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Extraction of hysteresis model parameters from magneto-optical experiments

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The paper presents an efficient method for the extraction of hysteresis model parameters with physical meaning, starting from the real-time visualization of the magnetic microstructure by magneto-optical Kerr effects. It is shown how the digital acquisition and processing of the obtained images allow to extract the statistical distribution of the switching fields for each image pixel, so the numerical function of the classical Preisach model.

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1. Introduction

The magnetization process of a material is related to its micromagnetic structure and it can be studied through the visualization of the magnetic domains and walls dynamics, using magneto-optical effects [1]. The local magnetic hysteresis behavior can be characterized using a magneto-optical magnetometer and this procedure could be very useful both for the experimental investigation of magnetic materials (e.g. [2], [3] and [4]) and for the identification of hysteresis model parameters. These numerical parameters are usually identified [5] starting from a set of experimental data (first magnetization curve, major hysteresis cycle or first order reversal curves – FORC) obtained for example with a vibrating sample magnetometer (VSM) [6].

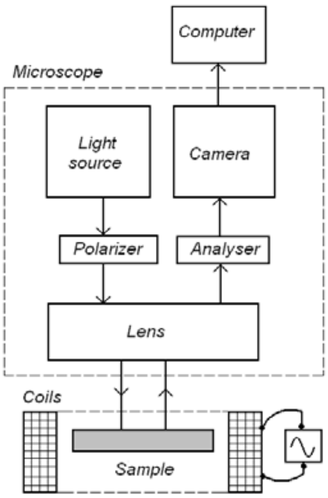
The magneto-optical microscopy was used for the direct observation of local magnetic properties, including the local hysteresis loops, in various magnetic thin films (e.g. ferromagnetic [7] or Tb(FeCo) [8]). The results show that the coercivity distribution is asymmetric and far from any well-known theoretical models (Gaussian, Lorentzian, log-normal-Gaussian or factorized Lorentzian distributions), due to the local interactions [7]. The shape of this Preisach distribution also depends of the time interval between successive values of the applied magnetic field [8].

The paper presents an efficient method for the extraction of hysteresis model parameters with physical meaning, starting from the real-time visualization of the magnetic microstructure by magneto-optical Kerr effects. The obtained macroscopic model will be used in engineering computation (e.g. for magnetic material modeling in electromagnetic field problems), so the local variations of the magnetic properties could be approximated; the Preisach distribution will be computed using the entire image area (400 x 400 μm^2). Using a polarized light microscope and a certain variable magnetic field applied to the sample, one can obtain the movie of the magnetic microstructure evolution for the considered direction. The digital acquisition and processing of the obtained images [9] allow the identification of physical parameters. For example, by assuming that each pixel of the magneto-optic image corresponds to a hysteron of the Preisach model, the macroscopic behavior of the magnetic material results from the statistic sum of all hysterons (pixels). The statistical distribution of the switching fields for each image pixel gives the numerical Preisach function of the classical model. If the Kerr effects (polar, transversal and longitudinal) are combined, the method could be used for the identification of a vector function.

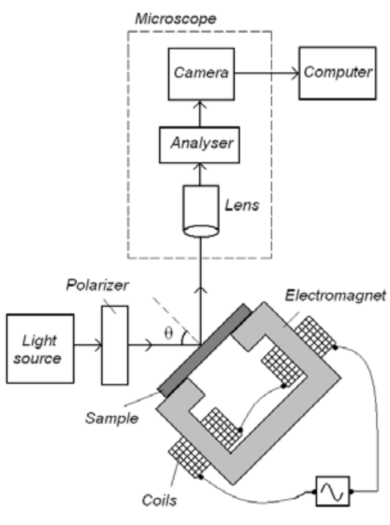
2. Experimental setup

Our experimental setup is based on the polarized light microscope Axiolab, video-camera AxioCam Hsm and AxioVision software – all from Zeiss®. Applying a sinusoidal magnetic field to the sample, the corresponding magnetization dynamics, at microscopic scale, can be recorded in a movie file. The delay time between successive values of the applied magnetic field is very short (miliseconds) because the sinusoidal magnetic field is controlled by a shape function generator. Consequently, the asymmetry of the coercivity distribution will be weak [8]. The investigation can use the polar Kerr effect or the longitudinal Kerr effect, depending on the magnetic material type. The two experimental configurations are presented in Fig. 1; the longitudinal component of the magnetization is available if an external polarized light source is used. The magnetic field is produced in the device coils and the optimal value of the incidence angle θ corresponds to a maximal contrast of the image.

The acquired magneto-optic frames (images) have a large number of pixels, allowing a statistical study. The digital acquisition and processing of the obtained frames (images) allow the separation of the magnetic information, by subtracting a reference image (corresponding to the saturation state) from each frame. The image contrast and brightness are also optimized by the hystogram control in AxioVision software [10].



(a)



(b)

Fig. 1. Experimental setup for magneto-optical Kerr microscopy: a) polar Kerr effect; b) longitudinal Kerr effect.

3. Extraction of hysteresis model parameters

The study of the magnetization process, recorded by digital magneto-optic images, allows the identification of basic hysteresis model parameters, like those that correspond to the coercivity, remanence or saturation points. It is also possible to build the first magnetization curve or the major hysteresis cycle. However, the digital processing of the magnetization movie can provide more sophisticated information, related to the microscopic behavior of the material, like in the Preisach statistic model; our study is focused on this subject.

The classical Preisach model [2] considers that a ferromagnetic material is made up of dipoles (hysterons) having a magnetic behavior described by a rectangular hysteresis cycle. The distribution of these elementary operators with respect to their up- and down-switching values (*a,b*) identifies the modeled material. If the model output is the normalized magnetization $m=M/M_s$, where M_s corresponds to the saturation, the model computes:

$$m(H) = \iint_{S_+(H)} P(a,b)\cdot \mathrm{d}a \cdot \mathrm{d}b - \iint_{S_-(H)} P(a,b)\cdot \mathrm{d}a \cdot \mathrm{d}b \qquad (1)$$

where $P(a,b)$ is the Preisach distribution function and S_+, S_- are the areas corresponding to the positive and negative saturated hysterons in the Preisach triangle ($-H_s \le b \le a \le +H_s$) – see Fig. 2. The boundary between S_+ and S_- is a staircase line depending on all the previous values of the magnetic field H (the model input).

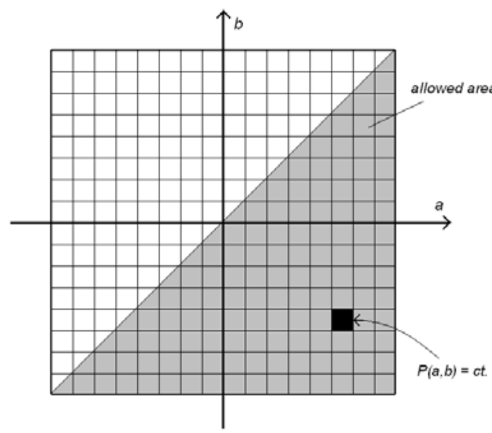


Fig. 2. Preisach triangle with uniform meshing

Our study starts from the statistical nature of the classical Preisach model and proposes a new identification procedure. The analysis of the gray-level evolution for each pixel indicates the frames where it changes the color (between black and white) - when the pixel magnetization changes its direction. The values (*a*, *b*) of the switching magnetic fields (corresponding to the frames) could be determined for each pixel, like in Fig. 3. If one assumes that a pixel corresponds to a Preisach hysteron, the value of the statistic Preisach function $P(a,b)$ will result by counting all the pixels having the same pair (*a*, *b*). The obtained numerical function can be directly used in any electromagnetic field computation that involves the Preisach hysteresis model. If the magneto-optic image has a good resolution, the pixels number is big enough to consider that a pixel corresponds to a hysteron. Supplementary, if the pixels have a gray-level evolution closed to a rectangular shape, like a Preisach hysteron, one may decide if the Preisach model is suitable for the analyzed magnetic material.

The local interactions influence the local hysteresis loops, so the identified Preisach distribution depends of the applied magnetic field. If the field is sinusoidal and saturates the sample, then the identified distribution corresponds to the major loop and the model will be accurate only for major hysteresis loop. This kind of Preisach distribution is very useful for steady-state electromagnetic problems in Electrical Engineering.

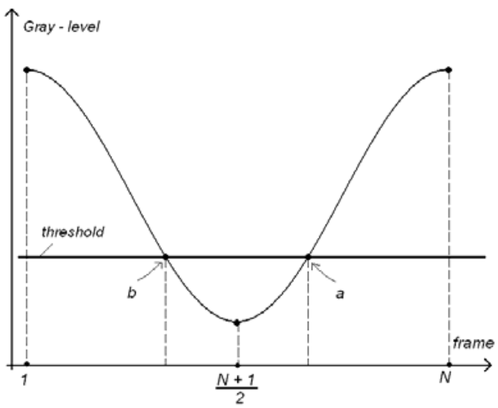


Fig. 3. Extraction of the up- and down-switching values (a, b) from the magnetization movie

4. Experimental and numerical tests

The proposed identification method was tested on two types of magnetic materials: YIG garnet and Fe-Si sheet. Applying a sinusoidal magnetic field (frequency = 0.1 Hz), perpendicular to the YIG garnet sample, the corresponding magnetization dynamics, at microscopic scale, can be recorded in a movie file, using the polar magneto-optic effect (see Fig. 1.a); for thin films, the other two components of the magnetization can be ignored. The acquired frames (images) have (588 x 792) pixels, allowing a statistical study. The mean gray-level evolution is presented in Fig. 4 and the images corresponding to the saturation zone and to the coercivity one are shown in Fig. 5.

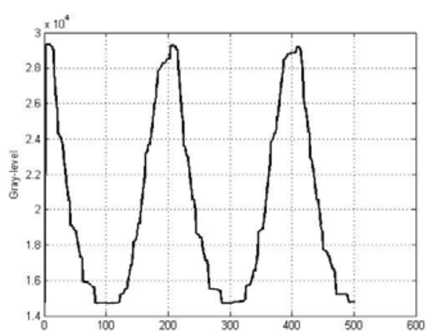
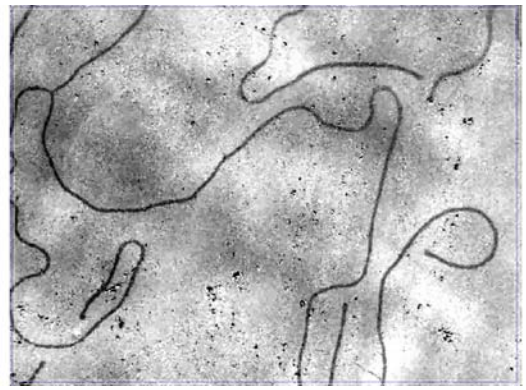
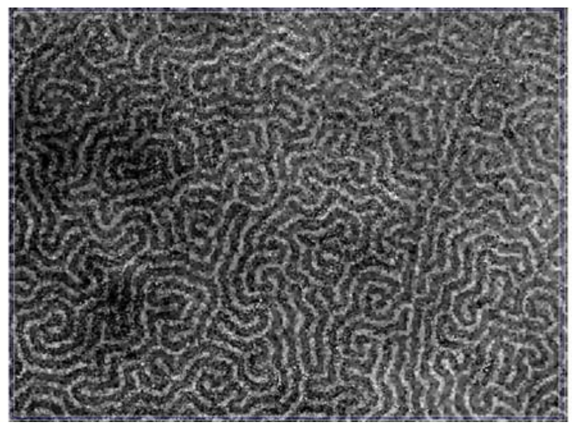


Fig. 4 Mean gray-level for a sinusoidal magnetization movie.



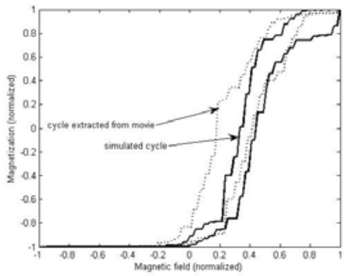
(a)



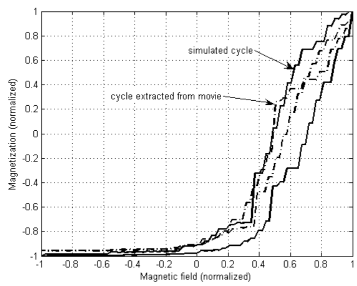
(b)

Fig. 5. Magneto-optic images for frame no. 10 (a) and frame no. 51 (b).

The jumps in the saturation zone are critical for the identification of the frames that correspond to a hysteresis cycle. Indeed, Fig. 6 shows the difference between the hysteresis cycles obtained by averaging the gray-level of all pixels (cycle extracted from the movie) and by numerical simulation using the identified Preisach model (simulated cycle) using frame intervals close to each other, like (3, 205) and (15, 185). The staircase shape of the simulated cycle results from the fact that the computed function has many peaks. The evolution of the magnetic domains during the magnetization process is not continuous, due to the jumps of the coil current and to the material surface defects. All these jumps influence the correct determination of (a, b) values for each pixel. The number of valid pixels, from the point of view of the Preisach model, also depends of the considered frame interval – see Table 1.



(a)



(b)

Fig. 6. Hysteresis cycles for frames in the interval (3, 205) (a) and (15, 185) (b).

The second investigated material was a Fe-Si sheet, under a longitudinal sinusoidal magnetization (see Fig. 1.b). The longitudinal Kerr effect is not as sensitive as the polar effect and the image contrast is weak. For an applied magnetic field of 1 Hz, the gray-level evolution, for frames having (660 x 492) pixels, is presented in Fig. 7 and the obtained hysteresis cycles are shown in Fig. 8. The numerical simulation by finite elements indicates that the electromagnet geometry also induces transversal and polar components of the magnetization in the sample, so a preliminary separation could be very useful [11].

*Table 1**:** Number of valid pixels for various frames*

Frames	3 to 205	207 to 409	15 to 185	10 to 204
Valid pixels [%]	18.7	8.6	40.4	11.3

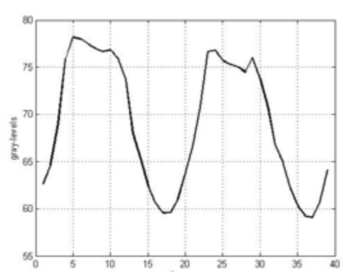


Fig. 7. Gray-level evolution for a Fe-Si sheet under 1 Hz applied magnetic field

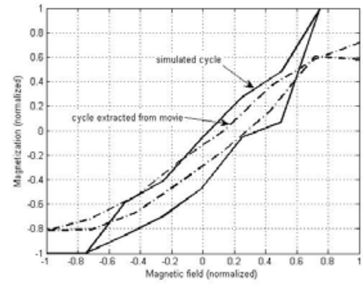


Fig. 8. Hysteresis cycle for Fe-Si sheet

5. Conclusions

The proposed method allows a direct extraction of the hysteresis model parameters, like the discrete values of the Preisach function. The procedure, including the experimental data measurement, is very fast and promises an efficient way for the identification of the hysteresis vector models for thin magnetic films, the used experimental information being given by the magnetic microstructure of the sample surface.

The method allows the adaptation of the model parameter to a specific geometrical zone; for example, the discrete Preisach function can be computed for each desired area (e.g. finite elements) which may be an advantage in the study of high frequency electromagnetic field. Despite the accuracy dependency on the experimental setup, especially on the preparation of the sample surface, the identification method could be very useful to test new dynamic or vector hysteresis models for magnetic thin films.

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