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Journal of Alloys and Compounds 434–435 (2007) 604–607

Journal of ALLOYS AND COMPOUNDS

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Zipping method applied to Barkhausen noise: A new tool to investigate the micromagnetic disorder in amorphous magnetic materials

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Available online 12 October 2006

Abstract

The degree of micromagnetic disorder in magnetic amorphous materials is investigated by applying the packing method to the time series obtained, both from Barkhausen noise experiments and simulations of domain wall motion. The observed dependences of the estimated entropy on the applied stress, in the case of experimentally obtained time series, and the width of the Gaussian noise used in simulations, are explained in terms of two regimes of the effect of an external stress applied.

PACS: 75.60.Ej; 75.40.Mg; 75.50.Kj; 75.60.Ch; 05.40.−a; 05.10.Gg

Keywords: Barkhausen noise; Domain wall motion; Complex systems; Entropy estimation

1. Introduction

Barkhausen noise (BN) is detected as a series of voltage pulses appearing on the extension of a coil placed near or involving a ferromagnetic sample subjected to a varying external field. The effect is associated to the sudden topological and geometrical changes occurring in the domain structure of a ferromagnetic material as the magnetization proceeds. It is therefore an effect strongly dependent on the magnetic microstructure of the sample. As a matter of fact, BN can be considered a fingerprint of the complex systems composed of the magnetic domains, domain walls (DW) and a reservoir of defects that act to pin the DWs [1]. A number of papers have been dedicated to the statistical aspects of hysteresis and Barkhausen noise, but very few are aimed at the application of BN as a non-destructive analysis technique that can be used to characterize the amount of defects and its evolution with thermal treatments, or under the action of an external drive as an applied stress. From the theoretical point of view, the estimation of the degree of disorder in a real system is a very important issue, as the disorder in simulations is always taken as the width of a Gaussian responsible for some sort of noise or random field [2,3]. In recent years, some authors [2] have associated the degree of disorder to the temperature in exchange-biased NiFe/CoO films. However, in Ref. [2], the authors are concerned with a disorder-induced phase transition [3] and have assumed that the temperature is a measure of the degree of disorder associated to the antiferromagnetic CoO film as the Néel temperature was crossed. In this work we are concerned with the degree of disorder or the entropy at the micromagnetic level of ferromagnetic amorphous samples. This disorder is strongly associated to the time series that are the typical output of a Barkhausen noise experiment, with a given size and resolution in time. The time series may carry information of part or a whole hysteresis loop. In general, they are acquired along a small part of the hysteresis loop, for H near the value of the coercive field (H_C). The main point to be addressed here is how to estimate the degree of micromagnetic disorder or entropy from such output. One method could be the calculation of the Chapman–Kolmogorov entropy, but this method is not practical for the typical time series obtained with the experimental setup used in this work. The solution for such a problem may be to apply the method recently proposed by D. Benedetto et al. [4] that have shown to be possible to estimate the relative entropy of a given system by applying the zipping method [1,4] to a time series or to an image or text. In this method, the relative entropy is estimated through the size of the packed file that contains the information in the form of a string of characters. The

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doi:10.1016/j.jallcom.2006.08.090

packing process is performed with the LZ77 algorithm, which is the standard algorithm present in programs such as WinZip, Pkzip, etc.

In order to control the degree of micromagnetic disorder in the samples studied in this work, stress has been applied in the range 0–350 MPa. The effect of the applied stress is to control the magnetic microstructure by establishing a preferred orientation for the domain walls (DW), straightening these walls and decreasing the domain wall thickness [5]. In principle, it should be expected a decrease of the degree of disorder with increasing stress. The method was shown to be sensitive to the stress in the above mentioned range. The magnetic domain microstructure was also studied by Kerr microscopy. Although the method has already been proved to be sensitive to modifications on the degree of magnetic disorder of amorphous samples [1], there is yet no evidence on the functional dependence of the degree of disorder (measured as the size of the packed files) with the applied stress or annealing temperature. In this work we try to solve this issue by applying the zipping method to simulate time series obtained from the integration of the equation of motion for domain walls [6–8]. In these simulations, the degree of disorder is again taken as the width of a Gaussian distribution that is an ingredient for a Wiener noise increment as described below. The difference of this simulation with respect to simulations based on the Random Field Ising Model (RFIM) is that the BN details are better described with the method presented here.

2. Experimental and numerical methods

$Fe_{78}B_{13}Si_9$ amorphous ribbons with positive magnetostriction ($\lambda_S = 27 \times 10^{-6}$) under stress were studied prior and after a pre-annealing treatment at 300 °C for 15 min. Sample dimensions were 60 mm × 2 mm × 27 μm. Barkhausen noise time series were obtained in an open magnetic circuit consisting of a long compensated solenoid excited by a DS345 function generator and low distortion power amplifier. The signal was detected by a small (50-turn) pick-up coil wound around the central part of the sample, amplified by a low-noise pre-amplifier (SR560) and digitized by a Tektronix TDS320 oscilloscope. The whole setup was controlled by an Agilent VEE program that acquires 100 time series at a given trigger field, while the sample was swept through its hysteresis curve, for each stress level. Stress in the range 0–350 MPa was applied by using calibrated weights attached to one end of the sample. The BN time series for each stress level were stored in a PC computer for further processing. Hysteresis curves for each sample were obtained by the fluxmetric method in the same magnetic circuit of Barkhausen noise measurements. All measurements were performed at room temperature. The relative entropy for each stress level was estimated by packing the set of 100 times series with the LZ77 algorithm.

The simulated Barkhausen noise time series were obtained by numerical integration of the stochastic equation of motion for domain walls in the Langevin form [6], given by

$$\dot{v}(t) = -\frac{G_S v(t)}{\tau_{\text{eddy}}} + \dot{H}_C(t) \tag{1a}$$

$$\dot{H}_C(t) = -\frac{v(t)}{\tau_{\text{eff}}} + \dot{W}(t) \tag{1b}$$

where $v(t) = \dot{\phi}(t)$ is the flux rate responsible for the output of the sensing coil, G_s a geometrical constant [6–8], τ_{eddy} the eddy current time constant that takes into account the resistivity of the material, τ_{eff} the coercive field time constant that depends on the free energy landscape for a given material and W(t) is a Wiener noise [6–8]. The Wiener noise increments that appear in the discretized version of Eqs. (1a) and (1b) depend on a Gaussian noise whose width has been varied in the simulations performed in this work. All the other parameters were kept constant at convenient values. For the numerical integration, the Euler method has been used. For each Gaussian width, 100 time series with 100 000 points were generated. Although the numerical resolution was high, the vertical resolution of each time series was reduced to 256 step (8 bit) in order to compare it directly with the experimental vertical resolution of the oscilloscope. The time series were also packed with the LZ77 software under maximum compression.

3. Results and discussion

In Fig. 1, the experimental time series for $Fe_{78}B_{13}Si_9$ amorphous ribbons under selected stress levels are shown. The corresponding entropy values, here taken as the size of the corresponding packed time series are shown in Fig. 2; the entropy initially increases and finally reaches saturation.

In Fig. 3, the simulated time series for relative Gaussian width varying from 1 to 6 are shown. The corresponding sizes of the packed time series are shown in Fig. 4. The parabolic fit is a guide to the eye. The numerical results show the estimated entropy that increases with the width of the Gaussian. If this increase corresponds to an increase of the applied stress is a point we will try to clarify below.

First of all, the experimental results seem contradictory as the entropy increases with the applied stress. The apparent contradiction can be understood as follows. First of all it has to be noticed that the domain + DW + defect system is particularly complicated in non-stressed amorphous ribbons due to the absence of magnetocrystalline anisotropy. In the absence of any applied stress, the domain structure of a soft magnetic ribbon is likely to be the well known “maze pattern structure”. When the stress is applied, two mechanisms take place:

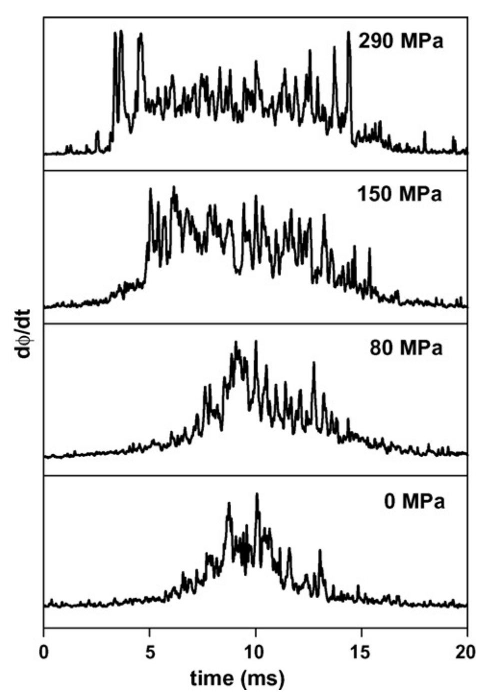

Fig. 1. Selected experimental BN time series for amorphous $Fe_{78}B_{13}Si_9$ ribbons under increasing stress levels.

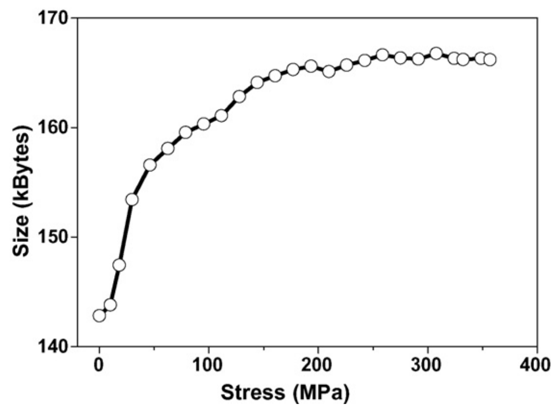

Fig. 2. Entropy estimated as the size of the packet set of 100 time series similar to the ones shown in Fig. 1.

(a) The domain structure is ordered, the domains size increases, the domain walls straighten [5] and the domain wall width, given by

$$\delta_w = \sqrt{\frac{A}{K_{\rm eff}}}, \tag{2}$$

decreases. In expression (2), A is the exchange constant ($\approx 10^{-11}$ J/m^3 for an amorphous magnetic alloy) and $K_{\rm eff} = 3/2\lambda_S\sigma + K_0$, where λ_S is the saturation magnetostriction at a given stress level σ, and K_0 is the anisotropy due to the residual stresses present in a magnetic amorphous ribbon. This residual anisotropy is written as $K_0 = \langle K_0\rangle + K(r)$, where K_0 is the average anisotropy due to the residual stress, surface roughness or some sort of anisotropy induced during the fabrication process. On the other hand, the term $K(r)$ accounts for the fluctuations on the anisotropy due to built-in stresses. These fluctuations carry information on the defects that will pin the domain walls along the magnetization process. When a given domain wall moves under the pressure of an applied field, there is always a counteracting pressure that keeps the DW motion reversible and stable. This regime is described by the minimum conditions $\delta K(r) = 0$ and $\delta^2 K(r) > 0$. When $\delta^2 K(r) = 0$, the position of the domain wall becomes unstable and it jumps to the next position where the condition $\delta^2 K(r) > 0$ is satisfied. Therefore, the domain wall motion is the fingerprint of $K(r)$ and of the domain structure present in a sample.

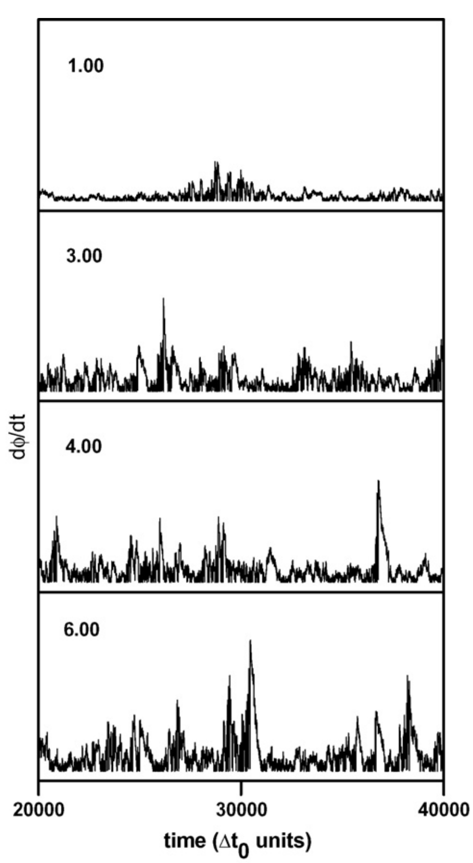

Fig. 3. Selected simulated time series for increasing width of the Gaussian used to generate the Wiener noise increments within the Euler integration of Eqs. (1a) and (1b).

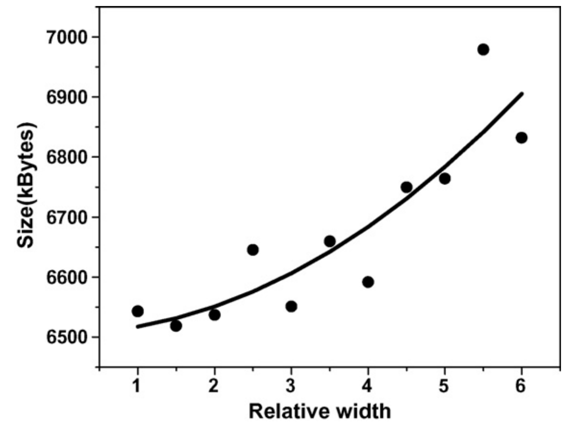

Fig. 4. The corresponding estimation of the entropy for the simulated time series. The parabola is a guide to the eye.

(b) Above a given stress value, there is no further ordering of the DS or DWs. On the other hand, the domain wall width becomes the minimum length scale probed in the free energy fluctuations $K(r)$. Therefore, the extent of the energy fluctuations probed by a given DW is increased. As the typical length decreases, and the average magnetization is kept constant, faster BN jumps appear and the overall BN activity increases as well as the number of higher amplitude voltage impulses present in the time series. This effect can be seen in Fig. 1. If the distribution of size of fluctuations in the free energy is roughly assumed to be described by a normalized Gaussian $g(r)$, then the number of Barkhausen jumps or pulses can be calculated as

$$n \propto \int_{\delta_W}^{L\to\infty} g(r)\,\mathrm{d}r \approx b[1 - \mathrm{erf}(a\delta_W)] \tag{3}$$

where L is the width of the sample, here taken as infinity when compared to the domain wall width δ_W, and erf(x) is the error function. In Fig. 5, the size of the packed time series is shown as a function of the domain wall width δ_W (see Fig. 2). The line is the fitting with expression (3). There is a reasonable

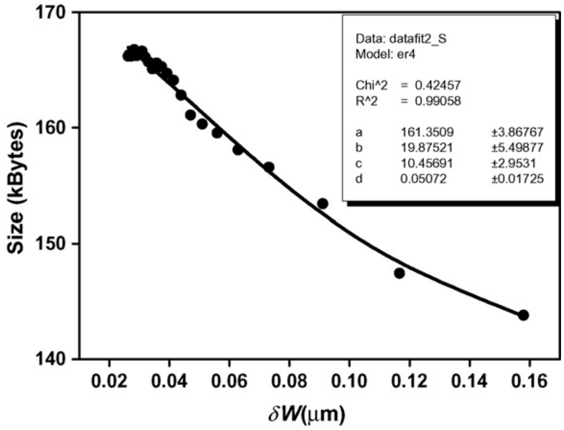

Fig. 5. Same as Fig. 2 but as a function of the domain wall width. The fitting is made with expression (3).

agreement between the fitted and experimental data, corroborating the hypothesis of the domain wall width as the limit for the smaller features in $K(r)$ that can be probed by BN experiments.

We have yet to compare the results obtained from the simulated time series. Our first comment is that the effect described by the time series can only be compared with the stress range where the domain structure is significantly changed by the stress. Domain structure observations performed in the same samples under stress have shown that above 40 MPa there are no detectable changes in the domain structure. Therefore, the observed decreasing trend of the entropy with the relative width of the Gaussian used in the numerical integration can only be observed for stress levels below 40 MPa, for the particular set of samples studied in this work. It must be emphasized that the simulations of the domain wall motion performed in this work do not take into account any modifications in the domain wall width. The simulation and equations of motion for DW should be improved to take into account this kind of effect, an issue that will be addressed in a further publication.

4. Conclusions

In conclusion, we have shown that the packing or zipping method is sensitive to modifications in domain structure and also sensitive to domain wall width and its interplay with the spatial fluctuations of the magnetic free energy in an amorphous magnetic material. The method, when applied to simulations of DW motion, was also shown to be sensitive to the Gaussian noise width used as one of the ingredients of the numerical calculation. The functional relation between the degree of disorder and the relative entropy calculated by the packing method has yet to be further investigated.

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