On the study of the Barkhausen Effect and the Microstructure of Ferromagnetic Materials

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Abstract

During the 19th World Conference on Non-Destructive Testing in 2016 Y Gao et al reported on experimental methods to investigate the correlation between magnetic Barkhausen noise and the microstructure of ferromagnetic materials. In this contribution theoretical investigations on the Barkhausen effect are presented. From a minimization of the free energy of a domain wall a theoretical model calculation determines the domain wall thickness, the energy per unit area, the restoring force, and the coercitivity. Magnetization curves $M(H)$ for various angles with respect to the easy axis of magnetization are plotted. The magnetic anisotropy and mathematical description of the Barkhausen effect are discussed. The latter is then used to model eddy current losses in ferromagnetic metals. Furthermore, as the motion of domain walls depends on the distribution and strength of pinning sites such as dislocations, impurities, and cracks, mathematical models are useful to detect structural changes in the ferromagnetic material. However, due to the limited penetration depth of the Barkhausen signal such characterizations are restricted to the surface layer of the material only. The theoretical results are compared with experimental data. These results are good, satisfactory, and can be regarded as reliable.

1. Introduction

During the long service life of power plant components gradual microstructural changes occur. To monitor the material degradation it is often useful to relate the microstructural state to magnetic properties. When the domain walls move the magnetization changes in small finite steps; the discontinuities are in the literature known as Barkhausen effect or Barkhausen jumps [1]. The discontinuous changes in the magnetization induce electric pulses according to Faraday’s law that may then generate noise like signals in an earphone. One thus also speaks of magnetoacoustic emission (MAE) or magnetic Barkhausen noise (MBN). As the domain wall motion is influenced by grain boundaries, material imperfections and dislocations, the Barkhausen effect can be used to measure microstructural features in the ferromagnetic material. The correlation between MBN and domain wall motion is investigated experimentally using for example the magneto-optical Kerr effect, magnetic force microscopy, or scanning electron microscopy. Due to the sensitivity to stress it is also useful as a non-destructive evaluation (NDE) technique to measure material degradation with time. Corresponding experimental evidence was presented at the WCNDT-conference of 2016 by Y Gao et al.
Therefore this study is restricted to the theory of the Barkhausen effect. While magnetization processes that occur in ferromagnetic materials are experimentally measured in the form of magnetic hysteresis loops, standard models of magnetism make a couple of theoretical assumptions that are not fulfilled in a real solid. These are:

1. The real lattice is not perfectly periodic. Lattice defects, for example vacancies, impurities, or lattice mismatches are known to improve magnetic order even in nominally non-magnetic solids [3]. They may also cause phenomena such as spin glass behaviour, frustration, and Kondo effect. As lattice defects are excitations of the perfectly periodic crystal their electronic structure remains theoretically difficult to describe.

2. The applied field is parallel to the crystal axis and the magnetic moments align parallel to it. This easy axis is the energetically most favourable direction for the spontaneous magnetization. On the other hand, if the above assumption is not fulfilled, then the magnetic properties become direction dependent and one speaks of magnetic anisotropy.

3. The existence of ferromagnetic domains is neglected in standard models of magnetism. Ferromagnetic materials consist of domains that are magnetized in different directions. They were first theoretically proposed by P E Weiss and then experimentally verified by H Barkhausen. Later L.D. Landau explained the motion of domain walls in the presence of an external magnetic field from the equation of motion for a ferromagnet; the corresponding effect is known as ferromagnetic resonance [4].

Increasing the magnetic field \( H \), (a) increases the size of the domains until the multi domain state becomes a single domain state, and (b) rotates the magnetization vector to align with the external magnetic field. Especially this second process is usually irreversible resulting in the hysteresis loop \( M(H) \). The motion of Bloch walls furthermore causes a few interesting phenomena. Changes in the magnetization may be accompanied by changes in the material’s dimensions. Due to the anisotropy effect this causes a strain in the material known as magnetostriction. A relationship between the MAE signal and magnetostriction data has been suggested [5]. As a consequence dynamic processes like the degradation of mechanical properties due to stress may thus be monitored by MBN. Another important application in this regard turns out to be metal magnetic memory testing [6] which measures the magnetic field around stress concentration zones.

The article is organized as follows. In Section 2 the Heisenberg model is used to obtain an expression for the energy of the domain wall. From this the domain wall thickness, the energy per unit area, the restoring force, and the magnetization \( M(H) \) are calculated. In Section 3 the theoretical results are numerically evaluated and compared with experimental data. Eddy current losses in ferromagnetic metals are successfully modeled and applications to NDE are discussed.

### 2. Mathematical Modeling

According to the Heisenberg model of magnetism the domain wall energy has two contributions, namely an exchange energy and an anisotropy energy. It can be written in the form

\[
E = \frac{A}{Na} + K Na
\]  

(1)
The second term of Eq (1) above denotes the anisotropy energy which tends to align the magnetic moments with the crystal axis and is smallest when the domain wall thickness is small. On the other hand, the first term of Eq (1) describes the exchange energy which aligns the magnetic moments parallel to each other and therefore increases the domain wall thickness. Here \( a \) denotes the lattice constant, \( K \) is the anisotropy constant which is an energy per unit volume while the parameter \( A \) is given as

\[
A = \frac{k_B T_C}{2a}
\]  

(2)

It is related to the Curie temperature

\[
k_B T_C = 4JS^2
\]

(3)

of the ferromagnetic material.

Using a minimization approach similar to that in reference [7] the energetically most favorable domain wall thickness is given by

\[
\delta = (N\alpha)_{\text{min}} = \sqrt{\frac{A}{K}}
\]

(4)

while the domain wall energy is expressed in the form

\[
\gamma = \frac{E_{\text{min}}}{2\sqrt{KA}}
\]

(5)

and the anisotropy field is written as

\[
H_k = \frac{2K}{\mu_0 M_0}
\]

(6)

The characteristic values for the domain wall thickness \( \delta \) and the surface energy \( \gamma \) are determined by the anisotropy and exchange constants \( K \) and \( A \) and the lattice spacing \( a \). The anisotropy field is the field where the restoring force on the domain wall reaches a maximum value. The critical field needed for the reversal of \( M \) can at most be equal to \( H_k \). This is the result of the Stoner Wohlfarth model [8] and constitutes an upper limit for the critical field. In general the coercitivity \( H_C < H_K \) while for hard magnetic materials the result \( H_C \approx \frac{1}{10} H_K \) has been found to be a reasonable estimate.

When an external magnetic field \( H \) is applied the domains parallel to \( H \) first grow via domain wall motion; these deformations are reversible. However, if \( H > H_C \) the magnetization vector \( M \) is rotated towards the direction of \( H \). The domain wall breaks away from the pinning site. Such processes are irreversible yielding discontinuities in the ratio \( \frac{dM}{dt} \). The corresponding magnetoacoustic emission is known as Barkhausen noise. Domain wall motion contributes less energetically compared to changes in the domain wall surfaces due to their pinning and depinning. The domain wall is in equilibrium if it occupies a position for which its surface area attains a minimum value. It turns out that this happens at the position of lattice defects that restrict their motion. The pinning phenomenon is furthermore directly linked to hysteresis losses which is pointed out in reference [9]. The magnetization depends on the preliminary treatment of the ferromagnetic material and these divergences increase with \( M \). The hysteresis dependence \( M(H) \) is not reproduced by standard models of magnetism due to the above mentioned theoretical assumptions made. Instead the magnetization \( M \) is calculated from

\[
\frac{M}{M_0} = \tanh\left(\frac{mH}{k_B T}\right)
\]
where $H$ is along the easy axis of magnetization. Corresponding numerical results are depicted in Figure 1 below. With increasing magnetic field the magnetic moments become more and more aligned until saturation

$$M = M_0 = \frac{N}{V} m$$

is attained. This saturation value is reached with decreasing temperature at lower values of $H$. In the next section the results of Figure 1 will be generalized to arbitrary values of the angle $\alpha$ between the magnetic field and the crystal axis. This effect is known as anisotropy.

![Figure 1. Magnetization as a function of the external magnetic field as calculated by standard models of magnetism $x \sim H$.](image)

To investigate this further we restrict ourselves to a single domain ferromagnet according to the Stoner Wohlfarth model where the magnetization is given as

$$M/M_0 = \tanh(\mathcal{A} H \cos \alpha)$$

with the abbreviation

$$\mathcal{A} = \frac{m}{k_B T} = \text{const}$$

$M_0$ denotes the saturation magnetization and is the total magnetic moment per unit volume. Equations (4) to (7) are to be numerically evaluated in Section (3) below.
3. Calculations and Discussion

Numerically evaluated are the domain wall thickness $\delta$, the domain wall energy $\gamma$, and the coercitivity $H_C$ taking the values for the anisotropy constant $K$ and the exchange constant $A$ from reference [7]. Values for the Curie temperature $T_C$ and the saturation magnetization $M_0$ are taken from the literature [10]. Table 1 below summarizes these magnetic properties for selected bulk materials.

Table 1. Magnetic properties for selected bulk materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$M_0$ in $\frac{MA}{m}$</th>
<th>$T_C$ in $K$</th>
<th>$\delta$ in nm</th>
<th>$\gamma$ in $\frac{mJ}{m^2}$</th>
<th>$H_C$ in $\frac{kA}{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiFe</td>
<td>0.84</td>
<td>800</td>
<td>258.2</td>
<td>0.077</td>
<td>0.28</td>
</tr>
<tr>
<td>Fe</td>
<td>1.71</td>
<td>1043</td>
<td>12.65</td>
<td>1.265</td>
<td>4.65</td>
</tr>
<tr>
<td>Co</td>
<td>1.44</td>
<td>1393</td>
<td>4.344</td>
<td>4.604</td>
<td>58.6</td>
</tr>
</tbody>
</table>

The domain wall thickness $\delta$ for Fe and Co is of the order of nm and therefore much smaller than the typical domain size $L \sim \mu m$. Those values also qualitatively agree with those given in reference [7]. On the other hand, the NiFe wall thickness is practically of the same order of magnitude as $L$ which also explains its small domain wall energy. The values for the coercitivity $H_C$ agree quite well with those from other sources even though the Fe-value seems to be a bit overestimated [11]. Finally, the Curie temperature $T_C$ measures the strength of the ferromagnetic coupling; the corresponding magnetizations are huge.

Secondly, the effect of anisotropy on the magnetization curves $M(H)$ of a ferromagnetic material is to be discussed. Using Eq (7) above the magnetization $M(H)$ is evaluated as a function of external magnetic field $H$ for different angles $\alpha$ of $H$ with respect to the easy axis of magnetization, $x = A \cdot H \cos \alpha$. The corresponding results are plotted in Figure 2 below.

If $\alpha$ is close to $\pi/2$ the argument $x$ becomes small and $M$ linearly increases with $H$ until saturation is obtained for fields $H > H_k$, i.e. the anisotropy field of Eq (6) above. For smaller angles $\alpha$ the magnetization increases more rapidly and saturation is already reached at smaller fields $H$. Finally, if $\alpha \equiv 0$, $H$ is along the easy axis of magnetization, and $M = \pm M_0$ for all values of $H$. In that case the material is easily magnetized. The numerical values for $\alpha = 0^0$ agree with those of Figure 1 above. Also qualitative agreement with the results of reference [12] is noted.
Figure 2: Magnetization as a function of the external magnetic field for different angles $\alpha$ relative to the easy axis of magnetization. Solid line: $\alpha = 90^\circ$, bold line: $\alpha = 45^\circ$, dotted line: $\alpha = 15^\circ$, and starred line: $\alpha = 0^\circ$.

A quantitative description of the Barkhausen effect is complicated due to its random fluctuating nature. The Bertotti model [13] is a stochastic model that determines the number of Barkhausen events in a given time interval to be a fluctuating function similar to a random walk model. The idea of the Bertotti model is to provide a statistical interpretation of eddy current losses and their relation to the hysteresis. Eddy current losses are considered to be anomalous due to their association with the discontinuous motion of domain walls. Furthermore, the model turns out to be useful for stress measurements [12]. Similar to other authors [14] conducting plates of thickness $d \ll \lambda$, with $\lambda = \sqrt{\frac{\mu_r \mu_0}{\sigma \omega}}$ denoting the penetration depth of the electromagnetic wave, are considered. With $\lambda \sim 10^{-3} m$ this implies that we concentrate on small frequencies $f \sim 50 Hz$. From Eq (8) it also becomes obvious that in electrically conducting materials the penetration depth is very limited. Barkhausen signals can thus only be used to characterize the microstructure close to the surface of the magnetic material.

Eddy current losses are due to the conversion of energy into heat. The power lost per unit mass $P \sim f^2$. However, the actual eddy current loss is larger than the corresponding theoretical value with the ratio $F = \frac{P_a}{P_t}$ defining the anomaly factor. The anomaly factor $F > 1$ as some heat is regenerated as electricity. Anomalous losses are due to domain wall contributions where a group of neighboring walls become simultaneously active to produce short range internal correlation fields. Using as basis the numerical values provided in reference [15] the anomaly factor $F$ is plotted in Fig 3 below as a function of frequency $f$. 

$$\Delta = \sqrt{\frac{2}{\omega \sigma \mu_r \mu_0}}$$

(8)
With decreasing frequency the anomaly factor increases. Furthermore, one may prove that

$$\lim_{f \to 0} F = \infty$$

$$\lim_{f \to \infty} F = \frac{1}{1 - \eta}$$

The asymptotic value of the anomaly factor is related to the thermal efficiency $\eta$ describing the fact that some heat energy is regenerated as electricity. However, the upper limit for the thermal efficiency is given by the Carnot principle and the second law of thermodynamics.

Regarding applications to NDE it is noteworthy to point out that magnetoacoustic emission MAE predominantly arises during the discontinuous motion of Bloch walls when the magnetization vectors in neighboring domains are not collinear and have to be rotated. As both MAE and domain wall motion are influenced by material imperfections and dislocations the Barkhausen signal can be used as an effective NDE technique to measure the degradation of mechanical properties in magnetic materials with time. While in principle the MAE signal can detect flaws even in the bulk of the material, such characterizations are, due to the limited penetration depth of the BE-signal restricted to a thin layer close to the surface of the material. Furthermore, mechanical properties depend on the service life of the specimen. Power plant components for example are expected to have a service life of thirty years or more even when exposed to high temperatures and pressure. Although microstructural changes do occur during the service life it is found that components can often be safely used beyond this time limit [16].
4. Conclusions

The article presents a theoretical investigation on the magnetic Barkhausen noise and dynamic domain wall motion. From the Heisenberg Hamiltonian important magnetic properties, for example the domain wall thickness, the domain wall energy, and the magnetization $M(H)$ are calculated in qualitative agreement with results of other authors [7,11,12]. From a quantitative description of the Barkhausen effect eddy current losses in ferromagnetic metals are successfully modeled. The results are consistent with the second law of thermodynamics. Magnetoacoustic emission turns out to be useful for detecting microstructural features in magnetic materials. Electromagnetic techniques in non-destructive evaluation have a special role to play here as both electromagnetic and mechanical properties are influenced by the same microstructural parameters and the way they change during material processing and degradation.

References

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