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Spectral density of Barkhusen noise in FINEMET-type materials

G. Eszenyi [a,*], A. Bükki-Deme [a], L. Harasztosi [a], F. Zámborszky [b], J. Nyéki [b], Z. Erdélyi [a], D.L. Beke [a], I.A. Szabó [a]

[a] University of Debrecen, Department of Solid State Physics, 4010 Debrecen, P.O. Box 2, Hungary
[b] Magnetec Ungarn KFT, H-3200, Gyöngyös, Pipis hegy, Hungary

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ABSTRACT

Barkhausen noise experiments, performed on different, heat treated FINEMET-type (Fe75Si15NbCu) ribbons, are discussed. The spectral density of the noise, measured under a constant magnetization rate, exhibits a definite change with the nanostructure of the ribbons. Thus mechanical sensitivities (δ) were compared with the Fourier spectra of the samples. It is found that the high and low frequency portions of the spectral density of the noise display a definite correlation with δ. This is similar to the one observed between the full dissipated Barkhausen noise energy of one exciting cycle and the mechanical sensitivity in our previous paper. Our results indicate that the investigation of the spectral density provides a rationale for non-destructive testing during industrial preparation of FINEMET-type materials.

1. Introduction

The Barkhausen noise (BN) technique is widely used as an effective tool to investigate the magnetic properties of ferromagnetic alloys in industrial applications [1,2]. For example it was shown in [1,3,4] from transmission electron microscopy (TEM), scanning calorimetry and X-ray investigations that the volume fraction of nanocrystalline Fe particles in the amorphous matrix of FINEMET-type materials (Fe(75)Si(15)NbBCu) gradually increased from zero to approximately 70% during isochronal heat treatments in the 673–873 K temperature interval. Since products obtained from initially amorphous ribbons are widely used soft magnetic materials for industrial and everyday applications (e.g. ground fault current circuit breakers, chokes, filters, transformers, etc.) there is a large interest for non-destructive testing during industrial preparation of these materials. Thus it was shown in our previous paper [5], that there exists an useful correlation between the mechanical sensitivity and the BN level (the value of the probability frequency curve, $P(A)$, of the peak area, A, at a certain value of A) or the full dissipated energy of the BN for one exciting cycle, E_t. E_t was determined from the integral of the peak energy distribution function, $P(E)$; $E=\int u^2(t)\,dt$, where $u(t)$ and t are the apparent voltage and the time, respectively and the integral runs from the start to the end of the individual peak. It is worth noting that E_t corresponds to the so called resulting $\langle V^2\rangle$ power of BN, averaged upon successive loops and usually taken as a significant measuring parameter [6,7]. Furthermore, the resulting $\langle V^2\rangle$ power of BN is the integral of the spectral density of the noise, $S(i)$, by the frequency, f.

In a recent paper [6] it was illustrated, by a proper spectral analysis and by the application of constant rate of magnetization while traversing the loop, that the spectral density of the noise exhibited a defined dependence on the deformation in cold rolled or tensile strained strips of low carbon steel. Interestingly the low and high frequency portions of the spectra displayed opposite trends with the deformation. Nevertheless, it was concluded in [6] that such correlation can be useful in non-destructive testing by magnetic methods. In the light of these results it is worth to investigate is there a similar correlation between the mechanical sensitivity and the BN spectral density, $S(f)$, of the same FINEMET-type material as obtained by us in [5] e.g. between E_t and δ.

2.1. Methodology, experimental

We carried out the measurements on the same samples used in [5]. Spooled cylindrical ribbons (shape of the products for application) were deformed parallel to the diameter, and change of permeability was measured after this deformation. The definition of mechanical sensitivity is the following: $\delta=(\mu_0-\mu_\varepsilon)/$

* Corresponding author. Tel.: +36 52 512 900; fax: +36 52 316 073.
E-mail address: fizikus13@freemail.hu (G. Eszenyi).

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($\varepsilon\mu_0$); where μ_0 and μ_ε are the initial and the apparent values of the permeability, ε is the relative deformation under compression.

The 20 μm thick ribbons used in magnetic measurements were 10 mm wide and 100 mm long. The measurements were carried out with two common pick-up coils connected in series opposition at a distance of 30 mm endowed with 100 turn. In this way the spurious electromagnetic signals are compensated and it is possible to measure reliably the power spectral density at low frequencies [6]. A triangular exciting signal was used and the noise could be sampled off-line, and then the Fast Fourier Transformation, FFT, could be carried out on the as received data. In the application of our evaluation program (run on a PC) one had to take into account that the sensitivity of FFT can be different depending on how many channels were used during processing the sampled data. Increasing the number of channels, we could receive more detailed information on the medium and high frequency portion of the noise spectra.

According to [6–9] it is very much recommended to keep the magnetization rate constant for unambiguous interpretation of determined BN spectral density as a function of a given technical parameter (material constant). Indeed in the expression (9.60) of [9] the spectral density is proportional to the magnetization rate dI/dt, to a parameter determined by phenomenological constants characterizing different materials and contains a factor which describes the frequency dependence. Accordingly the ratio of $S(f)$ and dI/dt has to be plotted versus the frequency on a log–log plot, as it was done in [6]. Thus our measurements were carried under constant magnetization rate 0.2 T/s, similar to one used in [6] (0.1 T/s). For comparison some experiments were carried out at higher (2 T/s) magnetization rates too. In fact in SI units $\mathbf{B}=\mu_o\mathbf{H}+\mathbf{I}$ and dH/dt can be neglected with respect of dI/dt [8] and thus $dB/dt \cong dI/dt=(dI/dH)(dH/dt)=\mu dH/dt$, where the differential permeability, μ is given by $\mu \equiv dB/dH \cong dI/dH$. Since the permeability of our samples was varied between 30,000 and 700,000 [3,4], it was indeed very important to adjust the dH/dt values in order to keep dI/dt constant. The acquisition of the BN signals was made up to 20–70 (depending on the permeability) successive steps over an appropriate window. In order to avoid contributions other than due to domain wall motions, this window was centered around $I=0$ (covering about 8% of the linear part of the exciting triangular signal).

The measurements were carried out on melt spun, Fe(75)Si(15)Nb(3)B(6)Cu(1) ribbons, annealed at different temperatures (for the details see [5]). The most characteristic parameter of the samples is the maximum heating temperature, leading different δ values, which was changed in the range of 693–873 K and the heating rate was 10 K/min. The mechanical sensitivity parameters obtained in [5] were used here too.

Measuring the BN 200 kHz sampling rate was used. The power spectrum $S(f)$ was determined via standard discrete FFT algorithm, written in C programming language [10], from the recorded Barkhausen signals. After the FFT the program took the squared sum of the real and imaginary parts of the transformed data.

2.2. Results and discussion

Figs. 1 and 2 show the results on the hysteretic curves in mechanically stressed and non stressed states for two samples with different mechanical sensitivities. It is clear that in the case of zero mechanical sensitivity there is indeed no change in the hysteresis by straining the sample, while for sample with $\delta=5.5$ the change is remarkable. It can also be seen from the comparison of the two figures that the permeabilities of the two samples differ considerably.

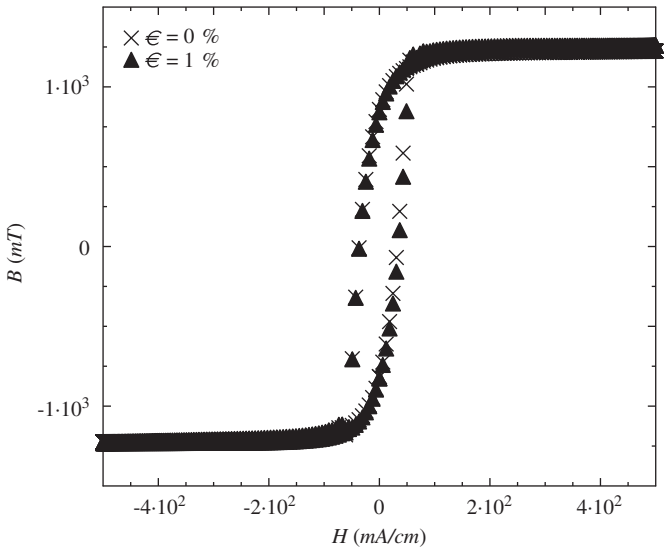

Fig. 1. Hysteretic curves of sample with zero mechanical sensitivity with and without mechanical deformation of 0.01 along the diameter of the coil.

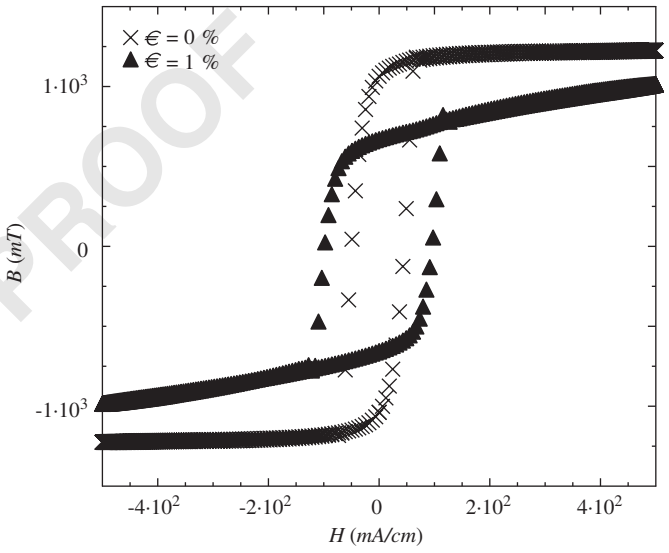

Fig. 2. Hysteretic curves of sample of 5.5 mechanical sensitivity with and without mechanical deformation of 0.01 along the diameter of the coil.

Fig. 3 shows the BN spectral density for samples with different mechanical sensitivity. It can be seen that these have usual shape, i.e. can be described by a function [8,9]

$$S(f) = [4qA/(\sigma G)^2](dI/dt)[f^2/(f^2+\tau^{-2})(f^2+\tau_c^{-2})], \quad (1)$$

where q is the specimen cross section, σ the electrical conductivity, $G=0.1356$, $\tau=\sigma G q \mu$, $\tau_c=\xi/q(dI/dt)$ (ξ the correlation length, directly related to the microstructure), and A a material constant. Note that usually it is recommended to plot the $S(f)$ function normalized by dI/dt, but since in our measurements this factor was the same, the $S(f)$ functions can be directly compared. It can be seen in Fig. 3 that while the positions of the maxima are approximately the same, there is a remarkable change in the slopes. Even the value of $S(f)$ is not monotonic with δ at a fixed f value. For example at 4 kHz first it decreases with decreasing mechanical sensitivity having the smallest value for the smallest $\delta=0$, then suddenly increases again for negative δ. It is worth

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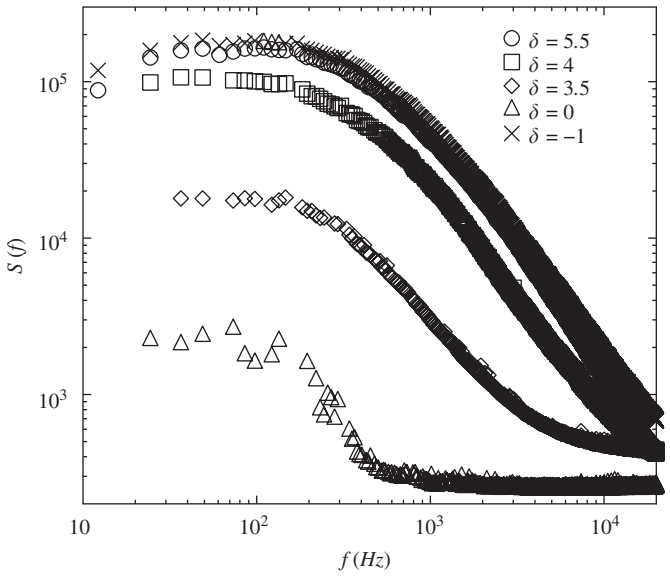

Fig. 3. Power spectral density versus frequency for heat treated samples with different mechanical sensitivities at dI/dt=0.2 T/s magnetization rate.

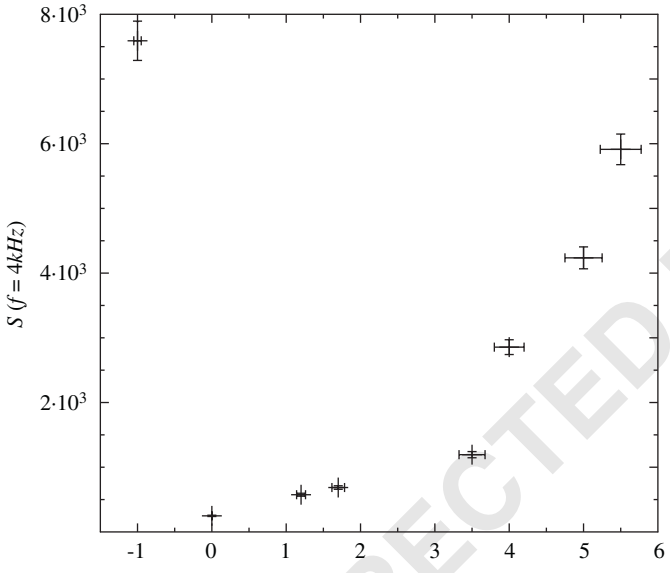

Fig. 4. Correlation between the mechanical sensitivity and the power spectral density of the investigated samples at 4 kHz.

mentioning that at sufficiently high frequencies (1) leads to a $1/f^2$ frequency dependence of $S(f)/(dI/dt)$, providing that the slope of the curve is independent of f. It is clear that this is not the case here. Interestingly the $1/f^2$ dependence is approximately valid for the sample with higher mechanical sensitivity (see the upper curve in Fig. 3).

Following a similar evaluation route as in [6] and plotting the values of $S(f)$ versus δ, one arrives at a nice correlation shown in Fig. 4 at 4 kHz and in Fig. 5 at 200 Hz. This is similar to the correlation obtained between E_t, (calculated from the integral of the $P(E)$ function) in our previous paper [5]. As it was already mentioned in the introduction, E_t correlates with the so called resulting power of BN, $\langle V^2 \rangle$. However, the integral of $P(E)$ (or the power density spectrum by f) can have different dependence on the technological parameter in question, and the integration limits can also play a role. In fact this was one of the motivation in [6] and here too, because this manifests a limitation to get not contradictory claims regarding the correlation between BN and a microstructural parameter investigated.

Fig. 5 shows the correlation between the power spectral density and the mechanical sensitivity at low frequency of 200 Hz. It can be seen that the correlation at this two frequencies are very similar.

Fig. 6 shows the power spectral densities for a given mechanical sensitivities at different magnetization rates. It can be seen, that at δ=5.5 for which the high frequency part showed a $1/f^2$ dependence, the two functions at different dI/dt, as it is expected (see Fig. 9.14 in [7]), falls on each other and they deviate at low frequencies only. The curve for dI/dt=2 T/s runs below the one for dI/dt=0.2 T/s.

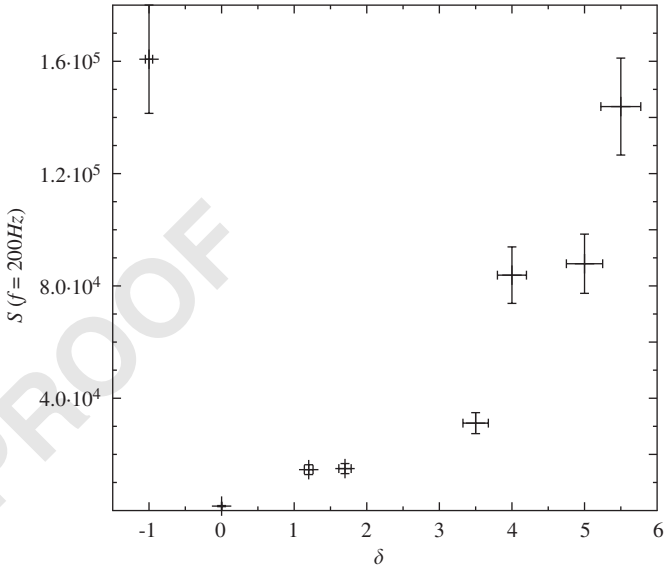

Fig. 5. Correlation between the mechanical sensitivity and the power spectral density of the investigated samples at 200 Hz.

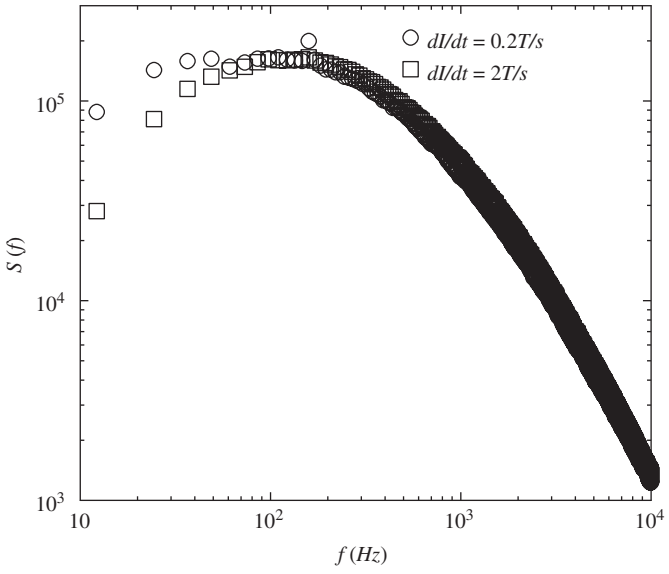

Fig. 6. Power spectral density curves for 5.5 mechanical sensitivity sample taken with two different magnetization rates.

It is important to note that in [6] the spectral density of the noise exhibited an opposite dependence on the deformation in cold rolled or tensile strained strips of low carbon steel at the low and high frequency portions of the spectra. This observation was interpreted by different roles of the surface and bulk magnetization processes in the noise build up.

In the BN extremely localized reversals (tiny portions of domain walls released by pinning centres) trigger a cascade of events (avalanches) and the propagation velocity is determined by the eddy currents and the size of the avalanche is hindered by internal and external demagnetizing fields. The fast locale events are fingerprints of the fine structures of the domain wall pinning fields and thus these determine the intensity of $S(f)$ at high frequencies [6]. Furthermore, at high frequencies, since signals originating from the bulk are shielded and smoothed out by eddy currents, $S(f)$ is dominantly related to transitions taking place in the near-surface layer of the sheet. With decreasing f the dynamics is influenced by slow, low-range propagation of Barkhausen reversals and thus $S(f)$ will be more and more influenced by demagnetizing field dependent processes occurring in the bulk.

In order to decide whether a physical picture described above could explain our observations or not one would need more information on the depth dependence of the domain structure and stress distribution in our sheets. Nevertheless it is worth mentioning that in [11] it was observed that in FINEMET-type amorphous or amorphous/nanocrystalline ribbons the domain structure, observed by Kerr microscopy, shown a peculiar depth dependence (see e.g. Fig. 13 in [11]) due to a complex interplay of frozen in residual stresses or local stresses caused by oxidation of the surface. Thus for a more solid interpretation of the details of our power density spectra the knowledge on the depth dependence of domain structure and the contributions of different reversals in the bulk and in the near-surface layer to $S(f)$ is desired. These experiments are in progress and the results will be published shortly.

3. Conclusions

The frequency dependence of the spectral density of the Barkhausen noise, $S(f)$, of FINEMET-type ribbons follows the theoretical expression (1). It is shown that the spectral density, measured under a constant magnetization rate, exhibits a definite change with the nanostructure. It is found that the high and low frequency portions of $S(f)$ display a similar correlation with the mechanical sensitivity of the samples. The results can be very useful in non-destructive testing during industrial preparation of FINEMET-type materials.

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