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Preisach modeling of magnetization and magnetostriction processes in laminated SiFe alloys

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In this article, magnetization loops under mechanical stress and magnetostriction loops under quasistatic magnetic excitation conditions are discussed. In both cases, the hysteresis loops are modeled using the Preisach theory. The identification procedure of the material parameters is described. The article discusses first the shape of the Preisach distribution function for the study of magnetostriction loops. Next, a Preisach model is proposed for the description of magnetization loops under mechanical stress starting from the magnetization loop obtained without applying mechanical stress. A setup has been constructed for the measurement of magnetization loops under compressive or tensile stress. Also, a measuring system based on a single sheet tester and on optical displacement measurement techniques is used to establish the magnetostrictive behavior of laminated SiFe alloys. It is shown that a good correspondence between the calculated and measured magnetization and magnetostriction loops is obtained.
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I. INTRODUCTION

It is well known that the magnetic properties of most ferromagnetic materials are affected by applied stress.[1,2] Moreover, when the magnetization of a ferromagnetic alloy is altered, the change in magnetization is in general accompanied by a change in dimensions, which is known as magnetostriction. In some cases, the magnetostrictive effect must be small in order to minimize the noise production in electromagnetic devices.[3] In other cases, the magnetostrictive effect is functionally exploited, e.g., in sensors or transducers.[4] Sensitivity of most ferromagnetic alloys to strain can be ascribed directly to their magnetostriction properties. In discussing the effect of a unidirectional stress, it is convenient to divide materials into two classes, which have positive or negative magnetostriction. In materials of the first class, the magnetization increases by tension and the material expands when magnetized. For the second class, the magnetization decreases by tension and the material contracts when magnetized.[5] Magnetic materials exhibit hysteresis behavior with respect to the magnetization and magnetostriction characteristics.[6,7] In this article, we focus on the description of the hysteresis effects in the magnetization loops under mechanical stress and the magnetostriction loops for laminated SiFe alloys.

II. EXPERIMENTAL EVALUATION OF MAGNETIZATION LOOPS UNDER MECHANICAL STRESS AND MAGNETOSTRICTION LOOPS

Sensitive measuring devices are required to investigate the magnetostrictive phenomena. Two major measurement techniques are found in literature: the strain gauge technique[8] and the optical techniques.[9] A measuring system for magnetostriction λ of silicon steel sheet is devised to establish, under quasistatic conditions, the magnetostriction loops. The system makes use of a double yoke single sheet tester with a magnetic path length of 45 cm, combined with optical methods. The samples have a length of 60 cm and have 12 cm width. The upper yoke is movable such that the yokes do not clamp the sheet. Instead, the sample is clamped by a suction cup system placed at one end of the sample, while the strain $\lambda = dl/l_0$ is measured at the other end by mounting a small light reflector, l_0 being the length of the sample at demagnetized state. A fiber-optic measurement system performs noncontact displacement measurements. The sensor head is composed of adjacent pairs of light-transmitting and light-receiving fibers. The operating principle is based on the fact that the intensity detected by the light receiving fibers changes with varying distance between the light transmitting fibers and the reflector. The resolution of the sensor is approximately 0.03 μm. The strain λ is measured as a function of magnetization M at each time point t_i.

The experiments on mechanical stress require a specific device suitable to apply a magnetic field as well as a mechanical tensile stress in the longitudinal direction of the sample. This device is derived from a small single sheet tester around which a mechanical yoke is constructed. This mechanical yoke allows enforcing a mechanical tensile or compressive stress. The single sheet tester uses samples with minimum length of 60 mm and a width of 20 mm and is calibrated with respect to the Epstein frame measurements. A magnetic flux through the strained specimen is created by the excitation winding around the sample (outer winding). The measuring coil (inner winding) around the sample measures the variations of the magnetic flux.

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III. PREISACH HYSTERESIS MODEL

A. Preisach magnetization model

The Preisach model rests upon the idea of a material structure containing an infinite set of dipoles.[7] Each dipole has a rectangular nonsymmetric hysteresis loop defined by two characteristic parameters, which are denoted by α and β $(\beta \leqslant \alpha)$. The state ϕ_p of a given elementary dipole will be $+1$ when $H_e > \alpha$ and -1 when $H_e < \beta$ where the effective field equals $H_e = H_a + \kappa M$. H_a and κM are the applied and demagnetizing field, respectively. In the case that $\beta < H_e < \alpha$, the state ϕ_p of the Preisach dipole will depend on the last extreme value $H_{\mathrm{e,last}}$, which is lying outside the interval $(\beta,\ \alpha)$ and which physically is remembered in the domain structure of the material.

$P(\alpha,\beta)$ is the Preisach distribution function (PDF). The magnetization M of the entire material is obtained from the accumulated magnetization of all the dipoles

$$M[H_e(t),H_{\mathrm{e,past}}(t)] = M_{\mathrm{rev}}[H_e(t)] + \frac{1}{2}\int_{-\infty}^{+\infty} d\alpha \int_{-\infty}^{\alpha} d\beta \times P(\alpha,\beta)\,\phi_p(\alpha,\beta,H_e(t),H_{\mathrm{e,past}}(t)). \tag{1}$$

B. Preisach magnetostriction model

In order to describe the magnetostrictive properties of SiFe alloys using the Preisach theory, we take the magnetization $M(t)$ as input of the model and the strain $\lambda(t)$ as output. The strain λ at magnetization $M(t)$ reads

$$\lambda[M(t),M_{\mathrm{past}}(t)] = \lambda_{\mathrm{rev}}[M(t)] + \frac{1}{2}\int_{-M_s}^{+M_s} d\alpha \int_{-M_s}^{\alpha} d\beta \times Q(\alpha,\beta)\,\phi_\lambda(\alpha,\beta,M(t),M_{\mathrm{last}}(t)). \tag{2}$$

In Eq. (2), M_{last} is the last extreme value of the magnetization kept in memory while M_s equals the saturation magnetization.

The function $\lambda_{\mathrm{rev}}(M)$, describing the reversible part of the magnetostriction, is obtained by the slope of the returning branch $d\lambda/dM$ at each reversible point m of a finite set of experimentally obtained magnetostriction loops, symmetrically with respect to M. Then $\lambda_{\mathrm{rev}}(M)$ reads

$$\lambda_{\mathrm{rev}}(M) = \lambda_{M_s} + \int_{-M_s}^{M} \frac{d\lambda}{dM}(m)\,dm. \tag{3}$$

The terms $d\lambda/dM(m)$ and λ_{rev} are given in Fig. 1. The identification of the PDF $Q(\alpha,\beta)$, describing the irreversible contribution to the magnetostriction, can be performed in different ways.[10] Procedures based on the experimental evaluation of numerous return magnetostriction branches is very general and does not impose constraints on the PDF, however it requires a large amount of measured data. A reduction of the input data needed for the identification of the PDF can be obtained by introducing a factorization of the PDF as $Q(\alpha,\beta) = f(\alpha)g(\beta) - f(-\beta)g(-\alpha)$. This factorization guarantees $Q(\alpha,\beta) = -Q(-\beta,-\alpha)$ and results in a distribution function which takes negative values, contrary to the situation when describing magnetization loops. These negative values of the PDF give rise to the special shape of the magnetostriction loops, the so-called "butterfly" loops.

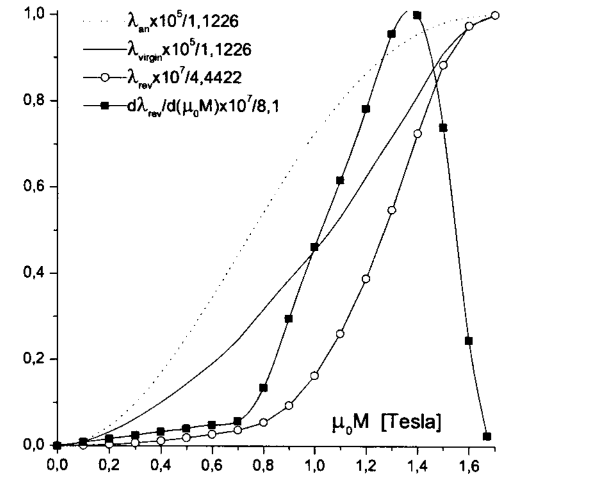

FIG. 1. Measured reversible part of the magnetostriction; anhysteretic and virgin magnetostriction curve obtained from the Preisach model.

Here, we used the Everett function $E(M_1,M_2)$,[11] from which the PDF can be obtained as the second order derivative, i.e., $Q(\alpha,\beta) = -(\partial^2 E/\partial M_1 \partial M_2)_{M1=\alpha,M2=\beta}$. According to the Everett theory, the function $E(M_1,M_2)$ is identified experimentally as the variation of λ when considering a branch from M_1 to M_2; M_1 is the last extreme value of the magnetization and no extrema are evaded from the memory along the branch between M_1 and M_2. The Everett function corresponds to

$$E(M_1,M_2) = \int_{M_1}^{M_2} d\alpha \int_{M_1}^{\alpha} d\beta\, Q(\alpha,\beta). \tag{4}$$

Figure 2 shows the Preisach function $Q(\alpha,\beta)$ while Fig. 3 illustrates the good agreement between the measured quasistatic $\lambda(M)$ loops and the ones calculated by the Preisach model. The demagnetized state $(\lambda = 0)$ corresponds with

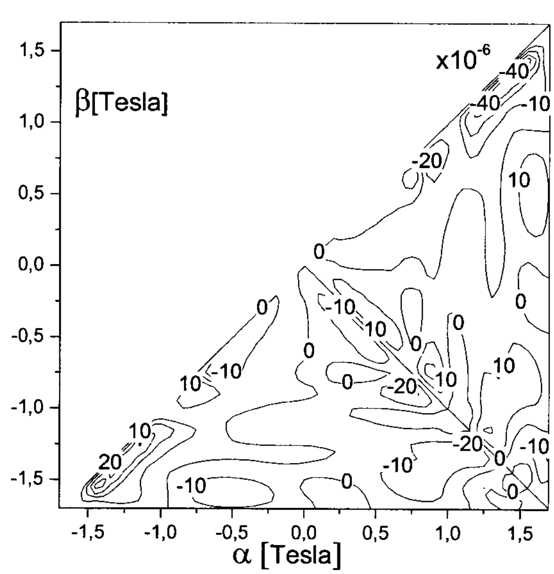

FIG. 2. Preisach distribution function $Q(\alpha,\beta)$ for the modelling of magnetostriction hysteresis effects and obtained by the Everett theory.

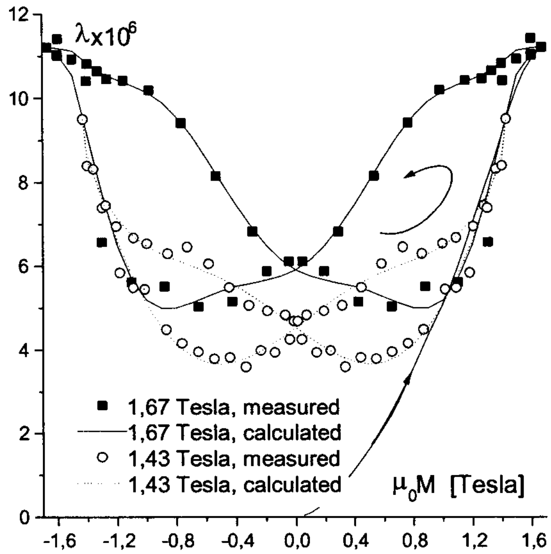

FIG. 3. Comparison of measured and calculated magnetostriction loops.

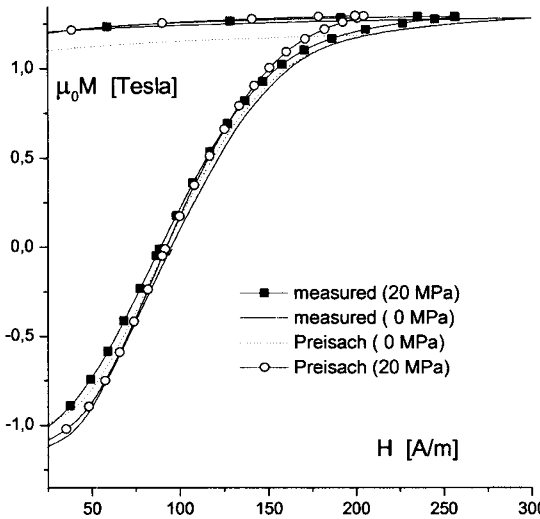

FIG. 4. Comparison of measured and calculated magnetization loop at 20 MPa tensile stress and $\mu_0 M_{\mathrm{peak}} = 1.3$ T.

$\phi_\lambda(\alpha,\beta,t)$ equal to $+1$ in case $\alpha+\beta<0$ and to -1 for $\alpha+\beta>0$. The virgin magnetostriction at magnetization M (>0) is defined as $\phi_\lambda(\alpha,\beta,t)$ equal to $+1$ in case $\alpha+\beta<0$ or $\alpha<M$, while $\phi_\lambda(\alpha,\beta,t)$ equals -1 in the other cases. This Preisach model also describes the lift-off phenomenon, resulting from the presence of a reversible and irreversible magnetostriction component and observed experimentally.[5,12]

C. Preisach magnetization model under mechanical stress

When the changes in stress and magnetostriction are small and reversible, a thermodynamic relation between the change of magnetization $\mu_0 M$ with stress σ, and the change of the strain λ with the magnetizing field strength H can be given[5]

$$\left(\frac{\partial\lambda}{\partial H}\right)_\sigma \sim \left(\mu_0 \frac{\partial M}{\partial\sigma}\right)_H . \quad (5)$$

Equation (5) suggests a modification of the effective field by introducing an additional stress field H_σ, see, e.g., Ref. 6. The total effective field H_e then becomes

$$H_e = H_a + \kappa M + \frac{3\sigma}{2\mu_0}\left(\frac{\partial\lambda}{\partial M}\right)_{\sigma,T} . \quad (6)$$

A Preisach analysis for the description of the magnetization loops (absence of external mechanical stress) of the material considered in the previous section has been performed according to former techniques.[10]

A magnetization loop under mechanical stress $M_\sigma[H(t)]$ can be obtained from the loop without stress $M_0[H(t)]$ by introducing for each time point t_i a modification of the magnetization level, such that at each time point one has $M_\sigma[H(t_i)] = M_0[H(t_i)] + dM_\sigma[H(t_i)]$, with

$$dM_\sigma[H(t_i)] = \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{\partial\lambda}{\partial M}\right)_{t=t_i}\left(\frac{\partial M}{\partial H}\right)_{t=t_i} . \quad (7)$$

As Eq. (5) only holds in case of reversible processes, dM_σ in Eq. (7) must be calculated using single-valued magnetization and magnetostriction characteristics. Therefore at each time point t_i, $M(H)$ is replaced by the anhysteretic curve $M_{\mathrm{an}}(H)$ and the magnetostriction loop $\lambda(M)$ by $\lambda_{\mathrm{an}}(M)$.

Figure 4 shows the measured magnetization loop without and with stress (20 MPa) as well as the corresponding magnetization loops calculated by the Preisach model using Eqs. (1) and (7).

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