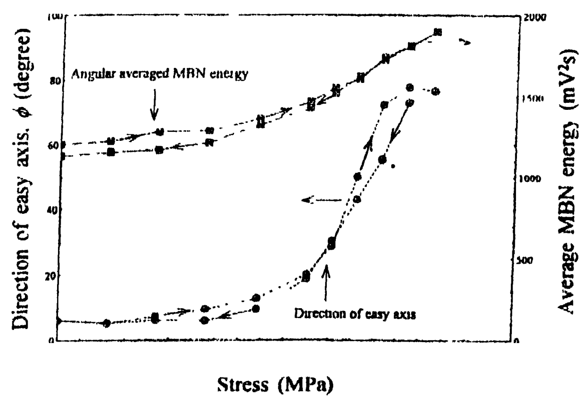

Figure 5. Stress dependence of angular averaged MBN energy (■) and the direction of magnetic easy axis (O)

The MBN energy has been measured using read-head probe around the defect in the presence of different stresses to detect the stress variation around it. For clarity, they are plotted in Figure 6 for two extreme limits, $\sigma = 0$ and 220 MPa. This figure indicates the maximum change in MBN energy with stress along the 0°–180° direction which is perpendicular to the applied stress direction. On the other hand, two curves almost coincide with each other along 90° and 270° direction. All these effects are in accord with the theoretical results predicted earlier [6]. To study the stress concentration in more details, the change in MBN energy with distance from the defect edge has been measured at the 0°, 90°, 180° and 270° positions. For the 0° position, the results are shown in Figure 7 for 0 and three other applied stresses. A rapid large change in MBN energy takes place near the defect edge when a stress is applied.

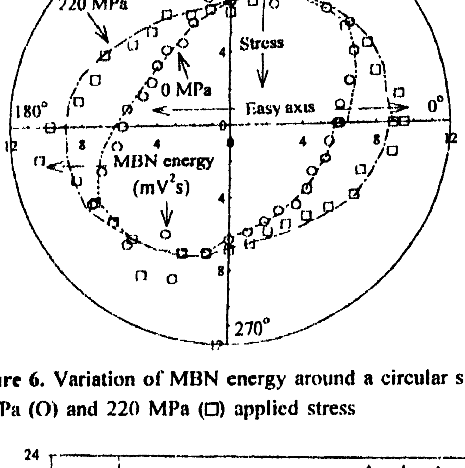

Figure 6. Variation of MBN energy around a circular shaped defect for 0 MPa (O) and 220 MPa (□) applied stress

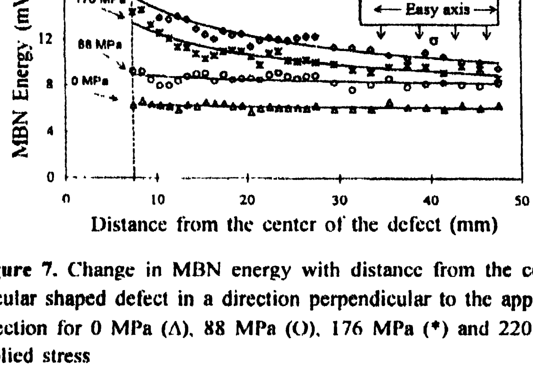

Figure 7. Change in MBN energy with distance from the center of a circular shaped defect in a direction perpendicular to the applied stress direction for 0 MPa (Δ), 88 MPa (O), 176 MPa (*) and 220 MPa (◇) applied stress

The results at 180° position also exhibit the same trend of variations as shown in Figure 7. The results at 90°and 270° positions are similar. Figure 8 shows the experimental results

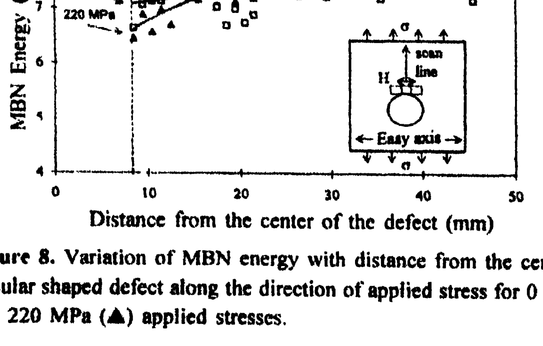

Figure 8. Variation of MBN energy with distance from the center of a circular shaped defect along the direction of applied stress for 0 MPa (□) and 220 MPa (▲) applied stresses.

at 90° position only for 0 and 220 MPa applied stresses. At this position, MBN energy increases slowly with increasing distance from the defect edge when an external stress is applied. The stress *versus* MBN energy calibration curve was measured using the read-head probe at the defect position and prior to its creation, along the 0°–180° direction and perpendicular to it (Figure 9). These calibration curves were used for the estimation of stress along the respective directions.

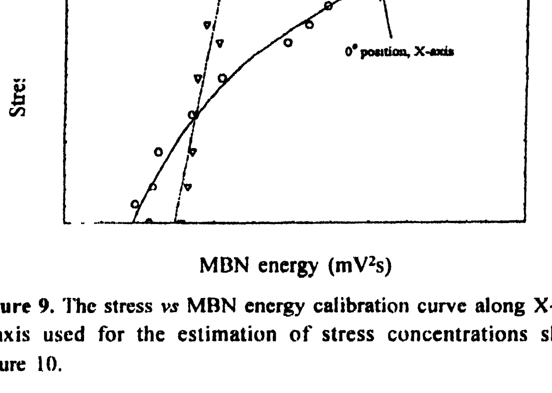

Figure 9. The stress *vs* MBN energy calibration curve along X-axis and Y-axis used for the estimation of stress concentrations shown in Figure 10.

Ferromagnetic steel samples are polycrystalline materials with grain sizes in the range of 10–50 μm. The easy axis direction varies from one grain to another. Before any kind of processing, the magnetization vectors try to align themselves along one of the cubic axis of the crystal, *i.e.*, the <100> direction that is energetically favorable [7]. During the manufacture of steel plates, however, the steel slabs are rolled. This produces an easy axis in each grain by directional order caused by slip-induced anisotropy. All these local easy axes combine to form a net macroscopic easy axis of the material close to the direction of rolling. In the case of polycrystalline materials, an excess population of 180° domain walls is aligned along the local easy axis of each grain and their sudden irreversible motion gives rise to the maximum MBN energy along the macroscopic easy axis of the materials. The application of an external stress modifies the easy axis in each grain by inducing a magnetoelastic anisotropy energy along the direction of stress. The direction of magnetic easy axis is then determined by the minimization of magnetocrystalline as well as magnetoelastic anisotropy energies.

In the case of positive magnetostrictive steel, the presence of an external tensile stress increases the 180° domain wall population along the direction of stress. The reduces its magnetoelastic anisotropy energy and enhances the MBN signals. So, when a stress is applied to the steel sample, in a direction perpendicular to the initial magnetic axis of the sample, the easy axis shifts towards the direction of the applied stress, *i.e.*, perpendicular to the initial easy axis direction. This change can be detected by the shift in the position of the maximum in the MBN energy *versus* angle curves (Figure 4). The change in MBN energy around the defect (Figure 6) can also be explained by the variation in stress surrounding the same. The maximum change in MBN energy is observed at 0° and 180° positions where the largest stress concentration should exist [6,8].

From these experimental data, the variation of stress with distance from the defect edge and along the 0°–180° axis has been estimated and is shown in Figure 10.

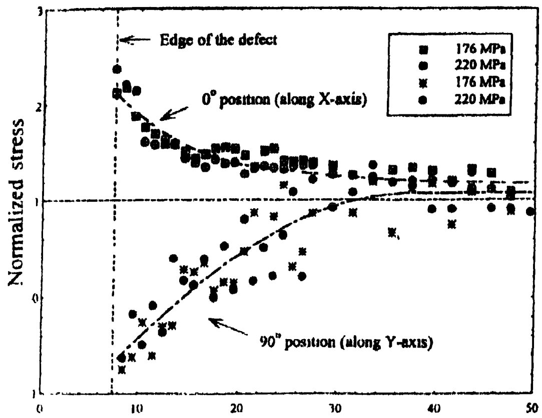

Figure 10. Change in stress (normalized with respect to the applied stress) with distance from the center of the defect and along the direction of applied stress and perpendicular to it.

The stress *versus* MBN energy calibration curve, shown in Figure 9, has been used for this estimation. The values of stress normalized with respect to the applied stress, are plotted for 176 and 220 MPa applied stress. They almost coincide with each other and indicate a stress concentration at the defect edge having a magnitude twice that of the applied stress. This value is close to that (~1.9) obtained by finite element calculation for a similar pit with 50% penetration in the wall.

At 90° and 270° positions, a compressive stress component is developed at the defect edge. This reduces the 180° domain wall population and hence the MBN energy. The stress variation estimated along this direction to also shown in Figure 10. The normalized stress values for both 176 and 220 MPa applied stress show a slow variation of stress along that direction with a stress contraction (compressive) of ~ – 0.6 times the applied stress at the defect edge.

5. Conclusions

Magnetic Barkhausen noise measurement can be used extensively for the characterization of magnetic materials. In the present work, MBN measurement has been used successfully to estimate the stress distribution around a circular shaped defect on a polycrystalline ferromagnetic steel sample. The direction of magnetic easy axis in a magnetic material and its change with external parameter such as stress can also be studied with the help of MBN measurement.

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